Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 9165

A three-dimensional surficial geology model of southern Ontario

C.E. Logan, H.A.J. Russell, A.K. Burt, R.P.M. Mulligan, D.R. Sharpe, and A.F. Bajc

2024

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 9165

A three-dimensional surficial geology model of southern Ontario

C.E. Logan[1], H.A.J. Russell[1], A.K. Burt[2], R.P.M. Mulligan[2], D.R. Sharpe[1], and A.F. Bajc[2]

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario
[2]Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario

2024

Permanent link: https://doi.org/10.4095/pudw24j7tx

This publication is available for free download through the NRCan Open Science and Technology Repository (https://ostrnrcan-dostrncan.canada.ca/).

Recommended citation
Logan, C.E., Russell, H.A.J., Burt, A.K., Mulligan, R.P.M., Sharpe, D.R., and Bajc, A.F., 2024. A three-dimensional surficial geology model of southern Ontario; Geological Survey of Canada, Open File 9165, 1 .zip file. https://doi.org/10.4095/pudw24j7tx

Publications in this series have not been edited; they are released as submitted by the author.

ISSN 2816-7155
ISBN 978-0-660-70449-4
Catalogue No. M183-2/9165E-PDF

A three-dimensional surficial geology model of southern Ontario

Charles E. Logan[1], Hazen A.J. Russell[1], Abigail K. Burt[2], Riley P.M. Mulligan[2], David R. Sharpe[1], and Andy F. Bajc[2]

Abstract

To support improved groundwater geoscience knowledge for southern Ontario, a regional 3-D model of the surficial geology of southern Ontario has been developed as a part of a collaboration between the Ontario Geological Survey and the Geological Survey of Canada. Covering approximately 66,870 km^2 in area, the model is a synthesis of existing geological models, surficial geology mapping, and subsurface data. The model is a simplified 9-layer reclassification of numerous mapped local surficial sediment formations in places over 200 m thick with a total volume of approximately 2,455 km^3. The model integrates 1:50,000 scale surficial geology mapping with 90 m bathymetrically corrected topographic digital elevation model (DEM) and 8 existing local 3-D models. Archival subsurface data include 10,237 geotechnical and stratigraphic boreholes, 3,312 picks from geophysical surveys, 15,902 field mapping sites and sections, 537 monitoring and water supply wells and 282,995 water well records. Roughly corresponding to regional aquifer and aquitard layers, primary model layers are (from oldest to youngest): Bedrock, Basal Aquifer, Lower Sediment, Regional Till, Post Regional Till Channel Fill, Glaciofluvial Sediment, Post Regional Till Mud, Glaciolacustrine Sand and Recent Sediment / Organics. Modelling was completed using an implicit modelling application (LeapFrog®) complemented by an expert knowledge approach to data classification and rules-based Expert System procedure for data interpretation and validation. An iterative cycle of automated data coding, intermediate model construction and manual data corrections, expert evaluations, and revisions lead to the final 3-D model. A semi-quantitative confidence assessment has been made for each model layer surface based on data quality, distribution and density. This surficial geology model completes the development of a series of regional 3-D geological and hydrogeological models for southern Ontario.

[1] Geological Survey of Canada, 601 Booth St., Ottawa, Ontario K1A 0E8
[2] Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5

Corresponding author: Charles Logan (charles.logan@nrcan-rncan.gc.ca)

Logan, C.E., Russell, H.A.J., Burt, A., Mulligan, R.P.M., Sharpe, D.R., and Bajc, A.F. 2024. A three-dimensional surficial geology model of Southern Ontario. Geological Survey of Canada, Open File 9165. 36 p.

Contents

Introduction

The Geological Survey of Canada (GSC) and the Ontario Geological Survey (OGS) began a collaboration in 2015 to develop a regional 3-D geologic model of southern Ontario based primarily on existing subsurface data, geological mapping and local 3-D model publications. The current modelling effort is an attempt to distill and blend the interpreted data and conceptual knowledge developed over multiple decades of geological study and work producing 2-D and 3-D geological maps and models. This involved the development of two separate 3-D models – 1) a Phanerozoic bedrock model published in 2019 as a version 1 lithostratigraphic model (Carter et al., 2019), in 2021 as version 2 lithostratigraphic model (Carter et al., 2021) and in 2022 as a hydrostratigraphic model (Carter et al., 2022); and 2) the Quaternary surficial geology model initially documented in Logan et al., 2020 and a revised version documented and made available with this publication. A beta version of this 3-D model was used in a modified form in a regional, physically based, integrated groundwater–surface water model (Frey et al., 2019).

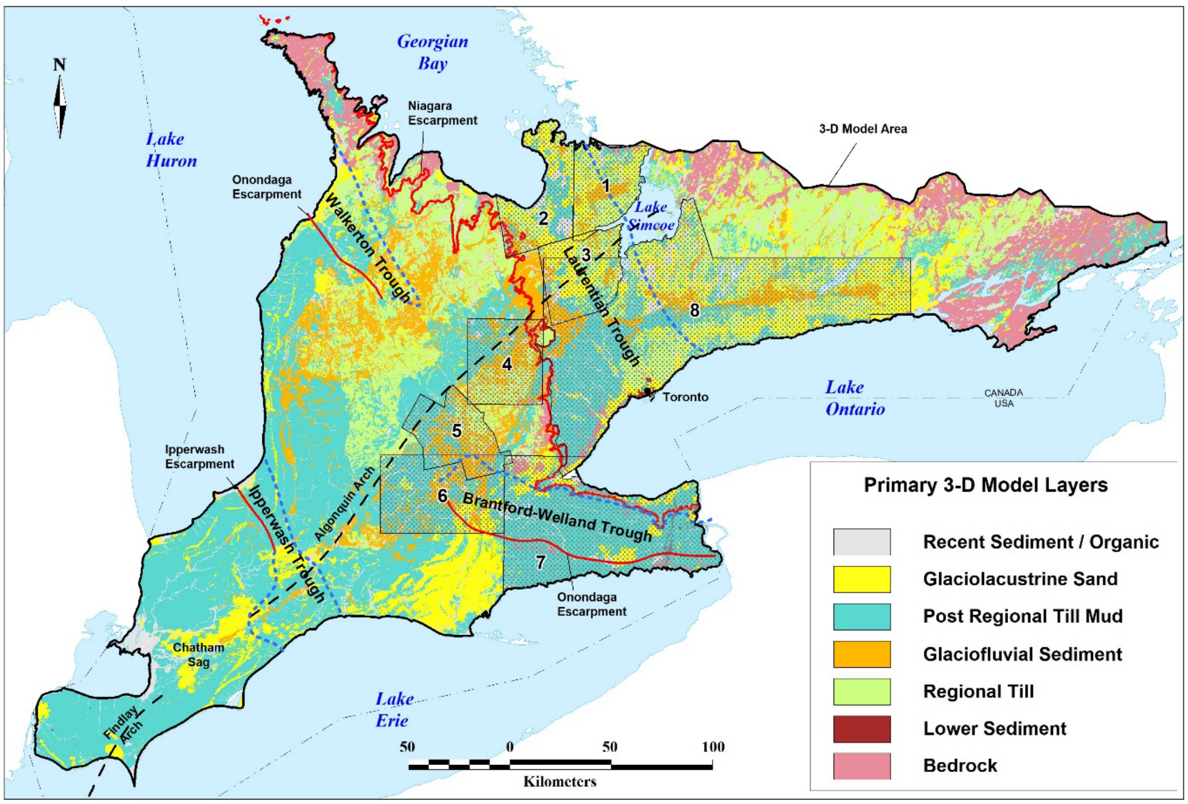
The surficial geology and companion bedrock 3-D models were developed in response to a need for increased clarity and regional context required to address province-wide and international issues related to groundwater resource safety and security in the Great Lakes Basin (e.g., Ontario's Clean Water Act S.O., 2006, c.22; International Joint Commission, 2015). Approximately 1,000,000 people rely on groundwater in southern Ontario for potable water and groundwater is an important source of water for agriculture and ecological function (e.g., Sharpe et al., 2014). Several related studies have been completed by the OGS and GSC in targeted localities across southern Ontario to better understand both bedrock and surficial sediment aquifer complexes (e.g., Brunton et al., 2007; Hamilton, 2015; Mulligan et al., 2018a; Gerber et al., 2018; Mulligan and Bajc, 2018; Sharpe et al., 2018; Mulligan, 2019;) including 3-D modelling efforts (Logan et al., 2005; 2006; Bajc and Shirota, 2007; Bajc and Dodge, 2011; Burt and Dodge, 2011, 2016; Bajc et al., 2014; Burt, 2017a, 2020; Mulligan, 2018;). Existing 2-D maps and 3-D models have involved using geoscience expertise to interpret preexisting subsurface data and some combination of new boreholes, shallow field reconnaissance sampling and geophysical surveys to refine a conceptual understanding of the geology (e.g., Russell et al., 2018; papers in Russell and Kjarsgaard, 2020).

The southern Ontario surficial 3-D model is a synthesis of current geological knowledge blending existing 3-D and 2-D products, archival geoscience and geotechnical data with the widespread coverage of Ontario water well logs accessed from the Water Well Information System (WWIS) to complete a seamless model for southern Ontario. Significant challenges were encountered in developing a viable surficial model due to both the geologic complexity of heterogeneous glacial sediment coupled with sometimes divergent conceptual realizations depicted in existing models that were developed independently over decades of work. The current regional model adheres to published maps and local 3-D models as closely as possible, however across the model area, changing geological processes and stratigraphic interpretations affect the consistency of the model. Consequently, as with all models, the authors recognize that subsequent investigation, data collection and new insights may result in refinements to portions of this model.

This report documents development of the accompanying digital 3-D model. Building on documentation from Logan et al. (2020), this report provides the final details on the datasets, methodology, and observations for the model.

Geological Setting

The southern Ontario surficial 3-D model occupies 66,870 km^2 and represents the Quaternary sediment cover extending from the Great Lakes in the south and west to the Precambrian margin in the northeast (Figure 1). Sediment consists of sequences of tills, glaciolacustrine, glaciofluvial, fluvial, and lacustrine sediments deposited over multiple glaciations (e.g., Barnett, 1992; Boyce and Eyles, 2000; Sharpe et al., 2002a; Burt, 2018; Bajc et al., 2019).



Surficial geology modified from MRD128-REV, Ontario Geological Survey, (2010)
Bedrock troughs modified from Gao, (2011)

Figure 1. 3-D Model study area with mapped surficial geology reclassified to primary model layers. Bedrock topography elements are shown for reference. Existing OGS and GSC 3-D model areas are shown as shaded regions: 1. Barrie-Oro Moraine (Burt and Dodge, 2011); 2. Central Simcoe (Mulligan, 2018); 3. South Simcoe (Bajc et al., 2019); 4. Orangeville-Fergus (Burt and Dodge, 2016); 5. Waterloo (Bajc and Shirota, 2007); 6. Brantford-Woodstock (Bajc and Dodge, 2011); 7. Niagara (Burt, 2017a, 2020); 8. Oak Ridges Moraine (Logan et al., 2005; 2006). Red lines indicate bedrock escarpments and blue dotted lines indicates the approximate margins of bedrock troughs.

Quaternary sediment unconformably overlies Paleozoic sedimentary bedrock strata of the eastern Michigan structural basin and the northern Appalachian foreland basin (Armstrong and Carter, 2010) as well as local inliers of underlying Precambrian crystalline bedrock to the north. Paleozoic strata straddle the southwest to northeast trending Precambrian Algonquin Arch and Findlay Arch structural highs (see Figure 1). The Niagara Escarpment forms a primary topographic divide across the model area with 100-250 m of local relief and up to 400 m of total relief on the bedrock surface extending from Georgian Bay southeast to Lake Ontario. West and south of the Niagara Escarpment, bedrock strata are lower Silurian to upper Devonian age (Armstrong and Carter, 2010) while Cambrian and upper Ordovician bedrock strata subcrop east and north of the Niagara Escarpment. Trending southwest of the Niagara Escarpment, lower Silurian to upper Devonian strata form a saddle structure with beds dipping off the flanks of the arches toward the Michigan basin in the northwest, the Appalachian basin in the southeast and between the arches into the Chatham Sag (Armstrong and Carter, 2010) (see Figure 1). Two other less-prominent bedrock escarpments extend roughly parallel to the Niagara Escarpment to the south and west – The Onondaga Escarpment and the Ipperwash Escarpment. Similarly, bedrock troughs are formed to the east of these escarpments – the Walkerton Trough and Brantford-Welland Trough next to the Onondaga Escarpment, and the Ipperwash Trough next to the Ipperwash Escarpment (see Figure 1) (Gao, 2011).

Running subparallel to, and east of the Niagara Escarpment, the Laurentian Trough extends from Lake Ontario to Georgian Bay (e.g., Eyles et al., 1985; Sharpe et al., 2018). Thicker sediment up to ~200 m (50.7 m avg.) occupies the lower elevation (70-130 m asl) bedrock trough and extends to the east, notably along the axis of the Oak Ridges Moraine (ORM). Glacial sediments in the eastern portion of the model area are dominated by pre-late Wisconsinan formations (Lower Sediment) up to ~175 m thick, which are overlain by regionally-extensive, drumlinized, sandy to silty-sand till commonly <30 m thick. Newmarket Till (Gwyn & DiLabo, 1973; Gwyn, 1976) is the most prominent such late glacial till across the Greater Toronto Area (GTA) (e.g., Sharpe et al., 2006). The commonly drumlinized stoney sandy-silt till east of the Niagara Escarpment, locally named Northern till (Boyce et al., 1995; Boyce and Eyles, 2000) and Bowmanville till (Brookfield et al., 1982), is here regarded as Newmarket Till. These sediments are dissected by elongate erosional features up to several kilometres wide, 175 m deep, and tens of kilometres in length (Brennand et al., 2006). Interpreted as tunnel channels/valleys, these features are infilled with thick successions of coarse-grained glaciofluvial sediment (up to ~100 m thick) and capped locally by predominantly muddy glaciolacustrine deposits (up to ~30 m thick). Thick deposits of stratified glaciofluvial sediment (locally up to ~100 m) above the regional tills form pronounced topographic expressions (e.g., Oak Ridges Moraine, Oro Moraine). Broad till plains, that may include Lower Sediment, regional till equivalents (e.g., Catfish Creek Till), younger glaciolacustrine muds and muddy tills, or some combination of these dominate the terrain to the west of the Niagara Escarpment with a combined thickness of up to ~150 m (35.3 m avg.). Larger accumulations of Lower Sediment occur near Paris, Ontario (up to ~50 m thick) and deposits of glaciofluvial sediment near Waterloo, Brantford and Orangeville form stratified moraine deposits (up to ~70 m thick). Across the entire model area, thinner mud-rich tills, glaciolacustrine muds and sands blanket large areas (up to ~45 m thick). Minor recent lake, river, wind-blown and organic deposits complete the surficial geology landscape throughout the model area (see Figure 1).

Modelling Procedure

Model Layers

The surficial geology model layers are broad generalizations that group widespread and/or spatially disconnected but chronologically, episodically or texturally similar formations. Published geological studies over the past 100 years (e.g., Taylor, 1912; Chapman and Putnam, 1984; Karrow, 1967, 1974; Barnett, 1992) are the basis for the till stratigraphic framework used in this 3-D model. Continuous core, seismic profiles and measured sections were used to develop sedimentological and stratigraphic context (e.g., Morris and Kelly, 1997; Pugin et al., 1999; 2011; Sharpe et al., 2003; Bajc et al., 2014b; 2019; Burt, 2017b, 2018, 2020; Burt and Chartrand, 2014; Pugin et al., 2011). The current 3-D model groups local diachronous formations into simplified layers suitable for a regional synopsis as documented in Logan et al. (2020), however the model layers have been revised. The current model layers are groupings of multiple geological units representing regional-scale hydrostratigraphic units. The model consists of 9 layers (from oldest to youngest): 1) Bedrock, 2) Basal Aquifer, 3) Lower Sediment, 4) Regional Till, 5) Post Regional Till Channel Fill, 6) Glaciofluvial Sediment, 7) Post Regional Till Mud, 8) Glaciolacustrine Sand and 9) Recent Sediment / Organics. In two cases, model layers represent a collection of texturally or chronologically distinct units that are individually too underrepresented in the data (i.e., Lower Sediments) or too texturally indistinct (i.e., Post Regional Till Mud) to be resolved separately in a regional model. The addition of the Basal Aquifer layer, the Post Regional Till Channel Fill layers and the merging of the upper till formations with glaciolacustrine mud into Post Regional Till Mud highlight the model layer changes from those described in Logan et al. (2020). Table 1 outlines the model layers and local unit names and/or materials they comprise.

Table 1. Model layer summary with geological map units from Barnett (1992) and Ontario Geological Survey (2010). Local unit names, common properties and references are provided.

Age	3-D Model Layer	Material(s) / Stratigraphic Formation(s)	Properties
Holocene	**Recent Sediment / Organics**	organics, colluvium, alluvium, eolian, lacustrine sediment	Thin, discontinuous. Fine to coarse grained sediment and organics
	Glaciolacustrine Sand	glaciolacustrine sand	Thin (10 - 15 m), discontinuous. Fine to medium sand
	Post Regional Till Mud	glaciolacustrine mud	Thin (10 - 15 m*), discontinuous. Varved silt and clay with minor sand Up to 30m thick, discontinuous massive silty clay to silty sand till and laminated clay and silt (Karrow, 1967, 1974; Sharpe and Russell, 2016)
		Dunkeld Till	
		Halton Till	
		Kettleby Till	
		Mornington Till	
		Maryhill Till	
		Neustadt Till	
		Port Stanley Till **	
		Rannoch Till	
		Stratford Till	
		St Joseph Till	
		Southern Till	
		Stirton Till	

Late Wisconsinan		Tavistock Till **	
		Wartburg Till	
		Wentworth Till	
	Glaciofluvial Sediment	Galt Moraine	Up to 150 m thick, coarse-grained stratified kame, esker and subaqueous fan deposits comprising stratified moraines ((Barnett et al., 1998; Sharpe et al., 2002a; Russell et al., 2004; Bajc et al., 2014a,b; Burt, 2018; Sharpe and Russell, 2023)
		Oro Moraine	
		Oak Ridges Moraine	
		Paris Moraine	
		Orangeville Moraine	
		Waterloo Moraine	
	Post Regional Till Channel Fill	Glaciofluvial and/or Glaciolacustrine fms	Thick beds of sand to sandy silt within incised channels up to 150 m thick (Russell et al., 2003)
	**Regional Till ** **	Catfish Creek Till	10-30 m thick (locally up to 70 m), dense, compact, over-consolidated sand-silt till. Local equivalents: Northern (Boyce et al., 1995) and Bowmanville tills (Brookfiled et al., 1982)
		Elma Till	
		Leaside Till	
		Newmarket Till	
Middle Wisconsinan to Illinoisan	**Lower Sediment**	Thorncliffe Formation	Wide range of textures and physical properties including diamicton, gravel, sand, mud, organics (Karrow, 1967)
		Canning Till	
		Lower Stony Till	
		Meadowcliffe Till***	
		Port Hope Till	
		Sunnybrook Till	
		Scarborough Formation	
		Don formation	
		York Till	
	Basal Aquifer	Basal aquifer	Sand, gravel and fractured bedrock
Paleozoic - PreCambrian	**Bedrock**	Bedrock	

* Thicknesses up to 100m have been identified locally (e.g., Bajc et al., 2019)
** Drumlinized areas of Port Stanley Till and Tavistock Till have been grouped with Regional Till in the area between the Orangeville and Waterloo Moraines.
***mud diamicton local to Scarborough Bluffs; likely debris flow and part of Thorncliffe Formation glaciolacustrine sequence

Primary Borehole Data

The 3-D modelling software utilizes borehole log contacts as the primary data source for modelling. The southern Ontario 3-D model is based on borehole data from multiple sources. The data has a range of measurement and interpretation accuracy that requires some consideration when applying to model building. Based on data quality (accuracy and data content), boreholes are assigned to three classes. Class 1 consists of the lowest quality Ministry of Environment, Conservation and Parks (MECP) water well boreholes. Using secondary location information (e.g., lot/concession) roughly 30% of possibly mislocated water wells were removed, however some poorly located wells may persist. In addition, both reported depths and textural descriptions have limited reliability due to commonly used drilling methods that crush and/or mix sediments with drilling fluids (Russell et al., 1998). Water well material descriptions commonly lack geological plausibility (e.g., the lack of till descriptions and overuse of 'clay' term) (Russell et al., 1998). As a result, well logs may not provide realistic thickness estimates for some geological units and sediment associations. Class 2 boreholes are more reliable, accurately located, measured and recorded for geoscience investigations or geotechnical engineering assessments. Both Class 1 and 2 boreholes have only been logged in terms of generic material descriptions. Class 3 boreholes match the measurement accuracy of Class 2 but materials are interpreted sedimentologically and classified stratigraphically by geoscientists. Class 3 boreholes are strategically located to assess stratigraphic, hydrostratigraphic and sedimentological controls and unit properties often extending to bedrock depth. For example, in the Oak Ridges Moraine study, continuously-cored boreholes were positioned to calibrate seismic surveys targeting buried channel structures. Measured sections from river cuts and lake bluffs and shallow field holes used for reconnaissance and 2-D geological mapping are treated as Class 3 shallow boreholes. Borehole sources and summary statistics are shown in Table 2.

Table 2. Borehole data inputs for modelling grouped according to data class.

Data Quality Class	Agency	Data Source	Data Type	No. of Boreholes	Avg. Units per Borehole	Avg. Depth (m)	% to Bedrock
1	MECP	WWIS	borehole log	282995	4.2	27.7	45.6
2	Conservation Ontario	publication	borehole log	2	32.5	60.5	100
	OGS	various	borehole/meas. Section	2173	6.1	13.7	9.8
	OGS	various	shallow hole/field mapping	8899	1.6	1.4	0.9
	MTO	hardcopy	borehole log	408	3.8	11.6	27.7
	MECP	PMN	borehole log	134	6.7	37.4	20.1
	GSC	UGAIS	borehole log	3135	4.1	5.3	1.8
	GSC	WAGAIS	borehole log	3841	3.6	7.9	3.7
	Reg. Municipalities	digital database	borehole log	165	6.8	39	46.7
	GSC	digital database	shallow hole/field mapping	329	1.5	2	0.3
	University of Waterloo	digital database	borehole log	3	6.7	14.2	66.7
3	GSC	digital database	cored borehole (simplified)	33	53.5	107.4	48.5
	GSC	digital database	shallow hole/field mapping	2513	1.5	1.67	0.5
	OGS	various	cored borehole/meas. section	2186	6.8	18.6	21.4
	OGS	various	shallow hole/field mapping	3584	1.1	1	10.5
	OGSRL	OPDS	Bedrock top pick	199	NA	NA	100
	Consultant	various	borehole log	328	4	14.4	2.4
	MTO	hardcopy	borehole log	1053	3.3	15.3	25.7
	IWA	digital database	borehole log	255	9.8	37.9	14.5
	Consumers Gas	digital database	borehole log	76	3.5	5.3	40.8
	EC	digital database	borehole log	1	9	46.3	100
	Eldorado Nuclear Ltd.	digital database	borehole log	127	5.2	20.4	4.7
	LLRWMO	digital database	borehole log	89	3.4	7.7	12.4
	MECP	digital database	borehole log	86	8.7	101.9	38.4
	Reg. Municipalities	digital database	borehole log	192	9	64.3	29.2
	Siting Task Force	digital database	borehole log	66	6.4	19	6.1
	TTC	digital database	borehole log	22	7.4	28.6	0
	GSC	UGAIS	borehole log	500	5	11.3	6
	University of Guelph	digital database	borehole log	3	4	18	0

Organizations: EC - Environment Canada; GSC - Geological Survey of Canada; IWA - Interim Water Authority - LLRWMO: Low-Level Radioactive Waste Mgt. Office; MECP - Ministry of Environment, Conservation and Parks; OGSRL - Oil, Salt, Gas Repository Library; OGS - Ontario Geological Survey; MTO - Ontario Ministry of Transportation; TTC - Toronto Transit Commission

Data management systems: OPDS - Ontario Petroleum Data System; PMN - Provincial Monitoring Network; UGAIS - Urban Geology Automated Info. System; WWIS – Water Well Info. System; WAGAIS - Waterloo Area Geology Automated Info. System

Additional Model Control

In addition to the borehole logs and measured field sections, model control was enhanced by including digital meshes (surfaces), points and polylines. Both data measured below ground surface and data at ground surface are used. Additional sub-surface data consists of digitized unit contacts from geophysical surveys (e.g., seismic profiles) and unit surface meshes from local 3-D models. Ground surface data control for this model is a 1:50 000 scale digital geological map draped onto a topographic DEM. The 3-D geological map polygon boundaries are used to directly control model layers by mitigating data coverage gaps and aligning the model with surficial mapping. The application of these data controls will be discussed in later sections and are summarized in Table 3.

Table 3. Additional surface and subsurface data sources.

Data Type	Detail	Source
OGS 3-D models	1 km spaced surface point grids	Bajc and Shirota, (2007); Bajc and Dodge, (2011); Burt and Dodge, (2011, 2016)
Seismic profiles	260.4 line kilometres, interpretations and picks	Dietiker et al., (2019); Pugin et al., (1999, 2011, 2018)
Surficial geology 1:50,000	Map Polygon contacts, points and pseudo-boreholes	Ontario Geological Survey (2010)
Bathymetrically corrected DEM	SRTM plus published and unpublished bathymetry resampled to 400 m resolution	References in Logan et al., (2020)
Channel points	400 m spaced point grids	(Russell et al., (2003) Brennand et al., (2006)

Data Preparation

Contacts recorded in borehole logs are the primary source of data for the model. Although other types of data can be used to help estimate model surfaces, borehole logs are most useful since the entire formation depth interval is used in conjunction with the established layer chronology to control and potentially limit the 3-D volume of multiple layers. All sub-surface data collar / ground surface elevations are aligned to the topographic DEM that forms the upper 3-D model boundary to maintain consistency.

Geology Map-based Data Control

OGS surficial geology mapping at 1:50 000 scale (OGS, 2010) was used to provide the stratigraphic framework for the 3-D model. The surficial map is a compilation of decades of geological mapping in Ontario. Geological map unit names were re-classified to model layers (see Table 1 and Figure 1). In most cases this grouping was straightforward, however, some local tills did not appear to conform with the current and earlier OGS 3-D models. Regions of mapped drumlins were used as secondary evidence to support re-classification of mapped upper till to the older regional till (i.e., Catfish Creek Till). Based on this, in the Orangeville area, drumlinized portions of the till at lower elevations were coded as the Regional Till layer - a departure from the local OGS model. Higher-elevation, non-drumlinized portions that overlie Glaciofluvial Sediment (e.g., Orangeville Moraine) were modelled as Post Regional Till Mud layer. In the Brantford area, however, a small number of drumlins were disregarded as evidence for Regional Till. Here, till at higher elevation and overlying the Glaciofluvial Sediment was regarded as a rare occurrence of drumlinized Port Stanley Till (D Cowan, pers. correspondence) and classified as Post Regional Till Mud layer to be more in line with OGS modelling in this area.[1] Additionally, a small number of possible Lower Sediment polygons (total area 6.8 km^2) contained contradictory attributes and were re-evaluated based on expert knowledge. Those that indicated 'stratified sediment' and those that either did not include a named Lower Sediment formation name (e.g., Thorncliffe) or those that included non-Lower Sediment formation names (e.g., Halton Till) were assigned to younger model layers based on their geographic position and elevation. Based on expert assessment, to the south of the Oak Ridges Moraine, Lower Sediment has only been recorded at surface in river cuts where Newmarket Till is missing and base flow is enhanced or at other lower elevation locations nearer to Lake Ontario. These re-classed map polygons may need to be re-evaluated in the field to confirm this interpretation of the OGS geology map.

Three features were derived from the surficial geology map to help control the interpolated model surfaces: 1) Pseudo-boreholes, 2) 3-D point grids, and 3) 3-D map contact lines. The elevation of the topographic DEM was applied to add the 3-D component to these 2-D map features.

1. *Pseudo-Boreholes*

A pseudo borehole data set was developed for each model layer based on a regular 1000 m grid. Grid points were assigned the model layer code of the map polygon within which they are located. Grid points were compiled into a borehole collar table format using the point coordinates and DEM elevation. A related borehole lithology table was also compiled with a single 1 m depth record for each grid point and the corresponding mapped stratigraphy code. The modelling process utilizes the top contact of borehole depth intervals to interpolate upper layer contact surfaces, however borehole depth intervals will also suppress older layers. Thus, using map geology grid points as pseudo-boreholes has the advantage of not only helping to better align model layer surfaces with their mapped polygon equivalents, but also preventing older surfaces from breaching younger surfaces where the younger surfaces are mapped. Additionally, because the depth interval bottom does not directly control the layer bottom contact, a small depth will not cause the layer to be thinner than it should be. The disadvantage to using map polygon-based pseudo-boreholes is the computational complexity that a

[1] The validity of these exceptional configurations relies on geomorphological interpretation going back several decades and may be subject to reassessment with new data, process models and discussion.

large number of boreholes adds to the model processing. It was found that a 1 km grid resulted in a manageable number of pseudo-boreholes for the size of model area (i.e., 67,621).

2. 3-D Point Grids

Compared to the detail of mapped surface features, gridded map polygon pseudo-boreholes at 1000 m spacing provide only coarse resolution formation control. To ensure adequate geology map control, formation polygons are also gridded with additional points between the pseudo map polygon boreholes to reduce the spacing of surface control to 500 m. They are set to topographic DEM elevation and included directly as less computationally-demanding 3-D points into the model. These points provide surface elevation control for only the corresponding model layer and have no effect on older layers. Polygon centroids from mapped areas less than 250 km^2 that were not represented by other grid points are also added to include smaller mapped areas. These grids added a total of 204,719 3-D points to the model.

3. 3-D Map Contact Lines

Polylines can be directly added as surface interpolation support. To enhance the effect of geology map-based 3-D point grids, the mapped formation polygon boundaries are also extracted and added to model data support. Since older model layers take priority over younger layers in the modelling process, only the polyline contacts with younger layer formations were added to the data support for a given layer. Adding contacts with older layer formations would be redundant since these would already be included in the support for older model layers.

Figure 2 shows geology map-based data controls on a north-south cross section through the 3-D model in an oblique view to the east.

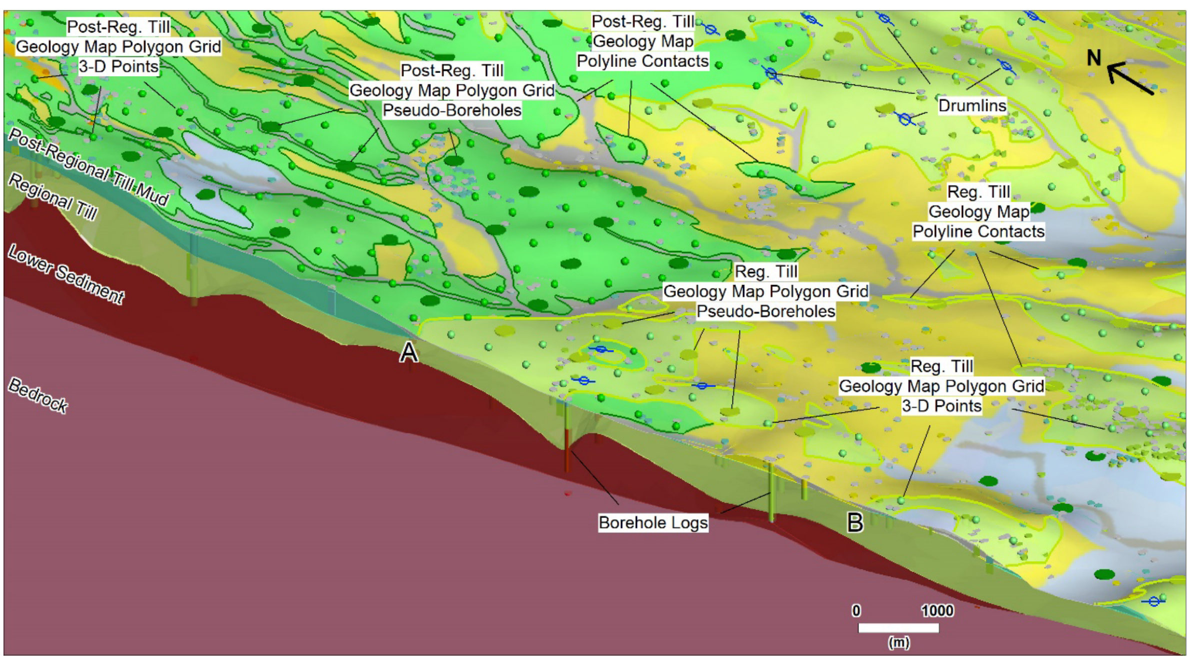


Figure 2. Oblique cross-section of 3-D layers illustrating geology map-based data controls. The younger Post Regional Till Mud layer (dark green objects) and the older Regional Till layer (light green objects) are highlighted to illustrate the data components. Large disks represent pseudo-boreholes in a regularly spaced 1000 m grid. Small dots represent 3-D points at a 500 m grid spacing. Geology map polyline contacts are also indicated (bold polygon outlines). At location 'A', pseudo-boreholes and 3-D points for the younger Post Regional Till Mud layer help the layer surface match the mapped extent while the pseudo boreholes also help to suppress the older Regional Till layer. At location 'B', the Regional Till layer surface is controlled by pseudo-boreholes, 3-D points and borehole contacts. At both locations A and B, the surface of Regional Till is also controlled by geology map contact polylines.

Seismic Profiles

Over 260 total line kilometres from 52 seismic profile lines were used to help control buried channel structures and related landforms. Contact lines were directly digitized on 3-D registered seismic profiles in the modelling software and added to the corresponding inputs to control surface estimations.

Local 3-D Models

Eight existing 3-D models focussed on smaller areas of southern Ontario were incorporated into the regional surficial model (See Figure 1 and Table 3). Boreholes prepared for local models were compiled as part of the model borehole datasets, and in addition, surfaces from four of the 3-D models were used directly. From models covering Barrie (Oro Moraine), Orangeville (Orangeville Moraine), Brantford (Paris Moraine) and Waterloo (Waterloo Moraine), surfaces equivalent to Lower Sediment, Regional Till, Glaciofluvial Sediment and Post Regional Till Mud were sampled and converted to 3-D points. To generalize the higher level of detail in local model layers and to better blend them with the coarser regional model, surfaces were sampled with a regular 1000 m spaced grid. These 3-D point grids were added to the corresponding model layer control datasets for surface interpolations.

Semi-Automated borehole stratigraphic interpretation

Class 1 and 2 borehole data consists of logged depth intervals with descriptive material terms. These terms are generic textures (e.g., silt, clay, gravel etc.) in either free-form descriptions or parsed into one or more fields. A reclassification / sorting algorithm was used to apply a more standardized geologically meaningful material code to log intervals. This process is a simplified version of the process documented in Logan et al. (2005, 2006) and mainly resolves similar terms into standard codes (e.g., 'stones', 'pebbles', 'cobbles' to 'gravel'), identifies term combinations that are likely to be a diamicton (e.g., 'clay' + 'stones') and identifies sequential intervals that indicate bedrock terms that are actually gravel (e.g., 'limestone' with non-bedrock term below).

Using a preliminary model built on Class 3 data and geology map-based data controls for guidance, an automated process for interpreting and coding Class 1 and 2 standardized material logs was then used. The elevations of preliminary model layer surfaces, the distance to control data and the mapped geology within which the boreholes are located were added to an attribute table for Class 1 and 2 data. The algorithm is a rules-based Expert System that attempts to fit appropriate materials to stratigraphy within a geometry defined by the preliminary model. Firstly, the uppermost (surface) interval is evaluated for inclusion in the mapped geology within which it is located. The process then proceeds to lower/older intervals. Acceptable materials, maximum thicknesses and maximum interbed thicknesses are factors that influence whether log intervals can be automatically coded near the depths of the preliminary surfaces. The constraints used are not necessarily definitive characteristics of the model layers. They are generalizations that help the automated algorithm achieve reasonable results based on data of limited quality (Table 4). All preliminary surfaces were only used up to a maximum distance from control data of 2000 m. Intervals that could not be interpreted in this process are given generic codes (i.e., UAF - undifferentiated aquifer, UAT - undifferentiated aquitard, UT - undifferentiated till, US - undifferentiated silt) for later use within the modelling software to help with manual selection and coding tools.

Table 4. Summary of automated coding constraints used for each model layer.

Model Layer	Acceptable Materials	Max Thickness (m)	Max Interbed Thickness (m)
Recent / Organic	organic, sand, silt	10	0
Glaciolacustrine Sand	sand, silt	20	1
Post-Reg. Till Mud	Diamicton (silty-sand to sand, sandy-silt to silt, clayey-silt to clay), silt, clay	50	1
Glaciofluvial Sand	gravel, sand, silt	60	2
Post Reg. Till Channel Fill	gravel, sand, silt	60	2
Regional Till	Diamicton (silty-sand to sand, sandy-silt to silt, clayey-silt to clay), clay	40	2
Lower Sediment	(all except bedrock)	150	1
Basal Aquifer	gravel, sand	5	0
Bedrock	Bedrock terms	NA	NA

Automated Anomaly Detection

Preliminary auto coding is next analysed with an anomaly detection process. To mimic the process of visually inspecting large numbers of borehole intervals in 3-D view to identify visible anomalies for potential removal, we use an automated anomaly detection process based on contact elevation and interval thickness of model layers coded in each borehole compared to those of nearby boreholes. The anomaly detection involves examining each borehole log location (test borehole) in turn and assembling a set of boreholes within a moving capture window (comparison boreholes) centered on the test borehole. First, elevation values are determined from each layer upper contact in the selected comparison boreholes and the average and standard deviation (σ) is found. Similarly, the average thickness and σ is found for the comparison dataset. Only those coded intervals with a coded bottom contact depth are used to confine the comparison to layer intervals with valid top and bottom depths. The total number of comparison boreholes within each cartesian quadrant centered on the test borehole are also tabulated.

A 'high' contact elevation anomaly is indicated if the test elevation is greater than the average contact elevation plus 3 times σ. A 'low' contact elevation anomaly is indicated if the test elevation is less than the average contact elevation minus 3 times σ. Thick or thin thickness anomalies are similarly determined. Assuming a normal distribution of comparison values, the mean +/- 3 times σ will statistically contain almost all values (i.e., 99.7%), while any value beyond this range is considered a potential outlier. Also, to qualify as an anomaly, comparison boreholes must exist in at least 3 of the 4 cartesian quadrants centered on the test borehole. Class 2 and Class 3 borehole contacts and thicknesses are given higher weights of 2x and 5x the weight of Class 1 respectively. The weights of Class 1 and 2 boreholes are doubled for those that have passed testing thus giving these more influence on the averages moving forward through the dataset. To eliminate the influence of identified anomalies on the evaluation of subsequent boreholes, they are flagged and not included in the statistics for testing subsequent boreholes. Elevation and thickness anomalies are then tabulated and evaluated in 3-D context.

In the modelling software, partially coded intervals were visually inspected in a series of parallel cross-sections and, when necessary, manually selected and re-assigned as corrected model stratigraphy or removed from model control using bulk selection and re-coding tools guided by nearby data trends in 3-D context. For the surficial geology model, only regionally extensive layers with significant buried portions were suitable for automated checking – Regional Till and Lower Sediment. It was found in this model area that for Regional Till, a capture window of +/- 2000 m and for Lower Sediment, a capture area of +/- 1000 m yielded the best balance between maximizing confirmed anomalies and minimizing false positives.

3-D Model Building

The southern Ontario surficial 3-D model development involved an iterative cycle of semi-automated borehole data coding, automated borehole data anomaly checking, data anomaly inspection, removal/correction of confirmed anomalies, intermediate 3-D model construction with all control data, and manual inspection and revised coding of Class 1 and 2 borehole log data. After manual code revisions, the semi-automated interpretation process was utilized to correct stratigraphic sequence errors and fill in coding gaps where possible and the anomaly detection process was re-applied.

The 3-D model was developed with Leapfrog® Works geomodelling software, version 2023.1.1. The modelling software utilizes a Radial Basis Function algorithm, FastRBF™, to estimate surfaces from control data. In the implicit model, a layer contact surface is defined as the zero set of a Radial Basis Function fitted to the contact data (Carr et al., 2001). The modelling process first establishes contact surfaces of all model layers as controlled by upper contacts in borehole logs and other vector data. Then, based on set chronology and surface type, the software resolves overlaps and constructs layer volumes between interpolated surfaces. Surface estimation can optionally avoid other formation intervals and as done in this modelling procedure, formations with indeterminate bottom depths (due to log gaps or boreholes terminated before encountering bedrock) were avoided by older formation surface interpolations. This has the effect of older surfaces being limited in elevation by younger formation log depth intervals if warranted.

A primary 3-D model was first developed using well-defined bedrock / sediment log contacts and mapped bedrock outcrop points and mapped polygon areas using the topographic DEM as the upper extent. This model consists of only two layers: bedrock and undifferentiated surficial sediment. The preliminary bedrock / surficial sediment model was developed early in the southern Ontario modelling project and served to define a 3-D boundary for the development of the companion lithostratigraphic bedrock model (Carter et al., 2021). In a secondary 'refined' model, the undifferentiated sediment volume provided a 3-D boundary within which the surficial sediment layers were developed.

The refined model was developed from the oldest to the youngest layer by defining upper contact surfaces. For sedimentary layer modelling, the software provides two surface type options that affect the way overlapping surfaces are resolved into 3-D volumes: erosional and depositional. Where surfaces overlap, erosional type surfaces will remove portions of older volumes, while depositional type surfaces will terminate at older surfaces to emulate onlapping. All layer surfaces were developed as depositional in the refined model except for Regional Till. The Regional Till surface represents a regional unconformity (Sharpe et al., 2004) which has been drumlinized and truncated by tunnel channels, thus the potential for abrupt topographic changes warrants the potential effect of the erosional surface type. Figure 3 illustrates the effect of surface type on the model layer volumes.

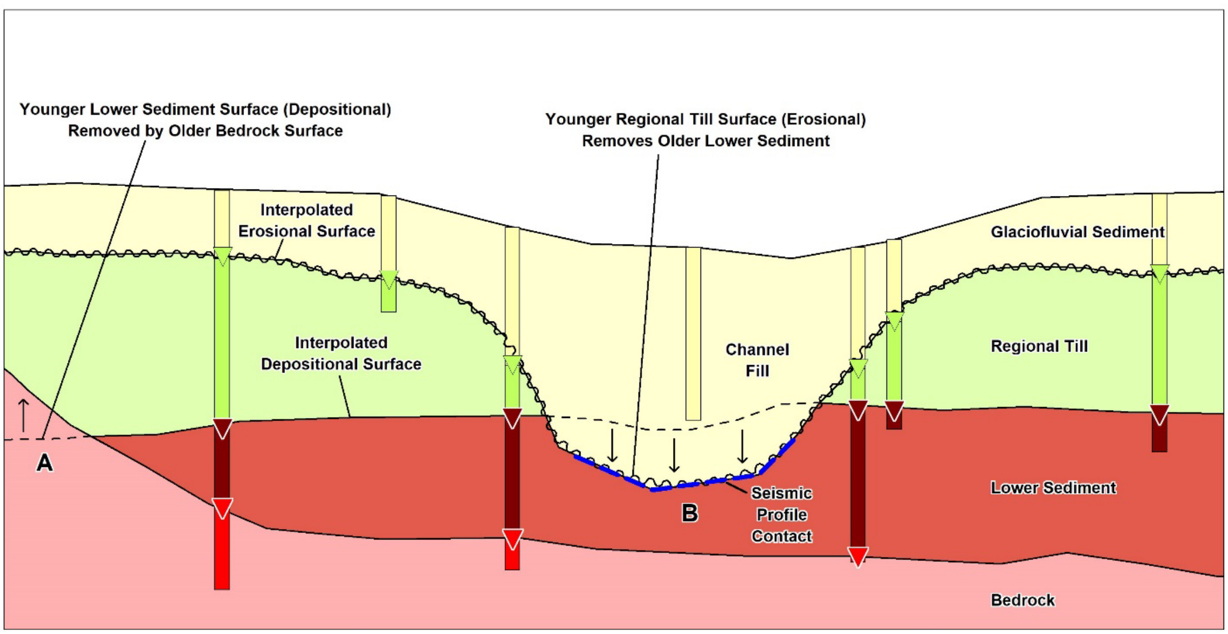


Figure 3. Conceptual cross-section showings the effects of interpolated surface type on layer volumes. Triangular points represent borehole contacts used to make the upper surface of like-coloured layers. A) Two depositional surfaces overlap causing truncation of the younger volume. B) The younger erosional surface overlaps an older depositional surface causing the removal of the older volume. In this conceptualization, the depressed Channel Fill base is controlled by a seismic contact (blue dashed line).

To limit the potential influence of data noise from poor quality of Class 1 water well log locations, depths and material descriptions, surfaces are set to snap only to Class 2 and 3 data, pseudo BH contacts and seismic profiles. Max snap distance is set for all surfaces to 2% of resolution (400 m) or 8 m. The snap distance is measured from the default surface to the input data. The default surface is developed by the software for each layer without snapping to input data for reference. With snapping set on, the actual interpolated contact surface will only snap to contact data if the distance is less than the max snap distance.

Model Layer Development

Model layers are developed from oldest to youngest based on the following considerations:

1.Basal Aquifer

The Basal Aquifer layer is defined by thin (<4 m), coarse-grained borehole intervals identified at the base of Lower Sediment directly on or within 3 meters of the bedrock surface. This layer is a subset of Lower Sediments that includes reported fractured bedrock. Selected log intervals occur infrequently in the data coverage especially in areas of thick (>50 m) total sediment where few water wells contact bedrock. In thick sediment, water wells are commonly completed within Post Regional Till aquifer formations or into upper portions of pre-Regional Till aquifer formations included within Lower Sediment (e.g., Thorncliffe Formation) that occur well above bedrock. As such, the resulting layer volume likely underrepresents a more laterally extensive layer. This is an additional layer to those described in Logan et al., (2020).

2. Lower Sediment

The Lower Sediment layer is comprised of sediment formations of Illinoisan to mid-Wisconsinan age that often include sandy, water-bearing units with intervening aquitards (see Table 1) (e.g., Karrow et al., 2001). Organic-rich and fossil-bearing beds are characteristic of the Scarborough Formation (Karrow, 1967), which forms most of the lower portions of this layer east of the Niagara Escarpment. The vast majority of this layer, (99.95%) based on surficial geology mapping (OGS, 2010), is buried beneath younger sediment. It is primarily defined by identifying the base of the more distinctive overlying Regional Till aquitard formations where subsurface data extends to sufficient depth.

3. Regional Till

Regional Till comprises several regionally-extensive sandy-silt tills (e.g., Newmarket Till, Catfish Creek Till) that are typically compact and display relatively uniform thickness (10 – 30 m) over large distances. Sandy interbeds (1-3 m) can occur as well as cementation and fracturing that may complicate the accurate determination of the unit base. The Regional Till upper surface is an erosional unconformity. Locally, if data trends dictate, this erosional surface may extend downwards as a result of erosion into Lower Sediment or further into bedrock. This can occur most commonly within exposed and buried tunnel channels (see Figure 3). The regional trend of this layer surface can abruptly change over small distances (1-5 km) due to the presence of tunnel channel features. Tunnel channels cross-cut the overall sub-horizontal to drumlinized Regional Till.

4. Post Regional Till Channel Fill

Where not completely buried (e.g., Newmarket Till uplands north of the ORM), tunnel channels/valleys are typically identified as linear to sinuous topographic depressions commonly with underfit streams and, where they host lakes (e.g., Lake Scugog, Kawartha Lakes) or marshy landscapes (e.g., northern parts of Holland Marsh), the resulting scarcity of water well and geotechnical logs makes the interpretation of the sediment within them difficult based on borehole data. The nature and origin of tunnel channel fill is the subject of ongoing debate and requires more weight of evidence to resolve across the entire model domain. In the GTA, continuations of tunnel channels below thicker Glaciofluvial Sediment (ORM) have been confirmed with seismic profiles (e.g., Pugin et al., 1999; 2018) and targeted boreholes (Sharpe et al., 2003; Barnett, 2012) that have indicated that channel fill is mostly coarse-grained Glaciofluvial Sediment. However, such channel fills have fining-upward, gravel-sand-mud sequences (Sharpe and Russell, 2023) sometimes similar to glaciolacustrine mud. In some areas, particularly low-lying areas north of the ORM (Simcoe County), tunnel channel/valley fill includes a larger portion (up to 108.6 m) of mud interpreted as glaciolacustrine (Mulligan et al., 2018a,b; Bajc et al., 2019). Tunnel channels range from approximately 500 m to over 6 km wide (typically ~2-3 km wide) and extend for tens of kilometres roughly north-south across the east portion of the model area (Russell et al., 2003). A departure from the layer structure described in Logan et al., (2020), the Post Regional Till Channel Fill layer was developed separately from Glaciofluvial Sediment to allow a more flexible model that could be adapted to multiple scenarios for potential model usage, such as hydrogeological modelling. Established within mapped channels and interpolated Regional Till depressions, this layer can be regarded, where confirmed, as mud or sandy silt and hydrogeological parameters adjusted accordingly.

5. Glaciofluvial Sediment

Glaciofluvial Sediment deposited during deglacial events are typically stratified coarse grained materials with minor clay layers. Up to ~ 100 m thick, Glaciofluvial Sediment comprises known deposits of large, stratified moraines (e.g., Oro, Oak Ridges, Orangeville, Waterloo) consisting of subglacial, subaqueous fan, fan to delta and ice-marginal sediment (Barnett et al., 1998; Burt and Dodge, 2011; 2016; Bajc et al., 2014b; Burt 2018; Sharpe and Russell, 2023). Glaciofluvial Sediment deposits typically occur as discontinuous topographically high landforms, however a variety of sediment and landforms are possible. For example, the Oak Ridges Moraine forms a west to east trending hummocky ridge across the eastern part of the model that was deposited under changing subglacial to proglacial conditions resulting predominantly in gravels, sands, silt-clay rhythmites and minor diamictons often in fining-upward sequences (Barnett et al., 1998; Sharpe and Russell, 2023). Paris and Galt moraines are characterized by hummocky terrain with ridges and secondary landforms (e.g., kettles, eskers, subaerial fans, and channels) composed of sand, gravel and loose stony-sand diamicton (Russell et al., 2013). Stratified Orangeville and Waterloo moraines are primarily composed of large, sandy fans.

Aside from local areas buried by overlying low permeability, Post-Regional Till Mud (e.g., western Oak Ridges, Orangeville and Waterloo moraine flanks), Glaciofluvial Sediment is relatively well-defined where mapped at ground surface and by the presence of coarse-grained material in borehole logs. In areas of thick Glaciofluvial Sediment, water wells are often completed within viable aquifers of the unit. The lower contact here is, thus, often under sampled. However, when encountered, the lower contact is generally well-defined by the transition from coarse-grained sediment to fine-grained, dense Regional Till sediment. The main exceptions occur where Regional Till and some or all Lower Sediment have been removed in tunnel channels.

6. Post Regional Till Mud

The Post Regional Till Mud layer is a composite of upper tills (including late glacial muddy and locally silty to sand tills) and glaciolacustrine mud (see Table 1). Upper tills overlie the flanks of stratified moraines throughout the model area (e.g., Waterloo, Orangeville and Oak Ridges Moraines). Thick, muddy glaciolacustrine mud and fine-grained diamicton is the dominant sediment package across much of the Niagara Peninsula (Burt, 2020). These units were described separately in Logan et al., (2020), but were modelled together here because, having similar fine-grained texture, upper till and glaciolacustrine mud are not reliably differentiated using water well log descriptions unless corroborated with surficial geology mapping. Additionally, interbedded upper till and glaciolacustrine laminated muds have been observed in outcrop (Sharpe and Russell, 2016). This complexity is beyond the model resolution and, unless these units are combined, potential alternating borehole log intervals would disrupt layer chronology causing interpolation problems. With similar textural characteristics, these combined formations are suitable for future hydrogeological modelling. The Post Regional Till Mud layer is relatively thin (typically 10-30 m) and predominantly defined by surficial mapping and to a lesser extent by the transition of mud to either compact till or coarse-grained material (e.g., Burt, 2020). There can be some ambiguity with the lower contact transition as this layer can directly overlie sediment from all older till units, sometimes with similar texture. Thickness constraints (<40 m) as well as control from surficial mapping helped to define this layer in the model.

7. Glaciolacustrine Sand

The thin Glaciolacustrine Sand unit is generally defined by the extent of 2-D surficial geology mapping. Locally, in the Waterloo area, it is represented as older than glaciolacustrine mud in the literature (e.g., Bajc and Dodge, 2011) including some archival borehole data. As layer chronology must be established in the modelling software, and complex layer interfingering was beyond the resolution of the model and data support, glaciolacustrine sand was selected to be younger than Post Regional Till Mud. A small number of out of sequence data in archival data was not used to prevent modelling problems. It is restricted to thin surface sand intervals (<10 m).

8. Recent Sediment / Organics

The remaining post-glacial to recent alluvium, eolian and organic material are combined to form the youngest model layer. This layer is only interpreted in very thin surface borehole intervals (typically <3 m) and where mapped at surface.

Screen Depth Influence

Screen depth intervals exist in 29.8% of water well logs. After encountering a viable aquifer formation, wells are completed in unlithified sediment by installing an impermeable casing down to a permeable screen within the aquifer to allow water flow. Shallower, low yield or smaller aquifers may be encountered, however the screened aquifer is typically selected based on water quality and well yield. It is therefore assumed that the screened aquifer represents a significant (more laterally extensive and permeable) water-bearing sediment formation and unscreened, thinner coarse-grained intervals likely represent poorly connected minor units or interbeds. Although materials and depths are not always reported accurately and thoroughly in well logs, as the primary reason for the well, it can be reasonably assumed that screens are accurately measured for depth and that they represent a more laterally extensive coarse-grained unit. Besides bedrock aquifers in areas of thin sediment, the primary sources for domestic water supply that are commonly screened are either within upper units within the Lower Sediment, Post Regional Till Channel Fill and Glaciofluvial Sediment. To exploit this secondary data, a database algorithm was developed to compare intermediate model layer depths at water well locations with reported screen depths. If the screen interval was within 5 m of the upper or lower depth of the Lower Sediment or Glaciofluvial Sediment, then the screen interval was flagged and included in the borehole data support for the corresponding layer. This has the effect of more closely aligning the water-bearing model layers with the more accurate screen interval depths.

Manual Edits

To enhance the continuity of tunnel channels/valleys in the 3-D model, some manual intervention was applied in the form of 3-D points and polylines. Within the modelling software, the construction of polylines and points can be made in 3-D space using data visualizations for context. These objects can then be used to help guide surface interpolations as manual edits. Although the model is predominantly controlled by the data components outlined in previous sections, some manual editing was undertaken using preliminary models, boreholes, seismic profiles and the surficial geology draped on the topographic DEM for guidance. Edits were added to offset data gaps and better depict layer geometries based on expert guidance and nearby data.

Subsurface data contact points that are dispersed wider than the size of buried features will be unlikely to encounter them let alone support their accurate rendering. Ideally, data spacing 2 or 3 times less than the dimensions of landforms would be more appropriate to properly resolve their geometries and continuity in a fully data-driven model. This level of data support is not realistic at regional scale and many landform details are therefore beyond the scope of this model.

Glacial features such as eskers, drumlins, moraines and incised tunnel channels/valleys mapped at ground surface are valuable for developing conceptual models of regional glacial processes. All but large-scale features like moraines and tunnel channels are too small to be fully rendered at the model resolution (400 m) and level of data support when obscured by younger sediment. The presence and continuity of buried tunnel channels/valleys in particular may significantly influence groundwater flow (e.g., Sharpe et al., 2002a) thus select tunnel channels/valleys were confirmed at depth with targeted seismic and downhole geophysical logging (Pullan et al., 2002; Crow et al., 2018). With sporadic data coverage, however, the trend of the overall surface overwhelms that of channels. The continuity of buried tunnel channels/valleys has been confirmed with cored boreholes, seismic profiles and hydraulic testing (e.g., Barnett et al., 1998; Sharpe et al., 2013; Gerber et al., 2018; Bajc et al., 2019), however one or a few profiles across channels 1-3 km wide and many 10s of km long are not sufficient for the modelling software to render them accurately. Where parallel seismic profiles exist on a channel (e.g., Holland Marsh tunnel channel/valley; Sharpe et al., 2018), polylines were constructed to join the channel/valley cross-sections. Some channel/valley lengths are supported by hydraulic monitoring to reach 20 km (Gerber et al., 2018), however, since not all tunnel channels/valleys were tested, the cross-sections of single profiles were very conservatively extended ~2 km along the estimated channel course. Minor polyline edits were also used beyond lateral model boundaries to improve layer continuity up to model edges.

Additionally, tunnel channel classes as mapped in Russell et al., (2003) were used to develop sets of 3-D points to enforce the partial or full removal of sediment formations. Class 1 tunnel channels are those that extend to bedrock while Class 2 tunnel channels have had only Regional Till eroded. Tunnel channels from Russell et al. (2003) were extended to cover the 3-D model area south and east of Lake Simcoe using surficial geology draped on the topographic DEM (Fig. 4) while modelled areas west of Lake Simcoe are guided by more recent surficial and subsurface investigation (Bajc et al., 2019; Burt and Dodge, 2011).

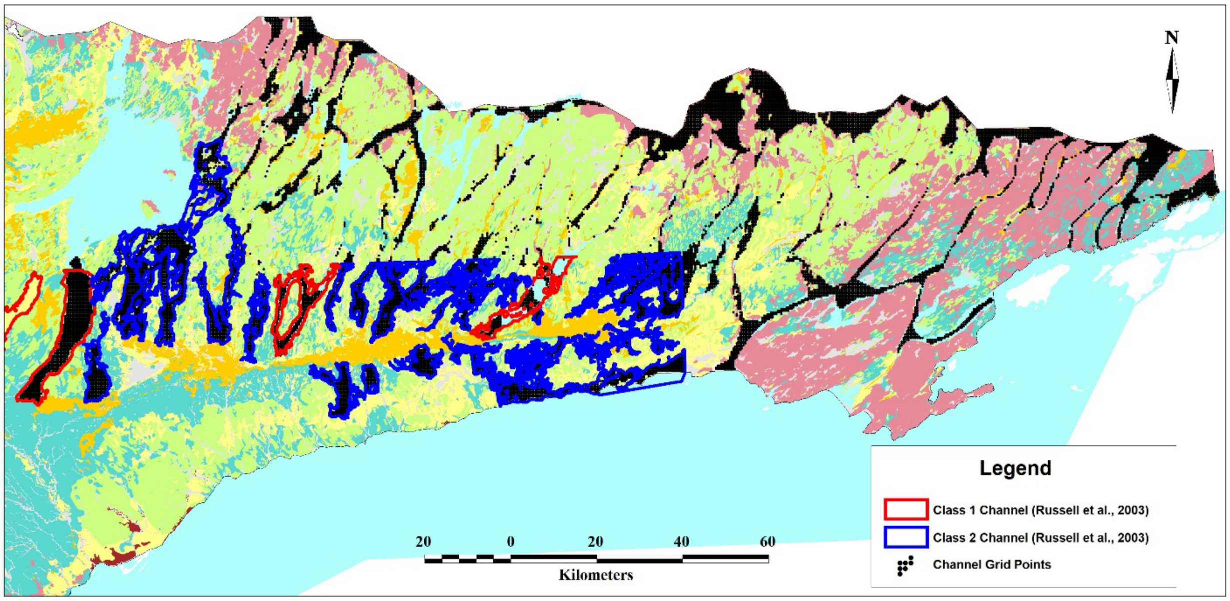


Figure 4. Tunnel channel classes modified from Russell et al., (2003) and channel grid points extrapolated to cover eastern portion of the 3-D model area. Class 1 tunnel channels are eroded down to bedrock and class 2 tunnel channels are eroded through Regional Till down to Lower Sediment. Refer to Figure 1 for surficial geology legend.

To facilitate this manual correction, a regular grid of points was constructed within tunnel channel boundaries at 400 m spacing. The points were set at an elevation below the elevations of preliminary bedrock and Lower sediment surfaces for Class 1 and 2 respectively. Adding Class 1 and 2 tunnel channel point datasets to the surface contacts for Regional Till and Class 1 tunnel channel points to Lower Sediment surface contacts acts to depress the interpolated surfaces below older formations thus removing their volume. These corrections affect only the portion of tunnel channels that are visible at ground surface to ensure that Regional Till does not infill them as a result of the interpolation connecting adjacent Regional Till-capped uplands where no other control data exists within the tunnel channel to prevent it (Fig. 5). With this correction, Post Regional Till Channel Fill and other younger formations are instead allowed to occupy buried valleys. The complex, time-transgressive and multi-episodic nature of regional glacial geology makes it difficult to clearly support a single conceptual model that applies to all buried tunnel channels/valleys in the model area. Since more than one scenario is possible, local interpretations had more influence on channel architecture where seismic data were lacking. For example, channel correction points were not applied to mapped tunnel channels to the northwest of Lake Simcoe where ongoing study interprets Regional Till within tunnel channels/valleys (e.g., Bajc et al., 2019).

A more accurate depiction of buried tunnel channel shape and location would require additional seismic profiles spaced 3 or 4 kilometres apart across the thalweg of the channels, however the manual extensions at least support a conservative rendition of areas of possible aquitard breaches. Although past work has supported the likelihood of tunnel channel-related aquitard leakance in the GTA (Desbarats et al., 2001), additional hydrogeologic study would be needed to test / confirm channel aquifer connectivity and the degree of aquitard leakance indicated by this model's channel architecture. As thorough regional testing is economically unfeasible, continued focussed testing is needed to support the conceptual tunnel channel model. Water balance estimates to date support a tunnel channel breaching scenario in the Oak Ridges Moraine area (Gerber et al., 2018).

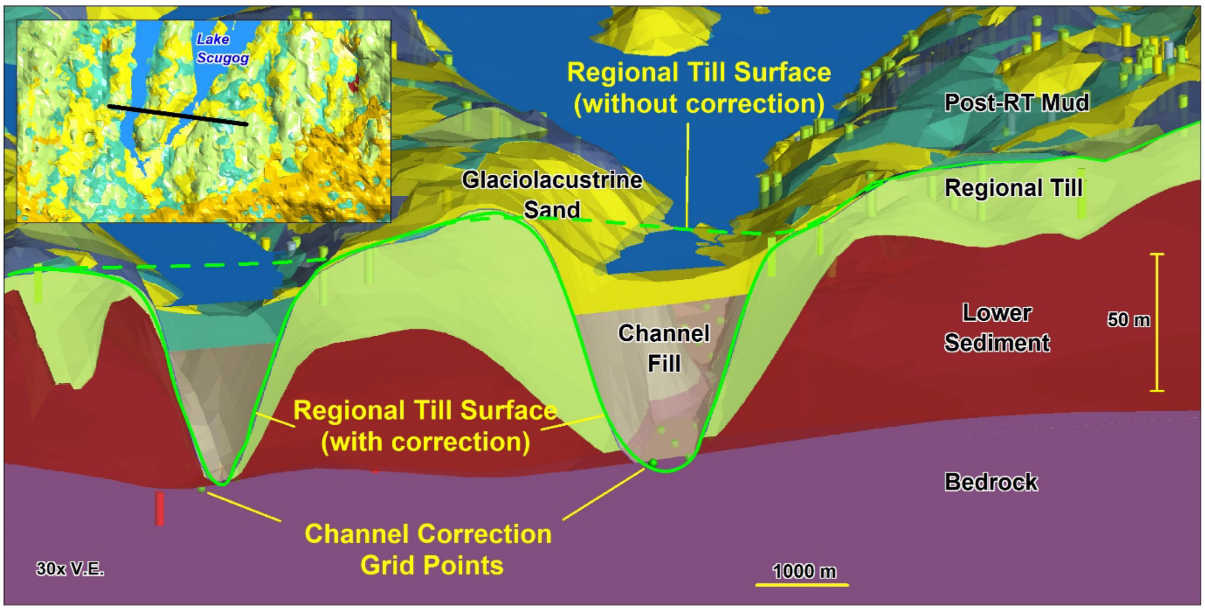


Figure 5. Perspective view of 3-D model with west-east cross-section across the south of Lake Scugog (inset) viewed from the south. The effect of channel correction grid points (green points) can be seen where the interpolated Regional Till surface interpolation is prevented from connecting borehole contacts spanning channels where little/no subsurface data occurs. Dashed green line indicates Regional Till surface interpolation without correction and solid green line indicates surface interpolation with correction.

Expert Guidance and Iterative Model Inspection

At the onset of model development and at various times throughout, the model conceptual geology was established, refined and used to assess intermediate model results. Both OGS and GSC geoscientists currently working in southern Ontario with decades of experience mapping, deriving process models and contributing to the collective geologic knowledge of the region have examined model layers in 3-D context. Feedback was used to refine and correct automated coding and other data issues in an iterative cycle towards approaching a consensus final structural model.

3-D Model Results

The distribution, thickness and other aspects of the modelled units are described in the following sections. Descriptive information is supported by isopach maps (Figure 6) and cross sections (Figures 7, 8).

Layer Summary

Lower Sediment (including Basal Aquifer)

The Lower Sediment occurs in disconnected volumes and in varying amounts throughout the model area. Lower Sediment is almost fully buried beneath other younger formations. It only accounts for 32.2 km^2 or 0.05% of the model's surface area based on OGS mapping (OGS, 2010). As with most other model layers, the thickness and distribution of Lower Sediment change significantly across the main bedrock topographic feature in the area – the Niagara Escarpment. From the 3-D model, the volume of Lower Sediment comprises 28.8% of the total volume of sediment, however west of the Niagara Escarpment it is only 10.3% while to the east it is 51.5%. The mean thickness is 26.7 m in the west and 44.4 m in the east with standard deviations (σ) of 11.4 and 35.3, respectively, reflecting the thicker, more variable geometry in the east. In the east, Lower Sediment forms a thick volume of sediment that occupies the Laurentian Trough from Georgian Bay to Lake Ontario possibly due to the accommodation space of the bedrock trough. Lower Sediment extends further east including a wedge of sediment running west to east underlying the Oak Ridges Moraine (Glaciofluvial Sediment) and south to Lake Ontario. This bulge of sediment may be the result of similar deposition during earlier glaciation phases (Barnett et al., 1998), however much Lower Sediment is glaciolacustrine in origin and not prone to forming sediment ridges (Sharpe et al., in prep). Hence, it is likely an artifact of the paucity of data at depth below the ORM. For sparse, deep wells completed within thick Glaciofluvial Sediment, a small number of mis-identified Lower Sediment log intervals can have an exaggerated effect and may incorrectly raise the surface of Lower Sediment. The Niagara Escarpment is believed to have been a significant natural barrier that influenced the development of the Laurentian Trough and the thick sedimentation therein during glacial advance/retreat oscillations in the Quaternary (Brunton et al., 2010; Sharpe et al., 2018; Sharpe et al., 2023). Basal Aquifer occurs as a patchwork of discrete, thin volumes at the bedrock-Lower Sediment interface. These were selected in borehole logs as coarse-grained intervals, restricted to less than 5 m in thickness and within 2 m of bedrock. Reported fractured bedrock at the bedrock/sediment contact were also included. The model size, resolution and lack of data where thick sediment occurs has likely caused this layer to be less continuous than it is believed to be, an effect also noted in the local Orangeville-Fergus 3-D model (Burt and Dodge, 2016).

Regional Till

The Regional Till occurs relatively consistently across the entire model area. The 3-D model volume of Regional Till is 33.5% of the total sediment volume. West of the Niagara Escarpment it comprises 38.2% of the sediment with an average thickness 15.1 m while in the east it comprises 27.7% of the sediment with an average thickness of 16.6 m. Thickness is relatively consistent west to east and, along with similar σ values of 10.2 and 14.4 respectively, it reflects a more tabular till sheet geometry. The tills that comprise the Regional Till model layer (mainly Catfish Creek, Elma and Newmarket tills) are known to be widespread dense, sandy silt diamictons, with generally low thickness variability (Barnett et al, 1998; Sharpe et al., 2002b; Bajc and Shirota, 2007; Bajc and Dodge, 2010; Bajc et al., 2019; Burt and Dodge, 2011; 2016). A notable exception is the Niagara Peninsula area where dense, sandy silt diamictons rarely exceed a few metres (Burt, 2020). A regional stony, sandy silt till was deposited as advancing ice eroded carbonate bedrock (Kjarsgaard et al., 2017). Areas of thin sediment downflow of bedrock escarpments and places where incised channels or drumlins occur cause abrupt geometry changes atypical of the regional trend. West of the Niagara Escarpment, the overall thin sediment, reliance on water well log data outside of OGS 3-D model boundaries and similarities in sediment textures make interpreting till, clay and mud descriptions difficult. Differentiating older Regional Till from the younger tills and glaciolacustrine mud that comprise the Post Regional Till Mud model layer relies on geological mapping synthesized from decades of independent work combined with interpretation of imprecise descriptions of archival water well records (Russell et al., 1998). An exception is likely associated with the identification of water-bearing sand and gravel units for which the drilling is targeted. Unless a coarse-grained formation intervenes, till/mud formations are often reported as a single, thick log depth interval with a generic description (e.g., clay, silt). For this reason, portions of the Post Regional Till Mud layer may extend too deep into what should actually be Regional Till where better quality subsurface data is lacking.

Glaciofluvial Sediment (including Post Regional Till Channel Fill)

The characteristics of Glaciofluvial Sediment change significantly from the west to the east side of the model. Like most other layers, Glaciofluvial Sediment is generally thinner and more widespread in the west. Overall, the Glaciofluvial Sediment comprises 15.1% of the sediment model. West of the Niagara Escarpment the percentage of the total volume is 18.4% and it is 11.0% in the east. The more discrete occurrences of highly variable Glaciofluvial Sediment in the ORM and Oro moraines in the east have a mean thickness of 20.1 m with a σ of 25.5. This contrasts with more dispersed less variable Glaciofluvial Sediment in the west with mean thickness of 12.7 m and σ of 10.9. Widespread deposits of thin (<20 m) Glaciofluvial Sediment interspersed with moderately thick (~40 – 90 m) moraines (Orangeville, Paris-Galt and Waterloo moraines) characterize the west portion of the model. Channel Fill material occurs primarily east of the Niagara Escarpment. It is present in lower portions of the Glaciofluvial Sediment and within known and extrapolated buried valleys with an average thickness of ~15 m, however it can be up to 200 m thick (Sharpe and Russell, 2023). Channel Fill occupies topographic lows in older layers that were explicitly modelled to coincide with mapped channels from Russell et al., (2003) that are locally corroborated with seismic profile data.

Post Regional Till Mud

Post Regional Till Mud is mapped over 39.6% of the model area yet it is relatively thin, comprising only 20.8% of the total 3-D volume. It is more widespread and continuous over the west part of the model area and more discontinuous in the east. It drapes the flanks of the Orangeville Moraine and it is the most prevalent unit on the Niagara Peninsula. Thicker sheets of this layer occur in the west with a mean thickness of 15.6 m. In the east, the Post Regional Till Mud occurs as thinner (avg. 8.8 m) deposits that drape the western flanks of the ORM, large swaths of Lower Sediment and Regional Till within the Laurentian trough and partially within exposed tunnel channels/valleys to the northeast. The Post Regional Till Mud is a low permeability layer that partially confines Lower Sediment and Glaciofluvial Sediment hosted aquifers (Burt, 2018).

Glaciolacustrine Sand

Glaciolacustrine Sand occurs as thin, highly dispersed and discontinuous surface units. Layer characteristics are consistent across the entire model area with a mean thickness of 4.1 m. The majority of Glaciolacustrine Sand volume extent coincides with corresponding areas from surficial geology mapping, however this layer may extend below Recent Sediment / Organic mapped areas.

Recent Sediment / Organics

The Recent Sediment / Organics layer, like Glaciolacustrine Sand, is very thin and dispersed with an overall mean thickness of 1.9 m. Consistent across the model area, Recent Sediment / Organics generally occupy local depressions (e.g., organic bogs and marshes), lakes (e.g., recent lacustrine), river valleys (e.g., recent alluvium) and areas with minor aeolian deposits. The Recent Sediment / Organics volume extent coincides with corresponding areas from surficial geology mapping.

Layer Volumes

Model volumes are provided with this publication in a format viewable in full 3-D context with navigation and cross-section tools using freely-available Leapfrog® Viewer software (available for download from the developer at the time of publication at https://www.seequent.com/products-solutions/leapfrog-viewer/). The model is also provided in 3-D DXF format – an industry standard for 3-D mesh surfaces (available from Open Maps (geo.ca): https://doi.org/10.23687/d9d3a8c5-b9a8-f90b-9a3c-a8f4d4027b95), and Open Mining Format (OMF) - an open-source format for use in compatible geomodelling software or custom applications (included with this publication). The following thickness isopach figures and cross-sections are an attempt to provide a broad overview highlighting the distribution of model layer sediment and the location of notable landforms found in the model (Figures 6, 7 and 8).

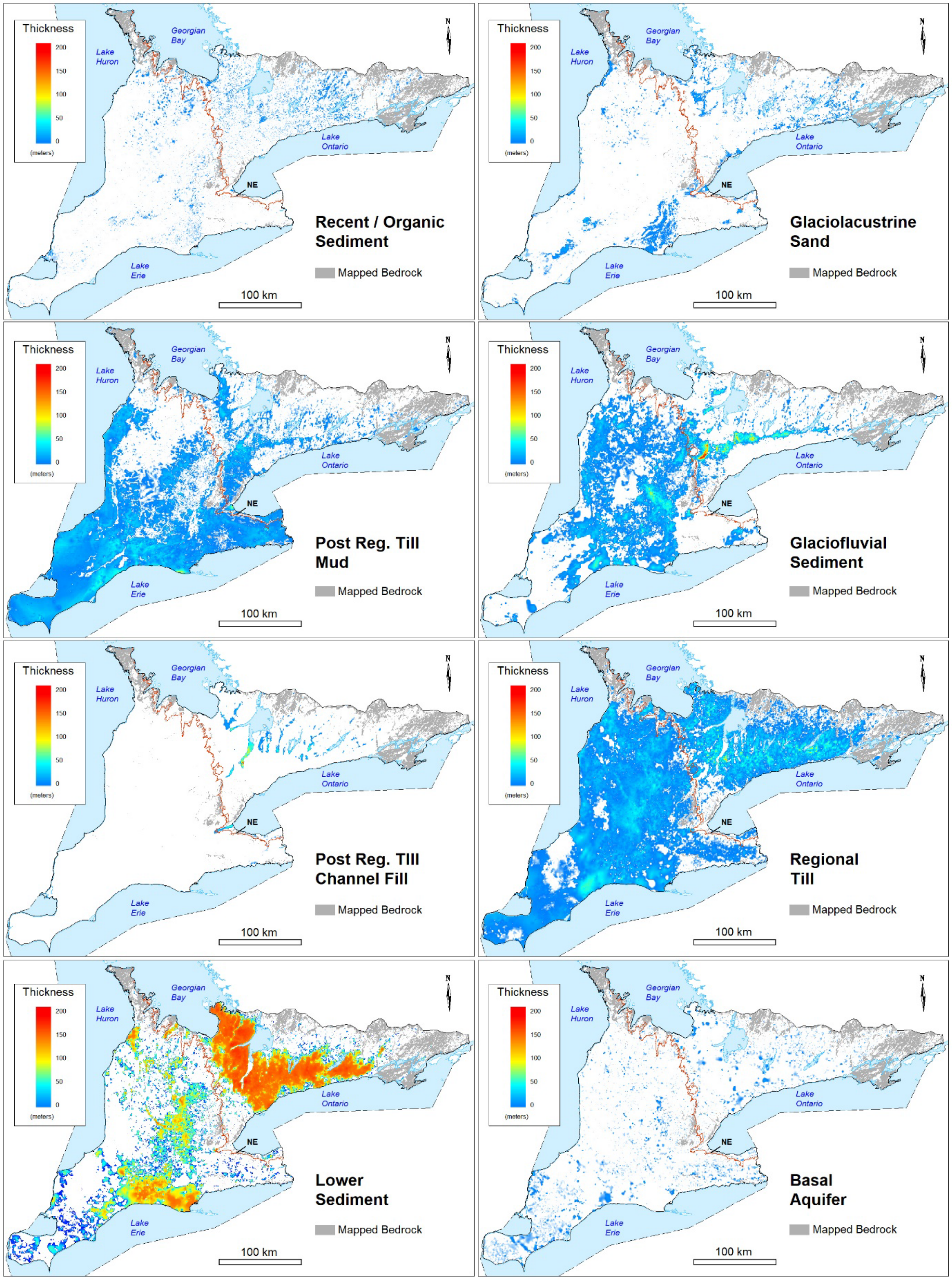


Figure 6. 3-D model sediment thickness isopach maps. Maps are shown with the same colour scheme to allow comparisons of the relative quantity of sediment from layer to layer as well as the overall

distribution of sediment for each layer. Mapped bedrock from MRD128-REV, Ontario Geological Survey, (2010). NE-Niagara Escarpment.

Model Cross-sections

The following cross-sections are produced directly from the accompanying 3-D model. Sections are located to include local OGS and GSC models. A very large vertical exaggeration (30x) was applied to make relatively thin (<200 m) formations visible across distances of many 10s of kilometres. As such, minor elevation differences are distorted causing very flat-lying formations with gradual topography changes to appear highly variable. Figure 7 shows the 3-D model in perspective with the locations of cross-sections. Cross sections profiles are shown in Figure 8.

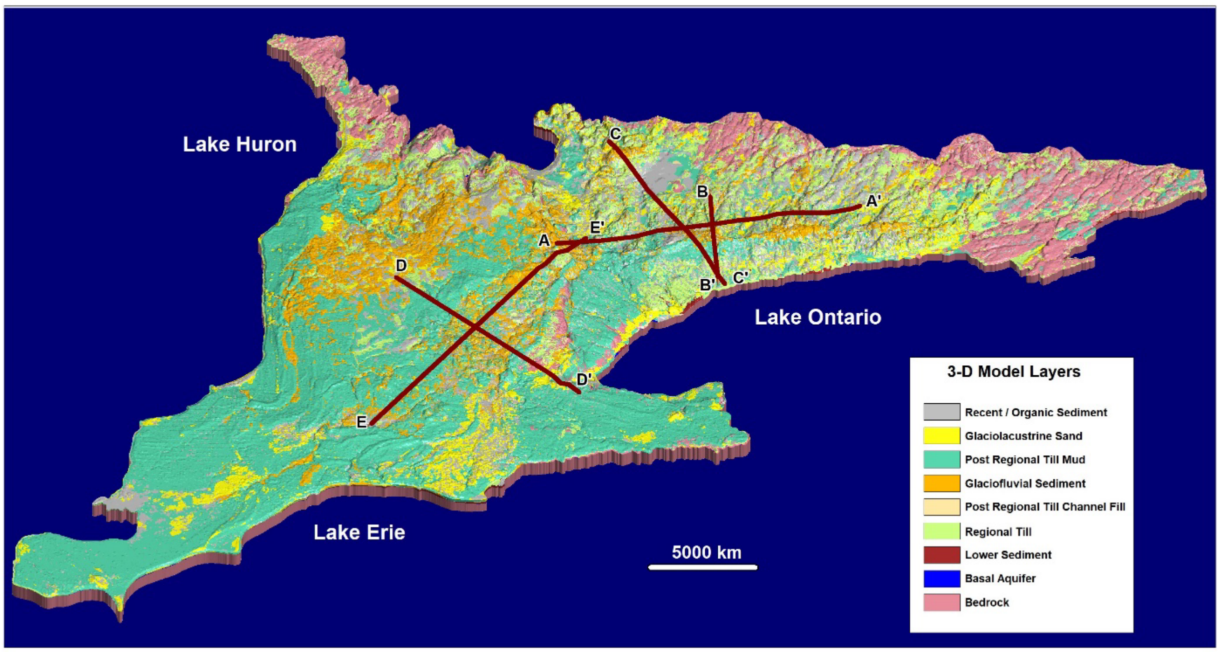


Figure 7. Surficial model in perspective view looking toward the north. Cross-sections shown in Figure 8 are labelled. Figure 8 cross section lines are shown. Cross section layer colours conform to this legend.

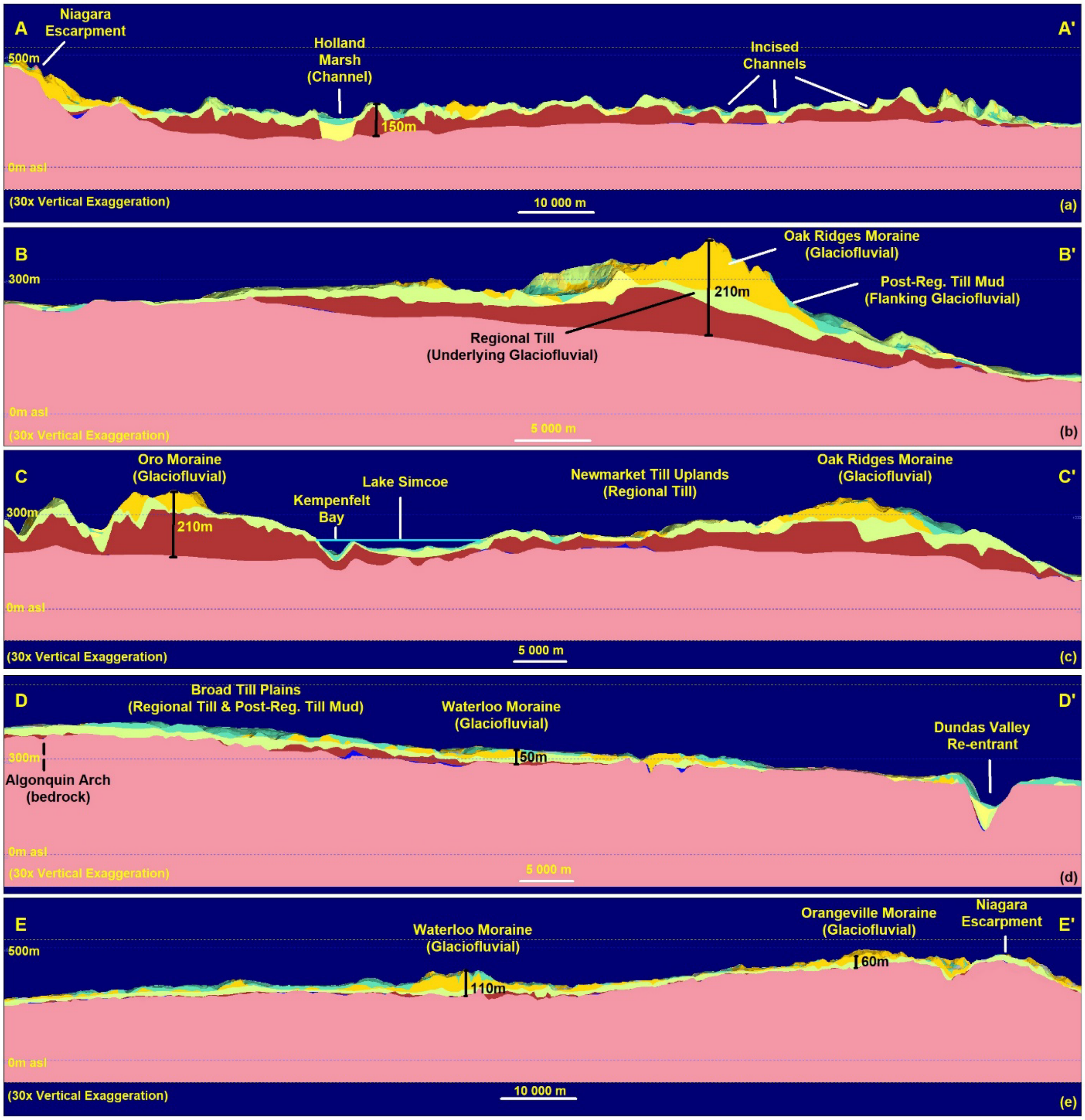


Figure 8. Surficial geology model cross-sections. Refer to Figure 7 for model layer colours. (a) Section A-A’ extends from the Niagara Escarpment in the west 150 km to the northeast parallel to and north of the Oak Ridges Moraine. The section traverses several incised tunnel channels/valleys in the Regional Till uplands including the Holland Marsh. (b) Section B-B’ is roughly 60 km long and runs perpendicular to A-A’. Thick Lower Sediment and Glaciofluvial Sediment is shown with continuous intervening Regional Till creating a low-permeability barrier and Post Regional Till Mud partially blanketing the southern slope of the Oak Ridges Moraine creating partial Glaciofluvial Sediment aquifer confinement. (c) Section C-C’ is sub-perpendicular to A-A’ and extends north of the Oro Moraine southward across Lake Simcoe, Regional Till uplands, and Oak Ridges Moraine to Lake Ontario for a total of 110 km. (d) Section D-D’ runs from the Niagara Escarpment and Dundas Valley near Hamilton 110 km to the northwest. A portion of the Waterloo Moraine is shown along with a disconnected volume of Lower

Sediment. Thin total sediment is apparent particularly in the broad till plains to the northwest. (e) Section E-E' runs roughly perpendicular to D-D' and the Niagara Escarpment approximately 160 km southwest. Both the Waterloo and Orangeville Moraines are shown in more representative thicknesses in contrast to the thinner surrounding till plains.

Model Confidence

Appropriate use of any model relies on understanding it's limitations. A measure of confidence applied to each layer has proven effective for establishing uncertainty in the companion lithostratigraphic bedrock model of southern Ontario (Bunn et al., 2022). Based on the diverse input data of varying quality, the highly variable formation layers and modelling process limitations, a more streamlined estimation of confidence will be used here. There are several factors that influence the overall confidence in the model layer geometry. They can be grouped into 3 broad types (Wellman et al., 2010): 1) data accuracy; 2) model uncertainty and 3) conceptual geologic model uncertainty. Data accuracy for the various archival subsurface data sources used in the southern Ontario surficial model are typically neither quantified nor reported. In some cases, uncertainty has been addressed qualitatively through inter data comparisons (e.g., Russell et al., 1998). The depths at which water well log formations are reported can be affected by the delay of cuttings washed to surface compared to the depth of the well bore during drilling and the skill and diligence of a wide variety of drillers over many decades. Cored borehole depths, although much more reliable, can be affected by core movement due to lost core within casings as well as basic measurement error. The accuracy of interpreted contacts on seismic profiles is affected by the contrast of seismic velocities at material contacts, the skill and experience of the geophysicists and the inherent accuracy of the measurement tools. The accuracy of map geology components depends on the scale of mapping, the supporting data and tools used (e.g., air photos, Digital Elevation Models) and the related generalization required to depict mapped formations. Some of these error quantities vary within datasets to an unknown degree and also from place to place within the region due to varying geology. All data used in the modelling is standardized to the topographic DEM for consistency and so elevation error can be associated with the accuracy and resolution of the DEM. The modelling process further complicates the assessment of confidence because interpolated layer surfaces actively avoid younger units in borehole logs. This means that surfaces are controlled not only by corresponding upper borehole contacts, they are also influenced by the base of younger intervals if they are deep enough to depress them. The subsets of younger intervals that affect older surfaces in this way are not possible to identify and their influence is not possible to isolate. A quantification of compounding type 1 data error would be incomplete or based on broad estimates and thus would be largely unreliable. Type 1 error will not be compiled in this exercise.

Type 2 model uncertainty assessment can be undertaken stochastically by producing a series of interpolation realizations based on model input perturbation (Wellman et al., 2010, Lindsay et al., 2012). The modelling software used to produce the Ontario surficial model does not allow automation of multiple realizations in this manner. Like the assessment done in Bunn et al., 2022, the model uncertainty will be regarded as the ability of the final model realization of each model layer upper contact surface to fit the corresponding data support.

The impact of type 3 conceptual model uncertainty can be significant but difficult to quantify. Moreover, in this model, the inclusion of published local 3-D models as data inputs would necessitate the assessment of varying conceptual understandings and biases for several smaller regions within the study area. An attempt to quantify type 3 error is beyond the scope of this publication, however the user is urged to refer to the local model publications for comparison.

For the above reasons, a qualitative assessment of confidence was developed based on proximity to and broad class of data control and related error quantity estimates will be based on type 2 error. Generally, the highest confidence of an interpolated surface will exist at the location of observed data dropping off to lower confidence with distance from data support at some rate of decay assuming all data is of equivalent accuracy. Given the relatively short distances involved, for simplicity, we assume a linear rate of decay from high to low confidence.

Fundamentally, ignoring type 1 errors, confidence is inversely proportional to data control distance (i.e., greater distance relates to lesser confidence and visa versa). For this model assessment, a 2-D location profile model is developed for each primary model layer upper surface. A location profile is a raster grid showing a measure of distance to data control points. Final location profiles are a blend of 3 preliminary profiles based on: 1) all data, 2) Class 2 data and 3) Class 3 data. The first preliminary location profile grid cells represent the average distance to the nearest 10 control data points using all data. By using the average distance to the nearest 10 control points, calculated grid cell values (i.e., distance) will be reduced where there are more nearby data and increased where there are less. This applies an increased confidence to locations where the surfaces are supported by more nearby data and less confidence to surface locations with sparse data control. Since the bulk of the model area relies on Class 1 (water well) data with potential location accuracy errors as well as the potential for large depth errors, high confidence is designated only for areas with several nearby data points. Using expert guidance, the maximum distance range for this profile is 2000 m. The second and third preliminary location profiles are radial distance buffer grids centered on the Class 2 and 3 datasets respectively (Note: Map polygon pseudo-boreholes are regarded as Class 3 data). The maximum number of points from which the distance is determined is set to 1 to cause the result to be a simple distance buffer where each cell represents distance to the nearest (single) data point. This results in high confidence at the location of all more reliable Class 2 and 3 data regardless of the proximity of other nearby data. Also, to reflect the higher quality of data in Class 2 and 3, the maximum distance range is set to 3000 m and 4000 m respectively. To simplify the location profiles, they are converted to a range of 0 to 1, 0 being the lowest confidence at the farthest distance and 1 being the highest confidence at the location of control data. This conversion is done with the following grid math formula:

[Confidence Grid] = 1 – ([Location Profile Grid] / [Max. Distance Range])

We assume high confidence for model layers mapped at surface. To complete qualitative confidence map for each layer surface, areas beyond the buffer ranges were assigned a value of 0 and corresponding map polygon areas were assigned a value of 1. To merge these layers with the location profiled data grids to produce each layer confidence map, a raster merge operation was employed with the result being the maximum value from the input grids. These confidence grid maps are included in this release and are shown in Figure 9a and 9b.

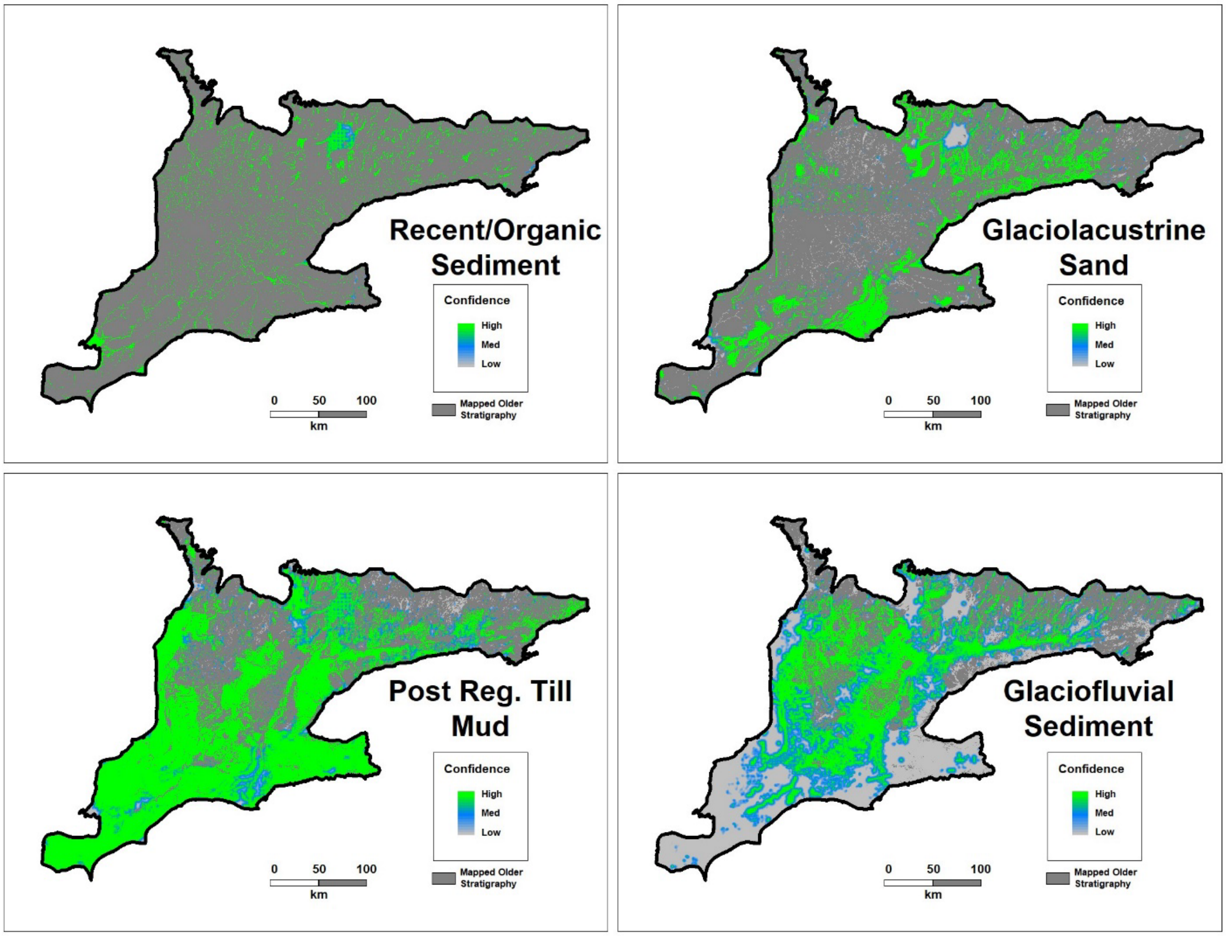


Figure 9a. Qualitative confidence maps for upper model layer contact surfaces based on proximity to data support and geology map coverage. Areas shown as 'Mapped Older Stratigraphy' indicate portions of the model area in which the given layer does not exist.

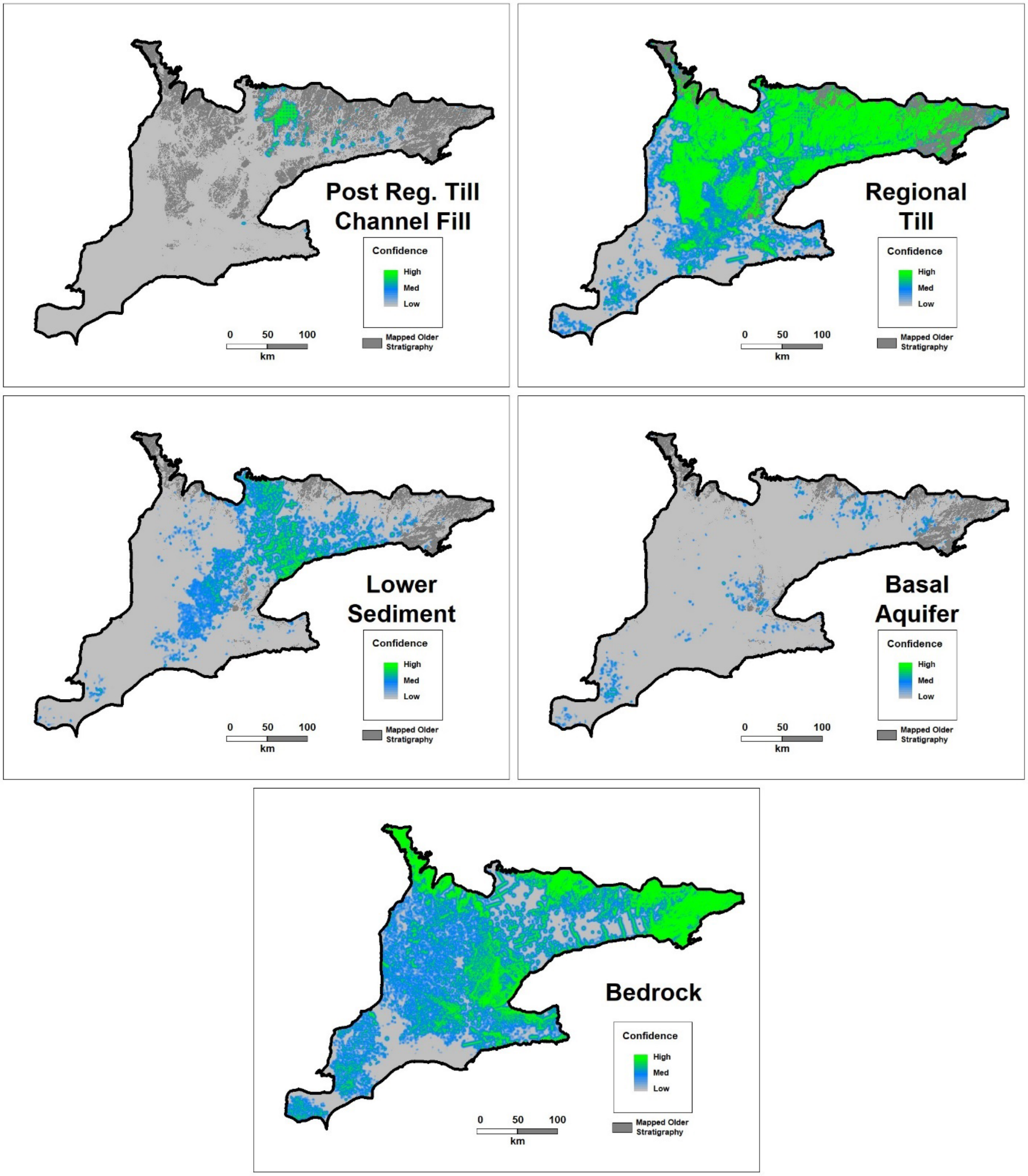


Figure 9b. Qualitative confidence maps for lower model layer contact surfaces based on proximity to data support and geology map coverage. Areas shown as 'Mapped Older Stratigraphy' indicate portions of the model area in which the given layer does not exist.

To semi-quantitatively evaluate the 'high confidence' model accuracy (i.e., confidence at data locations), each model layer surface was compared to the corresponding interpolated datasets. Layer surfaces were sampled at the location of their data control points. The average (absolute) difference between the model layer elevation and the control data elevation was compiled for each layer. The results are listed in Table 5. Class 1, 2 and 3 datasets were combined to enable a representative coverage. The total average of these was found to be approximately 4.5 m. Thus, the highest confidence value of 1 indicates an average model error of +/- 4.5 m.

Table 5. Average difference between primary model layer surfaces and data control points

Model Layer	Avg. Difference
Recent Sediment / Organics	3.2
Glaciolacustrine Sand	4.6
Post Reg. Till Mud	2.7
Glaciofluvial Sediment	5.3
Regional Till	6.1
Lower Sediment	6.4
Bedrock	3.0
Average	4.5

Quantifying the error at the lowest confidence is not as readily determined. It is here estimated by examining the natural variability of layer surfaces. A semivariance analysis was conducted for each primary model layer dataset to estimate the error value at the maximum range of 4000 m. The semivariance value was taken from the semivariogram plot at a lag distance of 4000 m and doubled to yield variance. The variance is a measure of the degree of spread of the data about the mean. The square root of variance is the standard deviation of the dataset elevations. Assuming a normal distribution at short distances of less than 4000 m, one standard deviation from the mean will contain the majority of values (i.e., 68.2%). We use one standard deviation based on the variance of the data at 4000 m distances as a proxy for the expected error due to natural surface variability at or beyond the zero value of the qualitative confidence maps (or low confidence). These values are listed in Table 6. Again, to achieve a reasonable coverage over the entire model area, all 3 data classes were combined.

Table 6. Semivariogram-based standard deviation of data contact elevations at 4000 m distances.

Model Layer	Std. Dev. @ 4000 m
Recent Sediment / Organics	10.5
Glaciolacustrine Sand	10.5
Post Reg. Till Mud	13.8
Glaciofluvial Sediment	11.8
Regional Till	11.3
Lower Sediment	10.5
Bedrock	10.1
Average	11.2

To quantify the estimated error using the variance of subsurface data contacts as a proxy for natural surface variation, we must account for variance as a result of measurement / reporting errors. Since we use the average difference to model surfaces listed in Table 5 as the quantitative estimate for measurement/reporting errors at data locations (i.e., high confidence), this minimum error value will be added to the error based on relative variance within the dataset. For example, the average error estimate for qualitative confidence values of 1 (or high confidence) is +/- 4.5m and for values of 0 (or low confidence) is +/- 15.7m (i.e., 11.2 + 4.5).

As it was not possible to isolate the data that influenced interpolated layer contact surfaces due to avoidance of younger borehole log intervals, these error estimates are not based on all data-related influence on the model layers. These confidence assessments are for the layer top contact surfaces only. The overall layer confidence (including layer thickness / bottom geometry) relies on underlying layer confidence as well.

Summary

The 3-D model of southern Ontario blends existing local models with regional surficial geology mapping, geophysical data and borehole data using the expertise of geoscientists currently working in the province. As such, its accuracy is dependant on that of the data, its coverage and interpretation. Derived from the data coverage, the confidence maps show that many data coverage gaps exist (e.g., in remote areas and in thick sediment at depth) thus more data collection is needed for an improved understanding of geological processes to help refine interpretations (e.g., buried tunnel channel connectivity). As this is the first attempt to blend existing knowledge and data into a regional 3-D model covering all of southern Ontario, there will inevitably be new data collected and revised interpretations for some or all of the legacy data that has contributed to its construction. This model should be viewed as a step towards understanding the complex geology of southern Ontario and that some features depicted may need refinement based on new insights. Currently, the 3-D surficial model can provide a basis for study of large-scale groundwater/surface water interactions (e.g., Frey et al., 2019) as well as regional 3-D context for more focussed hydrogeologic and geologic investigations. The model can also support large-scale, inter-jurisdictional groundwater study, provincial water resource management and serve as a tool for public outreach and educational applications. For example, where exposed at surface, areas of Glaciofluvial Sediment moraine hummocks and kettles can be important areas of groundwater recharge as closed depressions with coarse grained sediment and thus are economically and environmentally significant for large areas of southern Ontario.

Acknowledgements

Katie MacDonald and Matt Griffiths aided with developing a bathymetrically conditioned topographic DEM for this 3-D model. Matt Pyne prepared seismic data for Lake Ontario and Lake Huron and provided an interpolated Lake Huron bedrock DEM. Barbara Dietiker and André Pugin provided interpreted digital seismic profiles. Discussion of confidence assessment with Eric De Kemp and Mike Hillier were instructive. Constructive review by Melissa Bunn is very much appreciated. This work is a contribution of the Ontario Geological Survey Groundwater activity, and the Geological Survey of Canada Groundwater Geoscience Program, southern Ontario Groundwater and Archetypal Aquifer projects.

References

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

Barnett, P.J. 1992. Quaternary geology of Ontario; *in* Geology of Ontario. Ontario Geological Survey, Special Volume 4, Part 2, 1011-1090.

Barnett, P.J. 2012. Graphic borehole logs of sediments composing the Oak Ridges moraine, Whitchurch-Stouffville and Uxbridge township municipalities; Ontario Geological Survey, Miscellaneous Release—Data 290.

Barnett, P.J., and Karrow, P.F. 2018. Ice-marginal sedimentation and processes of diamicton deposition in large proglacial lakes, Lake Erie, Ontario, Canada Can. J. Earth Sci. 55: 846–862

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. doi:10.1139/e98-062.

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.

Bajc, A.F., and Shirota, J. 2007. Three-dimensional mapping of surficial deposits within the Regional Municipality of Waterloo, southwestern Ontario. Ontario Geological Survey, Groundwater Resources Study 3, 41p.

Bajc, A.F., Mulligan, R.P.M., and Dodge, J.E.P. 2019. Three-dimensional mapping of Surficial deposits in the southern part of the County of Simcoe, south-central Ontario. Ontario Geological Survey Groundwater Resource Study 18.

Bajc, A.F., Mulligan, R.P.M., Pugin, A.J.-M., and Rainsford, D.R.B. 2014a. An Update on the Final Phase of Subsurface Data Collection in the Southern Part of the County of Simcoe, Southern Ontario, Ontario Geological Survey, Open File Report 6300.33

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

Boyce, J.I., and Eyles, N. 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. Geological Society of America Bulletin, **112**(1): 98–118. doi:10.1130/0016-7606(2000)112<98:AEAATG>2.0.CO;2

Boyce, J.I., Eyles, N., and Pugin, A. 1995. Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario. Canadian Journal of Earth Sciences, 32: 1331–1349. https://doi.org/10.1139/e95-108

Brennand, T.A., Russell, H.A.J., and Sharpe, D.R., 2006. Tunnel channel character and evolution in central southern Ontario; *in* Glacier Science and Environmental Change, P.G. Knight (ed.); Blackwell Publishing, Malden, Massachusetts, p. 37–39.

Brookfield, M.E., Gwyn, Q.H.J., and Martin, I.P., 1982. Quaternary sequences along the north shore of Lake Ontario: Oshawa – Port Hope. Canadian Journal of Earth Sciences, **19**: 1836–1850. doi:10.1139/e82-162.

Brunton, F.R., Belanger, D., DiBiase, S., Yungwirth, G. and Boonstra, G. 2007. Caprock carbonate stratigraphy and bedrock aquifer character of the Niagara Escarpment – City of Guelph Region, southern Ontario; *in* Proceedings of the 60th Canadian Geotechnical Conference and the 8th joint Canadian Geotechnical Society–International Association of Hydrogeologists conference, Canadian Geotechnical Society, Ottawa, Ontario, p.371-377.

Brunton, F.R., Brintnell, C., Priebe, E.H., and Bingham, M. 2010. Update of Early Silurian sequence stratigraphy, Sedimentology and bedrock aquifer mapping of Niagara Escarpment cuesta; *in* Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6260, p. 33-1 to 33-7.

Burt, A.K. 2017a. Digging deep on the Niagara Peninsula: a drilling update. *in* Summary of Field Work and Other Activities 2017, Ontario Geological Survey, Open File Report 6333, p. 24-1 to 24-16.

Burt, A.K. 2017b. Graphic logs with analytical and geochronological data from hand auger, probe and section sites in the Niagara Peninsula; Ontario Geological Survey, Miscellaneous Release—Data 353.

Burt, A.K. 2018. Three-dimensional hydrostratigraphy of the Orangeville Moraine area, southwestern Ontario, Canada. Canadian Journal of Earth Sciences, 55, 802-828. https://doi.org/10.1139/cjes-2017-0077

Burt, A.K. 2020. Results of the 2014–2017 drilling programs on the Niagara Peninsula: Graphic logs, descriptions and analytical data; Ontario Geological Survey, Miscellaneous Release—Data 383.

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.

Bunn, M.I., Carter, T.R., Russell, H.A.J., and Logan, C.E. 2023. A semiquantitative representation of uncertainty for the 3-D Paleozoic bedrock model of Southern Ontario. Geological Survey of Canada, Open File 8965, 25 p. doi:10.4095/331658

Carr, J.C., Beatson, R.K., Cherrie, J.B., Mitchell, T.J., Fright, W.R., McCallum, B.C., and Evans, T.R. 2001. Reconstruction and representation of 3-D objects with radial basis functions; A.C.M. SIGGRAPH 2001, Computer graphics proceedings, ACM Press, New York, p.67-76.

Carter, T.R., Brunton, F.R., Clark, J.K., Fortner, L., Freckelton, C., Logan, C.E., Russell, H.A.J., Somers, M., Sutherland, L., and Yeung, K.H. 2019. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario. Geological Survey of Canada, Open File 8618, 2019, 45 p. doi:10.4095/315045

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Brunton, F.R., Cachunjua, A., D'Arienzo, M., Freckelton, C., Rzyszczak, H., Sun, S., and Yeung, K.H. 2021. A three-dimensional geological model of the Paleozoic bedrock of southern Ontario. Geological Survey of Canada, Open File 8795. (ed. version 2) 2021, 103 p., doi:10.4095/328297

Carter, T.R., Logan, C.E., Clark, J.K., Russell, H.A.J., Priebe, E.H., and Sun, S. 2022. A three-dimensional bedrock hydrostratigraphic model of southern Ontario. Geological Survey of Canada, Open File 8927, 2022, 58 p., doi:10.4095/331098.

Chapman, L.J., and Putnam, D.F. 1984. The Physiography of Southern Ontario, third edition Ministry of Energy, Northern Development and Mines, Special Volume 02

Crow, H.L., Hunter, J.A.H., Olson, L., Pugin, A.J.M., and Russell, H.A.J. 2018. Borehole geophysical log signatures and stratigraphic assessment in a glacial basin, southern Ontario. Canadian Journal of Earth Science. 55: 829–845. dx.doi.org/10.1139/cjes-2017-0016

Desbarats, A., Hinton, M., Logan, C., and Sharpe, D. 2001. Geostatistical mapping of leakance in a regional aquitard, Oak Ridges Moraine area, Ontario, Canada. Hydrogeology Journal, 9(1), pp.79-96.

Dietiker, B., Pugin, A.J.-M., Burt, A., Crow, H., Cartwright, T., and Brewer, K. 2019. High-resolution Shallow Seismic Reflection Profiles for Groundwater Studies in the Niagara Peninsula region, Ontario. Geological Survey of Canada, Open File 8561, 49p. https://doi.org/10.4095/314730

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F., and Eyles, C. 1985. The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario basin, Canada. Geoscience Canada 12: 22-32.

Frey, S.K., Khader, O., Taylor, A., Erler, A.R., Lapen, D.R., Sudicky, E.A., Berg, S.J., and Russell, H.A.J. 2019. A fully integrated groundwater-surface-water model for southern Ontario: proof-of-concept and data release Geological Survey of Canada, Open File 8639, 23 p. https://doi.org/10.4095/321042

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

Gerber, R.E., Sharpe, D.R., Russell, H.A.J., Holysh, S., and Khazaei, I. 2018. Conceptual hydrogeological model of the Yonge Street aquifer, south-central Ontario: A glaciofluvial channel–fan setting. Canadian Journal of Earth Sciences, 55: 730-767. Hamilton, S.M. 2015. Ambient groundwater geochemistry data for southern Ontario, 2007–2014; Ontario Geological Survey, Miscellaneous Release—Data 283–Revised.

Gwyn, Q.H.J. 1976. Quaternary geology and granular resources of the central and eastern parts of the regional municipality of Durham (parts of Reach, Whitby, East Whitby, Cartwright, Darlington and Clarke Townships) southern Ontario. Ontario Division of Mines Geological Branch; Open-File Report 5176, 25 pp.

Gwyn, Q.H.J., and DiLabio, R.N.W. 1973. Quaternary geology of the Newmarket area; southern Ontario. Ontario Division of Mines, Preliminary Map P836, scale 1:50 000

Hamilton, S.M. 2015. Ambient groundwater geochemistry data for southern Ontario, 2007–2014; Ontario Geological Survey, Miscellaneous Release—Data 283–Revised.

International Joint Commission 2015. Protection of the Waters of the Great Lakes: 2015 Review of the. Recommendations in the February 2000 report.

Karrow, P.F. 1967. Pleistocene Geology of the Scarborough Area; Ontario Ministry Natural Resources. Toronto, Rep. 46 108 p.

Karrow, P.F. 1974. Till Stratigraphy in Parts of Southwestern Ontario. Geological Society of America Bulletin 85: 761–768. https://doi.org/10.1130/0016-7606(1974)85<761:TSIPOS>2.0.CO;2

Karrow, P., McAndrews, J., Miller, B., Morgan, A., Seymour, K., and White, O. Illinoian to Late Wisconsinan stratigraphy at Woodbridge, Ontario 2001. Canadian Journal of Earth Sciences, Vol. 38, p. 921-942.

Kjarsgaard, B.A., Knight, R.D., Russell, H.A.J., Sharpe, D.R., Crow, H., and Olson, L. 2017. Newmarket Till aquitard: optimum grain packing with a pore-filling calcite-rich cement; *in* Regional-scale groundwater geoscience in southern Ontario: an Ontario Geological Survey and Geological Survey of Canada groundwater geoscience open house. Russell, H A J (ed.); Ford, D. (ed.), and Priebe, E.H. (ed.); Geological Survey of Canada, Open File 8212, 22 p.

Lindsay, M.D., Aillères, L., Jessell, M.W., de Kemp, E.A., and Betts, P.G. 2012. Locating and quantifying geological uncertainty in three-dimensional models: Analysis of the Gippsland Basin, southeastern Australia. Tectonophysics, v. 546–547, p. 10–27.

Logan, C.E., Russell, H.A.J., Bajc, A.F., Burt, A., Mulligan, R.P.M., and Sharpe, D.R., 2020. A three-dimensional surficial geology model of southern Ontario: progress report, *in* Southern Ontario groundwater project 2014-2019: summary report; Russell, H A J (ed.); Kjarsgaard, B A (ed.); Geological Survey of Canada, Open File 8536, p. 49-64, doi:10.4095/321084.

Logan, C., Russell, H.A.J., and Sharpe, D.R. 2005. Regional 3-D structural model of the Oak Ridges Moraine and Greater Toronto area, southern Ontario: version 2.1. Geological Survey of Canada, Open File 5062, 27 p. doi:10.4095/221490.

Logan, C., Russell, H.A.J., Sharpe, D.R., Kenny, F.M., and Harris, J.R. 2006. The role of GIS and expert knowledge in 3-D modelling, Oak Ridges Moraine, southern Ontario. Geological Association of Canada, Special Paper, **44**: 519–541. doi:10.4095/214575

Morris T.F., and Kelly R.I. 1997. Origin and physical and chemical characteristics of glacial overburden in Essex and Kent counties, southwestern Ontario. Canadian Journal of Earth Science, 34: 2 33–246. doi: 10.1139/e17-022

Mulligan, R.P.M. 2018. Last phase of subsurface data collection for Three-dimensional mapping in the central Part of the County of Simcoe, southern Ontario. In: Summary of Field Work and Other Activities 2018, Ontario Geological Survey Open File Report 6350, 25-1 to 25-10.

Mulligan, R.P.M. 2019. Tunnel valley genesis and subglacial dynamics in south-central Ontario (Ph.D. Thesis), McMaster University, Hamilton Ontario, 408pp.

Mulligan, R.P.M., and Bajc, A.F. 2018. The pre-Late Wisconsin stratigraphy of southern Simcoe County, Ontario: implications for ice sheet buildup, decay, and Great Lakes drainage evolution. Canadian Journal of Earth Sciences, 55, p. 709-729.

Mulligan, R.P.M., Eyles, C.H., and Bajc, A.F. 2018a. Stratigraphic analysis of Late Wisconsin and Holocene glaciolacustrine deposits exposed along the Nottawasaga River, southern Ontario, Canada. Canadian Journal of Earth Sciences 55, 863–884.

Ontario Geological Survey, 2010. Surficial geology of southern Ontario. Ontario Geological Survey, Miscellaneous Release—Data 128 – Revised. Ontario Government 2006. Clean Water Act (S.O. 2006, Chapter 22)

Pugin, A.J.-M., Pullan S.E., and Sharpe, D.R. 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences, **36**(3): 409–432

Pugin, A.J.-M., Pullan, S.E., and Sharpe, D.R. 2011. Seismic reflection data and hydro-stratigraphic implications for Ballantrae-Aurora area buried valley aquifers. Geological Survey of Canada, Open File 6685, 2011, 21 p. doi:10.4095/288542.

Pugin, A.J.-M., Dietiker, B., Mulligan, R.P.M., Crow, H.L., Brewer, K., Cartwright, T., Rainsford, D.R.B., Bajc, A.F., Sharpe, D.R., and Russell, H.A.J. 2018. High-resolution seismic reflection profiles for groundwater studies in Simcoe County, southern Ontario. Geological Survey of Canada, Open File 8383.

Pullan, S.E., Hunter, J.A., and Good, R.L. 2002. Using downhole geophysical logs to provide detailed lithology and stratigraphic assignment, Oak Ridges Moraine, southern Ontario. Current Research 2002-E8. Geological Survey of Canada, National Resources Canada. 12 pp.

Russell, H.A.J. and Kjarsgaard, B.A. (ed.) 2020. Southern Ontario groundwater project 2014–2019: summary report; Geological Survey of Canada, Open File 8536, 245 p. https://doi.org/10.4095/321078

Russell, H.A.J., Arnaud, E., Bajc, A.F., and Sharpe, D.R. 2018. Quaternary geology of southern Ontario and applications to hydrogeology. Canadian Journal of Earth Sciences, 55: v–viii.

Russell, H.A.J., Arnott, R.W.C., and Sharpe, D.R. 2003. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada. Sedimentary Geology 160, 33–55. https://doi.org/10.1016/S0037-0738(02)00335-4

Russell, H.A.J., Arnott, R.W.C., and Sharpe, D.R. 2004. Stratigraphic architecture and sediment facies of the western Oak Ridges Moraine, Humber River watershed, southern Ontario. Geographique physique Quaternaire. 58: 241–267. https://doi.org/10.7202/013141ar

Russell, H.A.J., Brennand, T.A., Logan, C., and Sharpe, D.R. 1998. Standardization and assessment of geological descriptions from water well records, Greater Toronto and Oak Ridges Moraine areas, southern Ontario. Geological Survey of Canada, Current Research, p. 89–102. doi:10.4095/209956

Russell, H.A.J., Sharpe, D.R., Brennand, T.A., Barnett, P.J., and Logan, C. 2003. Tunnel channels of the Greater Toronto and Oak Ridges Moraine areas, southern Ontario; *in* Geological Survey of Canada, Open File 4485, 2003, 1 sheet. doi:10.4095/214777

Russell, H.A.J., Bajc, A., Sharpe, D.R., and Cummings, D.I., 2013. Paris and Galt Moraines, southern Ontario: depositional elements, paleoglacial implications, and hydrogeological applications, Geological Survey of Canada, Open File 7153, 1 sheet. https://doi.org/10.4095/292705

Sharpe, D.R., Barnett, P.J., Brennand, T.A., Gorrell, G., and Russell, H.A.J. 2006. Digital surficial geology data of the Greater Toronto and Oak Ridges Moraine area, southern Ontario. Geological Survey of Canada, Open File 5318, 1 sheet, 15 pp. https://doi:10.4095/222772

Sharpe, D.R., and Russell, H.A.J. 2016. A revised depositional setting for Halton sediments in the Oak Ridges Moraine area, Ontario. Canadian Journal of Earth Sciences, 53: 281–303. https://doi.org/10.1139/cjes-2015-0150

Sharpe, D.R., and Russell, H.A.J. 2023. Sedimentary architecture and glacial hydrodynamic significance of the stratified Oak Ridges Moraine, southern Ontario, Canada. Boreas, p. 1-40. https://doi.org/10.1111/bor.12612

Sharpe, D.R., Dyke, L.D., Good, R.L., Gorrell, G., Hinton, M.J., Hunter, J.A., and Russell, H.A.J. 2003. GSC high-quality borehole, “Golden Spike”, data - Oak Ridges Moraine, southern Ontario. Geological Survey of Canada, Open File 1670, 2003, 23 p. doi:10.4095/214289

Sharpe, D.R., Hinton, M.J., Russell, H.A.J., and Desbarats, A.J. 2002a. The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, Southern Ontario. Geoscience Canada, 29: 3–20.

Sharpe, D. R., Leduc, G., Smart, C. S., and Shaw, J. 2023. Georgian Bay bedrock erosion: evidence for regional floods, Ontario. Geological Survey of Canada, Open File, 8909. https://doi.org/10.4095/331409

Sharpe, D.R., Piggot, A., Carter, T., Gerber, R.E., MacRitchie, S.M., de Loë, R.C., Strynatka, S., and Zwiers, G. 2014. Southern Ontario hydrogeological region; *in* Canada's groundwater resources; Rivera, A. (ed.); p. 443-499. https://doi.org/10.4095/296947

Sharpe, D.R., Pugin, A.J.-M., Pullan, S.E., and Shaw, J. 2004. Regional unconformities and the sedimentary architecture of the Oak Ridges Moraine Area, southern Ontario. Canadian Journal of Earth Sciences, 41: p. 183–198. https://doi.org/10.1139/e04-001

Sharpe, D.R., Pugin, A.J.-M., and Russell, H.A.J. 2018. Geological framework of the Laurentian Trough aquifer system, southern Ontario; *in* Quaternary geology of southern Ontario and applications to hydrogeology / Géologie quaternaire du sud de l'Ontario et applications à l'hydrogéologie; Russell, H.A.J. (ed.), Arnaud, E. (ed.), Bajc, A.F. (ed.), and Sharpe, D.R. (ed.), Canadian Journal of Earth Sciences, **55**: 677–708. doi:10.1139/cjes-2017-0113

Sharpe, D.R., Russell, H.A.J., Logan, C., Stolle, D., Piggott, A.R., and Crowder, J.J. 2002b. Geological characterization of a regional aquitard: Newmarket Till, Oak Ridges Moraine area, southern Ontario; *in* Ground and Water: Theory to Practice: Proceedings of the 55th Canadian Geotechnical and 3rd joint IAH-CNC and CGS

Groundwater Specialty Conferences; Stolle, D. (ed.); Piggott, A.R. (ed.); Crowder, J.J. (ed.); doi:10.4095/216708

Sharpe, D.R., Russell, H.A.J., and Pugin, A.J.-M. 2013. The significance of buried valleys to groundwater systems in the Oak Ridges Moraine region, Ontario: extent, architecture, sedimentary facies and origin of valley settings in the ORM region. Geological Survey of Canada, Open File 6980, 2013, 87 p. doi:10.4095/292673

Sharpe, D.R., Logan, C.E., and Pugin, A.-M. {in prep}. Thorncliffe Formation: conceptual model of a channel-fan aquifer system, Greater Toronto Region. Geological Survey of Canada, Open File 9067

Taylor, F. B. 1912, Pleistocene Deposits of southwestern Ontario, Geological Survey of Canada, Summary Report 1911 p. 262-272.

Wellmann, J.F., Horowitz, F.G., Schill, E., and Regenauer-Lieb, K. 2010. Towards incorporating uncertainty of structural data in 3-D geological inversion. Tectonophysics, v. 490, p. 141–151.