Ontario

Groundwater Resources Study 19

Geological Survey of Canada, Open File 8618

A Three-Dimensional Geological Model of the Paleozoic Bedrock of Southern Ontario

2019

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A Three-Dimensional Geological Model of the Paleozoic Bedrock of Southern Ontario

Ontario Geological Survey
Groundwater Resources Study 19

Geological Survey of Canada
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by

T.R. Carter[1], F.R. Brunton[2], J.K. Clark[3], L. Fortner[4], C. Freckelton[3], C.E. Logan[5], H.A.J. Russell[5], M. Somers[4], L. Sutherland[3,6], and K.H. Yeung[2]

2019

Users of OGS products are encouraged to contact those Aboriginal communities whose traditional territories may be located in the mineral exploration area to discuss their project.

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GEOLOGICAL SURVEY OF CANADA
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ONTARIO GEOLOGICAL SURVEY
GROUNDWATER RESOURCES STUDY 19

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OBJECTIVE

The *Groundwater Resources Study* (GRS) series seeks to better the understanding of Ontario's groundwater resources through the collection, evaluation and distribution of geoscience data. The main objective of the series is to provide accurate information on a range of groundwater-related themes, including local- to watershed-scale aquifer characterization and delineation; geologic controls and influences on groundwater quantity and quality; and methods development. Products of the groundwater program include geoscience reports, data sets and protocols for information collection and handling. Geoscience information generated through the series will find application in the protection and sustainable management of the province's groundwater resources.

DISCLAIMER

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NOTE

Abstract

A regional three-dimensional (3-D) lithostratigraphic model of the Paleozoic bedrock of southern Ontario has been completed. The model encompasses the entire Phanerozoic succession of southern Ontario (110 000 km^2), consisting of over 1500 m of sedimentary strata straddling regional arch, or forebulge, zones separating the Appalachian foreland basin from the Michigan structural basin. This initiative provides an unprecedented regional 3-D perspective and digital framework based on an updated regional lithostratigraphic chart. Constructed using Leapfrog® Works, an implicit modelling software application, the model format can readily support numeric groundwater-flow modelling.

Fifty-four Paleozoic bedrock layers representing 70 formations, as well as the Precambrian basement and overlying unconsolidated sediment, were modelled at a spatial resolution of 400 m. Borehole records in Ontario's public petroleum well database (Ontario Petroleum Data System (OPDS)) were the principal data source, supplemented by Ontario Geological Survey (OGS) deep boreholes, measured sections, control points and Michigan boreholes. A newly revised digital bedrock topography surface combined with revised subcrop geology and digitized 3-D surface polyline and point constraints were used to better align the modelled layers and their extrapolation to the subcrop surface. Model development was an iterative cycle of interim modelling, expert geological appraisal, and quality assurance and control (QA/QC) editing of geological data using geophysical logs, drill cuttings and core, supplemented by manual editing of model layers. The 3-D model provides a robust representation of regional bedrock geology.

A properly constructed borehole database and its supporting information is an essential requirement for construction of a 3-D model, but data errors, inconsistencies, data gaps, location errors, etc. can compromise the reliability of the model. From 2015 to 2018, project geologists and geological contract staff of the Oil, Gas and Salt Resources Library completed edits to 30 320 formation tops in a total of 7812 wells, resulting in a revised data set and permanent improvements to the petroleum well database. This report highlights the importance of QA/QC of well data, specifically formation top identification, and summarizes the data improvements made in support of the present 3-D model. No seismic data was available.

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Introduction and Objectives

Paleozoic sedimentary bedrock underlies Quaternary sediments across southwestern Ontario and the southern part of south-central Ontario. Bedrock composition, regional structure, heterogeneity and landform development govern penetration of meteoric water into the bedrock subsurface and the vertical and lateral movement of groundwater through the bedrock. Consequently, management of groundwater resources for agricultural, industrial, municipal and domestic supply is enhanced by an improved understanding of the sedimentary bedrock architecture, from subcrop into the deeper subsurface. Improved geologic knowledge and mapping of these rocks also supports natural resource extraction (e.g., water, gypsum, salt, gas, oil, aggregate, building and chemical stone), exploitation of geothermal energy, site selection for potential future CO_2 sequestration, industrial and nuclear waste disposal (e.g., Ontario Power Generation 2017), aquifer vulnerability studies, geological hazards analysis and sustainable municipal waste disposal.

In 2015, the Geological Survey of Canada (GSC) and Ontario Geological Survey (OGS) initiated a project to develop a three-dimensional (3-D) geological model of the Paleozoic bedrock geology of southern Ontario (Russell et al. 2015; Russell and Dyer 2016; Carter, Brunton et al. 2016; Brunton et al. 2017; Carter et al. 2017), as part of a collaborative initiative to advance knowledge of regional groundwater geoscience in Ontario. This work was completed in collaboration with the Ontario Ministry of Natural Resources and Forestry (MNRF) and the Oil, Gas and Salt Resources Library, London, Ontario (OGSRL). The resultant 3-D geological model is the first to include all of the Paleozoic stratigraphy of southwestern and south-central Ontario. A parallel project to model the geology and hydrogeology of the overlying unconsolidated surficial sediment is also underway (Russell et al. 2016; Logan et al. 2020).

The present study is focussed on the development of a 3-D bedrock lithostratigraphic model of the region. This model is an integration of previous and ongoing stratigraphic–sedimentologic studies and relevant geological data that define sedimentological (facies) and structural features. The model delineates the geological controls on the occurrence and movement of water within the bedrock formations of southern Ontario and is a necessary precursor for the development of a planned hydrostratigraphic model (e.g., Maxey 1964; Seaber 1988).

This report documents iterative geological model development, data sources, quality assurance and control (QA/QC), and plans for model delivery and applications. Information in previous reports and presentations (Russell et al. 2015; Russell and Dyer 2016; Carter, Brunton et al. 2016; Brunton et al. 2017; Carter et al. 2017; Carter et al. 2020; Russell et al. 2017) are superseded by this document. It is supported by and complementary to, reports on QA/QC (Davis 2017), data capture (Clark et al. 2020), construction of an updated lithostratigraphic chart (Brunton et al. 2017), and hydrochemical groundwater regimes (Carter and Sutherland 2018).

Three-dimensional models are data-driven. Model accuracy relies primarily on the accuracy and coverage of the available data in three dimensions. Consequently, project resources were heavily focussed on compiling existing data, identifying data gaps and anomalies, QA/QC review and edits to existing data, data enhancements, and new data created by project contributors.

PROJECT AREA

The project area encompasses the contiguous Paleozoic sedimentary rocks underlying southern Ontario west of the Frontenac Arch and south of the Precambrian Canadian Shield. The 110 000 km^2 area extends beneath the waters of the Great Lakes (Huron, Erie, Ontario) to the international boundary with the United States, and to the subcrop edge of these strata beneath the waters of Georgian Bay (Figure 1).

Stratigraphically, the project encompasses the complete Paleozoic sedimentary succession and includes the interface with the Precambrian crystalline basement rocks of the Canadian Shield (Figure 2). Above the bedrock erosional surface, the unconsolidated surficial sediments are included in the model as a single layer. The modelled volume consists of 54 Paleozoic bedrock layers totalling roughly 72 300 km^3 with 3477 km^3 of overlying unconsolidated sediment.

The maximum elevation of the model is 546 m above sea level (asl) along the Niagara Escarpment. The maximum thickness of Paleozoic bedrock is 1618 m near the U.S. border in Lake Huron. The lower model boundary is set to an arbitrary elevation of -2000 m asl within the Precambrian.

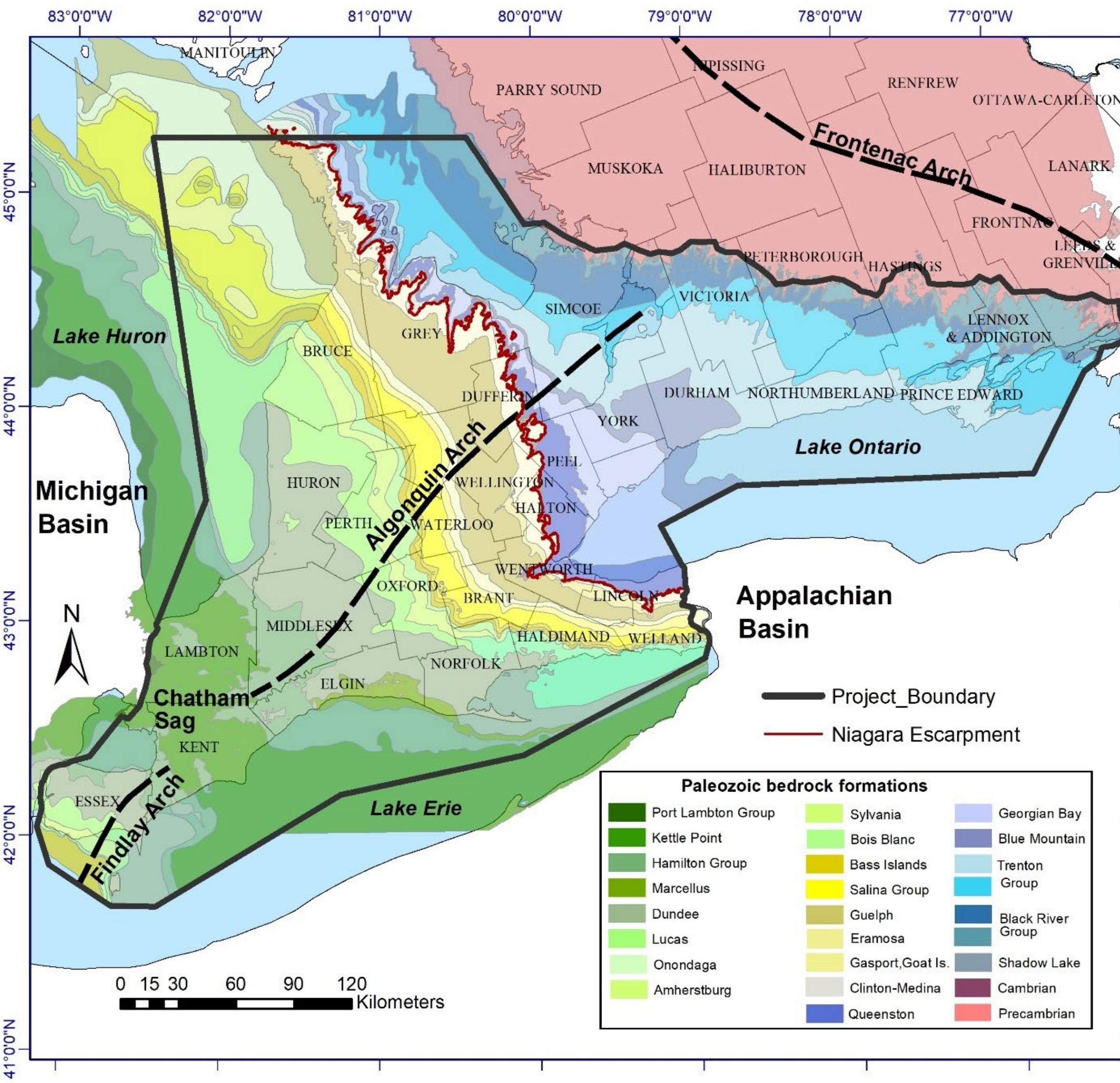

Figure 1. Simplified bedrock geology and project boundary of 3-D Paleozoic bedrock model area. The Niagara Escarpment forms a hydrogeologic boundary between the east and west portions of the study area (Brunton 2009a). Bedrock stratigraphy is *revised and updated from* Sanford (1969); Sanford and Baer (1971); Armstrong and Dodge (2007); Armstrong and Carter (2010); Cramer et al. (2011); Brunton et al. (2012); Armstrong (2017, 2018); Sun, Brunton and Jin (2017a, 2017b, 2017c); Sun (2018); and Brunton and Brintnell (in press).

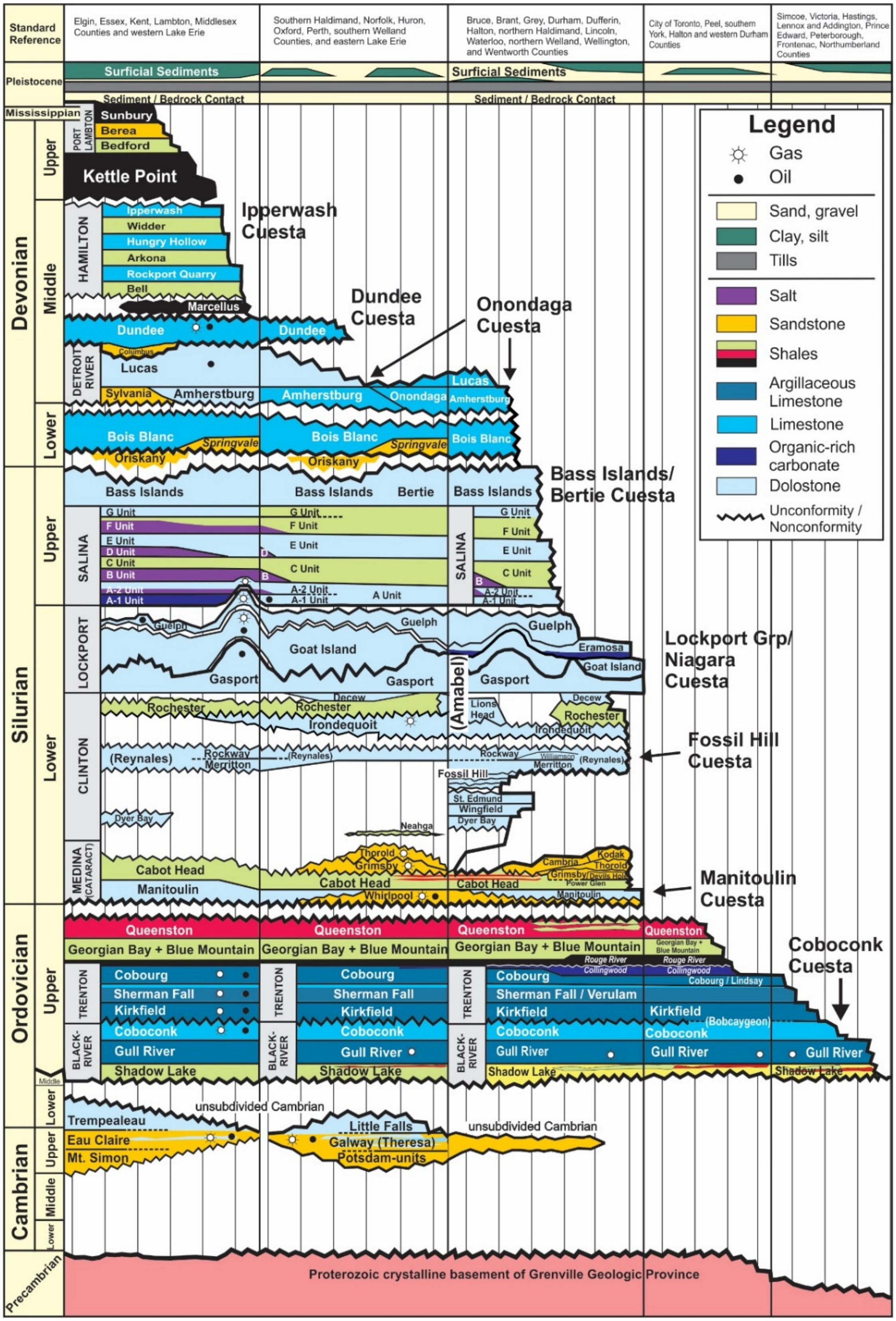

Figure 2. Lithostratigraphic chart of the Phanerozoic geology of southern Ontario, *modified from* Brunton et al. (2017). See details concerning regional architecture in Brunton and Brintnell (in press).

PREVIOUS GEOLOGICAL MODELLING WORK

Previous geological modelling in southern Ontario has been focussed on surficial units and more local studies to support hydrogeological studies. A noteworthy modelling initiative involved the regional bedrock geological model developed to support a local study at the Bruce nuclear generating station at Tiverton (Nuclear Waste Management Organization 2011; Hobbs et al. 2011; Itasca and AECOM 2011). It was converted to a hydrostratigraphic model for a numerical groundwater model for the same area (Sykes et al. 2011).

Two-dimensional geological and hydrogeological models for the Paleozoic strata of southern Ontario have also been developed (Brunton and Dodge 2008; Brunton 2009a, 2009b; Carter 2012; Carter and Fortner 2012; Carter et al. 2014; Sharpe et al. 2014).

PROJECT CO-ORDINATION AND OUTREACH

Project direction and co-ordination included bimonthly team teleconference meetings with written agendas, task assignments and recorded minutes. Annual one to two-day groundwater workshops were hosted by the OGS, GSC and Conservation Ontario at the Delta Hotel in Guelph, Ontario, at which team members made presentations on progress of the project. Written progress reports were prepared and published by the OGS and GSC (Russell et al. 2016; Russell and Dyer 2016; Carter, Brunton et al. 2016; Carter et al. 2017; Russell et al. 2017; Carter et al. 2020; Clark et al. 2020).

Geological and Hydrogeological Setting of Southern Ontario

South of the exposed Canadian Shield, southern Ontario bedrock comprises Paleozoic marine sedimentary rocks of the northern Appalachian foreland basin and eastern Michigan structural basin (Brunton et al. 2012), which straddle a broad northeast-oriented Precambrian basement structural high, referred to as the Algonquin Arch and its southwestern extension, the Findlay Arch. The Paleozoic sedimentary strata unconformably overlie the crystalline metamorphic, igneous and metasedimentary rocks of the Precambrian basement, all of which are largely covered by a veneer (of variable thickness) of unconsolidated and largely glacially derived surficial sediments. Bedrock strata consist of an interlayered succession of sandstones, carbonates, evaporites, shales, and siltstones. The bedrock formations dip to the southwest at 3 to 6 m/km along the crest of the Algonquin Arch and northeast along the crest of the Findlay Arch, into a structural low, the Chatham Sag, and at 3 to 12 m/km down the flanks of the arches westward into the Michigan structural basin and southward into the Appalachian foreland basin (Armstrong and Carter 2010; *see* Figure 1).

The Niagara Escarpment is the highest topographic landform in southern Ontario and therefore forms a natural hydrological and hydrogeological divide that separates the study area into 2 sections (*see* Figure 1). Paleozoic strata are much thicker to the west of the Niagara Escarpment, ranging from 540 m to nearly 1400 m in the Chatham Sag, and over 1500 m at the international border beneath Lake Huron. Strata range in age from late Cambrian to late Devonian and possibly early Mississippian (Armstrong and Carter 2010; Carter et al. 2017; Figures 1 and 2). To the east of the Niagara Escarpment, Paleozoic strata within the study area are late Ordovician in age because of the erosion of all younger sedimentary rocks. Maximum thickness of Paleozoic strata to the north and east of the Niagara Escarpment is 650 m at the Niagara River and 250 m on the south shore of Georgian Bay, thinning northeasterly to zero at the erosional edge in eastern Ontario (Armstrong and Carter 2010).

The bedrock surface is a low-relief angular unconformity resulting from chemical and physical erosion of the shallowly dipping Paleozoic strata over a period of subaerial exposure spanning at least 250 million years (Johnston et al. 1992). This surface is an important hydrogeological feature, forming the recharge area where variably karstic and shallowly dipping sedimentary bedrock is exposed at surface, as well as the interface between the fresh water-dominated unconsolidated surficial sediments and the relatively less permeable and porous and variably karstic sedimentary bedrock in the subsurface. This contact, or interface aquifer zone, is the most widespread potable water aquifer in southern Ontario (Husain, Cherry and Frape 2004; Brunton 2009a, 2009b; Carter 2012) and occurs at this variably karstic boundary beneath large parts of southern Ontario (Carter and Clark 2018).

Extensive karstic dissolution has occurred prior to and following the Holocene glacial retreat in areas of thin surficial sediments where carbonate rocks form the uppermost bedrock layer (Brunton 2013; Brunton and Dodge 2008; Brunton et al. 2016). These karstic strata form a complex system of enhanced porosity and permeability, which locally to subregionally contains potable water up to 250 m below the surface. These karstic strata and the shallow fresh water system are the subject of ongoing investigations by the OGS (Brunton et al. 2016; Brunton et al. 2017; Priebe, Neville and Brunton 2014, 2017; Priebe and Brunton 2016; Priebe et al. 2019).

In areas of thicker surficial sediment and areas underlain by shale, wells that penetrate the bedrock more than a few metres encounter groundwater that is brackish to saline and locally sulphurous. Conceptual modelling based on petroleum well data and geochemical and isotopic analyses has documented an intermediate to deep system of thick regional aquitards and thin confined aquifers containing brackish to highly saline water within the bedrock (Figure 3; Nuclear Waste Management Organization 2011; Hobbs et al. 2011; Carter 2012; Carter and Fortner 2012; Carter et al. 2014; Sharpe et al. 2014; Skuce 2015; Skuce et al. 2015; Skuce, Potter and Longstaffe 2015; Carter et al. 2016). Brackish to moderately saline water containing dissolved H_2S occurs at intermediate depths, from as shallow as 30 m to 350 m, overlapping with a deep brine regime that contains no dissolved H_2S and begins at depths greater than 200 m (Carter and Sutherland 2018, 2020).

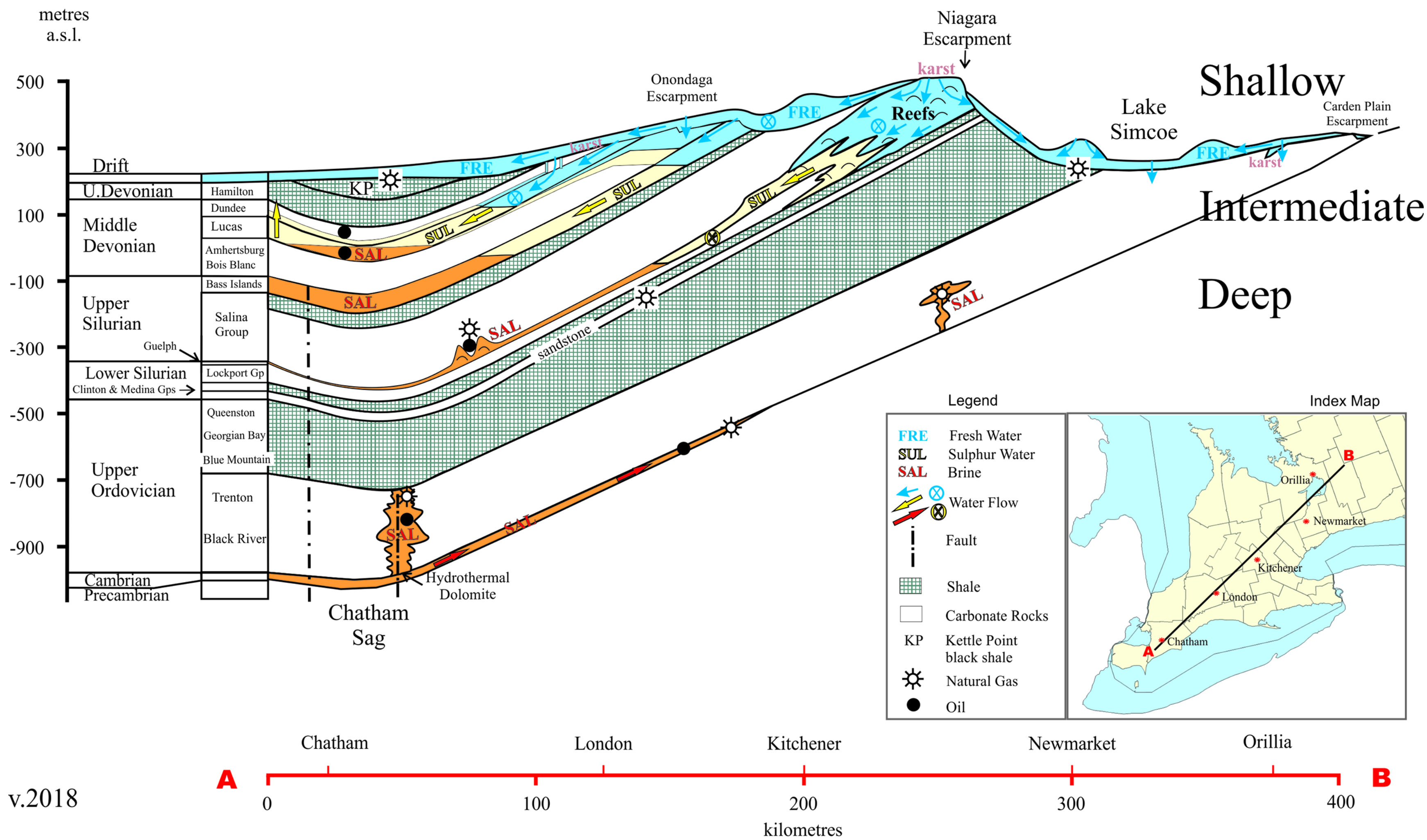

Figure 3. Conceptual model of regional groundwater regimes in the surficial sediments and bedrock of southern Ontario, showing hydrochemical zonation with depth (*modified after* Carter and Sutherland 2020; Carter 2012; Carter and Fortner 2012).

Conceptual Model Development

Development of a 3-D model that reliably represents the geology requires a multidisciplinary team of expert and experienced professionals. Team members for this project included a sedimentologist and Quaternary geologist (Hazen Russell), subsurface bedrock geologists (Terry Carter, Lee Fortner, Maia Somers), Paleozoic bedrock geologist, stratigrapher and karst specialist (Frank Brunton), GIS and data management specialists (Jordan Clark, Liz Sutherland, Kei Yeung), and a 3-D modeller (Charles Logan). Hydrogeological expertise was provided by Frank Brunton (shallow bedrock) and Terry Carter (deep bedrock).

In the initial stages of the project, the project geologists visualized the 3-D geology by combining the geological knowledge gathered from publications and reports on conventional geological outcrop mapping, subsurface geological maps and cross-sections, data from wells and boreholes, and their own knowledge and experience. This expert conceptual knowledge was essential in identifying shortcomings and inaccuracies while building and editing iterative versions of the model – the process is ongoing.

Lithostratigraphic Chart

A fundamental requirement for geologic modelling is definition of the model bedrock layers. For the 3-D bedrock modelling project the primary model layers are the Paleozoic bedrock formations of southern Ontario, and the undivided surficial sediments. Lithostratigraphic subdivisions were initially based on Johnson et al. (1992) and Armstrong and Carter (2010).

Revisions and updates to the lithostratigraphic chart by project geologists were based largely on recent work by the OGS (Brunton 2009b; Brunton and Brintnell 2011; Cramer et al. 2011; Brunton et al. 2012; Bancroft, Kleffner and Brunton 2016; Sun, Brunton and Jin 2017b, 2017c; Brunton et al. 2017; and Armstrong 2017, 2018). Revisions and updates to terminology included reassignment of the Amabel Formation to the Irondequoit and Lions Head formations of the Clinton Group, and the Gasport Formation and Niagara Falls member of the Goat Island Formation to the Lockport Group. The Eramosa Member was elevated to formation status and the Guelph Formation was included in the Lockport Group (Brunton 2009b; Cramer et al. 2011; Brunton et al. 2012). Strata previously referred to as the Reynales Formation constitute the younger, upper Fossil Hill/Merritton formations and the Rockway Formation. The true Reynales Formation is present at the Niagara Gorge in Ontario but is generally not present to the west and northwest of the Thorold area. The Merritton Formation is equivalent to the upper (informal) member of the Fossil Hill Formation (Brunton 2009b), inferring significant tectonic cut-down of almost 100 m of strata from Manitoulin Island to the Fergus–Elora area (Brintnell et al. 2009). In the Niagara Peninsula to Goderich regions, improved mapping and interpretation of stratigraphic relationships of the Middle Devonian Onondaga Formation and Detroit River Group strata was completed by OGS-based projects (Hurley et al. 2005; Luinstra, Brunton and Cowan 2006; Brunton 2009a; Sun, Brunton and Jin 2014, 2015, 2016, 2017a, 2017b, 2017c; Sun 2018).

Improvements in the identification and representation of depositional and erosional disconformities and unconformities is of importance for future hydrostratigraphic modelling (Brunton et al. 2017). Enhanced porosity and permeability of paleokarst in carbonate rocks at these surfaces (Smith, Grimes and Charbonneau 1988; Carter, Trevail and Smith 1994; Brunton and Dodge 2008; Brunton 2008, 2013; Carter 2012; Carter et al. 2014; Brunton and Brintnell, in press) are spatially associated with sequence stratigraphic breaks, which are the most significant controls on the occurrence of regional groundwater flow zones in the subsurface bedrock formations of southern Ontario (Brunton et al. 2007; Brunton 2008, 2009a, 2009b; Brunton et al. 2012; Carter et al. 2014; Banks and Brunton 2017; Brunton and Brintnell, in press).

The orientation of the Paleozoic stratigraphic chart (*see* Figure 2), from southwest (left) to northeast (right), was chosen to display regional dip, and lateral changes in facies, depth and thickness from southwest to northeast, with 5 columns representing different geographic areas in southern Ontario (Brunton et al. 2017; Carter et al. 2017). All stratigraphic units are colour-coded by lithology, for example salt, shale, sandstone, argillaceous limestone, limestone, organic-rich carbonate, and dolostone. Cumulative strata thickness ranges from over 1500 m to zero from left to right, southwest to northeast. Importantly, it illustrates the erosional profile of the Paleozoic strata and regional nature of the carbonate-capped cuestas and associated escarpment cliffs that form the subcrop edges of the stratigraphy (*see* Hewitt 1971; Brunton 2009a; Brunton et al. 2017). The erosional scarps of the stacked carbonate strata, especially the Silurian Lockport Group dolostones that form the Niagara Escarpment, are hydrogeologically significant because the ground elevations and current position of the erosional scarp result in significant precipitation in the uplands and the establishment of regional potable groundwater-flow systems (<200 m deep) in karstic carbonates (Brunton et al. 2007; Brunton 2009a, 2009b; Brunton and Brintnell 2011; Brunton et al. 2012; Brunton et al. 2017; Carter and Clark 2018). The up-dip subcrop and outcrop regions are also sites for infiltration of meteoric water into the subsurface, where it accentuates preglacial and glacially enhanced horizontal paleokarst-flow zones (Brunton et al. 2017).

Data Sources

Several data sets relevant to, and necessary for, model generation were identified (Table 1, Table 2) and compiled, utilizing the most relevant and up-to-date data (e.g., Clark et al. 2020).

Table 1. Primary data sources for lithostratigraphic modelling.

Data Set	Description	Application
Ontario Petroleum Data System (OPDS) database	26 952 petroleum well records with 300 000 formation tops, MNRF – Oil, Gas and Salt Resources Library	Primary data for model layer estimation
Oil, Gas and Salt Resources Library	Drill cuttings from 11 000 wells, well files, drill core from 1100 wells, >20 000 geophysical logs	QA/QC
Bedrock geology maps	Armstrong and Dodge (2007), GSC 1335A (Sanford and Baer 1971), GSC 1263a (Sanford 1969), Sun (2018), Armstrong (2017, 2018)	Constrain extrapolation from subsurface to subcrop
Digital bedrock geology map	Revision of Armstrong and Dodge (2007)	Constrain extrapolation of bedrock layers to bedrock surface
Measured sections	Bolton (1957)	Constrain extrapolation to Escarpment edge
Control points	Prognostic wells	Constrain estimation in data-poor areas
OGS stratigraphic tests	>300 diamond-drill holes	Constrain estimation in data-poor areas
Digital Elevation Model	https://www.ontario.ca/data/provincial-digital-elevation-model-version-30	Surface topography
Bedrock topography	Gao et al. (2006), revisions by GSC (Logan) and OGS (Yeung, Brunton, Armstrong)	Top of bedrock surface
Structure + isopach maps	Hand-interpreted formation layers (OGS 2011)	Constrain estimation in data-poor areas
Michigan petroleum wells	Lilienthal (1978)	Constrain extrapolation beneath Lake Huron
MECP water wells	Correct and/or verification of 5500 well records	Bedrock topography revisions
Great Lakes seismic	Shallow reflection seismic of top of bedrock	Bedrock topography of Great Lakes
NOAA, SRTM and CHS	Great Lakes bathymetry and topography of ground surface	DEM for surface of unconsolidated overburden

Abbreviations: *CHS – Canadian Hydrographic Survey; MECP – Ministry of the Environment, Conservation and Parks; NOAA – National Oceanic and Atmospheric Administration; SRTM – Shuttle Radar Topography Mission.*

Table 2. Secondary data sources that help define and constrain lithostratigraphic and hydrostratigraphic modelling.

Data Set	Description	Application
Oil interval data	OPDS – 6000 records	Fluid zonation, porous strata
Gas interval data	OPDS – 26 000 records	Fluid zonation, porous strata
Water interval data	OPDS – 35 000 records	Bedrock aquifers
Isotopic and geochemical analyses	130 analyses, Skuce et al. (2015), Skuce, Potter and Longstaffe (2015), Skuce (2015)	Hydrochemical zonation, groundwater flow, isotopic fingerprinting,
Petroleum industry water analyses	1024 standard water analyses	Hydrochemical zonation, salinity gradients, numeric modelling
Water type maps	89 maps of bedrock saline aquifers, Carter et al. (2015a)	Hydrochemical zonation, groundwater flow
Static level maps	17 maps of bedrock saline aquifers, Carter et al. (2015b)	Groundwater flow
NWMO 3-D model	1/3 of southern Ontario, Itasca and AECOM (2011)	Comparative analysis
Base fresh water map	GIS interpretation from water well records, Carter and Clark (2018)	Base of fresh water, hydrochemical zonation, contact aquifer, inferred karst, numeric modelling
Base of sulphur water map	Carter and Sutherland (2018)	Hydrochemical zonation, numeric modelling, hydrostratigraphic modelling
OGS groundwater mapping	In progress	Water well drilling, modelling of potable water aquifers
Petroleum industry core analyses	Data digitized late 2018	Hydrogeology, groundwater flow, hydrostratigraphic modelling
Structure and isopach mapping	Bailey (1984); Bailey and Cochrane (1984a, 1984b, 1985, 1986)	QA/QC of model layers

OIL, GAS AND SALT RESOURCES (PETROLEUM) WELL RECORDS

Petroleum well records of the Ontario Petroleum Data System (OPDS) are the primary data set used for modelling formation layers in the subsurface of southern Ontario. Three-dimensional modelling of formation layers would not have been feasible or cost-effective without the OPDS data. Consequently, most of the data QA/QC efforts were focussed on the review and editing of this data. The OGSRL petroleum well data is a weekly snapshot of the OPDS stored in a MySQL database. All further data editing and screening was done on the snapshot data in MySQL.

The OPDS is a custom Oracle database designed and maintained by the MNRF and OGSRL for managing data collected from the drilling and operation of petroleum wells in the province of Ontario (e.g., Carter and Castillo 2006). The digital data is sourced from hard copy well files collected and maintained by the MNRF. The OPDS has records associated with approximately 26 950 wells (Figure 4), with formation top depth and well collar elevation values for nearly 300 000 unique formation picks in the database.

Geographic co-ordinates are available for all boreholes, although at varying levels of confidence. A location accuracy code is recorded in OPDS for each borehole in the database. The co-ordinates have estimated horizontal accuracies varying from 1 m to over 1000 m. Over 95% of boreholes have co-ordinates with accuracies within 200 m of true locations, 71% are within 50 m, and 40% are within 20 m. Boreholes for which the location accuracy (error) is identified as greater than 1000 m are excluded from the model. Elevation values for well collars and associated formation tops have accuracies varying from 10 cm to 5 m.

Additional data includes collection and submission records of drill core and cuttings, drill core analyses, formation water analyses, nearly 20 000 geophysical logs, and oil, gas, and water interval data recorded while drilling. The unique identifier for each borehole is a licence number issued by the MNRF.

A curated collection of drill-cuttings samples from 13 000 wells and approximately 1100 drill cores is maintained in an indoor storage facility at the OGSRL and is available for public viewing and examination. Together with the geophysical logs this sample material is the principle source reference for QA/QC review, edit and enhancement of the well formation top picks in the OPDS.

Two sets of formation tops are recorded in the OPDS for each well. One set comprises picks submitted by industry well operators to the MNRF on drilling completion records, with a second set picked by geological staff of the MNRF or the OGSRL. Picks are made by examination and interpretation of drill cuttings samples and geophysical logs, and drill core if available. The industry picks have been completed by dozens of different geologists and nongeologists, with widely varying knowledge, skills and experience, and sometimes using differing standards. These picks can be inconsistent, especially for formations with similar lithologies and gradational contacts. Picks by MNRF and OGSRL are much more reliable as they have been made by fewer individuals using published standards of either Armstrong and Carter (2010) or Beards (1967). Repicking of formation tops by MNRF and OGSRL is incomplete.

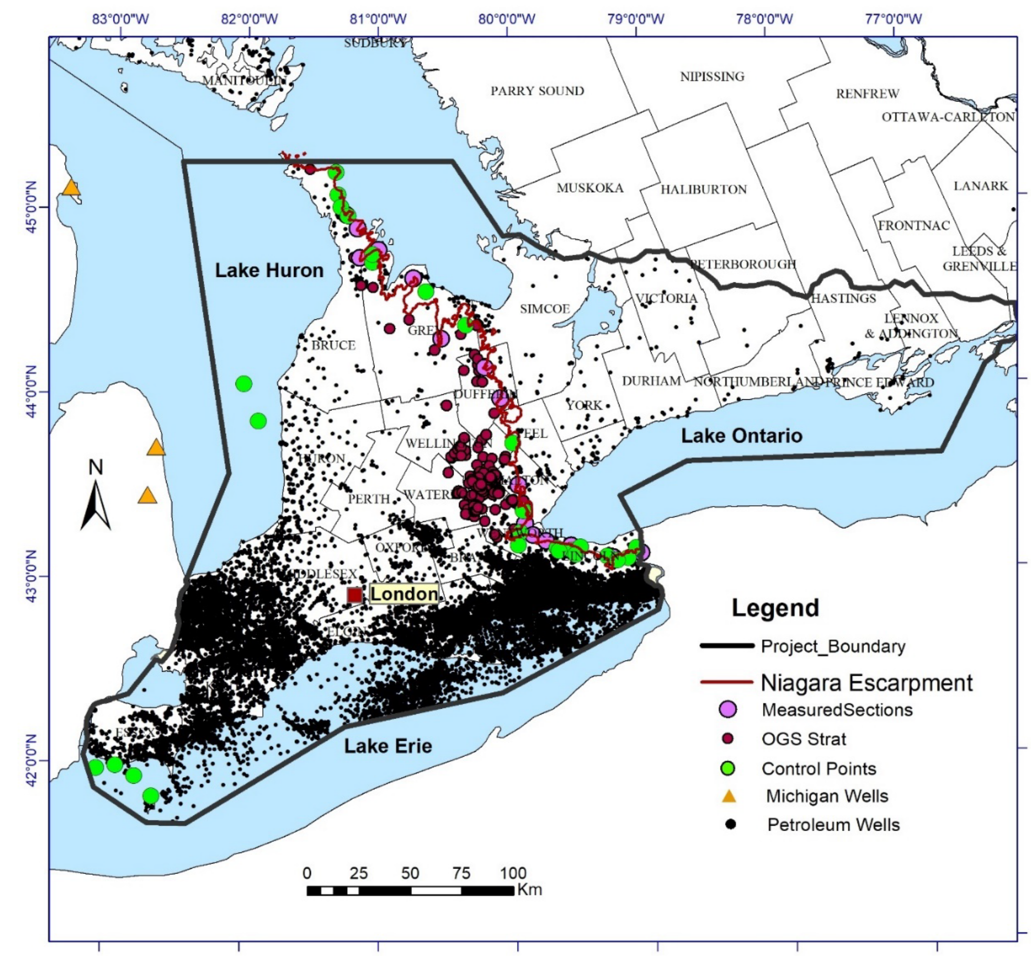

Figure 4. Location of well data points used as input to 3-D modelling. Data points labelled "OGS Strat" are stratigraphic test boreholes drilled by the Ontario Geological Survey.

Table 3. OPDS quality assurance (QA) codes for formation top picks recorded in the well database.

Code	Pick Confidence	Source	Description
2.0	Confirmed	MNRF P. Geo	The reviewer had good data—rock cuttings, geophysical logs, or rock cores—and is confident in confirming the pick.
1.9		P. Geo	
1.8		OGSRL Geologist in Training or Graduate	
1.7		OGSRL Geology Student	
1.5	Reviewed	MNRF P. Geo	The reviewer made the best possible pick based on the data available: rock cuttings, geophysical logs, or rock cores; however, more data or review should be considered.
1.4		P. Geo	
1.3		OGSRL Geologist in Training or Graduate	
1.2		OGSRL Geology Student	
1.0	Not Anomalous	MNRF well records	No geological review but does not cause anomalies in 3-D model
Null	Not Evaluated	MNRF well records	Default value for unedited well records submitted by well operators. No subsequent geological review.
-1.0	Anomaly, requires review	Any	Causing local anomalies when used in 3-D mapping and requires review.
-2.0	Anomaly, unresolvable	Any	Causing local anomalies when used in 3-D mapping but could not be confirmed or corrected because of an absence of data (rock cuttings, geophysical logs, or rock cores).

Consequently, a rigorous QA/QC process was required in this project to improve data quality and consistency of formation top picks for use in the 3-D model. Additional common data quality issues include such issues as data entry errors, inaccurate well locations and missing picks.

Formation tops reviewed by MNRF and OGSRL staff carry additional metadata in the OPDS, recording the reviewing geologists' confidence in the accuracy of the top picks. The metadata levels, referred to as QA Codes (Table 3), are used to prevent data from being reviewed multiple times and to explicitly filter data for interpretation or mapping and modelling, based on the quality of data and the confidence the reviewer has in the pick. In this study, formation top edits were made using a revised methodology and standards as outlined in Armstrong and Carter (2010), resulting in a revised stratigraphic chart prepared for this study (*see* Figure 2; Brunton et al. 2017; Carter et al. 2017). Formation top edits in the Niagara Peninsula incorporated new insights from detailed work by Shuo Sun and OGS staff (Sun, Brunton and Jin 2014, 2015, 2016, 2017a, 2017b, 2017c; and Sun 2018).

Three-dimensional modelling of formation layers would not have been feasible without the OPDS data. The initial task of data compilation and database construction was greatly facilitated by utilization of the existing OPDS data tables. This data was complemented by the addition of stratigraphic borehole data from the OGS, measured sections from field work, and control points at which the formation-contact depths have been interpolated based on neighbouring wells (*see* Figure 4). Control points were chosen at locations where there was insufficient data to guide modelling of stratigraphic layers.

Well data density was highly variable (*see* Figure 4), resulting in significant impact on model reliability. Of the total 26 950 wells in the petroleum-well data set, 21 412 wells were used to build the model. And of these wells, only 357 occur east of the Niagara Escarpment, over an area of 44 000 km^2, resulting in a density of 0.01 wells/km^2. West of the Niagara Escarpment, there are 639 wells north of the southern boundaries of Huron, Perth, Waterloo, Wellington and Halton counties, encompassing an area of 31 500 km^2, for a density of 0.02 wells/km^2. Within the remaining area of approximately 35 000 km^2 there are nearly 20 000 wells, with a density of 0.74 wells/km^2. Availability of formation top data also declines with depth and decreases the reliability of deeper model formation layers. And of the 916 (<0.4%) petroleum wells that penetrate the entire Paleozoic succession and intersect the Precambrian bedrock (Figure 5), only 93 have core to confirm the character of specific formational contacts.

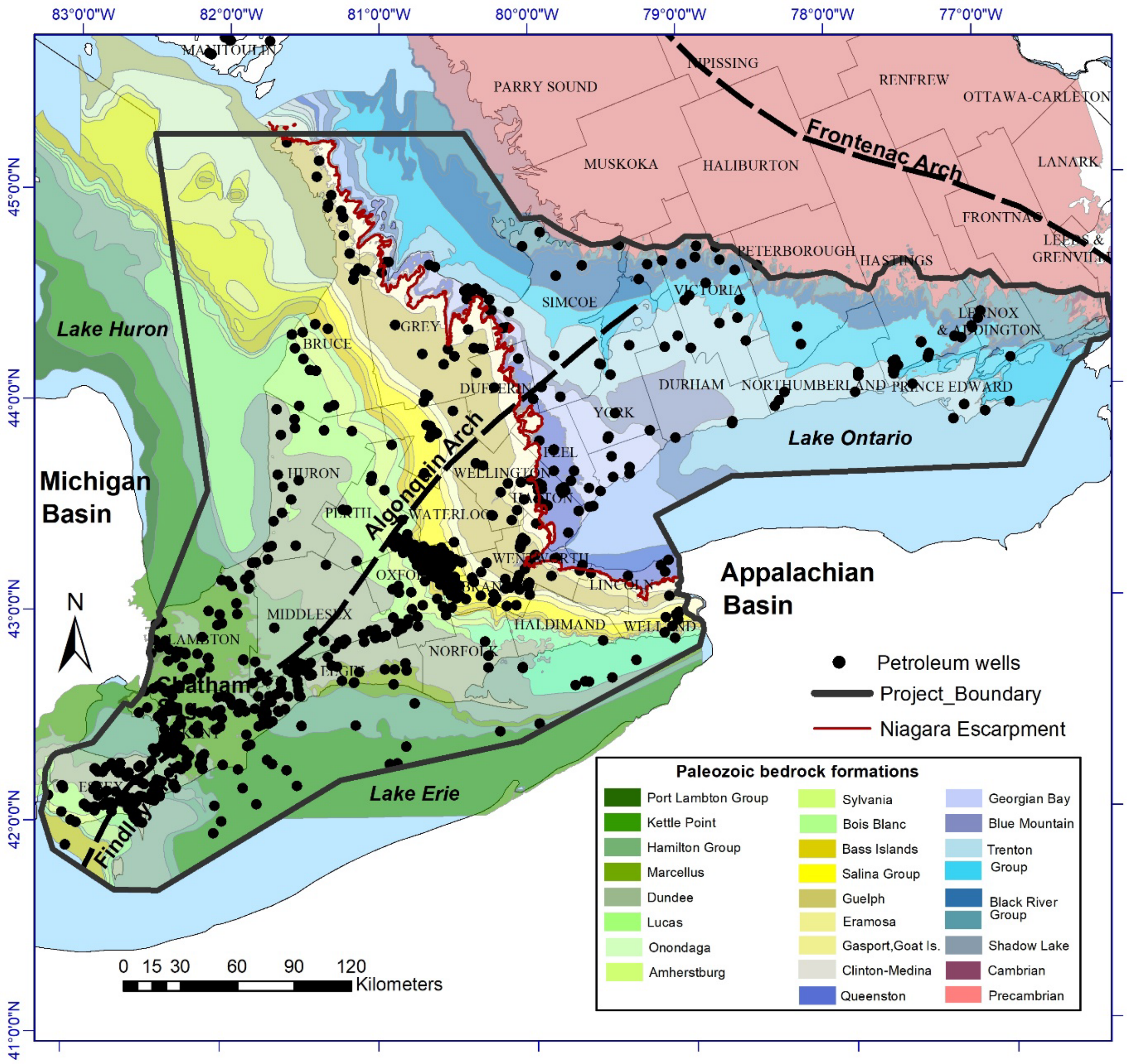

Figure 5. Location of 916 petroleum wells that penetrate to Precambrian bedrock within the study area.

MEASURED SECTIONS, STRATIGRAPHIC CONTROL POINTS AND MICHIGAN WELLS

After several modelling iterations, there remained areas where the modelled formation layers did not agree with existing mapping or exhibited unrealistic changes in thickness or structure. For example, model layers of many Silurian formations that outcrop on the face of the Niagara Escarpment either displayed gaps, did not extend to the escarpment edge, or extended past the escarpment edge. In many cases sparse data coverage was due to lack of petroleum wells and/or deep bedrock water wells drilled near the escarpment margin. The sparse data density does not provide enough guidance to the modelling algorithm to control estimation and/or extrapolation of layers. This was resolved, in part, by addition of a limited number of interpreted control points and measured sections to assist in formation layer extrapolation and to more closely match the published geological maps of the Paleozoic geology of southern Ontario. Control points and measured sections in the project database have unique codes as the borehole identifier so that these values can be removed in the future as new well data becomes available.

Formation top picks for 15 locations at the escarpment edge have been added using measured outcrop sections adapted from Bolton (1957), in addition to unpublished data from shallow OGS boreholes provided by Yeung and Brunton. Geologic data from 3 Michigan petroleum wells (Lilienthal 1978) were added to the project database to resolve an extrapolation issue beneath Lake Huron.

Prognostic or synthetic boreholes were created in areas with gaps in the modelled formation layers caused by sparse data. A prognostic well is a location for which the geological formation contacts have been interpreted based on the data available from the nearest petroleum wells and/or measured sections, at distances varying from 2 km to nearly 15 km. A total of 23 prognostic wells were added to the database as control points (*see* Figure 4). Ground elevation for these wells was derived from the MNRF Digital Elevation Model; depth to top of bedrock, from the OGS bedrock topography surface (Gao et al. 2006); and the latitude and longitude co-ordinates and the lot, concession, and township information, from the MNRF digital base maps of Ontario.

DIGITAL BEDROCK GEOLOGY SUBCROP MAP

For this model, digital bedrock topography and 2-D digital geological subcrop mapping are combined to assemble grids of 3-D points for each mapped formation. A regular grid at 1 km-spacing was imposed on the entire model area and attributed with the subcrop geology formation name and the bedrock surface elevation at each point location. These grid points optionally could be added directly as additional vector data control for corresponding layer surface estimation in the modelling software. However, they are more effective in the form of minimal thickness (i.e., 1 m) pseudo boreholes. As shallow pseudo boreholes, they act to adhere interpolated layer surfaces to mapped subcrop geology, while suppressing the estimation of older layer surfaces generated by the chronology-based model-building algorithm. Although vector points help to control individual layer surface estimations, they are not actively avoided by older layer surface estimations. These grid point pseudo boreholes were added to the borehole data set to better align layers to mapped geology in areas of little or no borehole data and to prevent extrapolation of modelled layers beyond the subcrop surface. Initial versions of the model utilized digital mapping by Armstrong and Dodge (2007). Shortcomings with that map were identified that necessitated preparation of an updated version of the map by MNRF to resolve issues with geographic extent, stratigraphic terminology, and bedrock unit polygon boundaries and subdivisions, and to incorporate new mapping (Armstrong 2017, 2018; Sun, Brunton and Jin 2017c; Sun 2018).

In 2016, the MNRF (Lee Fortner, Maia Somers) initiated an independent project to edit and update the digital subcrop map of the OGS (Armstrong and Dodge 2007) and GSC Map 1263A (Sanford 1969) for the model study area. The initial focus of this project was a review of the subcrop formation identifications recorded in OPDS, by comparison to the digital bedrock geology map. Inconsistencies between the formations identified as Top of Bedrock within petroleum well records in OPDS and the subcropping formations named in the corresponding locations on the digital map were identified. Subsequent corrections were made to bring OPDS and the mapped layer boundaries into geospatial continuity by either changing the formation designated as Top of Bedrock in OPDS or adjusting the boundaries of a formation's mapped area in the digital map, or both. Corrections were based, in part, on examination of drill cuttings, core and geophysical logs for 616 wells in OPDS. Other corrections, including some associated with legacy data entry errors, were identified after examination of original petroleum well drilling records. Detailed documentation of 68 revised formation top picks were made for the problematic subcropping of the Onondaga, Amherstburg, Bois Blanc and Bass Islands formations, and Salina Group formations in the Niagara Peninsula and Lake Erie.

Later stages of the subcrop geology project were integrated with the 3-D project to improve accuracy, precision and extent of 3-D point grids to control modelled formation layers. Extrapolation of the bedrock geology beneath Lake Huron and Lake Erie was based, in part, on GSC Map 1335A (Sanford and Baer 1971) and GSC Map 1263A (Sanford 1969), with new interpretations by project geologists for Lake Huron and Georgian Bay based on recently interpreted bedrock topography (Todd et al. 2020; Todd and McNamara 2018; McNamara and Todd 2018). The Salina Group polygon has been subdivided into formations based on Sanford (1969), and the Clinton–Medina (Cataract) Group polygon has been subdivided into the Clinton Group and the Medina (Cataract) groups as per Cramer et al. (2011). Formation contacts in the Niagara Peninsula were updated for consistency with new mapping by Armstrong (2017), Sun (2018) and Sun, Brunton and Jin (2017c). Detailed notes contain formation top depth and formation thickness, descriptions of drill cuttings, drill cutting photographs, as well as quality assurance codes and the geological reasoning for the revisions. Stratigraphic terminology and subdivisions are consistent with the revised stratigraphic chart (*see* Figure 2; Brunton et al. 2017). Further improvements are ongoing as the digital subcrop map is intended to be an active electronic document open to regular review and updates (see www.ogsrlibrary.com).

SURFACE DIGITAL ELEVATION MODEL AND BEDROCK TOPOGRAPHY

A topographic DEM is used to form the upper boundary surface of the unconsolidated sediments. This DEM is a composite surface composed of Shuttle Radar Topography Mission (SRTM) 90 m DEM data (http://www2.jpl.nasa.gov/srtm/), and Great Lakes bathymetry from the National Oceanic and Atmospheric Administration (NOAA), and Canadian Hydrographic Survey (CHS) (Vincent et al. 2015). For other large lakes within Ontario, lake bathymetry measurements extracted from CHS bathymetric field sheets were interpolated. These point depths were originally located and recorded by hand directly on bathymetric charts then later scanned to produce digital georeferenced images. To automate the digital capture of the depth points, a Python™ application was developed using a machine-learning optical character recognition algorithm (Griffiths, Russell and Logan 2020).

The OGS digital bedrock topography map (Gao et al. 2006) was used in early versions of the 3-D model to constrain the bedrock surface. From a companion model of the Pleistocene glacial sediments being concurrently developed by the GSC and OGS (Logan et al. 2020), a revised version of the bedrock topography has been produced. To make the models spatially compatible, the revised topography represents the contact between lithified bedrock and unlithified surficial sediment in both models. The revised bedrock topography is supported by surficial mapping, archival borehole logs, and geophysical data (Logan et al. 2020) revisions to bedrock terminology and location revisions in the southern Niagara Peninsula by OGSRL staff (Somers, Sun), and along the Niagara Escarpment by OGS staff (Brunton, Yeung). An additional 16 304 “top of bedrock” and “sediment thickness” values were supplied from the OPDS database by OGSRL staff, and 43 771 vetted Ministry of the Environment, Conservation and Parks (MECP) water well records were provided for part of the Niagara Escarpment region by OGS staff (Yeung, Brunton). As the surficial sediment model includes only the onshore portion of the bedrock model area, the bedrock topography surface was extended by using Great Lakes bedrock elevation surfaces derived from seismic sediment thickness maps of Lake Huron and Ontario (Todd et al. 2020; Todd and McNamara 2018; McNamara and Todd 2018) and “top of bedrock” picks from the OPDS database for Lake Erie.

OTHER DATA

Cultural features have been added to provide a practical geographic reference for the geological features of the model. The cultural features consist of highways, streams and shorelines, counties, municipalities, geographic townships, major towns, and the Great Lakes. The boundaries for geographic townships (Townships Improved), highways (Transportation), and streams and shorelines (Shorelines 100K, Water Bodies 10-50 K) were shapefiles exported from geospatial databases maintained by Land Information Ontario (https://geohub.lio.gov.on.ca). The boundaries for counties were shapefiles exported from the PetroGIS application maintained by the Petroleum Operations section of MNRF. Great Lakes polygons were downloaded as shapefiles from Open Government (NRCan) (https://open.canada.ca/en/open-government-licence-canada).

A large number of seismic surveys have been acquired by the petroleum industry in southern Ontario (http://www.ogsrlibrary.com/data_free_petroleum_ontario) but these are not publicly available to assist in the modelling process.

Data Quality Assurance and Quality Control

QUALITY ASSURANCE AND QUALITY CONTROL PROCESS

The formation top picks recorded in OPDS are the primary control on estimation of modelled layers in the 3-D model. Errors, inconsistencies and missing data create inaccuracies in the model. Considerable project resources focussed on identifying and correcting these data issues; in fact, it was the main focus of data QA/QC work in this project (Figure 6). Most of this work was completed at the OGSRL and by OGS staff.

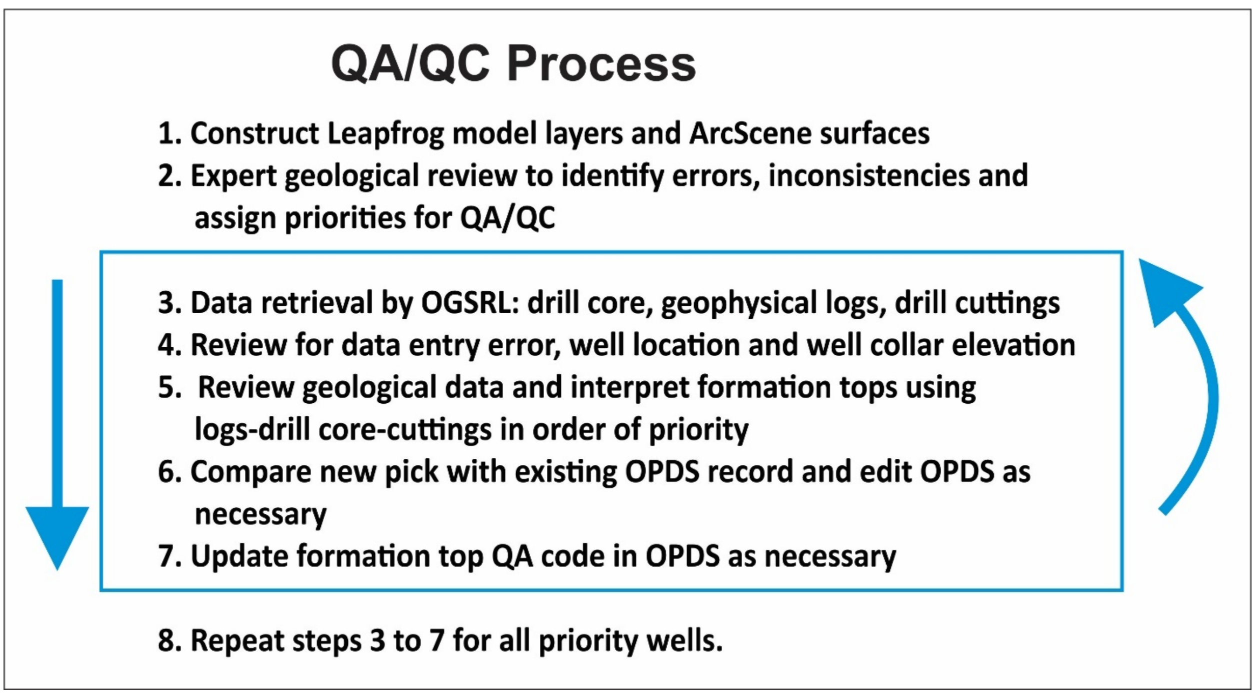

Figure 6. QA/QC process summary for review and edit of formation top data.

All formation top picks recorded in OPDS have been assigned a QA/QC code as an estimate of the reliability of the pick (*see* Table 3). The assigned code for a formation pick is updated when or if a pick is reviewed and either edited or confirmed. Codes are based on source of the well pick (MNRF well records, reviewer type), data available for pick determination (logs, drill cuttings, drill core) and whether the pick creates a visible model layer anomaly.

The first rounds of reviews and edits focussed on anomalies, principally structural highs and lows, produced by single wells or small groups of wells in the early iterations of the model. These are the easiest errors to detect, although it should be noted that not all anomalies are, in fact, errors. Anomalies are verified by examination of the source records and supporting data. Anomalies were identified visually from the 3-D model formation layers and from ESRI® ArcScene® formation top surfaces generated using the natural neighbour interpolator. Isopach layers were also generated for salt formations of the Salina Group using the natural neighbour interpolator in ArcGIS®, which identified 20 wells with negative thickness values. Correction of these data errors usually results in removal of structural highs and lows and a smoother formation surface with a more consistent formation thickness. During the QA/QC process, erroneous well locations and/or surface elevations were found to be the cause of some geologic anomalies. Any anomalies caused by bad location data were corrected in OPDS.

After completion of anomaly editing, the interim model was reviewed by the project geologists to identify geological priorities for review and edit formation top picks. The Lockport Group and Devonian sandstones were identified as the highest priorities as discussed below.

It was not possible to review and edit all the formation top picks for the priority formations because of project time and resource constraints. A quality scoring analysis was undertaken by data technicians at the OGSRL, under the guidance of the project geologists, to filter and select wells for review. The initial step in the analysis was the identification of wells with missing formation tops in the depth interval of interest. For example, wells drilled to the top of the Rochester Formation in Lambton County would be expected to encounter the Guelph Formation, Goat Island Formation and Gasport Formation of the Lockport Group, which are known to occur regionally in this area. If no formation top picks were recorded for any of these formations, the well would be selected for subsequent analysis. The selected wells were then assessed for quality of data available for review, namely geophysical logs, drill core and drill cuttings, in order of preference. Wells with no logs, core or cuttings were not considered for geologic QA/QC. The wells with the best available data were then filtered to provide a good geographic distribution of data, ideally with one well per lot, and then by TD date (the date the well reached total depth), with preference given to the most recently drilled wells due to generally improved data collection and quality compared to older wells. Some efficiencies were gained by having OGSRL clerical staff cross-reference database entries with original documents submitted by the well drillers and correcting data entry errors, saving time for the project geologist.

QA/QC of formation tops was a labour-intensive process involving repicking of questionable formation tops by project geologists using geophysical logs, drill cuttings, and/or drill core, in this order of preference and where available. The formation top picking procedure and standards for identification of southern Ontario formation tops in cuttings and logs was modified from Armstrong and Carter (2010).

From 2015 to 2018, project geologists and geological contract staff of the OGSRL completed edits to 30 320 formation tops in a total of 7812 wells (Table 4). Well revision edits included formation top additions, deletions, and pick depth changes. The work was completed as a series of 6 projects with discrete targets and deliverables, and within each of these projects, QA/QC proceeded by geographic area. Breaking up the study area into smaller areas, such as counties and/or townships, was beneficial as

Table 4. Geological QA/QC edits of the OPDS database included in the 3-D modelling project.

Date	Project	Number of Wells Reviewed	Formation Top Picks Reviewed and/or Edited
2014–2015	Chatham Sag	3638	All picks reviewed and verified not necessarily resulting in edits
2016	Devonian sands (Davis 2017)	1319	198 picks removed, 818 revised
2016–2017	Regional geology	1107	All formations top to bottom of each well not necessarily resulting in edits
2016–2017	Top of bedrock or subcrop	616	One per well
2016–2018	Anomaly edits	322	771 picks edited or removed
2018	Lockport Group	810	4572 Lockport, Salina, and/or Rochester picks reviewed, resulting in 500 edits; 6096 other formation tops reviewed, resulting in 1000 edits
2015–2018	Total	7812	30 320 formation top picks reviewed and verified or edited

individual formations and groups of formations have geographically related geological characteristics due to lateral facies changes. Plotting the wells, using programs such as QGIS®, ArcMAP® and Google Earth™, help to provide spatial context to the geology for the QA/QC analysis.

QA/QC of formation tops is a continuing process at the OGSRL, albeit at a slower pace than in the current project.

QA/QC of well collar elevations and well location co-ordinates were the focus of previous data editing projects (Carter and Castillo 2006). Since 1997, the operators of oil and gas wells in Ontario have been required to provide geographic co-ordinates for well locations in addition to a well location plan and rig floor and/or well collar elevation above sea level. Well location and well collar elevation are required to be reported with an accuracy of 10 cm. From 1954 to 1997 well operators were required to provide well location plans showing well location relative to surveyed geographic lot boundaries and the ground elevation of the well site, but with no accuracy requirement. Prior to 1954 well location plans were hand-drawn sketches. Geographic locations and elevation for all wells drilled before 1997 have been derived using GIS mapping and field acquisition of GPS co-ordinates. As noted above, 95% of the wells recorded in OPDS have co-ordinates within 200 m of the true location and 71% are within 50 m. Ground elevation at the well locations has been reviewed and edited where necessary by comparison with values from the Provincial Digital Elevation Model for the province of Ontario (https://www.javacoeapp.lrc.gov.on.ca/geonetwork/srv/en/main.home).

QA/QC PRIORITIES

Chatham Sag

In 2014–2015, OGSRL completed a GSC-funded project to review the formation top picks for wells within the Chatham Sag. The immediate objective was to provide reliable formation top picks for mapping and interpretation of faults. The project was a precursor to, and complementary to, the 3-D modelling project. The study area was geographically constrained to Elgin, Kent, Lambton and Middlesex counties. Within this area, at the time of the project, there were 5735 wells with either geophysical logs or chip samples suitable for making geological formation top picks. To further prioritize wells for review and provide good geographic coverage, a 1 by 1 km grid was created and one well per grid cell was selected for editing, with additional wells checked by drill date in reverse chronological order. A total of 3638 wells were reviewed.

Lockport Group

The Lockport Group formations, which include the Gasport, Goat Island, Eramosa and Guelph, in ascending order, form important regional aquifers in southern Ontario (Brunton 2009b; Brunton et al. 2012; Brunton and Brintnell 2011; Carter et al. 2014; Carter et al. 2015a, 2015b). These rocks have also produced significant quantities of oil and natural gas in the deeper subsurface and host 34 natural gas storage reservoirs with storage capacity for 269 billion cubic feet (bcf) of natural gas (Carter, Hamilton et al. 2016).

The top of the Lockport Group is intercepted by 15 585 wells of which 13 153 penetrate the full thickness. At the beginning of the project most of these wells recorded a formation top only for the Guelph Formation, with no picks for the stacked dolostones that form the 3 underlying formations of the Lockport Group (Eramosa, Goat Island and Gasport Formations; Brunton 2009b; Brunton and Brintnell 2011; Brunton et al. 2012). Without picks for the Eramosa, Goat Island and Gasport, the formations could not be modelled separately. Because it was not practical to edit all of the wells, geological QA/QC was prioritized to provide good geographic coverage of the project area, and also to provide picks for wells with fresh-water intervals recorded in the Lockport Group, all wells with core analyses, and wells in the Lockport subcrop area. Geological picks for these formations have been added to 810 wells in support of the 3-D modelling project. An estimated 9000 wells remain in the database with no formation top picks for the Eramosa, Goat Island and Gasport formations, and editing of Lockport Group picks in these wells remains a priority.

In 59 wells, the Lockport Group was referenced as Amabel Formation, which is an outdated term (Brunton and Brintnell 2011; Cramer et al. 2011; Brunton et al. 2012). Formation top picks for all of these wells were edited to remove the reference to Amabel Formation and substitute with revised stratigraphic nomenclature (*see* Figure 2).

Devonian Sandstones

Devonian sandstones were identified as a priority because of inconsistent identification of these sands in the OPDS well records and their importance as potential water-bearing intervals due to enhanced porosity and permeability. Four distinct quartzose sandstone units occur within the Middle to Lower Devonian succession: the Columbus Formation sand lithofacies, which has been correlated with the uppermost member of the Lucas Formation (Birchard et al. 2004); the Sylvania Formation; the Springvale Member of the Bois Blanc Formation; and the Oriskany Formation. Enhanced porosity and permeability in these sandstones make them significant from a hydrogeological and petroleum reservoir perspective. Numerous inconsistencies in identification of these sandstones were identified by contract geological staff at the OGSRL, and a separate project was initiated to re-examine and re-interpret the distribution and characterization of these sands (Davis 2017).

Over 1300 wells containing Devonian-aged strata were examined using binocular microscopy of drill cuttings, interpretation of geophysical well logs, and GIS queries of OPDS database well records. These included wells drilled since the last time that these sands were mapped (Bailey and Cochrane 1985). The geographic extent of all 4 sandstone formations were updated, with sandstones identified in areas not previously documented. In other cases, stratigraphic assignments were corrected. Petrographic characteristics of the sandstones, based upon examination of samples of drill cuttings, are now documented. A total of 818 formation or member top picks have been added or edited, and 198 picks determined to be erroneous have been deleted from OPDS. The revised data has been incorporated into the 3-D model.

Subcrop – Top of Bedrock

Comparison of bedrock geology maps and formation top picks recorded in the OPDS indicated widespread discrepancies between the mapped subcrop formation and the formation named as top of bedrock in the OPDS. These discrepancies resulted from both errors in the subcrop maps or incorrect formation picks for top of bedrock in the OPDS. A new project was initiated by the MNRF to edit the OGS digital subcrop geology map for southern Ontario originally produced by Armstrong and Dodge (2007). The project corrected map discrepancies and reviewed and edited the top of bedrock picks for 616 wells. The revised map (Somers et al. in prep.) has been utilized in the 3-D project to constrain formation layer extrapolations to the subcrop surface.

Anomaly Edits

During successive model iterations, initial model review by project geologists focussed on identification of isolated anomalies in either formation thickness or on formation surfaces. The wells at which these anomalies occurred were identified and prioritized for review and edit of formation tops. A total of 322 wells were reviewed in this process, resulting in correction of 771 formation tops (*see* Table 4).

Data Preparation for Modelling

The edited and enhanced formation top data was exported from the OPDS Oracle database and provided to the modeller in tabular format. Prior to creation of the tables, the data was processed through a series of filters as a final data quality routine and to prepare the data in a format suitable for modelling.

Data was extracted from the OPDS by staff of the OGSRL using a direct connection to the database available at the library. The data extraction process was run on a weekly basis and used by the OGSRL to update petroleum well data on the library's website and to provide data access to library clients and partners, including those involved in modelling. The OGSRL and MNRF have security measures in place to ensure only nonconfidential geological data is exported. In Ontario, newly drilled petroleum development well results remain confidential for 30 days after reaching total depth, and exploration well results remain confidential for a year. Regardless of suitability for modelling, geological data from confidential wells was not included. This resulted in excluding less than 20 wells.

The OPDS geology data was stored as formation top picks with each row being one pick. However, for modelling, the lithology table must contain complete depth top to bottom values to prevent layer thickness over-estimation when portions of the stratigraphy are missing from the log. Although not explicitly recorded in the OPDS, the bottom of any formation was assumed to be the top of the next formation below it. Problems arose when the top of the next formation had not been picked or had not been picked correctly or when the next expected formation was not present due to lateral facies changes, erosional removal or nondeposition. These problems were resolved by assigning the formation bottom depth to be the depth to the top of the uppermost underlying formation, which has a top depth recorded in the OPDS, selected from a range of possible formations as per Table 5. In the case of formations that are known to be present in the depth interval penetrated by the well, but formation tops have not been picked, this was a practical but temporary solution which ideally will be resolved by future QA/QC edits to add picks for the missing formations. For formations which have not been individually modelled, thicknesses were combined with the immediately overlying modelled formation(s) to create a composite model layer. The deepest formation intersected by a well has only a formation top recorded in the database and was assigned a thickness based on the total depth of the well.

Table 5. Protocol for designation of deepest formation to be used for assignment of a bottom depth for model formation layers.

Sequence Number	Model Layer Name	Deepest Formation Bottom
300	Port Lambton Group	Kettle Point
301	Kettle Point	Hamilton Group
303	Hamilton Group	Dundee
305	Marcellus	Dundee
306	Dundee	Amherstburg
308	Columbus	Lucas
309	Lucas	Sylvania
311	Amherstburg, Onondaga	Bois Blanc
312	Sylvania	Bois Blanc
314	Bois Blanc	Bass Islands/Bertie
315	Springvale	Bass Islands/Bertie
318	Oriskany	Bass Islands/Bertie
400	Bass Islands/Bertie	G Unit
401	G Unit	F Salt
402	F Unit	C Unit
403	F Salt	C Unit
404	E Unit	C Unit
405	D Unit	C Unit
406	C Unit	A-2 Carbonate
407	B Unit	A-2 Carbonate
408	B Equivalent	A-2 Carbonate
409	B Salt	A-2 Carbonate
410	B Anhydrite	A-2 Carbonate
411	A-2 Carbonate	Guelph
412	A-2 Shale	Guelph
413	A-2 Salt	Guelph
414	A-2 Anhydrite	Guelph
415	A-1 Carbonate	Guelph
416	A-1 Evaporite	Guelph
418	Guelph	Gasport
420	Eramosa	Gasport
421	Goat Island	Gasport
422	Gasport	Irondequoit
427	DeCew	Irondequoit
428	Rochester, Lions Head	Irondequoit
429	Irondequoit, Rockway, Merritton (Fossil Hill), Reynales	Cabot Head
432	Neahga	Cabot Head
433	Thorold	Cabot Head
434	St. Edmund	Wingfield
435	Wingfield	Dyer Bay
436	Dyer Bay	Cabot Head
439	Grimsby	Cabot Head
440	Cabot Head	Whirlpool
441	Manitoulin	Queenston
442	Whirlpool	Queenston
500	Queenston	Georgian Bay–Blue Mountain
502	Georgian Bay–Blue Mountain	Cobourg

Sequence Number	Model Layer Name	Deepest Formation Bottom
511	Cobourg	Sherman Fall
515	Sherman Fall	Kirkfield
517	Kirkfield	Coboconk
519	Coboconk	Gull River
522	Gull River	Shadow Lake
523	Shadow Lake	Precambrian
600	Cambrian	Precambrian
700	Precambrian	*Precambrian Top + ~500 m*

The base depth for the model was set arbitrarily at -2000 m asl. This creates a minimum thickness of 500 m for the Precambrian layer.

A final filter was applied using the QA/QC codes (*see* Table 3) that had been added during the geologic QA/QC process. Geologic formation picks with a QA/QC code of -1 or -2 were removed from the modelling data. A total of 1352 picks were removed from the model by this filter. These picks had been observed to cause anomalies but could not be corrected in the project timeframe (QA/QC code: -1) or could not be corrected or verified in the absence of geologic data (QA/QC code: -2).

DATA EXPORT

Geological data was exported for modelling, from the project database, in 2 text-based comma-separated value (*.csv*) databases. A primary table containing approximately 194 000 geologic picks, with *both* formation tops and formation bottoms, was exported to create the main layer volumes. A secondary table containing approximately 52 000 formation top picks for which there were no formation bottoms, was exported to assist the modeller in filling gaps in the model surfaces. The secondary geologic table does not have overlapping formation picks with the primary table, and data exists in this table only when a corresponding bottom pick could not be found for a formation. An additional 46 000 formation top picks in the OPDS belong to formations or groups that were not modelled or were combined into 1 model layer as described below (*see* Appendix 1).

Well collars located with latitude, longitude and elevation (above sea level) were provided in a separate *.csv* table. All corrections to geologic data and well collars in the OPDS automatically become available to all OGSRL clients and partners on a weekly basis with each refreshed database snapshot.

3-D Modelling

The project objective was to create model layers at the formation rank for all Paleozoic sedimentary strata in the subsurface of southern Ontario. This was not practical because of constraints caused by data quality, data density, missing data and formation thickness, as described below, resulting in 54 modelled bedrock layers out of a total of 70 formations (*see* Figure 2 and Appendix 1).

Modelling was an iterative process (*see* Figure 7) which generated 7 successively improved versions of the model (Table 6). An initial 3-layer model of the unconsolidated surficial sediments, the Paleozoic bedrock, and the Precambrian basement has evolved to the latest model version that contains 56 layers, of which 54 are modelled Paleozoic bedrock layers, one is Precambrian basement, and one is the overlying unconsolidated surficial sediments (*see* Figure 8).

Table 6. Summary of model development.

Iteration	Layers and Data Sources	Application
1	3 layers: overburden, Paleozoic, Precambrian with DEM and bedrock topography (Gao et al. 2016); assemble team, prepare project work plan	Proof of concept, project planning, project scope
2	Leapfrog® Hydro, 61-layer model using unedited OPDS data, OGS bedrock geology (Armstrong and Dodge 2007), bedrock topography (Gao et al. 2016), DEM	Test feasibility of 61-layer model, identify QA/QC priorities
3	61-layer model, incorporate 2016 QA/QC	Test results of initial formation top edits, identify new QA/QC priorities
4	61-layer model correcting modelling issues and new anomalies from edited well data, revised lithostratigraphic chart (Brunton et al. 2017), Devonian sandstone study (Davis 2017)	Incremental improvements. Identify new QA/QC priorities
5	61-layer model with 2017 QA/QC edits (Lockport), Great Lakes bathymetry, GSC bedrock geology (Sanford and Baer 1971), OGS stratigraphic tests (boreholes), measured sections (Bolton 1957)	Incremental improvements, identify new QA/QC priorities
6	Leapfrog® Works, 58-layer model, correct new anomalies from edited well data, new bedrock geology (Somers et al. in prep), Michigan wells, new bedrock topography and overburden (Logan et al. 2020), new Great Lakes bedrock topography (Todd et al. 2020; Todd and McNamara 2018; McNamara and Todd 2018)	Further incremental improvements, identify new QA/QC, identify cultural layers
7	56-layer model, revised bedrock geology (Somers et al. in prep), add cultural layers, anomaly edits, control points	Finalize model development, final review, prepare for release

Model resolution is 400 m. Attempts to model at 100 m resulted in unreasonably long processing time and failure of the modelling run due to hardware constraints. At the project scale, and with average data density varying from only 0.01 to 0.74 wells/km^2, modelling at 100 m scale for the entire project area is arguably not justified.

MODELLING SOFTWARE

From 2015 to 2018, LeapFrog® Hydro, an implicit 3-D modelling application developed by Seequent Limited (formerly ARANZ Geo Limited), was used for modelling. Leapfrog® Works implicit 3-D modelling software was used to develop the final model. The speed and flexibility of implicit modelling lends itself well to the large geographical size, large data sets and multiple iteration cycles involved in the development of the southern Ontario geological model. The software requires the model extents to be defined in 3-D space by a base elevation or surface, X/Y lateral extents or a polygon boundary and an upper surface – usually obtained from a topographic DEM. These boundaries truncate contact surfaces and layer volumes when the model is rendered for visualization.

The modelling workflow expects that borehole log contacts will act as the primary data input for the model. Surfaces and 3-D vector objects can augment borehole contacts. The modelling software utilizes a proprietary Radial Basis Function algorithm, FastRBF™, to estimate (or imply) surfaces from input data. In the implicit model, a layer contact surface is defined as the zero set of a Radial Basis Function fitted to the layer contact data (Carr et al. 2001). Implicit model surfaces are directly estimated from borehole contacts and other measured contact data (e.g., geological mapping and field observations); however, manually constructed (explicit) trend surfaces and polyline editing can be applied independently in areas of low-data support to evaluate multiple scenarios.

In the modelling software, several options exist to control how support data (e.g., interpreted borehole contacts) are rendered into model layer volumes. In the configuration used for bedrock modelling, an upper contact surface for each model layer is developed that both honours contact data and avoids all younger borehole lithology intervals. Aside from avoiding younger borehole formations, the contact surfaces are estimated in 3-D space independently from one another. Upper, lower and lateral layer volume boundaries are defined by contact surfaces in chronological succession and overall model boundaries. Along with establishing a younging direction, 4 options are available in the modelling software to assign to each layer, which determines how layer volumes are derived from intersecting contact surfaces: 1) deposit, 2) erosion, 3) intrusion and 4) vein. “Deposit” contacts will not remove any older layer volumes that they intersect, giving the appearance of younger layers conformably deposited on older layers. “Erosion” contacts will cut away intersecting older layers to give the appearance of an erosional or unconformable contact. “Intrusion” and “vein” contacts are similar in that they both remove existing older layers and establish an enclosed lithology on the interior or young side of the contact surface. These contact types define how surface overlaps are resolved; they don’t necessarily need to be directly associated with the actual geological contact type. For the southern Ontario model, it was found that if erosion contacts were used for unconformity contacts, an excessive amount of older lithologies were eliminated while overestimating the younger layer above. A higher data density may allow erosion contacts to be used effectively where appropriate; however, for this regional model, with both varying data densities and varying geologic complexity, it was found that deposit contacts applied to all layers yielded acceptable results. It was, however, possible to add a bedrock–overburden erosional surface by using a refined model. An initial primary model was developed consisting of only overburden and undifferentiated bedrock. The refined model was then developed using the undifferentiated bedrock volume as a container. This simplified modelling the bedrock layers since they are automatically truncated at the upper boundary of the refined container. This technique could not be applied to other bedrock erosional surfaces because the modelling software does not allow multiple nested refined models.

MODEL LAYERS

There are presently 70 identified bedrock strata in southern Ontario at formation rank and 9 groups (*see* Figure 2). These formations are represented in the 3-D model as 54 bedrock layers because of issues related to a combination of lateral facies changes, complex stratigraphic relationships, and sparse or missing formation top data, as discussed below.

All Cambrian formations are represented as an unsubdivided Cambrian layer. In onshore portions of southern Ontario, the Cambrian thins to only a few metres in thickness and consists entirely of quartzose sandstone. Subdivision of these sandstones into their constituent formations has not been attempted and may not be possible. The Cambrian thickens rapidly into the Michigan and Appalachian basins beneath Lake Huron and Lake Erie. There are no wells in Lake Huron but in Lake Erie, 3 formations have been identified: the Mt. Simon, Eau Claire and Trempealeau formations in western Lake Erie, and their lateral equivalents to the east, the Potsdam, Galway/Theresa, and Little Falls formations. These formations have been modelled as 1 layer together with the unsubdivided onshore Cambrian strata to maintain lateral layer integrity.

The Ordovician Blue Mountain and Georgian Bay formations are represented as 1 layer, as there are no formation top picks in the well database for the Blue Mountain Formation. Formation top picks for the Collingwood Member of the Cobourg (Lindsay) Formation are inconsistent in the well database so it is not modelled. In many cases the Collingwood has been erroneously included in the basal Blue Mountain Formation in the database and, consequently, it is likely included in the Georgian Bay–Blue Mountain model layer. This is an identified QA/QC issue (*see* Appendix 3). Recent studies of a basal organic-rich black shale known as the Rouge River Member of the Blue Mountain Formation have identified criteria for picking formation tops for this unit, but picks are not yet consistently recorded in the OPDS, so this black shale is incorporated in the Georgian Bay–Blue Mountain model layer.

There are no formation picks in the OPDS for the Lower Silurian Cambria, Kodak or Devils Hole formations, which have a very localized distribution in the Niagara area. The Power Glen Formation is not picked in the well database and is grouped with the Cabot Head Formation. The Lower Silurian Irondequoit, Rockway, Merritton, Fossil Hill and Reynales formations are generally less than 3 to 5 m in combined thickness and are difficult to differentiate in logs and drill cuttings, so have been grouped together. The Lions Head Formation is correlated with the Rochester Formation and has been modelled in a single layer.

The Lower Devonian Onondaga Formation has been grouped with the Amherstburg Formation because of the lack of formation top picks for the Onondaga in the well database. Recent work by Sun, Brunton and Jin (2017) and Sun (2018) has demonstrated that the stratigraphic relationships are more complicated than this simple grouping. The Middle Devonian Ipperwash, Widder, Hungry Hollow, Arkona, Rockport Quarry and Bell formations of the Hamilton Group are represented at the group level, as are the Upper Devonian Sunbury, Berea and Bedford formations of the Port Lambton Group. There are no formation top picks for these formations in the well database.

MODELLING PROCESS AND WORK FLOW

After initial data compilation, QA/QC, and addition of enhanced and updated data was complete, all data sets were loaded into the modelling software. Model construction is an iterative process consisting of the following:

- interim model construction incorporating all loaded data,
- critical geological appraisal of the interim model,
- identification of errors and inconsistencies and priorities for editing,
- QA/QC data review and editing of errors and inconsistencies, and
- remodelling using the edited and updated data set.

The process was repeated as necessary to achieve a level of geological integrity based on the available data and expert knowledge in accordance with the level of detail and modelling goals of this release version (Figure 7).

Borehole log “Depth From – To” data is the primary data source as the modelling software utilizes the formation depth intervals to enforce model layer chronology. However, surfaces can also be augmented by 3-D vector objects and 3-D polylines. For this model, digital bedrock topography and 2-D geological subcrop mapping were combined to assemble grids of 3-D points for each mapped formation. These point elevations were added to corresponding model formations to better align them to mapped geology in areas of little or no borehole data, particularly east of the Niagara Escarpment and beneath water bodies. The bedrock topography surface was also used to constrain the geometry of bedrock layers by acting as a boundary between bedrock and unconsolidated surficial sediments. This boundary effectively truncates upward-trending bedrock layers and enforces the structural discontinuity between bedrock and unconsolidated surficial sediments layers.

In some cases, areas with a low data support density required additional control to maintain proper layer thickness integrity and geometry based on expert feedback. Gradual undulations of strata over large distances may result in layers that are rendered too thick, too thin or potentially removed completely if data control points are too sparse. Consistent layer thicknesses and trends were maintained across areas of sparse data by additional 3-D digitized polyline edits. This surface editing was employed to correct layer irregularities that were identified by project geologists on interim models. The Ordovician Shadow Lake Formation, for example, extends across almost the entire model area yet the average thickness of this formation from borehole logs is approximately 3.3 m and locally is much less. With only 1119

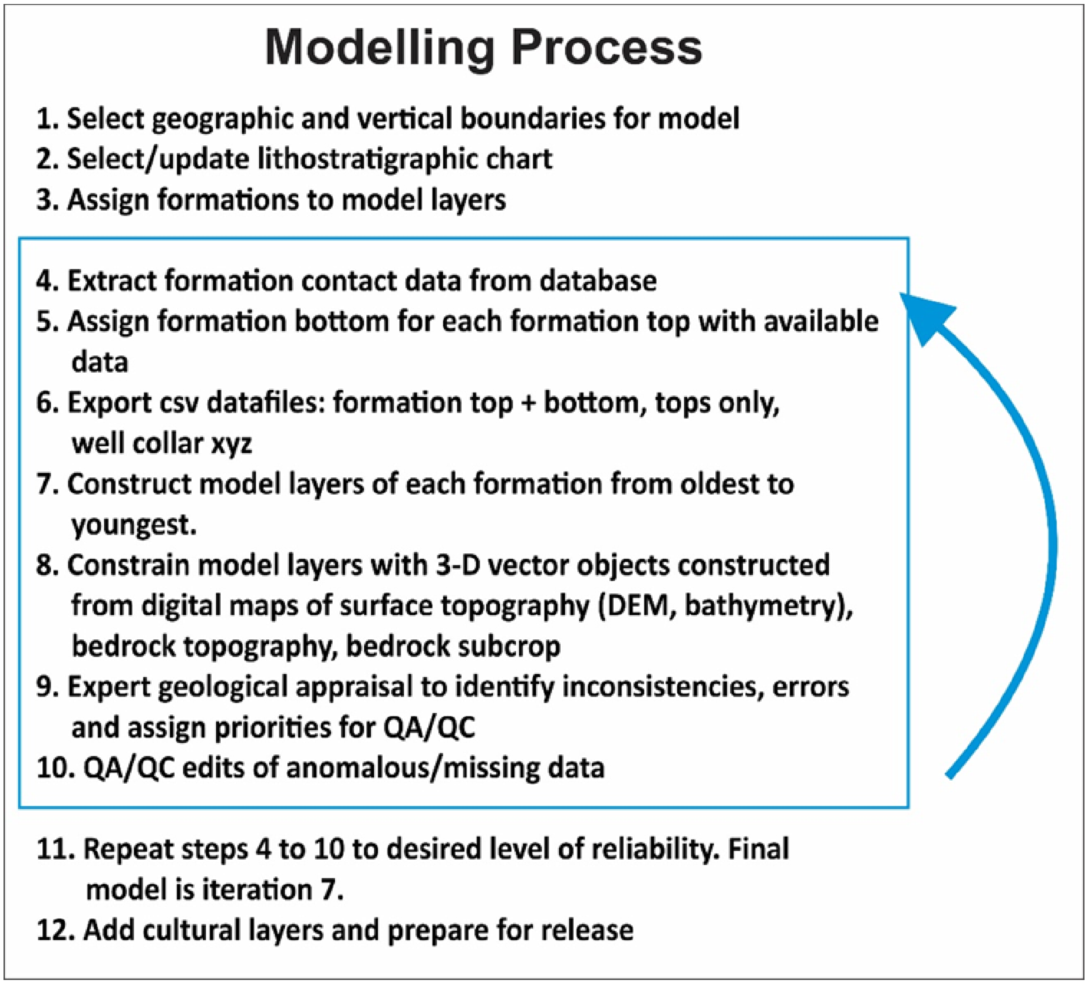

Figure 7. Work flow summary of modelling process.

boreholes having recorded Shadow Lake Formation (or roughly 1 borehole contact per 98 km^2), surface control points can be separated by many tens of kilometres. Polyline edits helped prevent large gaps in this and other thin layers by mirroring the regional structural trends of the other modelled strata while maintaining a nominal thickness. Although the model automatically re-renders with these guidelines in effect, these edits were kept to a minimum as a reassessment was needed after each model iteration to ensure borehole data revisions did not cause conflicts. Revisions to the digital bedrock geology map, the utilization of the bedrock topography as an erosional surface and the addition of mapped geology point elevations greatly reduced the need for manually digitized guidelines.

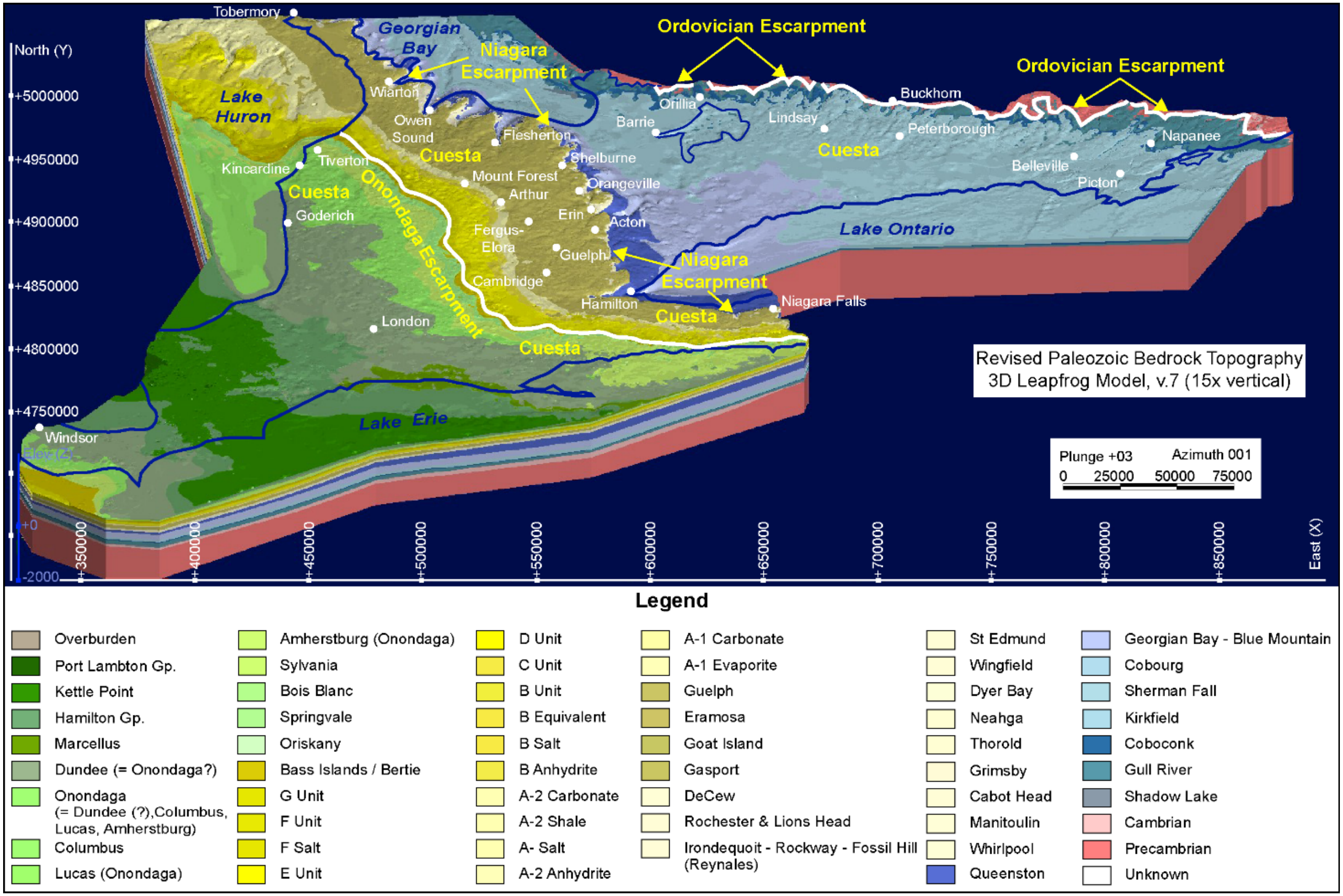

Figure 8. Three-dimensional model of the Paleozoic bedrock geology and topography of southern Ontario, outlining the major bedrock scarps and cuesta landforms and positions of the current Great Lakes shorelines (*from* Brunton and Carter, in prep.). The model is displayed at 15x vertical exaggeration, tilted towards the viewer, with the tilted horizontal plane showing the bedrock surface with the overlying layer of unconsolidated overburden removed.

Using the 3-D Model

To explore the 3-D model, a free viewer software application is available from the developer's website at http://www.leapfrog3d.com/products/leapfrog-viewer. Leapfrog® Viewer is software that can be used to view the model, create slices, export views, rotate or zoom the model, etc. It is an invaluable tool for using the model to visualize the subsurface bedrock geology of southern Ontario.

Additionally, model layer volumes are provided in ASCII 3-D grid point and 3-D DXF file formats. These file formats allow some flexibility for importing the model into 3-D geological modelling applications to support more advanced analysis (e.g., regional hydrogeological flow modelling).

GEOGRAPHIC AND CULTURAL FEATURES

Users can navigate the model using simple tools provided in the viewer software. The software actively displays Universal Transverse Mercator co-ordinates and elevation corresponding to the pointer location. In this version of the model the authors have also included cultural layers, which can be turned on or off to assist users with orientation relative to surface features. Cultural layers include major highways, towns, major rivers and shorelines, the Great Lakes, and boundaries for counties and geographic townships.

GEOLOGICAL FEATURES

Scenes of selected geological features prepared using the viewer tool are provided in the "docs" folder of this Groundwater Resources Study–Open File and are also posted at www.ogsrlibrary.com in portable document format (PDF) as an illustration of some of the practical applications of the model and as a resource for public use. Figure 9 is a geological legend for the model layers and for Figure 8.

Geological scenes have been created for regional bedrock geology with (and without) surficial sediments, regional structures, subregional faults, reefs, bedrock topography, bedrock valleys and escarpments, salt dissolution and collapse features, and Ordovician hydrothermal dolomite structures.

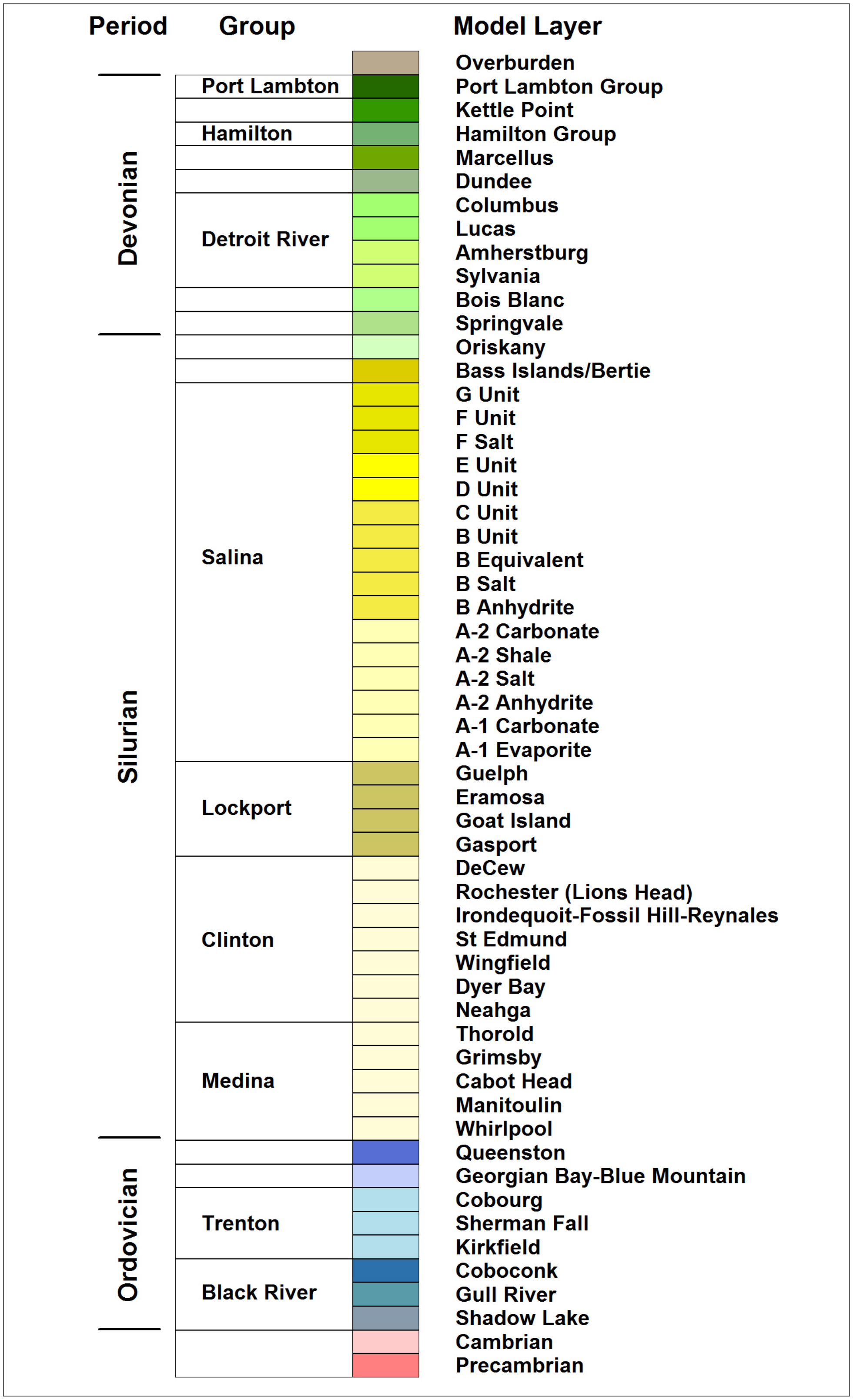

Figure 9. Legend for model layers and assigned colour of units for Phanerozoic stratigraphy of southern Ontario (*see* Figure 2; Brunton et al. 2017).

VIEWING WELL DATA

Well locations and well paths are included as a layer in the 3-D model. Well paths are colour coded with the geological formation. Attribute data from the project well database is linked to the well path and can be viewed by clicking on the well path (Figure 10), but this feature is only available to users who have purchased a data licence from the OGSRL (www.ogsrlibrary.com). The Library will provide licensed data users with an extended version of the model which includes a link to the OPDS data set used to create the model.

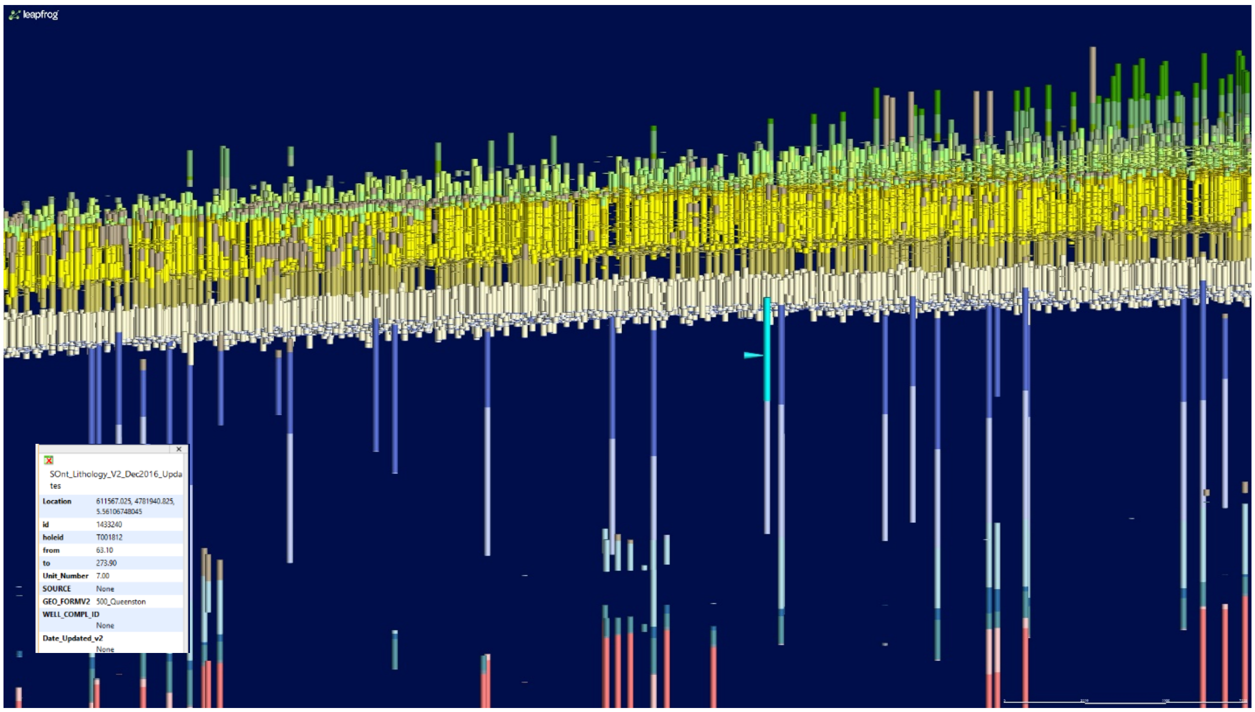

Figure 10. Screen shot of wells layer in 3-D showing example of data viewing tool.

Discussion

The published model has a large vertical exaggeration of 20x. This is necessary to show regional structural trends in a manageable size for viewing at such a large areal extent. During the model development a vertical exaggeration of 30x was utilized to highlight subtle anomalies during QA/QC editing of the model. Users are cautioned that the effect of locally amplifying elevation changes results in the appearance of some uncharacteristically steep dips and sharp peaks, especially for pinnacle reefs of the Lockport Group (*see* Appendix 2).

Several recognized model issues exist and can be categorized as

- isolated anomalies in layer thickness or structure caused by incorrect formation top depths,
- gaps in layers principally caused by areas of sparse data,
- outliers caused by data anomalies,
- incomplete and/or inaccurate layers caused by missing or incomplete formation top data in areas where the formation is expected to occur,

- missing formations due to lack of formation top picks in the OPDS,
- difficulty in accurately relating geological features to surface geographic locations,
- no representation of mapped faults, and
- no representation of subsurface resource uses including salt mines, natural gas storage areas, oil and gas reservoirs.

The data issues described above create uncertainties about the reliability of certain model layers. Additional sources of uncertainty are related to possible future revision of stratigraphic relationships resulting from new and ongoing research. This research also can result in changes to the standards used to identify formation tops and lateral continuity of formations. There is uncertainty related to the accuracy of some individual formation top picks caused by the availability of, or lack of, drill core, geophysical logs and drill cuttings and the quality of those core, logs and cuttings, but these types of issues now affect only a small minority of the picks. At a more areally extensive scale there are uncertainties in the estimation of model layers resulting from biases in the algorithm and especially because of large gaps in data distribution.

The assessment of uncertainty is an important consideration for ensuring 3-D models are used appropriately; however, it is beyond the scope of this model version. There is no algorithmic tool available in the modelling software for a statistically based assessment of layer uncertainty. In this project each model layer has been reviewed by project geologists and the judgement of reliability of the layer and identification of anomalies and shortcomings is based on expert opinion (*see* Appendix 2 and 3). Methods of quantifying uncertainty in the southern Ontario model will be investigated in a 2019–2023 modelling project (Russell and Carter 2019).

The OPDS and its supporting information was a key source of data for this 3-D model and illustrates the value of a properly constructed and actively maintained well database. Mapping and modelling of the subsurface bedrock geology of southern Ontario is only possible thanks to a long history of petroleum well data collection and data management efforts by many individuals and organizations, initiated by the GSC in the late 1800s and continued by the MNRF since 1971. The first digital petroleum well database was created in 1964 and has undergone a long history of updates, enhancements and replacements since that time (Carter and Castillo 2006), without which this project would not have been possible.

Practical applications of the model include

- visualization of geological features,
- public outreach and education,
- studies related to deep geological disposal of nuclear wastes,
- exploration for and development of hydrocarbon and mineral resources,
- regional context for local-scale studies,
- identification of gaps in knowledge and data,
- identification of shortcomings in modelling algorithms,
- modelling of hydrochemical zonation in groundwater,
- numeric modelling of regional groundwater flow,
- mapping salt dissolution and collapse structures and interpretation of timing of salt dissolution,
- CO_2 sequestration, and
- hazards prediction (fault and seismic mapping, scarp instability).

The authors have identified the following priorities for future QA/QC edits of the OPDS well data which would contribute to improvements to future 3-D models:

- Editing of formation tops for the Lockport Group to add picks for the Goat Island, Gasport and Eramosa formations. Many of the existing wells that penetrate the Lockport Group have only top picks for the Guelph Formation.
- Editing of formation top picks for the DeCew Formation to add picks in wells where it has not been picked but is known to be present.
- Editing of formation top picks for the Collingwood Member of the Cobourg Formation to correct inaccurate picks and add picks for wells where it has not been picked.
- Addition of picks for the Rouge River Member of the Blue Mountain Formation.
- Further QA/QC of well collar elevations to identify and correct issues created by edits and corrections to well locations.
- Addition of formation top picks for the Lucas Formation for wells with water records. For many shallow wells in Lambton County, the Lucas has not been picked and water intervals may be incorrectly attributed to the overlying Dundee Formation.
- Where possible, add formation top picks for the Cambrian where it is presently identified as “unsubdivided”. Cambrian strata both host a regional brine aquifer and have considerable potential as a hydrocarbon play.

As with all models, this model is a data-driven algorithmic representation and interpretation of the actual bedrock geology. It is the first published version and is essentially a work-in-progress. Updates are ongoing as more data becomes available and improvements are made to existing data, modelling algorithms, and data processing capabilities. This will lead to future refinements and revisions. At a regional scale the model layers are reliable, with exceptions as described above (*see* Appendix 3). If used at a local scale, users are advised to verify critical information, especially any model layers with anomalous values. Note that complex fault block modelling was beyond the capability of the software utilized in this model version; however, this will be investigated in future versions. Users are encouraged to report model issues to the authors of this report.

Summary

The first complete 3-D geological model of the western St. Lawrence Lowland region of south-central and southwestern Ontario has been completed. The model provides a lithostratigraphic basis for future development of a full hydrostratigraphic model. Model construction was guided by an updated regional lithostratigraphic chart and utilizes Leapfrog® Works, an implicit modelling application.

There are 54 modelled Paleozoic bedrock layers representing 70 formations, plus the Precambrian basement rocks and overlying unconsolidated Quaternary sediments. Model spatial resolution is 400 m. Borehole records in Ontario’s public petroleum well database (Ontario Petroleum Data System (OPDS)) are the principal data source, supplemented by Ontario Geological Survey (OGS) deep boreholes, and MECP water well records. A newly revised digital bedrock topography surface combined with revised subcrop geology and digitized 3-D surface polyline and point constraints were used to better align the modelled layers and their extrapolation to the subcrop surface. Model development was an iterative process involving interim modelling, expert geological appraisal, and QA/QC editing of geological data.

A properly constructed well database (OPDS) and its supporting information was an essential requirement for construction of the model.

Three-dimensional modelling of the subsurface bedrock geology of southern Ontario is a fundamental improvement to, and the logical next step in, the evolution of geological mapping. It illustrates the geological connections and continuity between the surface and subsurface, a necessary precursor for understanding the regional hydrogeological connections between surface water systems and groundwater systems in unconsolidated surficial sediments and Paleozoic sedimentary bedrock.

Significant improvements have been made to the geological data infrastructure of southern Ontario through a process of capture and compilation of existing data, QA/QC edits to existing data, and creation and addition of new data with edits completed to 30 320 formation top picks in 7812 wells. These improvements are instrumental to ongoing programs of data collection and improvement at the OGS, MNRF and OGSRL, and will be of permanent and ongoing benefit to all users of the database. Further improvements to formation top picks in the OPDS are still needed, which can in turn be used for future improvements to the 3-D model.

Acknowledgments

This project could not be completed without the extensive archive of physical and digital petroleum well data collected, managed, and maintained by the Petroleum Operations Section of the MNRF and the Oil, Gas and Salt Resources Library. Data query and display tools in PetroGIS, an ArcGIS® application designed and built by MNRF, greatly expedited the data QA/QC process and creation of raster surfaces, in particular the digital bedrock geology map.

We thank all of the early and modern data visionaries at the GSC and MNRF for their recognition of the value of collection and management of subsurface geological data from the drilling of petroleum wells in Ontario. Since 1998, funds for the continued management of this data and for public access at the Oil, Gas and Salt Resources Library have been provided in large part by the petroleum industries of Ontario through the Oil, Gas and Salt Resources Trust. The Ontario Petroleum Institute is thanked for providing administrative and management support to the Library in its role as Trustee of the Oil, Gas and Salt Resources Trust.

An internal review at the GSC by Eric de Kemp is much appreciated. Contributions to data enhancement and QA/QC were made by staff at the Oil, Gas and Salt Resources Library. This work is a contribution to the GSC–OGS southern Ontario project on groundwater 2014–2019.

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Appendixes

Appendix 1. Table of modelled bedrock and sediment layers.

Group	Formation(s)	#	Model Layer
		1	Overburden
Port Lambton	(unsubdivided)	2	Port Lambton Group
	Kettle Point	3	Kettle Point
Hamilton	(unsubdivided)	4	Hamilton Group
	Marcellus	5	Marcellus
	Dundee	6	Dundee
Detroit River	Columbus	7	Columbus
	Lucas	8	Lucas
	Amherstburg, Onondaga	9	Amherstburg
	Sylvania	10	Sylvania
	Bois Blanc	11	Bois Blanc
	Springvale	12	Springvale
	Oriskany	13	Oriskany
	Bass Islands, Bertie	14	Bass Islands/Bertie
Salina	G Unit	15	G Unit
	F Unit	16	F Unit
		17	F Salt
	E Unit	18	E Unit
	D Unit	19	D Unit
	C Unit	20	C Unit
	B Unit	21	B Unit
		22	B Equivalent
		23	B Salt
		24	B Anhydrite
	A-2 Unit	25	A-2 Carbonate
		26	A-2 Shale
		27	A-2 Salt
		28	A-2 Anhydrite
	A-1 Unit	29	A-1 Carbonate
		30	A-1 Evaporite
Lockport	Guelph	31	Guelph
	Eramosa	32	Eramosa
	Goat Island	33	Goat Island
	Gasport	34	Gasport
Clinton	DeCew	35	DeCew
	Rochester, Lions Head	36	Rochester (Lions Hd)
	Irondequoit	37	Irond-FH-Reynales
	Rockway+Merritton+Reynales+Fossil Hill	37	Irond-FH-Reynales
	St. Edmund	38	St. Edmund
	Wingfield	39	Wingfield
	Dyer Bay	40	Dyer Bay
	Neahga	41	Neahga
Medina	Thorold	42	Thorold
	Grimsby	43	Grimsby
	Cabot Head	44	Cabot Head
	Manitoulin	45	Manitoulin
	Whirlpool	46	Whirlpool
	Queenston	47	Queenston
	Georgian Bay + Blue Mountain	48	Georgian Bay-Blue Mtn.
Trenton	Cobourg, Collingwood	49	Cobourg
	Sherman Fall	50	Sherman Fall
	Kirkfield	51	Kirkfield
Black River	Coboconk	52	Coboconk
	Gull River	53	Gull River
	Shadow Lake	54	Shadow Lake
	Cambrian (unsubdivided)	55	Cambrian
	Trempealeau, Eau Claire, Mt. Simon	55	Cambrian
	Precambrian	56	Precambrian

Notes:

1. *Onondaga members can be correlated with members of the Amherstburg and Lucas; however, the Onondaga is combined with the Amherstburg because of modelling constraints.*
2. *Lions Head is age-equivalent to the lower member of the Rochester Formation and therefore is combined to simplify model.*
3. *Irondequoit, Fossil Hill, Merritton, Rockway and Reynales are not consistently identified in the well database and therefore is combined in model.*
4. *Age relationship between the Dyer Bay and Neahga remains uncertain currently; Collingwood picks in database are inconsistent.*
5. *Subdivision of Cambrian units is incomplete in well database; no picks for the Blue Mountain Formation in database, so is therefore combined with the Georgian Bay.*
6. *No picks in well database for the 3 formations of the Port Lambton Group or 6 formations of the Hamilton Group.*

Appendix 2. Descriptions of model layer, layer formation(s), formation member or model feature.

Layer / Fm. / Member / Feature	Description
Overburden	regional; clay, sand silt, gravel, till; single combined layer, SRTM upper surface, modelled separately; average tens of metres thick
Port Lambton Group	confined to Lambton County; 3 formations; black shale, sandstone, grey shale; maximum 60 m thick
Kettle Point	confined to Chatham Sag and central Lake Erie; black shale; average 20 to 30 m up to 100 m thick
Hamilton Group	confined to Chatham Sag; grey shale and limestone in 5 formations; average 50 to 80 m thick
Marcellus	confined to central Lake Erie and adjoining shoreline; black shale; prolific shale gas production in United States; average 6 m up to maximum 25 m thick
Dundee	regional; fossiliferous limestone, oil reservoirs, regional aquifer in lower Dundee; 35 to 45 m thick
Columbus	scattered distribution in Lambton, Kent, Elgin, Middlesex and Essex counties; sandstone, sandy limestone, oil reservoirs; 1 to 20 m in thickness
Lucas	regional; restricted marine limestone, dolostone, anhydrite; regional aquifer; 20 to 40 m to maximum 90 m thick
Amherstburg	regional; bituminous, fossiliferous and cherty limestone and dolostone; average 25 to 40 m up to 70 m thick
Sylvania	Essex County; friable quartzose sandstone; < 3 m to maximum 35 m thick
Bois Blanc	regional; fossiliferous, bioturbated, limestone and dolostone with abundant chert; 3 to 50 m thick
Springvale	scattered lenses in central Lake Erie and adjoining onshore areas; white to green glauconitic quartzose sandstone and sandy carbonates; 3 to 10 m up to maximum 30 m thick in salt dissolution collapse depressions
Oriskany	scattered erosional remnants in central L. Erie and adjoining onshore areas; quartzose sandstone; generally, 1 to 2 m thick
Bass Islands/Bertie	regional; dolomudstone, variably laminated, sparsely fossiliferous, minor anhydrite; 10 to 90 m up to 150 m in salt dissolution depressions
G Unit	regional; anhydrite and restricted marine dolostone; average 12 m thick
F Unit	regional; restricted marine shaly dolostone with anhydrite nodules; average 30 m thick
F Salt	Michigan Basin, halite with interbeds of anhydrite and dolostone; up to 110 m thick
E Unit	regional; restricted marine dolostone; average 25 m thick
D Unit	Michigan Basin; halite with interbeds of anhydrite and dolostone; maximum 16 m thick
C Unit	regional; restricted marine shaly dolostone with anhydrite nodules; 23 to 30 m thick
B Unit	regional; anhydrite and shaly dolostone; 10 to 15 m thick
B Equivalent	Michigan Basin; rubble of anhydrite and dolostone; 1 to 15 m thick
B Salt	Michigan Basin; halite with interbeds of anhydrite and dolostone; up to 90 m thick
B Anhydrite	Michigan Basin; anhydrite; 1 to 3 m thick
A-2 Carbonate	regional; restricted marine dolostone and minor limestone; 10 to 30 m thick
A-2 Shale	regional; thin marker horizon of black shaly dolostone; 1 to 3 m thick

Layer / Fm. / Member / Feature	Description
A-2 Salt	Michigan Basin; halite, thin interbeds of anhydrite, dolostone; up to 30 m thick
A-2 Anhydrite	Michigan Basin; anhydrite; 1 to 3 m thick
A-1 Carbonate	regional; restricted marine limestone, dolostone; thickening east to west from 3 to 45 m thick into the Michigan Basin
A-1 Evaporite	Michigan Basin; anhydrite; 1 to 5 m thick
Guelph	uppermost formation of Lockport Group; regional; fossiliferous, reefal, karstic, dolostone and limestone; major regional aquifer with down-dip hydrochemical zonation from shallow potable water to intermediate salty sulphur water to deep brine; thickness varies from 2 m (inter-reef) to as much as 100 m (reefal)
Eramosa	localized distribution in Niagara and Bruce Peninsula; bituminous dolostone
Goat Island	regional; fine-grained argillaceous dolostone with locally abundant chert; average 6 to 20 m up to 35 m thick
Gasport	regional; coarse-grained crinoidal dolostone; 4 to 15 m up to 60 m thick
DeCew	regional distribution east of Algonquin Arch; argillaceous to arenaceous dolostone with locally abundant shale interbeds and partings; < 4 m thick
Rochester (Lions Head)	regional, thinning and pinching out to northwest; calcareous grey shale with argillaceous and silty dolostone interbeds; max. 25 m thick in eastern Lake Erie.
Irondequoit	regional; fossiliferous dolostone; average 2 to 3 m up to 6 m thick
Fossil Hill, Rockway, Merritton, Reynales	regional; dolostone and argillaceous dolostone; up to 25 m thick on Bruce Peninsula but otherwise 2 to 5 m thick
St Edmund	restricted distribution in Manitoulin Island and northern Bruce Peninsula; dolostone; < 25 m thick
Wingfield	restricted distribution in Bruce Peninsula; argillaceous dolostone and subordinate noncalcareous shale; < 15 m thick
Dyer Bay	restricted distribution in Bruce Peninsula and Essex County; blue-grey to brown fossiliferous and argillaceous dolostone with shaly partings; max. 8 m thick
Neahga	restricted to Niagara Peninsula; grey to greenish grey fissile shale, minor limestone, phosphatic lag at base; < 2 m thick
Thorold	absent west of Algonquin Arch; grey-green to white quartzose sandstone; < 9 m thick
Grimsby	absent west of Algonquin Arch; interbedded red shale and sandstone; up to 24 m thick
Cabot Head	regional aquitard; grey to green and locally red noncalcareous shale, subordinate sandstone and carbonate beds; 12 to 40 m thick
Manitoulin	absent in easternmost Niagara Peninsula, dolostone, argillaceous dolostone, minor grey-green shale; average 6 m up to 20 m thick
Whirlpool	absent west of Algonquin Arch; marine and fluvial quartzose sandstone, shaly sandstone; 3 to 6 m thick
Queenston	regional; red shales, subordinate green shale, siltstone, limestone, thinning from southeast to northwest with increasing carbonate content; 50 to 275 m thick; important regional aquitard
Georgian Bay-Blue Mtn.	regional; unsubdivided amalgamation of the Georgian Bay Formation with the underlying Blue Mountain Formation; grey shales, with siltstone, limestone, sandstone interbeds especially in Georgian Bay; black shale of basal Rouge River Member; important thick regional aquitard; thins southeast to northwest from 260 m beneath eastern Lake Erie to 100 m on Bruce Peninsula
Rouge River Member	lowermost member of the Blue Mountain Formation; black organic-rich noncalcareous shale; potential source of unconventional crude oil
Collingwood Member	uppermost member of Cobourg Formation; black organic-rich shaly limestone; crude oil source rock

Layer / Fm. / Member / Feature	Description
Cobourg	regional; nodular limestone and argillaceous limestone; Collingwood Member is organic-rich, bituminous black shaly limestone; regional aquiclude; 17 to 70 m thick (Cobourg)
Sherman Fall	regional; fossiliferous limestone and shaly limestone; regional aquiclude; 15 to 65 m thick
Kirkfield	regional; fossiliferous limestone with shaly partings; regional aquiclude; 15 to 55 m thick
Coboconk	regional; bioclastic limestone; regional aquitard; 5 to 30 m thick
Gull River	regional; very fine-grained limestone, lesser dolostone and shale; regional aquitard; 20 to 125 m thick
Shadow Lake	regional distribution but heterogeneous thickness and lithology, red and green sandy shale, sandstone, minor argillaceous dolostone, glauconitic; average 2 to 3 m thick
Cambrian	not present over crest of Algonquin Arch; dominated by quartzose sandstones where unsubdivided beneath most of southern Ontario; erosional removal over Algonquin Arch; subdivided into basal sandstone (Mt. Simon/Potsdam), overlying sandstone and dolostone of Eau Claire/Galway, and uppermost dolostone (Trempealeau/Little Falls);
Precambrian	regional; igneous and metamorphic basement of the Canadian Shield > 1 Ga.
Bedrock topography	bedrock surface, profound unconformity representing > 250 Ma of weathering and erosion

Appendix 3. Model layer issues and comments.

Model Layer	Model Issues and Comments
Port Lambton Group	50+ outliers, anomalies - F007435, T008299, T001510, F007439, T006415, no picks in well database for its 3 constituent formations
Kettle Point	Anomalies, 7 depressions along model edge beneath L. Erie
Hamilton Group	Outliers, 3 depressions along model edge beneath L. Erie, mismatch with subcrop map at Ekfrid/Dunwich and east of Rodney oil pool, well data - T005835, T004933, T006769, T005841, gap near T004757; Sarnia Ridge
Marcellus	Large and numerous gaps, a few outliers
Dundee	Thickness in Lake Huron, Kettle Point; Haldimand–Welland–eastern Lake Erie relation to Onondaga; Essex County subcrop edge; scattered anomalies
Columbus	Very scattered distribution - correlate/confirm by comparison to Davis 2017 GSC OF8286 to identify and remove outliers
Lucas	Ragged subcrop edge Lake Huron; transition to Onondaga/pinchout in Haldimand
Amherstburg	Anomalies, especially Lambton County and T002800 + F011854, transition to Onondaga in Haldimand; gaps
Sylvania	50+ outliers, match to Davis 2017
Bois Blanc	Good; a few gaps; low priority
Springvale	Very scattered distribution - correlate/confirm by comparison to Davis 2017 GSC OF8286 to identify and remove outliers
Oriskany	Very scattered distribution - correlate/confirm by comparison to Davis 2017 GSC OF8286 to identify and remove outliers
Bass Islands/Bertie	Good; a few anomalies; some gaps
G Unit	Many gaps; many outliers northeast of subcrop edge
F Unit	Good; a few gaps, a few outliers
F Salt	Many outliers; important salt resource in Windsor area and potentially in Lambton County
E Unit	Numerous anomalies dues to inconsistent picks, see Armstrong and Carter, a few gaps; anomalous thickness offshore Port Elgin - add control point?; irregular subcrop edge in Haldimand–Welland
D Unit	Poor quality! Very inconsistent with gaps/outliers due to inconsistent picks; addition of a pick for D Salt would be useful; add control point in Lake Huron
C Unit	Small anomalies; large gap beneath Lake Huron offshore Port Elgin
B Unit	Numerous gaps, large gap beneath Lake Huron offshore Port Elgin
B Equivalent	Poor quality but low priority! Very inconsistent with gaps/outliers due to inconsistent picks; low priority; could be useful indication of depositional limit of B Salt and down-dip penetration of meteoric water
B Salt	High priority as salt resource and aquiclude; anomalous thinning beneath Lake Huron offshore Goderich – add control point; outliers
B Anhydrite	Poor quality but low priority; numerous gaps due to inconsistent picks
A-2 Carbonate	Anomalous thinning and gaps beneath Lake Huron offshore Goderich – add control point; gaps along subcrop edge
A-2 Shale	Poor quality but medium priority; numerous gaps due to inconsistent picks; would be a useful stratigraphic marker horizon
A-2 Salt	High priority as important high-purity salt resource; outliers, questionable extension beneath northern Lake Huron – add control points/check Michigan wells
A-2 Anhydrite	Poor quality but low priority; numerous gaps due to inconsistent picks
A-1 Carbonate	Numerous gaps especially near subcrop edge in Haldimand–Welland
A-1 Evaporite	Poor quality but low priority; numerous gaps due to inconsistent picks
Guelph	High priority due to importance as regional aquifer; in OPDS the Guelph is often the only formation of the Lockport for which formation tops are recorded; sparse well/data coverage beneath Lake Huron–Bruce County–Huron County; excellent representation of pinnacle reefs

Model Layer	**Model Issues and Comments**
Eramosa	Poor quality; formation tops for this formation are rarely picked or recorded in OPDS; many outliers due to inconsistent/missing picks; this formation is known to form an aquitard in the shallow potable water system so an improved representation in the database and model is important.
Goat Island	High priority; formation top picks are often not made/recorded in OPDS outside of Lambton and Kent counties; numerous gaps due to missing/inconsistent picks, especially in Huron–Haldimand–Bruce Peninsula; some droops at Niagara Escarpment in north
Gasport	High priority; poor quality; many gaps due to inconsistent/missing picks; Formation top picks are often not made/recorded in OPDS outside of Lambton and Kent counties
DeCew	Poor quality; outliers and gaps due to missing/inconsistent picks; Formation top picks are often not made/recorded in OPDS consequently the formation extent and continuity is not accurately represented in the model
Rochester (Lions Hd)	Good in south; gaps in north need confirmation; very few picks for Lions Head
Irond-FH-Reynales	Many large gaps especially beneath Lake Huron, some minor droops over the Niagara Escarpment, surface roughness in Niagara Peninsula
St Edmund	Limited distribution; good
Wingfield	Limited distribution; good
Dyer Bay	Outliers and gaps in Essex County
Neahga	Poor quality but low priority; numerous gaps due to inconsistent/missing picks
Thorold	Poor quality due to numerous gaps and outliers; pinchout edge should be confirmed by reference to Bailey and Cochrane; high priority as natural gas reservoir
Grimsby	Poor quality due to numerous gaps and outliers; pinchout edge should be confirmed by reference to Bailey and Cochrane; high priority as natural gas reservoir
Cabot Head	Good quality but a few gaps and anomalies, edge problems along Niagara Escarpment and offshore Bruce Peninsula
Manitoulin	Some gaps; very irregular distribution on pinchout edge in Niagara Escarpment due to inconsistent picks; one droop on Niagara Escarpment at same location as Irondequoit; low priority
Whirlpool	Westerly extent needs confirmation; large gaps and outliers; high priority as natural gas reservoir and potential aquifer
Queenston	Good quality; some anomalies near Niagara River and Niagara Peninsula, tendency for drooping of edges along northern Niagara Escarpment
Georgian Bay-Blue Mtn.	Good quality; no picks for Blue Mountain so cannot be modelled separately; picks for Rouge River Member are needed to facilitate shale oil assessment
Cobourg	Good quality; a few outliers and small gaps; Collingwood picks are inconsistent and need verification to enable modelling and facilitate shale oil assessment
Sherman Fall	Good quality
Kirkfield	Good quality; some small gaps
Coboconk	Good quality; some gaps along erosional edge in northeast
Gull River	Good quality; one large gap
Shadow Lake	A few large gaps in model layer due to sparse data distribution and thinning to 1 metre or less, may require manual intervention
Cambrian	High priority; need to confirm pinchout edge over Algonquin Arch vs literature
Precambrian	High priority, Good quality; confirm anomaly at F002315

Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
			LENGTH		
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
			AREA		
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
			VOLUME		
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
			CAPACITY		
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
			MASS		
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton(short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 9**	t
			CONCENTRATION		
1 g/t	0.029 166 6	ounce (troy) / ton (short)	1 ounce (troy) / ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights / ton (short)	1 pennyweight / ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

*Note: Conversion factors in **bold** type are exact. The conversion factors have been taken from or have been derived from factors given in the* Metric Practice Guide for the Canadian Mining and Metallurgical Industries*, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.*