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Abstract

An updated regional three-dimensional (3-D) lithostratigraphic model of the Paleozoic bedrock of southern Ontario has been produced using Leapfrog© Works software, improving a model completed in 2019. The model encompasses the entire Phanerozoic succession of southcentral and southwestern Ontario consisting of approximately 1500 metres of Paleozoic bedrock and an area of 110,000 km^2. Fifty-three 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. Petroleum well records in the Ontario Petroleum Data System (OPDS) were the principal data source, supplemented by Ontario Geological Survey (OGS) deep boreholes, measured sections, control points, Michigan boreholes, and select bedrock provincial water well records. The model format can readily support numeric groundwater-flow modelling.

From 2019 to 2020, project geologists and data support staff of the Oil, Gas and Salt Resources Library (OGSRL) completed edits to 17,595 formation tops in a total of 3,419 wells, resulting in a revised data set and permanent improvements to the petroleum well database. Formation top data from a total of 20,836 Ontario petroleum wells, 199 OGS stratigraphic tests, 15 measured sections, 3 Michigan petroleum wells, and 30 control points were utilized, including seven new control points added to improve layer extrapolation beneath Lake Huron. The new model improves the resolution of the subcrop surface and there is a more accurate and realistic rendering and correlation of the topography and bedrock geology of the Niagara Escarpment. Many anomalous outliers and structural and thickness anomalies in model layers have been identified and removed and gaps in the model are reduced. A model layer of the Salina D Salt has been added. There was a focus on improving the data quality and quantity for the formations of the Lockport Group in support of improved bedrock model layers and future hydrostratigraphic modelling. New features added to the model include: 3-D volumes of salt beds leased for underground mining at Ontario's 2 salt mines, solution-mined caverns in salt beds including those constructed for storage of liquified hydrocarbons and petrochemicals, two-dimensional representations of oil and natural gas reservoirs, regional faults, and lithotectonic boundaries in the Precambrian metamorphic basement.

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Introduction and Objectives

Advances in hardware and software, together with improved quality and quantity of digital geological data now enables 3-D visualization and representation of modelled subsurface geological features at regional scales with limited loss of complexity. 3-D modelling can promote and improve geological understanding by creating a spatial context that is easily viewed and understood and provide practical tools for interpretation and analysis and resource development. It also provides a powerful new tool for geological education and public outreach.

Paleozoic sedimentary bedrock underlies most of southern Ontario and are important contributors to the economic and social health of Ontario. Bedrock landforms such as the Niagara Escarpment provide recreational opportunities and tourist attractions, and control or influence the movement of surface water and groundwater. Near-surface bedrock formations are mined for construction aggregate, building stone, chemical stone and production of cement, and are used as a geothermal heat sink for ground-sourced heat pumps. Salt beds in the deep subsurface are mined for production of salt used for human consumption, water softening, for use in the chemical industry and for winter ice-control on highways. The salt beds are also used for storage of liquified petroleum products and petrochemicals in solution-mined salt caverns at refineries and petrochemical plants in the Sarnia and Windsor area, and for compressed-air energy storage at Goderich. Crude oil and natural gas are produced from deep subsurface bedrock formations, and natural gas is stored underground in some of the same formations for winter heating of homes and businesses. There is also potential to utilize bedrock formations for long-term storage of nuclear wastes from Ontario's nuclear power plants (e.g., Ontario Power Generation 2017; NWMO 2018) and for carbon capture and storage.

Bedrock formations are important sources of potable groundwater at shallow depths. Bedrock composition, regional structure, heterogeneity due to facies changes and diagenesis, weathering/karstification, and landform development govern penetration of meteoric water into the subsurface bedrock and the vertical and lateral movement of groundwater through the bedrock. In the deep subsurface ancient seawater has been trapped for millions of years in porewater and in deep regional brine aquifers, with an intermediate zone of saline and sulphurous groundwater. These aquifers are used for disposal of saline oilfield water produced as a by-product of petroleum production operations and have been used in the past for disposal of liquid industrial wastes. There is potential for CO_2 sequestration in the deep brine aquifers within the bedrock (Shafeen et al. 2004; Carter et al. 2007). Hydrochemical and isotopic zonation of groundwater also provides data about the origin of the water, its residence time in the subsurface, and history of movement, which provides supporting scientific knowledge to develop a safety case for deep disposal of industrial wastes, including nuclear wastes.

Three-dimensional models provide a powerful visualization tool for improving our understanding of the bedrock geology and sedimentary bedrock architecture. This supports and enhances management of groundwater resources for agricultural, industrial, municipal and domestic supply, from subcrop into the deeper subsurface, natural resource extraction, and construction of tunnels and foundations for infrastructure projects. 3-D models are also excellent tools for illustration of geological concepts for outreach to the general public and public education, and for training of the next generation of earth scientists and engineers at universities and colleges (e.g., Johnson et al. 2020) as described below.

Three-dimensional models of the subsurface are data-driven. Model accuracy relies primarily on the accuracy and coverage *and consistency* of the available data in three dimensions. Consequently, project resources were heavily focussed on compiling existing data, identifying data gaps, anomalies, and outliers, QA/QC review and edits to existing data using consistent published standards, data enhancements, and new data created by project contributors. The process of constructing the model also has revealed shortcomings in our knowledge and understanding of the bedrock geology, and additional gaps in the data that support that understanding.

In 2019, the Geological Survey of Canada (GSC), Ontario Geological Survey (OGS), and the Oil, Gas and Salt Resources Library initiated a 3-year project to: i) develop version 2 of the 3-D geologic model of southern Ontario (Carter et al. 2019; 2020), and ii) develop a 3-D hydrostratigraphic model for southern Ontario based on Carter et al. (2021). This work is part of an initiative by the GSC and OGS to advance knowledge of regional groundwater systems in southern Ontario.

This report supplements documentation in Carter et al. (2019, 2020) of the version 1 lithostratigraphic model. The detailed work completed on QA and QC in 2019-2020 is presented along with modifications in the data support and modelling techniques employed for version 2 of the model. Plans for model delivery and application is also discussed.

Project Area

The project area is the same as in the first model (Carter et al. 2019), encompassing all the contiguous Paleozoic sedimentary rocks underlying southern Ontario west of the Frontenac Arch and south of the Precambrian Canadian Shield. The 109 800 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 erosional surface of the Paleozoic bedrock, the unconsolidated surficial sediments are included in the model as a single layer. The modelled volume consists of 53 modelled Paleozoic bedrock layers totalling roughly 71 600 km^3 with 3 520 km^3 of overlying unconsolidated sediment.

The maximum elevation of the model is 546 m above sea level (asl) near the village of Dundalk in the southeast corner of Grey County, along the Niagara Escarpment. The maximum modelled thickness of Paleozoic bedrock is 1618 m near the U.S. border beneath Lake Huron, and approximately 1425 m beneath the land areas. For display purposes, the lower model boundary is set to an arbitrary elevation of -2000 m asl within the Precambrian.

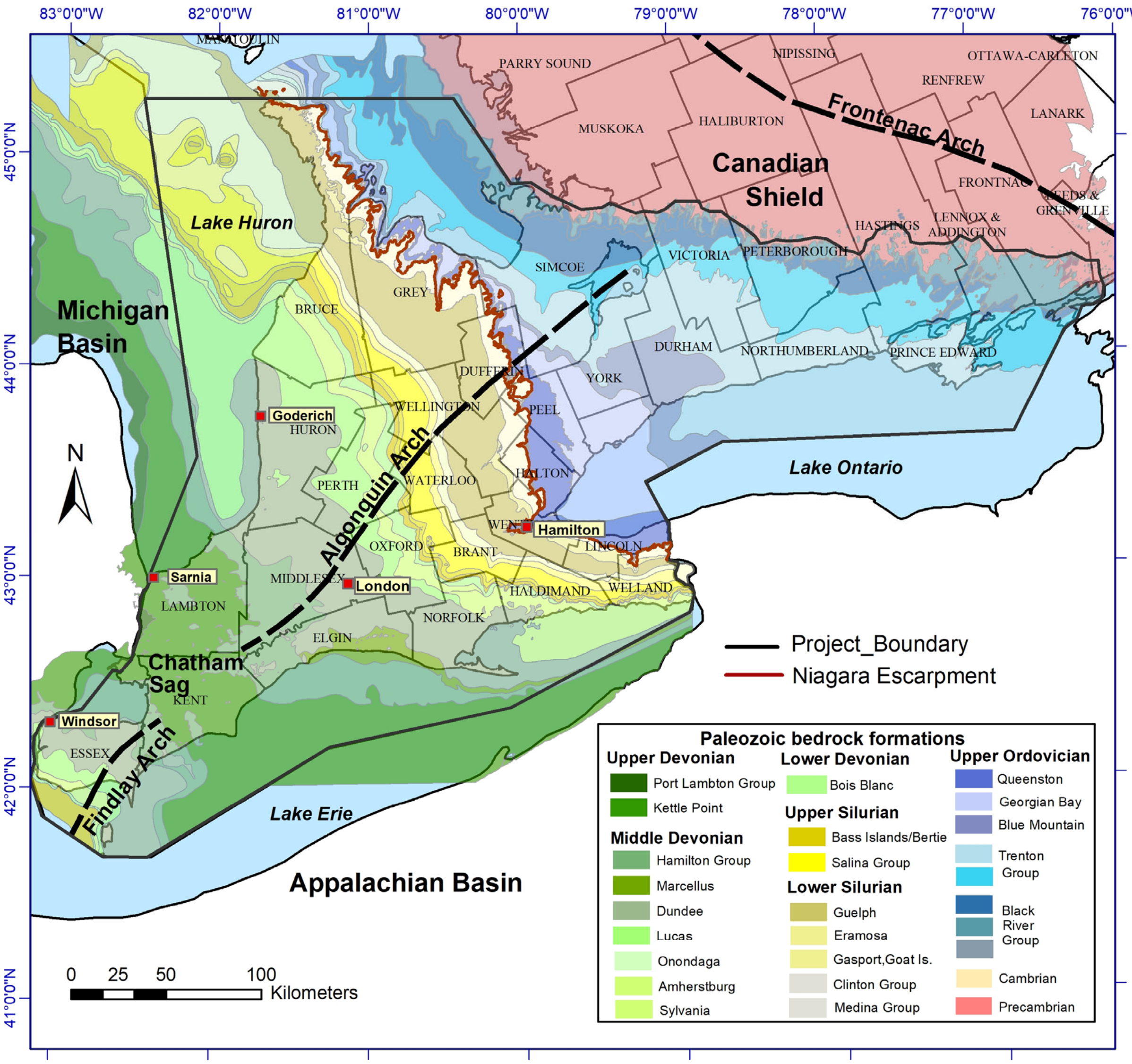

Figure 1. Simplified bedrock geology and project boundary adapted from Carter et al. (2019).

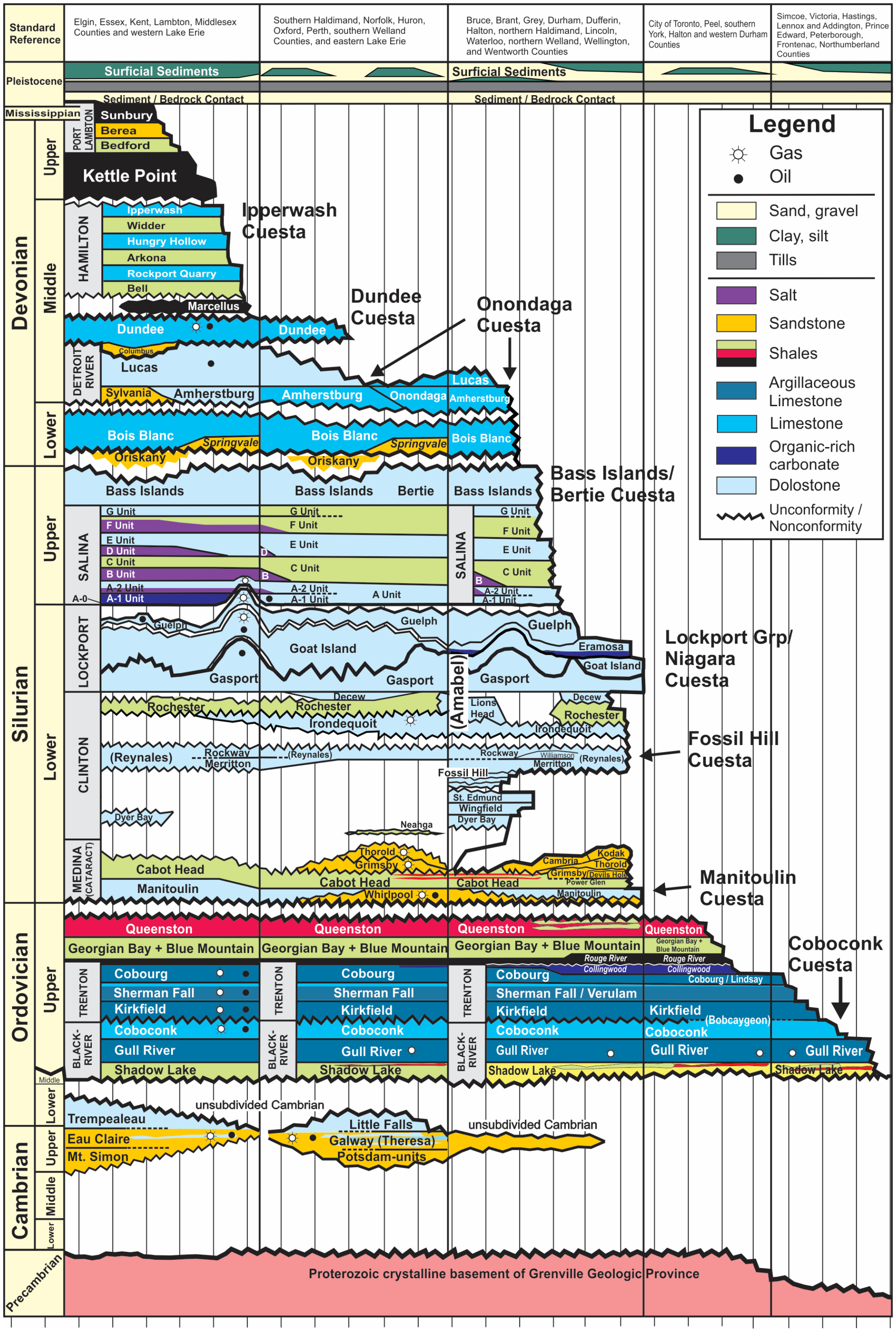

Figure 2. Lithostratigraphic chart of the Phanerozoic geology of southern Ontario, *modified from* Brunton et al. (2017) and Carter et al. (2017).

Project Co-ordination and Outreach

Project direction and co-ordination included bimonthly online team meetings with written agendas, task assignments and recorded minutes. Team members attended and made presentations on model progress at annual one to two-day groundwater workshops hosted by the OGS, GSC and Conservation Ontario. Progress reports were presented at the GSA Online 2020 Conference (Carter et al. 2020b) and Geoconvention Calgary 2020 (Carter et al. 2020a; Sun et al. 2020).

Geological and Hydrogeological Setting of Southern Ontario

The following description of the regional geology and hydrogeology is quoted from Carter et al. (2019), with updated citations and an updated version of Figure 3. The reader is referred to Armstrong and Carter (2010) for more detailed descriptions of Paleozoic bedrock formations.

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 carbonates, evaporites, shales, sandstones 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 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 1600 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 up to 250 million years (Johnson 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; Carter et al 2021) 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 sub-regionally 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, 2017; Brunton and Brintnell 2020; Priebe et al. 2014, 2017; Priebe and Brunton 2016; Priebe et al. 2019; Priebe et al. 2021).

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. Mapping and conceptual modelling of deep groundwater using petroleum well data and geochemical and isotopic analyses have 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, 2016, 2021; Sharpe et al. 2014; Skuce 2015; Skuce et al. 2015; Skuce, Potter and Longstaffe 2015). 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).

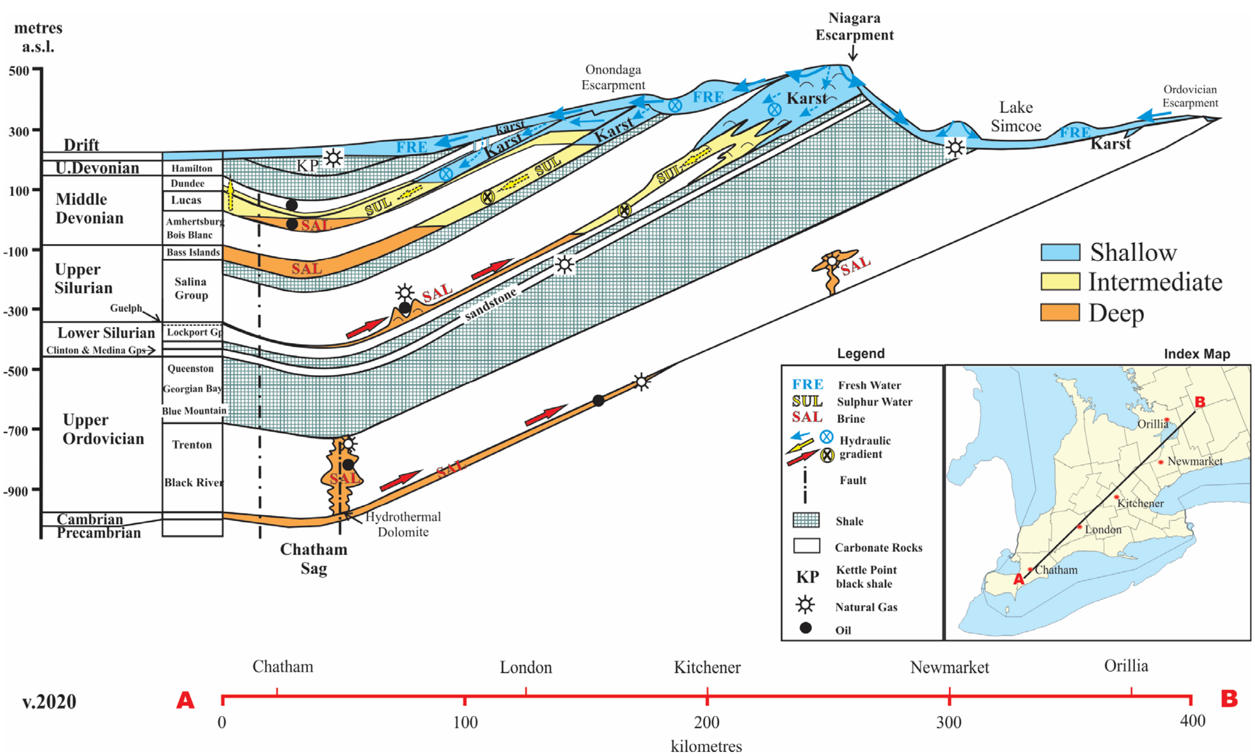

Figure 3. Conceptual model of regional hydrochemical groundwater regimes in the bedrock of southern Ontario. Updated from Carter et al. (2019, 2021).

Conceptual Model Development

Team members for this project comprised a multidisciplinary team of expert and experienced professionals, including a sedimentologist and Quaternary geologist (Hazen Russell), subsurface bedrock geologist (Terry Carter), QA/QC geologists (Alexandre Cachunjua, Candace Freckelton, Hanna Rzyszczak, Shuo Sun), Paleozoic bedrock geologist, stratigrapher and karst specialist (Frank Brunton), GIS and data management specialists (Jordan Clark, Maryrose D'Arienzo), and a 3-D modeller (Charles Logan). Hydrogeological expertise was provided by Frank Brunton (shallow bedrock) and Terry Carter (intermediate to deep bedrock). Team lead was Hazen Russell and project coordinator was Terry Carter.

In the initial stages of the project, the project geologists used version 1 of the 3-D model to visually identify shortcomings and inaccuracies relative to published and generally accepted knowledge of the bedrock geology and select priorities for model improvement. This process continued through the five iterations of the revised model.

Lithostratigraphic Chart

The Paleozoic bedrock formations of southern Ontario comprise the primary model layers, together with the overlying unconsolidated sediments (overburden) and the Precambrian basement. A revised lithostratigraphic chart developed by Brunton et al. (2017) and Carter et al. (2017) was implemented in version 1 of the 3-D model (Carter et al. 2019) and is adopted here (Fig.2). Erosional stratigraphic breaks in the chart represent periods of subaerial exposure and erosion, and karstification of exposed carbonate rocks. These paleokarst intervals are the most significant control on the occurrence of regional aquifers in the subsurface bedrock formations of southern Ontario (Brunton et al. 2007; Brunton 2009a, 2009b; Brunton et al. 2012; Carter et al. 2014; Banks and Brunton 2017; Brunton and Brintnell 2020).

The five columns of the chart represent different geographic areas in southern Ontario arranged updip from thickest to thinnest, from west (left) to east (right). All stratigraphic units are colour-coded by lithology. Importantly, it illustrates the erosional profile of the Paleozoic strata, and 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 cuestas of the Silurian Lockport Group dolostones that form the Niagara Escarpment are especially hydrogeologically significant because the topographic relief and location of the escarpment result in significant precipitation in the uplands and the development of regional karstic aquifers of potable groundwater (Brunton et al. 2007; Brunton 2009a, 2009b; Brunton and Brintnell 2011; Brunton et al. 2012; Brunton et al. 2017; Carter and Clark 2018) in the shallow and subcropping bedrock. Infiltration of meteoric water into the subsurface in these areas accentuates preglacial and glacially enhanced horizontal paleokarst flow zones (Brunton and Brintnell 2020).

Data Sources

The principal data sets were the same as in Carter et al. (2019) (Table 1, Table 2), but with added QA/QC edits to selected formation top records of the OPDS petroleum well database. Seven new prognostic wells were added in Lake Huron as control points to better constrain extrapolation of bedrock model layers beneath the lake downdip into the Michigan Basin. Model bedrock layers from Carter et al. (2019) were used as a starting point for the modelling process.

New data added to the model included:

- Oil and natural gas reservoirs

- Hydrocarbon storage and solution mining caverns in salt beds
- Underground salt mines
- Grenville basement lithotectonic domains
- Regional faults

Table 1. Primary data sources for lithostratigraphic modelling, updated from Carter et al. (2019).

Data Set	Description/Source	Application
Ontario Petroleum Data System (OPDS) database	26 952 petroleum well records with 300 000 formation tops, Ministry Natural Resource and Forestry – OGSRL	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 1981), GSC 1263a (Sanford 1969), Sun (2018), Armstrong (2017, 2018)	Constrain extrapolation from subsurface to subcrop
Digital bedrock geology map	Carter et al. 2019	Constrain extrapolation of bedrock layers to bedrock surface
Measured sections	15 measured sections from Bolton (1957)	Constrain extrapolation to Niagara Escarpment edge
Control points	30 prognostic wells	Constrain estimation in data-poor areas, esp. along Niagara Escarpment and extrapolation beneath Lake Huron
OGS stratigraphic tests	199 diamond-drill holes (Brunton and Brintnell 2020)	Constrain estimation in data-poor areas in shallow bedrock
Digital Elevation Model	https://data.ontario.ca/dataset/provincial-digital-elevation-model	Surface topography
Bedrock topography	Gao et al. (2006), revisions by GSC (Logan)	Top of bedrock surface
Structure + isopach maps	Bailey (1984); Bailey and Cochrane (1984a, 1984b, 1985, 1986; Ontario Geological Survey (2011)	Constrain estimation in data-poor areas
Michigan petroleum wells	3 wells from Lilienthal (1978)	Constrain extrapolation beneath Lake Huron
MECP water wells	Correction 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
3-D model version 1	Carter et al. 2019	Foundation for building of revised model

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, provide geologic and geographic context, and illustrate resource extraction. Updated from Carter et al. (2019)

Data Set	Description/Source	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, numerical modelling
Base of sulphur water map	Carter and Sutherland (2018)	Hydrochemical zonation, numerical 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
Cambrian isopach	Bailey and Cochrane (1984a); Sanford and Quillian (1959); Trevail (1990), OPDS well records	Interpretation of Cambrian zero edge on flanks of Algonquin Arch
Grenville lithotectonic domains	Easton and Carter (1995)	Structural features in crystalline metamorphic basement that influence structure of Cambrian and lowermost Ordovician strata.
Petroleum reservoirs	Oil, Gas and Salt Resources Library	Identify areas of extraction of crude oil and natural gas. These are also locations of enhanced porosity and permeability in the bedrock formations
Hydrocarbon storage & solution mining caverns	Oil, Gas and Salt Resources Library	3-D volumes of solution-mined caverns in salt beds and resource use of the caverns
Underground salt mines	Salt leases – Ministry of Northern Development and Mines	3-D volumes of underground salt mining
Regional faults	Locations of regional faults with mapped vertical displacement of Rochester Formation surface, compilation by Armstrong and Carter (2010)	Vertical 2-D planes along fault traces

Oil, Gas and Salt Resources (Petroleum) Well Records

As in version 1 of the model, petroleum well records of the OPDS are the primary data set used for modelling formation layers. Data QA/QC efforts were focussed on edits to the formation top data in the OPDS well records. The OPDS has digital records for approximately 26 950 wells (Figure 4), of which 20 836 wells having at least one formation with both a top and bottom pick were utilized in the model, supplemented with 996 additional wells having at least one formation top pick but no formation bottom depths. To boost confidence in the quality assurance data around formation subcropping areas geologists noted when they were not able to detect the specific subcropping formation. This was done by assigning the geologists' affirmative quality assurance code in the QA code field of the formation table and assigning the formation top a value of null. There are a total of 5 457 null formation tops assigned in 1 667 wells. These null values confirm the absence of a specific formation in the given well and indicate the model layer should be pinched out at the well location. Formation top depth and well collar elevation values are available for nearly 300 000 unique formation picks in the database.

Drilling of petroleum wells has declined dramatically in Ontario, consequently the initial formation top data and technical specifications of the data available for modelling was essentially the same as in Carter et al. (2019). Geophysical logs and drill cuttings samples are the principal source material available for QA/QC review of existing data and/or for making new formation top picks (Table 1). Drill core is available for 1100 wells over depth intervals of a few tens of metres on average for each of these wells.

Formation tops reviewed by the Ministry of Natural Resources and Forestry (MNRF) and OGSRL staff are assigned QA codes in OPDS which record the confidence of the reviewer in the accuracy of the picks. The QA codes (Table 3) are used to prevent multiple reviews of the same data, to label data which requires further review, and to filter data used for interpretation or mapping and modelling. Data with a negative QA value are known to be anomalous and are excluded from modelling or mapping.

The OPDS well data was supplemented by stratigraphic borehole data from the OGS and measured sections from fieldwork. Control points (see below) with interpolated and/or extrapolated formation top depths have been added at locations where sparse data coverage compromised the quality of the model layer (see Figure 4).

Data distribution is very uneven (*see* Figure 4), resulting in significant local variability on model reliability. There are only 357 wells east of the Niagara Escarpment over an area of 44 000 km^2 compared to nearly 20 000 wells within an area of 31 500 km^2 south of the southern boundaries of Huron, Perth, Waterloo, Wellington and Halton counties. Availability of formation top data also declines with depth (Figure 5) and decreases the reliability of deeper model formation layers.

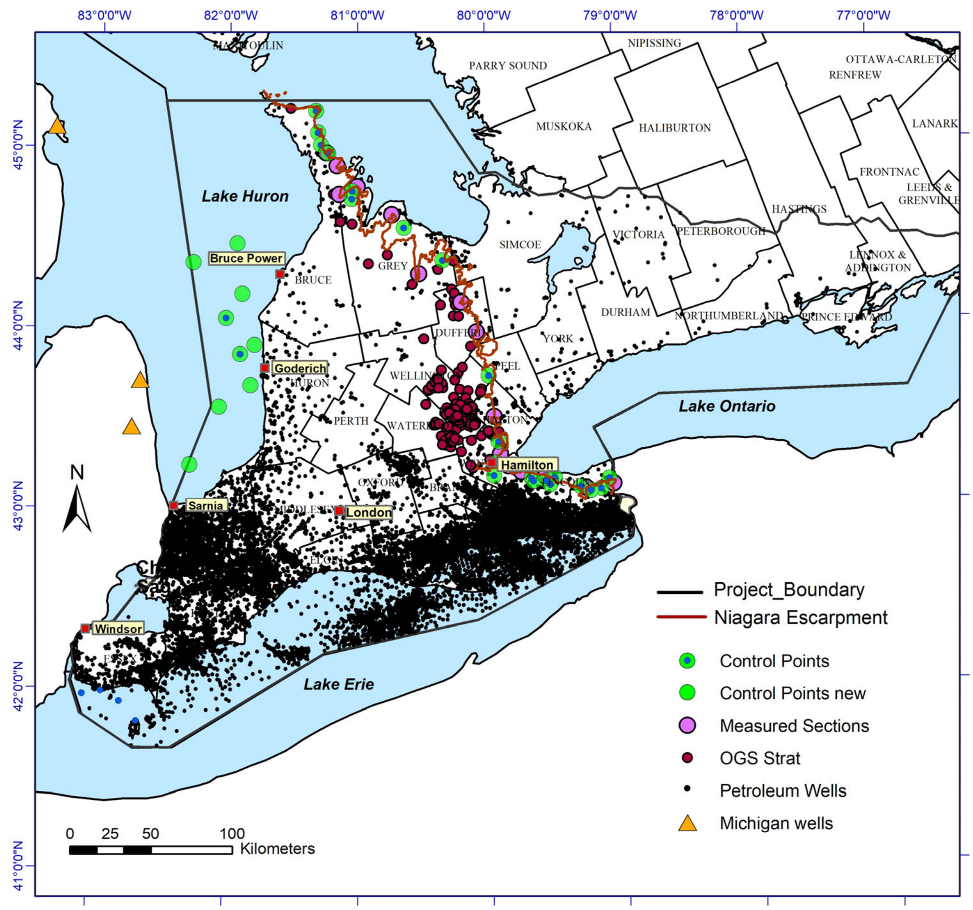

Figure 4. Location of well data points used as input to 3-D modelling. Data points labelled "OGS Strat" are stratigraphic test boreholes drilled by OGS. The wells are the same as in Carter et al. (2019) with the exception of seven new control points added in Lake Huron to better control model layer extrapolation in this area of sparse data.

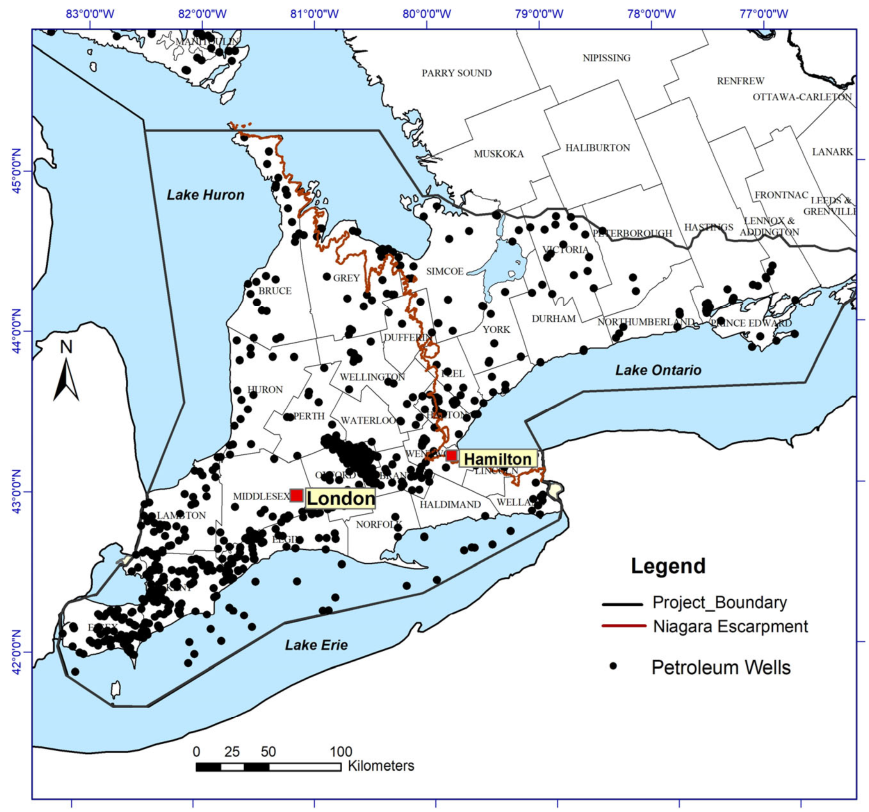

Figure 5. Location of 916 petroleum wells that penetrate to Precambrian bedrock within the study area.

Measured Sections, Stratigraphic Control Points and Michigan Wells

Sparse data density in parts of southern Ontario compromised the quality of the modelled formation layers. This was an issue particularly beneath Lake Huron and at the cuesta face of the Niagara Escarpment. To resolve these issues, it was necessary to add a number of interpreted control points to control layer extrapolation and attempt to more closely match the mapped bedrock geology with rapid changes in topography. Control points have all been assigned unique identifiers to facilitate their identification for possible removal in future modelling initiatives. Control points are prognostic wells with interpreted geology based on data derived from nearby petroleum wells. A total of 30 control points are utilized, seven more than in version 1 of the model (*see* Figure 4). Location and ground elevation information are derived from MNRF digital base maps and digital elevation model and depth to top of bedrock is derived from Gao et al. (2006) for land areas and from seismic sediment thickness maps for Lake Huron (Todd et al. 2020; Todd and McNamara 2018; McNamara and Todd 2018).

Formation top picks have been added for 15 locations at the cuesta face of the Niagara Escarpment using measured outcrop sections adapted from Bolton (1957). Geologic data from 3 Michigan petroleum wells (Lilienthal 1978) were added to the project database to improve extrapolation beneath Lake Huron.

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, the pick is considered to have a significant amount of uncertainty.
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).

OGS Stratigraphic Tests

The Ontario Geological Survey has drilled approximately 200 shallow (<200 m) diamond drill holes north of Hamilton (Figure 4) over the past 10 years to collect information on the stratigraphic relationships and groundwater flow zones in the subcropping Silurian bedrock formations in this area (Brunton and Brintnell 2020). These boreholes provide high-quality stratigraphic data in an area where petroleum well density is very sparse and of low quality.

Surface Digital Elevation Model and Bedrock Topography

A topographic DEM was 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 geo-located digital scans of CHS bathymetric field sheets were interpolated. To automate the digital capture of the depth points, a Python™ application was developed using a machine-learning optical character recognition algorithm (Griffiths et al. 2020).

A revised bedrock topography surface was produced from a companion model of the Pleistocene glacial sediments (Logan et al. 2020). This surface 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, geophysical data (Logan et al. 2020), revisions to bedrock terminology and location revisions in the southern Niagara Peninsula by OGSRL staff, and along the Niagara Escarpment by OGS staff. 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. 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.

Digital Bedrock Geology Subcrop Map

The model utilizes a digital subcrop map updated from Armstrong and Dodge (2007), Armstrong (2017), Sanford (1969), Sanford and Baer (1981) and Somers (2017) by the MNRF and OGSRL for version 1 of the model (Carter et al. 2019). To adhere interpolated layer surfaces to mapped bedrock geology, the digital subcrop map was combined with the digital bedrock topography to assemble grids of 3-D points for each modelled formation. As in Carter et al. (2019), 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 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 adhere surface estimations to subcrop map geology while actively suppressing the estimation of layer surfaces beyond their mapped subcrop extent.

Grenville Lithotectonic Domains

The Precambrian rocks that comprise the basement to the Paleozoic strata have all been affected by the Grenville Orogeny, comprising several episodes of deformation and high-grade metamorphism. The last major orogenic event involved northwest-directed thrusting and imbrication of the upper crust, approximately 1050 to 1070 Ma, interpreted to be caused by collision with a continental landmass located to the southeast (Easton 1992, 2000). This resulted in formation of a mountain chain that probably exceeded the height of the Himalayas that has since been eroded nearly flat by a period of subaerial exposure lasting up to 450 million years (R.M. Easton, 2020, personal communication).

The rocks are dominantly gneisses of granitic composition, with subordinate monzonitic, syenitic and tonalitic composition, most of which were derived from metamorphosed plutonic and clastic sedimentary rocks, and less commonly marbles and metavolcanic rocks. They have been tectonically segmented into a collection of lithotectonic domains and terranes separated by narrow zones of intense deformation. Within each domain and terrane the rocks are characterized by similarities in composition, metamorphic grade, internal structure and geophysical signature (Easton and Carter 1991, 1995).

Domain and terrane boundaries have been digitized from Easton and Carter (1991, 1995) and have been draped onto the surface of the Precambrian model layer.

Petroleum Reservoirs

Oil has been actively produced in southern Ontario since 1858 and natural gas since 1889 when the first wells were drilled and commenced production. There are currently approximately 1,200 wells producing oil and 1,200 producing natural gas in commercial quantities and an additional 550 "private gas wells" utilized by landowners for their own consumption (Carter et al. 2016).

Hydrocarbons are produced from reservoirs ("pools") formed by a subsurface accumulation of oil and/or natural gas in a body of porous and permeable rock. The hydrocarbons are trapped in the rock by lateral and vertical seals of impermeable rock. There is recorded production from 330 discrete reservoirs in 5 principal hydrocarbon "plays". A play is a group of petroleum reservoirs or prospective reservoirs in the same region that have common geological features (Doust 2010). Principal plays in southern Ontario (Carter et al. 2016) are:

- structural and stratigraphic traps in Cambrian and Shadow Lake sandstones and sandy dolomites
- fault-related hydrothermal dolomite reservoirs in Trenton and Black River Group limestones
- stratigraphic traps in sandstones and associated carbonates of the Lower Silurian Clinton and Medina groups
- reefs and structural traps in Silurian carbonates (A-1 Carbonate, Guelph Formation), and
- structural traps in Middle Devonian fractured, dolomitized carbonates and sandstones.

Two dimensional outlines of each petroleum pool, grouped into plays, have been draped on the surface of the uppermost formation in each play.

Hydrocarbon Storage and Solution Mining Caverns

Halite is actively mined by the solution-mining method at Windsor and Goderich, and in the recent past in the Amherstburg area south of Windsor. The solution mining method utilizes wells drilled into the salt beds to inject fresh water to dissolve the salt. The resultant brine is pumped back to the surface using the same or nearby wells and the salt is recovered in an evaporation plant. The very high-purity salt produced by this method is used for human consumption and in the chemical industry. The mining method creates a tall cylindrical cavern in the salt beds (e.g. Warren 2006).

Refineries and petrochemical plants in the Sarnia and Windsor areas of southern Ontario utilize purpose-built solution-mined caverns in the salt beds of the Salina Group for temporary storage of crude oil, liquified petroleum gas, and petrochemicals, prior to shipment to customers. There is storage capacity for approximately 22 million barrels of product in 71 caverns serviced by approximately 105 wells, at depths of 400 to 700 metres (Carter et al. 2016).

Current regulations in Ontario require that sonar surveys be completed in solution-mined caverns to document their extent, a hard-copy of which must be provided to the MNRF and the OGSRL. The surveys are acquired by lowering a sonar tool down the access wells into the cavern. The OGSRL has digitized the sonar surveys for 141 caverns to create 3-D volumes that have been added to the model as a separate layer. The 3-D volumes of the caverns can be viewed inside the salt beds, within which they are located, by applying a transparency to the salt bed model layer. The digitization process of the 3-D volumes is described below.

Underground Salt Mines

Conventional room and pillar mining of halite occurs at Windsor and Goderich. At Goderich, mining occurs in the A-2 Salt Unit of the Salina Group which averages 24 to 27 metres in thickness at this location, thickening to the west. At Windsor mining has historically been from the F Salt bed of the Salina Group, but in 2016 the shaft was deepened to initiate mining in the B Salt. At Goderich salt is extracted from Crown lands beneath Lake Huron, and at Windsor from Crown lands beneath the Detroit River, on the Canadian side of the border with the United States. The salt is extracted from mining leases issued under the authority of the Mining Act of Ontario.

The mines do not publish maps of their underground workings, but digital maps of the mining lease boundaries are published by the Ontario Ministry of Northern Affairs and Mining. Consequently, the underground mine workings are represented in the model as 3-D volumes with geographic boundaries corresponding to the boundaries of the salt leases, and vertical boundaries including the full thickness of the salt beds for which they have mining leases. Actual mined thicknesses at the two mines are less than the full salt thickness, and the mined volumes within the mine horizons amount to approximately 60% of the salt in place. In addition, the present extents of mining are well within the lease boundaries. Mining may not reach the leased boundaries for several tens of years.

Regional Faults

A number of faults have been identified by mapping of linear vertical displacements of formation top surfaces in the subsurface Paleozoic bedrock formations (Brigham 1971a, b; Bailey and Cochrane 1984a, b, 1985, 1986, 1988a, b) using petroleum well data. The faults have been interpreted to have a normal sense of movement. Strike-slip faults have been identified in the Ordovician carbonates of eastern North America (Davies and Smith 2006), but it has not been possible to document this in Ontario. A compilation of mapped faults was prepared by Armstrong and Carter (2010) where they identified the youngest formation on which fault displacements had been mapped. An analysis of aeromagnetic lineaments in the Precambrian basement completed by Béland-Otis (2020) did not result in identification of any previously unidentified faults.

There is a concentration of closely spaced, east-west faults in the Chatham Sag which displace the Rochester Formation surface, and all deeper formations as well. The maximum mapped displacements on these faults are approximately 100 m on the Electric Fault and 40 to 50 metres on the Dawn Fault. The Dawn Fault is downthrown on the south side and forms the northern edge of the Chatham Sag. The first author has reviewed evidence for displacement on formation surfaces younger than the Rochester and was able to identify vertical displacements of the Dundee Formation and/or the Hamilton Group (Middle Devonian) on all except two of these faults. Vertical 2-D planes of these regional faults have been added to the 3-D model at the fault locations as mapped on the Rochester Formation surface.

Mapped faults in the rest of southern Ontario have dominantly northerly trends consistent with the structural grain of the Precambrian basement, with mapped displacements only on the surface of the Cobourg Formation (Upper Ordovician) or older formations. They display less vertical displacement, have shorter mapped lengths than the regional faults in the Chatham Sag, and far fewer data points for validation of the fault locations and displacements. These fault traces are not represented in the model.

Cultural and Geographic Data

The 3-D model includes cultural and geographic layers to provide locational context to the geologic model. These include major roads, towns, geographic township boundaries, county/municipal boundaries, shorelines. The Great Lakes and a selection of other major lakes, including Lake Simcoe, are represented as two dimensional polygons displayed at their mean elevation relative to sea level. The boundaries for geographic townships (Townships Improved), highways (Transportation), and streams and shorelines (Shorelines 100K, Water Bodies 10-50 K) were obtained from geospatial databases maintained by Land Information Ontario (https://geohub.lio.gov.on.ca). The boundaries for counties were obtained 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). Except for the Great Lakes polygons, the polylines representing the other cultural and geographic features are draped on the topographic DEM, (https://data.ontario.ca/dataset/provincial-digital-elevation-model) slightly above the surface for display clarity.

Formation Top Data Quality Assurance and Quality Control

QA/QC Process

As in Carter et al. (2019), considerable project resources were focussed on quality assurance and quality control review (QA/QC) of formation top picks recorded in the Ontario Petroleum Data System (OPDS) for petroleum wells drilled into the Paleozoic bedrock formations of southern Ontario. This was the principal contribution of the OGSRL (Figure 6). Data editing and screening was done on a snapshot of the OPDS data stored in a relational database. Assigned QA/QC codes in OPDS for each formation top pick were updated when or if a pick was reviewed and either edited or confirmed (see Table 3).

QA/QC edits focussed on issues identified as priorities for review and correction in Carter et al. (2019) and were used as project milestones for progress monitoring. The editing priorities for this project comprised:

- structural and thickness anomalies and outliers and gaps in model layers
- formation top picks for the Gasport, Goat Island, Eramosa and Guelph formations of the Lockport Group for wells which previously only had picks for the Guelph Formation.
- formation top picks for all formations intersected by petroleum wells in Huron and southern Bruce counties.
- formation top picks for black shales of the Ordovician Collingwood Member of the Cobourg/Lindsay Formation and the Rouge River Member of the Blue Mountain Formation
- gaps in model layers
- zero edge of the Cambrian formations on the flanks of the Algonquin Arch

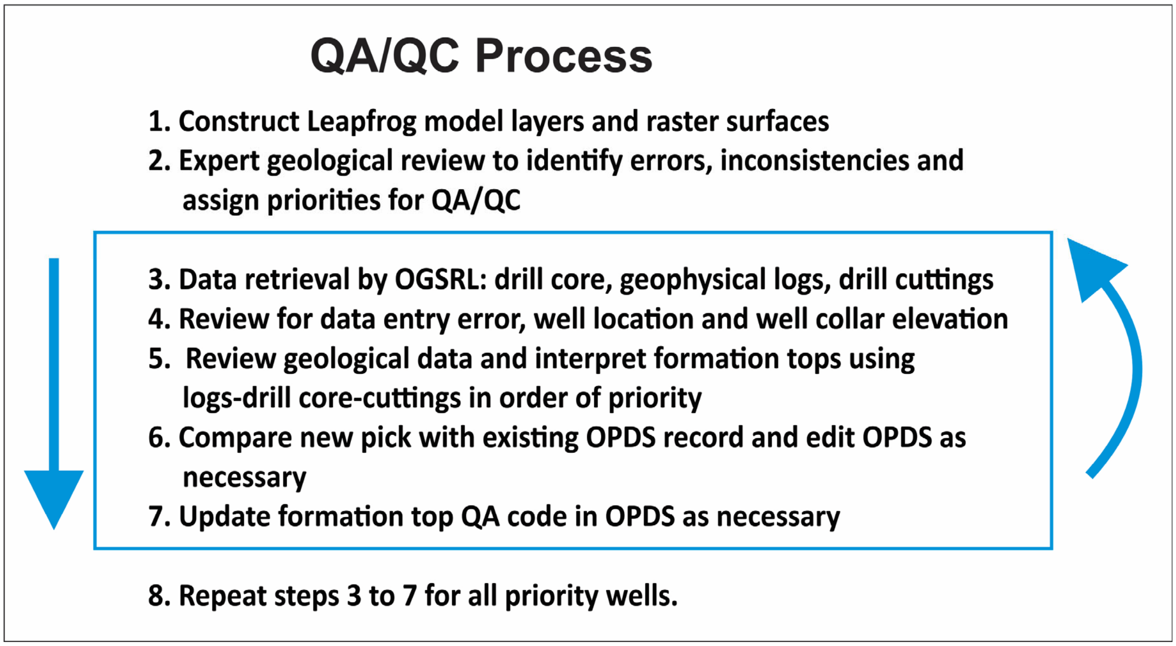

Figure 6. QA/QC process summary for review and edit of formation top data.

Interim model revisions were generated at project milestones and reviewed by project geologists to monitor progress and provide an opportunity for early identification of data editing issues. Any identified issues were referred back to the QA/QC team for investigation and correction if necessary, by examination of geophysical logs, drill cuttings, drill core, and well file reports. Wells with no logs, core or cuttings were only considered for geologic QA/QC when they caused anomalies in the model layers, in which case the formation picks were reviewed for data entry errors or were assigned a QA code of -2 to remove the data from the model. The formation top picking procedure and standards was adopted from Armstrong and Carter (2010) with modifications to accommodate local facies changes not included in the standard. QGIS®, ArcMAP® and Google Earth™ were used in the QA/QC process to provide spatial context to the geology for the QA/QC analysis.

A total of 30 320 formation top picks were reviewed or added to OPDS from 2015 to 2018 by Carter et al. (2019). From 2019 to 2020, project geologists completed edits to 17,595 formation tops in a total of 3,419 wells (Table 4). Revisions included formation top additions, deletions, and pick depth changes. The work was completed as a series of projects with discrete targets and deliverables, as described below.

QA/QC for well locations and drill collar/rig floor elevations were the subject of previous data editing exercises (Carter and Castillo 2006; Carter et al. 2019). As noted by Carter et al. (2019), 95% of the wells recorded in OPDS have co-ordinates within 200 m of the true location and 71% are within 50 m.

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

Date	Project	Number of Wells Reviewed	Formation Top Picks Reviewed and/or Edited
2019-2020	Huron and southern Bruce counties	292	6051 formation tops reviewed/edited, 2,546 new formation top picks
2019-2020	Lockport Group - regional	587	4,433 picks reviewed, 3,101 new formation top picks
2019-2020	Lockport porosity/permeability	149	1 533 picks reviewed, 474 changed, 134 new

2020	Ordovician black shales	317	1,748 picks reviewed; 706 new formation tops added
2020	Anomalies and outliers	2,067	3,600 picks edited; 1,775 new picks added
2020	Control points	7	230 interpreted formation tops
2019–2020	Total	3,419	17,595

QA/QC Results

QA/QC Geological Review: Lockport Group

The Lockport Group is comprised of the Gasport, Goat Island, Eramosa and Guelph formations, in ascending order. These formations form important regional aquifers in southern Ontario (Brunton 2009b; Brunton et al. 2012; Brunton and Brintnell 2011, 2020; Carter et al. 2014; Carter et al. 2015a, 2015b), have produced significant quantities of oil and natural gas from the deeper subsurface, and host 34 natural gas storage reservoirs with storage capacity for 269 billion cubic feet (bcf) of natural gas (Carter et al. 2016).

The top of the Lockport Group is penetrated by 15 585 wells of which 13 153 penetrate the full thickness. At the beginning of the project most of the wells which penetrated the Lockport Group recorded formation top picks in OPDS for only the Guelph Formation with no picks for the stacked dolostones of the underlying Eramosa, Goat Island and Gasport formations. The resulting sparse distribution of data had compromised model layer quality for the latter 3 formations, misrepresented the stratigraphy within pinnacles, and resulted in numerous gaps in the 3-D model.

Geological QA/QC was prioritized to provide good geographic coverage of the project area, with priority assigned to wells with water intervals recorded in the Lockport Group, all wells with core analyses, and all wells which penetrate pinnacles. Formation tops picks were reviewed in two parallel projects. Sun et al. (2020) reviewed 1,533 formation tops for 149 wells which penetrate Lockport Group “pinnacles”, resulting in addition of 134 new formation top picks to OPDS and edits to 474 existing picks. QA/QC review of Lockport Group formation top picks outside of pinnacles is described in detail in Appendix 4. A total of 4 433 formation top picks were reviewed with addition of 3 101 new formation top picks to OPDS, in a total of 587 wells.

QA/QC Geological Review: Huron and Southern Bruce Counties

NWMO has selected a location near Teeswater in southern Bruce County as the location of a proposed underground geological repository for waste nuclear fuel from Canada’s nuclear power generating facilities. The NWMO study area includes all of southern Bruce county and most of Huron County. Consequently, all wells in Huron County and southern Bruce County, and all formations in those wells, were selected for review and edit. A total of 6 051 formation top picks were reviewed with addition of 2 546 new formation top picks to OPDS, in a total of 292 wells. A detailed summary of the QA/QC review of formation top picks is included in Appendix 5.

QA/QC Geological Review: Organic-rich Shales of the Collingwood Member (Cobourg Formation) and Rouge River Member (Blue Mountain Formation)

Organic-rich black shales of the Rouge River Member of the Blue Mountain Formation and shaly carbonates of the Collingwood Member of the Cobourg Formation have potential to host unconventional resources of oil and natural gas. Recorded picks for the Collingwood Member are incomplete and inconsistent and the Rouge River Member had not been picked in the OPDS data tables. A detailed summary of QA/QC edits to the formation top picks for these organic-rich strata in included in Appendix 6.

QA/QC Geological Review: Anomalies, Gaps and Outliers

For each of the interim models every formation layer was visually examined for anomalies, gaps and outliers. The wells at which these anomalies occurred were identified and prioritized for review and edit of formation tops. Structural anomalies are highs or lows on the model layer surface with local relief varying by 5-10 metres or more on the regional surface. These are formed by single wells or a small group of wells and are identified by visual inspection of the model layers or from QGIS© raster surfaces generated using the natural neighbour interpolator. Outliers are isolated polygons which occur beyond the subcrop edge of a formation and do not correlate with mapped outliers. Gaps in layers are areas ranging from a few km^2 to several tens of km^2 at locations where the formation is mapped as having a continuous distribution.

A total of 2,067 wells were reviewed in this process, resulting in 3,600 formation top corrections and addition of 1,775 formation top picks (*see* Table 4).

QA/QC Geological Review: Cambrian

Cambrian formations are dominated by quartzose sandstones in most of the onshore portion of southern Ontario. Beneath Lake Erie and Lake Huron they consist of both quartzose sandstones and clean dolomitic mudstone. Cambrian strata are absent over the crest of the Algonquin Arch and thicken into the respective flanking basins reaching as much as 500 metres beneath Lake Huron and 180 m beneath Lake Erie (Ontario Geological Survey 2011; Bailey Geological Services Ltd. and Cochrane 1984a) on the Ontario side of the border with the United States. The Cambrian strata experienced a prolonged period of exposure and erosion at the end of the Early Ordovician, as indicated by an extensive and intensive paleokarst horizon at the Knox Unconformity (Mussman et al. 1988; Trevail 1990) and erosional removal over the crest of the Algonquin Arch (Johnson et al. 1992).

Trevail (1990) and Sanford and Quillian (1959) have interpreted and mapped the erosional pinch-out edge of the Cambrian strata over the Algonquin Arch in southern Ontario. An ArcGIS shapefile incorporating minor updates of the Cambrian zero edge was inserted into the model as a polyline edit to force the Cambrian model layer to terminate along the mapped zero edge. The interpreted zero edge was further refined by editing of 255 incorrect formation top picks in 85 wells in OPDS.

Data Preparation for Modelling

The description in this section is copied from Carter et al. (2019) and included here for convenience.

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 non confidential 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 non-deposition. 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. The sequence number is an alphanumeric code assigned to each formation used to identify its stratigraphic position relative to other formations.

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	Onondaga-Amherstburg	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

Sequence Number	Model Layer Name	Deepest Formation Bottom
402	F Unit	C Unit
403	F Salt	C Unit
404	E Unit	C Unit
405	D Unit	C Unit
405.1	D Salt	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
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
428	DeCew-Rochester-Lions Head	Irondequoit
429	Irondequoit-Rockway-Fossil Hill	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
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 for display purposes. 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. 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 two text-based comma-separated value (*.csv*) databases. A primary table containing approximately 199,330 geologic picks, with *both* formation tops and formation bottoms, was exported to create the main layer volumes. A secondary table contained 45,752 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 duplicate formation picks with the primary table; the data exists in this table only when a corresponding bottom pick could not be found for a formation. An additional 19,187 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 asl 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.

Digitization of Hydrocarbon/Solution Mining Caverns

Representations of all solution mined caverns with available sonar surveys were created as 3-D objects that have been included within the 3-D model. Sonar surveys were available for 141 distinct caverns.

Sonar surveys are acquired by lowering a sonar tool on a wireline down the wellbore into the cavern. The centre point of the survey is always a petroleum well with known UTM coordinates. Many caverns have multiple sonar reports acquired from surveys completed at different times over the operational history of the caverns. An image from the most recently submitted report was always selected. The data is acquired digitally but only hard-copy reports were available in the MNRF well files. The hard-copy survey reports include scaled vertical profiles of the solution mined caverns showing the maximum cavern radii as a function of depth. For consistency, the closest profile survey to the east-west direction was chosen. The images were scanned as 300 dpi PNG files and were digitized using Blender open-source 3-D modelling software.

With the image correctly scaled and oriented the cavern profile can be traced. A simple 2-D plane is added to Blender in the same orientation as the image. The height of the plane is stretched to match the height of the cavern and the width of the plane is stretched to encapsulate one side profile of the cavern, with one side of the plane remaining at the origin. A series of subdivisions are added to the other edge of the plane and in edit mode the vertices are dragged directly over the cavern profile in the image. A 2-D tracing of the cavern profile now exists. This cavern profile is then rotated 360 degrees around the vertical axis using the spin tool, resulting in a 3-D volume. Volumes are improved for use in Leapfrog using mesh clean up tools in Blender by merging vertices by distance, fixing non-manifold objects, and normalizing outside face.

Modelling in Blender was completed at a 1:1 scale, real-world scale. The resulting model was placed at its correct real-world location by assigning its origin to the UTM coordinates of the well from which the sonar survey was collected. The resulting models can be exported as 3-D object (OBJ) files and will appear in the regional 3-D geologic model in the correct locations. All objects can be combined into a single OBJ file that can be used in Leapfrog as an aid for visualizing caverns. Caverns in the model are represented by a single profile. At the scale that caverns will appear in Leapfrog this gives users a reasonable approximation of the cavern envelope, shape, and volume. A total of 141 caverns were converted to 3-D objects for display inside the Leapfrog model.

3-D Modelling

Ideally all 70 Paleozoic bedrock formations in southern Ontario would be represented by model layers. This was not practical with the time and resources available, and technical limitations caused by data quantity and quality, hardware and software constraints, thin formations, uneven data distribution and sparse data, etc, as described below. Consequently, the model comprises 53 modelled Paleozoic bedrock layers, plus the overburden and the Precambrian basement (*see* Figure 2 and Appendix 1). Modelling was an iterative process, with five model releases/iterations which required a complete model layer review by the project team (Table 6).

Table 6. Summary of model development.

Iteration	Layers, Data Edits, Modelling Activities	Application and Model Review
1.1	54 layers model - 52 Paleozoic layers, 1 Overburden, 1 Precambrian; incorporation of A-2 Shale into A-2 Carbonate; incorporation of DeCew into DeCew-Rochester-Lions Head; formation top edits of Lockport west of Algonquin Arch, initial formation tops in Huron and Bruce counties	Improvements to Goat Island, Gasport, Eramosa formations; identify anomalies/outliers/gaps
1.2	Anomaly/gap/outlier edits all layers	Incremental improvements
1.3	Anomaly/gap/outlier edits to all layers with focus on Goat Island and Gasport formations, 3 new control points in Lake Huron; addition of last new data for Lockport Group and Huron and Bruce counties; added oil & gas reservoirs, Grenville lithotectonic domains and hydrocarbon storage/solution mining caverns	Incremental improvements; identify new QA/QC priorities
1.4	55 layers model with addition of D Salt Unit; added underground salt mines and regional faults, 4 new control points in Lake Huron; anomaly/gap/outlier edits all layers; removal of G Unit outliers	Incremental improvements; identify new QA/QC priorities
2.0	55 layers model – 53 Paleozoic, 1 Overburden, 1 Precambrian; edits to top of Georgian Bay-Blue Mountain, removal of F Unit outliers, scattered anomalies	Finalization of model development, prepare for release, prepare report

Model resolution is 400 m. Data density varies from as little as 0.01 wells/km^2 to 0.74 wells/km^2 so modelling at a denser scale is probably not justified. Attempts to model at 100 m resolution resulted in modelling run failures and unreasonably long processing times. Test runs of smaller segments of the model in areas with dense data also did not show significant improvement.

Modelling Protocol

Leapfrog® Works (Seequent Limited) implicit 3-D modelling software was used to develop the 3-D geologic model. A full description of this software and methodologies for model construction can be found in Carter et al. (2019) however a brief summary highlighting procedural changes follows.

The geo-modelling software primarily uses lithologic contacts in borehole log data to support 3D implicit modelling. Borehole contacts and other 3D vector objects are used to imply continuous, smooth surfaces through the model space. Surfaces are also governed by the established layer chronology and are influenced by trend surfaces and manual editing guided by expert knowledge. Manual editing is limited to areas of sparse data to help render complex geometries more accurately (e.g., lateral truncations due to topography, pinnacle reef structures) and to help maintain the continuity of thin layers (1-5m).
A two-layer preliminary model (overburden and non-subdivided bedrock) was developed to support a refined model bounded by the generic bedrock volume. The upper boundary was defined by the topographic DEM while the bedrock/overburden contact was defined by the bedrock topography surface.

The refined model allows the construction of a separate sequence of bedrock layers that are truncated by the bedrock/overburden erosional contact. The refined bedrock layers were built from the Precambrian base up to the youngest layer by defining a series of upper surfaces from borehole contacts. Each layer surface avoids younger log depth intervals and ignores older ones. Where surfaces overlap, younger surfaces are truncated and, since layer volumes are established between successive surfaces, the younger layer volume will be removed. Manual edits in the form of 3D polylines help to correct surface overshoots, undershoots and erratic surface interpolations at the edges of model extents where data support is insufficient. In the current model version, most 3D polylines are constructed beyond the model boundary to help maintain consistent layer thicknesses at the model extents where layers are truncated. Previously, these edits extended into the model sometimes conflicting with borehole data. Some polyline edits remain within the model domain to prevent surface overlaps / layer holes due to data coverage gaps where indicated by expert guidance. Because the edits are generally within data gaps, conflicts with borehole data were minimized.

Like version 1 of the bedrock model, this version underwent several iterative rounds of development. In each iteration, a model was built from borehole formation pick datasets, reviewed by project geologists, problems identified and corrected. In the current version, however, additional data screening was undertaken prior to modelling in an effort to streamline the identification of potential data errors. A custom Artificial Intelligence (AI) application was developed using Visual BASIC for Applications (VBA) within Microsoft® Access® to identify possible data errors that would result in local thickness and elevation anomalies. The algorithm uses a moving data capture window centered on each borehole location in turn, to identify a local borehole subset to compare to the test borehole. To conservatively select only very thick nearby formation outliers, an anomaly was flagged only if the test thickness exceeded the local average thickness by greater than 3 standard deviations (i.e., greater than 99.7% of the nearby thickness values assuming a normal distribution). Abnormally thick log intervals may create ‘lows’ in older layers as surface estimations attempt to avoid them. Abnormally thin formations are not assessed because these do not cause older layers to deviate upward given the modelling process and parameters that were used. Only formation intervals with known depth bottom were included in this test. Elevation anomalies can manifest as local high or local low points. A similar moving window systematically tests each borehole; however a tabulation of slope values and azimuth is made between the test location and each subset location and for each model layer. In the broad sense, if the majority of slope values are either all positive or all negative and they are distributed evenly in all directions outward from the test location, a local high (~all negative slopes) or a local low (~all positive slopes) is flagged. Similar to the thickness check, to account for natural elevation variations, an outlier is flagged only if the average magnitude of test slope values exceeds a cut-off value that is equal to the mean slope plus 3 standard deviations. From evaluating slope maps derived from preliminary model surfaces, statistical analyses of grid slope values were used to determine the mean slope over the model area and thus a measure of natural variation. Based on this and preliminary trials, a value of 0.6 degrees for the slope cut-off value was found to account for most natural variance and limit ‘false positive’ anomaly detection. As the process proceeds through the entire dataset and in subsequent iterations, anomalous data is recorded and eliminated from further thickness and slope test averages to improve accuracy. Flagged outliers were then visually inspected in 3D context to confirm a final set of data anomalies to remove from the model and re-evaluate for future model iterations.

Model Layers

There are presently 70 identified bedrock strata in southern Ontario at formation rank (*see* Figures 2, 7, 8). These formations are represented in the 3-D model as 53 bedrock layers because of issues related to a combination of lateral facies changes, complex stratigraphic relationships, sparse or missing formation top data, thin formations, and limitations of time and resources, as mentioned above and further discussed below. Modelling of layers less than 3-5 metres in average thickness is not practical at the regional scale of this project. Formations which have been grouped together for modelling purposes or which have been modified from the earlier version of the model Carter et al. (2019) are discussed below (see Appendix 2, 3).

Beneath western Lake Erie, three (3) formations; the Mt. Simon, Eau Claire and Trempeleau of Cambrian age have been identified, and their lateral equivalents to the east; the Potsdam, Galway/Theresa and Little Falls formations. These formations thin rapidly on the flanks of the Algonquin Arch and have been removed by erosion over the crest and are unsubdivided beneath most of the land area of southern Ontario (Sanford and Quillian 1959; Trevail 1990; Armstrong and Carter 2010). The Cambrian is modelled as one unsubdivided layer to maintain layer integrity and more clearly represent the thickness distribution of the Cambrian strata.

The Ordovician Blue Mountain and Georgian Bay formations are represented as one layer, as a formation top picking standard is not available to establish reliable picks in the well database for the Blue Mountain Formation. New formation top picks have been made for the Collingwood Member of the Cobourg (Lindsay) Formation for a selection of wells in the database but there are still insufficient corrected data to produce a reliable model layer. New formation top picks for an organic-rich black shale known as the Rouge River Member of the Blue Mountain Formation have been made, but it is modelled together with the Georgian Bay-Blue Mountain Formation to maintain layer integrity (see Appendix 6).

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 lower Rochester Formation (Brunton and Brintnell 2020) and the two formations are modelled in a single layer, together with the DeCew Formation for which formation top picks are sparse and inconsistent. The A-2 Shale is not modelled as a separate layer as it is a stratigraphic marker within the A-2 Carbonate with no formal stratigraphic status and has a sparse and irregular data distribution. The D Salt has been added as a modelled layer due to its importance as a potential salt resource and for consistency with modelling of the other salt beds of the Salina Group: the A-2 Salt, B Salt and F Salt.

The Lower Devonian Onondaga Formation is stratigraphically correlative, in part, with both the Lucas and the Amherstburg formations (Sun et al. 2014, 2015, 2017; Sun 2018) and has been grouped with the Amherstburg for modelling purposes. 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.

Using the 3-D Model

To explore the 3-D model, free viewer software is available from the developer's website at https://www.seequent.com/products-solutions/leapfrog-viewer/. Leapfrog® Viewer includes simple tools that can be used to view the model, create slices, export views, rotate or zoom the model, add/remove layers, add transparency, etc. It actively displays UTM coordinates and elevation corresponding to the pointer location. It is an invaluable tool for visualization of the subsurface bedrock geology and observation of regional trends in formation thickness and surface structure.

The final model is published with a vertical exaggeration of 20× to provide a practical display for viewing such a large geographic area with relatively thin formations. The use of vertical exaggeration accentuates the apparent vertical size of geologic features and the apparent dip on their flanks, especially for pinnacles of the Lockport Group (see Appendix 4). Borehole locations can be viewed by turning on the "collar" layer. Well bore traces and the formation tops for these wells can be viewed in the model by turning on the "borehole lithology" layer. The wellbore path is colour-coded by depth according to the depth interval at which formations were encountered. Attribute data from the project well database is linked to the well path and can be viewed by clicking on the well path, but this feature is only available to users who have purchased a data licence from the OGSRL (www.ogsrlibrary.com). The Library provides licensed data users with an extended version of the model which includes a link to the data set used to create the model.

Additionally, model layer volumes are available in Open Mining Format (OMF) and 3-D DXF file formats. These file formats allow some flexibility for importing the model into 3-D geological modelling applications (e.g. SKUA-GOCAD™) to support more advanced analysis such as numeric groundwater modelling (e.g. Sykes et al. 2011; Khader et al 2020).

Model layers can also be exported as .obj files for 3-D printing. A companion project will produce 3-D printed versions of the regional model and portions of the model. These can be used in public outreach initiatives to obtain community acceptance for industrial, commercial, infrastructure or resource development projects, and for regulatory approvals.

The digital 3-D model has been adopted as a teaching tool in undergraduate geology at the University of Waterloo (Johnston et al. 2020; Kamutzi et al. 2020; Kamutzi 2020; Worthington 2019). A printed 3-D model will complement the digital model and provide a simplified and tactile reference. This is the subject of further research in a related project (John Johnston, personal communication, 2020).

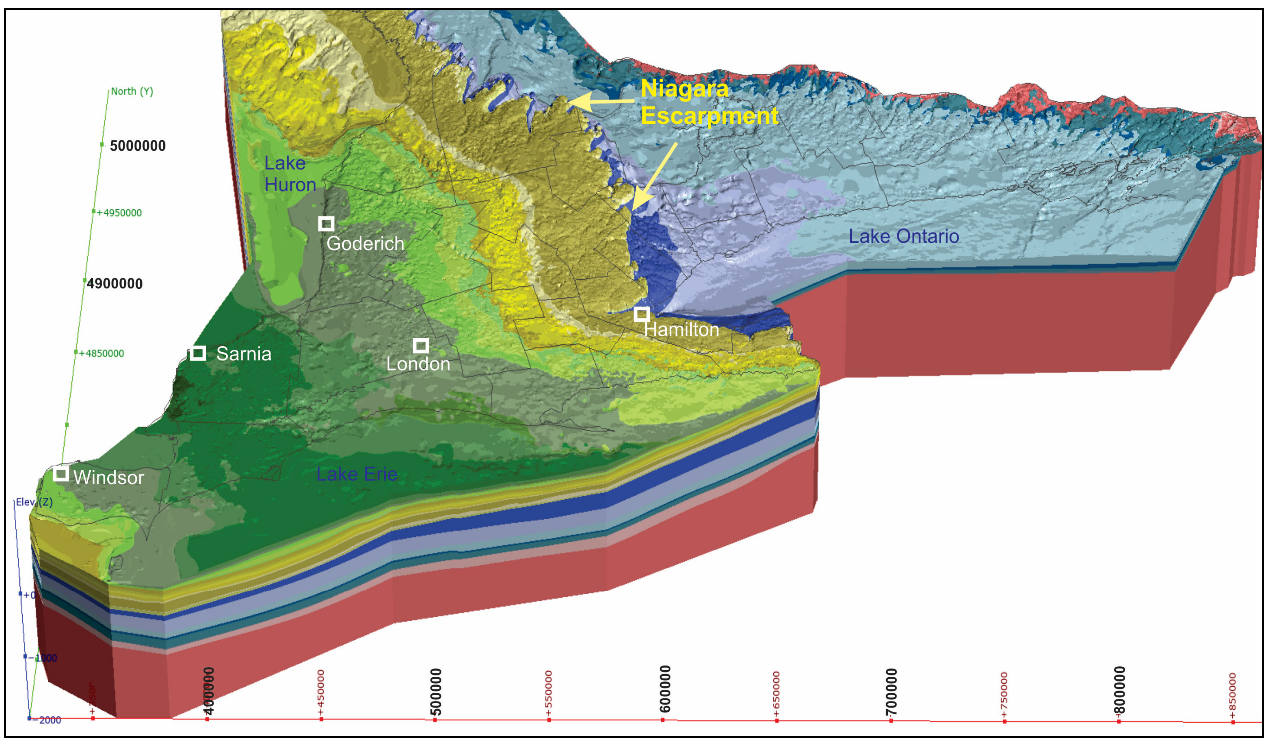

Figure 7. 3-D model of the bedrock geology of southern Ontario. Subcrop formations are draped on the topographic surface of the bedrock. See Figure 8 for geological legend.

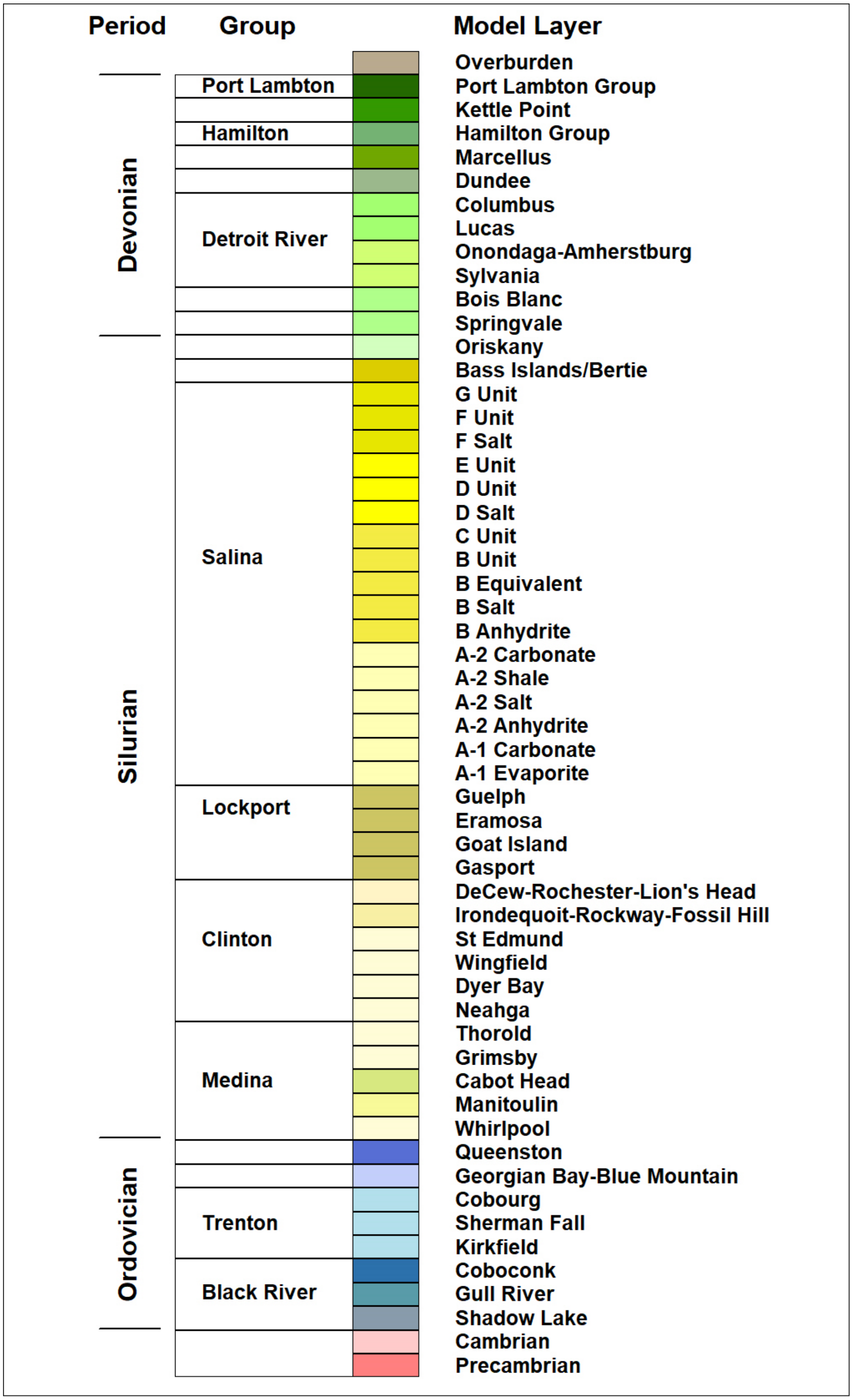

Figure 8. Legend for model layers and assigned colour of units for Phanerozoic stratigraphy of southern Ontario.

Discussion

Leapfrog Works does not provide a statistical tool for uncertainty analysis of model formation layers. Methods for statistical quantification of uncertainty will be investigated in a subsequent study. For this model the assessment of uncertainty of model layers is a qualitative visual exercise based on expert knowledge. Each model iteration has been reviewed by the project team. Every model formation layer in the final three model iterations were individually reviewed by the first author, including examination of vertical slices at 5 km spacing. Features flagged for referral for further QA/QC review included steep slopes on formation surfaces, anomalous highs or lows on formation surfaces not related to reefs or salt dissolution, outliers beyond the subcrop edge of a formation, irregular and rapid variations in thickness not related to salt dissolution, and gaps in layers expected to form a continuous distribution. Not all issues, irregularities, and omissions have been resolved. These are documented in Appendix 3, together with suggestions for improvement.

Data issues that contribute to uncertainty about the accuracy/reliability of model layers include:

- isolated anomalous formation top picks,
- sparse data and missing or incomplete data causing gaps in layers,
- data outliers beyond the known extents of model formation layers, e.g. beyond erosional subcrop boundaries,
- missing formations due to lack of formation top picks in the OPDS,
- inaccurate correlation between geology and bedrock topography, in particular at cuesta edges and steep-sided bedrock gorges,
- limited availability of geophysical logs,
- poor quality drill cuttings samples, in particular from wells drilled with rotary tools,
- wells with no drill cuttings, drill cores or geophysical logs,
- local variations in depositional facies for which a standardized formation top pick is not available,
- deficiencies in the modelling algorithm,
- unrecognized/misinterpreted geological features.

The authors have identified the following priorities for improvement for future versions of the model:

- Further editing of formation tops for the Lockport Group to increase the density and geographic distribution of available picks for the Goat Island, Gasport and Eramosa formations,
- editing of formation top picks for the DeCew Formation to add enough data to create a viable model layer,
- edit formation top picks for the Bois Blanc Formation to resolve inconsistent identification and resultant inconsistent formation thickness and structure, which also affects the modelled thickness of the overlying Onondaga-Amherstburg model layer,
- improve correlation between bedrock topography and formation top picks along the Onondaga Escarpment. This would improve the representational accuracy of this important bedrock

topographic feature. In the present model caprock lithologies locally extend past the cuesta edge and ”droop” down the slope,

- further editing of formation top picks for the Collingwood Member of the Cobourg Formation to remove erroneous industry picks and add sufficient picks to create a viable model layer,
- further QA/QC of well collar elevations to identify and correct issues created by edits and corrections to well locations,
- QA/QC review and edits of formation top data for the Georgian Bay-Blue Mountain Formation,
- addition of formation top picks for the Lucas Formation for wells with Dundee water records. For many shallow wells in Lambton County, the Lucas Formation 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 host a regional brine aquifer with potential for carbon capture and storage and have considerable potential as a hydrocarbon play,
- accurate mapping of the location, lateral extent, displacement, and sense of movement of faults that displace the bedrock formations of southern Ontario, and interpretation of the timing of their formation.

Significant improvements have been made in this second version of the 3-D bedrock geology model. Most model layers are well-constrained by data and are considered reliable at a regional scale. Users are reminded that this is a modelled representation of the geology with algorithmic interpolations and extrapolations of the geology, and it should be used with caution. Improvements can and should be made to the model as documented above and in Appendix 3. Users are encouraged to report model issues and suggestions for improvement to the authors of this report.

Summary

An updated 3-D geological model of the bedrock geology of southern Ontario has been completed utilizing Leapfrog Works©, an implicit modelling application. The model provides an improved lithostratigraphic basis for development of a 3-D hydrostratigraphic model.

There are 53 modelled Paleozoic bedrock layers representing 70 formations, plus the Precambrian basement rocks and overlying unconsolidated Quaternary sediments, for a total of 55 layers. 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 OGS deep boreholes, and MECP water well records. The digital bedrock topography surface utilized in version 1 (Carter et al. 2019) has been enhanced to better define bedrock valleys, cuestas, and subcrop exposure. The correlation between bedrock topography and bedrock geology has been greatly improved along the Niagara Escarpment.

Further improvements to the geological data infrastructure of southern Ontario have been made, building on previous improvements. QA/QC edits completed in this study have resulted in addition and/or revision of 17,595 formation top picks in 3,419 wells. These edits and additions will be of benefit to all users of OGSRL data.

The robustness of the updated geological model demonstrates the practical value of 3-D mapping and modelling of subsurface geology. It greatly extends the scope of traditional outcrop mapping and reduces the limitations and inaccuracies inherent in extrapolation of outcrop observations into the much greater volumes of rock in the subsurface. 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. The 3-D visualization improves geological understanding and interpretation and has numerous potential practical applications including: construction of tunnels and foundations for infrastructure, public outreach and education, mining, construction and operation of solution-mined hydrocarbon storage caverns, disposal of industrial and nuclear wastes, exploration for mineral, petroleum and groundwater resources, etc. Further initiatives to improve geological data quality and quantity are recommended.

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As in version 1 of the model, this project could not have been 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 OGSRL. Operation of the OGSRL is funded by mandatory fees on petroleum well licences, drill core and drill cutting sample processing fees, Library user fees, and data sales, paid to the Oil, Gas and Salt Resources Trust. The Ontario Oil, Gas and Salt Resources Corporation, through 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.

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Appendix 1. Table of modelled bedrock and sediment layers.

Group	Formation/*Member*(s)	#	Model Layer
	Overburden	001	Overburden
Port Lambton	Bedford, Berea, Sunbury	300	Port Lambton Group
	Kettle Point	301	Kettle Point
Hamilton	Bell, Rockport Quarry, Arkona,	303	Hamilton Group
	Hungry Hollow, Widder, Ipperwash	303	Hamilton Group
	Marcellus	305	Marcellus
	Dundee	306	Dundee
	Columbus	308	Columbus
Detroit River	Lucas	309	Lucas
	Onondaga, Amherstburg	311	Onondaga-Amherstburg
	Sylvania	312	Sylvania
	Bois Blanc	314	Bois Blanc
	Springvale	315	Springvale
	Oriskany	318	Oriskany
	Bass Islands, Bertie	400	Bass Islands/Bertie
	G Unit	401	G Unit
	F Unit	402	F Unit
	F Salt	403	F Salt
	E Unit	404	E Unit
	D Unit	405	D Unit
	D Salt	405.1	D Salt
	C Unit	406	C Unit
	B Unit	407	B Unit
Salina	*B Equivalent*	408	B Equivalent
	B Salt	409	B Salt
	B Anhydrite	410	B Anhydrite
	A-2 Carbonate	411	A-2 Carbonate
	A-2 Salt	413	A-2 Salt
	A-2 Anhydrite	414	A-2 Anhydrite
	A-1 Carbonate	415	A-1 Carbonate
	A-1 Evaporite	416	A-1 Evaporite
	A-0 Carbonate	418	Guelph
Lockport	Guelph	418	Guelph
	Eramosa	420	Eramosa
	Goat Island	421	Goat Island
	Gasport	422	Gasport
	DeCew, Rochester, Lions Head	427	Decew-Rochester-Lions Head
	Irondequoit, Rockway, Merriton	429	Irondequoit-Rockway-Fossil Hill
	Reynales, Fossil Hill	429	Irondequoit-Rockway-Fossil Hill
Clinton	St. Edmund	430	St. Edmund
	Wingfield	431	Wingfield
	Dyer Bay	432	Dyer Bay
	Neahga	433	Neahga
	Thorold	434	Thorold
	Grimsby	439	Grimsby
Medina	Cabot Head	440	Cabot Head
	Manitoulin	441	Manitoulin
	Whirlpool	442	Whirlpool
	Queenston	500	Queenston
	Georgian Bay, Blue Mountain	502	Georgian Bay-Blue Mountain.
	Rouge River	502	Georgian Bay-Blue Mountain
	Cobourg, *Collingwood*	511	Cobourg
Trenton	Sherman Fall	515	Sherman Fall

Notes:

1. *Onondaga members can be correlated with members of both 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. Decew is not consistently identified in the well database and is combined with the Rochester*
3. *Irondequoit, Fossil Hill, Merritton, Rockway and Reynales are not consistently identified in the well database and therefore are combined in model.*
4. *Age relationship between the Dyer Bay and Neahga remains uncertain currently.*
5. *Collingwood Member picks in database are inconsistent and is combined with the Cobourg.*
6. *Subdivision of Cambrian units is incomplete in well database.*
7. *No picks for the Blue Mountain Formation in database, so is combined with the Georgian Bay.*
8. *No picks in well database for the 3 formations of the Port Lambton Group or the 6 formations of the Hamilton Group.*
9. *A-0 Carbonate is not picked separately from the Guelph Formation in OPDS so is grouped with Guelph as a model layer.*

	Kirkfield	517	Kirkfield
Black River	Coboconk	519	Coboconk
	Gull River	522	Gull River
	Shadow Lake	523	Shadow Lake
	Cambrian (unsubdivided)	600	Cambrian
	Trempealeau, Eau Claire, Mt. Simon	600	Cambrian
	Precambrian	700	Precambrian

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
Onondaga-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, several thick beds of halite separated by interbeds of anhydrite and dolostone; up to 110 m thick
E Unit	regional; restricted marine dolostone; average 25 m thick
D Unit	Michigan Basin; shaly dolostone and anhydrite east of depositional edge of D Salt, 2-3 m thick
D Salt	Michigan Basin; two halite beds separated by bed of shaly dolostone, maximum 16 m thick
C Unit	regional; restricted marine shaly dolostone with anhydrite nodules, becoming more shaly eastwards; 23 to 30 m thick
B Unit	regional; anhydrite and shaly dolostone; 10 to 15 m thick where B Salt halite is absent
B Equivalent	dissolution rubble of anhydrite and dolostone east of B Salt; 1 to 15 m thick
B Salt	Michigan Basin; halite with numerous interbeds of anhydrite and dolostone; up to 90 m thick

Layer / Fm. / Member / Feature	Description
B Anhydrite	Michigan Basin; anhydrite at base of B Salt; 1 to 3 m thick
A-2 Carbonate	regional; restricted marine dolostone and minor limestone; 10 to 30 m thick
A-2 Salt	Michigan Basin; halite, thin interbeds of anhydrite and dolostone; up to 30 m thick
A-2 Anhydrite	Michigan Basin; anhydrite at base of A-2 Salt; 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, halite and sylvite in Michigan
Guelph	uppermost formation of Lockport Group; regional; fossiliferous, reefal, karstic, dolostone and limestone; major regional brine aquifer in deep subsurface, salty sulphur water at intermediate depth, shallow potable water; thickness varies from 2 m (inter-reef) to as much as 40 m (pinnacles)
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	regional, thinning and pinching out to northwest; calcareous grey shale with argillaceous and silty dolostone interbeds; max. 25 m thick in eastern Lake Erie.
Lions Head	restricted distribution to the Bruce Peninsula; dolostone with abundant chert; 2-3 m. thick; interpreted as lateral stratigraphic equivalent to Rochester Formation (Brunton et al, 2017)
Irondequoit	regional; fossiliferous dolostone; average 1 to 3 m up to 6 m thick
Rockway, Merritton, Fossil Hill, Reynales	Restricted distribution; dolostone and argillaceous dolostone; up to 25 m thick on Bruce Peninsula but otherwise 2 to 5 m cumulative 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 non-calcareous 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 non-calcareous 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

Layer / Fm. / Member / Feature	Description
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 non-calcareous shale; potential source of unconventional crude oil
Collingwood Member	uppermost member of Cobourg Formation; black organic-rich shaly limestone; crude oil source rock
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; can be misidentified as Cambrian sandstone when it directly overlies quartzose sandstone of the Cambrian
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
Topography	Digital elevation model topography of the overburden surface.
Petroleum pools	Subsurface reservoirs of oil and natural gas defined by drilling of petroleum wells; 2-D representation, five oil and gas "plays"; mapped reservoir boundaries are draped on shallowest producing formation in the play. Cambrian reservoirs are draped on the Cambrian surface, Trenton-Black River reservoirs are draped on the Cobourg surface, Clinton-Medina reservoirs are draped on the Thorold surface, Guelph-Salina reservoirs are draped on the Guelph surface, and Devonian reservoirs are draped on the Dundee surface.
Solution-mined salt caverns	Caverns in the halite beds of either the A-2 Salt or B Salt created by solution mining method. Caverns are utilized for either temporary storage of liquified hydrocarbons and petrochemicals at refineries and petrochemical plants in the Sarnia and Windsor areas, or for past or current solution mining of salt.
Grenville lithotectonic domains	Large contiguous blocks of metamorphic and igneous rocks in the Grenvillian basement with common structural and lithological features, metamorphic grade and geophysical (aeromagnetic) signature, separated by deformation zones up to several km in width characterized by well-developed tectonic layering, as mapped and defined by Easton and Carter (1995).
Towns	Principal towns and cities in southern Ontario.
Regional faults	Regional faults with documented linear structural displacements of formation surfaces using formation top data from petroleum wells, as compiled by Armstrong and Carter (2010). Plotted as 2-D graphic planes to illustrate fault locations. Subregional faults that do not displace rocks younger than the Cambrian are not shown
Township, county boundaries	Surveyed boundaries of geographic townships, original administrative boundaries of counties.

Layer / Fm. / Member / Feature	**Description**
Shorelines	Major streams and rivers and shorelines of lakes
Collar	Location of petroleum wells utilized as source of formation top data
Borehole lithology	Petroleum wellbores colour coded by formation and depth of formation top contacts.
Lakes	Major lakes in southern Ontario, including the Great Lakes

Appendix 3. Model layer known issues, comments, and recommendations.

Model Layer/Feature	Model Issues and Comments
Port Lambton Group	Good representation of extent and thickness. No picks in well database for its 3 constituent formations
Kettle Point	Good representation of extent and thickness.
Hamilton Group	Good representation of extent and thickness. No formation top picks in database for its 6 constituent formations.
Marcellus	Restricted distribution matching mapped extent of formation; some gaps in Lake Erie that need verification.
Dundee	Good representation of extent and thickness.
Columbus	Discontinuous distribution matching mapped extent of formation. (Davis 2017)
Lucas	Good representation of extent and thickness.
Onondaga-Amherstburg	Variations in thickness due to inconsistent formation top picks in the underlying Bois Blanc Formation, but much improved from previous model iterations. Contact with Bois Blanc is very difficult to pick consistently in cuttings and cannot be picked using geophysical logs. More data QA/QC required.
Sylvania	Restricted distribution matching mapped extent of formation
Bois Blanc	Variations in thickness due to inconsistent formation top picks, but much improved from previous model iterations. Contact with overlying Amherstburg Formation is very difficult to pick consistently in cuttings and cannot be picked using geophysical logs. More data QA/QC required.
Springvale	Discontinuous distribution matching mapped extent of formation (Davis, 2017).
Oriskany	Discontinuous distribution matching mapped extent of formation (Davis, 2017)..
Bass Islands/Bertie	Good representation of extent and thickness.
G Unit	Good representation of extent and thickness. A few small gaps.
F Unit	Scattered depressions in layer surface. These may be due to data errors, but some also accurately depict result of salt dissolution and collapse in the underlying B Salt Unit.
F Salt	High priority as salt resource and aquiclude. Good representation of extent and thickness.
E Unit	Good representation of distribution and thickness, with a few small holes. Extrapolated thickness in northern Lake Huron is locally excessive due to lack of data constraints and possibly inaccurate subcrop interpretation. QA/QC of digital subcrop control is recommended.
D Unit	Very irregular distribution with numerous gaps reflecting sparse data support.
D Salt	New layer. High priority as salt resource and aquiclude. Good representation of extent and thickness.
C Unit	Good distribution and thickness. A few small holes. Extrapolated thickness in northern Lake Huron is locally excessive due to sparse data and possible inaccurate inferred subcrop extrapolation. QA/QC of digital subcrop control is recommended.
B Unit	Good representation of distribution and thickness
B Equivalent	Discontinuous distribution reflecting sparse data. Eastern extent may be over-represented. Could be useful indicator of depositional limit of B Salt and down-dip penetration of meteoric water.
B Salt	High priority as salt resource and aquiclude. Good representation of extent and thickness.
B Anhydrite	Discontinuous distribution reflecting sparse data, but representative of mapped extent of formation.
A-2 Carbonate	Good representation of distribution and thickness.
A-2 Shale	Removed from this model. Informal stratigraphic marker with sparse data.
A-2 Salt	High priority as salt resource and aquiclude. Good representation of extent and thickness.

Model Layer/Feature	Model Issues and Comments
A-2 Anhydrite	Discontinuous distribution reflecting sparse data, but representative of mapped extent of formation.
A-1 Carbonate	Good distribution and thickness. A few scattered gaps due to relief in the underlying Guelph formation or possibly missing data – needs verification.
A-1 Evaporite	Discontinuous distribution reflecting sparse data, but representative of mapped extent of formation. In Michigan this formation thickens considerably and is an important salt resource. Eastern extent is probably excessive.
Guelph	High priority due to importance as regional aquifer. Many of the gaps at the base of pinnacles in previous model iterations have been removed Excellent representation of crests of pinnacle reefs.
Eramosa	Much improved representation of distribution and thickness from version 1. Data support is still sparse as it is difficult to identify in drill cuttings. This formation is known to form an aquitard in the shallow potable water regime.
Goat Island	Good representation of thickness and distribution. Formation top picks are often not made/recorded in OPDS by petroleum industry outside of Lambton and Kent counties due to difficulty of identification in drill cuttings. A few remaining gaps but much improved with addition of 472 new formation top picks vs model version 1. Representation within pinnacle reefs is much improved.
Gasport	Good representation of thickness and distribution. Formation top picks are often not made/recorded in OPDS by petroleum industry outside of Lambton and Kent counties due to difficulty of identification in drill cuttings. Representation within pinnacle reefs is much improved. A few remaining holes due to anomalous highs in underlying DeCew-Rochester-Lions Head that should be verified/corrected
DeCew-Rochester-Lions Head	Numerous gaps that require verification. All three of the constituent formations for this layer are thin, with restricted distributions. The DeCew is restricted to the Niagara Peninsula and eastern and central Lake Erie; the Rochester is widespread in Lake Erie and the southern portion of the model area but pinches out north of Hamilton and London (Brunton et al, 2012). The Lions Head is restricted to the Bruce Peninsula, with very few available data points.
Irondequoit-Rockway-Fossil Hill	Includes Merriton and Reynales. A lot of gaps, probably due to sparse data and thinness of layer and restricted distribution of all but the Irondequoit Formation. Additional QA/QC required.
St Edmund	Limited distribution; good representation.
Wingfield	Limited distribution, sparse data, possibly under-represented in Bruce Peninsula.
Dyer Bay	Reasonable representation of restricted distribution; difficult to identify in drill cuttings; gaps in layer should be verified.
Neahga	Poor quality but low priority; numerous gaps due to inconsistent/missing picks
Thorold	Natural gas reservoir. Good representation of distribution and thickness. Suspect outlier near Town of Arthur and in western Lake Erie.
Grimsby	Natural gas reservoir. Good representation of distribution and thickness except for outliers in Lambton, Essex counties which are questionable and require verification. Possible misidentification of uppermost Cabot Head Formation.
Cabot Head	Good representation of distribution and thickness, but a few small gaps
Manitoulin	Good representation of distribution and thickness but problem with rugosity of layer surface in Niagara Peninsula mimicking the underlying Queenston; two holes in Kent County.
Whirlpool	Good representation of distribution and thickness but excessive rugosity on layer surface in Niagara Peninsula mimicking the underlying Queenston.
Queenston	Good representation of distribution and thickness. except in Niagara Peninsula where the surface is very irregular at a fine scale, probably caused by small errors in the rig floor elevations from well to well in this area. Rig floor elevations were estimated from DEM surface elevations. The DEM surface at individual wells has a variation from the actual surface of up to 5 metres. This rugosity has been suppressed with increased smoothing.
Georgian Bay-Blue Mtn.	Good representation of distribution but numerous thickness anomalies which create irregularities in the layer surface, especially over the Innerkip gas reservoir. Formation top is picked 20 to 30 m too high when geophysical logs are not available. Editing of formation tops is needed.
Cobourg	Good representation of distribution and thickness. Collingwood Member is included in the Cobourg layer due to sparse data.
Sherman Fall	Good representation of distribution and thickness.
Kirkfield	Good representation of distribution and thickness.
Coboconk	Good representation of distribution and thickness.

Model Layer/Feature	Model Issues and Comments
Gull River	Good representation of distribution and thickness
Shadow Lake	Good representation of distribution and thickness.
Cambrian	Good representation of distribution and thickness.
Precambrian	No issues.
Onondaga Escarpment	Poor match between bedrock geology and bedrock topography with caprock lithologies frequently extrapolating past the cuesta edge and drooping down the escarpment face

Appendix 4. QA/QC Geological Review: the Lockport Group

Prepared by: Alexandre C.M Cachunjua

Executive Summary

A QA/QC review of formation top picks recorded in the Ontario Petroleum Data System (OPDS) for the Silurian Lockport Group and lower Salina Group in southern Ontario, has been completed. Formation tops were reviewed using drill cuttings and geophysical logs (gamma-ray, neutron and density) from boreholes drilled under the authority of the Oil, Gas and Salt Resources Act (OGSRA) and stored at the Oil, Gas and Salt Resources Library (OGSRL) in London, Ontario. Geological formation top depths (picks) recorded in OPDS were compared to both drill cuttings and geophysical logs, as available, using published standards in Armstrong and Carter (2010). A total of 4433 formation top picks were reviewed for 587 wells including a total of 3101 new formation top picks added to the database.

Introduction and Purpose

One of the principal data issues identified in the first 3-D geological model was missing formation top picks for the constituent formations of the Lockport Group (Carter et al. 2019). Many of the existing wells recorded in OPDS that penetrate the Lockport Group only have top picks for the Guelph Formation, the uppermost formation of the Lockport Group.

The principal objective of this study is to complete a QA/QC review of formation top picks recorded for wells that penetrate the Lockport Group within the interpinnacle karst and carbonate platform facies, described below, and add missing picks and edit existing picks. A further objective is to review formation top picks for the lowermost formations of the overlying Salina Group. The new formation tops will then be used to update the 3-D geologic model of southern Ontario and improve data quality and quantity for subsequent development of a 3-D hydrostratigraphic model.

Part 1 of this report addresses the QA/QC work completed on Lockport wells in Lambton, Kent and Essex Counties, and part 2 describes QA/QC work completed on wells east of the Algonquin Arch focusing on wells that have recorded water intervals in OPDS within the Lockport Group.

Geological Setting

The Lockport Group forms a gently dipping layer, thickening from west to east, deposited on an easterly-dipping carbonate ramp (Brintnell 2012; Brunton and Brintnell 2020), and underlies all of southern Ontario west and south of the Niagara Escarpment. The Lockport Group is comprised of the Gasport Formation, Goat Island Formation, Eramosa Formation and Guelph Formation in ascending order. A distinctive series of lithofacies belts are preserved in the Guelph Formation (Fig.4-1) as a result of a complex depositional, erosional, and diagenetic history. The overlying Salina Group is a succession of carbonates and evaporites deposited in a hypersaline, restricted marine environment (Armstrong and Carter 2010).

In the area west of the carbonate platform the Guelph Formation was subject to severe karstic weathering during an extended period of subaerial exposure, which reduced the Guelph to a paleokarst breccia/paleosol rubble (Smith 1990; Carter et al. 1994; Brunton and Brintnell 2020), extending downward into the uppermost Goat Island Formation. Within the eastern extent of the paleokarst is a 50 km wide belt of ”pinnacles” separated by the same paleokarst breccia. Pinnacle crests exhibit penetrative paleokarst, with additional karstic intervals at different levels within the pinnacles (Smith et al. 1988; Smith 1990). The pinnacles are interpreted as “karst towers” by Brunton and Brintnell (2020), while most previous workers have considered them to be pinnacle reefs (see Fig.4-2).

There are considerable differences in carbonate lithologies, formation thicknesses, sedimentary structures, and stratigraphic relationships of the Guelph Formation and the lower Salina Group in the different lithofacies belts. This is reflected in different criteria for picking formation tops, consequently the QA/QC edits are described separately below.

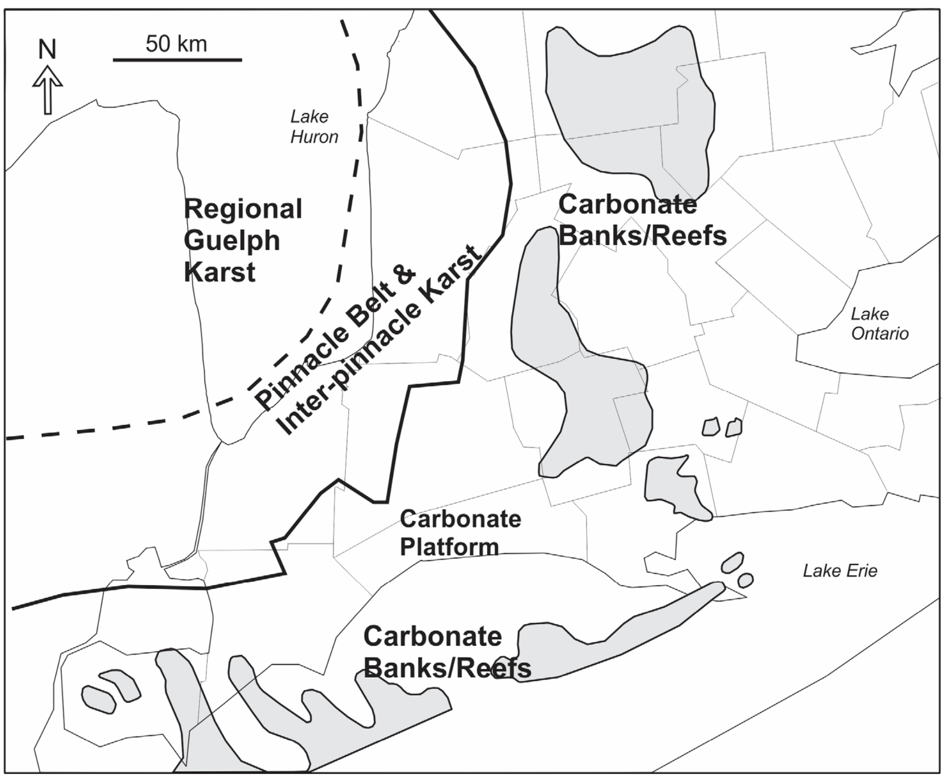

Figure 4-1. Lithofacies belts of the Guelph Formation in southern Ontario, showing carbonate banks/reefs on a southeast-dipping carbonate ramp and inner carbonate platform, and regional paleokarst breccia/paleosol rubble to the west, with an intervening 50 km wide belt of pinnacles and interpinnacle karst. Guelph Formation thickness increases from as little as 2 m in the regional and interpinnacle karst to greater than 100 m in carbonate banks/reefs, with 20 to 50 metres of local relief. Revised from Sanford (1969), Bailey (1986), and Carter et al. (1994), using data from Bailey and Cochrane (1988a) and 3-D visualization (Carter et al. 2019), and reinterpreted by reference to Brunton and Brintnell (2020) and Scholle et al. (1983).

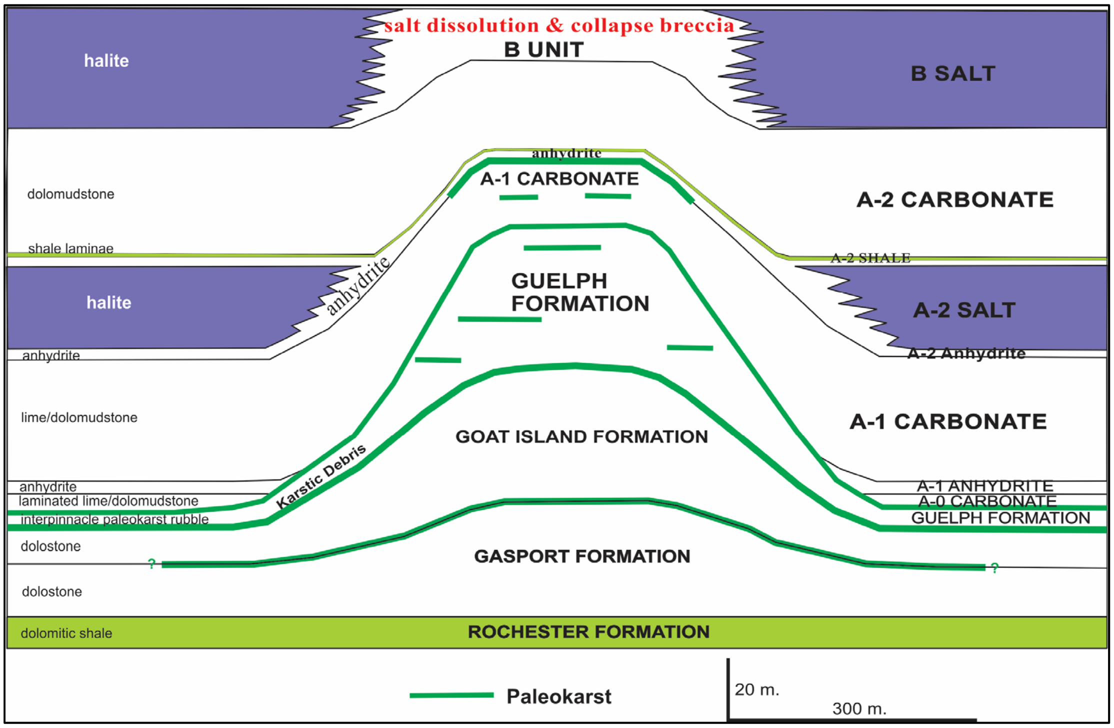

Figure 4-2. Conceptual model of a Lockport Group pinnacle in Lambton County, showing variations in thickness, lithology, stratigraphy and structure, and paleokarst intervals, within and between pinnacles and the overlying Salina Group. Modified from Carter et al. (1994) and Brunton and Brintnell (2020).

Data Sources and Study Method

Information obtained from OPDS for the purpose of geological QA/QC included Well License number, Well name, County, Latitude, Longitude, Total Depth Date, Ground Elevation, Total vertical Depth (TVD), status, sample tray number, core identification, and logging record. The geographic information system QGIS was used to geographically view and query the data during the study. As part of the QA/QC process, well location accuracy was confirmed for every well reviewed. Additionally, well card information on the Library's website was always confirmed with information in geophysical logs, drilling reports, and sample tray to reduce the uncertainty of the results.

Due to time constraints and poor data quality for some wells it was not possible to review formation tops for all wells in southern Ontario that penetrate the Lockport Group. Formation tops were reviewed for a selection of wells with high-quality data in the two parts of this study to obtain a regional distribution of edited data of sufficient density to enable 3-D modelling. Formation top picks for a total of 244 wells were reviewed in part 1, and 343 wells in part 2. Well selection criteria and QA/QC results are described below.

QA/QC Part 1

Part 1 of the study comprises wells located in Lambton, Essex and Chatham-Kent counties and western Lake Erie. A total 244 wells were reviewed using either geophysical logs or drill cuttings or both (Figure. 4-3). A total of 2337 formation top picks were examined/reviewed for QA/QC and this resulted in 1669 new formation top picks added to the database and 707 formations top picks changed/confirmed in OPDS as summarized in Table 4-1. All the wells examined are located in the interpinnacle karst facies and in the carbonate platform west of Essex County and in western Lake Erie.

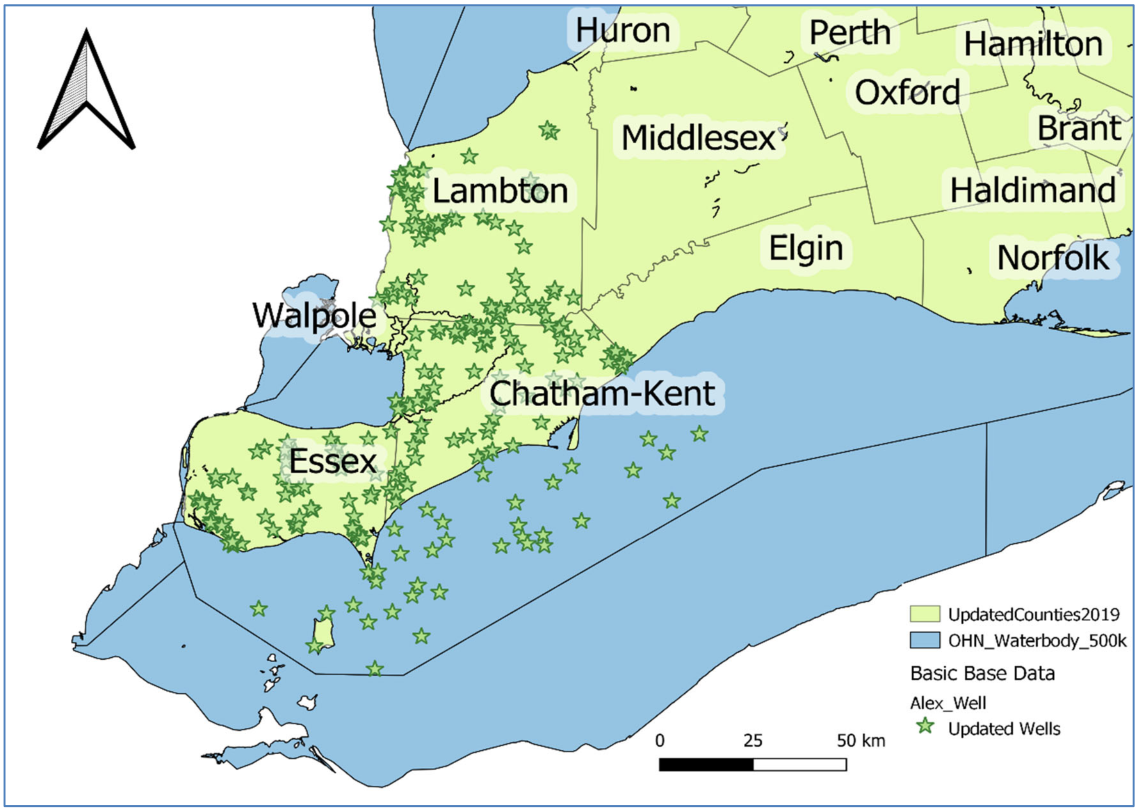

Figure 4-3. Part 1 study area showing petroleum wells for which formation tops were reviewed

Table 4-1. Number of new formation picks added to the database, by formation.

Formation	Number of new tops	Formation	Number of new tops
A-2 Carbonate	183	A-0 Carbonate	145
A-Shale	187	Guelph	129
A-2 Salt	153	Goat Island	155
A-2 Anhydrite	135	Gasport	161
A-1 Carbonate	179	Rochester	91
A-1 Evaporite	151	**Total New Formation Tops**	**1669**

Well Selection Criteria

Wells considered for review included:

- all Lockport wells with core and core analysis,
- wells for which less than two picks have been made in the Lockport Group, and
- wells in interpinnacle locations

Of the 704 wells identified for consideration a total of 244 wells were selected for review. Picks for wells located within pinnacle and incipient reefs are being reviewed by Shuo Sun in a related project.

GIS symbology was used to prioritize wells based on information available (logs, chips, core), and record data changes in a dynamic attribute table. Attribute tables were backed up on a weekly basis and reviewed by the GIS & Database Technician for quality assurance.

Formation tops were picked preferentially using geophysical logs and then confirmed by examination of drill cuttings. Wells with only drill cuttings samples were examined as a second priority to ensure acquisition of an even geographic distribution of well data. Formation top picking criteria for geophysical logs is presented in Fig. 4-4, for wells in the interpinnacle karst.

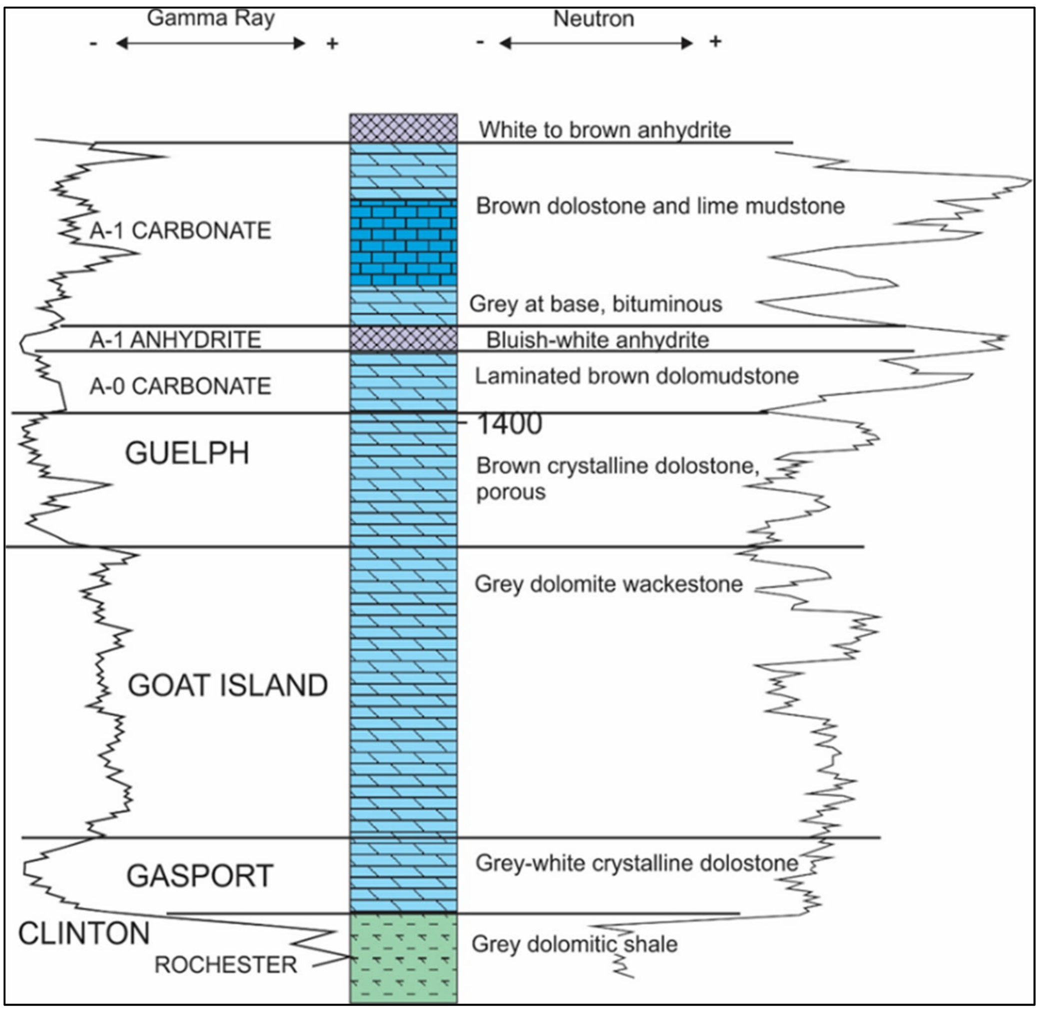

Figure 4-4. Reference log in Lambton County illustrating log pick criteria for interpinnacle facies of the Lockport Group and lower Salina Group. Modified from Armstrong and Carter (2010).

Geological Observations by Geographic Area

Typical geologic characteristics of the studied formations are summarized below. Descriptions are ordered in stratigraphic sequence from oldest to youngest.

Lambton County and Chatham-Kent: Interpinnacle Belt

Observed lithofacies in the interpinnacle belt in Lambton County, excluding the pinnacles and incipient reefs, are described below.

Rochester Formation

The top of the Rochester Formation marks the base of the Lockport Group in this area and it consists of dark grey to black calcareous shale. It has an elevated gamma response and the top can be picked where the gamma ray intensity gradually decreases at the sharp contact with the clean dolostone of the overlying Gasport Formation. In drill cuttings the Rochester Formation shales are much darker and finer than the overlying coarse white dolostone of the Gasport Formation.

Gasport Formation

The Gasport Formation consists of fine to coarse, blue-grey crystalline dolostone and dolomitic limestone with abundant crinoid debris with a very low gamma response. The top of the Gasport Formation is picked where the gamma ray increases due to an increase in argillaceous content of the overlying Goat Island Formation dolostone. In drill cuttings there is an obvious change in lithology from the bluish-white dolostone of the Gasport to the finer dark grey dolostone of the Goat Island Formation.

Goat Island Formation

In Lambton County, the Goat Island Formation is a dark-light grey, finely crystalline, argillaceous dolostone underlying the Guelph Formation. The Goat Island Formation has a slightly higher gamma ray response than the overlying Guelph Formation and the underlying Gasport Formation. In logs the top of the Goat Island Formation is picked at the first sharp gamma ray peak at the base of the Guelph Formation. In drill cuttings, the light grey dolostones of the Goat Island Formation grade vertically into the brown sucrosic carbonates of the overlying Guelph Formation.

Guelph Formation (interpinnacle)

The interpinnacle facies of the Guelph Formation is a regional karst breccia/paleosol with a fairly consistent thickness ranging from 3 to 6 metres and well-developed intergranular porosity. Where it is not possible to identify the overlying A-0 Carbonate due to lack of geophysical logs its thickness includes the 2 metres of the A-0 Carbonate. The interpinnacle Guelph Formation in Lambton County consists of light to dark brown, sucrosic carbonates, usually dolomite. In geophysical logs the Guelph Formation has a very low gamma response with a characteristic narrow gamma ray peak in the middle of the formation. The top of the Guelph Formation is picked at the slight increase of gamma ray response at the contact with the overlying A-0 Carbonate. The interpinnacle Guelph is a regional aquifer which is evidenced by a very subdued neutron response due to the water-saturated pore space. In areas where the A-0 Carbonate is not present, the top of the Guelph Formation is picked where the gamma ray decreases, and neutron increases at the contact with the A-1 Evaporite.

A-0 Carbonate

The A-0 Carbonate is a dark brown, thinly laminated, bituminous limestone that is overlain by the A-1 Evaporite and underlain by the sucrosic crystalline dolostone of the Guelph Formation. The A-0

Carbonate is approximately 2 meters thick and cannot be picked with confidence in cuttings. In well logs a characteristic log response has been identified by Armstrong and Carter (2010) (Figure 7).

A-1 Evaporite

The A-1 Evaporite consists mainly of anhydrite and minor dolostone with local occurrence of a thin bed of halite. The A-1 Evaporite has a very low gamma response and a high neutron reading. In geophysical logs the top of the A-1 Evaporite is picked where the gamma ray peak increases, at the contact with organic-rich carbonates of the A-1 Carbonate. In drill cuttings the contact is readily picked at the lithologic change from anhydrite to limestone and dolomite.

A-1 Carbonate

The A-1 Carbonate consists of tan to grey to black limestone and dolostone with evaporitic interbeds near the top. In Lambton County, the lower A-1 Carbonate is often dark brown to grey to black bituminous limestone or dolostone with a moderately high gamma ray response. The upper A-1 Carbonate is a light brown finely crystalline limestone -dolostone with laminations and evaporite minerals, with a lower gamma peak than the lower A-1 Carbonate. In geophysical logs, the top of the A-1 Carbonate is picked where the gamma ray and neutron decrease at the contact with the A-2 Anhydrite. In drill cuttings, the contact is picked where the light brown dolostone of the A-1 Carbonate changes into the white to brownish-white anhydrite of the A-2 Anhydrite.

A-2 Anhydrite

The A-2 Anhydrite underlies the A-2 Salt and it has a slightly higher gamma ray peak than the A-2 Salt. The formation top is picked at the inflection of the gamma marker which usually corresponds with a decrease in the neutron log in Lambton County. In samples, the A-2 Anhydrite is a layer of white anhydrite with minor very fine-grained brown dolostone.

A-2 Salt

The A-2 Salt underlies most of Lambton County (Sanford 1977) and northern Kent County and consists of thick beds of coarsely crystalline halite. The top of A-2 Salt can be easily picked in geophysical logs and samples by its lithology. In logs, the A-2 Salt displays very low gamma and neutron readings relative to all other lithologies.

A-2 Shale

The A-2 Shale is an informal marker bed that occurs within and near the base of the A-2 Carbonate. The top of the A-2 Shale is easily picked on its upper part where it displays a very high gamma ray peak relative to the subdued response of the enclosing carbonates. The A-2 Shale is a black fissile shale which is usually only a few centimetres thick. In drill cuttings it may be hard to identify because of the paucity of cuttings caused by its thinness.

A-2- Carbonate

The upper contact of the A-2 Carbonate is easily picked in drill cuttings at the lithologic change to limestone or dolostone from salt or anhydrite in the overlying B Salt and/or B Anhydrite. In geophysical logs the A-2 Carbonate top can usually be readily identified by a decrease in gamma ray response and lower porosity on the neutron log.

Essex County and Western Lake Erie

There is considerable variability in lithology in the studied formations in Essex and southern Kent counties and western Lake Erie within the Lockport carbonate platform, compared to the interpinnacle facies of northern Kent and Lambton counties. Another significant change is the absence of the A-2 Salt, A-0 Carbonate and A-1 Evaporite in this area. The A-2 Shale is also sometimes absent. Major differences in lithologies were also observed in the Lockport Group as discussed in further detail below.

Rochester Formation

The picking criteria of the Rochester Formation in Essex County is the same as in Lambton County. The DeCew Formation has been picked by well operators in some wells but could not be reliably identified in this study so has not been picked. All “DeCew” picks have been reassigned to the Rochester Formation. This issue should be revisited in future studies.

Gasport Formation

The Gasport Formation consists of coarsely crystalline bluish grey crinoidal dolostone and dolomitic limestone (encrinites). The Gasport Formation is slightly more argillaceous in Essex County and western Lake Erie than in Lambton and Kent counties. When the Niagara Falls Member occurs in the overlying Goat Island Formation, it is difficult to pick the top of the Gasport Formation using geophysical logs because they both have very subdued gamma readings (gamma ray is slightly higher in Niagara Falls member than in Gasport Formation). In drill cuttings, the encrinites of the Gasport Formation are coarser than the encrinites of the Niagara Falls member so the top of the Gasport is picked where the encrinites become finer.

Goat Island Formation

In this area the Goat Island Formation can be subdivided into an upper Ancaster Member and a lower Niagara Falls Member (Brunton et al. 2012; Brunton and Brintnell 2010). The Ancaster Member is a dark to light brown crystalline cherty limestone to dolostone. The Niagara Falls Member is a finely crystalline white to light-grey dolomitic limestone dominated by encrinites, with minor anhydrite and chert.

In areas where the Ancaster Member is present it is easier to differentiate the lithologies but in areas where the Niagara Falls Member of the of Goat Island Formation is present, the top of the Goat Island Formation is hard to pick because it is lithologically similar to the underlying Gasport Formation and the overlying Guelph Formation. The gamma ray double peak described in Armstrong and Carter (2010) at the top of the Goat Island Formation in the interpinnacle karst belt is not present in Essex County and western Lake Erie. In these areas, there is a gradational decrease in the gamma response near the top of the Goat Island Formation which can be used to pick the formation top. In drill cuttings, the top of the Goat Island is picked where the dark brown dolostones of the Goat Island (Ancaster) Formation (Fig. 4-5) gradually changes to the light grey (less argillaceous) carbonates of the Guelph Formation. Figure 4-6 shows characteristic gamma ray and neutron log signatures of wells that are in Essex County and Western Lake Erie.

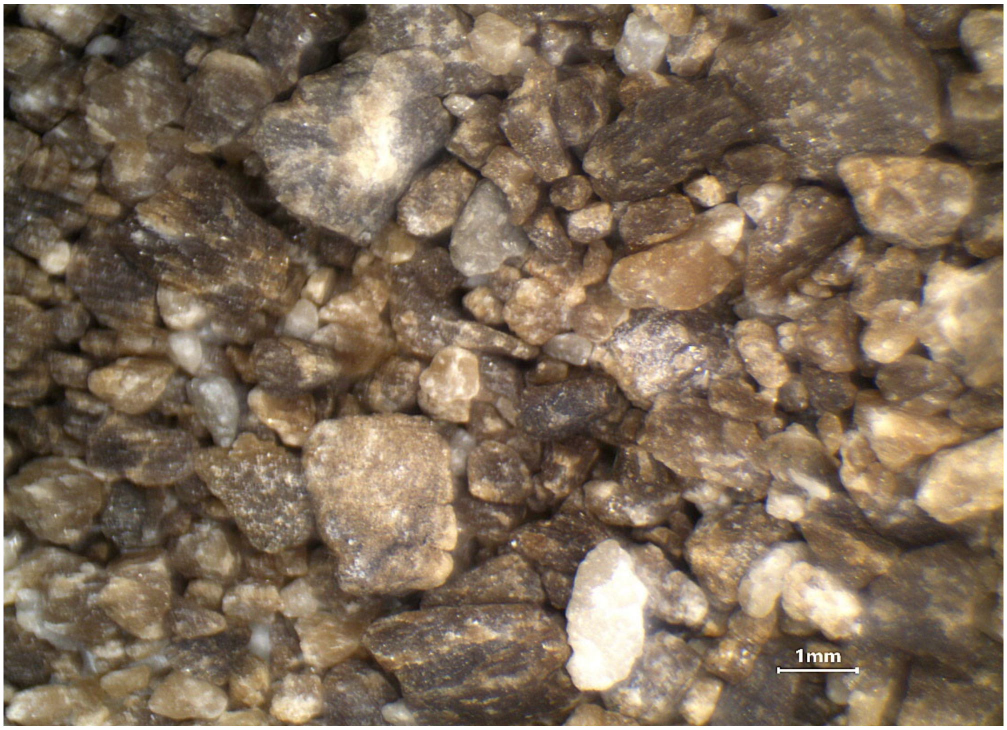

Figure 4-5. Well T000565, Photograph of drill cuttings from sample tray #3019-20, at a depth of 1324 to 1332ft, showing dark brown crystalline dolomite of the Goat Island Formation, Ancaster Member. Photo by Alexandre Cachunjua.

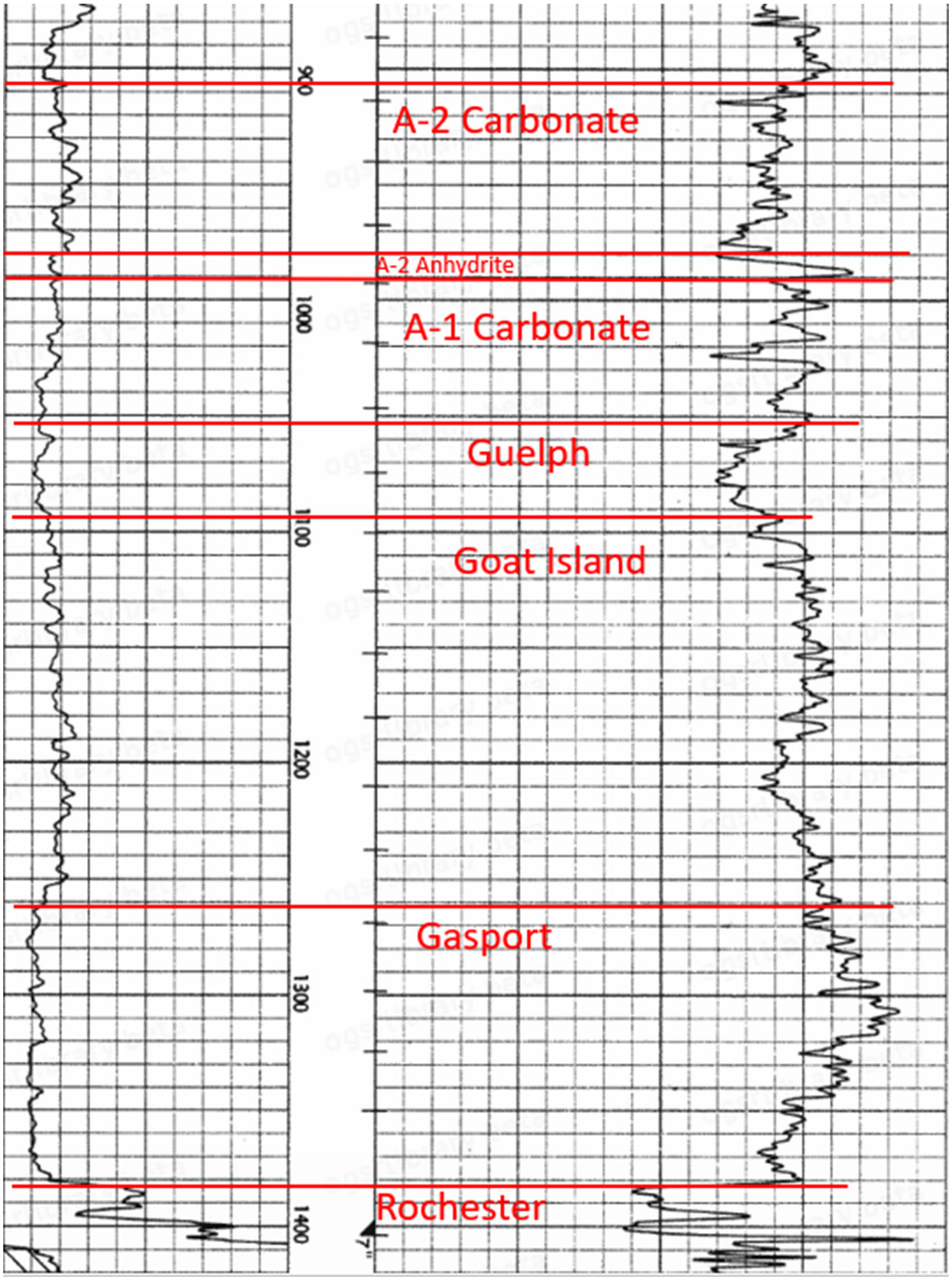

Figure 4-6. Well T000923 showing a typical gamma ray-neutron signature for wells in Essex and Western Lake Erie.

Guelph Formation

The formation picking criteria described in Armstrong and Carter (2010) for the Guelph Formation does not always apply in the Essex area. In some areas, the Guelph Formation consisted of sucrosic light-medium brown coarsely crystalline limestone as observed in Lambton County but in other areas it was more argillaceous and dolomitic. In most of this area the lower Guelph Formation is comprised of argillaceous dolomites and the upper Guelph Formation is white crystalline dolomite (Figure 4-7) with a very low gamma ray signature. In rare cases the lower Guelph Formation consists of porous light brown/creamy white limestone (see Figure 4-8). The top of the Guelph Formation was consistently picked at the increase in gamma ray response where the Guelph Formation is overlain by dark grey to light brown dolomitic A-1 Carbonate.

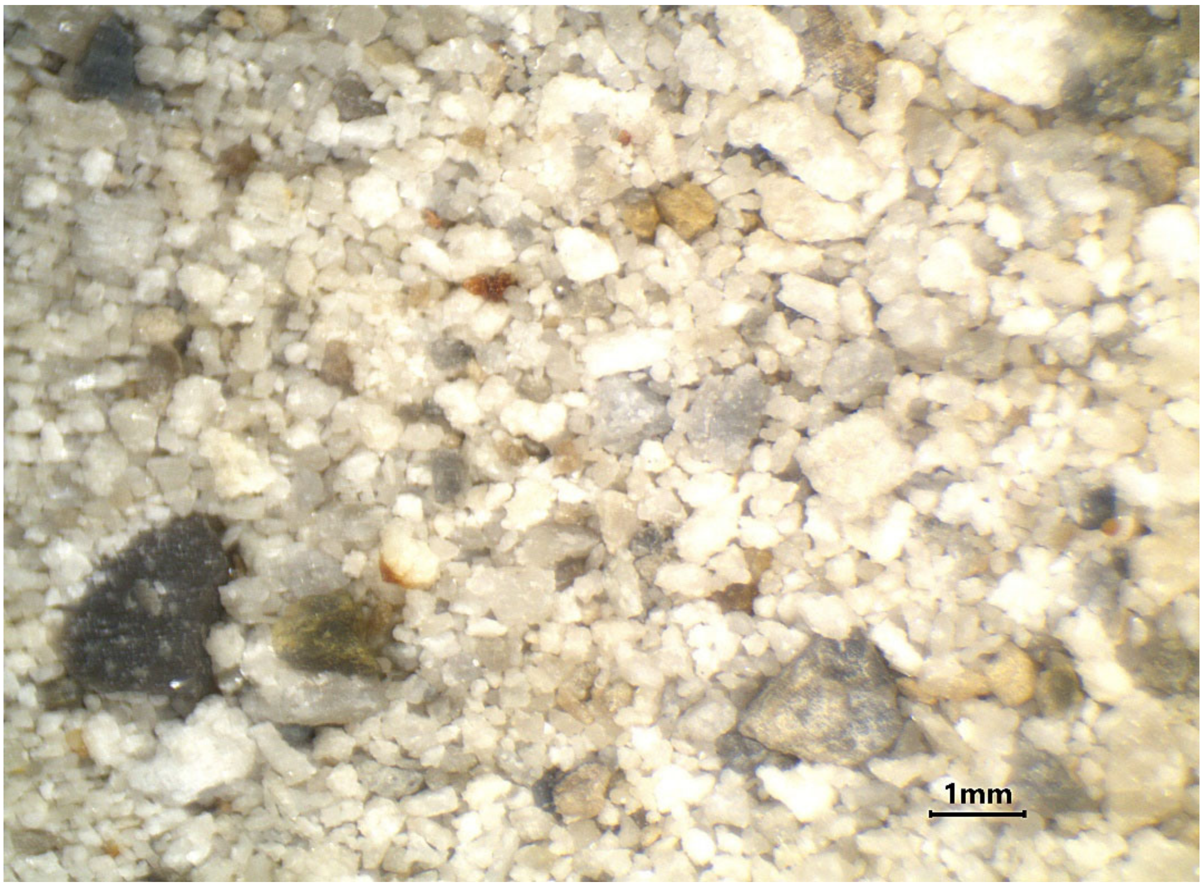

Figure 4-7. Well T000154, photograph of drill cuttings, sample tray #4980, at depth of 1299 to1305 feet. Upper Guelph Formation consisting of white dolomite. Photo by Alexandre Cachunjua.

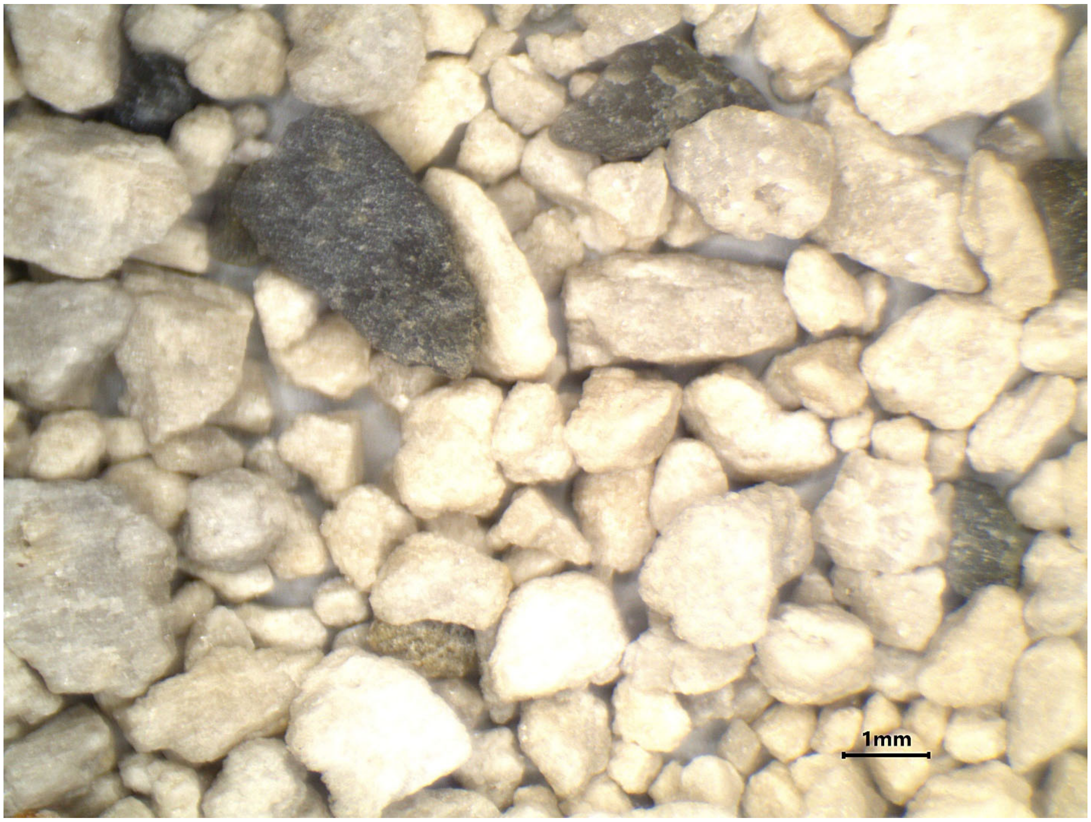

Figure 4-8. T000568 Sample Tray 7773-75, at a depth of 1492ft_10x_Guelph Formation. Creamy white dolostone of the Guelph Formation mixed with dark brown Goat Island Formation (Ancaster Member) chips. Photo by Alexandre Cachunjua.

A-1 Carbonate

A-1 Carbonate in this area is usually thinner than in Lambton County. It consists of light grey to brown finely crystalline dolostone with laminations. The lower A-1 Carbonate mostly consists of dark-grey, green dolostones and its upper part is composed of light brown fine-grained dolomitic limestones. In some areas of Essex and adjoining Lake Erie, the basal A-1 Carbonate has a greenish colouration (Figure 4-9) which is usually associated with a very high gamma response.

Figure 4-9. Well T000154, sample tray 4980, from 1285 to1292 feet A-1 Carbonate with green dolomite fragments. Photo by Alexandre Cachunjua.

A-2 Carbonate, A-2 Shale and A-2 Anhydrite

The A-2 Carbonate, A-2 Shale and A-2 Anhydrite have the same lithological descriptions as in Lambton as described in Armstrong and Carter (2010). The only significant difference is that the lower Salina Units in this area are generally much thinner than those of Lambton County.

Southern Kent County

In southern Kent County, the A-2 Salt is mostly absent. In cases where the salt is present, the A-2 Anhydrite is not always obvious or appears to be quite thin. Furthermore, the A-0 Carbonate could not be identified and the A-1 Evaporite was not always present. Otherwise, formation lithologies for the interval from A-2 Carbonate to the Guelph Formation are similar to the Essex-western Lake Erie area.

Rochester Formation

The Rochester Formation consists of dark grey to black calcareous shale with a moderately high gamma ray response just as in Lambton and Essex counties.

Gasport Formation

The Gasport Formation is comprised of white to light grey coarsely crystalline, crinoidal limestone and dolostone. It has a very low gamma ray signature, and the top is picked at the inflection point of increased gamma ray intensity at the contact with the Goat Island Formation.

Goat Island Formation

In Kent County the Goat Island Formation is dominated by the Ancaster Member which is a dark-light grey, finely crystalline, cherty limestone to dolostone. It is argillaceous, with a higher gamma ray reading than Gasport Formation. The Niagara Falls Member appears westward into Essex County.

Recurring Issues

Historically, in the pinnacle reefs only, the oil and gas industry picked the top of the Guelph Formation on the assumption that the A-1 Carbonate is not present on the tops of the reefs; therefore, the recorded top of the Guelph Formation was picked too high (where the A-1 Carbonate should be). Although this was a standard picking criterion restricted to wells in pinnacle reefs, the same criteria had been used in the past for picking wells in interpinnacle regions. There were 20-30 instances where the top of the Guelph Formation in the interpinnacle regions had been previously picked as the A-1 Carbonate; this issue has been corrected and updated in the database. In rare cases, the formation top depth of the Guelph Formation was picked as the A-2 Carbonate. There were minor issues in Lambton County of inconsistent formation top picks in the lower Salina Group. There were instances where the A-1 Carbonate and the A-2 Anhydrite were picked 2-3m, higher than the inflection point in the gamma ray.

Formation top picks in OPDS for the Eramosa and DeCew formations in this area were determined to be inconsistent and have been removed. The DeCew Formation mis-picks were examined and reassigned to the Rochester Formation and the Eramosa mis-picks were re-picked as the top of the Goat Island Formation after confirming with geophysical logs and samples.

A recurring issue found in Essex County was the misidentification of the A-2 Shale (marker). Some wells in western Essex County and Lake Erie often had A-2 Shale picks assigned to them but when those wells were reviewed with geophysical logs and drill cuttings, they did not display any characteristics of shales in either geophysical logs or drill cuttings. The A-2 Shale was not modelled separately in the 3-D model so this did not impact project results.

There were many missing formation top picks for the Goat Island and Gasport formations. Most of the new formation tops assigned in this study were for these two formations. In Essex County, the presence of the Niagara Falls Member of the Goat Island Formation made it difficult to reliably distinguish the Gasport Formation, Niagara Falls Member (Goat Island), and Guelph Formation. Many Gasport/Goat Island picks have been given low QA codes of 1.3 due to the uncertainty of the formation top picks. However, there is still a significant number of Gasport and Goat Island formation picks in Essex and Kent counties which were made with high confidence and were assigned QA codes of 1.8.

Study Area 2 – Lockport Group East of the Algonquin Arch

The second phase of the Lockport QA/QC update involved review of wells located east of the Algonquin Arch within the Carbonate Platform and Carbonate Bank/Reef lithofacies belt (Fig. 4-1). Formation top depths have been reviewed from top of the Gasport Formation to the top of the A-2 Carbonate for a total of 343 wells (Fig. 4-10). The top depths for the DeCew and the Rochester formations were not reviewed in this second phase of the project due to the lack of a reliable standard for identification of the DeCew. This issue should be revisited in a future studies.

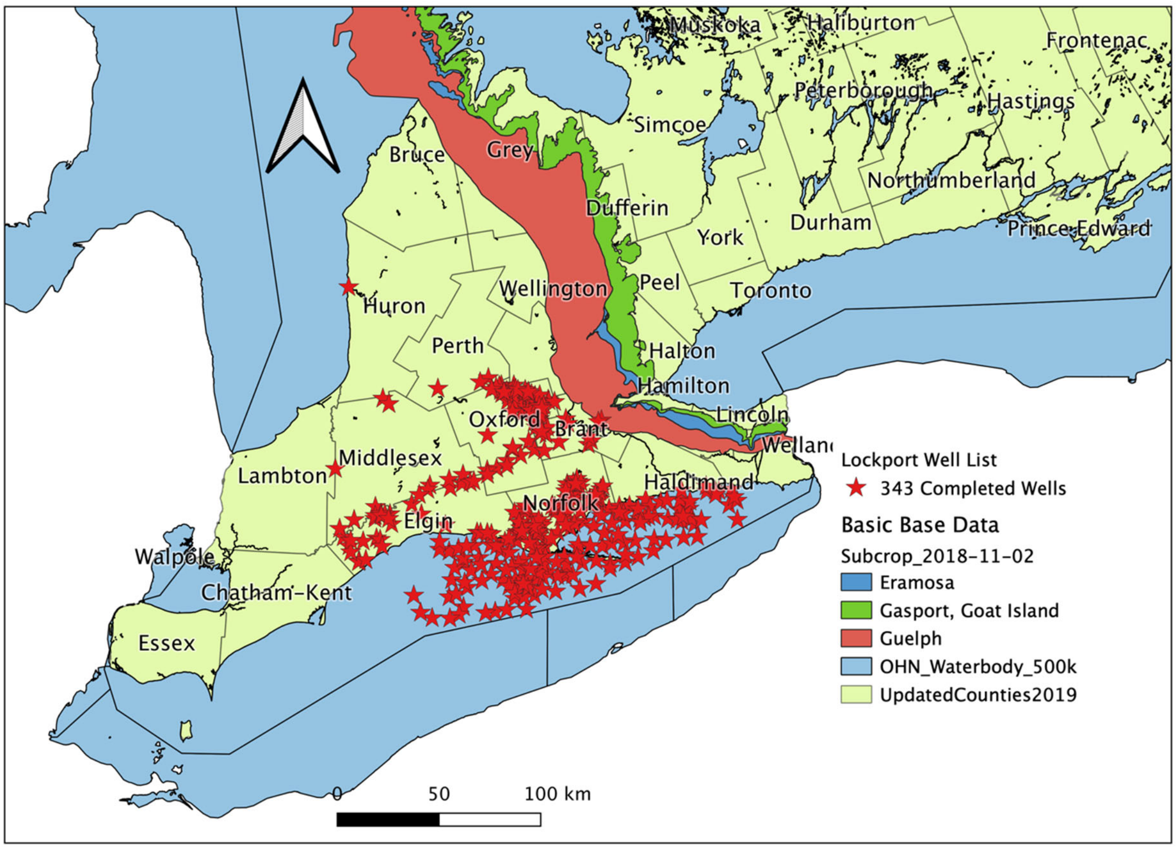

Figure 4-10. Geographic distribution of 343 reviewed Lockport wells east of the Algonquin Arch

Well Selection Criteria

The well selection criteria described above was also applied to this phase of the project. Wells selected for study had to penetrate the DeCew Formation or Rochester Formation and have at least one formation top depth missing within the Lockport interval. Wells with recorded water shows in the Lockport Group were prioritized for review. The query resulted in a list 2130 wells located within the study area. Wells with both geophysical logs and drill cuttings were prioritized for assessment (898 wells). Of these 898 wells a total of 343 were selected for review to achieve a well distribution of sufficient density to produce a reliable modelled layer. In onshore areas with a dense well population wells were selected to achieve a 400 m spacing distance whenever possible. Wells in Lake Erie were selected for review by selecting one well within each survey block in the lake grid geographic survey system of blocks and tracts.

QA/QC Edits

A total of 2096 formation tops were examined/reviewed for part 2 of the project. This includes 1432 new formation top picks which were added to the database and 664 formation top picks which were changed/updated in the database. Table 4-2 shows the number of new formation tops added and their corresponding formations.

Table 4-2. New formation top picks added to OPDS in study area 2.

Formation	Number of new tops	Formation	Number of new tops
A-2 Carbonate	175	Goat Island	317
A-Shale	193	Gasport	319
A-2 Anhydrite	175		
A-1 Carbonate	154	**Total New Formation Tops**	**1432**
Guelph	99		

COVID-19 Impacts

Of the 343 wells reviewed in total, 87 were reviewed using both geophysical logs and drill cuttings before physical access to the OGSRL was restricted. The remaining 256 wells were reviewed using well logs only. The majority of the wells in onshore areas were completed in the office with the aid of logs and samples with the exception of wells in Oxford County. The only geophysical logs available in the Lockport depth interval in Oxford County were gamma ray logs and cuttings samples could not be accessed. The increased uncertainty with the picks in Oxford County is captured in the QA codes. Some wells have been assigned a QA code of 1 which means that these wells need sample confirmation when Library operations return to normal.

The same issue applies to wells in Lake Erie. Geophysical logs often displayed ambiguous results which could only be confirmed by drill cuttings or core which were not available for examination. Additionally, it was not possible to pick formation tops for the Eramosa Formation as it can only be confirmed with samples.

Geological Observations by Geographic Area

There are regional variations in the lithology of the Lockport Group which are not adequately described in Armstrong and Carter (2010) and are documented below. Middlesex and Elgin counties display similar lithological characteristics as in Kent County. The descriptions of lower Salina formations by Armstrong and Carter (2010) match with the characteristics observed in Elgin and Middlesex counties.

Wells in Central Lake Erie are mostly within the carbonate platforms and there are no obvious subdivisions in the far offshore areas. In offshore wells proximal to the shore, lithological variations match with the descriptions of the onshore counties (Elgin, Essex, Norfolk).

Formation top picking criteria in geophysical logs is represented in Figure 4-11 for regions in eastern Lake Erie and Niagara Peninsula. There is a fairly consistent gamma signature of formations east of Norfolk County, eastern Lake Erie and the Niagara Peninsula.

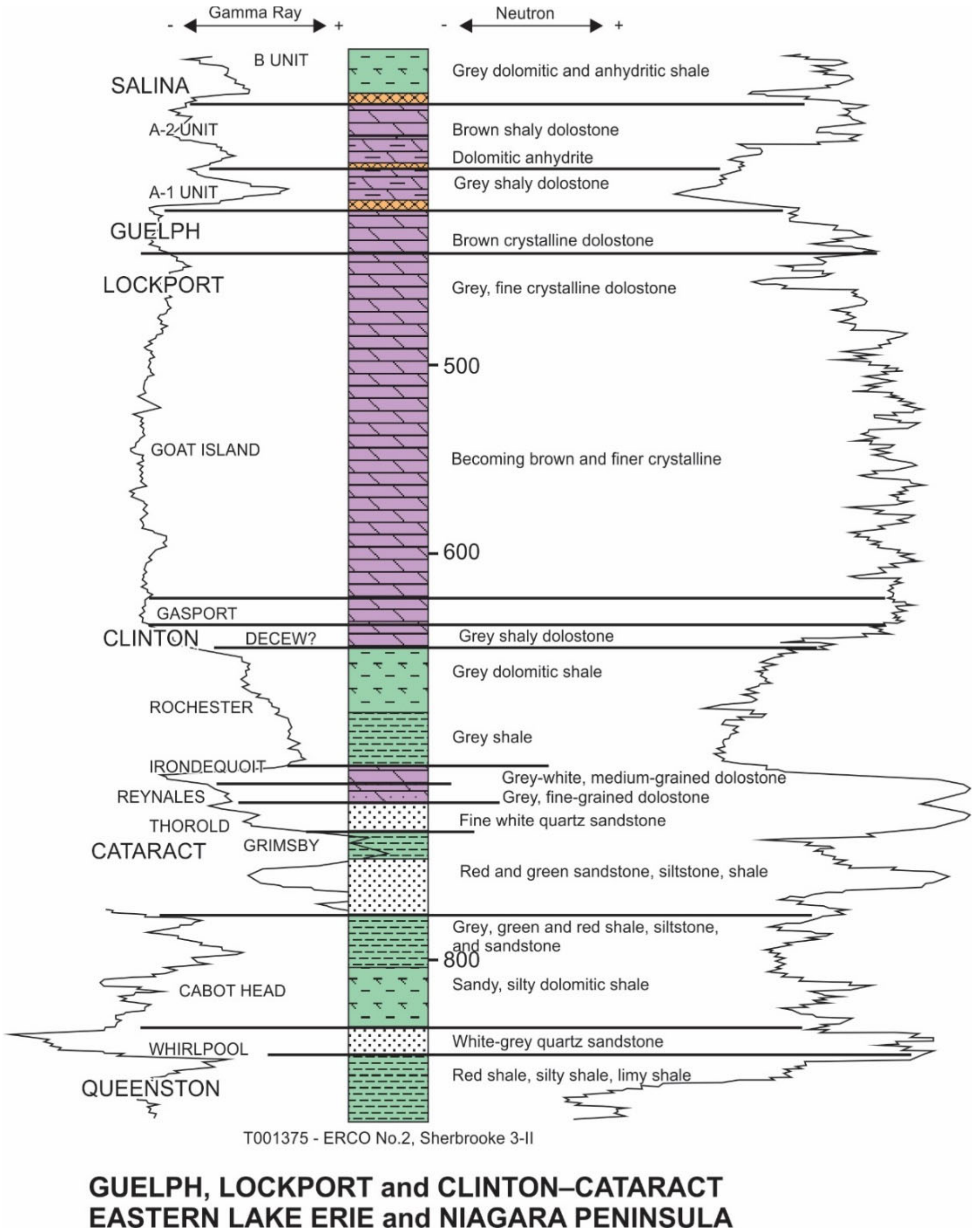

Figure 4-11. Geophysical log illustrating formation pick criteria for wells in Eastern Norfolk, Eastern Lake Erie and Niagara Peninsula. Modified from Armstrong and Carter (2010).

Norfolk, Brant and Southern Oxford Counties

Formation descriptions are in ascending stratigraphic order. In this area, the lower Salina formations (A-2 Carbonate and A1 Carbonate) thin eastwards until it is impossible to differentiate them and they are picked simply as the A Unit.

Gasport Formation

The Gasport is comprised of white to light grey, coarsely crystalline, crinoid-rich limestone and/or dolostone. It has a very low gamma-ray intensity, and the top is picked in logs at the increase in gamma-ray intensity in the overlying Goat Island Formation. In Brant County specifically, the Gasport Formation occasionally presented itself with two parts, an upper and lower Gasport. The lower Gasport is the usual coarsely crystalline bluish grey crinoidal limestone. The upper Gasport is a fine-medium crystalline light brown limestone/dolostone with corals and crinoids. Although having similar features to the Goat Island Formation, the upper Gasport contains no evaporites nor sponge fossils and it displays a very clean gamma ray signature (Fig. 4-12)

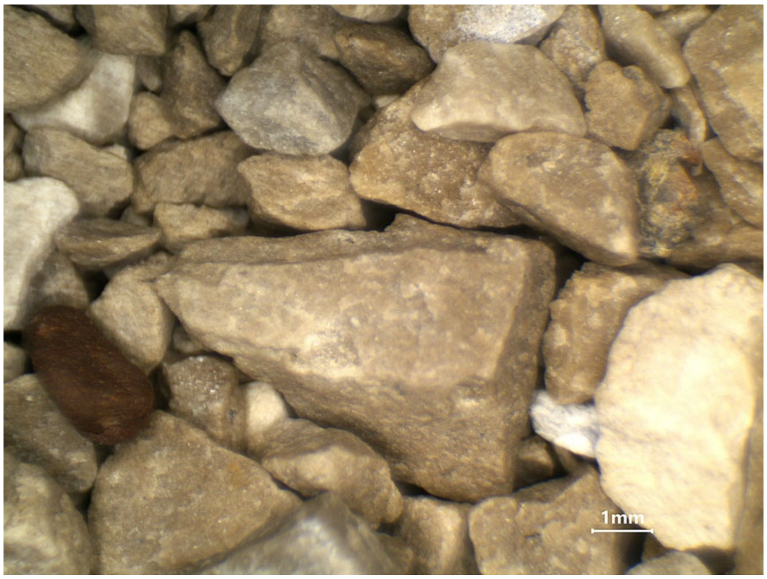

Figure 4-12. Well T001810, photograph of sample tray number 5236-37 at 713 ft depth, 10x magnification- Light brown upper Gasport in Brant County. Photo by Alexandre Cachunjua.

Goat Island Formation

The Goat Island Formation consists of dark to light grey, fine- to medium- crystalline, argillaceous dolostone. Its shaly nature gives it a moderately elevated gamma-ray response relative to the overlying Guelph and the underlying Gasport formations. The top is picked at the inflection point of a relatively sharp increase in gamma ray intensity followed by fairly consistently high gamma (often following a sharp gamma peak in Guelph). In samples, the brown carbonate of Goat Island Formation changes upward into the light grey or white, coarsely crystalline carbonates of Guelph Formation. This region is dominated by the Ancaster Member of the Goat Island Formation.

Guelph Formation

In these regions the Guelph Formation consists of a lower Guelph, comprised of light grey to white, coarsely crystalline, fossiliferous limestone, and an upper Guelph which is a light- to medium- grey, moderately fossiliferous limestone. The contact with the overlying A-1 Carbonate is placed at the first occurrence of medium- to dark- brown, evaporitic limestone. In geophysical logs, the top of the Guelph is picked at the rapid increase in the gamma ray intensity which is usually associated with a sudden decrease in the neutron log.

A-1 Carbonate

The A-1 Carbonate consists of tan-brown to black limestone and dolostone. It is very fine to medium grained. Where the A-2 Anhydrite is present, the top of the A-1 Carbonate can easily be picked in gamma ray logs at the sharp transition from overlying non-responsive anhydrite into the underlying shaly carbonate. Where the A-2 Anhydrite is absent, the A1 Carbonate cannot be distinguished from the A-2 Carbonate.

A-2 Carbonate

Descriptions for the A-2 Carbonate are same as for Lambton County.

Perth and Northern Oxford Counties

Wells in this area were initially reviewed only with geophysical logs, then formation tops were re-picked with samples when Library operations returned to normal in early July. Upon reviewing both geophysical logs and samples, it was determined that the picking criterion and descriptions listed in southern Oxford and Norfolk is applicable for wells in Northern Oxford and Perth counties with one exception. In this area, the Niagara Falls Member (Goat Island) is present, therefore, increasing the uncertainty when differentiating the Goat Island from the overlying Guelph Formation and the underlying Gasport Formation. All wells re-picked in this area were reassigned with an appropriate QA code reflecting the confidence of the pick.

Recurring Issues

Major challenges for consistent and accurate picking of formation tops for the Lockport Group are caused by the similarity of their lithological characteristics in both geophysical logs and drill cuttings. Other QA issues include inconsistent, missing and/or incorrect unit top picks for geological formations, and data entry errors. All of these issues have been resolved for the reviewed wells in this QA/QC project.

The A-2 Carbonate has often been mis-picked as the B Anhydrite or B equivalent in Elgin, Brant and Norfolk. This issue has been corrected as new formation tops added in OPDS.

There were a significant number of inconsistent and missing formation top picks for the Guelph Formation, which have all been resolved. In areas such as Haldimand and Eastern Lake Erie, the Guelph Formation top has sometimes been incorrectly picked as one of the lower Salina Group units.

The Gasport and Goat Island formations were rarely picked in this area; therefore, having fewer picks in the database prior to this project. As stated in sections above, this QA/QC project resulted in nearly 1000 formation top picks added to the database for the abovementioned formations. The most significant challenge encountered when reviewing these two formations was in areas such as central Lake Erie, northern Oxford, and western Lake Erie where reliable differentiation of the Gasport from the Goat Island is nearly impossible.

Summary

Formation top picks for the Lockport Group and lowermost Salina Group have been reviewed for a total of 587 wells. A total of 4433 formation tops were reviewed including 3101 new formation tops added to the database, and 1371 confirmed/changed formation top picks in the database. When performing QA/QC, geophysical logs and drill samples were used as the primary source of data. All formation tops were picked by following the standards of Armstrong and Carter (2010) for consistency and accuracy.

Revised and new formation top picks have been assigned a QA code which reflects the level of confidence/certainty of the pick. The following QA issues were encountered and corrected; inconsistent/missing formation top picks, data entry errors, and incorrect formation picks.

Appendix 5. QA/QC Geological Review: Huron and Southern Bruce Counties

Prepared by: Candace Freckelton

Executive Summary

A QA/QC geological review has been completed of Paleozoic bedrock formation top picks recorded in the Ontario Petroleum Data System (OPDS) for petroleum wells drilled in Huron and southern Bruce counties of southern Ontario. The study area encompasses 27 geographic townships within an area of 7,900 km^2. Formation tops were reviewed using petroleum well files (driller reports, Ministry Form 7 reports), drill cuttings, and geophysical logs (gamma-ray, neutron and density logs), for boreholes drilled under the authority of the Oil, Gas and Salt Resources Act (OGSRA) and stored at the Oil, Gas and Salt Resources Library (OGSRL) in London, Ontario. The formation top picking procedure and standards for identification of formation tops in cuttings and logs was based on Armstrong and Carter (2010). A total of 6,051 formation tops were reviewed, from 292 wells, with 2,546 of those picks being new additions to the database.

Introduction and Purpose

Formation top picks recorded in the OPDS petroleum well database are the primary data input for developing the 3-D geological model. The quality of the model depends directly on the accuracy and consistency of these picks.

This study focuses on QA/QC geological review of formation top picks for petroleum wells drilled within Huron and southern Bruce counties. The study area location (Fig. 5-1) comprises 27 townships and 7,900 km^2 which encompasses the subregional study area chosen by the Nuclear Waste Management Organization (NWMO) for investigation as a potential site for deep geological disposal of waste nuclear fuel under their Adaptive Phased Management (APM) program. The edited formation tops have been incorporated into OPDS and used to update the 3-D lithostratigraphic model for southern Ontario.

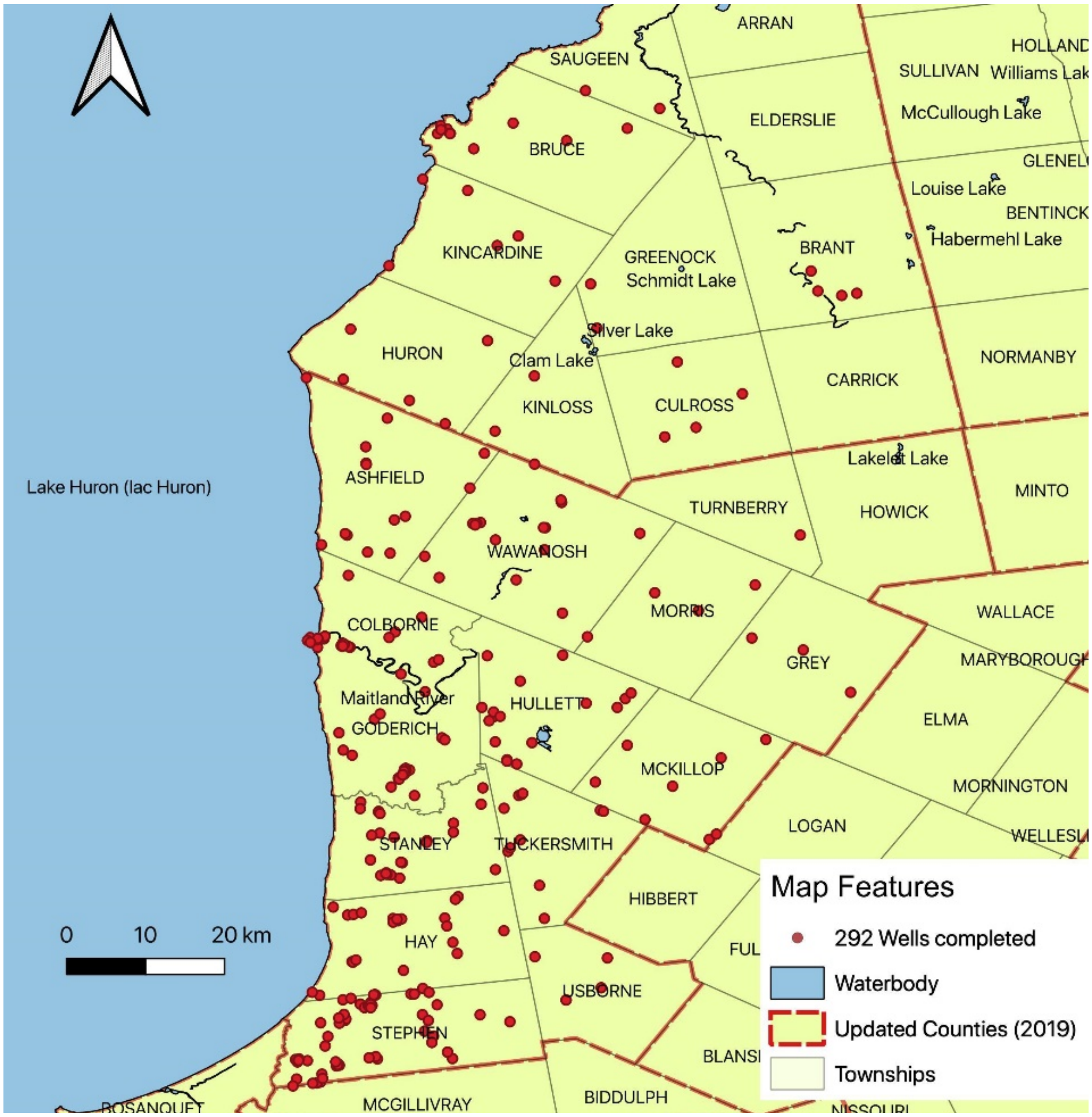

Figure 5-1. Locations of the 292 petroleum wells for which QA/QC review of formation tops has been completed. The study area encompasses 27 townships within Huron and southern Bruce counties (7,900 km^2). There are no records for petroleum wells in the townships of Howick, Carrick, Elderslie, and Arran.

QA/QC Results

Formation top picks were reviewed for 38 wells in Bruce County encompassing all wells drilled in the southern townships of Arran, Brant, Bruce, Carrick, Culross, Elderslie, Greenock, Huron, Kincardine, Kinloss, and Saugeen. All formation tops for the 254 wells in Huron County were reviewed. A secondary review was completed to verify/correct anomalous formation tops identified in the 3-D modelling iterations and on structure top and isopach maps. For each of the 292 wells reviewed, the formation top picks for 46 formations and members were examined, for a total of 6,051 picks, of which 3,505 were edits of previously recorded formation tops and 2,546 were new picks (Table 5-1).

Of the 292 wells within the study area, 146 wells had both samples and logs (50%), 12 wells only had logs available (4%), 106 wells only had samples available (36%) and 28 wells had only driller records or MNR form 7s (10%) (Fig. 5-2).

Table 1. Summary of the geological formations/members examined, the total number of picks for that formation within the study area, and the QA/QC method. Devonian formation tops and the Upper Silurian Bass Islands Formation were always verified from samples as a result of their generally unresponsive nature on gamma ray logs.

Age - Group	Formation/Member	# Formation Tops Reviewed	QA/QC Method
	Top of Bedrock	N/A	Samples/Geophysical/forms
Devonian	Dundee	198	Samples
	Lucas	263	Samples
	Columbus	17	Samples
	Columbus Equivalent	33	Samples
	Amherstburg	250	Samples
	Bois Blanc	256	Samples
	Springvale	16	Samples
	Oriskany	0	Samples
U. Silurian	Bass Islands	262	Samples
Salina	G-unit	258	Samples/Geophysical Logs
	F-unit	252	Samples/Geophysical Logs
	F-salt	80	Samples/Geophysical Logs
	E-unit	262	Samples/Geophysical Logs
	D unit/D Salt/D Equivalent	174	Samples/Geophysical Logs
	C-unit	262	Samples/Geophysical Logs
	B-unit (marker)	252	Samples/Geophysical Logs
	B-Salt	194	Samples/Geophysical Logs
	B-Anhydrite	223	Samples/Geophysical Logs
	A-2 Carbonate	223	Samples/Geophysical Logs
	A-2 Shale	142	Samples/Geophysical Logs
	A-2 Salt	121	Samples/Geophysical Logs
	A-2 Anhydrite	234	Samples/Geophysical Logs
	A-1 Carbonate	242	Samples/Geophysical Logs
	A-1 Evaporate	193	Samples/Geophysical Logs
L. Silurian – Lockport Group	Guelph	244	Samples/Geophysical Logs
	Goat Island	231	Samples/Geophysical Logs
	Gasport	214	Samples/Geophysical Logs
L. Silurian – Clinton Group	Rochester	148	Samples/Geophysical Logs
	Lions Head	60	Samples/Geophysical Logs
	Irondequoit	22	Samples/Geophysical Logs
	Rockway-Merriton (Reynales)	117	Samples/Geophysical Logs
	Fossil Hill	68	Samples/Geophysical Logs
L. Silurian – Medina Group	Cabot Head	167	Samples/Geophysical Logs
	Manitoulin	46	Samples/Geophysical Logs
	Whirlpool	0	Samples/Geophysical Logs
Ordovician	Queenston	43	Samples/Geophysical Logs
	Georgian Bay-Blue Mountain	35	Samples/Geophysical Logs
	Cobourg (including Collingwood)	36	Samples/Geophysical Logs
	Sherman Fall	34	Samples/Geophysical Logs
	Kirkfield	34	Samples/Geophysical Logs
	Coboconk	32	Samples/Geophysical Logs
	Gull River	32	Samples/Geophysical Logs
	Shadow Lake	31	Samples/Geophysical Logs
Cambrian	Cambrian	23	Samples/Geophysical Logs
Precambrian	Precambrian	27	Samples/Geophysical Logs

Technical Challenges with the Data

Several technical challenges arose during the project. Issues that were encountered include:

- typographic errors in drillers logs or forms, which would affect well locations or geological formation top values,
- obsolete geological formation nomenclature that was not previously translated or possibly misinterpreted,
- multiple drilling and completion reports or drillers logs for the same well with different formation picks.

Challenges with drill cuttings include:

- variability in sample quality, because of either poor sample processing or collection,
- broken vials,
- misplaced sample vials or vial sleeves within the trays, and
- sample interval gaps.

Challenges with geophysical well logs:

- old logs with faded gamma signatures or,
- only the condensed log scale being available, versus the expanded scale log.

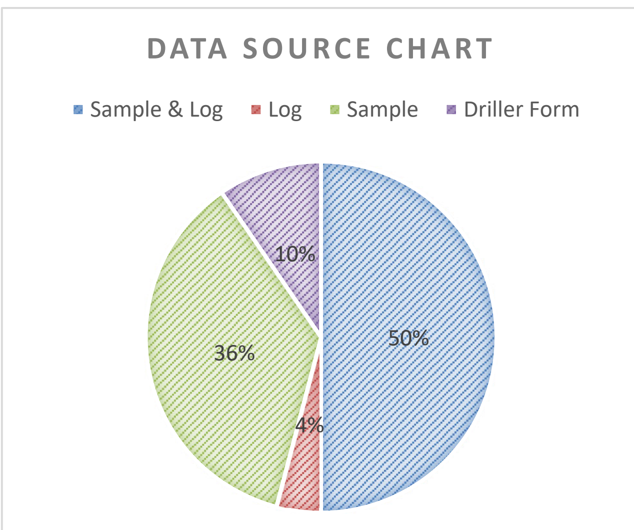

Figure 5-2. Data sources for formation top picks in the study area.

Geological Discussion and Observations

Issues encountered with inconsistent/incorrect formation top picks are described below. Formations with no issues are not discussed.

<u>Lucas-Dundee Subcrop and Columbus Sandstone</u>

The Dundee Formation is comprised of grey to tan-brown fossiliferous limestone with minor dolostone, containing algal cysts *Tasmanites* near the formation base, which are a useful and common lithological indicator of the formation contact. In contrast, the underlying Lucas Formation is a light tan-brown, finely crystalline poorly fossiliferous laminated dolostone and limestone, often with needle-like porosity from the dissolution of evaporite minerals (anhydrite and gypsum). A sandy limestone within the Lucas Formation, termed the Anderdon Member, can either cap the formation or be interbedded in the uppermost strata (Armstrong and Carter 2010). Misidentification of the two formations in subcrop was problematic in four wells in Stanley Township. The formation corrections and updates were consistent with the formation top picking standard and better aligned with the updated subcrop map (Carter et al. 2020).

Formation top picks for the Columbus Sandstone and the Columbus Equivalent also required editing in some wells. The Columbus Sandstone is a quartzose sandstone that ranges from a sandy limestone to limy sandstone to almost pure quartz sandstone, whereas the ‘Columbus Equivalent’ is a diagenetic carbonate facies, spatially associated with the Columbus Sand (Davis 2017). Within Huron and southern Bruce counties, 17 wells were determined to have Columbus sandstone, and 33 wells had Columbus Equivalent (Fig. 5-3).

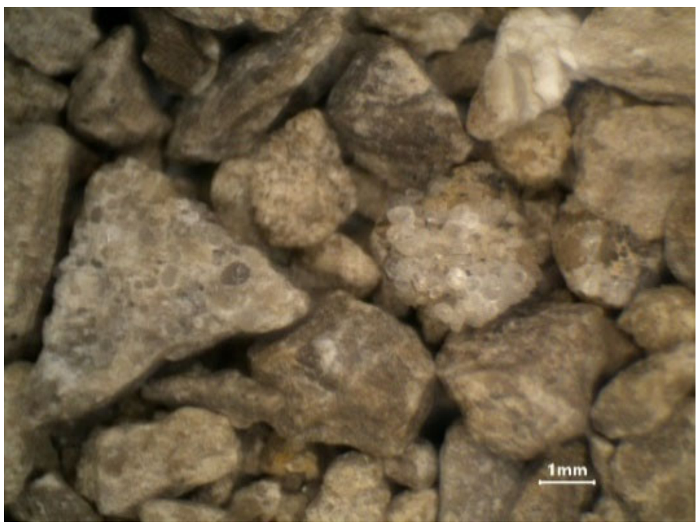

Figure 5-3. Photograph of drill cutting samples of Columbus Equivalent. Well Licence T007307, at depth of 54.9m (10x magnification). Photo by Candace Freckelton.
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Amherstburg Formation

The Amherstburg Formation is frequently not picked in OPDS for wells in Huron and Bruce counties. The contact with the overlying Lucas Formation is a reliable pick in samples and chosen where the light brown fine-grained evaporitic dolostones of the Lucas change downwards to a grey-brown to dark brown fossiliferous, bituminous, commonly cherty limestone/dolostone. In McKillop Township, the Amherstburg Formation appeared to be picked too high and has been edited. In Hullet Township thick intervals of anhydrite-rich dolostone were present in some wells near the base of the Amherstburg Formation. It is possible that the depth for these samples is mislabelled on the sample vials and are actually from the Lucas Formation.

The Amherstburg–Bois Blanc contact is gradational and is one of the most unreliable picks in the Paleozoic bedrock with an accuracy of ± 10 metres. The base of the Amherstburg Formation is variably cherty with dark grey to black chert which is very difficult to differentiate from the cherty limestone of the underlying Bois Blanc. The top of the Bois Blanc Formation is arbitrarily picked when samples contain ~60% white chert. At the base of the Bois Blanc, minor thin lenses of Springvale sandstone occur in Hullet Township but are not noted elsewhere.

Salina Group

In Huron and Bruce counties the formation top picks for the Salina Group formations are generally accurate and consistent, however issues of mis-identification were observed for the E Unit, D Salt/D Unit, B Unit/Equivalent, and A-2 Shale.

Where the F Salt is absent it is instead represented by a massive bed of dolostone which is often erroneously picked as “E Carbonate” by industry geologists and drillers. The correct E Unit top is picked at a distinctive grey to brown shaly dolomite/dolomitic shale marker bed with a slightly elevated gamma-ray response.

The C Unit is a widespread grey dolomitic shale with nodular anhydrite and typically a reliable pick in samples and logs, but exceptions were noted. In geophysical logs, a gamma ray peak may be present above the top of the C Unit shale and create ambiguity for the top pick, with a variability of as much as 10 metres (see Fig. 5-4). In most wells the formation top pick for the C Unit would be a more obvious decision, like that observed in the geophysical log for well T004105 (Fig. 5-4C), where the overlying gamma ray peak is more subdued.

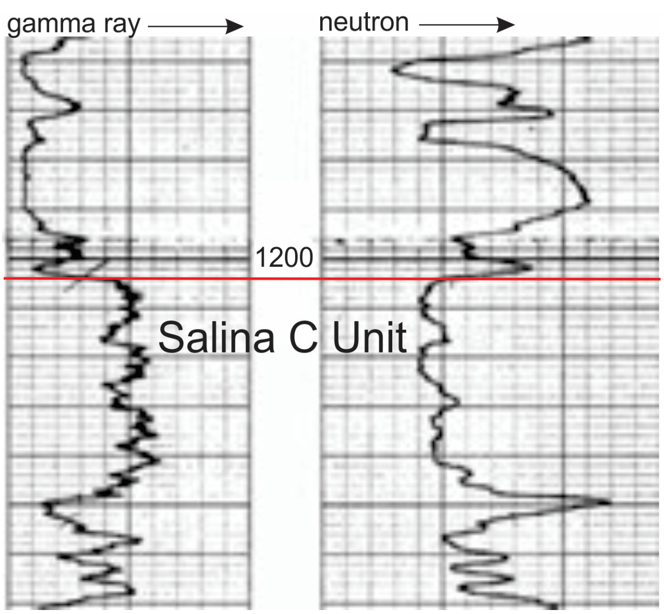


Figure 5-4. Geophysical log showing corrected formation top pick at 1204 feet (367 m) for the Salina C Unit, well T004105, located in Stephen Township, Huron County.

The B Unit comprises the informal ‘B Marker’, marking the top of the B Unit, and the underlying B Salt and B Anhydrite. Where the B Salt has been removed by dissolution the B Equivalent occurs. In some wells in West Wananosh Township the B Equivalent was mis-picked as the B Marker in wells where the B-Salt was present.

The A-2 Shale is a very thin shale marker bed near the base of the A-2 Carbonate (Fig.5-5). In Huron and Bruce counties the A-2 Shale was often picked too high at an argillaceous carbonate interbed within the A-2 unit.

Lastly, an interesting observation was made in well T003684 (Huron Township), where a 3m thick salt bed was observed in the A-1 Evaporite unit, instead of the anhydrite that occurs in the rest of the area.

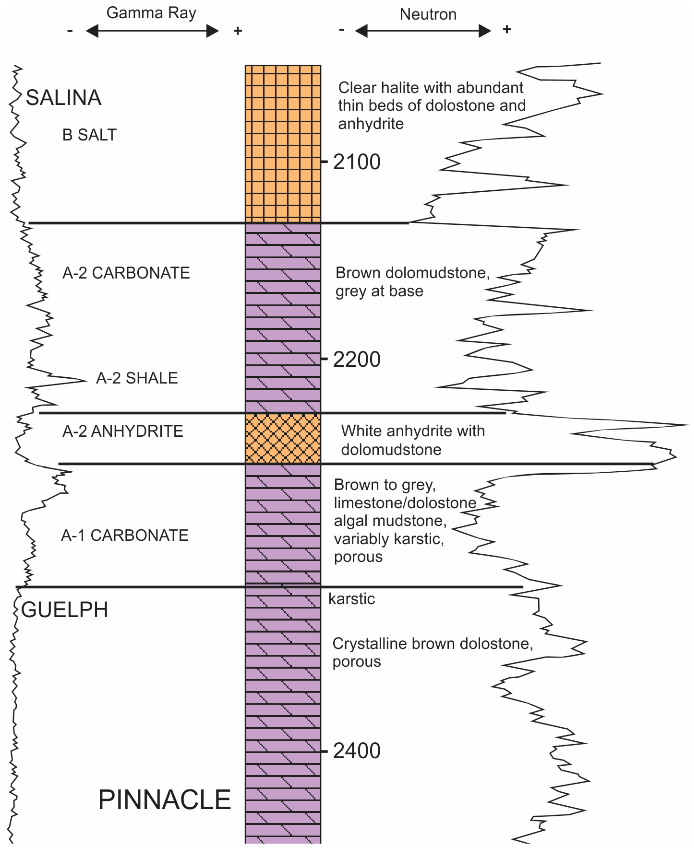


Figure 5-5. Gamma ray-neutron log signatures of the Guelph Formation and lower Salina Group within a Lockport Group pinnacle, modified from Armstrong and Carter (2010).

Lockport Group

The Lockport Group is comprised of the Guelph Formation, Eramosa Formation, Goat Island Formation, and the Gasport Formation, in descending order, with a distinctive series of lithofacies belts comprising, from west to east; a regional paleokarst/paleosol breccia, a pinnacle and interpinnacle karst belt, and a carbonate platform (see Appendix 4, Fig.4-1). The Eramosa Formation was not identified in any of the available wells in the study area. There are considerable differences in carbonate lithologies, formation thicknesses, sedimentary structures, and stratigraphic relationships between the three belts which is reflected in different criteria for picking formation tops as described below.

The interpinnacle Guelph is composed of porous, sucrosic, dark brown dolostone (Figure 5-6A). On geophysical logs the Guelph has a very low gamma signature with a characteristic narrow gamma ray peak in the middle of the formation. The top of the Guelph is picked at the slight increase of the gamma response at the contact with the overlying A-0 Carbonate. The A-0 Carbonate is a laminated, dark brown to black bituminous dolomudstone, typically only a few meters thick and only confidently distinguished from the Guelph Formation when geophysical logs were available. In areas with no logs the top of the Guelph Formation is picked in samples at the top of the first carbonate bed beneath the A-1 Evaporite.

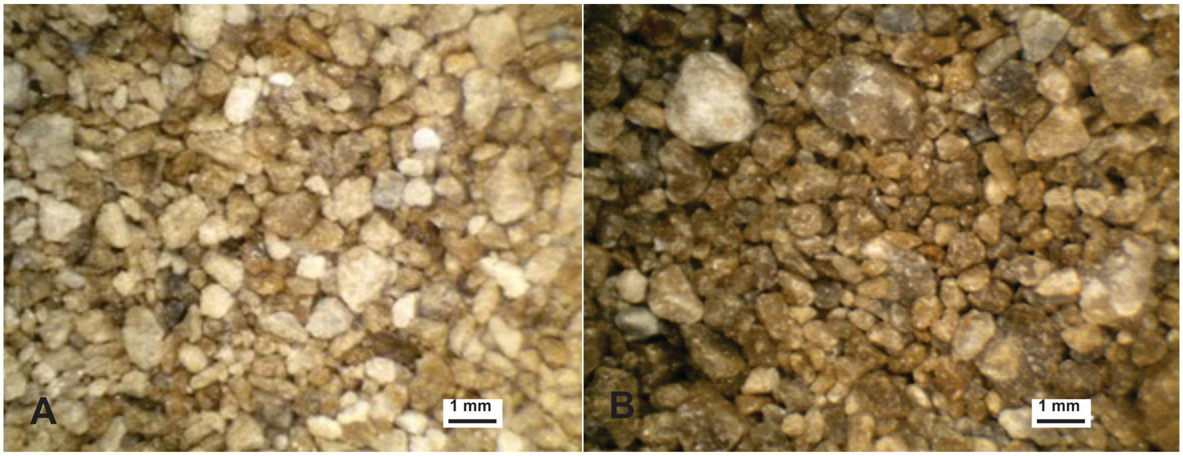


Figure 5-6. Photographs of Guelph Formation drill cuttings samples in Huron County. (A) Guelph Formation from an interpinnacle well located in Hullett Township (F011989), at depth of 1765ft (10x magnification). (B) Guelph Formation from a pinnacle reef in Stanley Township (T006807) at observed depth of 505m (1657ft) (10× magnification). Photo by Candace Freckelton.

Guelph Formation top pick criteria within pinnacles differ from the interpinnacle Guelph. The A-0 Carbonate is not present over the tops of pinnacles, and the Guelph Formation is a crystalline brown to grey-white porous dolostone (Figure 5-6B). Significant formation top corrections were made for the top of the Guelph Formation in pinnacles. Historically in Ontario, the entire thickness of pinnacles has been identified as Guelph Formation. The uppermost 10 to 30 metres of pinnacles is now recognized to be comprised of porous, karstic A-1 Carbonate, and the lower portions are comprised of the Guelph, Goat Island and Gasport formations (Brintnell 2012; Brunton et al. 2012; Brunton and Brintnell 2020).

Within the study area 244 wells intersected the Guelph Formation, with a maximum thickness of 108.2 m within pinnacles and a minimum of 3.1m in the interpinnacle karst, with 56 wells where Guelph >40m. In wells that intersected pinnacles, the Guelph top was repicked up to 30 meters lower than the recorded top Guelph, where there was a lithology change from brown-grey laminated dolomudstone (A-1 Carbonate) to a more crystalline brown porous dolostone (Guelph). In the geophysical logs this formation top is picked at a decrease in the gamma ray intensity (Figure 5-5).

The Goat Island Formation is a dark grey, finely crystalline dolostone (Fig. 5-7). In geophysical logs the gamma signature is slightly higher than the overlying Guelph Formation and underlying Gasport. In interpinnacle wells, the formation top is picked at the first sharp gamma peak at the base of the Guelph Formation. Errors were noted when the minor gamma log peak that occurred above the Goat Island was picked as the formation top. Within pinnacles, the Goat Island Formation top is a much more challenging pick. In geophysical logs, the pick would be made where there was a slight increase in gamma ray intensity, with a corresponding neutron shift. (See Fig. 5-8)

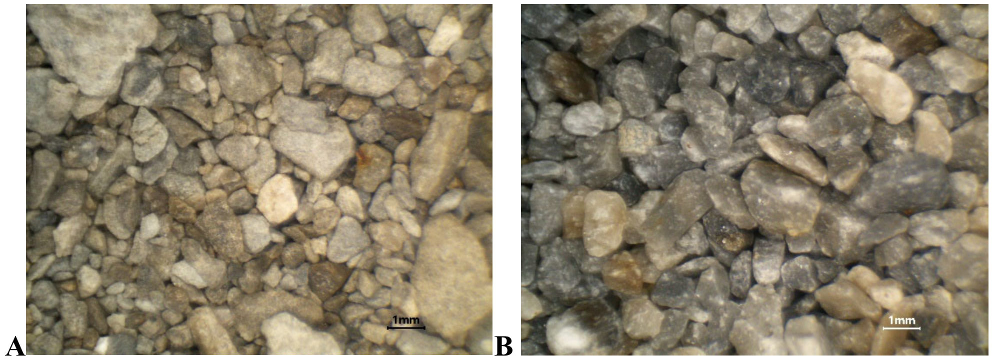


Figure 5-7. Photographs of Goat Island Formation drill cuttings. (A) Goat Island Formation from an interpinnacle well, in Hullett Township (Well F011989), at a depth of 544.1 m (1785ft) (10x magnification). (B) Goat Island Formation from a pinnacle well in Stanley Township (Well T006307), at a depth of 556 m (1824ft) (10× magnification). Photo by Candace Freckelton.

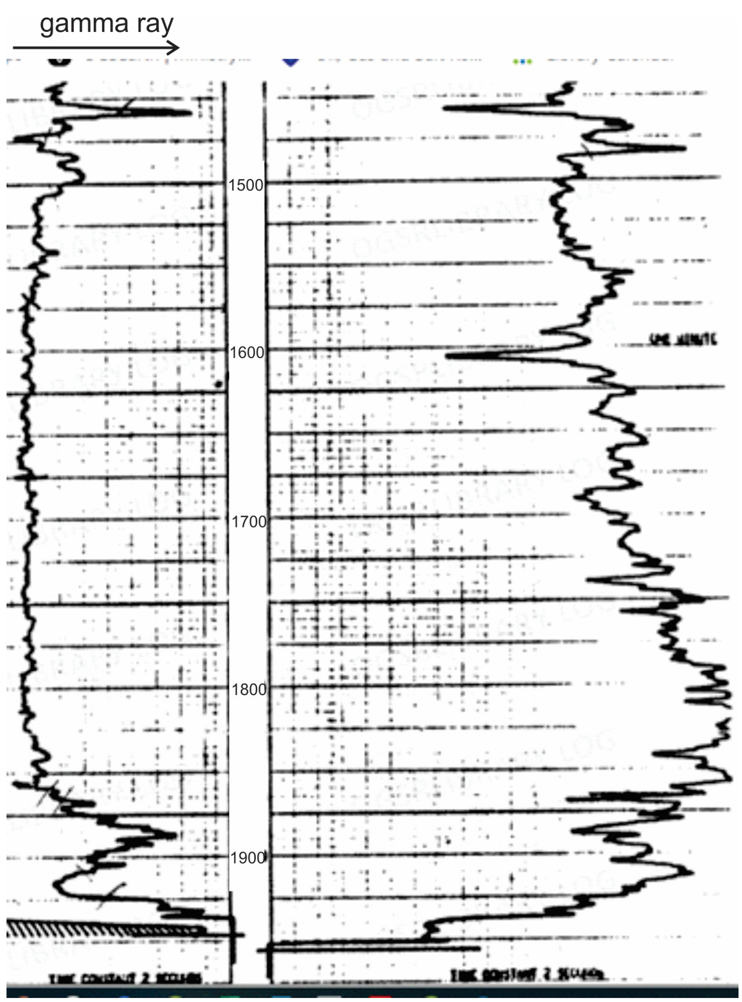


Figure 5-8. Gamma ray (left) and neutron (right) log for a pinnacle well F011850, in Huron County, Hay Township, illustrating the challenges of determining the Goat Island and Gasport formation top picks from geophysical logs. Goat Island is picked at 1758 feet (535.8 m) and Gasport at 1790 feet (545.6 m).

The Gasport Formation is a crinoidal grainstone and crystalline dolostone with a diagnostic white to dark blue grey colour (Fig. 5-9). In geophysical logs, the Gasport Formation has a low gamma response relative to the slightly elevated gamma ray response of the overlying Goat Island Formation.

Rochester and Lions Head Formations

North of London and Hamilton, the Rochester Formation has a lateral transition into the carbonates of the Lions Head Formation. In this area, the Rochester Formation is composed of a dark grey calcareous shale (Fig. 5-10) varying in thickness from 0.5m to 6.7m, with an average of 3.4m. In contrast, the Lions Head Formation is typically composed of a light-grey to grey brown, fine crystalline, sparsely fossiliferous dolostone, with locally abundant chert nodules (Armstrong and Carter 2010; Brunton and Brintnell 2020) (see Fig. 5-11). Within the transition zone it is difficult to consistently distinguish these formations in drill cuttings.

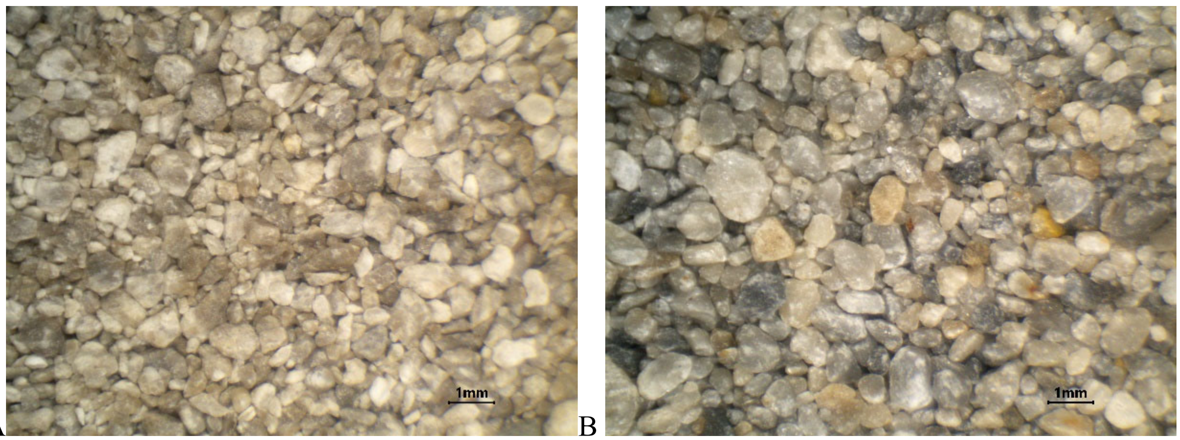
A


Figure 5-9. (A) Photograph of light tan brown crystalline dolostone drill cuttings from the upper Gasport Formation in an interpinnacle well in Hullett Township (F011989), at a depth of 554.7 m (1820 ft) (10x magnification). (B) Photograph of light tan brown to grey to bluish-white crystalline dolostone drill cuttings from the upper Gasport Formation in a Lockport pinnacle in Stanley Township (T006307), at a depth of 568 m (1864ft) (10x magnification). Photo by Candace Freckelton.

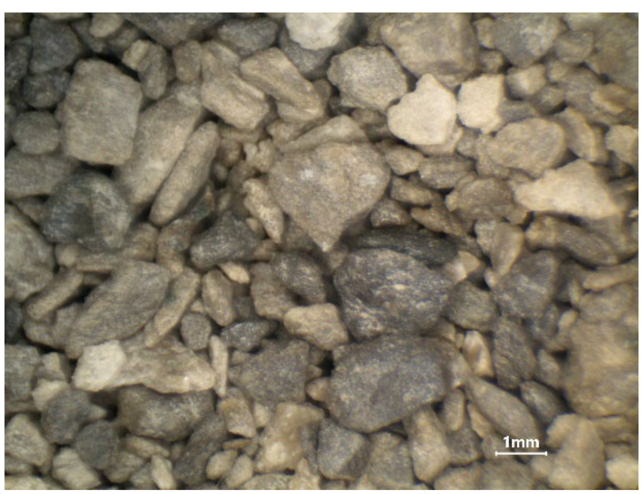


Figure 5-10. Photograph of grey calcareous shale of Rochester Formation in drill cuttings from Stanley Township (T007307), at a depth of 592 m (1942 ft) (10× magnification). Photo by Candace Freckelton.

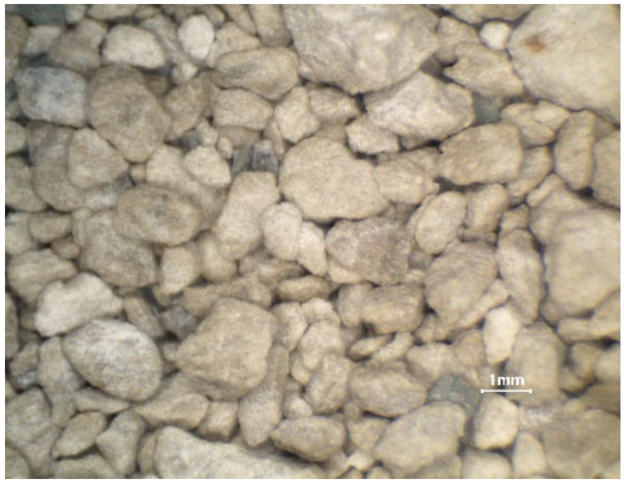


Figure 5-11. Photograph of fine-grained dolostone of Lions Head Formation in drill cuttings from Greenock Township (T002730), at a depth of 424.3 m (1392 ft) (10x magnification). Photo by Candace Freckelton.

In geophysical logs, the Lions Head Formation gamma signature is more attenuated compared to the elevated gamma response of the Rochester Formation shale. In the townships of West Wawanosh, Morris and Grey (Huron County), the geophysical log response of the Lions Head Formation was often misinterpreted as the Rochester Formation shale, as confirmed by sample examination.

Irondequoit Formation

The Irondequoit Formation is too thin to be reliably identified in drill cuttings or logs in this area.

Rockway/Merritton (Reynales) -Fossil Hill Boundary

Within the OPDS the Rockway and Merriton formations are grouped and called the Reynales/Fossil Hill which is known to be incorrect based on work completed by Brunton et al. (2012) after the database was coded. There are challenges in distinguishing the Rockway/Merriton (Reynales) and Fossil Hill formations within their transitional boundary south of Goderich. Instances where the Rockway/Merriton formations were mis-identified as the Fossil Hill Formation occurred. Lithologically the Rockway/Merritton (Reynales) formations consist of light to dark grey-brown, finely crystalline dolostone, compared to the Fossil Hill Formation which consists of light brown to tan, fine to coarse crystalline fossiliferous dolostone, which can contain minor glauconite (See Fig. 5-12) (Brintnell et al 2009). Chert nodules are occasionally observed in the upper part of the formation and increase westward into Michigan Basin (Sanford 1969).

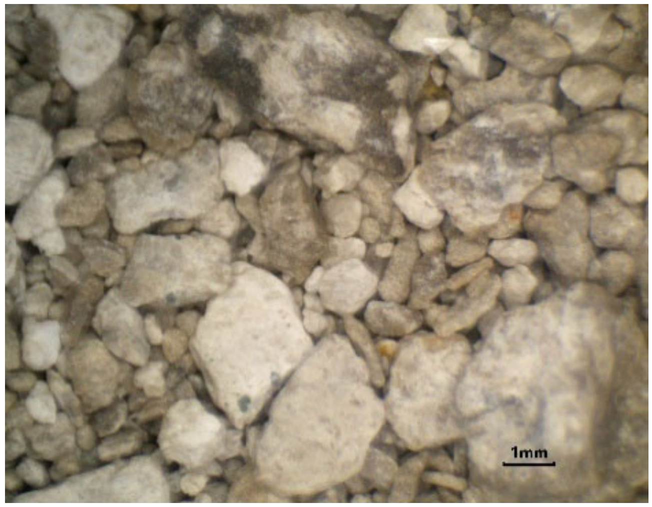


Figure 5-12. Photograph of Fossil Hill Formation drill cuttings from Greenock Township (T002730), at a depth of 426.1 m (1398 ft) (10x magnification). Fine grains of glauconite are present. Photo by Candace Freckelton.

In Stephen and Stanley townships (Huron County), the Rockway, Merritton (Reynales) and Fossil Hill formations cannot be distinguished, as in well T005130, in Stanley Township (Fig. 5-13). Further investigation is needed.

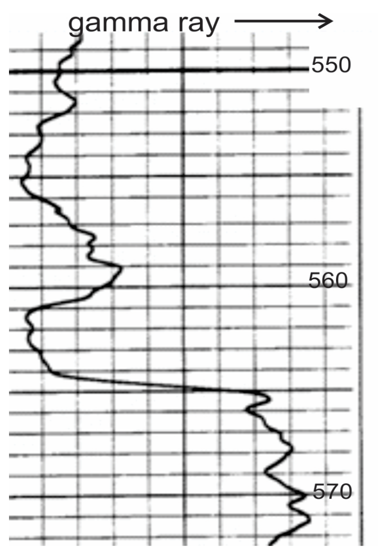


Figure 5-13. Geophysical log for well T005130 (Stanley Township), showing pick for top of Rockway/Merritton at 560.6m and Fossil Hill at 562.5 based on the gamma ray inflection points.

Manitoulin Formation

The Manitoulin Formation consists of grey-brown, fine to medium crystalline dolostone, argillaceous dolostone and minor grey-green shale. It is moderately fossiliferous and commonly contains chert nodules or lenses or silicified fossils (Johnson et al. 1992; Armstrong and Carter 2010). In the study area the Manitoulin Formation sharply and unconformably overlies the Upper Ordovician Queenston Formation and thickens westward towards the Michigan basin. The observed thickness ranged between 4.9 to 22.5m with an average of 11.4m. The gradational contact with the overlying Cabot Head shale formation had created inconsistencies in previous Manitoulin Formation top picks, which resulted in the top being picked too high (Fig.5-14). In this study, consistent formation top picks were made at the lowermost significant Cabot Head shale bed using both geophysical logs and drill cutting according to the standard established by Armstrong and Carter (2010).

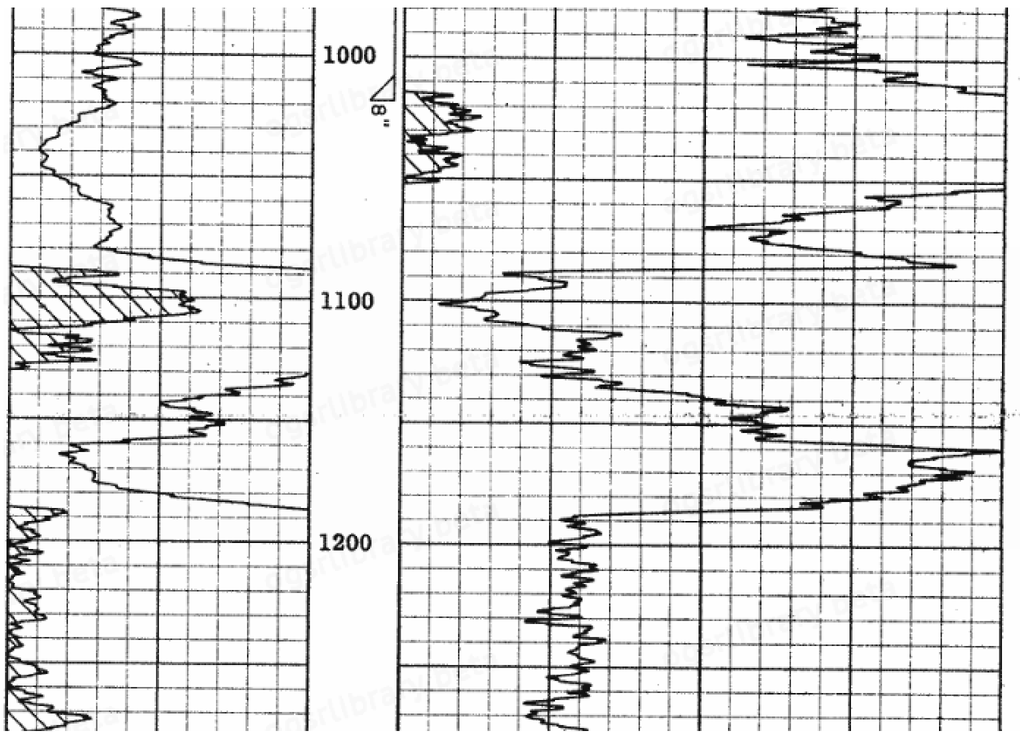


Figure 5-14. Geophysical log displaying gamma and neutron logs for well T001892 in Saugeen Township. Original pick was made at 338.33m (1110ft) but the corrected Manitoulin Formation top is at 353m (1157ft).

Ordovician Formations

A distinctive limestone bed occurs at the base of the Queenston Formation, immediately above the top of the Georgian Bay Formation. There may be several limestone beds in this interval, making it difficult to pick reliably in cuttings without the aid of logs. In such cases the Georgian Bay- Blue Mountain Formation top was frequently picked too high, by 20 to 30 metres. Issues also occurred with misidentification of the black shales of the Rouge River Member of the Blue Mountain Formation as the organic-rich shaly limestone of the Collingwood Member, Cobourg/Lindsay Formation (see Appendix 6).

Shadow Lake - Cambrian Contact

A total of 31 wells in this study intersect the Shadow Lake Formation, which underlies the entire area and unconformably overly the Precambrian basement or, when present, on Cambrian strata. Cambrian strata thin and pinch out in the eastern part of the two counties (Sanford and Quillian 1959; Trevail 1990). Reliable identification of the contact between the Shadow Lake and Cambrian is problematic near the erosional edge of the Cambrian when drill cuttings are the only available data source.

In this area the Shadow Lake Formation is characterized by poorly sorted, red and green sandy shales, argillaceous and arkosic sandstones, and minor sandy argillaceous dolostones and rare basal arkosic conglomerate. The presence of coarse frosted sand grains are usually diagnostic of the Shadow Lake Formation, but where the underlying Cambrian is also a quartzose sand it can be difficult to make a reliable pick for the formation top. When geophysical logs are available this contact pick is more reliably determined at a decrease in the gamma ray response from the Shadow Lake shale/argillaceous sandstones to a clean quartzose sands, dolomitic sandstones or sandy dolostones of the Cambrian. No issues were encountered identifying the Precambrian.

Summary

A total of 292 wells were examined across Huron and southern Bruce counties, which encompassed 23 townships within an area of 7,900 km^2. Using standardized criteria for identification of southern Ontario formation tops in cuttings and logs (Armstrong and Carter 2010), discrepancies and inconsistencies in previous formation picks made by drillers for the 49 Paleozoic bedrock formations in the study area have been identified and updated. A total of 6,051 formation top picks were reviewed. Prior to this study, 3,505 formation tops were recorded in OPDS for this area, and after review 2,546 new formation top picks were documented. General QA/QC issues identified in this study are summarized below.

- Misidentification of the Lucas and Dundee formations in subcrop. Problematic wells have been edited and once corrected they better align with the most recent Paleozoic subcrop map (Somers et al. 2019). The Columbus Equivalent was occasionally misidentified as Columbus sandstone.
- The gradational contact between the Amherstburg and Bois Blanc formations was one of the most unreliable contact picks in the Paleozoic bedrock. Corrections were made as per Armstrong and Carter (2010), which resulted in a more consistent surface and thickness of the Bois Blanc Formation.
- The Salina Group formations were generally found to have reliable unit top picks, however issues of poor documentation and misidentification were observed for the F-Salt, E-Unit, D-Salt/Equivalent, B-Unit/Equivalent, and the A-2 Shale marker bed. In certain instances, the Salina C-shale unit top pick was too high caused by confusion with an overlying shaly dolostone interbed. Several corrections and edits were also made to better refine the Lockport's various carbonate lithofacies, which includes identification of the A-1 Carbonate in the crest of pinnacle reefs. Prior to this project industry practice has been to identify the entire thickness of a pinnacle as the Guelph Formation.
- Minor difficulties were encountered with determining the presence of the Cambrian near its erosional boundaries.
- The lateral transition from the Rochester Formation to the Lions Head Formation is poorly documented.
- The lateral and stratigraphic relationships of the Rockway/Merriton (Reynales) and Fossil Hill formations is poorly documented.
- The Georgian Bay- Blue Mountain Formation top was frequently picked too high, because of misidentification of the limestone marker bed at the base of the Queenston Formation, creating surface variances of 20 to 30 metres.
- The black shales of the Rouge River Member of the Blue Mountain Formation are usually erroneously identified as the Collingwood Member of the Cobourg/Lindsay Formation by industry geologists and drillers.

Appendix 6. QA/QC Geological Review: Queenston, Georgian Bay-Blue Mountain, Rouge River Member (Blue Mountain Formation), Collingwood Member (Cobourg Formation) and Cobourg Formations

Prepared by Candace Freckelton and Hanna Rzyszczak

Executive Summary

The primary objective of this study was to review, correct and add formation top picks for the Collingwood Member of the Cobourg Formation and the lower Rouge River Member of the Blue Mountain Formation. Historically, the lower non-calcareous Rouge River Member of the Blue Mountain Formation has often been misidentified as the Collingwood Formation (Churcher et al., 1991). A Quality Assurance and Quality Control (QA/QC) review of selected Paleozoic bedrock formation top picks for these formations has been completed, for selected wells, including picks for the Cobourg Formation, the Georgian Bay Formation and the Queenston Formation in the same wells.

Formation tops were reviewed using petroleum well file data (driller reports, Ministry Form 7 reports), drill cuttings, and geophysical logs (gamma-ray, neutron and density logs), for boreholes drilled under the authority of the Oil, Gas and Salt Resources Act (OGSRA) and stored at the Oil, Gas and Salt Resources Library (OGSRL) in London, Ontario. The formation top picking procedure and standards for identification of southern Ontario formation tops in cuttings and logs was based on Armstrong and Carter (2010).

A total of 317 wells were examined within 29 counties across southern Ontario. A total of 1,748 formation top picks were reviewed during the project, with 706 of those picks being newly added to the database.

Introduction and Purpose

One of the significant data issues identified in the first 3-D geological model were inconsistent and incorrect formation top picks for the black shales of the Collingwood Member of the Cobourg/Lindsay Formation (Carter et al. 2019). The basal non-calcareous Rouge River Member of the overlying Blue Mountain Formation was often misidentified as the Collingwood Member (Churcher et al. 1991) and the Rouge River Member had not been picked in the OPDS data tables. Recent studies (Sweeney 2014; Béland-Otis 2015a, b) indicate the black shales of the Rouge River Member have a much wider distribution than mapped by Russell and Telford (1983). The Collingwood and Rouge River are of significance as these organic-rich strata have potential to host unconventional resources of oil and natural gas.

This study focuses on QA/QC of formation top picks from petroleum wells that intersect upper Ordovician strata across southern Ontario, specifically the Rouge River Member of the Blue Mountain Formation, and the Cobourg Formation and Collingwood Member of the Cobourg Formation. Formation top picks have also been reviewed for the Queenston Formation, Georgian Bay Formation, and the Cobourg Formation in the same wells to establish reliable thicknesses for the Collingwood and Rouge River members.

The study area location (Fig.6-1) encompasses 29 counties across southern Ontario, including Manitoulin Island. The edited formation tops in this study will be added to OPDS and contribute to improving the 3-D geological model.

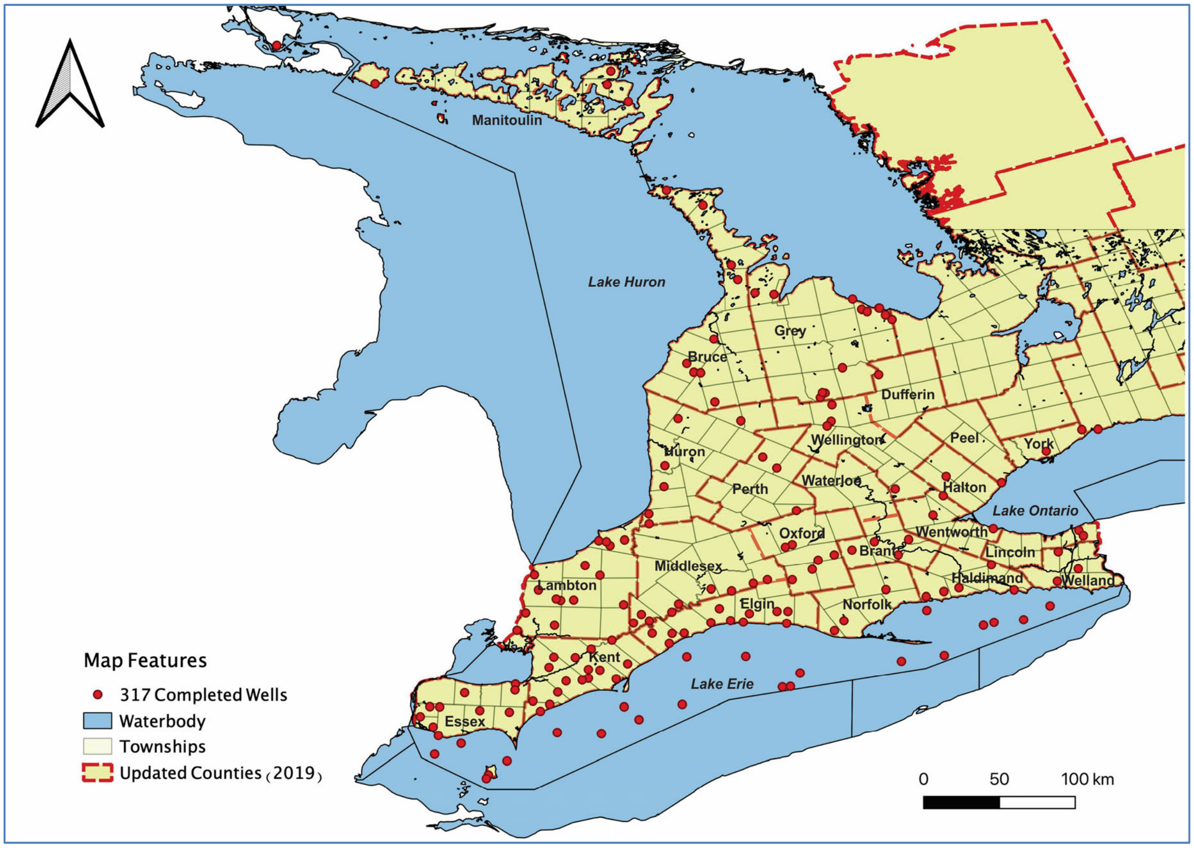


Figure 6-1. Location of petroleum wells for which formation tops were reviewed.

Geological Setting

The Upper Ordovician shales and carbonates examined in this study underlie most of southern Ontario. They form sedimentary rock layers from several metres to tens of metres in thickness dipping shallowly into the Michigan and Appalachian basins and form northwest-southeast trending subcrop belts (Johnson et al. 1992, Armstrong and Carter 2010).

The Upper Ordovician strata of southern Ontario and its resource potential has been discussed in several reports (Russell and Telford 1983; Churcher et al. 1991; Melchin et al. 1994; Hamblin 1999; 2006, 2018; Obermajer et al. 1999; Brett et al. 2006; Béland-Otis 2009, 2012a, 2012b, 2015a, 2015b; and Sweeney 2014). The Paleozoic formations examined in this study comprise, in ascending order, the Cobourg Formation and its Collingwood Member, the Rouge River Member of the Blue Mountain Formation, the Georgian Bay Formation and the Queenston Formation.

QAQC Study Methods

For this study, formation tops for 317 wells that intersect the Upper Ordovician shales and carbonates were reviewed. Information obtained from OPDS for the purpose of geological QA/QC included Well Licence number, Well name, County, Latitude, Longitude, Total Depth Date, Ground Elevation, Total vertical Depth (TVD), status, sample tray number, core identification, and logging record. The geographic information system *QGIS* was used to geographically view and query the data during the study. Data used to review and examine geological formation tops include petroleum well files (driller reports, Ministry Form 7 reports), drill cuttings, and geophysical logs (gamma-ray, neutron and density logs), stored at the Oil, Gas and Salt Resources Library (OGSRL) in London, Ontario. The OGSRL manages and provides online access to OPDS through its website at www.ogsrlibrary.com, including an extensive collection of scanned and digitized geophysical well logs.

Gamma ray logs were the primary data source used for determining geological formation unit tops. When uncertainty arose, drill cuttings and/or core samples were utilized. Geological formation top picking procedures and standards were based on Armstrong and Carter (2010) (see Fig.6-2). Published geological reports for previous studies of the Collingwood and Rouge River members were reviewed to ensure quality assurance alignment with recent scientific studies.

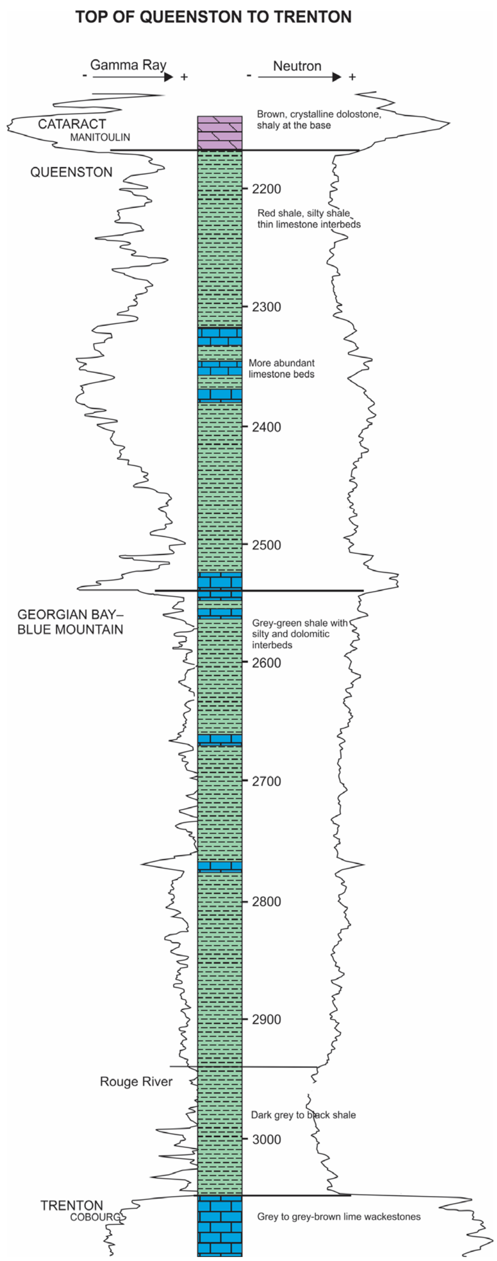


Figure 6-2. Geophysical reference standards used for formation top identification (Armstrong and Carter 2010).

Rouge River QA/QC

Fourteen wells that had been previously reviewed by Sweeney (2014) and Béland Otis (2015) were used to establish, confirm, and calibrate the Rouge River Member top picks (Table 6-1).

Table 6-1. Wells utilized as reference wells for establishing and calibrating the Rouge River Member formation top picking criteria. All wells were previously examined by Sweeney (2014) and Béland-Otis (2015a, b).

Well Licence	Well Name	County	Core ID	Core Interval	Geophysics	Sample Tray #
T001536	I.O.E. Bluewater et al	Middlesex	N/A	N/A	GR, neutron	5218-9
T002887A	CPOG Welland No.2A	Welland, Lake Erie	648	N/A	GR, neutron	7559-61
T004105	Firebird No.2	Huron	N/A	N/A	GR, neutron	3856-57
T004767	Pacific	Huron	N/A	N/A	GR, neutron	3985-86
T004985	Petromark et al	Perth	N/A	N/A	GR, neutron	4068-69
T005473	Anschutz No.4	Norfolk, Lake Erie	N/A	N/A	GR, neutron	6630-31
T006102	OGS 83-2 Clarkson	Peel, Toronto	N/A	N/A	GR, neutron	9142-44
H000015	OGS Deep Hole #1	Dufferin	1098	243.84- 730.0	GR, Density	9301-6
T006045	OGS 82-2	Kent	860	20.40 – 1180.8m	GR, Density *Geophysics not used for core; T005522 used	9329-40?
T005522	Dow Harwich	Kent	N/A	N/A	GR	7175-76
T006056	OGS 82-4	Bruce	862/ 1103	19.5-446.5m (7.60-602.8m?)	GR, Density	9352-53
T006078	OGS 82-3	Elgin (Port Stanley)	861	79.9 – 1168.5m	GR, Density	9341-51
T006120	OGS 83-1	Halton	1104	332.77 – 943.2	Gr, induction	9984-88
T012100	OGS – SG11-02	Wellington	outside	300 – 500m	GR, Density	11762-63

Quality Control Methodology

Formation tops were reviewed from a selection of wells containing high-quality data to obtain a regional distribution of edited data of sufficient density to enable 3-D modelling. A query of OPDS identified 1199 wells with the following available data: (1) drill cuttings, (2) geophysical data (i.e. any type of log), and (3) a formation top pick for Rouge River Member (Blue Mountain Formation), Collingwood Member (Cobourg Formation), Trenton Group or Cobourg Formation. The most recently drilled wells were assigned the highest priority for review with the objective of obtaining a data density of one well in every grid square of one-tenth of an arc degree. From this list, 242 wells were determined to be a 'high priority' for review. Poor quality data for some of these wells required the examination of nearby wells which expanded the number of wells reviewed to a total of 317 wells.

Further quality assurance edits were made based on anomalies identified in the 3-D modelling process and on structure top and isopach maps. Possible reasons for anomalies at this stage could be formations that were missed in the initial priority ranking, formation picks that need to be re-examined or data entry errors.

QA/QC Results

For each well reviewed, formation tops recorded for a total of five formations and members were examined: Cobourg Formation and its upper Collingwood Member, the Rouge River Member (Blue Mountain Formation), Georgian Bay Formation, and Queenston Formation. Prior to this study there were a combined total of 1,042 formation top picks in OPDS for these stratigraphic units in the selected wells.

After QA/QC review, 1,748 formation top picks are now available in the database, which provides 706 new formation top picks (see Table 6-2).

Table 6-2. Summary of formation top edits by formation tops reviewed and data source used.

Age	Formation	Formation Tops Examined	QA/QC Method
Ordovician	Queenston Formation	283	Geophysical Logs
	Georgian Bay Formation	306	Geophysical Logs
	Rouge River Member (Blue Mountain)	295	Geophysical Logs
	Trenton Group	298	Geophysical Logs
	Collingwood Member (Cobourg Formation)	272	Geophysical Logs
	Cobourg Formation	294	Geophysical Logs
	TOTAL	1,748	

Technical Challenges with the Data

Technical challenges encountered with the data include the following:

- Online access to geophysical logs
- Geophysical logs only displayed in the condensed format (versus expanded log)
- Breaks or gaps in the geophysical log run
- Fading of older geophysical logs
- Access to both the gamma-ray and neutron log in the geophysical records
- Restricted access to physical core and drill cuttings as a result of COVID-19

QA/QC Results and Discussion

Queenston Formation

The Queenston Formation is characterized by red shales with subordinate green shale, siltstone, sandstone and limestone and underlies all of southwestern Ontario. The Queenston is unconformably overlain by Lower Silurian sandstones (Whirlpool Formation) or dolostones (Manitoulin Formation), and conformably overlies the Georgian Bay-Blue Mountain Formation shales and limestones (Armstrong and Carter 2010).

The total number of Queenston Formation picks reviewed in this study was 283. The Queenston Formation thickness was observed to range between 49 and 315m. The Queenston Formation is characterized by a consistently elevated gamma ray expression except where there are carbonate interbeds. It is readily distinguished in samples and core by its reddish colour versus the light-coloured sandstones of the overlying Whirpool Formation or the tan to grey dolostone of the Manitoulin (Armstrong and Carter 2010). In gamma ray logs, the contact between the overlying Lower Silurian strata and the Queenston Formation typically displays a sharp upward decrease in intensity. Existing formation top picks recorded in OPDS for the Queenston Formation were typically accurate with few discrepancies. Observed inconsistencies usually occurred in cases where the geophysical log displayed a minor gamma ray peak at the Queenston Formation upper contact (see Fig. 6-3). In these wells, existing formation top picks varied between the top of either the upper or lower gamma peak which created irregularities in the formation's elevation top. For wells having these log signatures, the revised pick was made at the top of the uppermost elevated gamma ray peak.

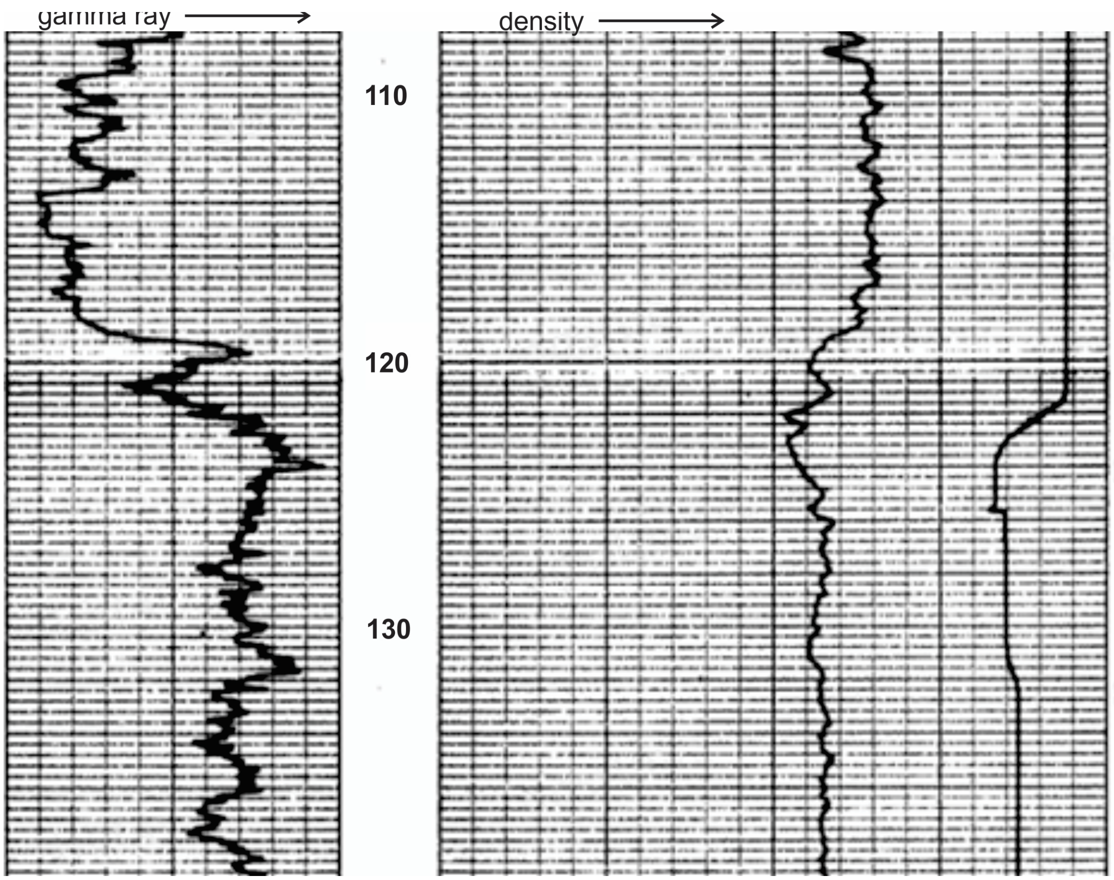


Figure 6-3. Well H000015, Dufferin County. DENL Geophysical Log. Queenston Formation double gamma peak. Previous OPDS formations picks were found to vary between the correct pick at the upper gamma peak (119.5m), and the lower gamma peak (123m), which creates a formation top difference of 4m.

Georgian Bay-Blue Mountain Formation

The Georgian Bay Formation is a greenish to bluish-grey shale interbedded with limestone, siltstone and sandstone. It is conformably overlain by the red shales of the Queenston Formation and conformably overlies the Blue Mountain Formation, which is a blue-grey to grey-brown shale with thin, minor interbeds of limestone and siltstone (Armstrong and Carter 2010). The Georgian Bay Formation and Blue Mountain Formation were mapped as one unit in this study, consistent with Armstrong and Carter (2010) due to the lack of an established standard for consistent identification of the Blue Mountain top in cuttings and logs. The lower Blue Mountain Formation (Rouge River Member) has a sharp lower basal contact with the regional limestones of the Cobourg Formation and/or shaly carbonates of the Collingwood Member of the Cobourg Formation. This contact is sometimes marked by a phosphatic horizon, suggesting a disconformable contact and possibly erosion of the Collingwood Member (where absent) (Russell and Telford 1983; Churcher et al. 1991; Johnson et al. 1992; Béland-Otis 2015a).

A total of 306 formation top picks were reviewed. The Georgian Bay-Blue Mountain Formation thickness ranged from 15.8 m to 283 m in this study. The Georgian Bay shales have a consistently elevated gamma ray intensity. The contact with the overlying Queenston Formation is a difficult and unreliable pick, as acknowledged by Armstrong and Carter (2010). The red colour of the Queenston is diagenetic and is an unreliable indicator (Hamblin 2018) but has been used as the primary formation top picking criteria by the petroleum industry in the absence of geophysical logs. Limestone beds of variable thickness occur in the interval corresponding to the downward colour change from red to grey-green shales and were utilized by Armstrong and Carter (2010) and Beards (1967) as a more reliable and consistent criteria. They assign the contact at the base of the lowermost discrete thick limestone bed, which is expressed as a reduced gamma ray signature relative to the elevated gamma signature of the underlying shales (see Fig. 6-2). In contrast, Hamblin (2018) assigns this interval of limestone beds to the Georgian Bay Formation. The presence of multiple limestone interbeds in this interval adds further difficulty in consistent picking of this contact. The standard established by Armstrong and Carter (2010) is adopted here as it can be picked with a higher level of consistency, but it is acknowledged that in future studies this must be revisited.

For the reasons noted above there is considerable variability in existing formation top picks recorded in OPDS, especially where no logs are available, with picks made both at the base and at widely varying intervals above the limestone marker bed (s). Difficulty also occurred when geophysical logs displayed an attenuated gamma ray signature, resulting in subdued limestone signatures that were not easily distinguishable (Fig. 6-4) or when multiple beds are present (Fig. 6-5). In these cases, verification with cuttings samples was attempted, but if still inconclusive a lower QA code was assigned.

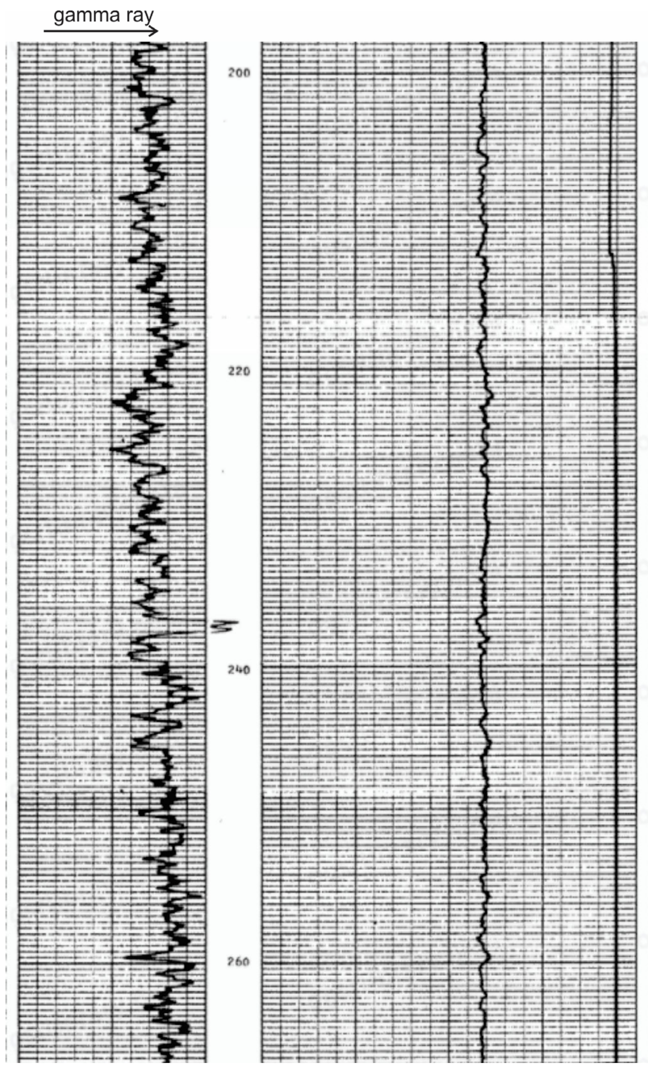


Figure 6-4. Well H000015, Dufferin County, DENL log. This well displays an attenuated gamma ray signature, which created difficulties in determining the top of the Georgian Bay-Blue Mountain Formation. In this well, the interpreted Georgian Bay-Blue Mountain Formation top is at 245m.

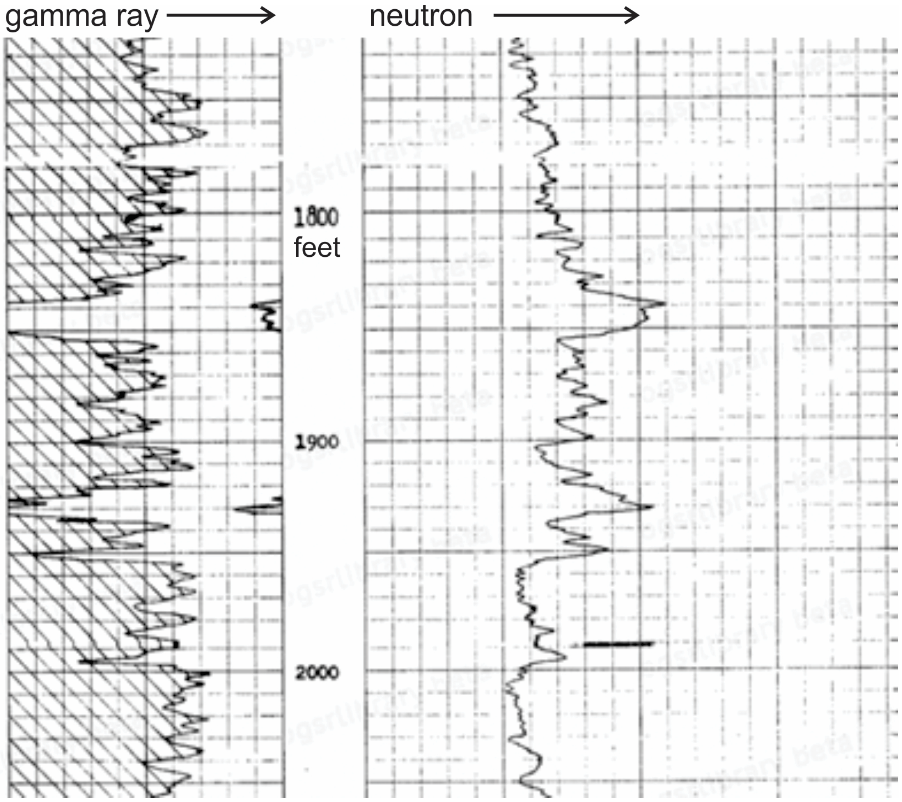


Figure 6-5. Well T005799, Oxford County, GRNL geophysical log. The gamma ray signature displays variability in thickness and frequency of the carbonate interbeds that exist at the Queenston-Georgian Bay contact. This would lead to variation in previous OPDS unit picks, with possible picks at 1937 feet (590.4 m), 1953 feet (595.3 m), or 1997 feet (608.6 m). Examination of drill cuttings samples is required in this case to make a reliable pick at 1953 feet (595.3 m).

Rouge River Member (Blue Mountain Formation)

The Rouge River Member is the basal member of the Blue Mountain Formation and consists of dark brown to black, non-calcareous shale and mudstone. The Rouge River contains a high proportion of clays, reflecting deposition into a deep shelf environment during the initial phase of the Taconic Orogeny. Analysis of organic matter types in the Rouge River Member indicate a mixture of marine and terrestrial sources (Béland-Otis 2015a). The allostratigraphic framework proposed by Sweeney (2014) for the Blue Mountain Formation, including the Rouge River Member, is not adopted here.

The contact between the Blue Mountain Formation and the Rouge River Member is gradational and occurs at a downward transition from grey to greenish-grey shales to a very dark grey/blueish/black non-calcareous shale, along with the disappearance of the limestone and siltstone interbeds (Béland-Otis 2015a). In drill cuttings, the Blue Mountain-Rouge River contact is identified at the first appearance of the bluish-grey bed, but this contact can be difficult to determine in samples so geophysical logs are useful in constraining the contact. The gamma-ray signature of the organic-rich Rouge River shales is slightly elevated compared to the overlying grey shales of the upper Blue Mountain Formation (Fig. 6-2). Occasionally, the resistivity log expression of the Rouge River Members is also elevated.

A sharp but subtle basal contact exists at the contact with the underlying Trenton Group (Cobourg Formation and Collingwood Member), which is sometimes marked by a phosphatic horizon (a phosphatic nodule bed of about 1 cm thick). This is suggestive of a disconformable relationship with the underlying units, possibly even an erosion of the Collingwood Member where it is absent (Russell and Telford 1983; Churcher et al. 1991; Johnson et al. 1992; Béland-Otis 2015a). The gamma-ray and neutron porosity log expressions are considerably elevated relative to the limestone and shaly limestone of the Cobourg Formation and its Collingwood Member.

The total number of Rouge River Member formation top picks in this study were 295. Thicknesses ranged between 2 and 55m. Hamblin (2006) and Béland-Otis (2009) reported thicknesses of 2 to 35 m, and Sweeney (2014) recorded thicknesses of 45-50 m along Lake Erie, thinning to less than 20m on the Bruce Peninsula (Fig. 6-6).

Discrepancies observed in previous Rouge River Member picks occurred when the upper Rouge River contact was picked at an upward gamma ray increase versus decrease. These tops were corrected to be consistent with the criteria established in this study. Other variations in Rouge River Member top picks occurred when a lower allomember of the Rouge River was picked as the top.

Challenges in determining the Rouge River Member occurred when its gamma ray signature was subdued compared to overlying Blue Mountain Formation shales (Fig. 6-7). In these instances, Sweeney's (2014) Rouge River Member isopach map (see Fig. 6-6) was used as a guide for expected regional thickness, in addition to the examination of drill cuttings from nearby wells.

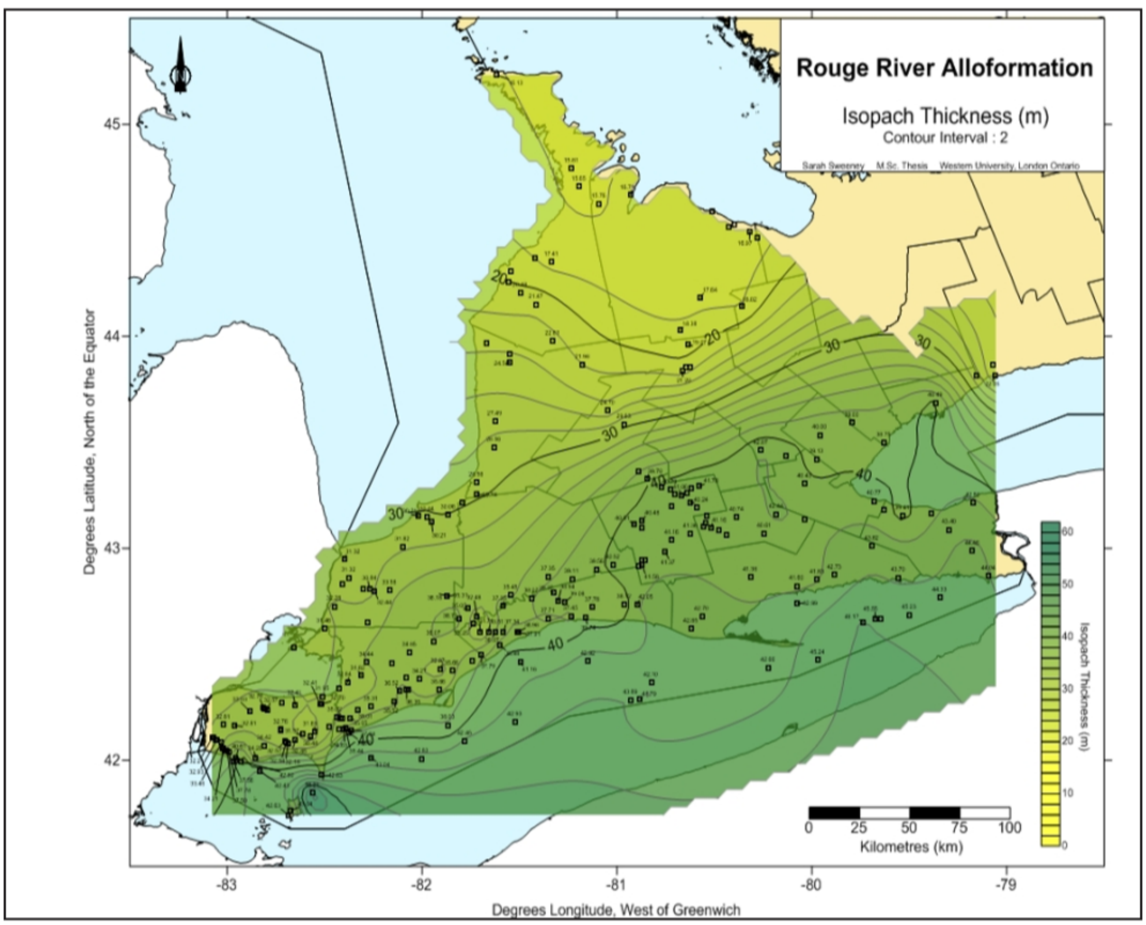


Figure 6-6. Rouge River Member isopach map (Sweeney 2014).

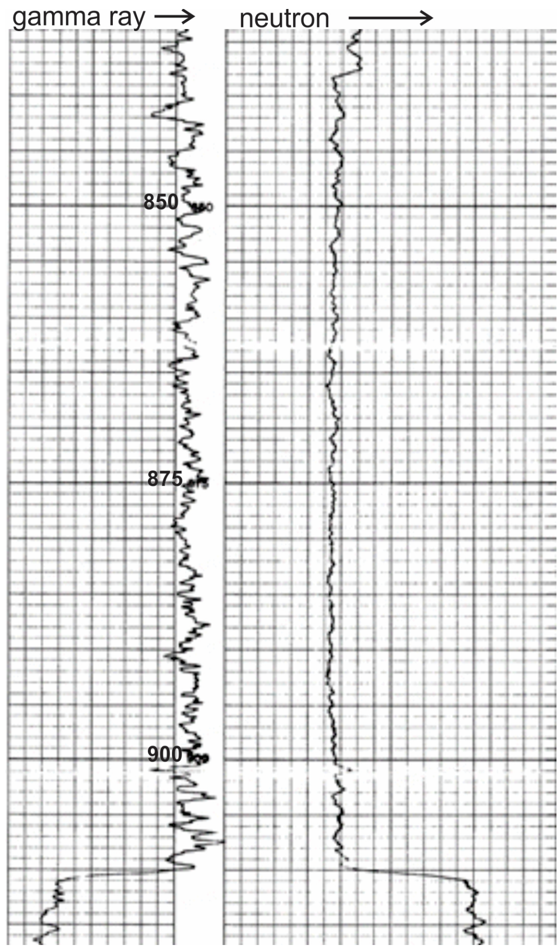


Figure 6-7. Well T005522, Kent County, GRNL log. The gamma ray signature is relatively flat compared to the overlying Blue Mountain Shale, making a reliable identification of the top of Rouge River problematic. The Rouge River top is picked at 873.8m but has been assigned a low QA code.

Regional Variations in Gamma Signature of Rouge River

In northern Bruce County and the Bruce Peninsula, thickness of the Rouge River Member ranges between 3.8m and 34.8m. It typically displays an elevated gamma ray response compared to the overlying shales (Fig. 6-8 A). In upper central southwestern Ontario (Wellington County), thickness ranges between 20.7 m and 54.3 m. In this area the Rouge River Member has more well-defined elevated gamma ray response compared to the upper Blue Mountain shales, however there are discrepancies with previous reports (Sweeney 2014; Béland Otis 2015). For example, in well T012100 the Rouge River top in this study is picked at 456.9 m, compared to 458.6 m (Sweeney 2014) and 463.3 m (Béland Otis 2015) (Fig. 6-8 B). A possible explanation for variance in formation top picks could be that drill core not properly calibrated for depth was used to determine formation top, versus geophysical logs. In Huron County, thicknesses range between 19.6 m and 32.6 m. Gamma ray signatures in this area were not always strongly elevated, compared to the upper Blue Mountain shales, but would display a more compacted and 'cleaner' gamma pattern (Fig. 6-8 C). Along the eastern Niagara Escarpment (Halton County), the Rouge River Member ranges in thickness between 24.5m and 39.4m and has a notably stronger gamma ray response compared to the upper grey shales (Fig.6-8 D).

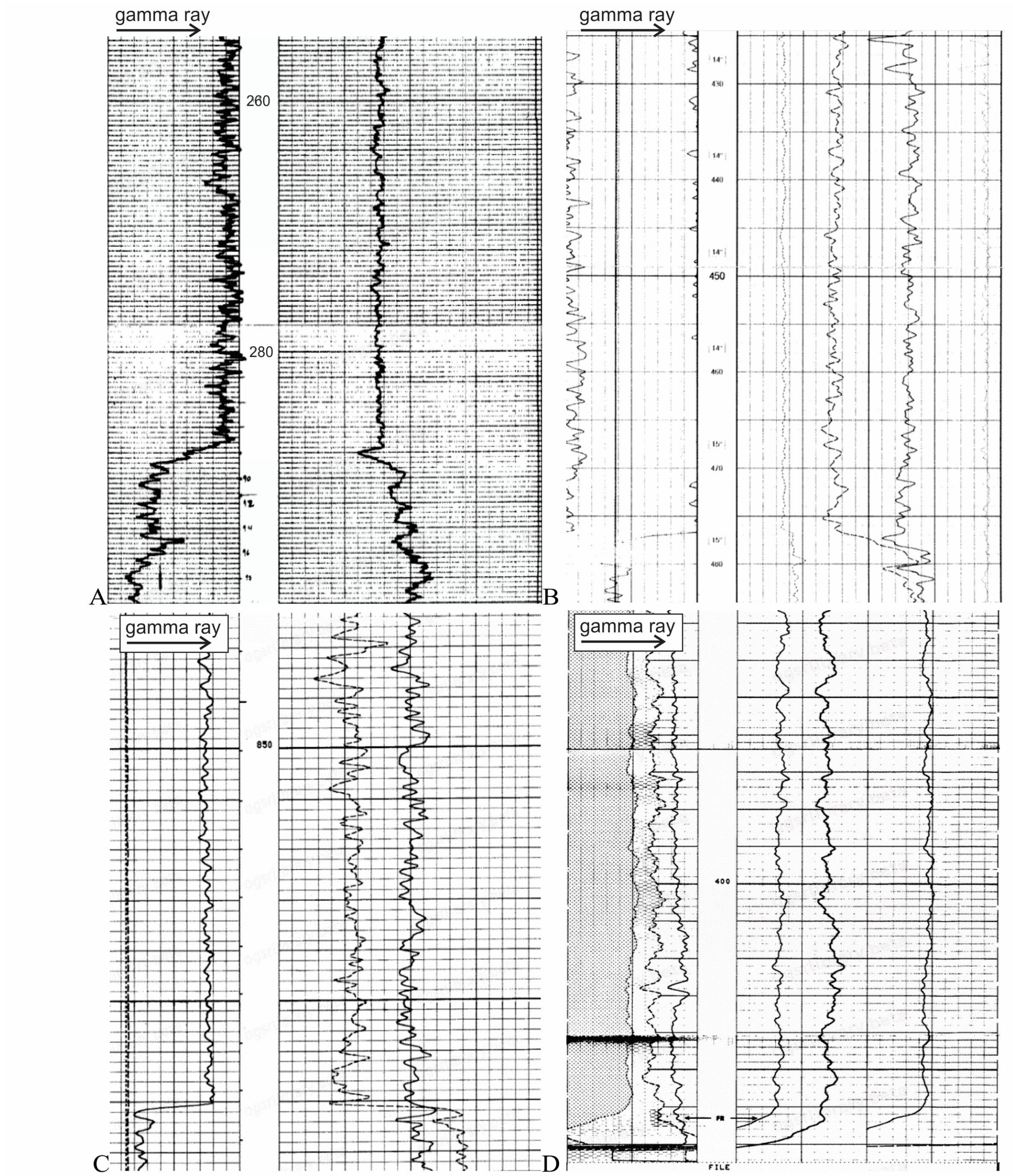


Figure 6-8. (A) Well T006056, Bruce County, GRFD Geophysical log. The Rouge River Member top is picked at 273.6m; (B) Well T012100, Wellington County, DENL Geophysical log. The Rouge River Member top pick is at 456.9m; (C) Well T006364, Huron County, CNFD Geophysical log. The Rouge River Member top is picked at 859m; (D) Well T006120, Halton County, 0GRL Geophysical log. The Rouge River Member top is picked at 399m.

Beneath Lake Erie there appear to be variations in the thickness of the Rouge River Member, particularly in the western area. There is a notable thickening of the Rouge River Member near Peele Island which was also noted by Sweeney (2014). The Rouge River Member in this area displays a particularly stronger gamma ray response, compared to the overlying grey shales (Fig. 6-9 A). In mid-Lake Erie, Elgin County, the Rouge River Member displays a distinct increase in gamma ray response, compared to the overlying Blue Mountain shales with a thickness ranging between 37.8m and 48.2m (Fig.6-9 B). Similarly, in eastern Lake Erie within Haldimand County, the thickness varies between 39.5 and 43.4m (Fig. 6-9 C).

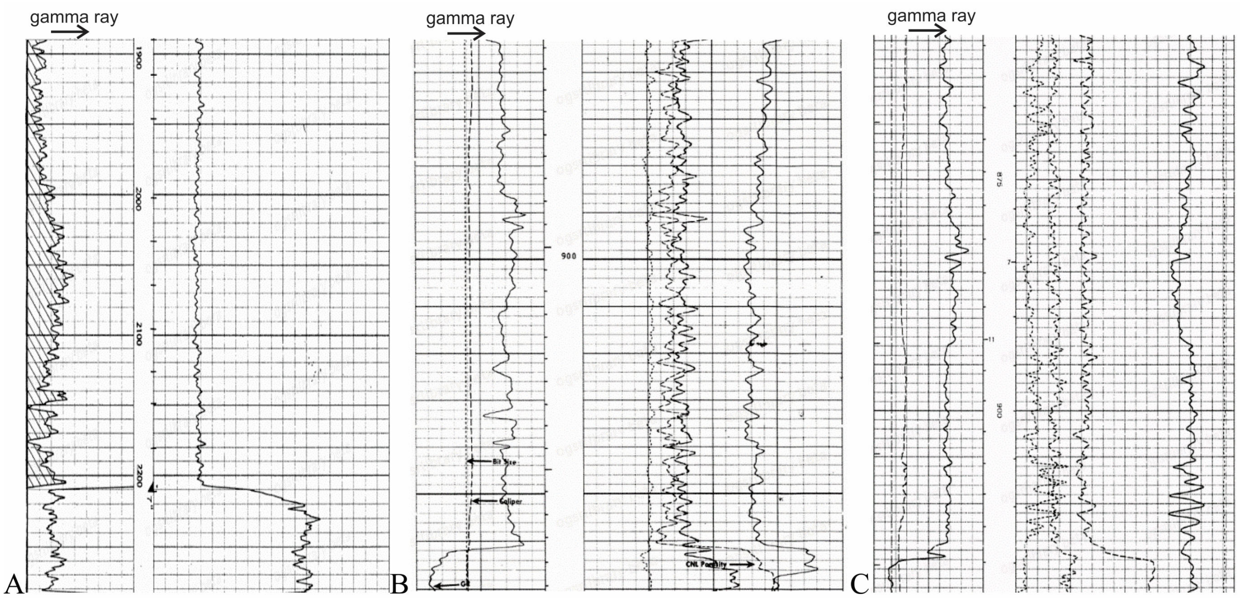


Figure 6-9. (A) Well T000015, Essex, Lake Erie, GRNL Geophysical log. The top of the Rouge River Member is picked at 2047 feet (623.9 m). (B) Well T006818, Elgin Lake Erie, CNF1 Geophysical log. The top of the Rouge River Member is picked at 893.2m. (C) Well T010043, Haldimand, Lake Erie, 0CNL log. The top of the Rouge River Member is picked at 875.8m.

An area that was challenging during this study was Anderdon Township in Essex County. Several wells in this area displayed highly attenuated geophysical signatures for the Rouge River Member (Fig. 6-10). As a result, some of the unit top picks are highly variable compared to Sweeney (2014). It would be beneficial to investigate this area in further detail and compare rock cuttings and geophysical log signatures.

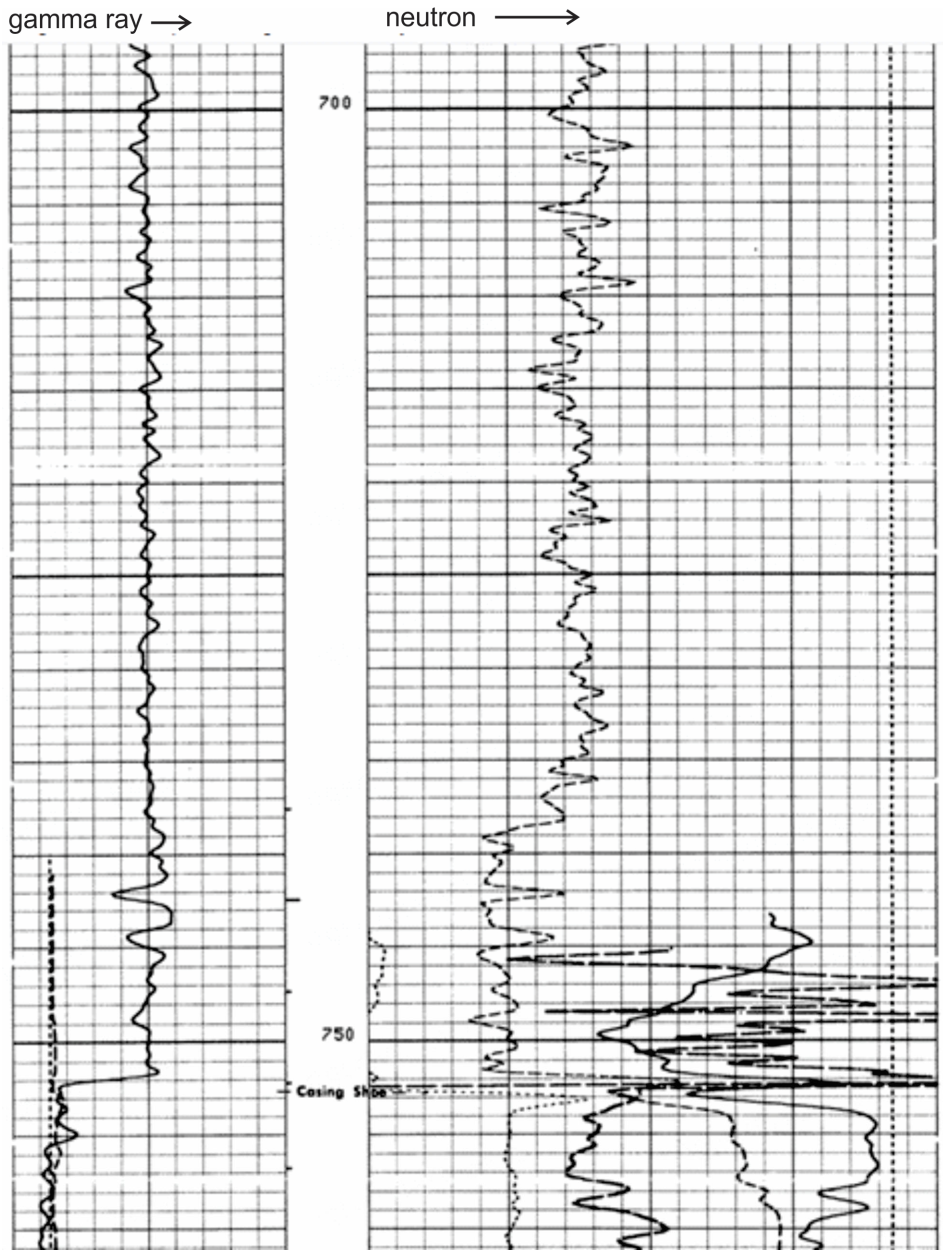


Figure 6-10. Well T007191, Anderdon Township, Essex County, CNFD log. The Rouge River Member is picked at 712m with a thickness of 40m. Sweeney (2014) has picked the Rouge River top at 719.2m.

Collingwood Member (Cobourg Formation)

The Collingwood Member of the Cobourg Formation is an impure limestone or lime marlstone with high organic content. It is a dark grey to black, organic rich calcareous shale with thin, fossiliferous bioclastic interbeds containing mainly trilobites or brachiopods (Russell and Telford 1983; Macauley et al. 1990; Armstrong and Carter 2010; Beland Otis 2012a, b). Rancourt (2009) divided the Collingwood Member into two facies zones. The first is characterized as an organic-rich mudstone with rare bioturbations and the second is a biomicrite/wackestone. It is suggested that the Collingwood Member was deposited in a shallow shelf environment and represents the initial drowning of a carbonate ramp (Brookfield and Brett 1988; Coniglio, Melchin and Brookfield 1990; Johnson et al., 1992; Rancourt 2009). Stratigraphically, the Collingwood Member has an unconformable contact with shales of the overlying Blue Mountain

Formation and is separated by a phosphatic bed, representing a depositional time break (Churcher et al. 1991; Rancourt 2009; Beland Otis 2012a, b). The base of the Collingwood Member gradationally overlies the Cobourg Formation limestones. The Collingwood member has a limited geographic extent, with a southerly pinchout at the Lake Erie shoreline near Port Dover, in the Niagara Peninsula, extending west-northwest to Lake Huron (Russell and Telford, 1983; Churcher et al. 1991).

The Collingwood Member typically displays a subdued gamma-ray signature compared to the overlying shales of the Blue Mountain Formation, but slightly elevated relative to the underlying limestones of the lower Cobourg Formation (Fig. 6-11).

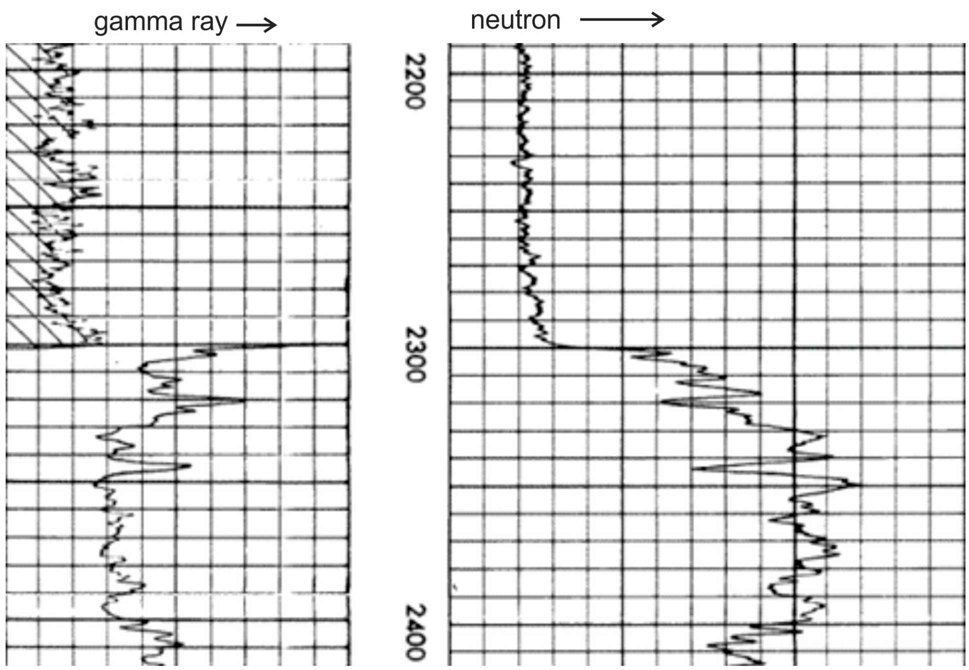


Figure 6-11. Well T001925, Bruce County, GRNL(HD) log. The Collingwood Member top is picked at 2300 feet (701 m) and the top of the lower Cobourg at 2328 feet (709.6 m).

The majority of previous Collingwood Member picks in OPDS were coincident with the pick for the top of the Rouge River Member. If there was pick for the Collingwood Member, a new pick was made.

The total number of Collingwood Member unit picks reviewed in this study were 272. The Collingwood Member thickness ranges between 1.0m and 12.2m across southern Ontario. Throughout northern Manitoulin and Bruce County, thicknesses range between 2.74m and 9.1 m. These findings are consistent with previous studies that reported thicknesses ranging up to approximately 10 m (Johnson et al. (1992).

In Wellington and Perth counties, thicknesses range between 3.6m and 12.2m. In this area, the Collingwood Member gamma ray expression is less distinct compared to the lower Cobourg, creating difficulties in assigning a reliable pick. To correct this uncertainty new formation top picks were compared and calibrated to picks made from drill core and gamma ray logs for wells at the Bruce Power Generating Station on Lake Huron near Tiverton (see Fig. 6-12 A-C).

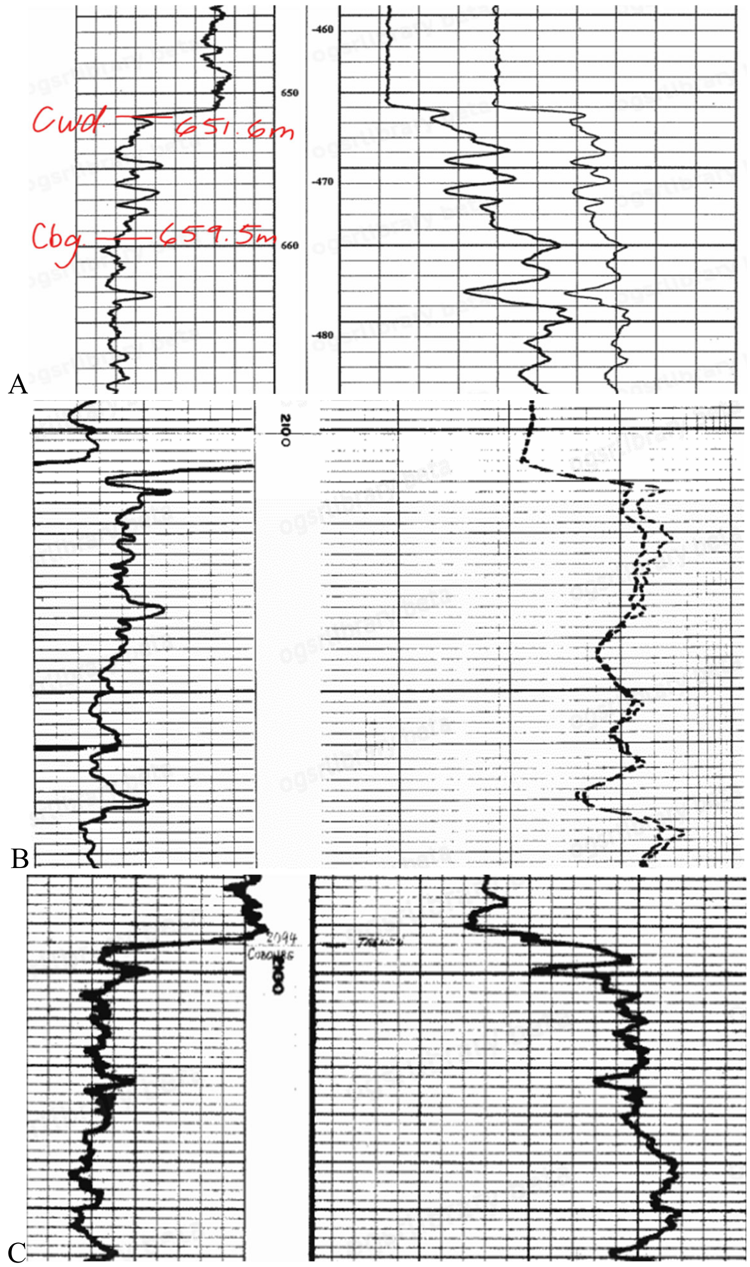


Figure 6-12. (A). Well T0011583, Bruce County, GRNL log. The Collingwood Member was picked at 651.60m and the Cobourg Formation at 659.5 m (Collingwood Member thickness of 7.9m). (B) Well T004730, Perth County, GRNL log. Collingwood Member picked at 642.8 m (2109 feet) and updated Cobourg Formation pick at 653.2 m (2143 feet), where it was previously picked higher in the gamma log at 2136 feet (651.1 m). (C) Well T004985, Perth County, GRNL log. Collingwood Member picked at 638.6 m (2095 feet) and the Cobourg Formation updated to 650.1 m (2133 feet), which was previously picked higher in the gamma log at 2124 feet (647.4 m). Picks for T004730 and T004985 were revised for consistency with nearby wells. In all three logs the gamma ray curve is displayed in the left column.

In southern Perth County the Collingwood Member gamma ray signature is not easily recognizable (see Fig.6-13) and drill cuttings samples must be used to confirm the presence of the Collingwood.

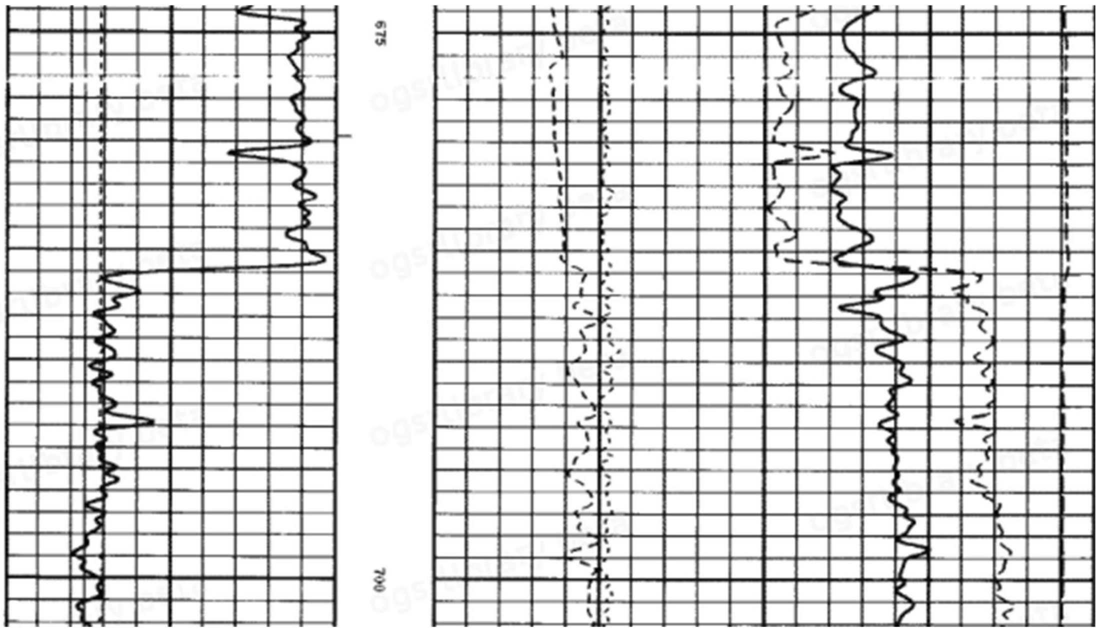


Figure 6-13. Well T008532, Perth County, CNFD log, gamma ray in left column. OPDS pick for top of Collingwood was within the Rouge River Member (Blue Mountain Formation) at 673.1m. The Collingwood Member top was revised to 685.8m, where a downward decrease in gamma ray response occurs. The base of the Collingwood was picked at 692.9 m.

Further south, in Elgin County, thicknesses range between 1.2m and 4.3m thick (see Fig. 6-14). In mid- and eastern Lake Erie, the Collingwood is not recognized. However, many offshore wells displayed a minor gamma-ray peak below the base of the Rouge River (Figs. 6-15; 6-16), which may represent the start of a thin Collingwood Member, but no Collingwood related rock fragments could be identified in drill cuttings. Drill core would be needed for a more definitive determination.

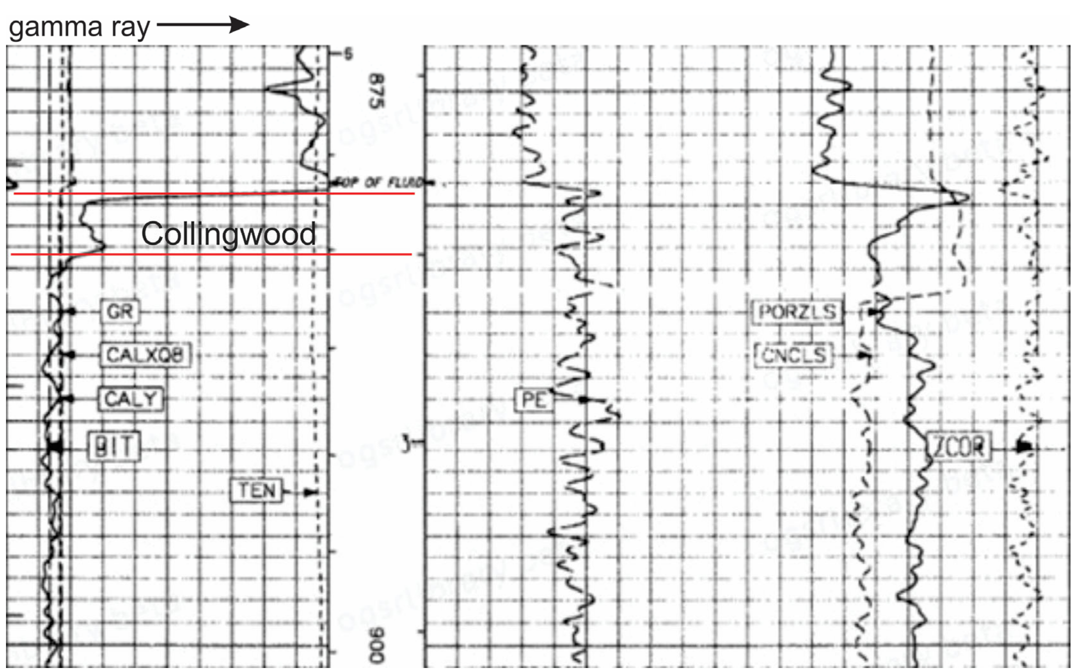


Figure 6-14. Well T011202, Elgin County, CNFD log. The top of the Collingwood Member was picked at 879.5m and the base was picked at 883.3m.

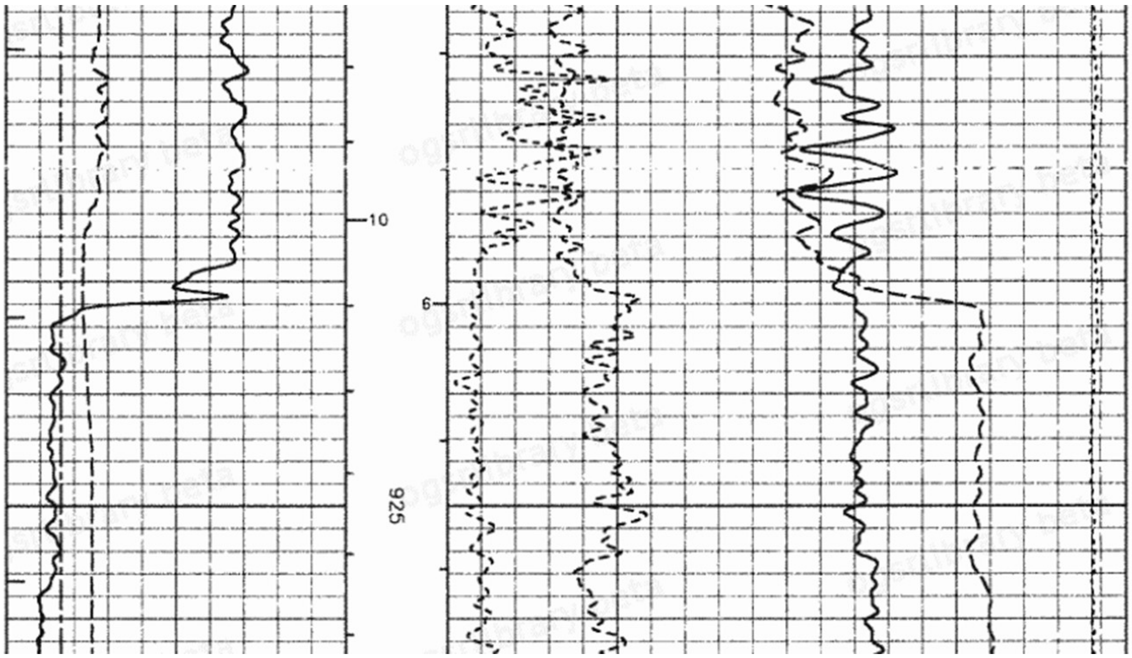


Figure 6-15**.** Well T010043, Haldimand County (east Lake Erie), CNL Geophysical Log, with gamma ray in left column. The contact between the Rouge River Member (Blue Mountain Formation) and Trenton Group is at the sharp change in gamma ray intensity at 916 m. Collingwood was not identified in drill cutting samples of this well.

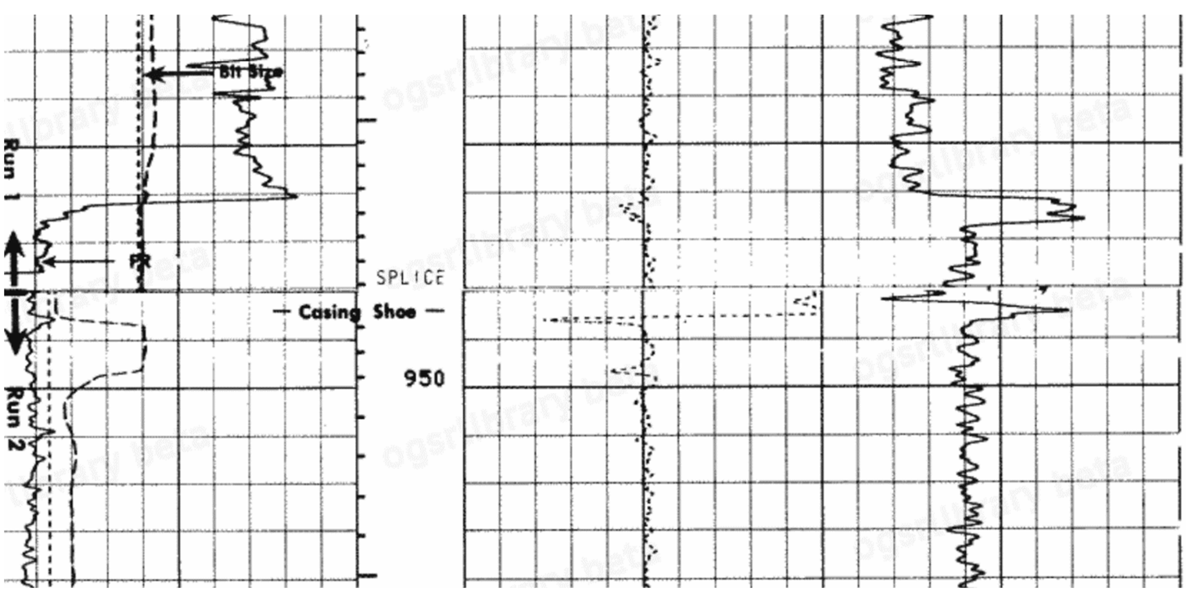


Figure 6-16**.** Well T006818, Elgin County (mid Lake Erie), CNF1 Geophysical log, gamma ray in left column. There is a sharp decrease in gamma ray intensity moving downward from the Rouge River Member (Blue Mountain Formation) to the Upper Cobourg Formation. Cuttings were examined for this well and there was no identifiable Collingwood, and it was recorded as having *Null* Collingwood.

Reliable identification of very thin Collingwood near the pinch-out edge is problematic. For these cases, top picks for the Collingwood Member have not been made and are recorded as *Null* within the database rather than choosing a zero thickness. Disagreements between geophysical logs and drill cuttings also occur. In well H000032 in Grey County, the Collingwood Member was identified in cuttings from 1034 to 1048 feet (315.2 to 319.4 m) but corresponding gamma ray log depth interval is 1047 to 1066 feet (319.1 to 324.9 m). In this situation the log depths are used in preference to the cuttings.

Cobourg Formation

The Cobourg Formation consists of fine- to very fine-grained, fossiliferous, grey-brown limestones and argillaceous limestones. Shaly partings are common and thin shale interbeds are locally common. When the Collingwood Member is present, it gradationally overlies the Cobourg Formation limestones and if absent, the Cobourg Formation has a sharp contact with the overlying Blue Mountain shales.

In drill cuttings the Cobourg Formation top is picked where the Cobourg limestone is sharply overlain by the non-calcareous grey-black shales of the Rouge River Member (Blue Mountain Formation). The contact with the Collingwood Member is more subtle and very difficult to pick with consistency and is picked at the upward transition with black, organic rich bituminous limestones and calcareous shales.

The Cobourg Formation generally exhibits a subdued to flat gamma ray response. When the Collingwood Member is present, the gamma ray response displays a gradual upwards increase (See Fig. 6-11, Well T001925). Where the Collingwood Member is *absent*, as confirmed by the examination of cuttings, the sharp contact between Blue Mountain Formation shales and the underlying Trenton Group limestone is marked by an abrupt change in gamma-ray intensity (See Fig. 6-17).

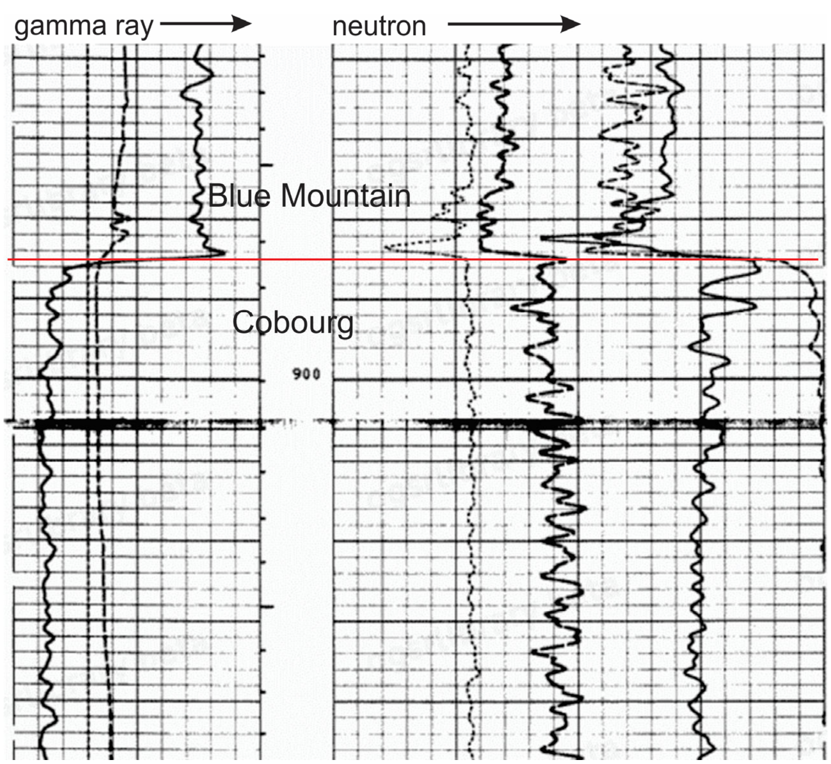


Figure 6-17. Reference Well T006965 showing the contact between the Blue Mountain shales and Cobourg Formation limestone at 892.5m.

The total number of Cobourg Formation picks reviewed in this study were 294. Thickness of the Cobourg Formation was not determined as part of this report. Discrepancies in existing OPDS formation picks were observed for the Cobourg formation top pick, with the most common edit occurring when the Collingwood Member was observed to be present but not previously recorded (e.g. Fig. 6-18).

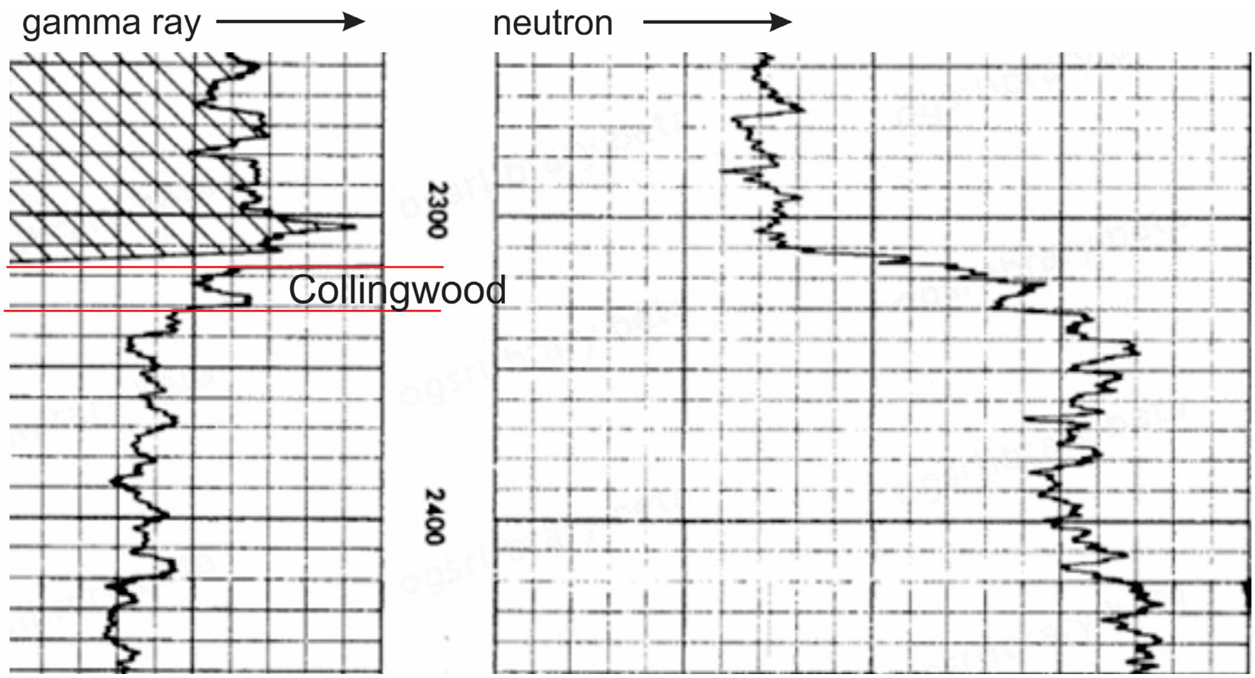


Figure 6-18. Well T001702, Burford County, GRNL log, gamma ray curve displayed in left column. No previous Collingwood pick made. Top of Cobourg (top of Trenton Group) previously picked at 2317 feet (705.9 m). Updated picks: top of Collingwood at 2317 feet (705.9 m) feet to its base at 2332 feet (710.8 m), where the gamma ray signature begins to decrease to the baseline of the rest of the Cobourg Formation.

Other problematic wells were T004730 and T004985, which were both located in Perth County (Fig. 6-12 B and C).

Summary

A total of 317 wells were examined for the Cobourg Formation, Collingwood Member of the Cobourg Formation, the lower Rouge River Member of the Blue Mountain Formation, the Georgian Bay-Blue Mountain Formation, and the Queenston Formation. Using standardized formation top picking criteria (Armstrong and Carter 2010) discrepancies made by drillers for the Upper Ordovician formations have been identified and updated. A total of 1,748 formation top picks were reviewed from the OPDS and 706 are new formation top picks into the database.

Queenston Formation picks are generally reliable and consistent. The picks for the top of the Georgian Bay-Blue Mountain Formation are unreliable and inconsistent, creating variability of 20 to 30 metres in the formation surface. The contact between the Blue Mountain Formation and its lower Rouge River Member is gradational and can be challenging to determine in samples so geophysical logs were the primary method of constraining the contact. Challenges and discrepancies existed when the geophysical log signature was subdued compared to the overlying Blue Mountain shales. The previously recorded Collingwood picks in OPDS were very inconsistent and frequently confused with the Rouge River

Member. For the corrected picks the Collingwood Member thickness ranges from 1 to 12.2 metres across southern Ontario. When the Collingwood member was found to be present, the base of the Collingwood was recorded as the Cobourg top to accommodate the OPDS data table structure.

Suggested future work includes performing surface and isopach maps on the Cobourg Formation, Collingwood Member of the Cobourg Formation, the Rouge River Member of the Blue Mountain Formation, the Georgian Bay Formation and the Queenston Formation, this would highlight potential data errors or discrepancies. A priority is further QA/QC to correct inconsistent formation top picks for the Georgian Bay-Blue Mountain Formation and refine the Rouge River and Collingwood zero-edges. There still remain a large number of wells in OPDS with incorrect formation top picks for the Collingwood Member which make it impractical and premature to create a model layer.