3D Geological Model for South Bruce and Surrounding Region: Model Version 1.0

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Nuclear Waste Management Organization

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ABSTRACT

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Abstract

Developing a site-scale 3D geological model is an essential part of the Descriptive Geoscientific Site Model. The objective of this report, and the 3D geological model for South Bruce and surrounding region is to develop a numerical representation of the subsurface that can be further used to evaluate the site for its potential to host a deep geological repository. This geological model forms the site framework to be used in associated geoscientific studies to develop discipline-specific sub-models, including geomechanical, thermal, hydrogeological, hydrogeochemical and radionuclide transport property models. This report defines the first iteration of the site-scale geological model of South Bruce, which incorporates a significant amount of information measured from the ground surface and subsurface information collected mainly from eight boreholes within the site-scale extent. Six of the boreholes are from the Oil, Gas and Salt Resources Library (OGSRL) database obtained from the Carter et al. (2021) 3D lithostratigraphic model, and the remaining two boreholes are from the recently drilled NWMO deep boreholes (SB_BH01 and SB_BH02).

This initial version 1.0 of the 3D model is sparsely constrained. It is acknowledged that building a 3D model with sparse data will have some uncertainty, and the projected information will most likely not be completely accurate. The main sources of uncertainty in this iteration of the 3D model are sparsity of data, accuracy of borehole collar locations in the OGSRL database, lateral extent of the Guelph reef, Cambrian zero edge boundary and potential faults. However, due to shallow dip and lack of deformation of the Paleozoic strata in southern Ontario, formations are expected to be continuous and predictable throughout the area, with the exception of pinnacle structures in the Lockport Group. Eventually, as additional data is acquired and used in the model, remaining uncertainties will be minimized. Continually updated models will ultimately

inform other geoscientific disciplines, and will form the framework used in the design of an underground repository and the assessment of long-term safety of the site.

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1. Introduction

A geological model constitutes a three-dimensional approximation of the subsurface. Commonly applied in sedimentary bedrock, the subsurface can be partitioned into formations that reflect regions of the subsurface with similar characteristics. Subsurface models attempt to honour the complexity of the subsurface while maintaining the ability to develop the model with a limited glimpse of the subsurface through borehole drilling and geophysical investigations. These models can be used to better understand the spatial arrangement and can be further queried to assist with planning subsequent field studies. Furthermore, the results from the South Bruce geological model can be used in subsequent geoscientific discipline studies (e.g., hydrogeological, geomechanical, etc) while recognizing the impact of its uncertainties and limitations.

The development of regional-scale geological models for the Paleozoic stratigraphy in southern Ontario have been refined over at least the past 15 years. A regional stratigraphic model was developed in 2008 to understand the stratigraphy surrounding the Bruce Nuclear Site for the proposed Deep Geological Repository (DGR) for Low and Intermediate Level Radioactive Waste (Gartner Lee, 2008). Itasca and AECOM (2011) later updated the model to include new data from additional boreholes and new criteria for interpreting formation tops (Armstrong and Carter, 2010). The resulting model area was approximately 35,000 km^2 centred around the DGR site, extending down to the Precambrian basement and was developed using stratigraphic formation top picks available from the Oil Gas and Salt Resources Library (OGSRL) database at that time, including local updates based on quality control procedures. In 2015, the Geological Survey of Canada (GSC) and Ontario Geological Survey (OGS) collaborated on a geological model for the entire Paleozoic bedrock across southern Ontario (Carter et al., 2019). This model was later updated through a collaboration between the Geological Survey of Canada (GSC) and Ontario Geological Survey (OGS), and the Oil, Gas and Salt Resources Library (OGSRL) (Carter et al., 2021b). The update incorporated a rigorous QA/AC review of formation top picks in the OGSRL database, involving edits to 17,595 formation picks from 3419 boreholes. The resulting stratigraphic model (Carter et al., 2021b) provides a regional-scale stratigraphic framework where formation top picks are consistent between boreholes and follow the picking criteria defined in Armstrong and Carter (2010). This stratigraphic model forms the regional framework that is followed within this geological modelling report.

An area located in South Bruce, southern Ontario was selected by the Nuclear Waste Management Organization (NWMO) following the Phase 1 of Geoscientific Desktop Preliminary Assessment summarized by Geofirma (2014). In 2021, the NWMO initiated the drilling and testing of two deep boreholes (SB_BH01 and SB_BH02) in South Bruce as part of Phase 2 Geoscientific Preliminary Field Investigations of the NWMO's Adaptive Phased Management (APM) Site Selection Phase. This report documents the results of a geological model for the South Bruce Site and surrounding region, which locally updates the stratigraphic formations/surfaces of Carter et al. (2021b) by incorporating new drillhole results from NWMO site investigations (i.e. SB_BH01 and SB_BH02).

1.1 Scope and Objectives

This report documents the input data sources and results from a 3D geological model of stratigraphy for an area around the South Bruce site. The model is developed following the lithostratigraphic framework that has been established through regional modelling completed by the Geological Survey of Canada (GSC), in collaboration with the Ontario Geological Survey, Oil Gas and Salt Resources Library (OGSRL), Ministry of Natural Resources and Forestry (MNRF) and Carter Geologic (Carter et al., 2019; 2021b). The results of Carter et al. (2021b) provide the stratigraphic framework for all of the Paleozoic strata for southern Ontario.

The objective of this South Bruce geological model is to locally update the stratigraphic surfaces of Carter et al. (2021b) by incorporating drillhole results from NWMO site investigations (i.e. SB_BH01 and SB_BH02). To satisfy this objective, the South Bruce stratigraphic model is developed to (1) honour the regional stratigraphic framework developed by Carter et al. (2021b); (2) honour the depth markers in the boreholes; and (c) integrate the new stratigraphic surfaces seamlessly with the surfaces derived from the Carter et al. (2021b) model.

Results from the geological model form the site framework to be used in associated geoscientific studies to develop discipline-specific sub-models, including geomechanical, thermal, hydrogeological, hydrogeochemical and transport (petrophysical) property models. The geological model, along with these additional sub-models, will be described in a Descriptive Geoscientific Site Model (DGSM) report. The discipline-specific models and the overall inter-dependencies between all these models and the geological framework model, within the DGSM, are illustrated in Figure 1. The key message represented in Figure 1 is the critical role of the geological framework model in developing all other associated sub-models.

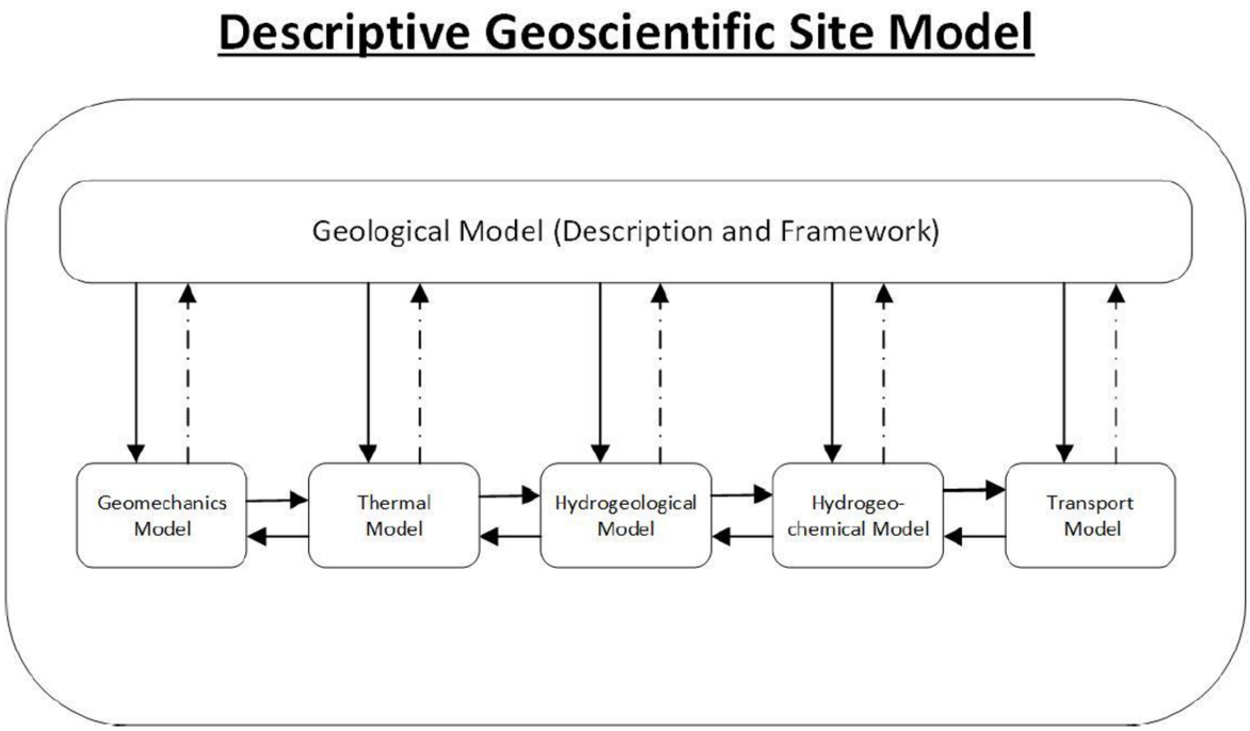


Figure 1: General elements of a Descriptive Geoscientific Site Model (DGSM).

1.2 Model Version

The geological model described in this report has been developed based on relevant geoscientific data compiled from NWMO Phase 1 and Phase 2 studies up until the end of 2022. It documents the initial version of the South Bruce 3D geological model and will be referred to as Model v1.0. After finalizing this report, any minor modifications to the results will be appended to this report and the model version will be updated as v1.1, and v1.2, and so on.

A data freeze has been implemented in the development of the model to organize and control the use of quality-assured geoscientific data, which represents the currently acquired geoscientific data for a defined period of time. During the period in which the model is being developed, site characterization and data collection activities continue in parallel. The data used in the initial site-scale model has undergone QA review and has been stored in the NWMO Geoscience Data Management System (GDMS).

The introduction of new geoscientific data following a data freeze will be included in short periods of time to limit the amount of new data. New data may include, for example, additional drilled boreholes with associated geoscientific data and test results, or interpretations from 3D seismic reflection data. Decisions around the timing, and types of additional geoscientific data to include into the model will be justified and documented in future versions of the model. The development of a new model, which would be accompanied by a new report, will include a new version number as v2.0.

The decision to implement a data freeze will be identified at stages when a model is required to support milestone decisions, such as repository design and safety assessment requirements, planning for borehole targeting and mapping activities, and development of geoscientific site model.

1.3 South Bruce Model Volume

The model extent has been established in collaboration with other NWMO functional groups. This model domain represents a smaller footprint to the recently published regional stratigraphic model released by the Geological Survey of Canada (Carter et al. 2021b), which covers the entire Paleozoic sequence for southern Ontario. The domain is a rectangular geometry covering a total of 300 km^2, where X and Y axis lengths are 20 km and 15 km, respectively. The model depth ranges from 400 to -1000 metres above sea level.

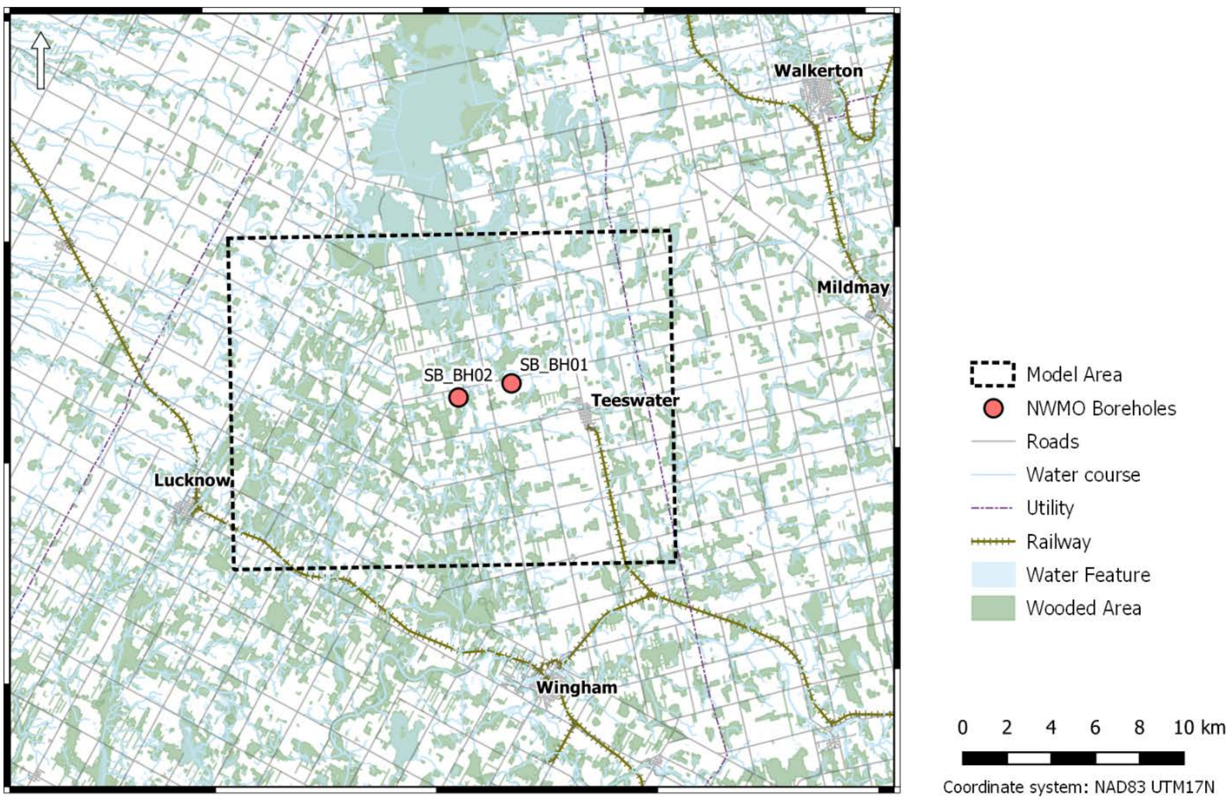


Figure 2. Location map of the 3D geological model domain for South Bruce. Model domain (black dashed) is 20 km by 15 km. Geographic features are derived from Geofirma (2014).

Table 1. Coordinates representing nodes of the 3D geological model domain for South Bruce.

Vertices	*X coordinate (m)*	*Y coordinate (m)*
SW corner	461000	4865000
NW corner	481000	4880000
SE corner	461000	4865000
NE corner	461000	4880000

1.4 Software

SKUA-GOCAD™ (v19) was used for the development of the South Bruce 3D Geological Model. This software is developed by Paradigm (now part of Emerson Paradigm LLC) and is coupled with the Integrated Modeling module as a part of the GOCAD® Mining Suite developed by Mira Geoscience Ltd. Model outputs can be exported and visualized in Mira Geoscience Analyst software (free viewer) to allow users to visualize and query the model. ArcGIS and QGIS were used to develop 2D maps presented as figures in this report.

1.5 Lithostratigraphic Terminology

The following section provides definitions for formal lithostratigraphic unit terms used for classification and naming of Paleozoic sedimentary bedrock units in southern Ontario. The terminology used is derived from The International Commission on Stratigraphy (ICS) (International Subcommission on Stratigraphic Classification, ISSC, 1999).

Lithostratigraphic unit - Lithostratigraphic units are bodies of rocks, bedded or unbedded, that are defined and characterized on the basis of their lithological properties, or combination of lithological properties, and their stratigraphic relations. Lithostratigraphic units are the basic units of geological mapping in sedimentary/supracrustal rocks. The traditional formal lithostratigraphic terms (names) as applied to sedimentary rocks are group, formation, member, bed.

Group - A succession of two or more contiguous or associated formations with significant and diagnostic lithological properties in common.

Formation – The primary formal unit of lithostratigraphic classification. No formation is considered justifiable and useful that cannot be delineated at the scale of geological mapping practiced in the region. The thickness of formations may range from less than a meter to several thousand meters. A formation name normally consists of a geographic name followed by either a descriptive geological term (such as the predominant rock type) or by the word “formation”.

Member – A named lithologic subdivision of a formation which possesses lithological properties distinguishing it from adjacent parts of the formation. Some formations may be completely divided into members, may have only certain parts designated as members, or may not be subdivided.

The ISSC guidelines have been applied in Ontario in the naming of stratigraphic units in the Paleozoic bedrock, although not rigorously. Descriptions of the stratigraphic relations and distinguishing features of named lithostratigraphic units in southern Ontario are contained in Armstrong and Carter (2010). They also provide type sections with 17 regional subsurface stratigraphic cross-sections utilizing 63 reference wells, supplemented by 11 reference outcrop sections. The stratigraphic chart utilized in Armstrong and Carter (2010) has been updated by the Ontario Geological Survey (Brunton et al. 2017, Carter et al. 2017 – see Figure 4) and has been adopted by the Geological Survey of Canada in 3D models of the Paleozoic bedrock of southern Ontario (Carter et al. 2021b). One naming convention utilized in Ontario that is not consistent with the ISSC is the use of the term “Unit” within the named formations of the Salina Group and is adopted from the original stratigraphic definitions utilized in Michigan.

2. Background Information

2.1 Geological Setting

Southern Ontario is underlain by a thick Paleozoic succession of undeformed sedimentary rocks, ranging in age from Cambrian to late Devonian, and Mississippian in some regions (Carter 2023). This succession of sedimentary strata rests unconformably on an erosional surface of the Precambrian crystalline basement of the Grenville Province, a tectonic subdivision of the Canadian Shield (Figure 3).

As shown in Figure 3, southern Ontario is located between two major sedimentary basins, the Michigan Basin to the west and the Appalachian Basin to the south. The Michigan Basin is a roughly circular, carbonate dominated intracratonic basin with evaporite deposits; and the Appalachian Basin is an elongate siliciclastic dominated foreland basin. The basins were ideal settings for the accumulation and preservation of marine sediments deposited in epeiric seas that periodically flooded this part of eastern North America, punctuated by periods of uplift and erosion in response to vertical epeirogenic movements and horizontal tectonic forces (Leighton 1996, Howell and van der Pluijm 1999). These two basins are separated by a regional structural high known as the Algonquin Arch which extends northeast through southern Ontario with a southwestern extension into the United States called the Findlay Arch. The Algonquin and Findlay arches are separated by a partially fault bounded structural depression known as the Chatham Sag. Figure 3 illustrates the relationship between the arches of the basins and how they are separated geographically. To the northeast of southern Ontario, the sedimentary strata thin and eventually pinch out on the southwestern side of the Frontenac Arch within the Grenville Province of the Canadian Shield.

The Paleozoic section underlying the South Bruce Site was deposited in the Michigan Basin. These same strata are largely overlain by unconsolidated sediments of mostly glacial origin. The unconsolidated sediments average tens of metres in thickness, locally reaching a maximum thickness of approximately 250 metres east of the Niagara Escarpment (Gao et al. 2006; Gao 2011).

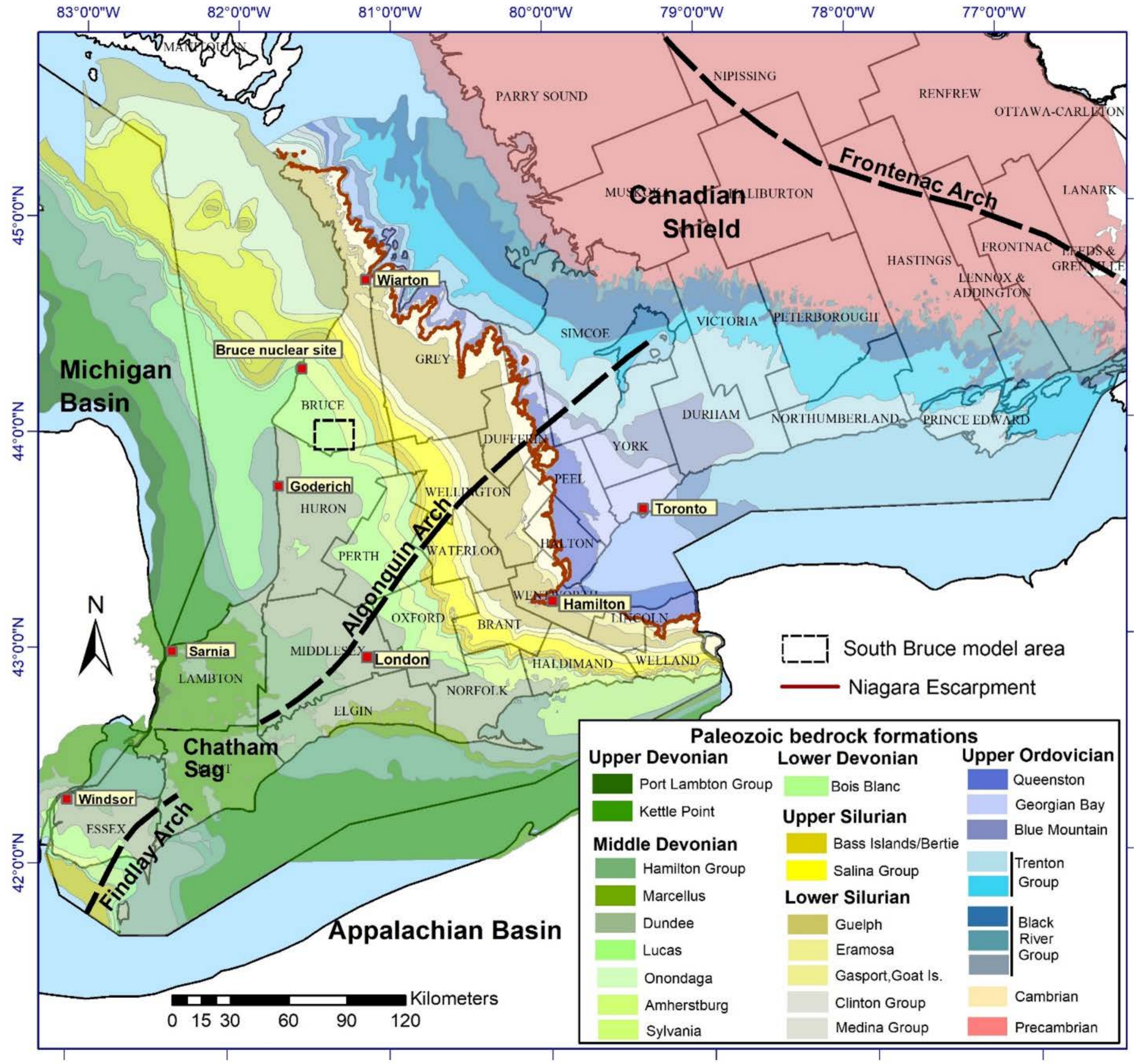


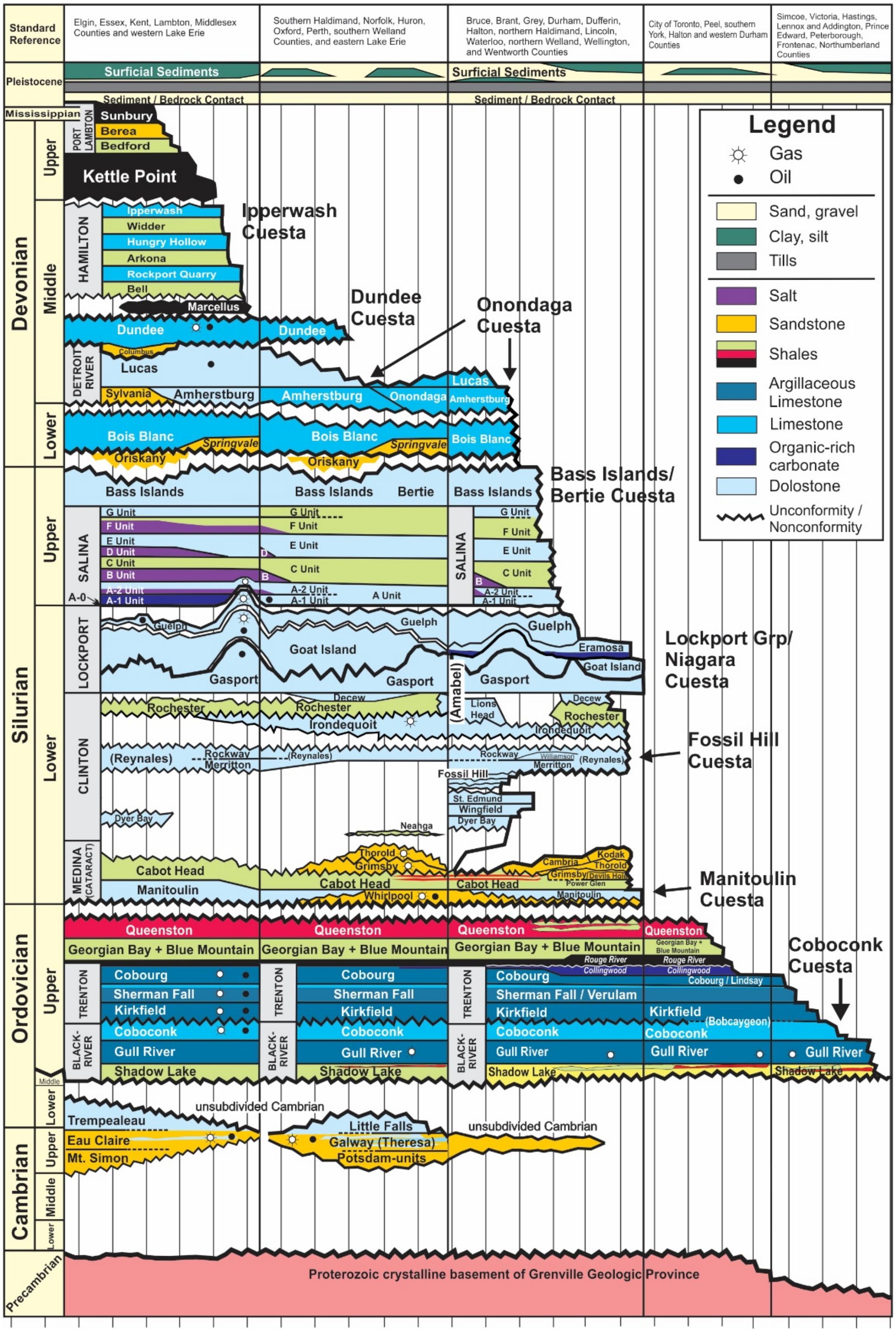
Figure 3. Bedrock geology of southern Ontario, modified and derived from Somers (2017), Carter et al. (2019, 2021b) and Carter (2023).

2.1.1 Paleozoic Geology

A relatively undeformed succession of marine sedimentary rocks overlies the Grenvillian (Precambrian) basement of southern Ontario. Rock types include limestone, dolostone, sandstone, shale, siltstone, anhydrite, and beds of halite (Armstrong and Carter 2010) deposited in a shallow epeiric sea that periodically covered this part of eastern North America during the Paleozoic Era from approximately 501 to 250 million years ago. In general, the stratigraphy in South Bruce is predominantly composed of carbonates (limestone, dolostone) with some beds of anhydrite/gypsum and shale layers. The central column of Figure 4 is representative of the stratigraphic succession encountered in the South Bruce area.

The maximum preserved thickness of Paleozoic rocks is approximately 4800 m in the Michigan Basin and 7000 m in the Appalachian Basin to the southeast (Armstrong and Carter 2010). In southern Ontario, the maximum preserved thickness of Paleozoic strata is approximately 1300 metres in the onshore portion of the Chatham Sag, thickening to 1450 metres beneath west-central Lake Erie and over 1500 metres beneath southern Lake Huron, thinning over the Algonquin Arch and towards the Frontenac Arch to the northeast. The Precambrian rocks that underlie southern Ontario are part of the Grenville Province comprising 2,690 to 990 million year old metamorphic rocks deformed during several orogenic events, the latest of which occurred 1,210 to 970 million years ago (Percival and Easton, 2007; White et al., 2000). Older tectonic events, including the 2.7 Ga Kenoran Orogeny, and the 2.0 - 1.7 Ga Trans-Hudson/Penokean Orogeny, built the Laurentian (proto-North American) craton, upon which Grenville deformation and metamorphism were imprinted. In South Bruce model area, the basement gneiss is overlain by approximately 900 metres of Paleozoic sedimentary rocks.

The Paleozoic strata dip shallowly at 3.5 to 12 m/km or $\leq 1^{o}$ down the flanks of the arches westwards into the Michigan Basin and southwards into the Appalachian Basin, steepening with depth and distance from the arches. Regional dip is 3 to 6 m/km along the crests of the arches into the Chatham Sag (Armstrong and Carter 2010).



Standard Reference
Elgin, Essex, Kent, Lambton, Middlesex Counties and western Lake Erie
Southern Haldimand, Norfolk, Huron, Oxford, Perth, southern Welland Counties, and eastern Lake Erie
Bruce, Brant, Grey, Durham, Dufferin, Halton, northern Haldimand, Lincoln, Waterloo, northern Welland, Wellington, and Wentworth Counties
City of Toronto, Peel, southern York, Halton and western Durham Counties
Simcoe, Victoria, Hastings, Lennox and Addington, Prince Edward, Peterborough, Frontenac, Northumberland Counties
Pleistocene
Surficial Sediments
Sediment / Bedrock Contact
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Upper
Middle
Lower
Sunbury
Berea
Bedford
Kettle Point
Ipperwash
Widder
Hungry Hollow
Arkona
Rockport Quarry
Bell
Marcellus
Ipperwash Cuesta
Dundee
Dundee Cuesta
Onondaga Cuesta
Lucas
Columbus
Sylvania
Amherstburg
Onondaga
Bois Blanc
Springvale
Oriskany
Bass Islands
Bertie
Bass Islands/ Bertie Cuesta
HAMILTON
DETROIT RIVER
PORT LAMBTON
SALINA
G Unit
F Unit
E Unit
D Unit
C Unit
B Unit
A-2 Unit
A-1 Unit
A-0
A Unit
LOCKPORT
Guelph
Goat Island
Gasport
Eramosa
Lockport Grp/ Niagara Cuesta
CLINTON
Rochester
Decew
Irondequoit
(Reynales)
Rockway
Merritton
Williamson
Lions Head
(Amabel)
Fossil Hill
Fossil Hill Cuesta
St. Edmund
Wingfield
Dyer Bay
Neahga
MEDINA (CATARACT)
Cabot Head
Manitoulin
Thorold
Grimsby
Whirlpool
Cambria
Kodak
Devils Hole
Power Glen
Manitoulin Cuesta
Queenston
Georgian Bay + Blue Mountain
Rouge River
Collingwood
Cobourg / Lindsay
TRENTON
BLACK-RIVER
Cobourg
Sherman Fall
Sherman Fall / Verulam
Kirkfield
(Bobcaygeon)
Coboconk
Gull River
Shadow Lake
Coboconk Cuesta
unsubdivided Cambrian
Trempealeau
Eau Claire
Mt. Simon
Little Falls
Galway (Theresa)
Potsdam-units
Proterozoic crystalline basement of Grenville Geologic Province
Legend
Gas
Oil
Sand, gravel
Clay, silt
Tills
Salt
Sandstone
Shales
Argillaceous Limestone
Limestone
Organic-rich carbonate
Dolostone
Unconformity / Nonconformity

Figure 4. Lithostratigraphy of southern Ontario, colour-coded by rock type. Adapted from Brunton et al (2017) and Carter et al. (2017) as updated from Armstrong and Carter (2010). The central column is representative of the stratigraphic succession encountered in the South Bruce area.

The Precambrian in southwestern Ontario is part of the Central Gneiss Belt of the Precambrian Grenville Province. This basement complex consists of a variety of metamorphic rock types ranging from felsic gneiss to mafic metavolcanic rock to marble (Armstrong and Carter 2010). The Cambrian bedrock in onshore portions of southern Ontario is dominated by white to grey quartzose sandstone, which unconformably overlies the Precambrian basement. Regional lithological variations include fine- to medium-grained crystalline dolostone, sandy dolostone and argillaceous dolostone to fine- to coarse-grained quartz sandstone (Hamblin, 1999). The Cambrian unit has been removed by erosion over the crest of the Algonquin Arch (Bailey Geological Services Ltd. and Cochrane, 1984a), and thus is expected to be absent in some or most parts of the South Bruce model area.

The Upper Ordovician is characterized by a lower sequence of carbonate rocks of the Black River and Trenton groups (oldest to youngest). The Black River Group consists of the Shadow Lake, Gull River and Coboconk formations (oldest to youngest). The Trenton group consists of the Kirkfield Formation, Sherman Fall Formation, the lower Cobourg Formation and the Collingwood member of the Cobourg Formation. With the exception of the Shadow Lake Formation, the Black River and Trenton groups form a thick succession of limestones underlying all of southern Ontario. The basal Shadow Lake Formation consists of glauconitic siltstone and sandstone with minor sandy shales, which uncomfortably overlie the Cambrian or the Precambrian when the Cambrian is absent. Above the carbonates of the Black River and Trenton groups, are the Blue Mountain, Georgian Bay, and Queenston formations (oldest to youngest) predominantly consisting of shales with subordinate carbonate interbeds.

The Silurian is subdivided into 4 major groups, Medina, Clinton, Lockport and Salina groups in ascending order. The Lower Silurian Clinton and Medina groups consist of alternating intervals of shale and limestone at the South Bruce site. More detailed descriptions of Silurian strata are presented in subsequent chapters and in a regional geology summary report (Carter 2023). The Lower Silurian Lockport Group is characterized by widespread carbonate deposition and regionally consisting of reefal carbonates of the Guelph Formation capped by the Salina Group (Johnson et al.1992). The Upper Silurian Salina Group is characterized by a succession of evaporites and carbonates deposited in a hypersaline, restricted marine environment (Armstrong and Carter 2010). The Bass Islands Formation is the uppermost formation of the Silurian and it has not been formally classified into any Silurian group.

The Devonian in the South Bruce model area consists of limestones, dolostones and cherty dolostones. The formations in the Devonian are named Bois Blanc, Amherstburg and Lucas formations in ascending order. The Bois Blanc Formation unconformably overlies the Upper Silurian Bass Islands Formation. These are all carbonate-dominated sedimentary rocks deposited in shallow seas.

2.1.2 Faults

Brigham (1971a, b) completed the first comprehensive analysis of the structural geology of southern Ontario and identified and named the principal faults. Subsequent mapping of the thickness and structure top of selected Paleozoic geological formations using petroleum well formation top data from Ontario Petroleum Data System (OPDS) provided better resolution of fault locations and identified additional faults (Bailey Geological Services Ltd. and Cochrane 1984a, b, 1985, 1986; Ontario Geological Survey 2011) (see Figure 5). Where these data are numerous, such as in the southwestern corner of southern Ontario, the faults are identified with a high degree of confidence, and are often named (e.g., Dawn Fault, Electric Fault, see Figure 5). In areas where oil and gas exploration wells are widely spaced, faults are identified with a lower degree of confidence. Faults were mapped by identification of linear vertical displacement of formation top surfaces. The top surface of the Rochester Formation was most commonly used for fault mapping due to its predictable structure and regional distribution. Secondary surfaces utilized are the top of the Cabot Head Formation, the Trenton Group and the Shadow Lake Formation. All mapped faults are presumed to displace all formations older than the mapped surface, including the Precambrian, but this often cannot be confirmed due to sparsity of data points for the deeper formations.

Faults are subvertical, consequently, the mapped locations of the faults can vary by several kilometres at different stratigraphic levels (Carter 2023). Both normal faults and strike-slip faults have been identified in the bedrock of southern Ontario (Armstrong and Carter 2010; Brigham 1971a, b). The most prominent faults occur in the Chatham Sag. Maximum vertical displacement on normal faults is 40 to 100 m (Brigham 1971a, b; Carter 1991; Bailey Geological Services Ltd. and Cochrane 1984a, b, 1985, 1986).

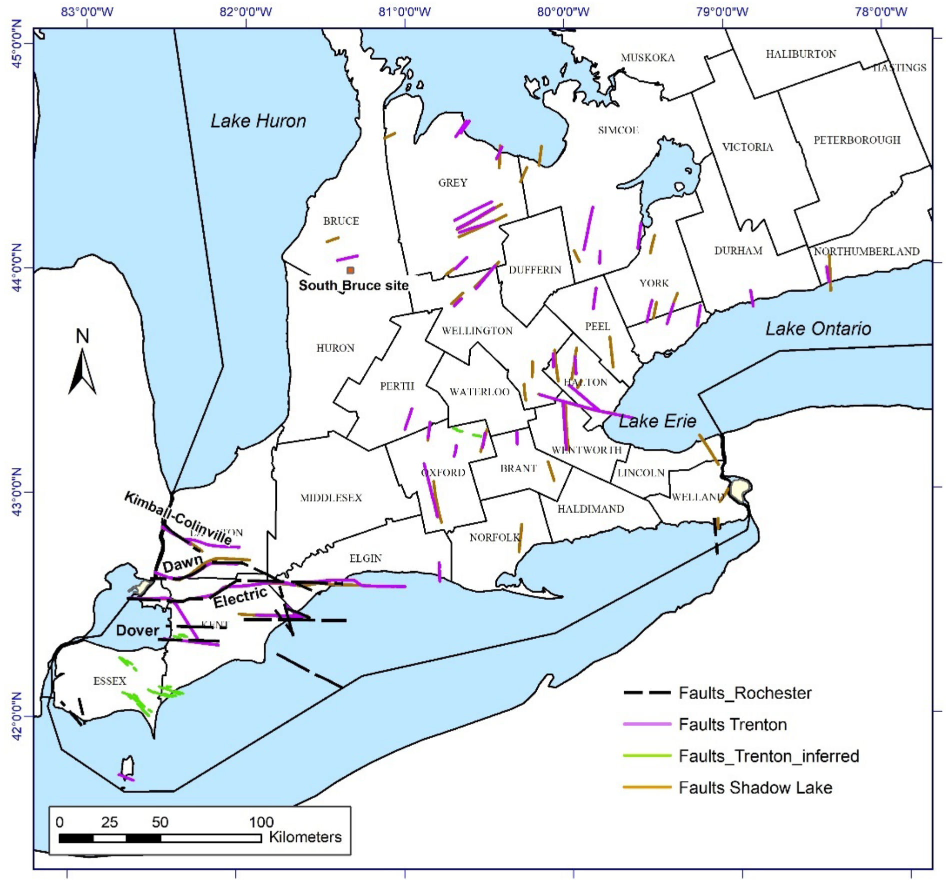


Figure 5. Location of faults with mapped vertical displacements of the Paleozoic bedrock formations, showing fault locations at different stratigraphic intervals. Faults are subvertical. Compiled from Bailey and Cochrane (1984a, b, 1985), Brigham (1971a, b) and Carter (2023) with minor edits. Inferred faults on the Trenton Group surface are based on location of fault-controlled "hydrothermal dolomite" oil and gas reservoirs in the Trenton and Black River Group carbonates.

2.1.3 Tectonic History

The Paleozoic bedrock succession of southern Ontario resulted from a complex interplay of regional tectonic forces that caused vertical and sometimes lateral movements of tectonic units such as subsidence and uplift, siliciclastic sedimentation associated with orogenic activity and eustatic/global sea level fluctuation (Johnson et al. 1992; Sanford 1993b). Subsidence in the Michigan Basin started by late Cambrian time and was followed by on and off periods of subsidence and uplift, continuing through to the Late Jurassic (Sloss 1988; Leighton 1996; Howell and van der Pluijm 1999; Brunton and Brintnell 2020). The cause of subsidence in intracratonic basins, and in this case the Michigan Basin, is still poorly understood but it has been variously ascribed to a hypothetical mantle plume, cooling of stretched mantle lithosphere, densification of underlying lithosphere due to phase changes and/or to a response to compressional effects of Appalachian collisional tectonics (Brunton and Brintnell 2020). The Appalachian foreland basin formed in response to major continental collision events related to plate tectonic processes that resulted in four major orogenies: the Taconic (Upper Ordovician to early Silurian), Salinic (Silurian), Acadian (Devonian), and Alleghanian (Pennsylvanian to Permian) orogenies (Johnson et al. 1992; Ettensohn 2008).

2.1.4 Burial/Erosion and Thermal History

Figure 6 shows maximum burial-erosion curves for carbonate rocks of Upper Ordovician age from two different locations within the Michigan Basin. The orange curve in Figure 6 was included in a study of Ordovician diagenesis (Coniglio and Williams-Jones 1992) and was drawn primarily based on stratigraphic information and data from Cercone (1984). Sediments accumulated within and were cemented and preserved in the basin during periods of subsidence and were eroded during periods of uplift.

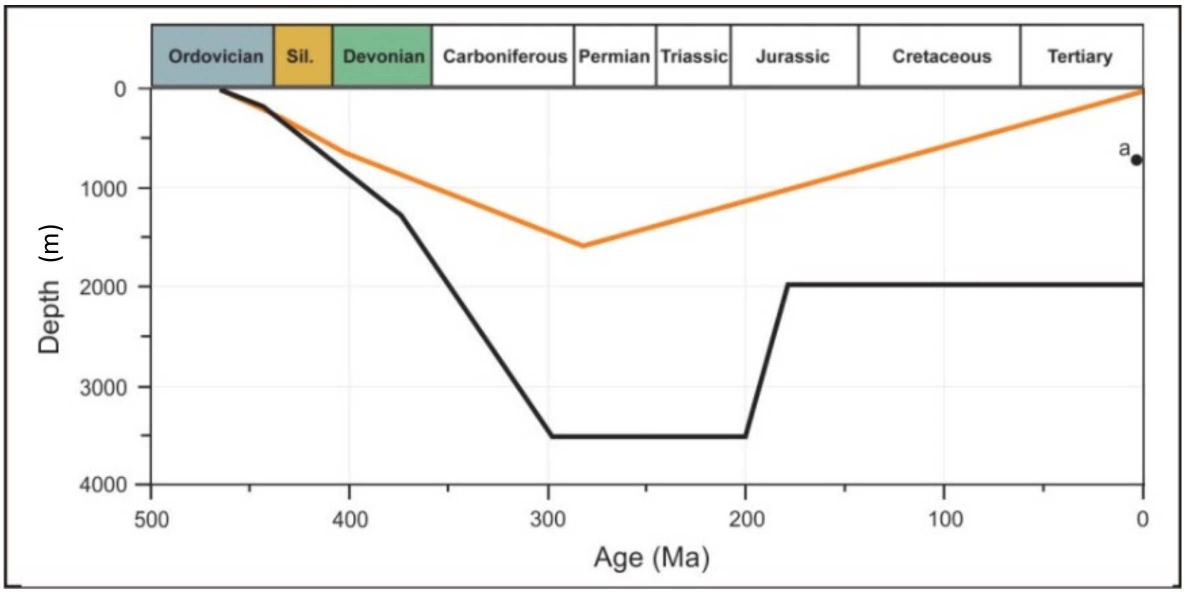


Figure 6. Hypothetical Burial History Curves for locations within the Michigan Basin. Interpretations are based on data collected from Upper Ordovician carbonate sedimentary rocks. Orange curve is from Coniglio and Williams-Jones (1992) after Cercone (1984). Black curve is from Wang et al. (1994). (a) Indicates the present day burial depth of approximately 675 m for the middle of the Upper Ordovician sedimentary succession at the Bruce Nuclear Site. See text for further discussion.

Coniglio and Williams-Jones (1992) estimate that a minimum of 1500 m of compacted Paleozoic sediment has been eroded from the Manitoulin Island region since Permo-Carboniferous peak burial. An analysis of regional apatite fission track dates from around the south-central portion of the Michigan Basin, focused more directly on understanding the complete burial-erosion history (black line in Figure 6), was completed by Wang et al. (1994). Wang et al. (1994) studied apatite fission tracks within Carboniferous sediments and documented a similar late Carboniferous to early Permian timing for peak burial of ~3500 m of sediment at this south-central location within the basin, and determined that a maximum of 1500 m of sediments had been eroded. Given that the top of the Upper Ordovician succession exposed at Manitoulin Island is encountered at 450 metres below ground surface (mBGS) beneath the Bruce Nuclear Site (INTERA 2011), and the Bruce Nuclear Site is located slightly closer to the Michigan basin centre, it is reasonably estimated that a maximum of approximately 1000 m of sedimentary rock has been eroded from above the existing Paleozoic succession at the site and the surrounding area (including the South Bruce model area).

Based on the above discussion, an approximate peak burial in situ temperature for the top of the Trenton Group limestones, at the top of the Collingwood Member of the Cobourg Formation (~650 mBGS), has been calculated (assuming no other factors are involved). Ziegler et al. (1977) and Morel and Irving (1978) both define a position for southwestern Ontario at around 10°-15° south of the Equator during the Ordovician which allows for a mean annual surface temperature of 25°C at this time. Geothermal gradients of 20-30°C/km (Legall et al. 1981) and ~23°C/km (Hogarth and Sibley 1985) are suggested for the central and northern parts of the basin, respectively. An additional 1000 m of sediment at the Bruce Nuclear Site would have placed the Trenton Group (Collingwood Member) top at approximately 1650 mBGS resulting in an in situ temperature of 63.0°C using a 23°C/km estimate, 66.3°C using a 25°C/km estimate, and 74.5°C using a 30°C/km estimate, respectively, for the geothermal gradient. Therefore 70°C is considered a reasonable conservative maximum in situ burial temperature for the top of the Trenton Group beneath the Bruce Nuclear Site and the model region. Temperature related to hydrothermal dolomitization (diagenesis) and thermal maturity are discussed separately in the Regional Geology Report (Carter 2023) and Engelder (2011).

The two burial curves in Figure 6 are considered to be suitable for constraining maximum peak burial conditions for rocks within the Bruce Nuclear Site, including the South Bruce model area. They vary, however, in their interpretation of the timing and rate of erosion. While the orange curve depicts a constant erosion rate since peak burial until the present day, the black curve indicates a non-constant erosion rate where much of the 1500 m was removed prior to the Middle Jurassic. This timing constraint is justified by the observation of a regional unconformity that separates Middle Jurassic sandstones from Pennsylvanian sandstones within the centre of the basin (Wang et al. 1994, Dickinson et al. 2010). Given that this unconformable relationship is regional in scale (e.g., Sloss 1963), and that the Bruce Nuclear Site shares a common geological history with the Michigan Basin, it is reasonable to suggest that much of the missing 1000 m of Paleozoic rocks at the Bruce Nuclear Site was eroded during the same (pre-Mid Jurassic) time interval. A late Paleozoic to early Mesozoic timing for the majority of the erosion at the Bruce Nuclear Site therefore coincides with the waning of the Alleghenian stage of the Appalachian Orogeny, the break-up of Pangaea and opening of the Atlantic Ocean.

2.1.5 Salt Dissolution

Dissolution of halite beds of the Salina Group has occurred at the margin of the Michigan Basin in a zone extending from the Bruce Peninsula south along Lake Huron and into southwestern Ontario, therefore encompassing the South Bruce model area. This process occurred primarily during the late Silurian phase of the Salinic Orogeny. A second major salt dissolution event occurred during the Devonian Acadian Orogeny (Sanford et al. 1985). Dissolution was by downdip infiltration of unsaturated surface water and shallow groundwater, beginning immediately after deposition and occurring until at least late Devonian time (Sanford 1969, Armstrong and Carter 2010, Carter 2023). Salt dissolution is also interpreted to have occurred via fluid migration through regional fractures including faults (Sanford et al. 1985) and above pinnacle structures in the underlying Guelph Formation. Removal of salt from the subsurface is interpreted to have created subsidence/collapse features (e.g., breccia) and initiated fracturing within the overlying Upper Silurian and Devonian strata. The zones affected by this dissolution are brecciated and characterized by veins and joints filled with evaporite (mainly gypsum) cement enclosing dolostone and anhydrite clasts. The pervasive cementation and fracture infilling has resulted in very low measured hydraulic conductivities in the Silurian rocks (Intera 2011).

2.1.6 Karst and Paleokarst

Karstic dissolution of carbonate and evaporite rocks can greatly enhance porosity and permeability. Karst and paleokarst horizons are the principal control on groundwater movement and the location of all significant aquifers in the Paleozoic bedrock of southern Ontario (Carter et al. 2021a). Carbonate and evaporite rocks are widespread in southern Ontario, particularly on the Michigan Basin side of the Algonquin Arch. Where these rocks are exposed at the surface or subcrop beneath thin unconsolidated surficial sediments (overburden), they are subject to dissolution by acidic meteoric water or shallow groundwater, most of which has occurred since the last phase of the Pleistocene glaciations (Carter 2023). This greatly increases the porosity and permeability of the rock forming a dual-porosity aquifer with water storage in the rock matrix and most flow through high-permeability interconnected pathways. Groundwater flow velocities through these high-permeability interconnected pathways are enhanced in comparison to fractured rock. Karstification is most pronounced in shallow freshwater zones with low concentrations of dissolved solids (Worthington 2011).

Paleokarst refers to karst that formed in the geological past during periods of subaerial exposure of carbonate and evaporite bedrock at major disconformities, and which has subsequently been buried, cemented, and preserved beneath younger rocks in the subsurface. Numerous disconformities occur in the Paleozoic bedrock of southern Ontario, some of regional extent while others are of local or undocumented geographic extent (Figure 4). Where these disconformities have affected carbonate rocks, paleokarst intervals of enhanced porosity and permeability have been formed. Enhanced porosity and permeability associated with paleokarst development occurs immediately below disconformities at the top of the Lucas (Uyeno et al

1982; Birchard 1990; Birchard et al. 2004), Bass Islands (Kobluk et al. 1977; Armstrong 2017, 2018; Sun 2018) and Guelph (Kahle 1988; Smith 1990; Brunton et al. 2012; Brunton and Brintnell 2020; Carter et al. 1994) formations, and the unsubdivided Cambrian (Coogan and Maki 1987; Desrochers and James 1988; Mussman et al 1986, 1988; and Carter 2023). Carter (2023) provides a more detailed guide of the distribution of karst and paleokarst in southern Ontario.

2.2 Quaternary Geology

Quaternary geology in the South Bruce area has been described in the Terrain and Remote Sensing Study Report (JDMA, 2014) and more recently in a Regional Geology Report (Carter 2023). Quaternary glaciations have played a major role in shaping and creating the landscape of southern Ontario (Barnett, 1992). Glacial landforms and associated unconsolidated sediments within the South Bruce area were deposited by the Huron and Georgian Bay lobes of the Laurentide Ice Sheet during the Late Wisconsinan 23,000 to 10,000 years ago. JDMA (2014) and AECOM and Intera (2011) have summarized the Late Wisconsinan glacial history of southern Ontario (see Table 2). Exposures of older glacial deposits are rare as they are mostly buried beneath the Late Wisconsinan sediments and can only be seen in such places as riverbank exposures, lake bluffs or man-made exposures in quarries and pits (Barnett, 1992). The surficial deposits have been mapped at the scale of 1:50,000 by Cowan (1977), Cowan et al. (1986), Cowan and Pinch (1986), Feenstra (1994), Karrow (1993), Sharpe and Broster (1977), Sharpe and Edwards (1979) and Sharpe and Jamieson (1982).

Table 2. Late Wisconsinan glacial history of southern Ontario, from AECOM and Intera (2011)

Age	Glacial Period	Deposit or Event	Lithology	Morphologic Expression
10,000 - present	Post-glacial	Modern alluvium and organic deposits	Silt, sand, gravel, peat, muck, marl	Present day rivers and floodplains
12,000-10,000	Two Creeks Interstadial	Glacial lacustrine deposits	Silt and clay	Flat-lying surficial deposits
		Glacial outwash	Sand, gravel and silt	Primarily buried (moraine)
		Ice contact (Saugeen Kames)	Sand, gravel	Kames, eskers
13,000 – 12,000	Port Huron Stadial	St. Joseph Till	Silt to silty clay till	Surficial tills
15,000 – 13,000	Mackinaw Interstadial	Glacial outwash	Sand, gravel, silt and minor clay	Thin buried surficial deposits
		Elma Till	Silt till	Surficial till
16,000 – 15,000	Port Bruce Stadial	Elma Till	Silt till	Surficial till
		Dunkeld Till	Silt till	Surficial till
		Mornington Till	Silty clay till	Surficial till
18,000 – 16,000	Erie Interstadial	Glacial lacustrine deposits	Silt	Wildwood silts
20,000 – 18,000	Nissouri Stadial	Catfish Creek Till	Stoney, sandy silt to silt till	Buried

Note: Modified after Karrow (1973), Chapman and Putnam (1984).

3. Sources of Data for 3D Geological Modelling

3.1 Digital Elevation Model

JDMA (2014) completed a comprehensive Terrain and Remote Sensing Study during the NWMO Phase 1 preliminary assessment, which included the municipality of South Bruce. Their study utilized the Canadian Digital Elevation Model (CDEM) which comprises grid cell resolution of 20 m and the elevations are representative of the topographic ground surface. In general, because of the extensive Quaternary overburden cover in the area, the DEM represents the top of the overburden unit. However, locally where bedrock is exposed it also includes outcropping rock. Shown in Figure 7, the DEM in this study was constructed by Natural Resources Canada (NRCan) using data assembled through the Water Resources Information Program (WRIP) of the Ontario Ministry of Natural Resources (MNR). CDEM datasets were referenced horizontally using NAD83 and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28) and the elevations are recorded in metres relative to mean sea level.

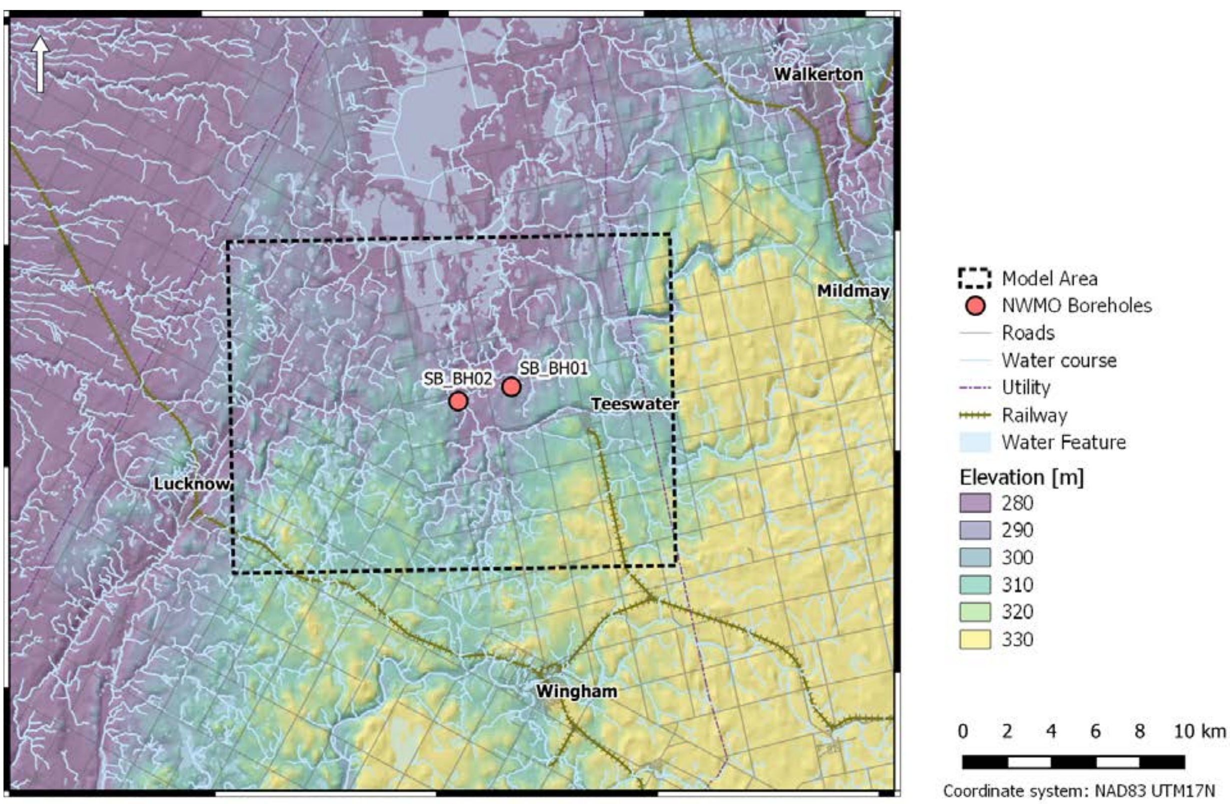


Figure 7. Digital elevation model (DEM) for the South Bruce area.

Based on data analysis by JDMA (2014), the CDEM provides a good quality representation of the land surface in areas with topographic relief. However, relatively poor-quality representation can be found in flat areas, where the elevation model is generally based on elevation values obtained from a single elevation contour. Despite the limitations discussed, the resolution and accuracy of this DEM is sufficient for the purpose of geological modelling at the scale of the South Bruce model extent.

Within the South Bruce model area, the ground surface measures a mean elevation of 298.09 m (standard deviation of 14.69 m), with elevations ranging from 271.08 m to 338.97 m. Topographic highs are generally along the southern and eastern boundaries of the model area and slope gradually towards the north to northwest. The central part of the model area is low-lying and locally covered by wetlands. Locally, creeks and streams cut through the topographic surface forming incised channels in the overburden sediments.

3.2 Overburden

The Paleozoic bedrock of southern Ontario is covered by variable thicknesses of unconsolidated sediments averaging a few tens of metres in thickness (Figure 8). The sediments are predominantly glacial in origin with local accumulations of modern sediments, largely in modern river valleys.

Gao et al. (2006) produced overburden thickness and depth to bedrock maps for overburden material overlying the Paleozoic bedrock in southern Ontario. They generated these maps by incorporating a network of Ontario Water Wells and Geotechnical Wells across southern Ontario totalling over 250,000 data points representing the depth to bedrock.

Figure 8 shows the elevation of the Paleozoic bedrock underlying the overburden cover. The elevation of the bedrock surface was determined by combining the results of two separate kriging approaches for thin cover and thick cover areas. The bedrock surface shows highest elevations in the southeastern part of the map which slopes shallowly towards Lake Huron to the west. Elevations range from approximately 230 m to 312 m above mean sea level, with a mean elevation of 272 m above mean sea level.

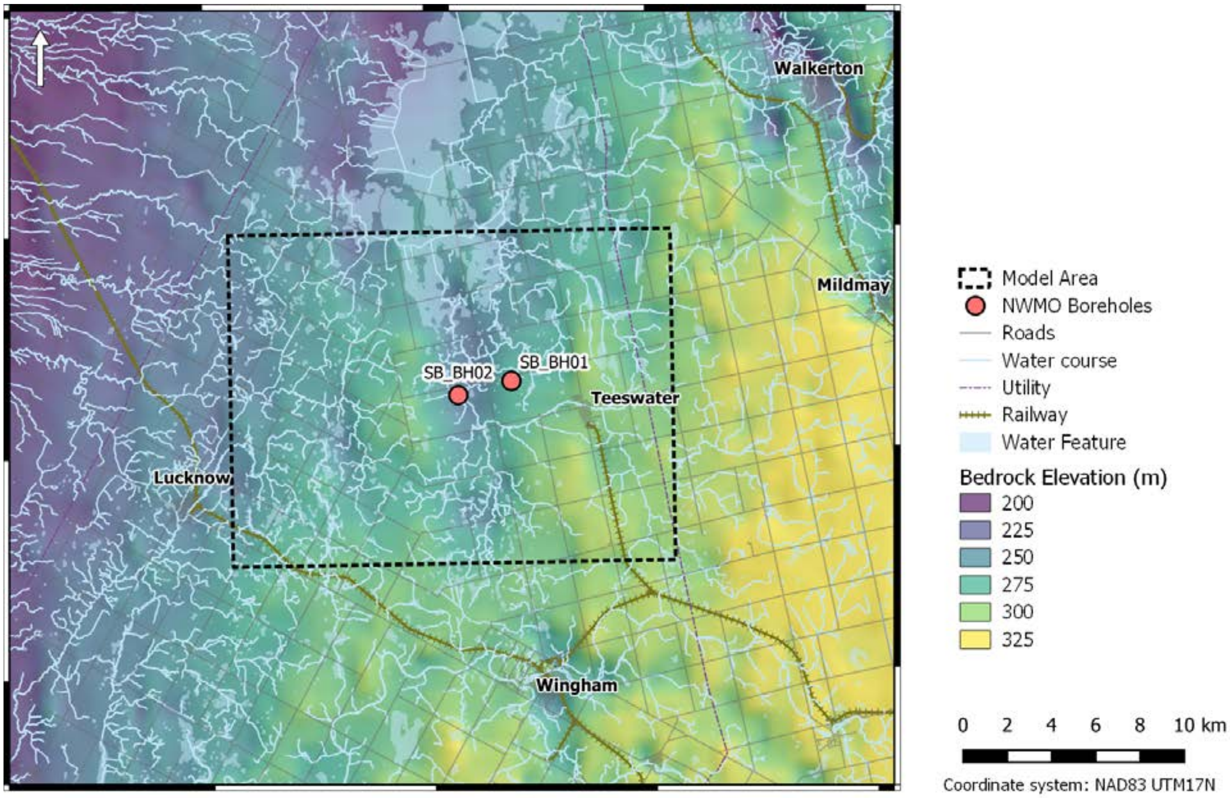


Figure 8. Topography of the bedrock surface for the model area covering the South Bruce (model area). Variability in the bedrock topography is adapted from Gao et al. (2006).

Figure 9 shows spatial variability of overburden thickness through the South Bruce model area. The overburden thickness is determined by simply calculating the difference between the bedrock surface elevation and the topographic surface elevation using the digital elevation model (Gao et al., 2006). Within the South Bruce model area, overburden thickness is very irregular, ranging from zero in areas of bedrock outcrops to a maximum of approximately 64 m along the western boundary of the model area (Figure 9). Within the South Bruce Site itself, average overburden thickness is approximately 25 m.

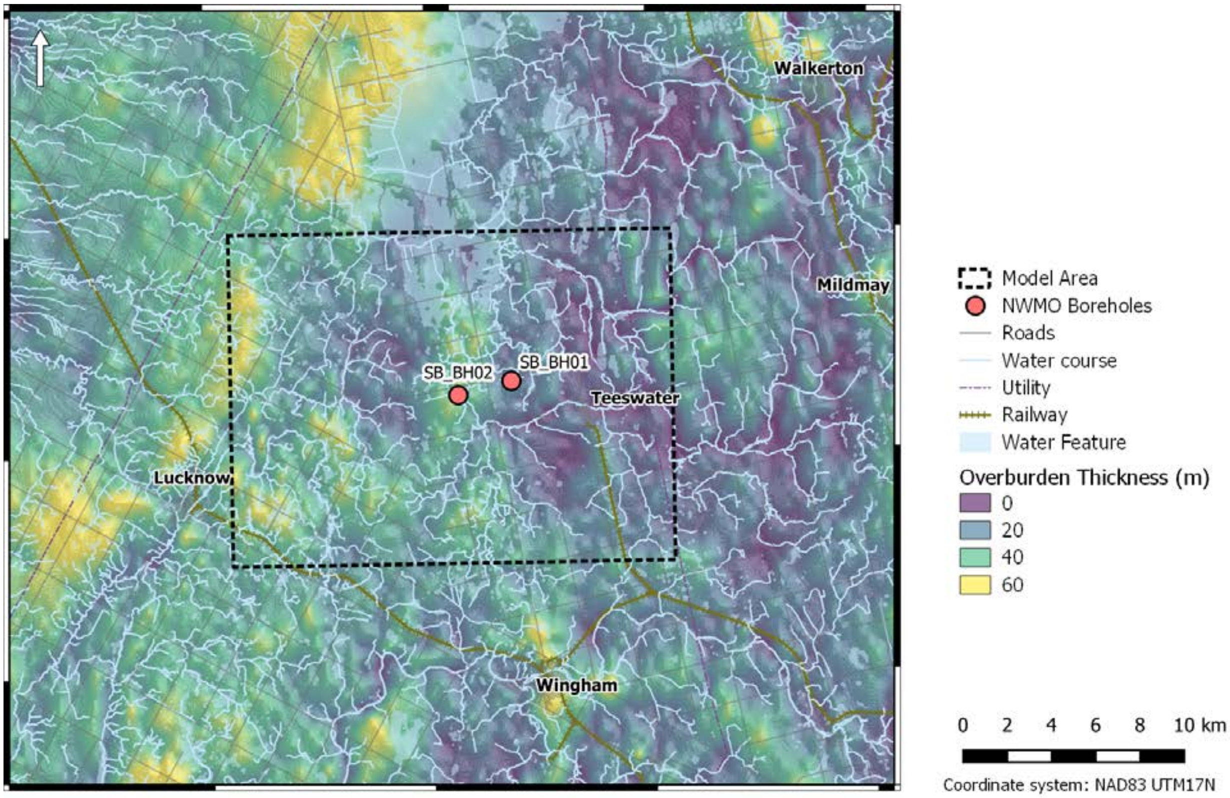


Figure 9. Overburden thickness in the South Bruce model area. Thickness grid adapted from Gao et al. (2006).

3.3 Existing Regional 3D Stratigraphic Model

A regional 3D geological model has been developed by the Geological Survey of Canada, in collaboration with the Ontario Geological Survey, Ontario Ministry of Natural Resource and the Oil Gas and Salt Resources Library (Carter et al. 2019, 2021b). The model encompasses an area of approximately 110,000 km^2 covering all southern Ontario west of the Frontenac Arch, with the exception of Manitoulin Island, and extending beneath the Great Lakes to the international border with the United States. Stratigraphically, the model includes all the Paleozoic bedrock formations of southern Ontario, plus the overburden cover and the Precambrian basement (Figure 10).

Formation top depths recorded in the Ontario Petroleum Data System (OPDS) for petroleum wells drilled in Ontario are the principal source of data for the model, including digital records for approximately 27,000 wells. The quality of the model depends directly on the accuracy and consistency of these formation picks. Therefore, a significant component of the Carter et al. (2021b) work involved reviewing and updating formation top picks based on a systematic criterion applied to each formation across southern Ontario (Armstrong and Carter 2010). Within the South Bruce region, which includes all of Huron County and the southern townships of Bruce County, 6051 formation tops were reviewed for quality assurance (QA) using available geophysical logs, drill cores and chip samples from 292 wells. A total of 3,505 formation picks were edited from picks previously in the OPDS database, and 2,546 picks were included as new additions to the database. The description of data sources and the results of the formation picks quality review for South Bruce region is described in Appendix 5 of Carter et al. (2021b).

The existing regional 3D stratigraphic model (Carter et al. 2021b) provides a main input into the South Bruce geological model. Results consist of formation top markers along the boreholes, modelled stratigraphic formation top surfaces and an enhanced distribution of subcropping formations below the overburden sediment. Stratigraphic surfaces in Carter et al. (2021b) were modelled prior to NWMO drilling boreholes SB_BH01 and SB_BH02. As such, elevations of these stratigraphic surfaces in the modelling work herein are expected to fluctuate in proximity to these new boreholes. Modelled stratigraphic formations were incorporated into the South Bruce geological model as formation top surfaces (dxf format). The sub-cropping formation limits were extracted as closed curves from these surface boundaries at the base of and beneath the overburden layer.

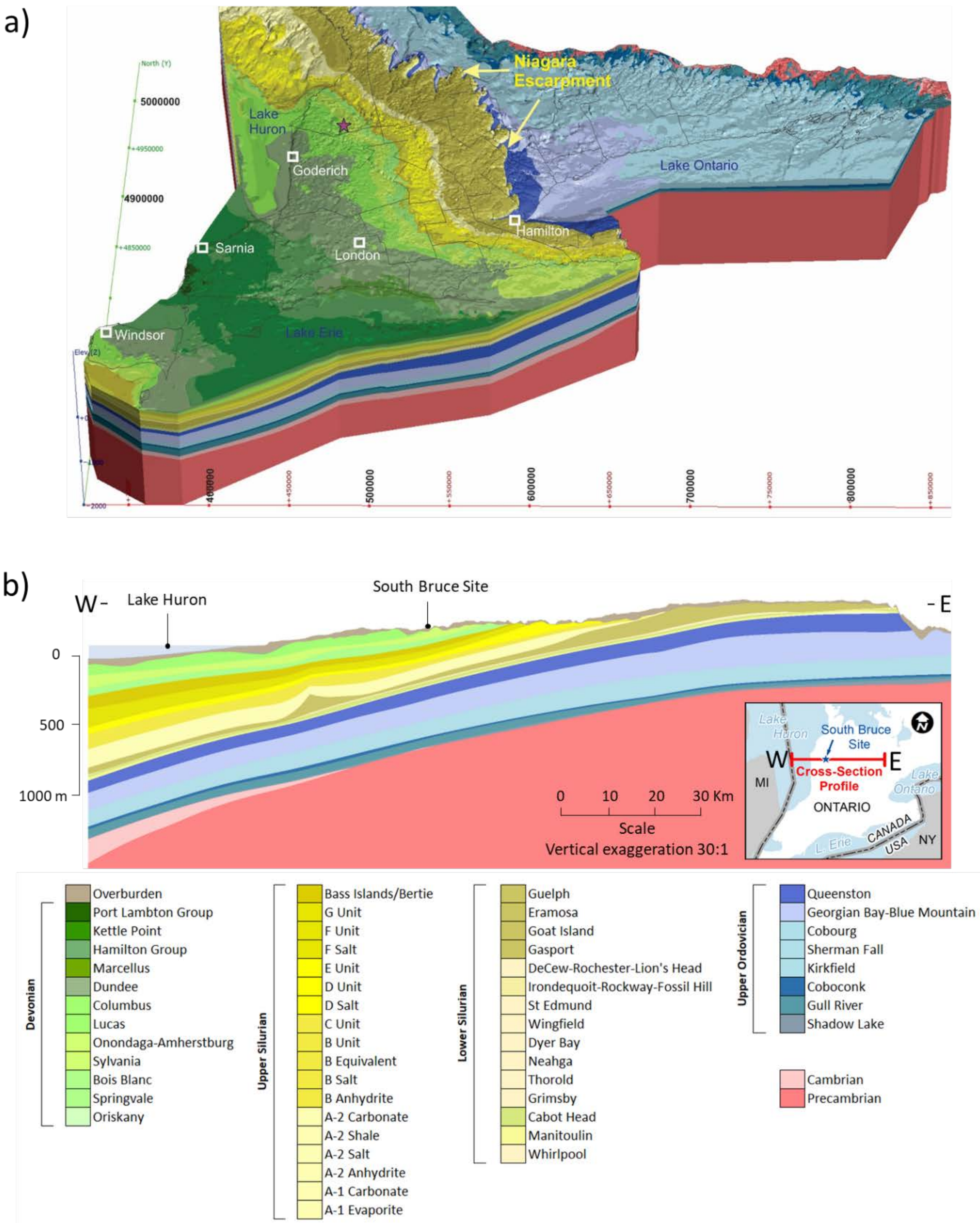


Figure 10. a) Regional 3-D geological model of southern Ontario. The upper boundary of the model view represents the distribution of Paleozoic outcropping or subcropping formations. Star symbol shows South Bruce site. b) An East-West cross section through the model showing westerly dipping stratigraphy (vertical exaggeration 30:1). Modified from Carter et al. (2021b).

3.4 Borehole Formation Top Markers

Formation top markers are a key input into subsurface geological modelling. Formation tops for this study are derived from two separate data sources: 1) geological model of Carter et al. (2021b), including information from six boreholes originally derived from the Ontario Petroleum Data System (OPDS) of the Ontario Oil, Gas and Salt Resources Library (OGSRL), and 2) NWMO borehole database interpreted within the two South Bruce boreholes (SB_BH01 and SB_BH02). The 8 boreholes used for the development of the South Bruce model consist of a total of 208 formation top markers (Table 3). The following section summarizes the sources of the Formation top markers used in this study.

Table 3. Count of formation top picks for each formation in the Paleozoic succession. Formation tops included in this table are from both NWMO and OGSRL boreholes.

Geological Period	Color Legend[2]	Formation and Member	Boreholes: Number of Formation Top Markers
Devonian		Lucas Formation	5
		Amherstburg Formation [1]	6
		Bois Blanc Formation	8
Upper Silurian		Bass Islands Formation	8
		Salina G Unit[1]	7
		Salina F Unit[1]	8
		Salina E Unit[1]	8
		Salina D Unit	6
		Salina C Unit	8
		Salina B Unit	8
		Salina B Unit Equivalent	4
		Salina B Salt	3
		Salina B Unit Anhydrite	6
		Salina A-2 Unit Carbonate	8
		Salina A-2 Salt	1
		Salina A-2 Unit Anhydrite[1]	8
		Salina A-1 Unit Carbonate[1]	8
		Salina A-1 Unit Evaporite	8
Lower Silurian		Guelph Formation	8
		Goat Island Formation [1]	7
		Gasport Formation [1]	7
		Lions Head Formation [1]	7
		Fossil Hill Formation [1]	6
		Cabot Head Formation	6
		Manitoulin Formation	5
Upper Ordovician[3]		Queenston Formation	5
		Georgian Bay Formation [1]	5
		Blue Mountain	5
		Cobourg Formation / Collingwood	5
		Cobourg Formation / Lower Member	
		Sherman Fall Formation	4
		Kirkfield Formation	4

		Coboconk Formation	4
		Gull River Formation [1]	4
		Shadow Lake Formation	4
		Cambrian Sandstone	0
		Precambrian	4

Notes:

1. Formation top depths updated based on drill core observations integrated with geophysical well log data.
2. Color legend assigned to formations and members is consistent with Carter et al. (2021) for the southern Ontario regional lithostratigraphic model.
3. Paleozoic stratigraphic nomenclature has changed between Bruce site drilling (2011) and South Bruce Site (2022). Changes to Ordovician time scale resulted in moving the Middle-Upper Ordovician boundary lower such that all of the strata traditionally referred to as Middle Ordovician in Ontario are now considered Upper Ordovician.

3.4.1 Formation Tops from OGSRL Boreholes

Modelling presented in this report uses a subset of the borehole formation top markers that have been used in Carter et al. (2021b). The South Bruce model area contains six boreholes from the Ontario Petroleum Data System (OPDS) (Table 4 and Figure 11). Two of these boreholes penetrate the entire Paleozoic sedimentary sequence and into the Precambrian basement rock, while the other four boreholes terminate in the Silurian or at the top of Upper Ordovician units. The OGSRL boreholes have been drilled between years 1941 and 1978 and include a limited suite of geophysical well logs, and in some cases only include chip samples collected along the borehole length. The majority of the boreholes in the OGSRL database do not have a deviation survey recorded. As a result, borehole paths for the subset used in this model are vertical, which is a reasonable approximation for the vast bulk of the dataset.

Table 4. Borehole specifications from the OGSRL database

Licence Number	KB[3] Elevation (m)	Ground Elevation (m)	Drilled Depth (m)	Easting[1] (m)	Northing[1] (m)	Location Accuracy[2] (+/- m)	Geophysics
T004604	308.76	307.24	528.52	461635.6	4865951	20	GR, Neutron porosity, density porosity, latero-log deep and shallow, delta -T
T003553	296.27	295.05	511.45	461679.7	4877090.1	20	GR, Neutron
T004881	295.3	294.1	882.7	473530	4869343.5	20	GR, Neutron
F012077[4]	283.5	282.9	726.6	474715.9	4878798.3	50	N/A
F012062	317.3	316.7	870.2	476381.5	4870517.4	50	N/A
F012068	318.5	318.2	323.09	480626.3	4874752	50	N/A

1. Easting and Northing coordinate are in NAD83 UTM17N
2. subjective assignment of the location accuracy obtained from the OGSRL database.

3. KB is the Kelly Bushing/rig floor. Formation depth references in OGSRL are assigned relative to KB.
4. Chip/drill samples and geophysical logs not available for this well. Formation tops obtained from driller forms submitted to OGSRL.

3.4.2 Formation Tops from NWMO Boreholes

As part of the site investigations, NWMO drilled two deep boreholes, SB_BH01 and SB_BH02, within the South Bruce Site (Figure 11). Boreholes SB_BH01 and SB_BH02 were planned to have a vertical path. However, based on measurements from a borehole gyroscopic probe (WP02; Geofirma 2023a; 2023b), there is some deviation measured from the vertical path. The inclination values are typically less than 2 degrees from vertical. For the boreholes drilled by the NWMO, the borehole path is incorporated by calculating position along the borehole using minimum curvature method.

Initial stratigraphic formation tops were interpreted as part of core logging (WP03: Geofirma, 2022a, 2023c), based strictly on drill core observations. However, formation tops can often be obscured by gradational lithological changes, and these changes can be better identified when integrated with an appropriate suite of geophysical well logs. As a result, the formation top picks in SB_BH01 and SB_BH02 were reassessed using core logging data together with geophysical log results (DesRoches et al. 2022; Cachunjua et al. 2023) using an approach that is consistent with the framework defined in Armstrong and Carter (2006, 2010), Intera (2011), and Carter et al. (2021b). Depths of formation top markers are imported into the model as measured depths along the boreholes. Table 5 presents the depth along borehole of the formation tops, and formation thicknesses for the units interpreted in boreholes SB_BH01 and SB_BH02. The A-0 Unit Carbonate is not well mapped in southern Ontario and is better known in Michigan (Armstrong and Carter 2010). Despite picking the A-0 Unit Carbonate in SB_BH02, this formation top is not consistently picked in OPDS due to its thinness and challenges with distinguishing it from the underlying Guelph Formation in the absence of geophysical logs or drill core. In Carter et al. (2021b), where picked, the A-0 Unit Carbonate is grouped together with the Guelph Formation as one model layer. For consistency, the same grouping has been adopted in this report. Similarly, although the Collingwood Member and the Lower Cobourg Member are represented as separate stratigraphic picks in SB_BH01 and SB_BH02, these members are represented here and in Carter et al. (2021b) as the Cobourg Formation. Lastly, despite expecting to intersect Cambrian sandstone at the base of the Paleozoic sedimentary rock, no Cambrian strata were present in either borehole SB_BH01 or SB_BH02 (represented as *NA* in Table 5). Formation descriptions and contacts from the two deep NWMO boreholes are reported in detail in the single borehole integration reports for SB_BH01 (DesRoches et al. 2022) and SB_BH02 (Cachunjua et al. 2023).

Table 5: Summary of top and thickness of formations and members interpreted through an integrated analysis of core observation and geophysical well log data for SB_BH01 and SB_BH02. Presented depths represent position along the borehole.

	Color Legend[2]	Formation and Member	SB_BH01		SB_BH02	
			Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)
	001	Overburden/Surface	0	19.6	0	34.6
Devonian	309	Lucas Formation	19.6	21.45	34.6	54.13
	311	Amherstburg Formation [1]	41.05	33.95	88.73	41.77
	314	Bois Blanc Formation	75	26	130.5	26.41
Upper Silurian	400	Bass Islands Formation	101	33.23	156.91	28.82
	401	Salina G Unit[1]	134.23	8.94	185.73	6.82
	402	Salina F Unit[1]	143.17	43.44	192.55	45.58
	404	Salina E Unit[1]	186.61	22.77	238.13	25.51
	405	Salina D Unit	209.38	2.42	263.64	2.76
	406	Salina C Unit	211.8	12.96	266.4	16.67
	407	Salina B Unit	224.76	6.05	283.07	7.53
	408	Salina B Unit Equivalent	230.81	19.74	290.6	14.39
	410	Salina B Unit Anhydrite	250.55	3.31	304.99	1.98
	411	Salina A-2 Unit Carbonate	253.86	20.14	306.97	25.27
	414	Salina A-2 Unit Anhydrite[1]	274	2.29	332.24	5.34
	415	Salina A-1 Unit Carbonate[1]	276.29	14.86	337.58	38.52
	416	Salina A-1 Unit Evaporite	291.15	0.15	376.1	7.08
	417	Salina A-0 Unit Carbonate	*NA*	*NA*	383.18	3.66
Lower Silurian	418	Guelph Formation	291.3	48.7	386.84	5.02
	421	Goat Island Formation [1]	340	45.12	391.86	16.14
	422	Gasport Formation [1]	385.12	6.08	408	7.3
	427	Lions Head Formation [1]	391.2	3.32	415.3	2.8
	429	Fossil Hill Formation [1]	394.52	1.46	418.1	1.18
	440	Cabot Head Formation	395.98	19.83	419.28	20.82
	441	Manitoulin Formation	415.81	8.56	440.1	9.15
Upper Ordovician[3]	500	Queenston Formation	424.37	84.73	449.25	85.45
	502	Georgian Bay Formation [1]	509.1	86.76	534.7	86.16
		Blue Mountain	595.86	48.91	620.86	48.83
	511	Cobourg Formation / Collingwood Member	644.77	7.88	669.69	7.85
		Cobourg Formation / Lower Member	652.65	39.94	677.54	38.83
	515	Sherman Fall Formation	692.59	45.07	716.37	45.66
	517	Kirkfield Formation	737.66	43.39	762.03	43.6
	519	Coboconk Formation	781.05	21.18	805.63	21.08
	522	Gull River Formation [1]	802.23	52.95	826.71	54.87
	523	Shadow Lake Formation	855.18	5.15	881.58	5.35
	600	Cambrian Sandstone	*NA*	*NA*	*NA*	*NA*
	700	Precambrian	860.33	-	886.93	-

NA = not present

Notes:

1. Formation top depths updated based on drill core observations integrated with geophysical well log data.
2. Color legend assigned to formations and members is consistent with Carter et al. (2021) for the southern Ontario regional lithostratigraphic model.

3. Paleozoic stratigraphic nomenclature has changed between Bruce site drilling (2011) and South Bruce Site (2022). Changes to Ordovician time scale resulted in moving the Middle-Upper Ordovician boundary lower such that all of the strata traditionally referred to as Middle Ordovician in Ontario are now considered Upper Ordovician.

3.4.3 Control Markers along Model Boundary

The geological model objective is to produce a model that conforms to the regional stratigraphic framework model produced by Carter et al. (2021b). To ensure the stratigraphic layers at the boundary of the model coincide with the layers from Carter et al. (2021b), it was important to incorporate a series of control wells along the perimeter of the model boundary. In total, 350 control wells were generated spaced 200 m apart. The elevation of the control boreholes was set at an arbitrary reference elevation of 350 m; high enough to ensure the borehole collar is above ground level. The length of the control boreholes extends to a reference elevation of -900 m (borehole length of 1250 m). This length was chosen to ensure that the boreholes extended through the entire Paleozoic sequence and into the Precambrian basement rocks. Based on the array of control boreholes (Figure 11), stratigraphic markers were extracted where the borehole path intersects with the stratigraphic model layers produced by Carter et al. (2021b). This marker set can be used to ensure the stratigraphic layers modelled here match the stratigraphic layers of Carter et al. (2021b).

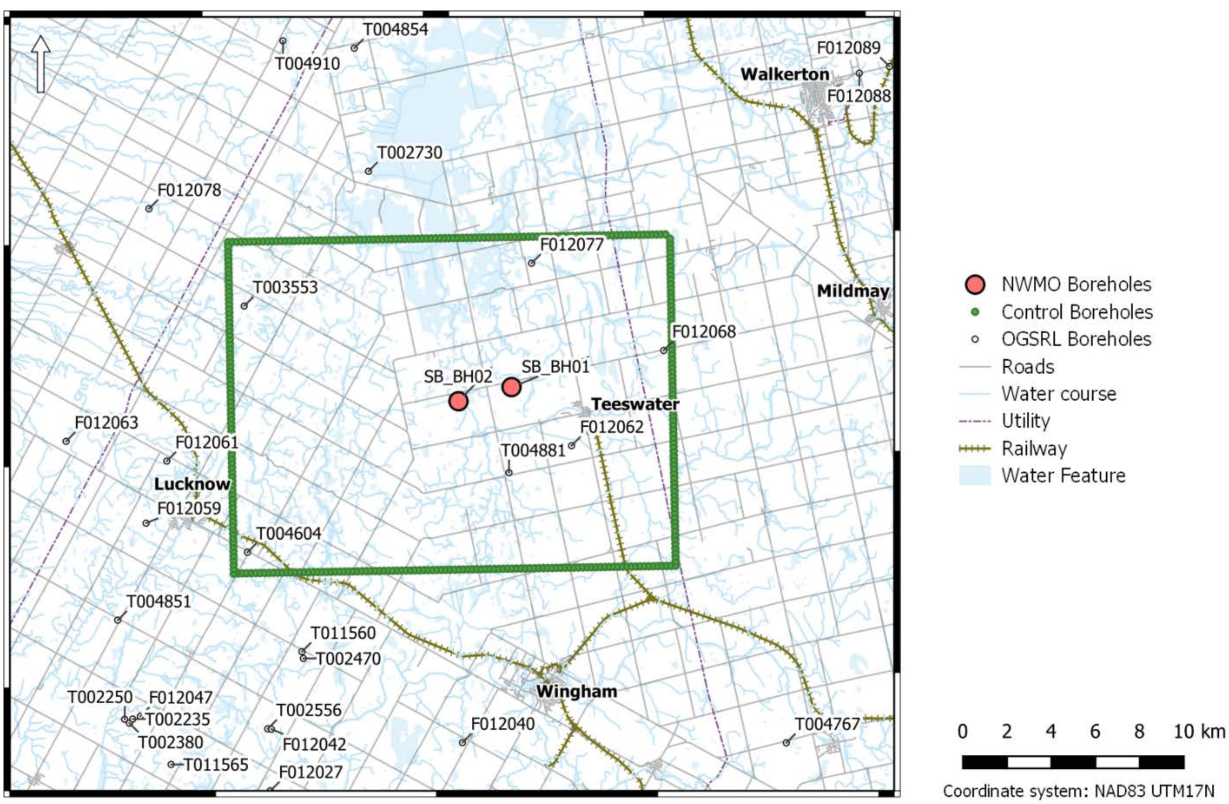


Figure 11. Network of deep boreholes from the OGSRL and NWMO. Around the margin of the model area is an array of control boreholes.

3.5 Available Seismic Reflection Data

As part of the NWMO preliminary site assessment, four available seismic reflection profiles were reprocessed and interpreted resulting in traces for 7 key stratigraphic formations (Geofirma, 2014). These formations represented significant formational boundaries that possess sufficient acoustic impedance contrasts to produce strong seismic reflections. One of the seismic profiles (Line 77-7, Figure 12) exists along the northern margin of the South Bruce model area. The eastern end of this line is located approximately 1 km from borehole F012077, which extends into the Cobourg Formation. Geofirma (2014) noted that the quality of the seismic data along this line is very poor due to the limited number of recording channels and sparse station spacing during acquisition in the 1970s. A seismic anomaly was interpreted along the western end of the profile between receiver stations 5700 and 6300. There was some coincidence noted between this interpreted seismic anomaly and the trace of a mapped subsurface fault. However, given the poor quality and limited lateral resolution of the seismic data at this location, the confidence in the exact location and nature of this fault, including its upward continuation into the Silurian succession, is very low.

To start the interpretation of stratigraphic horizons, a synthetic seismogram was constructed using sonic log data from borehole T007544 (~27 km to the west), as there were no other closer sonic data available. The trace interpretation resulted in picks of the Salina G Unit, the A-2 Unit Carbonate, the combined Cabot Head/Queenston Formations, Cobourg Formation and the Precambrian basement. Most reliable seismic reflectors are the A-2 Unit Carbonate, Cabot Head/Queenston, and the Cobourg Formation. However, due to the overall low quality of the seismic data, the interpretations of stratigraphic horizons have not been used to guide the South Bruce model development. However, deviations from the final model result are evaluated and documented in the uncertainties section.

In 2021, the NWMO acquired a 3D seismic survey in the site area (Figure 12) for the characterization of subsurface stratigraphy and structures (e.g. karst, pinnacles, etc.). The seismic survey area covered an area of approximately 15 km^2 (3400 acres) and the data was processed with a pre-stack time migration sequence. The interpretation of the seismic survey data is ongoing and will be incorporated into future iterations of the 3D geological model.

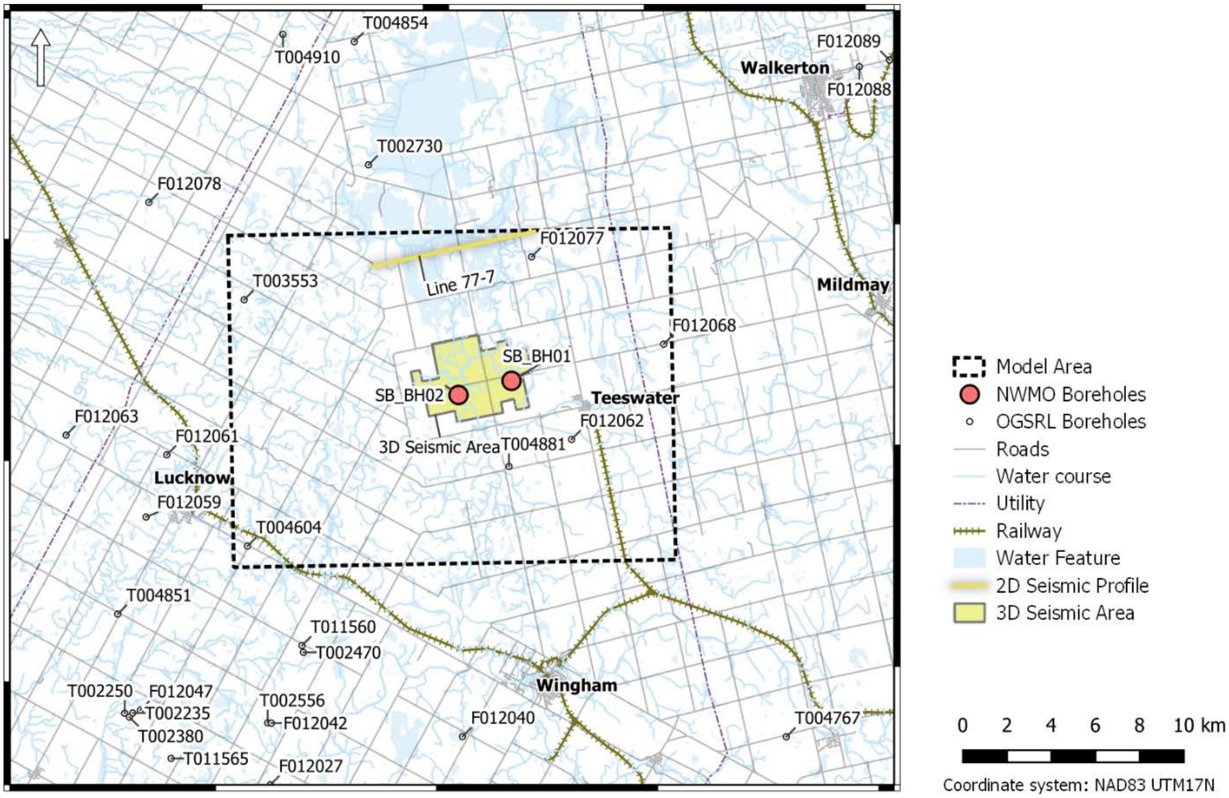


Figure 12. Location of 2D and 3D seismic reflection surveys within the South Bruce site.

3.6 Paleozoic Fault

Information on the location and relative age of potential faults within the Paleozoic bedrock succession are documented in Geofirma (2014). Armstrong and Carter (2010) have compiled basement-seated faults that displace the Paleozoic strata in southern Ontario. These faults are interpreted to originate in the Precambrian basement and propagate upwards through the Paleozoic succession and are classified based on the youngest geological unit that is offset.

There is a single basement-seated fault mapped within the South Bruce model area (Figure 13). The fault is mapped as about 10 km in length and is interpreted to strike east-northeast. The mapped subsurface fault is identified within the Trenton Group limestones and located in the northwest corner of the Municipality of South Bruce and extends west into the Township of Huron-Kinloss. This fault was initially interpreted by Bailey Geological Services Ltd. and Cochrane (1984a; 1984b) based on vertical offsets in structural tops from hand contouring and interpretation of picked formation top information in the OGSRL database. The fault trace was digitized and georeferenced separately by the OGSRL and the OGS based on different raster images. As a result, the interpreted fault has two different georeferenced locations (see Figure 13). This fault is defined based on about a 35 m interpreted offset in one well without geophysical logs, with the closest well (with geophysical logs) being 13 km away

(Geofirma,2014). Given the approach taken to identify this fault, the location of the interpreted fault is only accurate to the well spacing used in the interpretation. Given the sparse borehole data used to identify this Trenton Group fault there is some uncertainty associated to its location, orientation and existence. The fault, assuming it is real, could be located anywhere between the 13 km that separates the two wells.

The borehole geophysical log and 2D seismic assessment conducted by Geofirma (2014) included an assessment of seismic line 725937 (same as Line 77-7) in the Municipality of South Bruce within the model area (Figure 12). Unfortunately, the trend of the seismic line is approximately parallel to the above-mentioned subsurface fault, which is not ideal for imaging horizon offsets or displacements in the seismic data. Despite the line orientation, the assessment of this seismic line identified a seismic anomaly that broadly coincides with the location of the subsurface fault, which provides some confidence in the existence of the fault. However, given the poor quality and limited lateral resolution of the seismic data, the confidence in the exact location and nature of this fault, including its upward continuation into the Silurian succession, is very low.

Despite all the uncertainty in the interpretation, as well as ambiguity in the existence of the fault, this feature is incorporated into the current 3D South Bruce model. The fault trace located closer to the NWMO boreholes was chosen as it represents the closest limit to where this interpreted fault could be located. Other possible interpretations of this fault would be located further north, between boreholes F012077 and T002730.

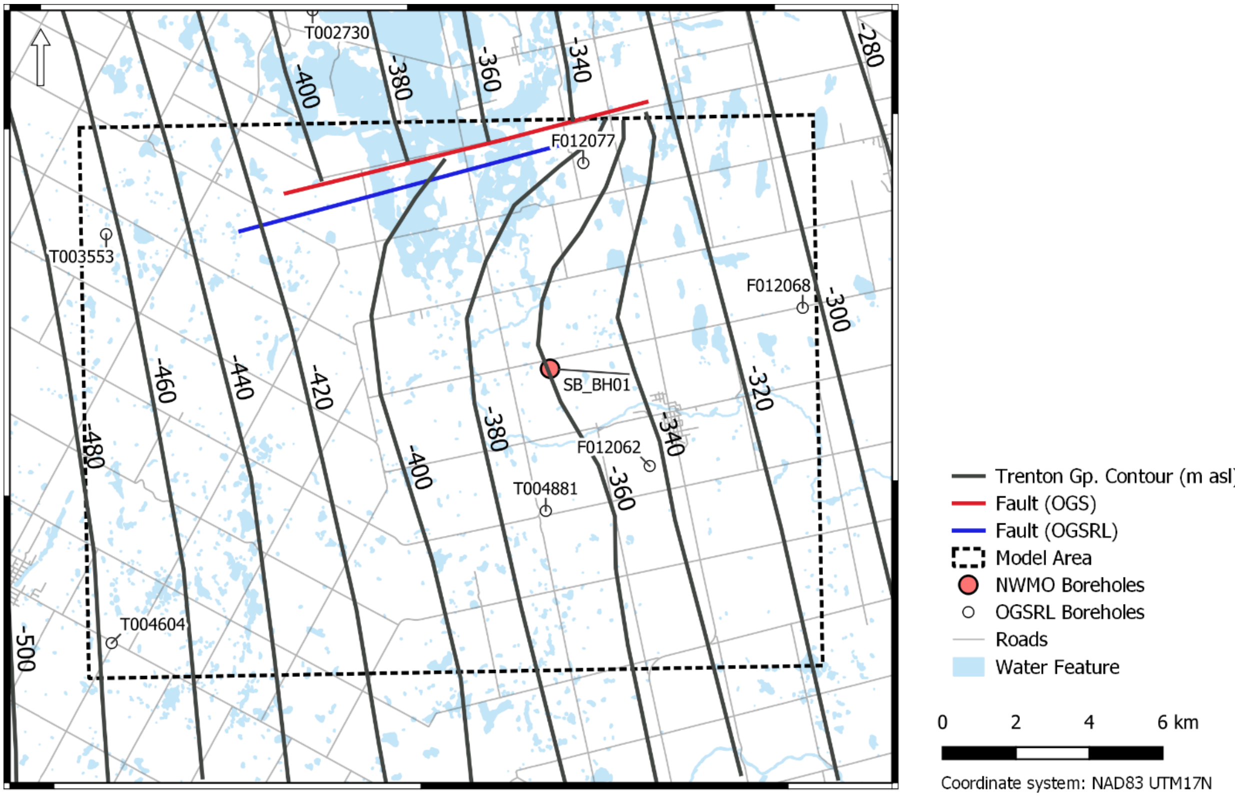


Figure 13. Structure top of Trenton Group in vicinity of South Bruce site, showing interpreted fault locations and structure top of the Trenton Group from Bailey and Cochrane (1984a, b).

4. Development of the Geological Model

Geological models are developed to represent the distribution of surface and subsurface geology and the associated physical rock properties, which can vary from simplistic geometries to complex patterns. Because geological model information is based on glimpses of the subsurface from borehole data, currently without the use of geophysical imaging (e.g., seismic), it is important to iterate the model development as additional information is obtained. Eventually, as additional data is acquired and used in the model, remaining uncertainties will be minimized. Continually updated models will ultimately inform other geoscientific disciplines and will form the framework used in the design of an underground repository and the assessment of long-term safety of the site.

Geological modelling in this study involves integration of geological and geophysical data types, including direct data (e.g., data based on direct observation and measurement) and indirect data (e.g., information based on inferences and interpretations based on expert judgement). The model is developed using input data (described below in Section 4.1) within the GOCAD-SKUA structure and stratigraphic modelling workflow (Figure 14). The workflow enables semiautomated tools through a structured process to accurately model the stratigraphy by constraining the model results directly to the input data and stratigraphic rules defined. The resulting model produces stratigraphic surfaces in which the contacts between the surfaces are completely sealed, and the workflow provides quality control tools for checking results.

Once the stratigraphic model is established the next phase of the workflow is used to construct a geological grid for modelling rock properties (Figure 14). The geological grid consists of a deformed tetrahedral mesh constrained by the geometry of the stratigraphic boundaries. Using the SKUA reservoir modelling module rock properties can be stochastically simulated through the geological formations. This rock property modelling stage will be completed in future model developments.

Figure 14. GOCAD-SKUA structure and stratigraphy workflow for building a stratigraphic model and geological grid.

4.1 Input Data

This section describes the data that was used directly in GOCAD-SKUA as input in the structure and stratigraphy modelling workflow. Within the model extent, formation top markers have been included as input data from 6 wells obtained from the updated OGSRL database. These updated markers are part of the development of the GSC regional stratigraphic model (Carter et al. 2021b). Because the initial objective is to produce a result consistent with the framework of the regional stratigraphic model (Carter et al. 2021b), formation top markers were extracted from the regional stratigraphic surfaces for the array of 350 control boreholes. These markers are consistent with the results of the GSC model. Lastly, markers from two boreholes drilled by the NWMO are incorporated into the model. These markers were interpreted following the picking criteria outlined by Armstrong and Carter (2010). The markers assigned to each stratigraphic horizon are embedded into the tetrahedral mesh prior to building the model. Prior to constructing the surfaces, the workflow ensures the horizons to pass through the markers for each modelled surface.

In order to constrain the extent of modelled stratigraphic surfaces to be consistent with Carter et al. (2021b), outlines are assigned to limit the area of deposition or erosion within the model. For this model, 9 of the 34 Paleozoic surfaces were assigned a boundary used to define the spatial limit of the modelled surface (see Table 6). The boundaries were defined based on the formation limits established in Carter et al. (2021b). The remaining 25 Paleozoic layers extend across the entire model volume.

Along the model boundary, the stratigraphic surfaces are expected to blend seamlessly with the stratigraphic surfaces from the GSC regional stratigraphic model. To achieve this, we incorporated a set of control wells along the boundary of the model area with a spacing between wells of 200 m. Formation tops markers were extracted at depths where the control wells intersected the regional stratigraphic layers modeled from Carter et al. (2021b).

Table 5 presents the formation tops that were interpreted in the NWMO boreholes (SB_BH01 and SB_BH02). Because these boreholes acquired continuous core and a comprehensive suite of geophysical logs, it was possible to identify formations and members that are not consistently picked within boreholes of the OGSRL database. For the modelled formations to be consistent with Carter et al (2021b), some of the interpreted formations in the NWMO boreholes (SB_BH01 and SB_BH02) were combined with adjacent formations. Where the Salina A-0 Unit Carbonate was present in SB_BH02, this formation was combined with the underlying Guelph Formation. Due to the presence of the pinnacle reef in SB_BH01, the Salina A-0 Unit Carbonate was absent. Within the Upper Ordovician rocks, the Georgian Bay and Blue Mountain formations are grouped to form a single model unit, as well, the Collingwood Member and the Lower Member are grouped as the modelled Cobourg Formation. The final combined formations included in the model are presented in Table 6.

4.2 Stratigraphic Column

To model the stratigraphy using the SKUA structure and stratigraphy workflow, the relative importance and chronology, and the stratigraphic termination relationships need to be established within the context of a local stratigraphic column. For southern Ontario the stratigraphic chart was developed by Brunton et al. (2017) and Carter et al. (2017) and was utilized in the development of a southern Ontario Regional Stratigraphic model (Carter et al. 2019, 2021b). The Carter et al. (2021b) stratigraphic model included 53 model stratigraphic layers. For the purpose of this model, 34 Paleozoic model stratigraphic horizons are included as the local stratigraphy, in addition to the Quaternary overburden cover and the Precambrian basement, and are presented in Table 6. The remaining 19 formations from the Carter et al. (2021b) model are not present in the geographic location of South Bruce.

4.3 Modelled Volume of Interest

For the SKUA workflow, it is important to limit the total volume of the model not to exceed the computational resources required to model the stratigraphic surfaces. The top and bottom of the model volume is assigned at an elevation of 400 m and -1000 m, respectively. The lower boundary of the model volume exceeds the total vertical depth of the top of the Precambrian surface. This depth is chosen to ensure the entire Paleozoic sequence contained within the model extent, as well ensure a sufficient volume of the Precambrian rock is characterized, which will both be used for modelling by other NWMO functional groups. The lateral boundaries are defined consistent with the model area presented in Figure 2 with an expansion of 0.05%, which is the equivalent to an extra 500 m on the eastern and western boundaries, and 375 m on the northern and southern boundaries. Once the final model is constructed, the additional surface area will be clipped using a vertical domain boundary.

4.4 Modelled Stratigraphic Surfaces

Following the structure and stratigraphy workflow, stratigraphic surfaces are built by computing a scalar field across the model volume of interest on a tetrahedral mesh. The tetrahedral mesh was defined using areal and vertical mesh resolution of 200 m by 100 m. At well marker locations, nodes are inserted into the tetrahedral mesh at the locations of formation tops identified in boreholes. Following the defined chronological succession of formations, their stratigraphic relationships and depositional limits, surfaces are extracted from a 3D scalar field as equipotential surfaces. The surfaces are extracted from bottom (oldest) to top (youngest) and terminate against each other following the stratigraphic relationships and sequence order. Before building the entire stratigraphic model, formation surfaces or groups of surfaces were modelled in preview mode to identify potential errors or inconsistencies in the modelling parameters or input data. These errors can be fixed in preview mode. Once all errors are fixed, the entire stratigraphic model is built in one step.

Table 6. Stratigraphic column highlighting formation top markers and depositional and/or erosional outlines.

Geological Period	Stratigraphic Sequence		Depositional/Erosional Outlines
	001	Overburden/Surface	
Devonian	309	Lucas Formation	Y
	311	Amherstburg Formation [1]	
	314	Bois Blanc Formation	
Upper Silurian	400	Bass Islands Formation	
	401	Salina G Unit[1]	Y
	402	Salina F Unit[1]	
	404	Salina E Unit[1]	
	405	Salina D Unit	Y
	406	Salina C Unit	
	407	Salina B Unit	
	408	Salina B Unit Equivalent	Y
	409	Salina B Unit Salt	Y
	410	Salina B Unit Anhydrite	Y
	411	Salina A-2 Unit Carbonate	
	413	Salina A-2 Unit Salt	Y
	414	Salina A-2 Unit Anhydrite[1]	
	415	Salina A-1 Unit Carbonate[1]	
	416	Salina A-1 Unit Evaporite	Y
Lower Silurian	418	Guelph Formation	
	421	Goat Island Formation [1]	
	422	Gasport Formation [1]	

	427	Lions Head Formation [1]	
	429	Fossil Hill Formation [1]	
	440	Cabot Head Formation	
	441	Manitoulin Formation	
Upper Ordovician[3]	500	Queenston Formation	
	502	Georgian Bay-Blue Mountain Formation [1]	
	511	Cobourg Formation *	
	515	Sherman Fall Formation	
	517	Kirkfield Formation	
	519	Coboconk Formation	
	522	Gull River Formation [1]	
	523	Shadow Lake Formation	
	600	Cambrian Sandstone	Y
	700	Precambrian	

Y = Yes.

Notes:

1. Formation top depths updated based on drill core observations integrated with geophysical well log data.
2. Color legend assigned to formations and members. Color template is consistent with Carter et al. (2021b) for the southern Ontario regional lithostratigraphic model.
3. Paleozoic stratigraphic nomenclature has changed between Bruce site drilling (2011) and South Bruce Site (2022). Changes to Ordovician time scale resulted in moving the Middle-Upper Ordovician boundary lower such that all of the strata traditionally referred to as Middle Ordovician in Ontario are now considered Upper Ordovician.

Figure 15 presents the results of the formation top surfaces extracted from the implicit scalar field within the volume of interest (15x vertical exaggeration). These results represent smooth surfaces that perfectly honour the formation top markers along the boreholes. Figure 15a shows an oblique view looking towards the northeast of the stratigraphic surfaces from the Precambrian basement upwards through to the overlying Quaternary overburden sediments. The blue vertical plane represents the cross-section location through the model, intersecting boreholes SB_BH01 and SB_BH02. The cross-section presented in Figure 15b shows a vertical slice through the model from west (left) to east (right) with the stratigraphic layers dipping shallowly towards the west. The Guelph Formation shows an anomalous thickness within SB_BH01 interpreted as a pinnacle reef (DesRoches et al. 2022). The modelled lateral geometry of the reef structure within the Guelph Formation is approximately 4 x 5 km but is only controlled by the proximity to neighbouring boreholes (Figure 16). It is highly likely that the reef structure is much smaller than this approximation and that structural interpretation and petrophysical inversion from the 3D seismic data will provide a better interpretation of this feature.

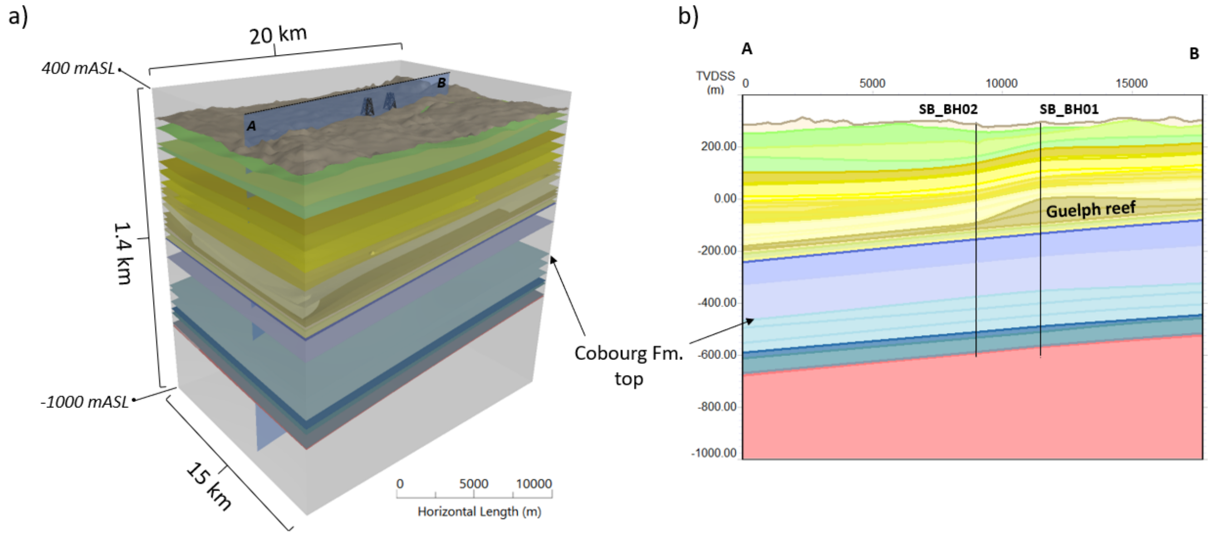


Figure 15. Modelled stratigraphic formation tops from SKUA implicit workflow. a) 3D oblique view of stratigraphic formation top surfaces with top of Cobourg Formation identified. b) cross section view through model intersecting boreholes SB_BH01 and SB_BH02 and showing the result of the pinnacle reef within the Guelph Formation of the Lockport Group intersected in borehole SB_BH01. Vertical exaggeration is 15x.

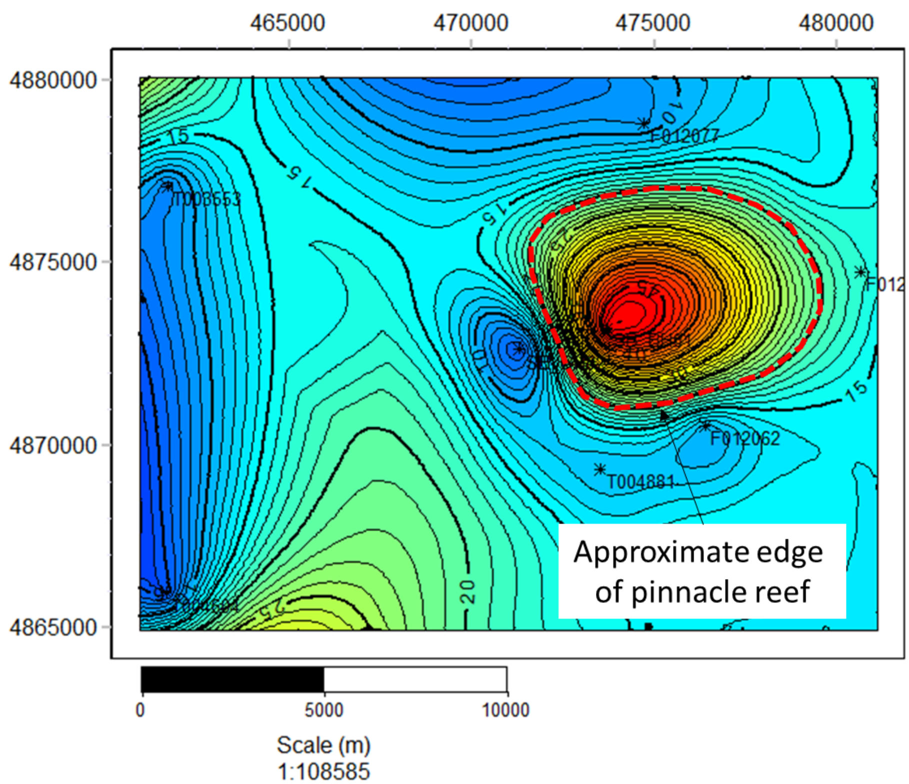


Figure 16. Modelled Stratigraphic thickness of Guelph Formation, in metres. Red dashed outline shows approximate edge of pinnacle reef.

4.4.1 Quality Checks

After the stratigraphic surfaces are built, the results can be qualitatively reviewed by visual inspection for artifacts, and quantitatively reviewed to evaluate the fit to the input data. There are two types of data to evaluate the fit: 1) the soft input data, such as modelled surfaces, and 2) the hard input data, such as borehole formation top markers. Although the GSC (Carter et al. 2021) modelled surfaces were used to guide the implicit function for some of the formations, the degree of fit was set to moderate. The objective was to gently guide the interpolation, but not to perfectly honour the fit from the modelled surfaces of Carter et al. (2021b). However, the modelled surfaces were conditioned to perfectly fit to the formation markers in boreholes. As a result, there was zero mismatch between the surfaces and the borehole formation top markers.

4.5 3D Stratigraphic Model Results

The South Bruce geological model is 20 km by 15 km and extends from elevation of -1000 to 400 m relative to mean sea level. The formations in the model are consistent with a regional stratigraphic model produced by Carter et al. (2021b). Formations modelled here comprise an update to the modelling work of Carter et al. (2021b) based on the input of new boreholes formation top data from SB_BH01 and SB_BH02 drilled by the NWMO. Table 7 presents summary statistics such as the mean, standard deviation, maximum formation thickness, and formation volume. Because the Precambrian unit extends to the base of the model, the thickness and volume is only representative of the portion of the geological unit included in the model.

Table 7. Summary of mean , standard deviation, maximum formation thickness, and formation volumes calculated from the surfaces through the South Bruce model.

Formation		Mean Formation Thickness (m)	Standard Deviation (m)	Max Formation Thickness (m)	Formation Volume (Km^3)
001	Overburden/Surface	25.54	12.34	62.97	7.76
309	Lucas Formation	48.55	20.01	79.68	11.02
311	Amherstburg Formation	43.30	11.42	70.75	13.26
314	Bois Blanc Formation	43.59	10.25	71.45	13.34
400	Bass Islands Formation	38.11	3.98	47.13	11.70
401	Salina G Unit	5.73	2.30	11.32	1.615
402	Salina F Unit	43.79	4.04	49.40	13.407
404	Salina E Unit	23.15	7.34	37.59	7.084
405	Salina D Unit	8.41	5.02	21.59	1.78
406	Salina C Unit	14.24	5.64	31.37	4.356
407	Salina B Unit	10.52	6.22	28.67	3.22
408	Salina B Unit Equivalent	16.29	8.30	34.98	3.022
409	Salina B Unit Salt	17.45	11.11	41.93	1.573
410	Salina B Unit Anhydrite	11.45	5.24	28.71	2.928
411	Salina A-2 Unit Carbonate	33.48	9.93	69.77	10.25
413	Salina A-2 Unit Salt	3.09	2.11	8.10	0.006
414	Salina A-2 Unit Anhydrite	5.16	3.63	20.97	1.578

415	Salina A-1 Unit Carbonate	29.19	10.67	45.03	8.931
416	Salina A-1 Unit Evaporite	5.02	3.30	12.74	1.186
418	Guelph Formation [3]	16.40	7.08	48.01	5.018
421	Goat Island Formation	14.38	8.79	46.15	4.245
422	Gasport Formation	5.28	1.75	20.46	1.614
427	Lions Head Formation	5.12	1.73	10.95	1.568
429	Fossil Hill Formation	2.91	1.19	7.98	0.889
440	Cabot Head Formation	21.04	2.26	32.67	6.436
441	Manitoulin Formation	9.04	0.55	10.73	2.766
500	Queenston Formation	90.26	8.50	117.38	27.621
502	Georgian Bay-Blue Mountain Formation	141.45	7.21	154.72	43.307
511	Cobourg Formation (Collingwood and Lower Members) [2]	33.13	7.32	48.41	10.147
515	Sherman Fall Formation	51.11	4.39	60.78	15.647
517	Kirkfield Formation	39.75	2.52	46.13	12.17
519	Coboconk Formation	18.40	4.09	22.45	5.63
522	Gull River Formation	56.17	2.19	63.89	17.194
523	Shadow Lake Formation	6.77	1.86	13.83	2.069
600	Cambrian Sandstone	2.71	1.50	6.89	0.112
700	Precambrian[1]	401.43	50.47	496.64	122.863

[1] *Thickness and volume calculations for the Precambrian are limited between the surface top and the base of the model*

[2] *Cobourg Formation comprises both the Collingwood and Lower Members.*

[3] *Guelph Formation in the model incorporates the thin overlying A-0 Unit Carbonate. This is consistent with the approach taken by Carter et al. (2021b).*

4.5.1 Precambrian and Cambrian

The Precambrian unit unconformably underlies the Paleozoic succession of southwestern Ontario. In SB_BH01 and SB_BH02 the Precambrian rocks consist of a medium to coarse grained syenitic to granitic gneiss which is picked based on a sharp unconformable contact between sedimentary rock and metamorphic crystalline rock. In the SB_BH01 and SB_BH02 core, the contact represents a change from glauconitic silty/sandstone of the Shadow Lake to pink and banded gneiss (Precambrian).

Throughout southern Ontario the Cambrian Sandstone is also interpreted to unconformably overlie the Precambrian and pinches out along the western and eastern flanks of the Algonquin Arch (Armstrong and Carter, 2010; Carter, 2023). The interpreted distribution of the Cambrian Sandstone is controlled by the well distribution from the OGSRL database. Despite the Cambrian unit being present in the model results of Carter et al. (2021b), new results from SB_BH01 and SB_BH02 indicate that the Cambrian Sandstone is absent from these boreholes. Given that no evidence of the Cambrian Sandstone was encountered in the boreholes, the actual zero thickness edge of the Cambrian is reinterpreted to occur further to the northwest than previously considered, in agreement with Carter (2023). Within the model extent, the Cambrian Sandstone overlies the Precambrian only within the northwestern portion of the model area with a mean thickness of 2.71 m (Figure 17).

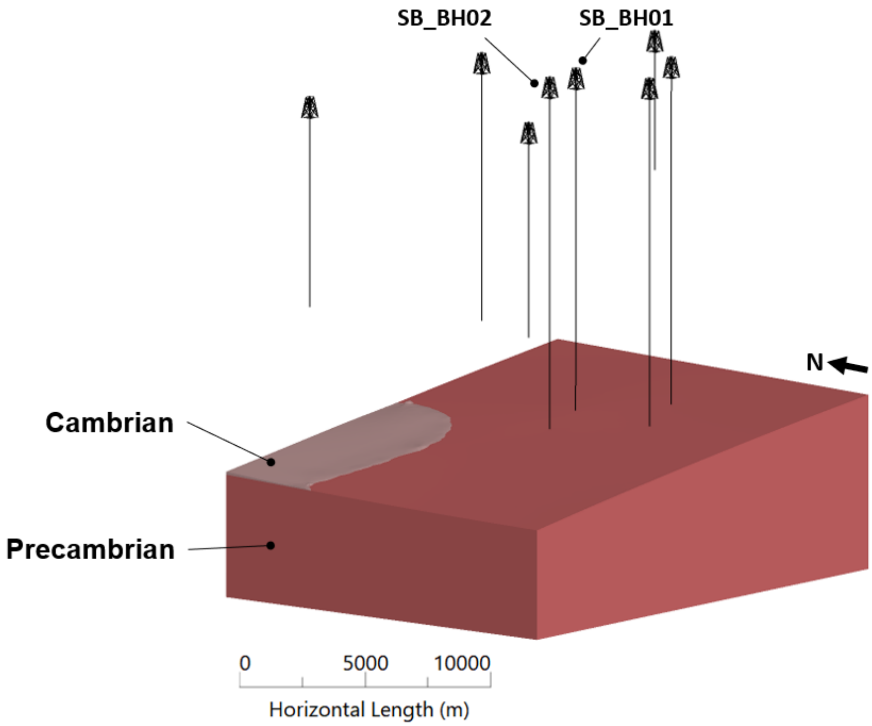


Figure 17. The Precambrian unit representing the crystalline basement rock, and the overlying undifferentiated Cambrian unit at the base of the Paleozoic succession. Vertical exaggeration is 15x.

4.5.2 Upper Ordovician Formations

The Upper Ordovician formations in the model include the Shadow Lake Formation through to the Queenston Formation (Figure 18). The Queenston and Georgian Bay/Blue Mountain formations mainly consist of shales with subordinate interbeds of fossiliferous limestone, and calcareous siltstone and/or sandstone. The underlying Cobourg, Sherman Fall, Kirkfield, Coboconk, Gull River and Shadow Lake formations mainly comprise argillaceous and fossiliferous limestone with shale interbeds. In the model, the Cobourg Formation is made up of the Collingwood Member and the Lower Member. In both boreholes SB_BH01 and SB_BH02, the Collingwood Member is 7.88m and 7.85 m thick, respectively, and overlies the Lower Member of the Cobourg Formation (Table 5). As a result, the top of the Lower Member of the Cobourg is first encountered approximately 7.9 m below the top of the modelled Cobourg Formation surface.

The Upper Ordovician stratigraphic units appear to have a near uniform thickness and extend across the model volume. Table 8 presents the average formation thickness from the South Bruce model as well as from boreholes at the OPG-DGR site and the South Bruce site. The Georgian Bay/Blue Mountain formation comprise the most significant thickness with a mean value of 141.45 m. This model value is comparable to the thickness of the Georgian Bay/Blue Mountain formation in the South Bruce boreholes as well as the OPG-DGR boreholes located approximately 30 km to the west-northwest, along the shore of Lake Huron. Overlying the Georgian Bay/Blue Mountain formations is the Queenston Formation with an additional thickness of 86.41 m. These stratigraphic units are composed of predominantly shales with lesser amounts of argillaceous limestones and represent a significant caprock to the Lower Member of the Cobourg Formation, which represents the target formation for the development of a deep geological repository (DGR).

The total thickness of the Upper Ordovician in the model area is 434 meters (sum of thickness values from each individual Ordovician formation, see Table 5). Based on the two boreholes drilled at the South Bruce site (SB_BH01 and SB_BH02), the thickness of the Upper Ordovician stratigraphy is approximately 436.82 m. Similarly, at the OPG-DGR site, the Upper Ordovician formations had a thickness of 395.1 m (Table 8), based on the sum of borehole formation thicknesses from DGR boreholes 1 through 6 at that site (Intera, 2011). This comparison illustrates that regardless of location, the thickness of individual Ordovician formations is regionally consistent, which demonstrates the continuity of these shale and limestone formations.

Table 8. Mean formation thickness from South Bruce model compared to OPG-DGR and South Bruce boreholes for the Upper Ordovician.

Formation		Modelled Mean Formation Thickness (m)	OPG-DGR Formation Thickness (m)[1]	South Bruce Formation Thickness (m)[2]
500	Queenston Formation	90.26	70.30	85.09
502	Georgian Bay-Blue Mountain Formation	141.45	133.60	135.33
511	Cobourg Formation (Collingwood and Lower Members)[3]	33.13	35.90	47.25
515	Sherman Fall Formation	51.11	28.80	45.36
517	Kirkfield Formation	39.75	45.85	43.49
519	Coboconk Formation	18.40	23.35	21.13
522	Gull River Formation	56.17	52.20	53.91
523	Shadow Lake Formation	6.77	5.10	5.25
	Sum of all Formations	**437.03**	**395.1**	**436.82**

[1] *OPG-DGR formation thickness are mean values from boreholes at the Bruce Power Plant (Intera 2011).*

[2] *South Bruce formation thickness are mean values from boreholes SB_BH01 and SB_BH02, drilled by NWMO at the South Bruce site.*

[3] *Cobourg Formation comprises both the Collingwood and Lower Members.*

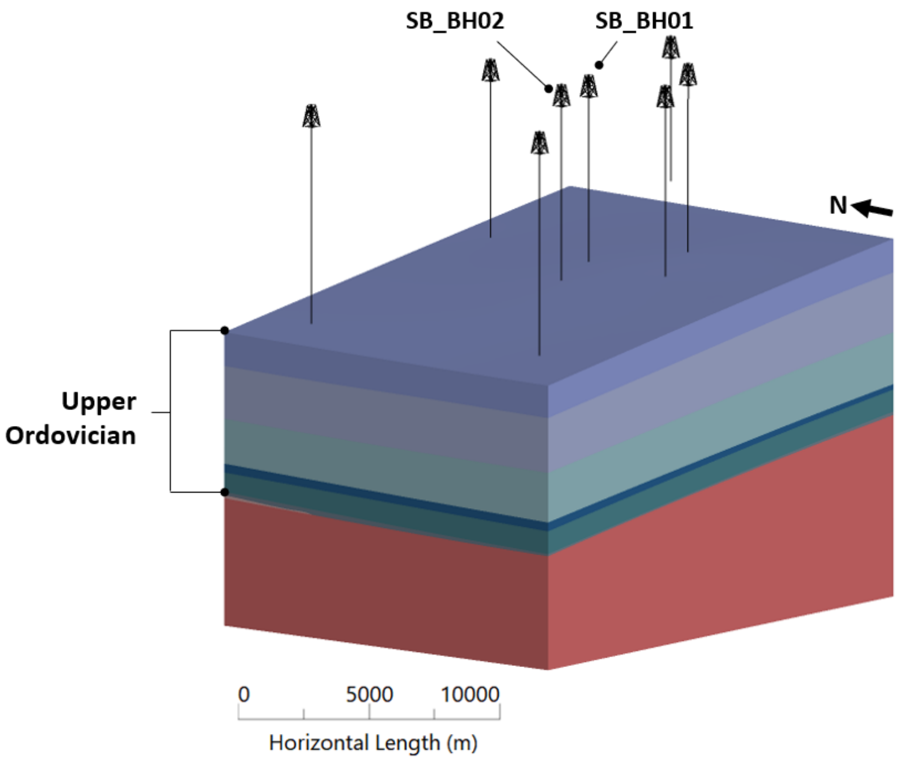


Figure 18. The Upper Ordovician-aged formations (Shadow Lake, Gull River, Coboconk, Kirkfield, Sherman Fall, Cobourg, Georgian Bay/Blue Mountain and Queenston Formations) overlying the older Paleozoic succession and the Precambrian. Vertical exaggeration is 15x.

4.5.3 Lower Silurian Formations

The Lower Silurian formations comprise the Manitoulin Formation through to the Guelph Formation, which overlies the Queenston Formation of the Upper Ordovician succession (Figure 19). The formations packaged together form the Lockport, Clinton and Medina groups consisting of alternating intervals of shale and limestone in the South Bruce model area. The Lower Silurian is also characterized by widespread carbonate deposition of the Lockport Group (Guelph, Goat Island and Gasport formations) and regionally consisting of reefal carbonates of the Guelph Formation. Table 9 presents a comparison between the mean formation thickness in the South Bruce model and the thicknesses from boreholes at the OPG-DGR and the South Bruce sites.

In terms of the upper sections of the Lower Silurian formations, a few key observations can be made. Overall, the formation thicknesses are similar between the model and the boreholes at the OPG-DGR and South Bruce sites. The main exception is that the Goat Island and the Guelph formations logged at the OPG-DGR site are only similar to the thicknesses logged in SB_BH02. These thicknesses are considered similar to formation thicknesses mapped regionally for these two formations within the interpinnacle karst belt (Armstrong and Carter.

2010, Carter et al. 2021b). However, SB_BH01 presents an anomalous thickness of the Goat Island and Guelph formations as a result of intersecting an interpreted pinnacle reef. The calculation of mean formation thickness in the model for the Guelph formation is also greater than the regional average because of the inclusion of the pinnacle reef. Though this discrepancy is large, it is a result of an expected local-scale variability in thickness of the Guelph and surrounding formations.

Table 9. Mean formation thickness from South Bruce model compared to OPG-DGR and South Bruce boreholes for the Lower Silurian.

Formation		Modelled Mean Formation Thickness (m)	OPG-DGR Formation Thickness (m)[1]	SB_BH01 Formation Thickness (m)	SB_BH02 Formation Thickness (m)
418	Guelph Formation [2]	16.40	8.1	48.7	8.68
421	Goat Island Formation	14.38	18.5	45.12	16.14
422	Gasport Formation	5.28	6.8	6.08	7.3
427	Lions Head Formation	5.12	4.4	3.32	2.8
429	Fossil Hill Formation	2.91	2.3	1.46	1.18
440	Cabot Head Formation	21.04	23.8	19.83	20.82
441	Manitoulin Formation	9.04	12.8	8.56	9.15
	Sum of all Formations	**74.16**	**76.7**	**133.07**	**66.07**

[1] *OPG-DGR formation thickness are mean values from boreholes at the Bruce Power Plant (Intera 2011).*

[2] *Guelph Formation in the model incorporates the thin overlying A-0 Unit Carbonate. This is consistent with the approach taken by Carter et al. (2021b).*

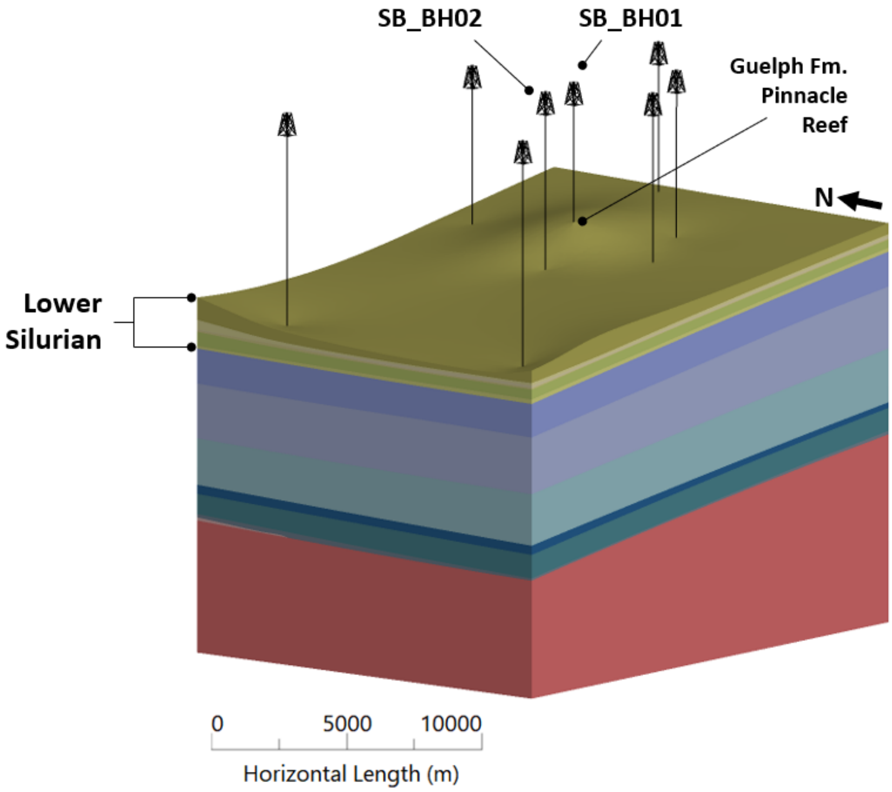


Figure 19. The Lower Silurian formations (Manitoulin, Cabot Head, Fossil Hill, Lion's Head, Gasport, Goat Island and Guelph Formations) overlying the older Paleozoic succession. Vertical exaggeration is 15x.

The formations within the Lockport Group belong to a distinctive series of lithofacies belts which resulted from complex depositional, erosional and diagenetic history (Brunton and Brintnell 2020, Carter 2023). The generally accepted paleoenvironmental interpretation of the Lockport Group stacked carbonates is of a subsiding Michigan Basin occupied by relatively deep water, fringed by an encircling belt of pinnacle reefs that grew in the shallower water on the sloping margins of the basin, which was in turn encircled by a barrier reef/ patch reef complex (e.g. Sanford 1969; Mesolella et al. 1974; Gill 1977; Gardner and Bray 1984; Rine et al 2017; Ritter and Grammar 2017; Trout et al. 2017). An alternative interpretation of pinnacle reefs as "karst towers" is proposed by Brunton and Brintnell (2020).

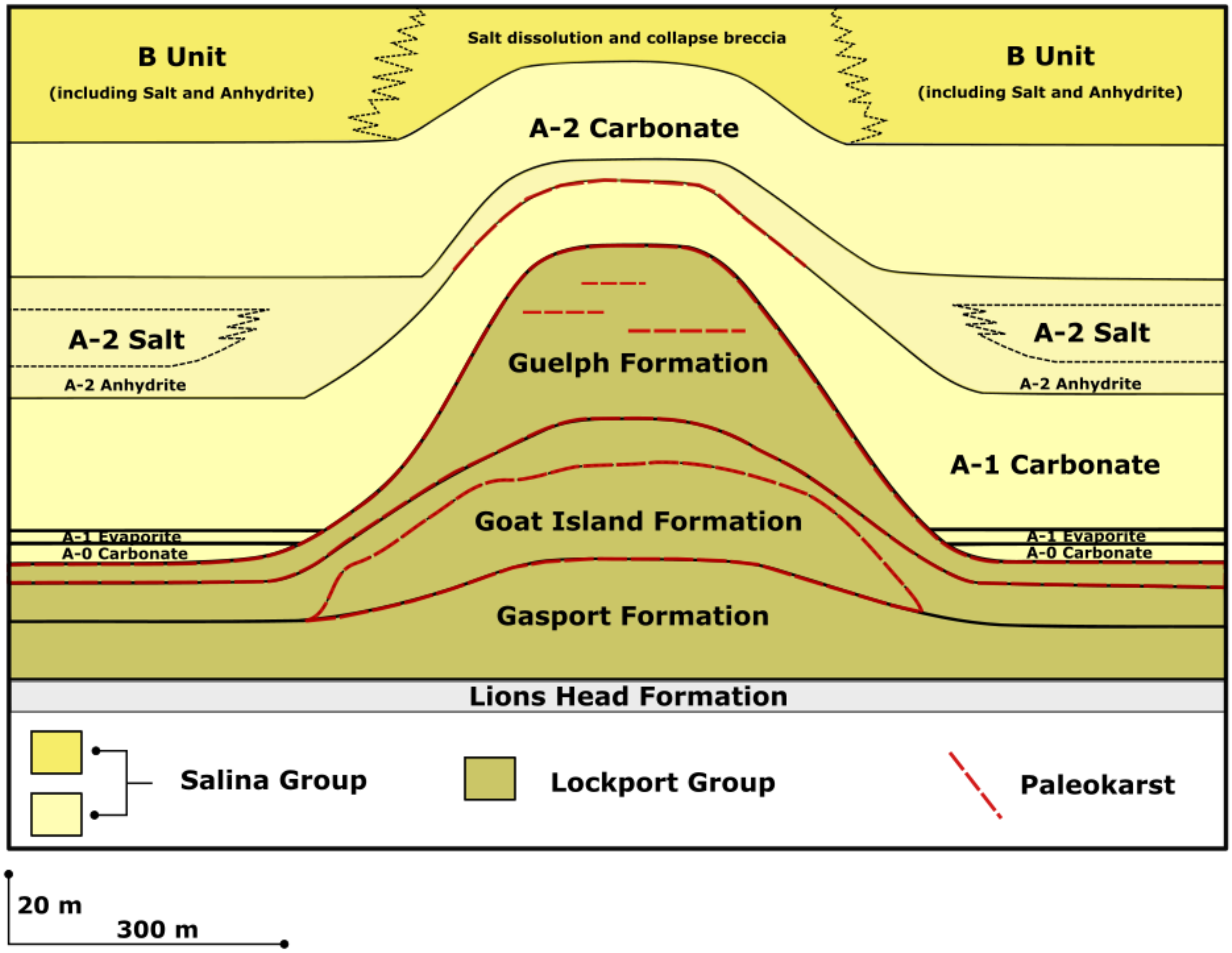


Figure 20. Conceptual model of a Guelph pinnacle reef showing stratigraphic, lithological and structural relationships with regional strata of the Lockport Group and lower Salina Group, within the Pinnacle and Interpinnacle Karst Belt of southern Ontario. Modified and adapted from Brintnell (2012), Brunton and Brintnell (2020), Carter et al. (2021b) and Carter (2023).

The Lockport Group carbonates vary in thickness by several tens of meters due to complex lateral variations in depositional environments and an extensive penetrative karstic erosional event post-dating deposition of the Guelph Formation (Carter 2023). Figure 20 shows a conceptual model of lithological and structural relationship between the formations within the Lockport Group. The thickness of the Guelph and Goat Island formations in SB_BH01 are largely attributed to the presence of the pinnacle reef, which causes a local anomaly in thickness. In southern Ontario, the Goat Island Formation is a regionally extensive rock unit that forms the fossiliferous core (reef base) for many of the stacked carbonate structures referred to as pinnacle reefs (Brunton and Brintnell 2020).

4.5.4 Upper Silurian Formations

The Upper Silurian Salina Group is characterized by a succession of evaporites and carbonates (Figure 21) deposited in a hypersaline, restricted marine environment (Armstrong and Carter 2010). The Upper Silurian is capped by the Bass Islands formation, which is the uppermost formation of the Upper Silurian.

Overall, the thickness of the Upper Silurian Formations is broadly consistent between the South Bruce model, the OPG-DGR boreholes and the South Bruce boreholes. Despite the similarity, there are a few key differences that are noted. The most significant difference is the thinning of the Salina A-1 carbonates and evaporites noted in SB_BH01. This thinning is attributed to the anomalous thickness of the underlying Guelph Formation in this borehole due to the presence of a pinnacle reef. The average of the South Bruce model and the thicknesses observed in the OPG-DGR boreholes and in SB_BH02 are similar, with a combined thickness of approximately 35 to 45 m (combined Salina A-1 units). The differences in thickness of the Salina A-1 Unit Carbonate is similarly expressed as an overall difference in the total thickness of the Upper Silurian formations, as previously mentioned, due to the pinnacle reef intersected in SB_BH01.

Although the Salina A-2 Salt and the Salina B Salt are present as stratigraphic units in the South Bruce model, these units are not present in either of the South Bruce boreholes drilled by NWMO, nor the boreholes drilled at the OPG-DGR site. In the model, these units are interpreted to intersect boreholes from the OGSRL database.

Regional stratigraphic modelling by Carter et al. (2021b) suggests that several Upper Silurian formations are not laterally continuous across the entire South Bruce model area. This is the result of eastward thinning/pinchout and facies changes, and post-depositional dissolution of salt beds, in particular in the B Salt (Carter 2023). Since the South Bruce model is conditioned to the regional stratigraphic model, the results here present similar formational boundaries for the Salina G Unit, D Unit, B Equivalent Unit, B Unit, B Anhydrite, B Salt, A-2 Salt and the A-1 Unit Evaporite where these units do not extend eastward across the entire model area.

Table 10. Mean formation thickness from South Bruce model compared to OPG-DGR and South Bruce boreholes for the Upper Silurian

Formation		Modelled Mean Formation Thickness (m)	OPG-DGR Formation Thickness (m)[1]	SB_BH01 Formation Thickness (m)	SB_BH02 Formation Thickness (m)
400	Bass Islands Formation	38.11	44.20	33.23	28.82
401	Salina G Unit	5.73	8.60	8.94	6.82
402	Salina F Unit	43.79	43.00	43.44	45.58
404	Salina E Unit	23.15	20.10	22.77	25.51
405	Salina D Unit	8.41	1.60	2.42	2.76
406	Salina C Unit	14.24	14.70	12.96	16.67
407	Salina B Unit	10.52	28.80 [2]	6.05	7.53
408	Salina B Unit Equivalent	16.29	NA	19.74	14.39
409	Salina B Unit Salt	17.45	NA	NA	NA
410	Salina B Unit Anhydrite	11.45	1.90	3.31	1.98
411	Salina A-2 Unit Carbonate	33.48	27.90	20.14	25.27
413	Salina A-2 Unit Salt	3.09	NA	NA	NA
414	Salina A-2 Unit Anhydrite	5.16	5.20	2.29	5.34
415	Salina A-1 Unit Carbonate	29.19	41.10	14.86	38.52
416	Salina A-1 Unit Evaporite	5.02	4.40	0.15	7.08
	Sum of all Formations	**265.07**	**241.50**	**190.30**	**226.27**

[1] *OPG-DGR formation thickness are mean values from boreholes at the Bruce Power Plant (Intera 2011).*

[2] *Thickness of the Salina B unit at the OPG-DGR site was not subdivided further into Salina B Unit Equivalent, which is likely the cause of the anomalous thickness.*

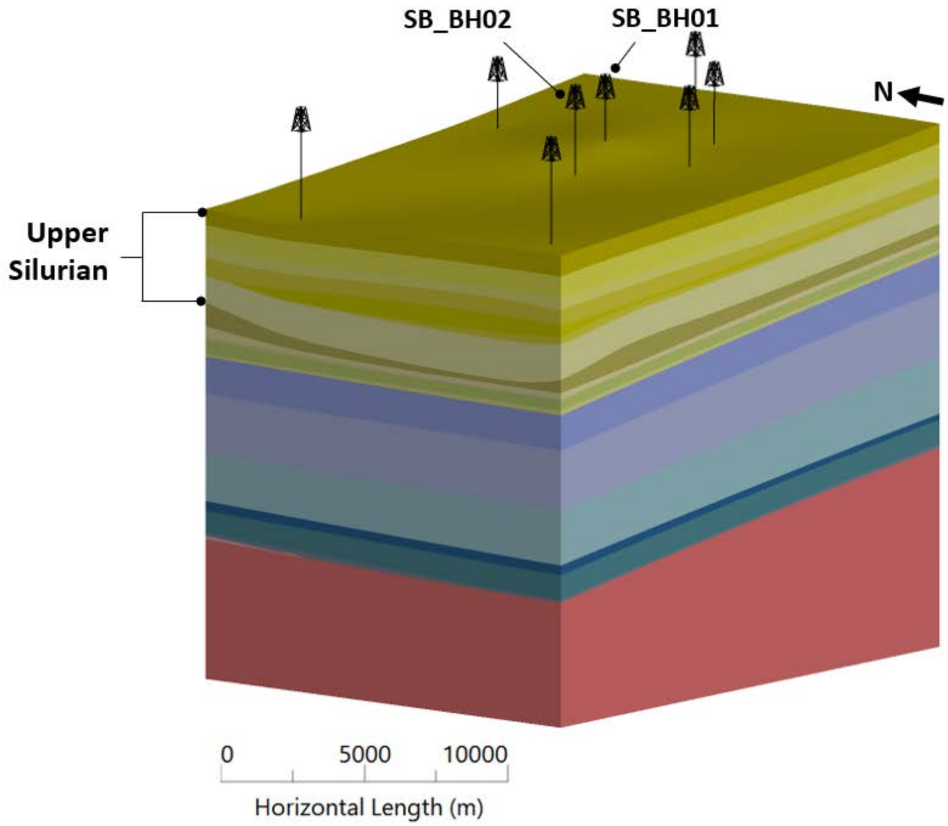


Figure 21. The Upper Silurian formations (A-1 Unit Evaporite, A-1 Unit Carbonate, A-2 Unit Evaporite, A-2 Unit Salt, A-2 Unit Carbonate, B Unit Evaporite, B Unit Salt, B Unit Equivalent, B Unit, C Unit, D Unit, E Unit, F Unit, G Unit and Bass Islands) overlying the older Paleozoic succession. Vertical exaggeration is 15x.

4.5.5 Devonian Formations

The Devonian formations (Figure 22) are characterized by a succession of predominantly limestones and dolostones that make up the Lucas, Amherstburg and Bois Blanc formations (Armstrong and Carter 2010). Within the South Bruce model, both the Lucas and the Amherstburg formations subcrop under the Quaternary overburden cover. In general, the Devonian formations gradually thin towards the eastern side of the model, which can be seen in Table 11, where SB_BH01 has total thickness of 81.4 m compared to 122.31 m observed in SB_BH02. The average thickness of the Devonian formations calculated in the South Bruce model (135.45 m) is thicker than each of the the two South Bruce boreholes. Although it is difficult to make a direct comparison, the Devonian formations logged in the OPG-DGR boreholes indicate an average thickness of 108.40 m, ranging from approximately 102 m to 135 m thick. It is inferred that the pronounced differences in thickness in the Devonian formations, particularly in the stratigraphically higher (younger) formations, is the result of the regional unconformity at the base of the Quaternary overburden.

Table 11. Mean formation thickness from South Bruce model compared to OPG-DGR and South Bruce boreholes for the Devonian.

Formation		Modelled Mean Formation Thickness (m)	OPG-DGR Formation Thickness (m)[1]	SB_BH01 Formation Thickness (m)	SB_BH02 Formation Thickness (m)
309	Lucas Formation	48.55	16.90	21.45	54.13
311	Amherstburg Formation	43.30	42.50	33.95	41.77
314	Bois Blanc Formation	43.59	49.00	26.00	26.41
	Sum of all Formations	**135.45**	**108.40**	**81.4**	**122.31**

[1] *OPG-DGR formation thickness are mean values from boreholes at the Bruce Power Plant (Intera 2011).*

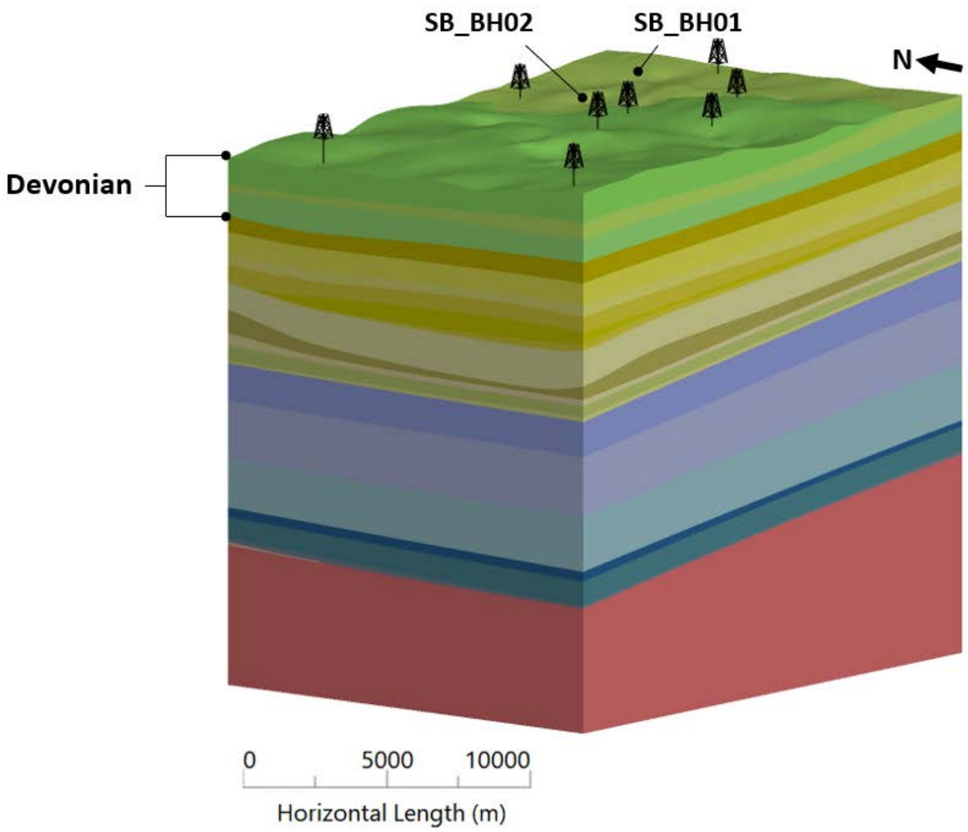


Figure 22. The Devonian formations (Bois Blanc, Amherstburg and Lucas formations) overlying the older Paleozoic succession. Vertical exaggeration is 15x.

4.5.6 Quaternary

The Quaternary overburden unit overlies a large majority of the model area with a mean thickness of 25.54 m and a maximum thickness of 62.97 m recorded along the western boundary of the model (Figure 23). Figure 24 shows the distribution of overburden thickness from the model. Since the model inputs were constrained by the results of Gao et al. (2011), the distribution of overburden thickness results is consistent, except for minor differences (mostly high-frequency variability) caused by modelling with a coarser mesh. As described in section 3.2, the overburden thickness in the South Bruce model site based on Gao et al. (2011) ranges from 0 to 64 m with an average thickness of 25 m. Both the model results and Gao et al. (2011) show a thinning of the overburden along the eastern side of the model, along specific portions of the Teeswater River. The areas coloured white in Figure 23 show locations of thin overburden cover and outcrop exposure.

Figure 23. Overburden stratigraphic thickness map for the South Bruce model area.

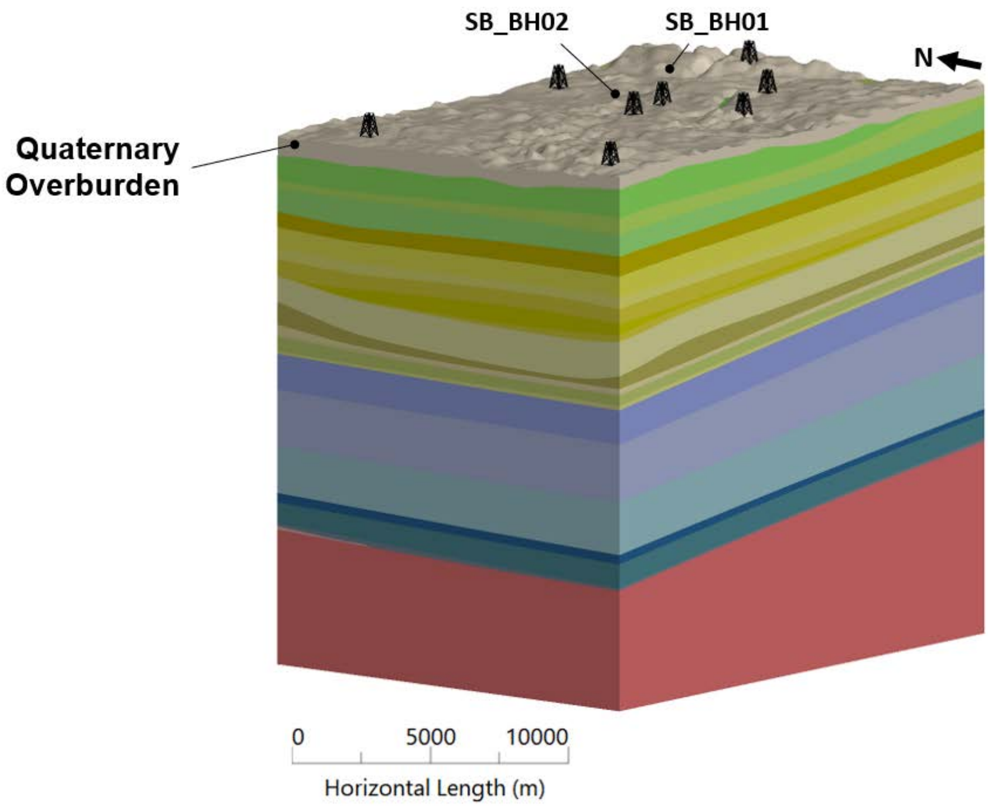


Figure 23. The Quaternary overburden sediments overlying the older Paleozoic succession. Vertical exaggeration is 15x.

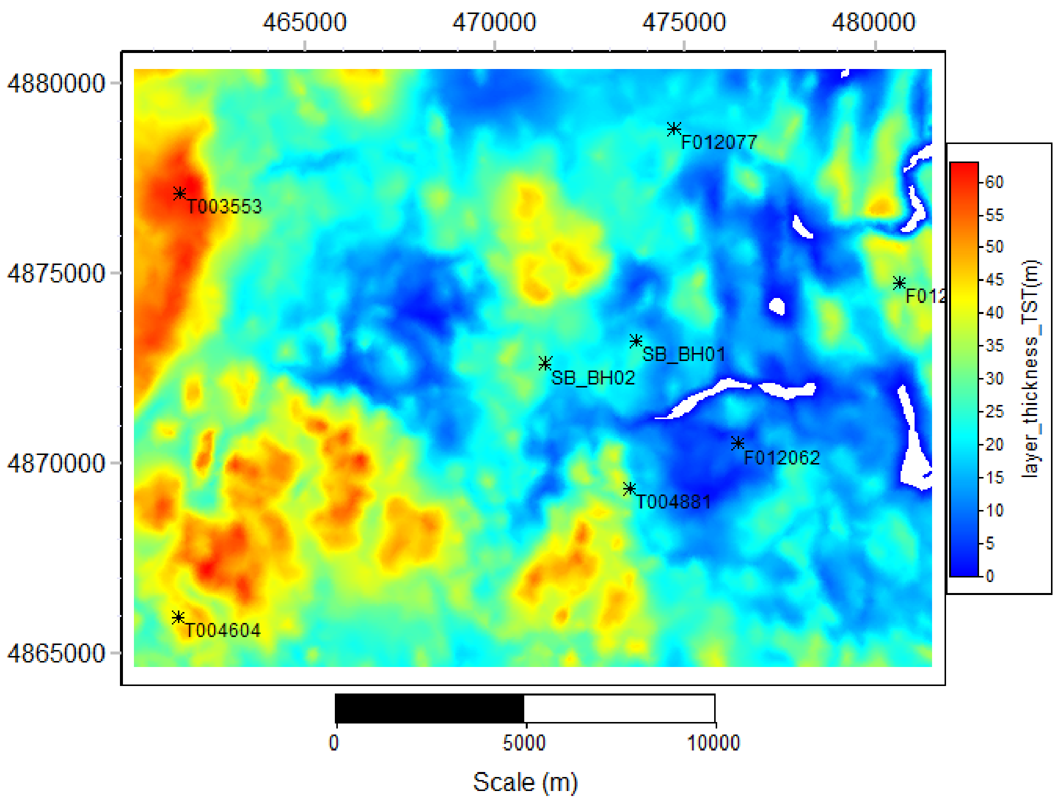


Figure 24. Overburden stratigraphic thickness map for the South Bruce model area.

4.6 Modelled Deterministic Fault

Despite the uncertainty in the interpretation of the fault presented in Section 3.6, a single fault striking ~75 degrees is included as a deterministic feature within the South Bruce model. This fault was initially interpreted by Bailey Geological Services Ltd. and Cochrane (1984a; 1984b) and is interpreted to extend from the Precambrian to the top of the Trenton Group (Cobourg Formation) with about 35 m of offset (Geofirma,2014). Because of the uncertainty, this feature was not embedded into the implicit modelling workflow to offset the stratigraphic formations. However, this fault is incorporated in the model as a vertical deterministic surface. In addition to a vertical representation of the fault, four additional realizations of the fault surface were modelled by assigning different dip magnitudes of 80 degrees and 70 degrees with surfaces dipping towards the NNW and the SSE. Figure 25 presents the modelled fault extending from the base of the model (within the Precambrian) to the top of the Cobourg Formation (Trenton Group). It is assumed that faults likely initiate in the basement rocks and propagate upwards through the Paleozoic. Although the occurrence of this fault is uncertain, it is important to evaluate its impact on the hydrogeological and transport system within the Paleozoic stratigraphy.

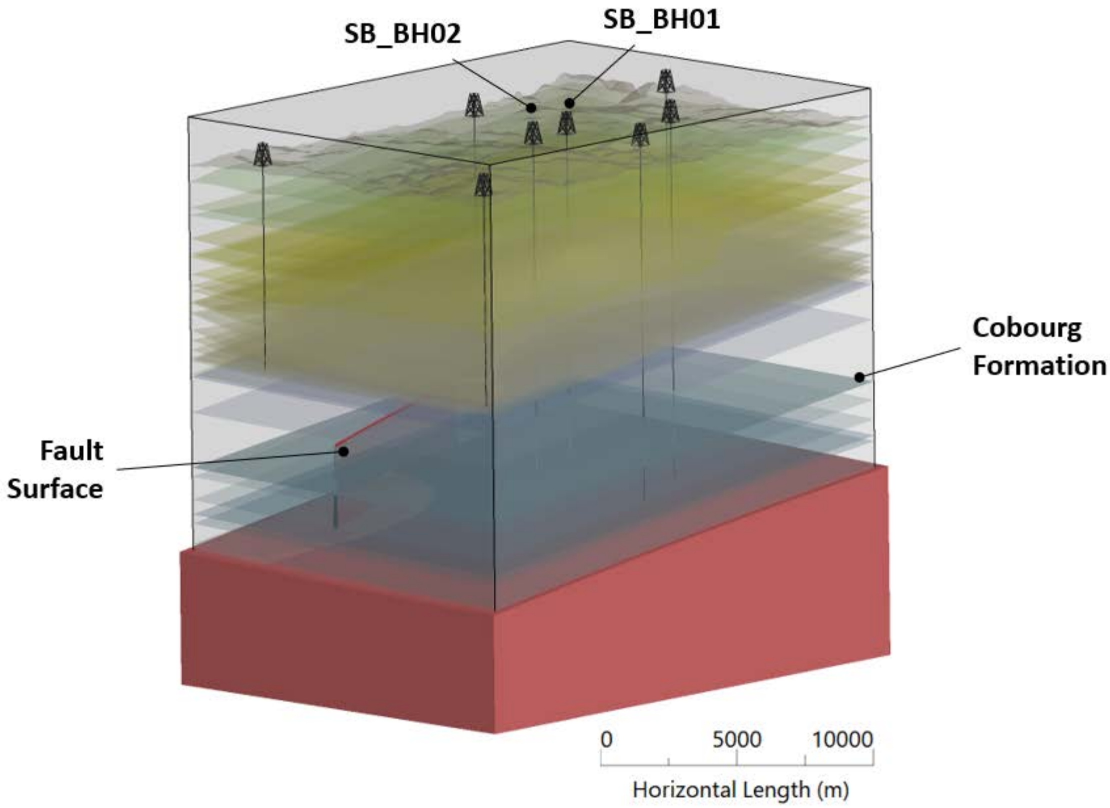


Figure 25. Deterministic fault extending from the base of the model (within the Precambrian) to the top of the Cobourg Formation (Trenton Group). Five representations of the fault surface are realized, vertical, dipping 80 degrees, and 70 degrees towards both the NNW and the SSE. Vertical exaggeration is 15x.

4.7 Comparison to Regional Stratigraphic Model

Formation top depth and formation thickness in the two deep NWMO boreholes are compared to the predicted formation tops from the Carter et al. (2021b) model (in the same locations of the two NWMO boreholes) and presented in Table 12, to assess the lateral predictability and consistency of the formations in the South Bruce model area. The comparison shows that the formation top depths and formation thicknesses encountered in SB_BH01 are generally in agreement with the predicted tops and thicknesses from Carter et al. (2021b) with the exception of the Upper Silurian, and the Guelph and Goat Island formations of the Lower Silurian. This variation is caused by a pinnacle reef (Guelph Formation) intersected at SB_BH01 but not predicted in the Carter et al. (2021b) 3D geological model. For SB_BH02, the table shows that formation tops and thicknesses are generally in agreement with the predictions from the Carter et al. (2021b) model with minor variations. These minor variations are likely more a function of the low degree of resolution of formations caused by a lower well density in the regional model versus the higher degree of resolution in the South Bruce model.

Table 12. Comparison of formation marker depths along NWMO boreholes (SB_BH01, and SB_BH02) with the intersection depths of stratigraphic formation surfaces extracted from the Carter et al. (2021b) model. Differences between formation depths and formation thicknesses for each formation throughout the Paleozoic succession are presented. Cells highlighted green and red represent the difference values within the upper and lower 10 percent.

Geological Period	Color Legend[1]	Formation and Member	SB_BH01						SB_BH02					
			South Bruce Model		Carter et al. 2021b		Difference		South Bruce Model		Carter et al. 2021b		Difference	
			Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)	Top Position along borehole (m)	Thickness along borehole (m)
	001	Overburden/Surface	*NA*	19.60	*NA*	19.35	*NA*	0.25	*NA*	34.60	*NA*	30.81	*NA*	3.79
Devonian	309	Lucas Formation	19.60	21.45	19.35	24.09	0.25	-2.64	34.60	54.13	30.81	36.57	3.79	17.56
	311	Amherstburg Formation	41.05	33.95	43.44	45.10	-2.39	-11.15	88.73	41.77	67.39	38.32	21.34	3.45
	314	Bois Blanc Formation	75.00	26.00	88.54	39.29	-13.54	-13.29	130.50	26.41	105.70	39.62	24.80	-13.21
Upper Silurian	400	Bass Islands Formation	101.00	33.23	127.83	37.88	-26.83	-4.65	156.91	28.82	145.32	37.68	11.59	-8.86
	401	Salina G Unit	134.23	8.94	165.71	5.39	-31.48	3.55	185.73	6.82	183.00	6.97	2.73	-0.15
	402	Salina F Unit	143.17	43.44	171.10	41.69	-27.93	1.75	192.55	45.58	189.97	43.21	2.58	2.37
	404	Salina E Unit	186.61	22.77	212.79	23.29	-26.18	-0.52	238.13	25.51	233.18	21.24	4.95	4.27
	405	Salina D Unit	209.38	2.42	236.08	7.52	-26.70	-5.10	263.64	2.76	254.42	8.10	9.22	-5.34
	406	Salina C Unit	211.80	12.96	243.61	19.59	-31.81	-6.63	266.40	16.67	262.52	18.98	3.88	-2.31
	407	Salina B Unit	224.76	6.05	263.19	12.58	-38.43	-6.53	283.07	7.53	281.49	13.18	1.58	-5.65
	408	Salina B Unit Equivalent	230.81	19.74	275.78	2.94	-44.97	16.80	290.60	14.39	294.67	6.91	-4.07	7.48
	410	Salina B Unit Anhydrite	250.55	3.31	278.72	4.64	-28.17	-1.33	304.99	1.98	301.58	7.55	3.41	-5.57
	411	Salina A-2 Unit Carbonate	253.86	20.14	283.36	40.06	-29.50	-19.92	306.97	25.27	309.13	37.62	-2.16	-12.35
	414	Salina A-2 Unit Anhydrite	274.00	2.29	323.42	2.77	-49.42	-0.48	332.24	5.34	346.74	3.78	-14.50	1.56
	415	Salina A-1 Unit Carbonate	276.29	14.86	326.20	29.33	-49.91	-14.47	337.58	38.52	350.52	31.19	-12.94	7.33
	416	Salina A-1 Unit Evaporite	291.15	0.15	355.53	5.83	-64.38	-5.68	376.10	7.08	381.71	6.04	-5.61	1.04
	417	Salina A-0 Unit Carbonate	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	383.18	3.66	*NA*	*NA*	*NA*	*NA*
Lower Silurian	418	Guelph Formation	291.30	48.70	361.36	9.82	-70.06	38.88	386.84	5.02	387.75	8.99	-0.91	-3.97
	421	Goat Island Formation	340.00	45.12	371.18	13.98	-31.18	31.14	391.86	16.14	396.74	13.31	-4.88	2.83
	422	Gasport Formation	385.12	6.08	385.16	4.47	-0.04	1.61	408.00	7.30	410.06	4.05	-2.06	3.25
	427	Lions Head Formation	391.20	3.32	389.63	5.73	1.57	-2.41	415.30	2.80	414.10	5.33	1.20	-2.53

	429	Fossil Hill Formation	394.52	1.46	395.35	2.74	-0.83	-1.28	418.10	1.18	419.43	2.79	-1.33	-1.61
	440	Cabot Head Formation	395.98	19.83	398.10	21.09	-2.12	-1.26	419.28	20.82	422.22	22.09	-2.94	-1.27
	441	Manitoulin Formation	415.81	8.56	419.18	8.60	-3.37	-0.04	440.10	9.15	444.31	8.53	-4.21	0.62
Upper Ordovician[2]	500	Queenston Formation	424.37	84.73	427.79	93.26	-3.42	-8.53	449.25	85.45	452.84	92.85	-3.59	-7.40
	502	Georgian Bay Formation	509.1	86.76	521.05	146.20	-11.95	-10.53	534.7	86.16	545.69	144.14	-10.99	-9.15
		Blue Mountain	595.86	48.91					620.86	48.83				
	511	Cobourg Formation / Collingwood Member	644.77	7.88	667.25	28.73	-22.48	19.09	669.69	7.85	689.84	28.03	-20.15	18.65
		Cobourg Formation / Lower Member	652.65	39.94					677.54	38.83				
	515	Sherman Fall Formation	692.59	45.07	695.98	50.71	-3.39	-5.64	716.37	45.66	717.87	52.47	-1.50	-6.81
	517	Kirkfield Formation	737.66	43.39	746.69	38.98	-9.03	4.41	762.03	43.60	770.34	38.46	-8.31	5.14
	519	Coboconk Formation	781.05	21.18	785.67	15.17	-4.62	6.01	805.63	21.08	808.80	16.61	-3.17	4.47
	522	Gull River Formation	802.23	52.95	800.84	57.34	1.39	-4.39	826.71	54.87	825.41	57.12	1.30	-2.25
	523	Shadow Lake Formation	855.18	5.15	858.17	3.41	-2.99	1.74	881.58	5.35	882.53	6.62	-0.95	-1.27
	600	Cambrian Sandstone	*NA*	*NA*	861.58	3.42	*NA*	-3.42	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
	700	Precambrian	860.33	*NA*	865.01	*NA*	-4.68	*NA*	886.93	*NA*	889.15	*NA*	-2.22	*NA*

Notes:

1. Color legend assigned to formations and members. Color template is consistent with Carter et al. (2021b) for the southern Ontario regional lithostratigraphic model.
2. Paleozoic stratigraphic nomenclature has changed between Bruce site drilling (2011) and South Bruce Site (2022). Changes to Ordovician time scale resulted in moving the Middle-Upper Ordovician boundary lower such that all of the strata traditionally referred to as Middle Ordovician in Ontario are now considered Upper Ordovician.

5. Confidence in Geological Model

In the context of developing a 3D geological model to be used in evaluating the South Bruce Site for a used nuclear fuel repository, it is important to understand how data and model uncertainty impact the site. Several studies present methodologies for quantifying and visualizing the uncertainties inherent in geological modelling (e.g., Suzuki and Caers 2008; Caumon et al. 2009; Cherpeau et al. 2010; Wellmann et al. 2010; Caers, J. 2011; Lindsay et al. 2012; Wellmann and Regenauer-Lieb 2012; Schweizer et al. 2017). This report presents the first iteration of a 3D geological model for the South Bruce Site, which incorporates information measured from the OGSRL and NWMO boreholes as well as key information from a regional stratigraphic model (Carter et al. 2021b).

It is acknowledged that data used to develop the South Bruce model is widely distributed across the model region and that there is some uncertainty in the modelled surfaces between these borehole locations. However, previous studies completed at the Bruce Nuclear Site suggest that the Paleozoic succession throughout the area dips very shallowly and consistently to the west or southwest between 0.23 and 1° (Intera 2011, Watts et al. 2009). Therefore, surface thicknesses and continuity are expected to be similar with some exceptions (zero edge boundaries, Guelph reef). The process of acquiring additional data, and updating the model is an important step, which allows the model to be iteratively evaluated. This step is considered critical in the process to validate the 3D model. However, despite any local uncertainties that may exist, we have confidence overall in the current model for the following reasons:

- Results from the two deep NWMO boreholes drilled in 2021 and 2022 indicate that formations are laterally continuous with minimum/small thickness variation from a regional scale. These formations are traced over hundreds of kilometers and presented in Carter et al. (2021b) with lateral continuity, traceability and predictability throughout southern Ontario and the South Bruce region. Drilling results from SB_BH01 and SB_BH02 highlight the lateral traceability and predictability of formation tops and thicknesses when compared to the Carter et al. (2021b) model, with the exception of a local variation caused by an interpreted pinnacle reef intersected in SB_BH01. Although this anomaly was not obvious/expected in the Carter et al. (2021b) model, reefs (in the Lockport Group) are expected to occur in this part of southern Ontario due to its paleodepositional setting.

- Formation tops in the current model were interpreted as part of the work by Carter et al. (2021b) in a consistent manner using the criteria outlined by Armstrong and Carter (2010). This re-evaluation of formation top picks allowed the formations to be assessed for ease of interpretation, reliability and consistency. This included rigorous Quality

Assurance/Quality control (QA/QC) of the data by experienced geologists in southern Ontario with the guidance of expert resources. The wells intersected in this model were reviewed with a high degree of confidence and reflect most accurate formation top representation. Additionally, a full suite of high-quality geophysical logs, in addition to expert review and interpretation of continuous drill core and geotechnical logging, acquired in the recently drilled NWMO boreholes (SB_BH01 and SB_BH02) were used for formation top picks for these same boreholes, thereby increasing the confidence and reliability of formation horizons and thicknesses in a local scale.

5.1 Main Uncertainties and Limitations

Despite the level of confidence in the geological model, sources of uncertainty are still embedded in the data itself and all stages of the geological interpretation process. Sources of uncertainty can include inaccurate input data, poor data quality and data density, suboptimal model resolution, human error, software limitations, etc. This uncertainty forecasted onto the model development can have an impact on the 3D representation of the subsurface geology and will impact future drilling plans and subsurface predictions. Since the South Bruce model was developed to honour the regional stratigraphic framework developed by Carter et al. (2021b), it is important to acknowledge that these two models are largely bound by the same uncertainties and limitations from a stratigraphic framework. The uncertainties and limitations associated with the regional stratigraphic framework model are described in Carter et al. (2021b). Additionally, a semi quantitative analysis of uncertainty completed by the GSC (Bunn et al. 2023 – in prep) describes the uncertainties of the 3D model of southern Ontario. A summary of the main sources of uncertainty of the South Bruce geological model are provided below:

- Large distances between boreholes, or known data points in the subsurface, are a main source of uncertainty in this early version of the geological model linked to the sparsity of available input data. As discussed previously, the South Bruce model is developed using formation tops/markers from a total of 8 boreholes over an area of 300 km^2. Locations in the model at greater distances to boreholes have higher uncertainty in the depth to the formation tops and thickness of formations. This uncertainty is due to the fact we have no geological data away from the boreholes. However, as we continue to drill new boreholes, and integrate interpretations from 3D seismic reflection survey, the confidence in the geological model is expected to increase as a result of increasing data density.

- Despite the formation tops being interpreted using a criterion consistent with Carter et al (2021b) and as defined in Armstrong and Carter (2010), there still exists difficulties in picking certain formation tops with a high degree of certainty or accuracy, e.g. the Bois Blanc Formation. This problem exists due to limited availability of geophysical logs, drill core and/or rock chip samples, and local variations in depositional facies for which standardized criteria are not available, therefore, leading to unrecognized or misinterpreted geological contacts. However, the majority of the formations are simple picks based on rock chip samples, drill core, or geophysical well logs. Bunn et al. (2023) have also noted that very few of the formation picks have a higher level of error implied in interpreting the pick. In light of the difficulties recognizing certain formations, some of the formations and members are grouped with neighboring units. Three examples are listed below.

- The Collingwood Member picks in the OGSRL database are inconsistent and therefore there is insufficient data to produce a reliable model layer as described in Carter et al. (2021b). For this reason, the Collingwood and Cobourg Lower Members are both grouped into a single model layer as the Cobourg Formation. Similarly, the Salina A-0 Unit Carbonate, where present, is grouped with the Guelph Formation as a single model layer. However, within the OGSRL database the Salina A-0 Unit Carbonate is generally not picked, and can only be reliably identified/picked in boreholes where core and/or geophysical logs are present (e.g. South Bruce and OPG-DGR sites). Lastly, although the Georgian Bay and Blue Mountain (GBBM) are separately picked in the NWMO deep boreholes (SB_BH01 and SB_BH02) and the Bruce Nuclear Site DGR wells, there are no picks in the OGSRL database for the top of the Blue Mountain Formation, and no defined criteria for picking in Armstrong and Carter (2010). Therefore, the Georgian Bay and Blue Mountain (GBBM) formations are grouped into a single model layer in the South Bruce model, similar to Carter et al (2021b). These grouped modelled layers/units are generally due to a limitation in the OGSRL database where some formation tops are not always consistently picked due to data sparsity and/or for very thin formations. A careful approach should be taken when assessing the above-mentioned grouped model layers.

- With regards to the Guelph Formation, and the interpretation of the reef structure, it is important to acknowledge that the overall lateral extents, thickness and shape of the reef structure intersected at SB_BH01 remains uncertain. Currently, its geometry is based only on the intersection of a single borehole. However, on-going interpretation and inversion of 3D seismic data acquired at the South Bruce Site will aid in assessing the extent and thickness of the reef structure and reduce this uncertainty. Findings from 3D seismic interpretation will be reflected in future iterations of the South Bruce model.

- In addition to challenges picking formation tops, there are other factors that influence the accuracy of the formation top picks, which are then projected onto the results of the geological model. These factors include accuracy in the borehole collar locations and the subsurface trajectory of the borehole. The location of borehole collars is categorized into groups based on positional accuracy as noted in Bunn et al. (2023).

- The distribution of the Cambrian Sandstone in the subsurface as recorded in the geological framework is based both on the distribution as recorded in the consulted literature (Bailey and Cochrane 1984) and the well distribution from the OGSRL database. Only a few wells penetrate the full Paleozoic sequence. For this reason, there are not enough data points or wells to define an accurate zero edge of the Cambrian in the South Bruce model area. Given that no evidence of a Cambrian Sandstone was encountered in the two deep NWMO boreholes (SB_BH01 and SB_BH02), the actual zero thickness edge of this unit is reinterpreted to occur further to the northwest. However, due to the low well density in the model area, there still remains uncertainty on where exactly the Cambrian Sandstone pinches out.

- Despite seismic reflection interpretation of a legacy 2D line completed within the South Bruce model area (Geofirma 2014), the interpretation results were not incorporated into the modelling workflow. This decision was made because of the uncertainty in those results due to the poor resolution of the seismic data (acquisition in the 1970s), and the difficulties in establishing an appropriate time to depth conversion using a sonic log taken from a well located far from the seismic line. The new 3D seismic data, which was acquired at the South Bruce Site in November 2021 and processed in 2022, will be used to interpret the horizons (surfaces) and to find their lateral extent between the boreholes. This will reduce the uncertainty between the two boreholes and help to find the lateral thickness variation in the interpreted formations. Given the full suite of geophysical logs in the two deep boreholes, SB_BH01 and SB_BH02, the seismic interpretation and inversion will help in understanding the geological features between the boreholes, which removes some uncertainties in the future model.

- It is also important to highlight that existence of potential faults in the subsurface may impact the thickness of formations locally, if there is vertical displacement. This is another source of uncertainty that will be investigated where 3D seismic data is available.

- Although the South Bruce 3D geological model results are consistent with the regional framework established by Carter et al. (2021b), we acknowledge that both models are a representation of the subsurface and the geology is based on an interpretation between boreholes.

The uncertainties and limitations summarised above provide a basis for evaluating the level of confidence in this initial South Bruce 3D geological model. It is acknowledged that this early model is developed using widely spaced borehole data to evaluate the subsurface. To reduce uncertainty, the desired solution is to acquire more data, such as additional borehole drilling, and to incorporate newly acquired 3D seismic data.

Prior to incorporating the new data into the model, data can be used to validate the current state of the model by measuring the spatial differences between the input data and the model data. After iterating the model based on new data inputs, the amount of spatial variation can be assessed by comparing the new model results against previous model versions. As the site is further investigated through additional borehole drilling and data integration, it is anticipated that the differences between subsequent model iterations will be reduced over time and the overall level of confidence in the model will increase.

Despite all the uncertainties described above, it is important to highlight that this initial version of the South Bruce 3D geological model focusses on the stratigraphic framework of the area. Results from the 3D South Bruce model and subsurface information from Carter et al. (2021b), indicate that the bedrock has an exceptionally high degree of lateral consistency and predictability, which is a key geological attribute of the stratigraphic units in the area. Additionally, the two deep NWMO boreholes have a good quality full suite of geophysical logs, and continuous drill core which were used to identify formation tops in the model area with high confidence, supported by a rigorous external expert review process. All of this information suggests that, despite the inherent uncertainty in some of the modelling elements (e.g. reef, possible faults, etc), there is a high degree of confidence in the stratigraphy represented in the model. Overall, the uncertainty embedded within these model elements are unlikely to play a significant role in the ability of the site to host a deep geological repository. However, the role of these geological elements will continue to be investigated through future studies.

6. Conclusions

Developing a 3D geological model for the South Bruce Site is an essential part of the Descriptive Geoscientific Site Model for the site. The objective of this report and the 3D geological model is to develop a numerical representation of the subsurface that can be further used to evaluate the site for its potential to host a deep geological repository. This geological model forms the stratigraphic framework to be used in associated geoscientific studies to develop discipline-specific sub-models, including geomechanical, thermal, hydrogeological, hydrogeochemical and transport property models. This report defines the first iteration of the site-scale geological model, which incorporates subsurface information from the 3D model of southern Ontario developed by the Geological Survey of Canada (Carter et al. 2021) with well formation data from OGSRL database and two deep NWMO boreholes (SB_BH01 and BH02) within the site-scale extent.

Main model inputs include:

1. Available data- fault maps, overburden cover, formation top data of 6 boreholes from the OGSRL database and 3D geological model of southern Ontario.

2. Newly collected and integrated data - borehole geological and geophysical logging from two deep NWMO boreholes (SB_BH01 and SB_BH02).

This initial version 1.0 of the 3D model is sparsely constrained. It is acknowledged that building a 3D model with sparse data will have some uncertainty, and the projected information will most likely not be completely accurate. The main sources of uncertainty in this iteration of the 3D model are sparsity of data, accuracy of borehole collar locations in the OGSRL database, lateral extent of the Guelph reef, Cambrian zero edge boundary, and potential faults. However, due to very gently dipping and undeformed nature of the Paleozoic strata in southern Ontario, formations are expected to be continuous and predictable throughout the area. Eventually, as additional 3D seismic and borehole data are acquired and used in the model, remaining uncertainties will be minimized. Continually updated models will ultimately inform other geoscientific disciplines and will form the framework used in the design of an underground repository and the assessment of long-term safety of the site.

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