OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Regional Geology – Southern Ontario

March 2011

Prepared by: AECOM Canada Ltd. and
Itasca Consulting Canada, Inc.

NWMO DGR-TR-2011-15

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EXECUTIVE SUMMARY

This report provides an overview of the regional geology of southern Ontario and represents one of the supporting technical reports for Ontario Power Generation's proposed Deep Geological Repository (DGR) project located in the Municipality of Kincardine, Ontario. The purpose of the regional geology study, in conjunction with the other supporting technical reports, is to present an understanding of the deep sedimentary formations beneath the Bruce nuclear site in relation to their long-term stability and ability to isolate and contain low and intermediate level radioactive waste. For the regional geology study, this includes establishing the existing geologic knowledge as it relates to structural geology, tectonics, basin history, sedimentology, thermochronology, depth of burial, economic resources, and glacial history.

This report was compiled from existing data, and is a synthesis of the current scientific understanding of the Paleozoic rock within the Regional Study Area (RSA), an area of approximately 35,000 km^2 surrounding the Bruce nuclear site. A key component of the synthesis of geological information is the recently developed three dimensional geological framework (3DGF) model of the RSA (ITASCA CANADA and AECOM 2011), which captures and presents the current geological understanding of the Palaeozoic sedimentary formations and their stratigraphy. All available data sets were used to construct the 3DGF including the Ontario Oil, Gas and Salt Resources Library Petroleum Well Database, borehole information from the Bruce nuclear site, and published maps.

The synthesis of geological information as presented in this regional geology report suggests the following.

- In southern Ontario the Paleozoic stratigraphy exhibits very shallow dips with formation thicknesses and lithofacies generally predictable over kilometre scale distances. The primary geological units relevant to demonstrating DGR suitability and safety are continuous throughout the RSA.
- The geology encountered in boreholes DGR-1, -2, -3, -4, -5 and -6 cored as part of site investigations is consistent with the regional geology as described in the current literature and summarized in this report. The lithological properties such as shale, evaporite, carbonate and clastic content and dolomite versus limestone distribution are predicted by regional data for a site located at the margin of the Michigan Basin.
- As predicted from the regional data, the Bruce nuclear site stratigraphy includes approximately 400 m of limestone and shale represented by the Middle Ordovician Trenton and Black River Groups, and the Upper Ordovician Blue Mountain, Georgian Bay and Queenston formations along with an additional 190 m of argillaceous dolostones and evaporites of the Upper Silurian Salina Group.
- The RSA can be characterized as one of the more structurally simple parts of southern Ontario. There are no known active faults within the Paleozoic rocks in the study area. Regional joint and fracture orientations in the Paleozoic rock resulted primarily from vertical compaction of sediments and tectonic loading during orogenic and basin formation events throughout the Paleozoic.
- Diagenetic events that have altered the Paleozoic rocks, excluding shallow bedrock water-rock interactions, occurred during the Paleozoic or early Mesozoic. Diagenetic events including dolomitization, Mississippi Valley Type mineralization, late stage calcite and evaporite cementation, and salt dissolution coincided with large scale tectonic events at the margin of the North American plate and to maximum burial depths and compaction.

- An evaluation of existing literature and results from DGR borehole core logging and supplementary laboratory analysis suggests that the probability of future identification of potential economic oil and/or gas resources associated with major geological structures adjacent to the proposed Bruce nuclear site is very low. The scarcity of petroleum resources within the RSA and absence of commercial petroleum extraction within 40 km of the Bruce nuclear site supports this assessment.

ACKNOWLEDGEMENTS

We would like to thank Derek Armstrong (Ontario Geological Survey) and Dr. Alexander Cruden (Monash University) for reviewing the report and helping develop an understanding of the site and regional geology. We would also like to extend our thanks to Dr. Richard Crowe, Andrew Parmenter, Dr. Monique Hobbs and Branko Semec from the Nuclear Waste Management Organization for reviewing this report and providing helpful comments and suggestions.

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1. INTRODUCTION

The regional geology study presented in this report represents one of the supporting technical reports prepared in support of Ontario Power Generation's (OPG) proposed Deep Geologic Repository (DGR) project located in the Municipality of Kincardine, Ontario.

The purpose of the regional geology study, in conjunction with the other supporting technical reports, is to present an understanding of the deep sedimentary formations surrounding the Bruce nuclear site. For the regional geology study, this includes establishing the existing geologic knowledge as it relates to structural geology, tectonics, basin history, formation sediment source areas, sedimentology, formation thermochronology, depth of burial, economic resources, and glacial history. This study is specifically designed to provide meaningful context to the site-specific investigations undertaken as part of the Geoscientific Site Characterization Plan (INTERA[1] 2006), and provides a framework for extrapolation of site conditions beyond the Bruce nuclear site boundary.

1.1 Methodology

This regional geology report was compiled from existing data, and is a synthesis of the current scientific understanding of the Paleozoic rock as it relates to the Regional Study Area (RSA). The RSA has an area of approximately 35,000 km^2 (Figure 2.1) and was delineated in order to fully encompass the hydrogeological modelling boundary used for the regional hydrogeological report (Sykes et al. 2011). The RSA boundary and the boundary used to develop the three dimensional geological framework (3DGF) model (ITASCA CANADA and AECOM 2011) are identical.

Data reviewed for this study included existing published literature from refereed and non-refereed journals, published mapping, government open file reports, consulting reports, and "grey" literature released by government agencies and professional organizations (e.g., field trip guides, annual reports, etc.) including the Ontario Geological Survey, Geological Survey of Canada, Ontario Ministry of Natural Resources, Ontario Petroleum Institute, Michigan Basin Geological Society, and the Michigan Geological Survey.

The primary data set used to construct the 3DGF as part of this study was the Ontario Oil, Gas and Salt Resources Library (OGSRL) Petroleum Well Database (OGSR 2004, 2006). A full methodology is provided in Chapter 6 describing how the geological framework was developed and verified. The regional hydrogeological model uses the 3D geological layers derived from this geological framework (Sykes et al. 2011).

The final interpretations of the regional geology as presented in this report are therefore based on the combined literature review and the 3DGF derived from the petroleum well database. In addition, the results of the Bruce nuclear site drilling program are integrated into this geologic interpretation. The interpretations and reporting of the Paleozoic stratigraphy are based on published facies models and sedimentological processes.

[1] Currently known as Geofirma Engineering Ltd.

1.1.1 Geological Hypothesis

In 2004, the Nuclear Waste Management Organization (NWMO) released a report on the Geoscientific Review of the Sedimentary Sequences in southern Ontario (Mazurek 2004). The purpose of this report was to complete an initial assessment of the suitability of the Paleozoic sedimentary rocks of the Michigan Basin within southern Ontario to host a DGR for storage of radioactive wastes. This report specifically examined aspects of the sedimentary rock relevant to long-term repository safety, including host rock predictability, geological stability, and litho-structural homogeneity.

The key geological conclusions or hypotheses derived from this initial assessment where:

- The Paleozoic geology is predicable over large distances;
- Geological unit/formation thicknesses are uniform and also predictable over distances of kilometres;
- Litho-structural properties are understood at scales relevant to DGR safety;
- There are multiple low permeability geologic barriers;
- There is a stable regional stress regime; and
- The origin and general processes of diagenesis, including dolomitization, are understood.

The regional geology investigation presented here provides a further test of these hypotheses and expands on concepts presented in the Mazurek (2004) report. The results of this investigation support the initial geological hypothesis outlined in the Mazurek (2004) report.

2. GEOLOGICAL HISTORY OF SOUTHERN ONTARIO

Geologically, the sedimentary rocks of southern Ontario rest on the southern margin of the Canadian Shield ranging in age from the Upper Cambrian to Upper Devonian/Mississippian (Figure 2.1). Progressively younger sedimentary units outcrop or subcrop from the Canadian Shield margin towards southwestern Ontario (Figure 2.1).

The Paleozoic rock sequences of southern Ontario rest unconformably on an erosional surface developed atop a crystalline basement composed of metamorphic rocks of the Proterozoic Grenville Province. Studies of the exposed unconformity surface between Georgian Bay and Kingston, Ontario together with subsurface data indicate that this erosional surface is characterized by topography with relief of tens to hundreds of metres with a strong preferred orientation controlled by the structural grain of the basement rocks (Andjelkovic et al.1998). The erosional surface was produced by uplift and erosion from the Grenville orogen ca. 1,100 million years (Ma) ago to an undulating peneplain by Cambrian times when the region experienced a marine transgression and deposition of the oldest Paleozoic sediments. Sediment accumulation was greatest in the Michigan and Appalachian basins and least above the intervening Algonquin Arch (Figure 2.2). The Michigan Basin has an area of ~316,000 km^2, centred over northern Michigan (Friedman and Kopaska-Merkel 1991) and formed as a result of crustal subsidence, with basin centred deposition occurring within an in-land sea. The maximum thickness of Paleozoic sediments in the Michigan Basin is approximately 4,800 m at the basin centre. The Appalachian Basin is a foreland basin created in response to tectonic loading during orogenic events at the margin of eastern North America. As a result of this tectonism and a supply of clastic sediments from the tectonic highlands, siliciclastic sediments dominate the Appalachian Basin. The maximum thickness of the Paleozoic strata in the Appalachian Basin is approximately 7,000 m, shallowing to approximately 850 m over the Algonquin Arch (Sanford 1993b).

Sedimentation in the Michigan Basin continued until the Mississipian but was punctuated by periods of uplift and erosion marked by regional unconformities. The Algonquin Arch acted as a major structural control on depositional patterns, rising and falling with respect to the Michigan and Appalachian basins in response to vertical epeirogenic movements and horizontal tectonic forces (Leighton 1996, Howell and van der Pluijm 1999).

2.1 Precambrian Geology

The structure of the Proterozoic basement of southern Ontario has been well characterized by surface mapping north of the Paleozoic/Precambrian basement boundary, regional geophysical data (aeromagnetics, gravity), seismic reflection surveys and geochemical, geochronological and petrographic analyses of samples recovered from boreholes (Easton and Carter 1995, Carter et al. 1996). Two major structures can be followed from their surface exposure northeast and east of Georgian Bay beneath the Paleozoic cover to the southwest: the Grenville Front Tectonic Zone (GFTZ), which marks the edge of the Grenville Orogen against the Southern and Superior shield Provinces, and the Central Metasedimentary Belt Boundary Zone (CMBBZ), which defines the tectonic contact within the Grenville Province between the Central Gneiss Belt to the west and the Central Metasedimentary Belt to the east (Easton 1992) (Figure 2.3). The Paleozoic succession beneath the Bruce nuclear site unconformably overlies the Central Gneiss belt.

Tectonic forces within the Precambrian basement controlled the formation of the Michigan Basin beginning with the initial mid continental rifting and associated subsidence approximately

1,100 Ma. This event was followed by thermal subsidence of the Precambrian basement approximately 580 Ma to 500 Ma (Klein and Hsui 1987). As the lithosphere thickened and cooled, thermal contraction caused the lithosphere rocks to become denser, resulting in thermal subsidence. Continuous sediment filling of the basin in turn caused the basement to flex and further subside from the added load of the sediments that were being deposited (Sleep 1971, Sleep and Snell 1976, Nunn and Sleep 1984).

More recent studies by Howell and van der Pluijm (1990, 1999) suggest that basin development was not caused by uniform continuous subsidence, but a series of tectonic events that occurred throughout the Paleozoic. Key differences in subsidence rates over time influenced the ultimate shape of the basin.

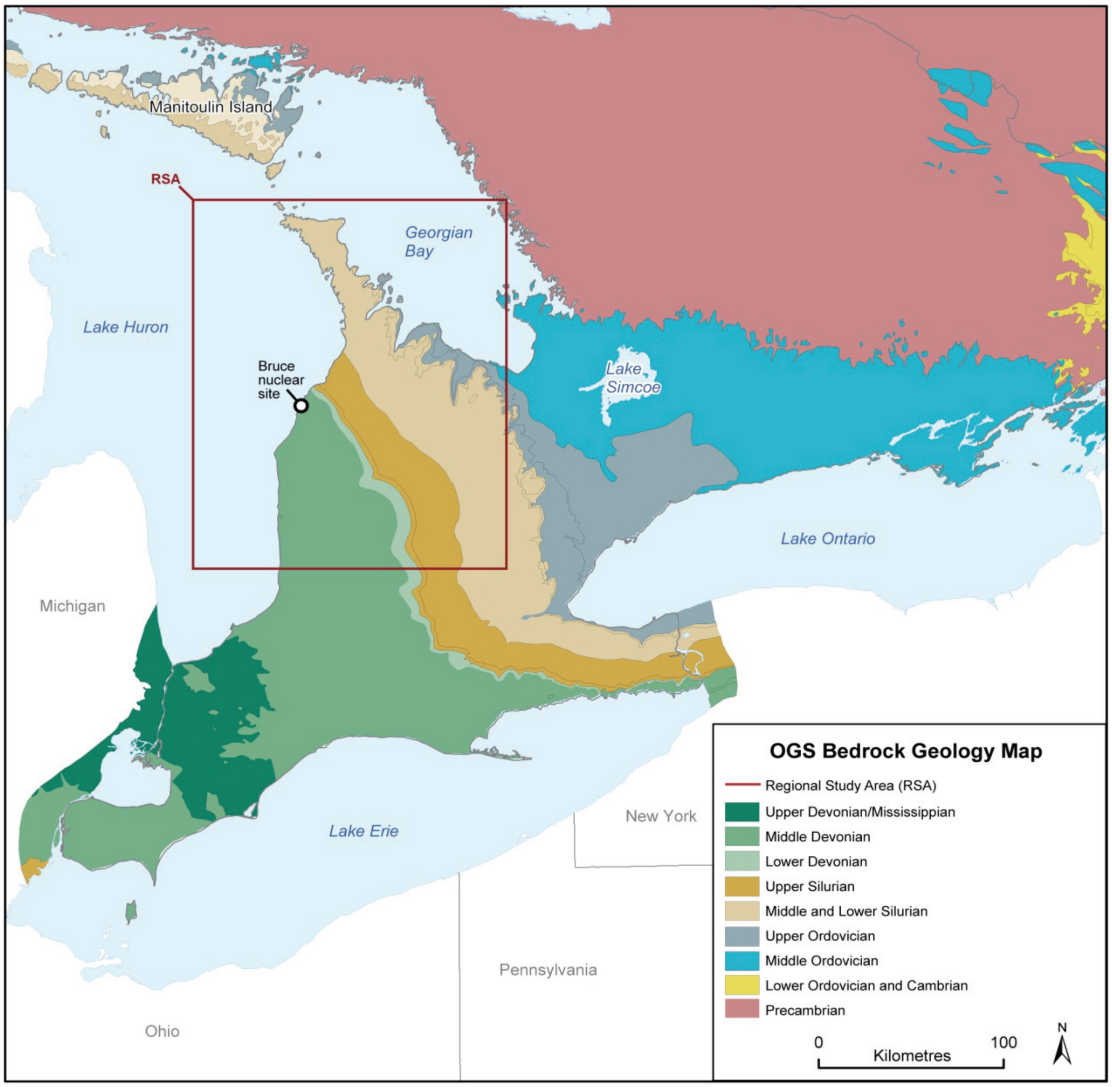
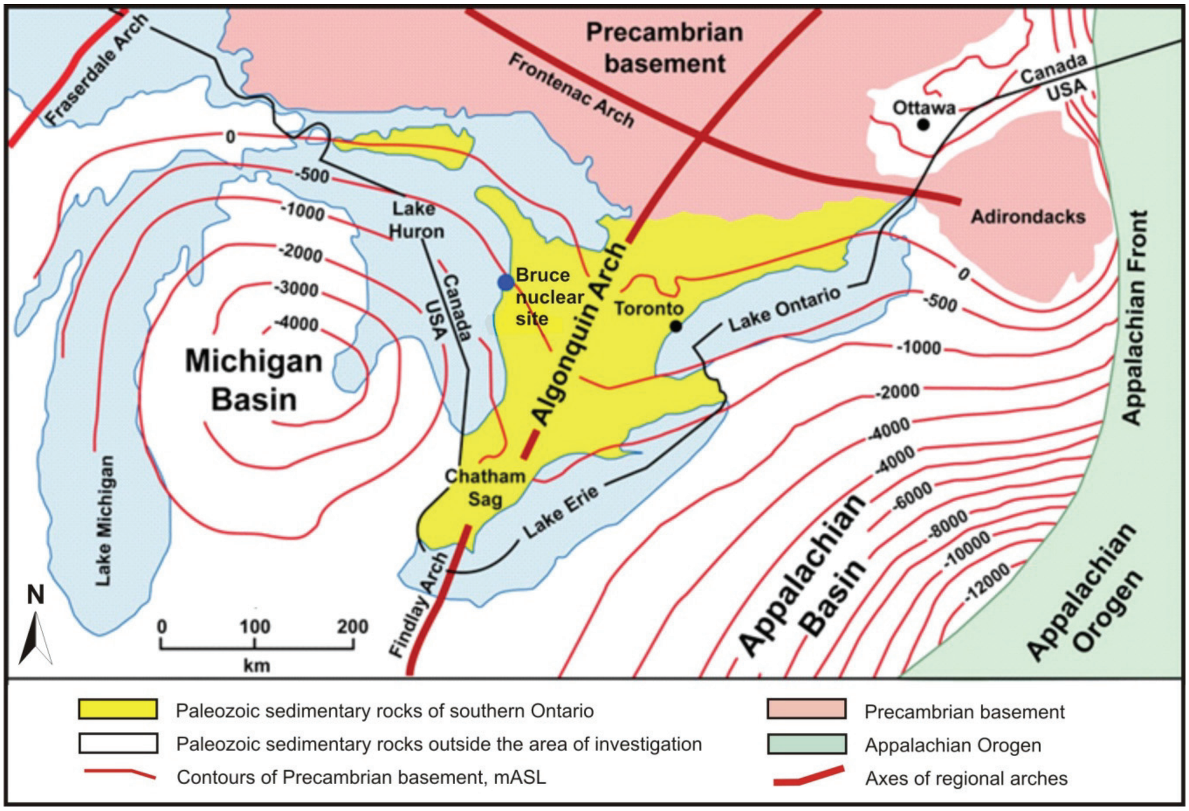


Figure 2.1: Geologic Map of Southern Ontario



Note: The figure is modified from Mazurek (2004) after Johnson et al. (1992).

Figure 2.2: Large-scale Tectonic Elements in Southern Ontario

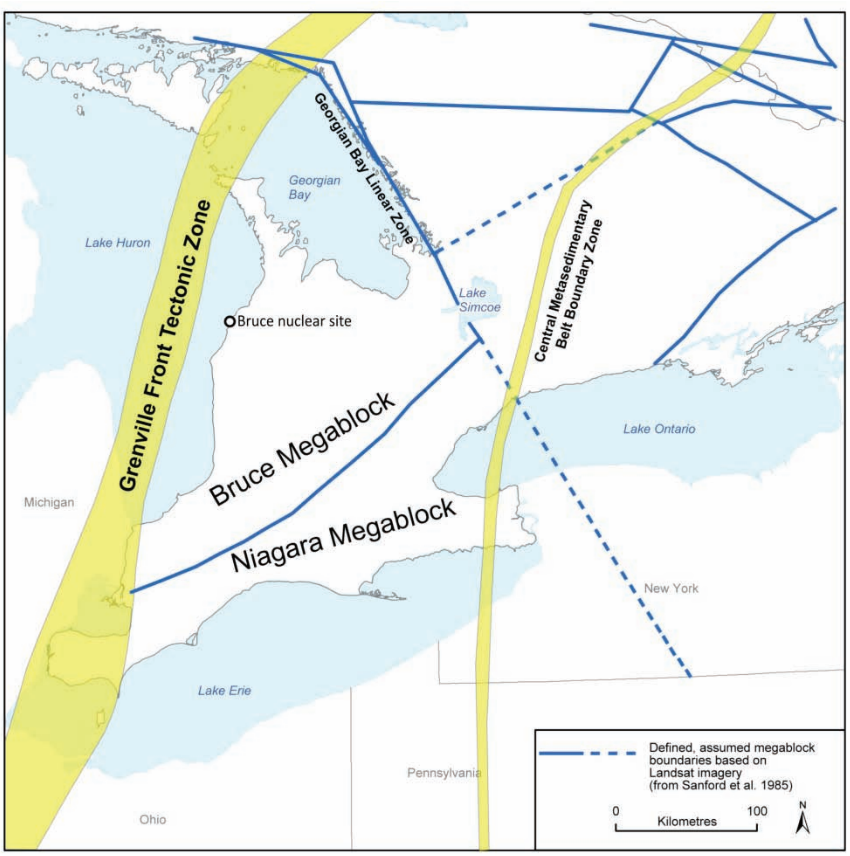
Figure 2.4 shows the major tectonic influences on eastern North America through time (Sanford 1985). The Taconic and Acadian orogenies in particular had a dominant control on the Paleozoic strata described in this report. The Caledonian and Alleghenian orogenies are interpreted to have played an important role in diagenetic fluid migration. Eastern North America has been in a passive margin phase for approximately the last 200 Ma (Figure 2.4).

2.2 Paleozoic Geology

The Paleozoic rocks within the RSA include sediments deposited and buried within two paleo-geological sedimentary basins, Michigan and Appalachian, and upon the Algonquin Arch, the basement topographic feature that separates the two basins (Figure 2.2). A structural low at the southwestern end of the Algonquin Arch referred to as the Chatham Sag, separates the Algonquin Arch from its tectonic equivalent in the United States, the Findlay Arch (Armstrong and Carter 2006). During the Paleozoic, these two basins were located in a marine environment flooded by shallow seas and as a result, the Paleozoic rocks are derived from marine sediments. Figure 2.5 presents the stratigraphy of the subsurface in southwestern Ontario with the position of major unconformities for locations at the eastern margin of the Michigan Basin, on the Algonquin Arch near the Bruce nuclear site and at the western margin of the Appalachian Basin.

The formation of the sedimentary rocks within the Michigan and Appalachian basins was largely dependent on two tectonic influences (Johnson et al. 1992). These were (a) the orogenic activity at the eastern margin of North America, which provided clastic input to both the

Appalachian and Michigan basins, and (b) the subsequent tectonic forces that controlled the positioning of the basins and arch separating the basins. The rate of basin subsidence in response to sediment loading and crustal subsidence by thermal contraction (thermal subsidence), combined with movement of the arch (e.g., uplift) are the key tectonic elements that controlled sedimentation patterns within the two basins.

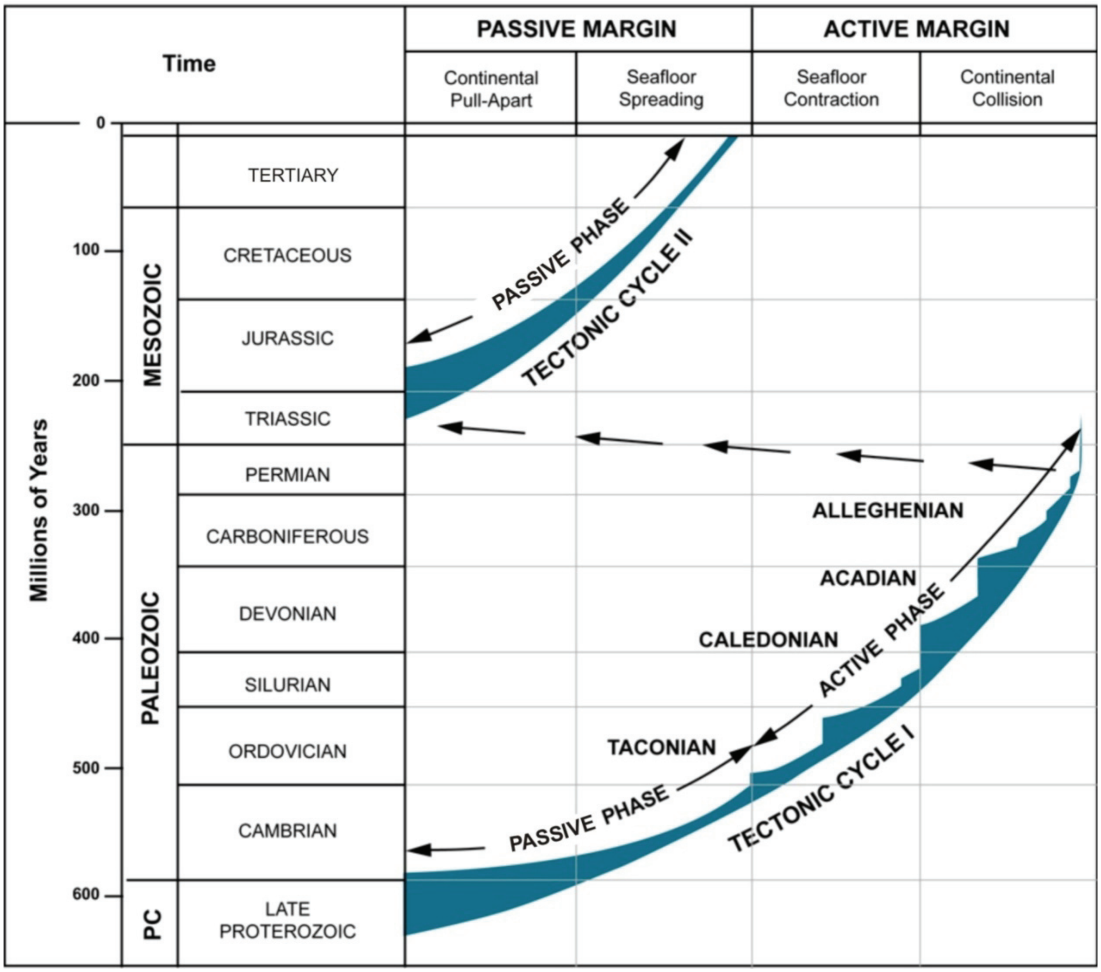


Notes: Interpreted contacts are derived from Landsat imagery. Modified from Sanford et al (1985).

Figure 2.3: Interpreted Tectonic Boundaries of Southern Ontario

The Michigan Basin is a roughly circular, carbonate-dominated, evaporite-bearing intracratonic basin. The isolated nature of this intracratonic basin is largely responsible for the dominant carbonate deposition, when compared with the more argillaceous (clastic) depositional setting of the Appalachian foreland type basin (described below). Given the relatively low relief between the two basins during most of the Paleozoic, however, the facies and lithological changes between the two basins across the Algonquin Arch are gradual, occurring over large distances. At the Bruce nuclear site there is a thick sequence (approximately 840 m) of marine sedimentary rocks (limestone, dolostone, shale and evaporites) ranging in age from Upper Cambrian to Middle Devonian. The cross-section presented in Figure 2.6, derived from gas and oil well records, shows the thickening of sediments westward into the Michigan Basin from the crest of the Algonquin Arch. The Niagara Escarpment truncates the eastern edge of

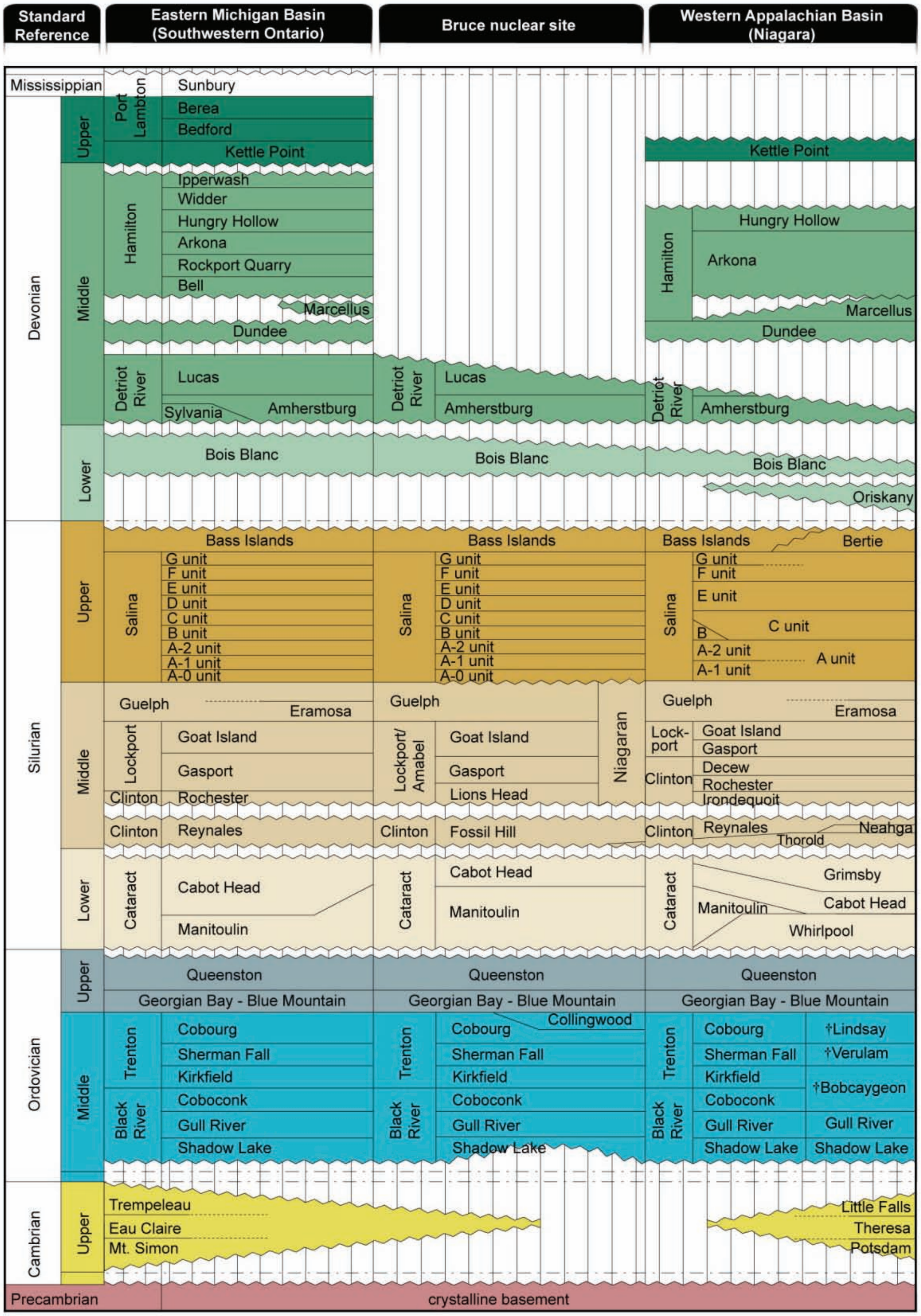
Figure 2.6 and the erosional valley located west of the escarpment is the Beaver Valley. The location of the detailed Three Dimensional Geological Framework (3DGF) described in Chapter 6 is also shown on Figure 2.6.



Notes: Band widths represent relative tectonic intensity. Figure is from Sanford et al. (1985).

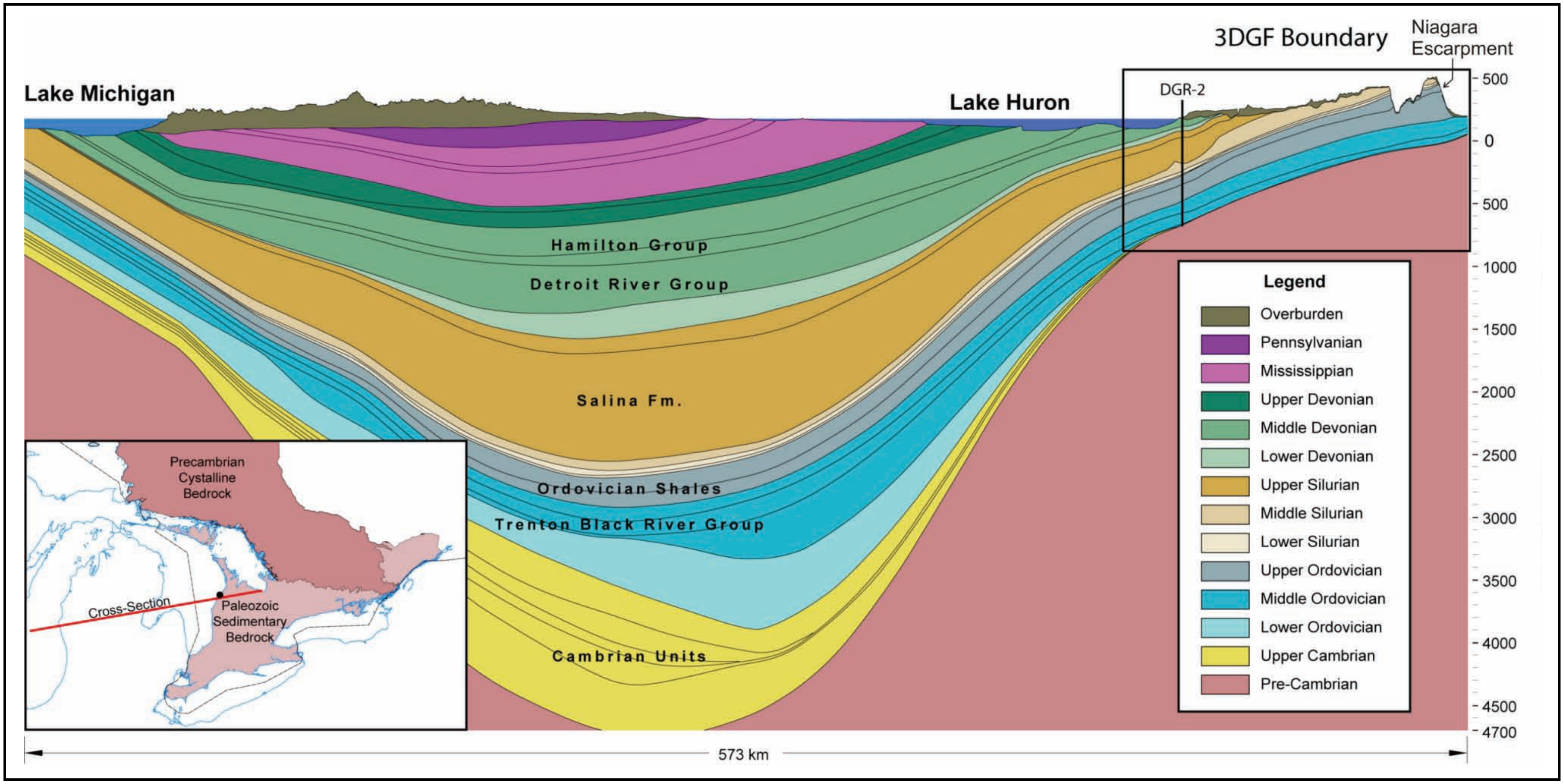
Figure 2.4: Phanerozoic Tectonic Cycles

Figure 2.7 (Sanford 1993) shows a regional cross-section from the Appalachian Basin (commonly referred to as the Alleghany Basin in US nomenclature) into the Michigan Basin and the associated geological formations and general lithologies. The dip of the Paleozoic strata typically ranges from 5.5 to 8.5 m/km away from the Algonquin Arch into each basin (Winder and Sanford 1972).



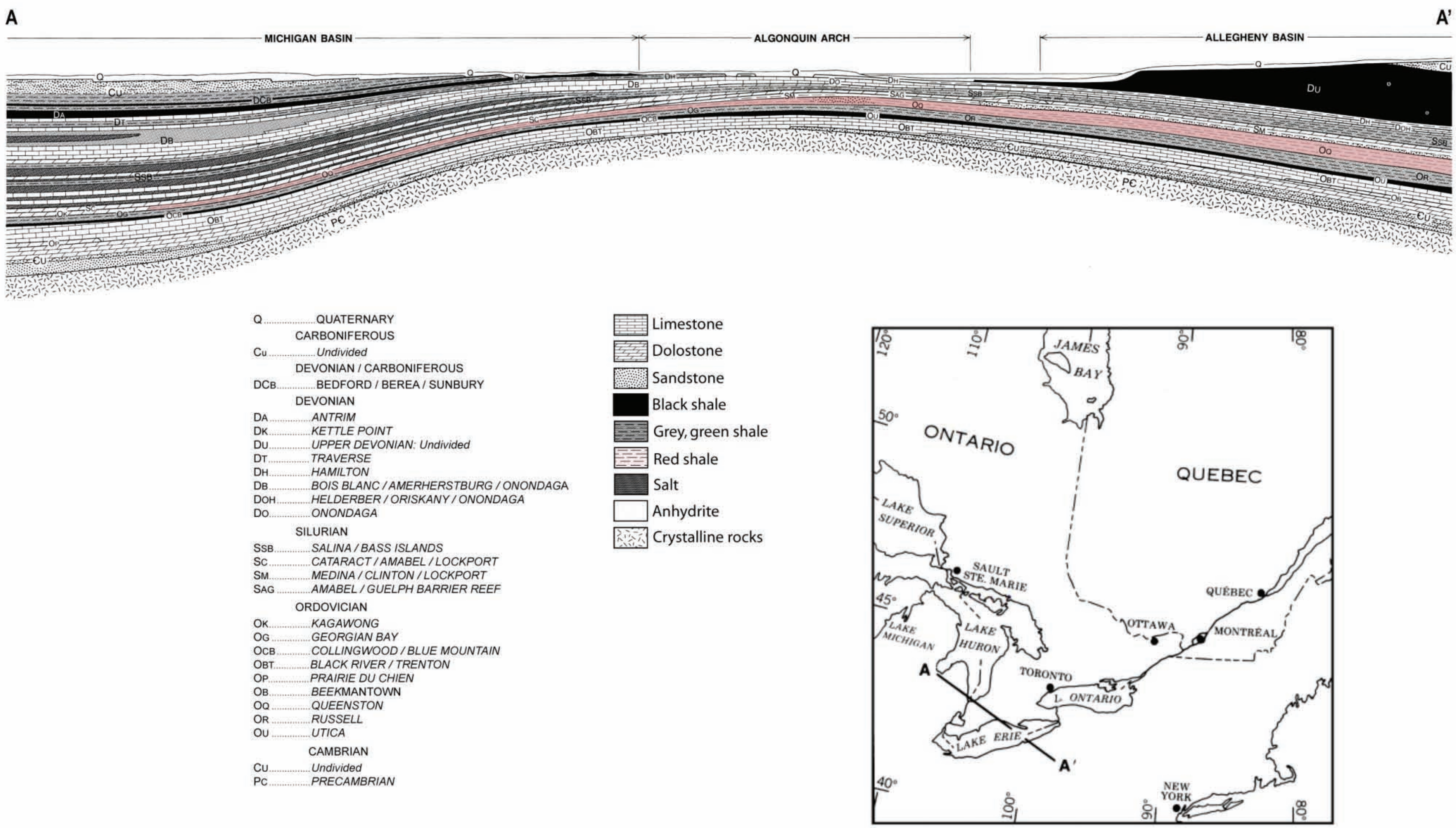
Notes: Includes nomenclature from locations in the Michigan Basin (left), Bruce nuclear site (centre), and Appalachian Basin (right). † indicates outcrop nomenclature for southern and eastern Ontario. Mondified from Armstrong and Carter (2006) after Winder and Sanford (1972).

Figure 2.5: Paleozoic Stratigraphy of Southwestern Ontario



Notes: Vertical axis is elevation in metres relative to sea level. Boundary of the regional 3D geological framework is indicated by black outline in top left corner of the cross-section. Mesozoic rocks overlying the Pennsylvanian sediments are too thin and discontinuous to shown on cross-section. DGR-2 borehole is projected on to geological cross-section. Vertical exaggeration approximately x45.

Figure 2.6: Geological Cross-section of the Michigan Basin



Notes: Cross-section location is shown as A-A' in inset map (from Sanford 1993).

Figure 2.7: Geological Cross-section Across the Algonquin Arch

3. STRUCTURAL GEOLOGY

The primary materials reviewed in preparation of the structural geology section were; a recent synthesis by Mazurek (2004) prepared for NWMO, the paper by Sanford et al. (1985) that introduced the "block" concept for Southern Ontario, publications by Easton and Carter (1995) and Carter et al. (1996) on the basement structure and evidence for Paleozoic faulting in Southern Ontario, and the Ontario Geological Survey synthesis report on the Paleozoic geology of Ontario (Johnson et al. 1992). Additional materials included publications on neotectonics (Wallach et al. 1998), jointing and pop-up structures (Rutty and Cruden 1993, Andjelkovic et al. 1996, 1997, 1998) in southern Ontario, and reports and publications on the structure and depositional history of the intraplate basins of North America, including the Michigan basin (Howell and van der Pluijm 1990, 1999, Leighton 1996, van der Pluijm and Craddock 1996, Wood and Harrison 2002 and references therein). A synthesis of joint measurement data, compiled by NWMO and AECOM (2011), pertinent to the study area was also made available.

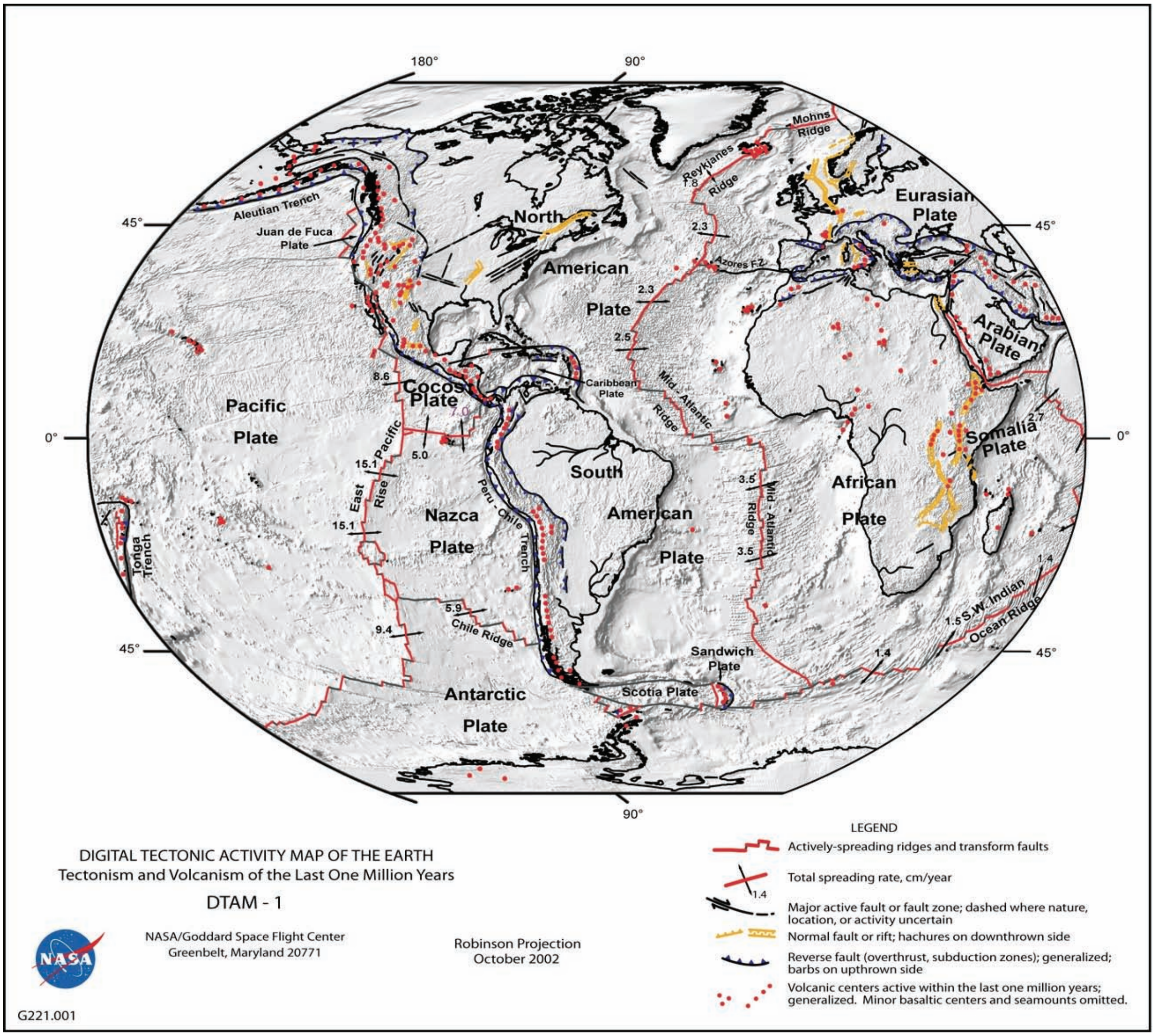
This chapter reviews the structural geology and tectonic history of southern Ontario. Particular emphasis is placed on the Precambrian basement and Paleozoic cover of the study area. Of particular interest are the deep sedimentary rocks at the Bruce nuclear site. These sedimentary rocks lie unconformably on a crystalline basement that formed during the Grenville Orogeny in Proterozoic times. Understanding the structural geology of the area requires:

- An analysis of the structure and tectonic history of the Proterozoic basement;
- Determination of the mechanism and tectonic controls acting on the development of the Michigan and Appalachian Basins and the intervening Algonquin Arch; and
- Understanding the subsequent tectonic loading events, including phases of the Paleozoic Appalachian orogen (Taconic, Acadian, Alleghenian), the Mesozoic breakup and development of the North Atlantic Basin, and the effects of Holocene glaciation and deglaciation.

Southern Ontario is located in the northeast part of the North American continent. It is part of the North American plate that extends from the mid-Atlantic Ridge in the east to the Juan de Fuca/Pacific plate margin in the west (Figure 3.1). Figure 3.2 shows an interpreted cross-section through the Grenville Province to the depth of the Moho. The Precambrian Shield of North America and its cover of platform and intraplate basin sediments (i.e., the North American Craton) are considered to have been relatively tectonically stable since the Paleozoic (e.g., Park and Jaroszewski 1994, van der Pluijm and Marshak 2004). Exceptions are remote from the tectonically stable Bruce site and include the following;

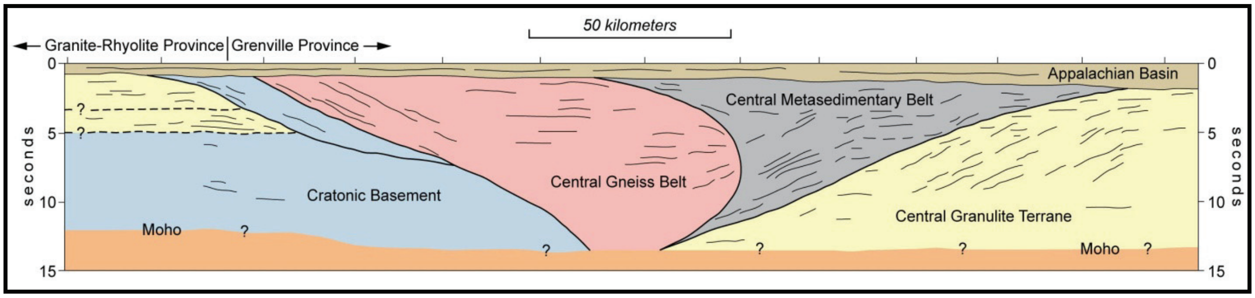
- Local deformation events associated with the Mesozoic opening of the Atlantic Ocean which resulted in rifting and volcanism in eastern Canada and the USA;
- Localized deformation associated with the Mesozoic to Cenozoic development of the North American Cordillera along the western margin of the continent (Laramide event); and
- Some domains of recent faulting and seismicity (e.g., New Madrid Seismic zone/Reelfoot Rift, Missouri and Tennessee, Saguenay Rift, St. Lawrence lowlands).

Figure 3.3 shows the Sanford et al. (1985) conceptual fracture distribution combined with the known basement faults as described by Carter et al. (1996). Within the conceptual fracture framework, the Bruce and Niagara Megablocks are characterized by different distributions of fractures. The fracture framework characterizes the Bruce Megablock as having a structure characterized by regularly spaced, ESE- to EW-trending faults with south-side-down normal displacement which offset and control facies variations and thicknesses within the Guelph carbonate and Salina B-unit. The trend of these faults is broadly coincident with faults observed within the Devonian Dundee Formation in the central Michigan Basin (Wood and Harrison 2002), although their spacing is significantly closer. Sanford et al. (1985) further suggest that salt dissolution was focused along regional fracture patterns resulting in an interpreted distribution of Salina salt as shown in Figure 4.9. The validity of the fracture dissolution model proposed by Sanford et al. (1985) has not been tested or resolved in the literature.



Notes: Figure indicates the locations of plates, plate boundaries, and regions of active faulting and volcanism (from NASA 2002 http://denali.gsfc.nasa.gov/dtam).

Figure 3.1: Digital Tectonic Activity Map of the Earth Over the Last 1 Ma



Note: Figure is adapted from Culotta et al. (1990).

Figure 3.2: NW-SE Oriented Interpretation of Seismic Images of the Grenville Province

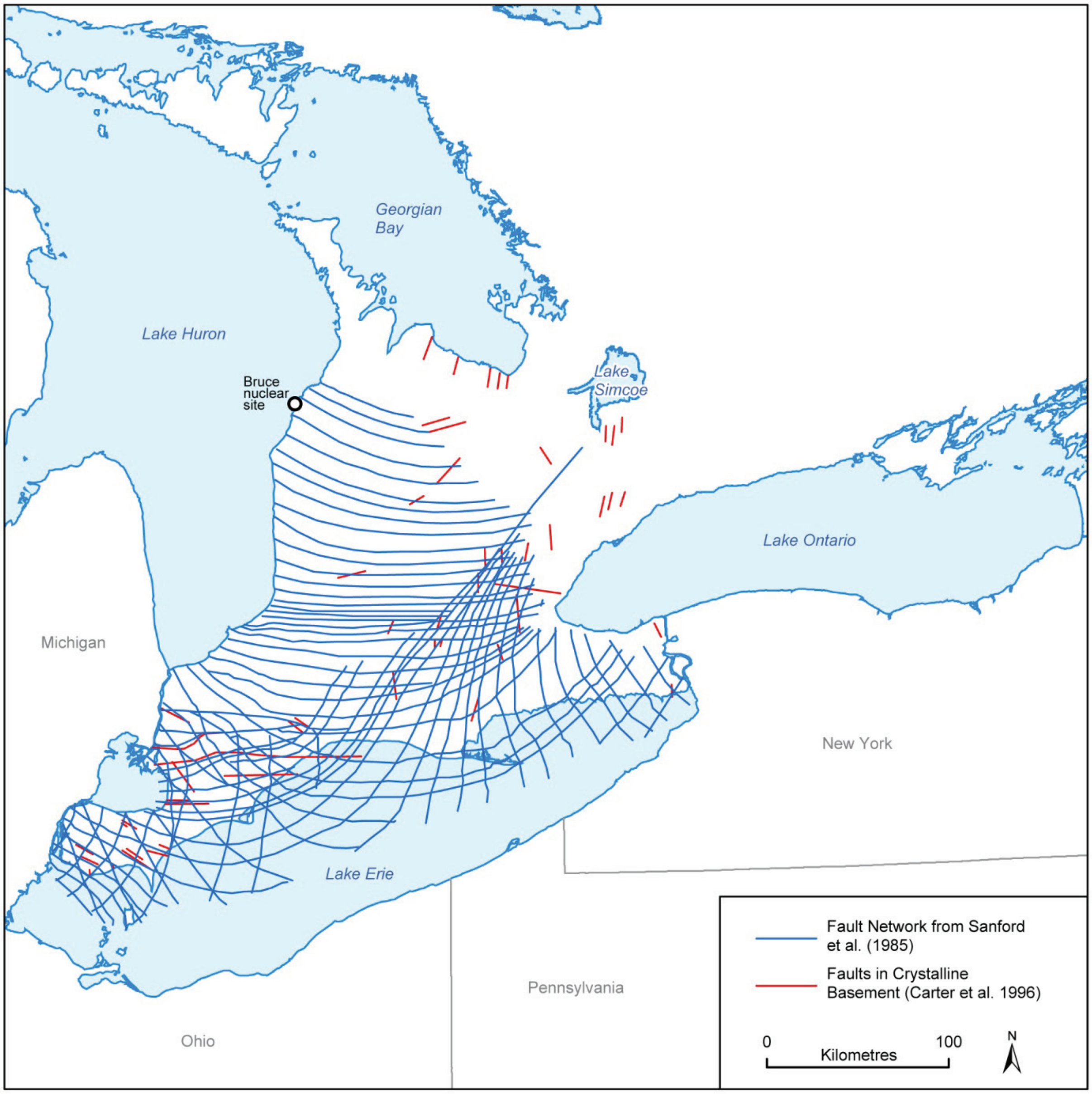
The block model is based on surface lineament patterns derived from low resolution Landsat imagery and compilation of major basement structures (Sanford et al. 1985). The use of low resolution imagery to interpret structural features in the Bruce-Niagara region is questionable because of the thickness of Quaternary surficial deposits, which tend to mask near surface expression of faults (should they be present) and fractures, compared to the exposed Precambrian to the north which typically has very thin to absent drift cover.

The subsurface distribution of faults deduced from borehole data as presented in the conceptual fracture framework, while broadly consistent with faulting in the central Michigan Basin (Wood and Harrison 2002), cannot be assessed because the locations of boreholes are not presented. The hand contouring of subsurface data by Sanford et al. (1985) for the conceptual fracture framework produced very systematic structural patterns with a spacing of 10 to 15 km in the Bruce area (Figure 3.3). An assessment of this conceptual framework is important because the presence of a fracture system may have implications for past hydrothermal fluid migration and associated porosity enhancing dolomitization. It is noteworthy, however, that such systematic fracture patterns are not observed in structural contours on the top of the Precambrian basement surface, nor are they consistent with known mapped faults that displace this surface (Figure 3.3, Carter et al. 1996, Armstrong and Carter 2010). Furthermore, it is difficult to reconcile Sanford et al.'s (1985) fracture framework model with known joint distribution data for southern Ontario, Michigan and northern New York (Holst 1982, Parker 1942, Nichelson and Hough 1967, Scheidegger 1977, Gross and Engelder 1991, Rutty and Cruden 1993, Andjelkovic et al. 1996, 1997, 1998, NWMO and AECOM 2011).

Johnson et al. (1992) note that although a fracture-framework may exist, the extensive fracture framework conceptualized by Sanford et al. (1985) has not been recognized. Data in this report supports the interpretation that the RSA is characterized by a relatively simple basement structure and very low historical seismicity compared to adjacent tectonic blocks.

Andjelkovic et al. (1998) concluded three major findings:

- Topographic lineaments are controlled by fractures in the underlying rocks (i.e., lineaments are a good proxy for characterizing bedrock fractures);
- Fractures in the Paleozoic rocks retain a remarkable consistency orientation across the region (i.e., they are systematic); and
- An important subset of the fracture population (NNE-trending set in the west, NE-trending set in the east) is controlled by the orientation of pre-existing structural trends in the underlying Precambrian basement.



Notes: Compilation includes faults interpreted to displace the Paleozoic-Precambrian unconformity surface. Figure is modified from Mazurek (2004) after Sanford et al. (1985) and Carter et al. (1996).

Figure 3.3: Proposed Fracture Framework and Mapped Faults of Southern Ontario

3.1 Discussion

3.1.1 Geologic Sequence

The Cambrian to Devonian strata preserved in southern Ontario dip at low angles (0.5°) towards the southwest in the Bruce area and towards the south in the Toronto-Niagara region. That is, towards the depositional centres of the Michigan and Appalachian Basins, respectively. The regional dip of these strata, together with differential erosion of resistant Silurian dolostones of the Amabel/Lockport Formation versus less resistant shales of the underlying Queenston Formation resulted in the development and southwestward retreat of the Niagara Escarpment. Similarly, erosion of the Paleozoic strata, which was originally more continuous to the north, has resulted in the exposure of the Paleozoic/Precambrian unconformity along an east-west orientation between Kingston and Georgian Bay. Regional stratigraphic dip and post Paleozoic erosion has resulted in progressive exposure of younger units to the south and southwest (Figure 2.1).

Following the Grenville Orogeny and the formation of the Proterozoic metamorphic basement, the region has experienced the effects of far-field stresses since the onset of the Appalachian-Caledonian orogen, which is characterized by three pulses of tectonic activity: Taconic (Ordovician), Acadian/Caledonian (Devonian) and Alleghenian (Carboniferous) (Sanford 1985, Figure 2.4). The climaxes of these orogenic cycles coincide with major phases of basin subsidence and arch uplift and influenced the sedimentary input into the region (Sanford et al. 1985). These stresses were likely large enough to cause local reactivation of basement structures and regional development of fractures (joints) in the Paleozoic cover.

The current stress regime in southern Ontario (e.g., NWMO and AECOM 2011) has its origins in the breakup of the Atlantic in the Jurassic and the subsequent establishment of sea floor spreading along the mid-Atlantic ridge in the Cretaceous. Since then the principal tectonic force affecting eastern North America has been provided primarily by gravity-driven ridge push, resulting in high, sustained ENE directed horizontal maximum in situ stresses. Since the Quaternary Period, these far-field tectonic stresses have interacted with vertical and flexural loads associated with continental glaciation and deglaciation events, culminating in the retreat of the Wisconsin ice sheet 12,000 years ago, to produce a variety of small-scale structures, such as open field pop-ups (Karrow and White 2002).

The structural geology of southern Ontario is best interpreted in the framework of the tectonic history described above, and summarized in Table 3.1.

3.1.2 Basins and Arches

As noted above, the Paleozoic depositional history in southern Ontario was controlled by relative vertical motions of the Michigan and Appalachian Basins and the intervening Algonquin Arch. In southwestern Ontario, the maximum depositional thickness of Paleozoic sediments is achieved in the Chatham Sag, which is a downwarp occurring between the Algonquin Arch and its continuation in Ohio and Indiana as the Findlay Arch (Figure 2.2).

The Appalachian Basin is spatially associated with the Appalachian orogen and is best interpreted as the foreland basin (or foredeep) that developed in response to tectonic loading associated with the different phases of that orogen. The Michigan Basin is one of several, broadly circular intracratonic sedimentary basins in North America, whose origins remain poorly understood.

Table 3.1: Timetable of Tectonic Events

Time Interval (Ma)	Major Tectonic Activity	Present Joint Orientation	Reference
1210 – 1180 1190 – 1180	Elzevirian Orogeny – regional metamorphism ➤ earliest thrusting in CMBBZ – closure of back arc basin		Easton 1992, Lumbers et al. 1990, Hanmer and McEachern 1992
1100 – 1060	Ottawan orogeny / Grenville orogeny ➤ thrusting, folding		Easton 1992
1080 – 1050	➤ reactivation of thrusting in CMBBZ ➤ possible continental collision to the SE		Hanmer and McEachern 1992
1060 – 900 900	➤ extension – collapse of thrust stack ➤ mafic dykes, faulting – precursor to Ottawa graben		Easton 1992
1000 – 500	➤ uplift and erosion (e.g., Frontenac Arch)		Easton 1992
Neoproterozoic to Early Cambrian	➤ extension, faulting along the Ottawa-Bonnechere Graben, possibly related to opening of the Iapetus ocean		Easton 1992
530 – 340	Subsidence of Michigan Basin and Arch Uplift (episodic)	NNE	Howell and van der Pluijm 1999, Sanford et al. 1985
458 – 431	Taconic Orogeny ➤ E-W to NW-SE compression, uplift (Frontenac and Algonquin arches)	SE	Quinlan and Beaumont 1984, Sloss 1982
410 – 360	Acadian Orogeny ➤ E-W to NW-SE compression, uplift (Frontenac and Algonquin arches)	SE	Gross et al. 1992, Marshak and Tabor 1989, Sutter et al. 1985
300 – 250	Alleghenian Orogeny ➤ E-W to NW-SE compression	SE	Gross et al. 1992, Engelder and Geiser 1980
200 – 50	➤ opening of the Atlantic ➤ St. Lawrence rift system created ➤ reactivated Ottawa-Bonnechere Graben ➤ NE-SW extension ➤ uplift	ESE	Kumarapeli 1976, 1985
50 – Present	➤ post-glacial uplift ➤ NE-SW compression (from ridge push)	ENE	Barnett 1992

These basins and their intervening arches were active over a protracted period of time (Cambrian to Carboniferous). A variety of mechanisms have been proposed for their origin (Leighton, 1996 and references therein). These mechanisms include:

- Vertical surface motions driven by thermal or density forces in the lithosphere;
- Mantle flow; or
- Subsidence and uplift related to horizontally transmitted principle tectonic stresses.

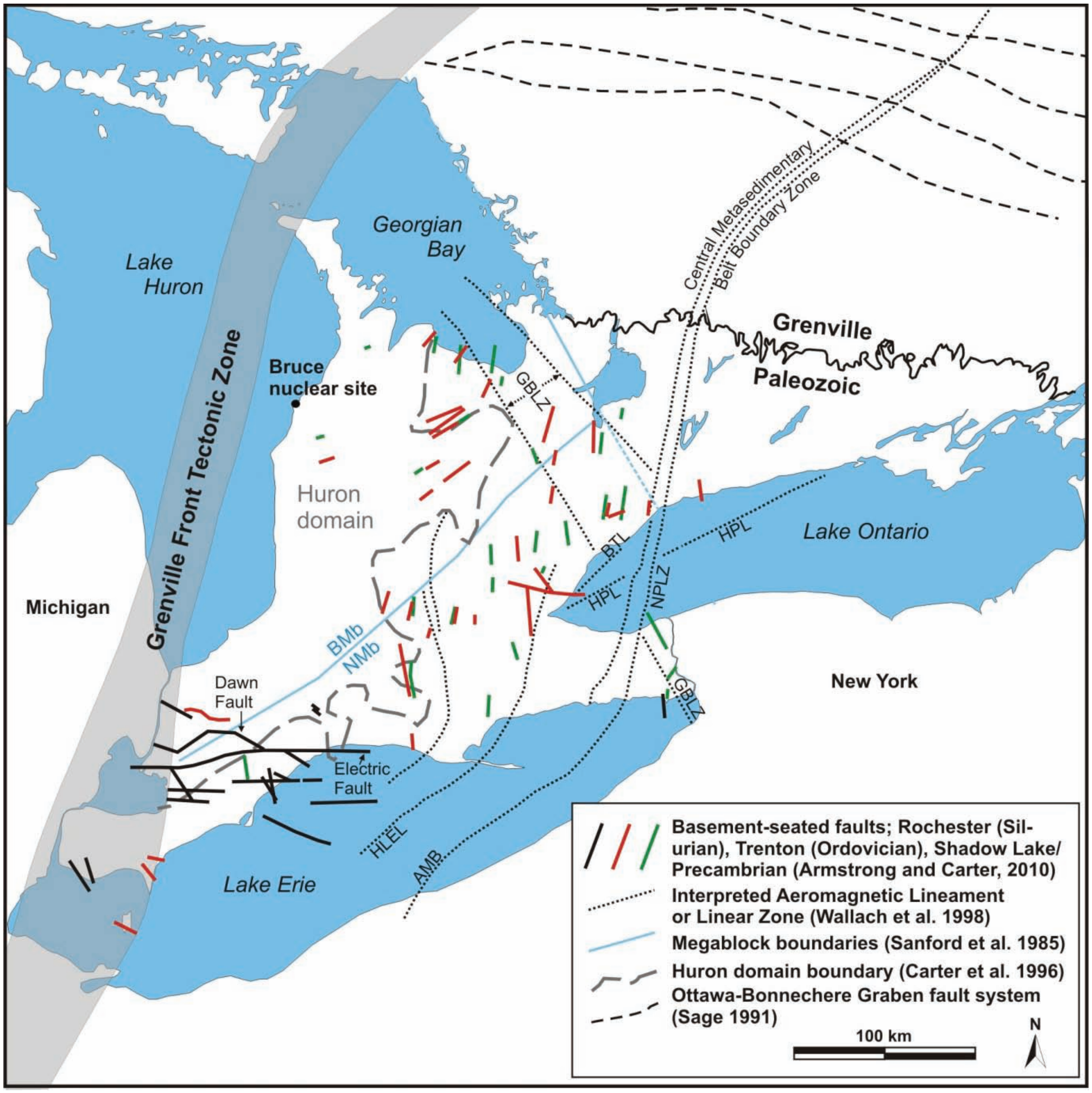
A detailed analysis of the subsidence history of the Michigan Basin by Howell and van der Pluijm (1999) concluded that its development involved alternation between periods of vertical crustal motion (epeirogeny) and regional tilting associated with phases of the Appalachian and possibly Cordilleran orogens.

3.1.3 Lineaments

The structure of the Proterozoic basement of southern Ontario has been well characterized by surface mapping north of the Paleozoic/Precambrian contact, regional potential field geophysical data (aeromagnetics, gravity), seismic reflection surveys and geochemical, geochronological and petrographic analyses of samples recovered from bore holes (Easton and Carter 1995, Carter et al. 1996). Figure 3.4 shows the structural subdivisions of Precambrian basement, updated locations of previously mapped major faults, and aeromagnetic lineaments. Two major structures can be followed from their surface exposure northwest and east of Georgian Bay beneath the Paleozoic cover to the southwest. The first is the Grenville Front Tectonic Zone (GFTZ), which marks the leading edge of the Grenville Orogen with the Southern and Superior shield provinces. The second is the Central Metasedimentary Belt Boundary Zone (CMBBZ), which defines the contact within the Grenville Province between the Central Gneiss Belt to the west and the Central Metasedimentary Belt (now called the Composite Arc Terrane) to the east (Easton 1992) (Figure 3.4).

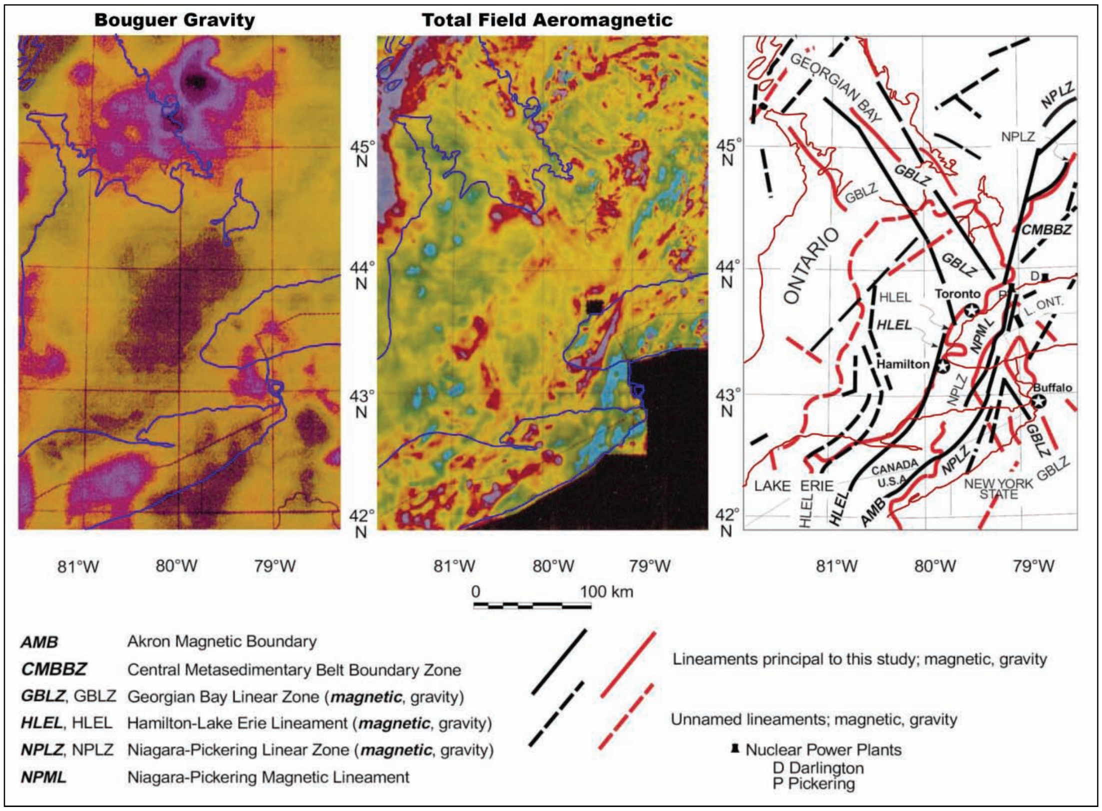
Seismic reflection profiles image these structures, which dip gently to moderately to the east (e.g., left side of Figure 3.2; White et al. 1994). The Grenville basement beneath southern Ontario has been further subdivided based on geophysical and borehole data (Carter et al. 1996). The largest subdivision is the Huron domain which exhibits a relatively featureless gravity and aeromagnetic anomaly pattern and whose domain boundary roughly coincides with that of the Bruce Megablock (Figures 3.4 and 3.5).

Figure 3.5 presents three maps of southern Ontario, including i) a gravity map, ii) an aeromagnetic map and iii) an interpretation of tectonic structure based on the gravimetric and magnetic lineaments (Wallach et al. 1998). Wallach et al. (1998) have characterized the eastern boundaries of the structurally featureless domain (including the RSA) presented in Figure 3.5 as coinciding with the aeromagnetically defined Georgian Bay Linear Zone and the CMBBZ, which they argue may be collinear with regions of anomalous recent seismic activity. In a review of Wallach et al.'s interpretation, as published in a report for the Atomic Energy Control Board (Wallach 1990), Roest (1995) states that, based on gravity and aeromagnetic data, the existence of the Georgian Bay Linear Fault Zone south of Georgian Bay proper is questionable. Carter et al. (1996) have compiled the occurrence of faults that displace the Precambrian/ Paleozoic unconformity based on geophysical and borehole data. As can be seen in Figure 3.3, with the exception of southwest Ontario, the correspondence between the mapped faults and the fracture framework inferred by Sanford et al. (1985) is marginal. A similar lack of correspondence can be noted when structure contours on the unconformity are compared with the fracture framework model.



Notes: Contacts are based on field mapping and interpretations aided by subsurface drilling, borehole stratigraphic correlation, and geophysics (Liberty 1961, and compiled by Brigham 1971, Bailey and Cochrane 1984a, Bailey and Cochrane 1984b, Sanford et al. 1985, Jacobi and Fountain 1993, Carter and Easton 1990, Easton and Carter 1995, Carter et al. 1996, Wallach et al. 1998, Ketchum and Davidson 2000, Boyce and Morris 2002). AMB: Akron Magnetic Boundary; NPLZ: Niagara–Pickering Linear Zone; HLEL: Hamilton–Lake Erie Lineament; BTL: Burlington–Toronto Lineament; PL: Hamilton–Presqu'ile Lineament; GBLZ: Georgian Bay Linear Zone; EF: Electric fault; DF: Dawn fault; BMb – Bruce Megablock; NMb – Niagara Megablock.

Figure 3.4: Tectonic Boundary and Fault Contacts in Southern Ontario



Notes: Bouguer gravity (left) and total-field aeromagnetic (centre) data sets are shown in comparison to an interpretation of the imaged features (right). Different shading reflects different densities on the gravity map and different intensities on the magnetic map (adapted from Wallach et al. 1998).

Figure 3.5: Selected Geophysical Data Sets for Southcentral Ontario

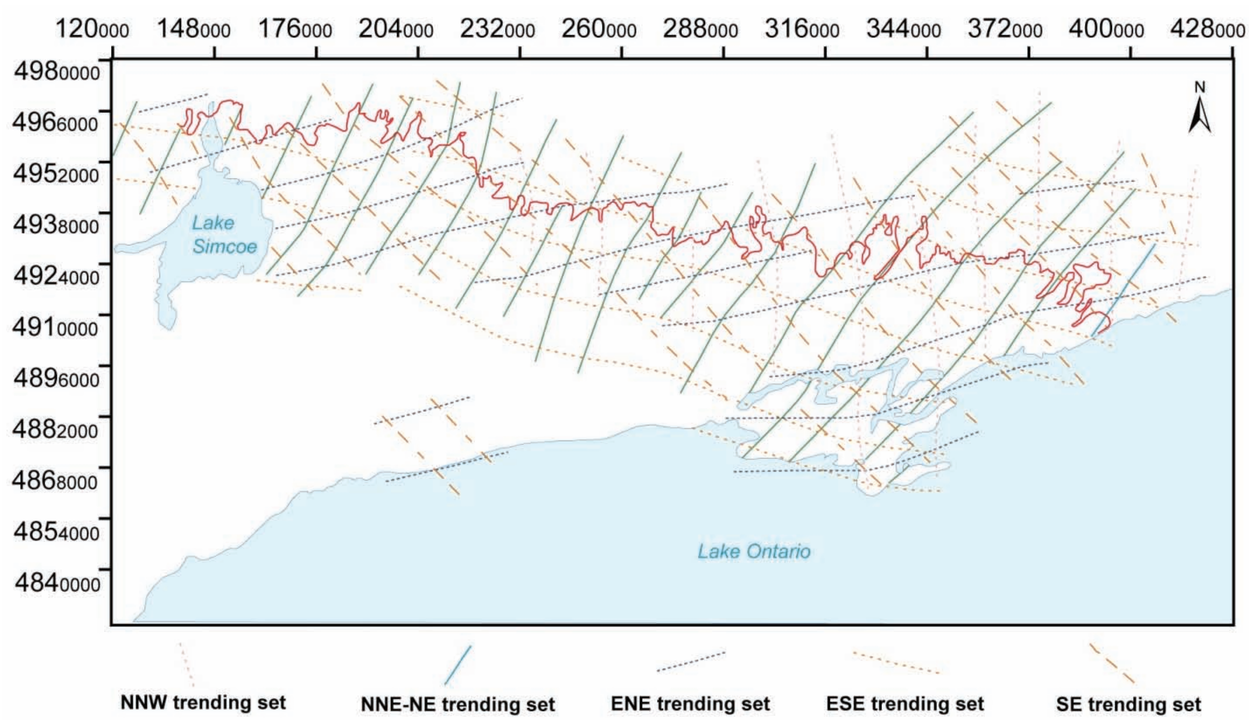
3.1.4 Tectonic Forces

Perhaps the best gauges of the history of tectonic forces in Southern Ontario are regionally consistent, systematic fractures and joints (e.g., Figures 3.6 and 3.7). The majority of fractures observed in Southern Ontario are joints. The Regional Geomechanics Report (NWMO and AECOM 2011) provides a review of the literature with respect to joint orientation and location both regionally and in the geologic column. Joints form in response to loading or unloading of the rock mass. The joint (or fracture) plane is oriented parallel to the maximum principal stress and normal to the minimum principal stress.

Jointing occurs under three types of loading regimes:

1. During vertical compaction and burial diagenesis under conditions of high pore fluid pressure;
2. During tectonic loading events:
    i. compressional = horizontal maximum stress + horizontal minimum stress;
    ii. extensional = vertical maximum stress + horizontal minimum stress; and

3. Unloading and isostatic rebound (horizontal maximum stress + vertical minimum stress).



Note: Figure is modified after Andjelkovic et al*.* (1997).

Figure 3.6: Trajectories of Peak Joint Orientations in Southcentral Ontario

Vertical joints in Southern Ontario have formed since the beginning of the Paleozoic due to mechanisms (1), (2i) and (2ii). Horizontal joints (often along bedding planes and called release joints) have formed due to mechanisms (1) and (3), and have most likely been enhanced during cycles of glacial loading and unloading during Quaternary glacial and interglacial events.

Andjelkovic et al*.* (1996, 1997, 1998) measured ~7,000 fracture orientations from outcrops and quarries between Georgian Bay and Kingston (Figure 3.6). The bulk of these measurements were from Ordovician strata (Shadow Lake, Gull River, Bobcaygeon, Verulam, Lindsay (Cobourg), Georgian Bay Formations) and from the crystalline Precambrian basement exposed north of the trace of the Precambrian/Paleozoic unconformity. This study was supported by analysis of thousands of lineaments detected from Landsat TM and Radarsat SAR images of the same area. Rutty and Cruden (1993) conducted a fracture study in the Balsam Lake area east of Orillia, where Ordovician rocks of the Bobcaygeon and Verulam Formations are exposed. Using a similar outcrop measurement and remote sensing approach to Andjelkovic et al*.* (1996, 1997, 1998) they determined that fractures in the area have peak trends oriented 027°, 091° and 152° (NNE, E, SSE, respectively). Post-glacial (i.e., <12,000 years) pop-up structures in the area are predominantly oriented 118°, and have nucleated on a sub-set of the ESE fracture set. These pop ups are interpreted to have formed during rapid release of high in situ tectonic stress shortly after the retreat of the Laurentian ice sheet.

Notes: This compilation includes data from Paleozoic and Precambrian outcrop measurements. Joints are plotted as Gaussian contoured and smoothed rose diagrams. Figure is from NWMO and AECOM (2011).

Figure 3.7: Joint Orientations of Southern Ontario and Part of the Northern United States

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Joints measured in the Eramosa, Vinemount, Ancaster, Niagara Falls and Gasport Members of the Silurian Lockport Formation exposed in quarries and excavations in the Smithville area have peak orientations at 018°, 082°, 132°, and 152° (Gartner Lee Ltd. 1996). The three listed in bold correspond to the NNE, E, and SSE and trending sets of Andjelkovic et al*.* (1997) in stratigraphically lower units to the northeast. There is, however, a subtle shift in some joint sets: the ENE from 82° to 91°, and the NNE from 18° to 27°. Yet the SSW remains the same at 152°. Examination of the joint sets reported in upstate New York show, albeit south of the Algonquin Arch in the Appalachian Basin, a subtle shift of about 50° from NNE to NNW as one moves from east to west (Figure 3.4) is also apparent in the major joint set at each point.

Of some interest are the Ordovician strata, which under the Bruce nuclear site would host the proposed DGR. East of Lake Simcoe the major fracture sets measured in Ordovician strata are oriented SE (122°-160°), NNE (011°-064°) and ENE (065°-089°) (given in decreasing order of abundance). Of relevance to the present study, a fourth major set trending ESE (090°-120°) becomes important along the northern flank of the basin and higher in the stratigraphy (Figure 3.7).

Andjelkovic et al*.* (1996, 1997, 1998) have proposed the following scenarios for the formation of the major systematic vertical joint sets in southcentral Ontario (Figure 3.6), in chronological order.

1. NNE-trending set: these joints track the orientation of the structural grain of the underlying Precambrian basement with remarkable consistency. They are interpreted to have formed due to differential compaction of Paleozoic sediments over a structurally controlled “corrugated” basement-cover interface under conditions of high pore fluid pressure (i.e., Mechanism (1) above).
2. SE-trending set: most likely formed due to high in-plane stresses transmitted into the foreland of the Appalachian orogeny (i.e., Mechanism (2i) above).
3. ESE-trending set: formed due to regional extension of the crust that affected all of eastern North America during the Jurassic breakup of the Atlantic Ocean (i.e., Mechanism (2ii) above).
4. ENE-trending set: may be neotectonic in origin (i.e., formed during the current tectonic stress regime, which is attributed to mid Atlantic ridge push and has remained approximately constant since the Cretaceous, Mechanism (2i) above).

Figure 3.7 shows a generalized map of joint orientations derived from a variety of sources (Andjelkovic et al*.* 1996, 1997, 1998; Gartner Lee Ltd. 1996, and others). The “propeller plots” shown on Figure 3.7 show the orientation of major and minor joint sets determined from many surficial measurements of joint orientations on the exposed bedrock surface at the given locations. The “stick plots” have been drawn to represent patterns in upstate New York, north of the Allegheny Front.

Recent processes are interpreted primarily to open pre-existing fractures, rather than create new ones. These recent processes include stress release due to the southwest erosional advancement of the Niagara escarpment (which is itself a pre-glacial landform) or quarry excavation activities, or solution effects during karst weathering. The only significant exception is the formation of new pop-ups created when quarry activities unload strata that were previously confined. These are typically oriented perpendicular to the presently existing principal horizontal stress.

3.2 Summary

The study area can be characterized as one of the more structurally simple parts of southern Ontario. Paleozoic strata dip gently towards the centre of the Michigan Basin and contain two principle fracture (joint) sets in surface exposures whose orientations are consistent with those elsewhere in southern Ontario. Previous work by Sanford et al. (1985) indicates that Silurian units (Guelph and Salina Formations) contain ENE- to EW-trending normal faults with ~10 km spacing and top to the south displacements. However, lack of evidence for the continuation of these faults to the basement or surface indicates that their significance requires further evaluation.

The Paleozoic rocks rest unconformably on a crystalline basement of Proterozoic age. Available aeromagnetic and gravity data (Easton and Carter 1995, Wallach et al. 1998) suggest that Proterozoic rocks underlying the study area are structurally simple. Currently no major basement structural features, as observed to the west (Grenville Front Tectonic Zone) or east (Central Metasedimentary Belt Boundary Zone), have been observed in the RSA. In addition, there are currently no known active faults within the Paleozoic rocks in the study area. This assessment is supported by the low level of seismicity in the Bruce Megablock (NWMO and AECOM 2011).

The metamorphic basement underlying the study area belongs to the Central Gneiss Belt of the middle Proterozoic Grenville orogen and lies between two major crustal structures, the Grenville Front Tectonic Zone and the Central Metasedimentary Belt Boundary Zone. These features and the intervening subsidiary structures formed under ductile to brittle-ductile conditions 1,100 Ma ago and they dip moderately to gently to the E and SE. As shown by various studies, some basement structures have subsequently influenced sedimentation, faulting and fracture development in the overlying Paleozoic sedimentary sequence. The precise nature of the influence of these basement structures remains poorly constrained and likely involved both reactivation and passive mechanisms (e.g., local stresses due to differential compaction over basement highs).

The Paleozoic cover sequences were deposited unconformably over the Precambrian basement on the margins of the Appalachian and Michigan basins and over the intervening Algonquin Arch. The basins and arches are tectonic features, their subsidence and uplift being controlled by both orogenic and epeirogenic forces that generated both horizontal and vertical stresses in the crust. Sedimentation in these basins continued episodically from the Cambrian to the Carboniferous in response to several episodes of basin subsidence and arch uplift. Paleozoic sediments reach their maximum thickness above the basin centres and are thinnest above the Algonquin Arch. Regional stages of uplift and non-deposition resulted in the formation of several major unconformities. There is evidence that local basement structures and faulting controlled sedimentation patterns locally (e.g., lateral facies variations, pinnacle and patch reef development). Early formed NE to NNE trending regional systematic joints in the Paleozoic cover rocks appear to have been controlled by the structural grain of the basement and most likely formed due to differential compaction above linear basement highs and lows formed during the pre-Paleozoic erosion of the Grenville orogen.

Generally NW-SE oriented far field horizontal stresses propagated outward from the Appalachian orogen throughout the Paleozoic rocks, reaching maximum intensities during the Taconic (Ordovician), Acadian (Devonian) and Alleghenian (Carboniferous) cycles. These stresses were large enough to induce at least one set (SE trending) of a number of regionally developed systematic joints in the Paleozoic sediments of southern Ontario and may also be responsible for the formation of many of the observed faults that offset the Paleozoic-Precambrian unconformity.

Breakup of the Atlantic in the Jurassic Period resulted in the re-activation of ancient rift structures in eastern North America (St. Lawrence, Ottawa-Bonnechere-Nipissing, and Hudson Valley) and far field effects caused both faulting and fracturing in southern Ontario. These events are ascribed to the formation of ESE-trending faults and systematic regional joints in Paleozoic cover rocks.

Development of the mid-Atlantic spreading centre and the resulting ridge push force in the Cretaceous put eastern North America into its current (neotectonic) stress regime, characterized by high horizontal maximum in situ stresses generally oriented ENE-WSW. The regionally developed ENE trending systematic joint set formed under this regime.

Vertical loading of the crust of southern Ontario during the growth of the Laurentian ice sheet depressed the surface (by up to 600 m) and resulted in a build up of the neotectonic stress field. Subsequence retreat of the ice sheet caused surface rebound and release of stored elastic energy. Although no major post-glacial faults are observed in southern Ontario numerous near surface pop-up structures have been documented (e.g., Armstrong 1989, Armstrong 1993). Most of these pop-ups are oriented at a high angle to the present maximum horizontal in situ stress direction, however it is noted that some are also oriented sub-parallel to it (e.g., Adams 1989).

4. PALEOZOIC STRATIGRAPHY AND SEDIMENTOLOGY OF SOUTHERN ONTARIO

A recently published update of the Paleozoic stratigraphy of southern Ontario (Armstrong and Carter 2010, their Table 3 and accompanying text) includes minor modifications to the terminology of reference ages for the strata as shown in Figure 2.5 and discussed below. The Middle Silurian designation has been removed and now the Upper and Lower Silurian are separated at the top of the Eramosa member of the Guelph Formation. In addition, the Black River and Trenton Groups now comprise the lower portion of the Upper Ordovician Period. Acknowledging these recent re-interpretations, the following descriptions herein still follow the main sequence stratigraphic associations of Armstrong and Carter (2006) and Johnson et al. (1992) with the exception that the Silurian Gasport and Goat Island Members of the Lockport Formation are considered to be formations as per Brett et al. (1995), as is the Lions Head Member.

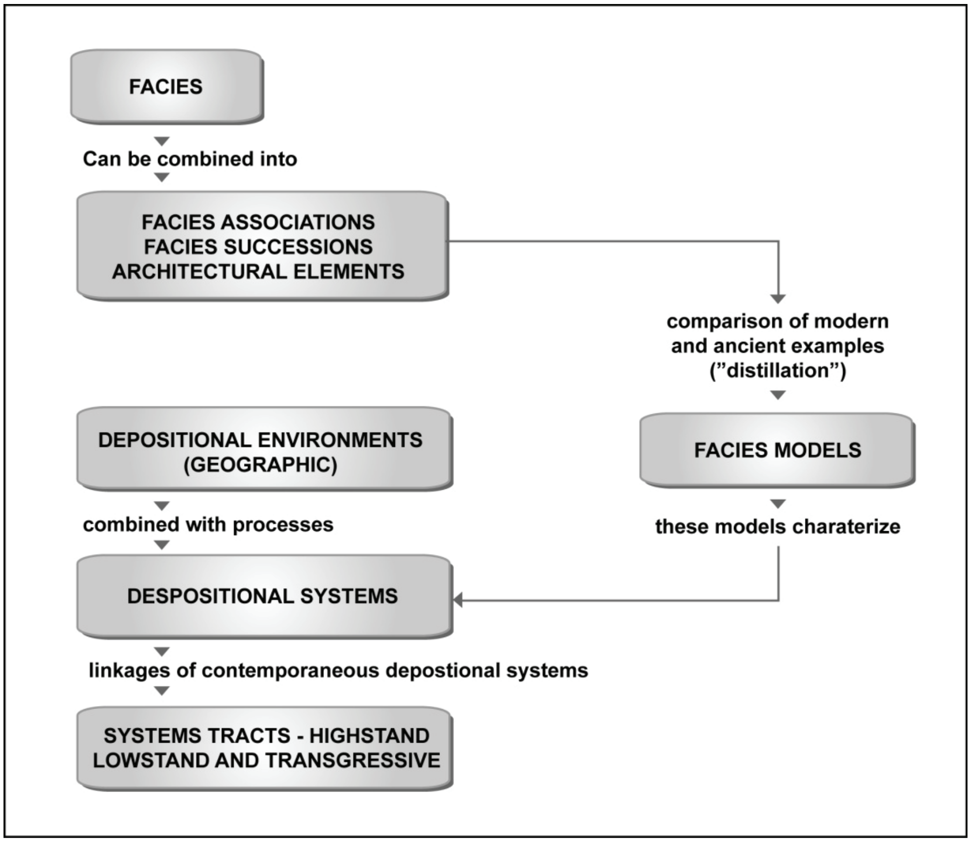
4.1 Sedimentology and Facies Models

Sedimentary rocks in the geologic record as well as modern, recent sediments can be combined into idealizations or facies models that characterize particular sedimentary environments (Walker 1992). Facies are defined by the American Geological Institute as the “aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin”. Facies generally describe the lithological and structural characteristics of rocks as observed in the field. Figure 4.1 (from Walker 1992) demonstrates the relationship between facies, and how they are combined into facies associations or successions. These associations are based on predictable and progressive changes in facies within a particular package of rock. These facies associations can then be compared with modern examples and with ancient examples from the vast sedimentary rock record and grouped into facies models. As shown in Figure 4.1, facies models describe or characterize depositional environments and depositional systems. These depositional systems can be further classified into systems tracks (highstand, lowstand and transgressive), which relate water level or eustatic controls to the facies models.

Understanding the broad depositional systems is a key component required to delineate the hydrostratigraphic framework of sedimentary units. Regional groundwater movement is dependent in part on the geometry of the sedimentary units (orientation of the bedding planes) and the geometric relationship of the facies associations. Jointing patterns and fracture orientations related to the tectonic history of the basin also control regional groundwater movement and occurrence.

Individual facies can be mapped or described on many scales. Facies characterizing the limestones and dolostones found within southern Ontario are relatively homogenous with respect to rock properties such as fractures, partings, porosity and permeability. Despite differences in the carbonate components (including fossils) of the original sediments, the final limestones are relatively homogenous for each facies association. The diagenetic process of lithification and burial compaction to form limestone progressively and significantly reduces any variability in the original sediments (James and Choquette 1990). As a result, it is sensible and common practice to group and correlate these rocks regionally based upon the broad facies association.

The small-scale facies changes associated with minor changes in carbonate/clastic material or fossil assemblages have little control on regional hydrostratigraphy. The combined lithological and structural components of the facies associations (comprising similar and predictable small scale facies) influence the hydrostratigraphy relevant to the DGR project. The broad scientific understanding of facies models from modern and ancient examples combined with field mapping and borehole data allows geologists to predict facies associations over large lateral distances with confidence.



Note: Modified from Walker (1992).

Figure 4.1: Facies Models Flow Chart

4.2 Discussion

The following descriptions are generally organized according to the main sequence stratigraphic associations in southern Ontario as shown in the middle column of Figure 2.5.

4.2.1 Cambrian Sandstones and Carbonates

The Cambrian units of Ontario were deposited over the irregular and weathered Precambrian surface. Subsequent diagenesis of the Precambrian surface resulted in further alteration. Carter and Easton (1990) noted the altered zone of the Precambrian basement rocks extended on average 2 to 5 m beneath the Pre-Cambrian/Cambrian unconformity. This alteration zone is characterized by secondary chlorite, illite and K-rich feldspar precipitated from regional brine migration (Ziegler and Longstaffe 2000a).

Cambrian deposits extend from the Appalachian Basin to the Michigan Basin but have largely been eroded over the Algonquin Arch (Bailey Geological Services and Cochrane 1984a). These deposits are up to approximately 1,200 m and 2,100 m in thickness in the middle of the Michigan (Figure 2.7) and Appalachian basins, respectively. Erosion of the Cambrian units along the Algonquin Arch was attributed to arch rejuvenation and uplift during Early Paleozoic times (Bailey Geological Services and Cochrane 1984a). Well log records obtained from the Oil, Gas, and Salt Resources (OGSR) Library - Petroleum Wells Subsurface Database indicates that Cambrian deposits are present at isolated locations over the arch. It is possible that these deposits are remnants of the eroded Cambrian or they represent isolated patches of sandstones of unknown origin/age as described by Bailey Geological Services and Cochrane (1984a). The distribution of the Cambrian is discussed further in the context of the regional geological framework model, the 3DGF, in Chapter 6 below. The lithology of the Cambrian units ranges from fine to medium crystalline dolostone, sandy dolostone, argillaceous dolostone to fine to coarse sandstone (Hamblin 1998a). In some locations, including the Bruce nuclear site, the Cambrian units have been altered by hydrothermal activity. Ziegler and Longstaffe (2000a) interpret that regional migration of the brines from the Appalachian Basin along the unconformity between the Precambrian basement and the overlying Paleozoic sedimentary rocks may have occurred in response to the Taconic Orogeny.

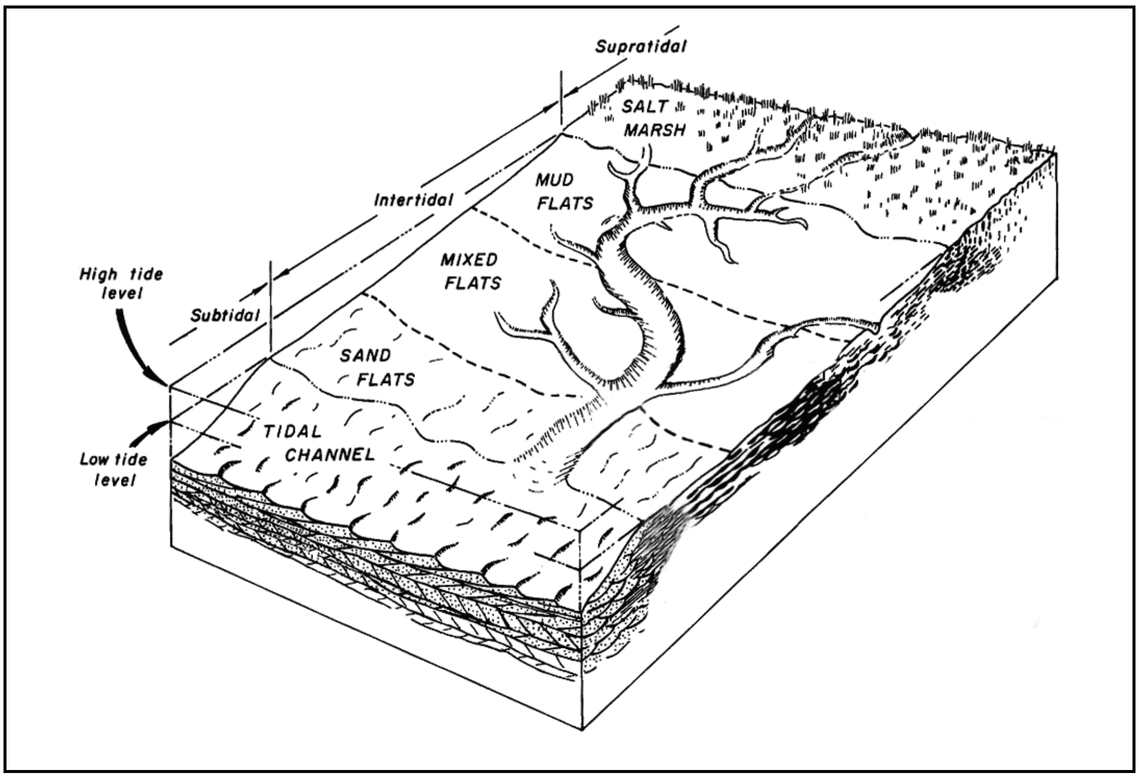
Johnson et al. (1992) describe the depositional environment of the Cambrian units in southern Ontario as undetermined. This reflects a scarcity of data on the Cambrian within the subsurface of southern Ontario. In general, the Cambrian deposits are considered to be a succession of marine sandstone and dolomite resulting from transgressive Cambrian seas that flooded across the broad platform of the Algonquin Arch and into the subsiding Michigan and Appalachian Basins (Hamblin 1998a). Within the RSA the Cambrian units are likely to include the Mount Simon Formation and/or the Eau Claire Formations. Geological log descriptions from DGR-2 are consistent with these units as described in the literature (Hamblin 1998a, Johnson et al. 1992, Trevail 1990). Trevail (1990) described the Mount Simon sandstones of Ontario as being formed in a tidal-flat tidal channel environment. Figure 4.2 (Dalrymple 1992) shows a typical tidal flat system, which can produce sandstone deposits similar to those described in the Cambrian of the Michigan Basin. These tidal systems can extend greater than 30 km in lateral extent as is the case for the modern tidal systems found for example in the Bay of Fundy, New Brunswick. The overlying Eau Claire Formation of oolitic dolostone and dolomitic sandstone is interpreted as a shallow shoal environment seaward of the tidal flat deposits of the Mount Simon Formation (Johnson et al. 1992). Carbonate shoal environments develop under wave dominated shallow systems, typically at the margin of deeper water carbonate ramp systems Figure 4.3(A) (Jones and Desrochers 1992).

As described above, Cambrian deposits beneath the study area and over the Algonquin Arch were mostly eroded during a period of Ordovician arch reactivation and regression of the tropical seas referred to as the “Knox” unconformity. Figure 6.4 shows the resulting distribution of Cambrian deposits in the RSA. A period of marine transgression during the Ordovician was responsible for the subsequent deposition of the Black River Group above the unconformity.

4.2.2 Ordovician Carbonates (Black River and Trenton Groups)

In the subsurface of southwestern Ontario, including the Bruce nuclear site, the Middle Ordovician carbonates are divided into the Black River Group and the overlying Trenton Group. The Black River Group includes three formations, the Shadow Lake Formation, Gull River Formation and Coboconk Formation while the Trenton Group is composed of the Kirkfield Formation, Sherman Fall Formation and Cobourg Formation. Where these Middle Ordovician rocks are exposed in outcrop in south-central and eastern Ontario they are classified as the Simcoe Group (central Ontario) or Ottawa Group (eastern Ontario) (Johnson et al. 1992).

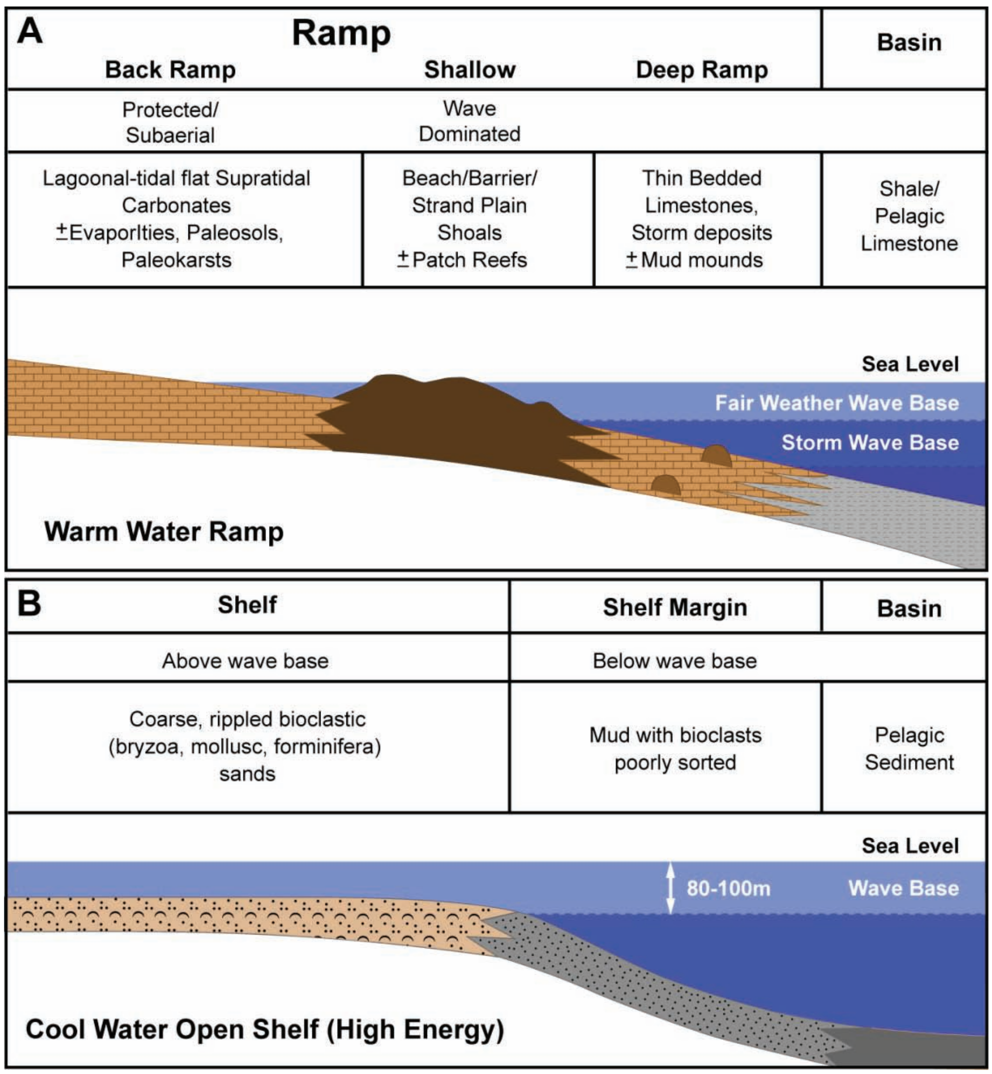
The marine transgression that followed the aforementioned Knox unconformity represents one of the greatest sea level rises in geological history (Coniglio et al. 1990). This transgression controlled the deposition of Black River and Trenton facies assemblages within an environment that evolved from supratidal and tidal flat clastics/carbonates into lagoonal carbonates then offshore shallow water carbonates and finally into deep shelf carbonates (Coniglio et al. 1990). During this time eastern North America formed a southeastward-facing shelf and passive margin (ramp) (Melchin et al. 1994) located at the paleogeographic latitude of approximately 15° (Van der Voo 1982). The Algonquin and Frontenac Arches had subdued relief unlike that of today. This extensive shelf and ramp depositional environment, that extended from the Taconic allochthon in New York State through the present Appalachian and Michigan Basins to near the middle of North America, is responsible for the uniform and extensive distribution of carbonates and calcareous shales that exist within the Black River and Trenton groups. Figure 4.4 from Sanford (1993b) presents the interpreted depositional setting with isopach thickness of the Middle Ordovician units, prior to the formation of the Michigan Basin.



Notes: Model displays showing setting and structures of siliciclastics deposits. The tidal flats fine toward the high-tide level, passing gradationally from sand flats, through mixed flats, to mud flats and salt marshes (Dalrymple 1992).

Figure 4.2: Depositional Facies Model for Cambrian Strata of SW Ontario

Facies distributions are reportedly complicated by the presence of Precambrian peninsulas, shoals and islands that existed in the Ordovician seas (Brookfield and Brett 1988). Melchin et al. (1994) suggested that in Central Ontario the Precambrian basement had low relief with knobs (paleo-relief) ranging from 6 to 30 m in height. These features were onlapped and progressively buried by younger Ordovician sediments. It should be noted that no significant knobs or other Precambrian highs are known within the RSA.

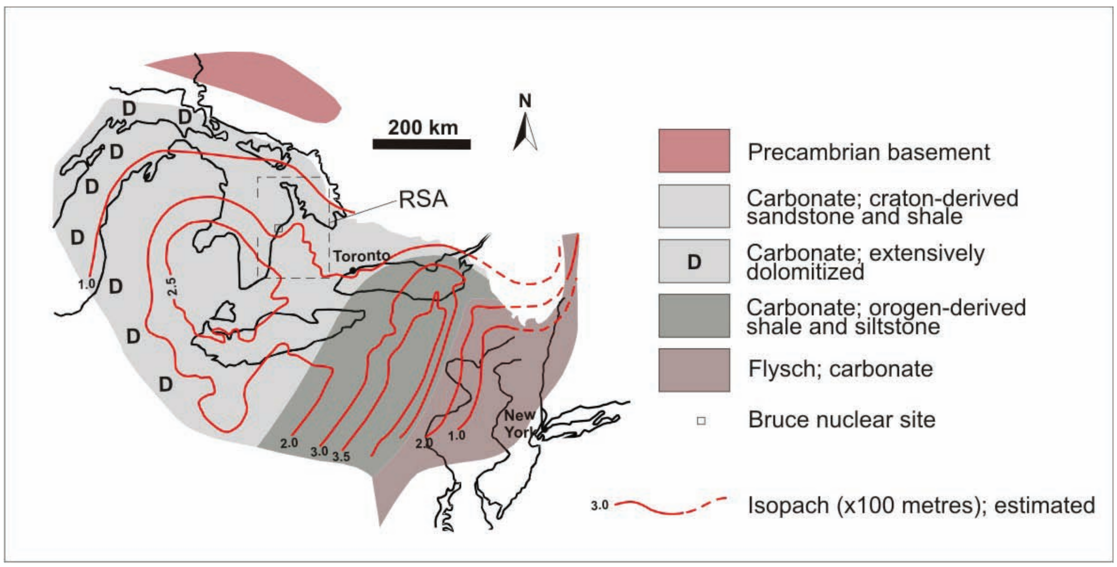


Notes: (A) applies to warm water ramp environment and (B) applies to cool water and high energy environment. Modified from Jones and Desrochers (1992).

Figure 4.3: Facies Models for Carbonate Formation

The facies model (tropical, arid shelf and ramp depositional environment) used to explain the Black River and Trenton limestone is well understood from modern examples. A comparison with very similar, modern carbonate forming environments provides for an understanding of the lateral and horizontal extent of large-scale facies within the Ordovican rocks. This lateral extent is confirmed by outcrop and well data across Ontario. Brookfield and Brett (1988) describe the Arabian (Persian Gulf) and Sahul (Southeast Asia) shelves as two modern examples closest to the Trenton seas. The ramp facies in the arid Persian Gulf, as described by Jones and Desrochers (1992), best represents the carbonate forming environments of the Black River and Trenton Limestones. Figure 4.3 (Jones and Desrochers 1992) shows an idealized unrimmed warm water carbonate shelf and ramp. This shelf ramp sequence was facing the southeast towards the Taconic allochthon in New York (Figure 4.5).

The rock types described for the succession of Ordovician carbonates in Ontario (subsurface and outcrop) range from coarse-grained bioclastic carbonates to carbonate mudstone with subordinate calcareous and non-calcareous shale. Individual facies demonstrate rapid vertical and lateral changes; however, the facies assemblages that comprise these Ordovician carbonates are predictable and well described regionally. In addition, the facies changes themselves have a minor impact on the physical/mechanical properties of the rocks (e.g., packstone to grainstone, etc.).



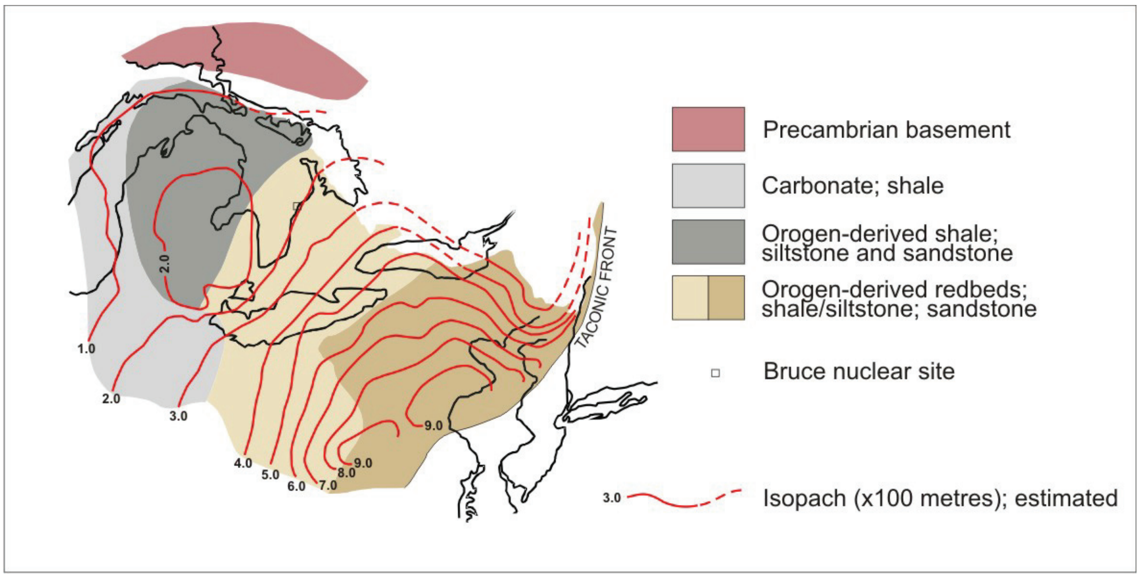
Note: Figure is modified from Sanford (1993).

Figure 4.4: Middle Ordovician Depositional Sequence and Isopach Thickness

The Trenton and Black River sediments below Michigan are primarily described as normal marine wackestones containing a range of Ordovician biota (Wilson et al. 2001, Cercone and Budai 1985). The Black River contains chert and increased lime peloidal mudstones and fewer packstone facies (Wilson et al. 2001). These Middle Ordovician carbonates in Michigan represent an open marine shelf setting (Wilson et al. 2001) consistent with the depositional setting described for the Ontario Black River and Trenton carbonates. Ontario was geographically closer to the Taconic allochthon, which was the source of the shale/argillaceous sediments. Predictably, the Ordovician carbonates in Michigan contain less shale (or no shale) than those in Ontario.

The Middle Ordovician stratigraphy includes the Shadow Lake Formation through to the Collingwood Member of the Cobourg Formation. These units contain facies representative of near shore supratidal through lagoon conditions into shallow shoal and finally into a deep shelf setting (Coniglio et al. 1990). The base of this Ordovician sequence, the Shadow Lake Formation, occurs sporadically around southwestern Ontario (Hamblin 1998b) including at depth within the DGR boreholes and in 26 wells within the RSA. The sequence from the Sherman Fall Formation through the Cobourg Formation represents a gradual deepening or marine transgression across the broad carbonate shelf. Hamblin (1999a) suggests that the Collingwood Member was deposited in relatively shallower water based on the presence of storm deposit facies. It must be noted however that the water in this part of the basin was never very deep and therefore the interpretation by Hamblin (1999a) is consistent with the conclusion that the deposition of the Collingwood Member occurred at the peak of a marine transgression, and prior to deposition of the overlying Ordovician Shales (Melchin et al. 1994).

The Collingwood Member is relatively restricted in its distribution and is typically found in a zone from Oshawa Ontario, east to Lake Huron and north to Manitoulin Island (Johnson et al. 1992). This unit is assigned to the Cobourg Formation (Lindsay Formation) due to its calcareous content, while the overlying Blue Mountain Formation is distinctly non-calcareous.



Note: Figure is modified from Sanford (1993).

Figure 4.5: Upper Ordovician Depositional Sequence and Isopach Thickness

4.2.3 Ordovician Shale (Queenston, Georgian Bay and Blue Mountain Formations)

Formation of the Trenton carbonates ceased in response to the collision of the passive margin with an island arc system that occurred during the Early to Middle Ordovician Taconian Orogeny. This tectonic event resulted in the loading at the margin by Taconic allochthons and collapse of the platform carbonates of the Trenton Group (Hamblin 1999). Subsidence and continuing northwest migration of the Taconic structural front led to the progressively westward inundation of the Trenton surface with orogen-derived clastic sediments (Hamblin 1999). Johnson et al. (1992) suggested that a drop in sea level related to glaciation of the North African continent may have also contributed to the dramatic change in the sediments of the Appalachian and Michigan Basins during the Upper Ordovician period.

The Upper Ordovician Blue Mountain Formation, Georgian Bay Formation, and Queenston Formation shale units resulted from the westward inundation of marine clastic (shale) sediments. Diecchio (1991) confirms that the clastic succession is older in the east (Appalachian Basin) than in the west. Predictably, the quantity of clastics decreases over the Algonquin Arch and into the Michigan Basin. The continuity of facies and thickness of the Upper Ordovician Shale units seems to support the interpretation by Beaumont (1984) that the Upper Ordovician eastward tilting at the Taconic front destroyed the circular form of the Michigan Basin (which had not fully developed) incorporating it, as well as the Algonquin Arch, into the Appalachian Basin. Figure 4.5 (Sanford 1993a) shows an isopach map and general lithology across North America during the late Ordovician. It is this tectonic setting that allowed for the deposition of the broad Upper Ordovician clastic sedimentary wedge which is pervasive across the RSA.

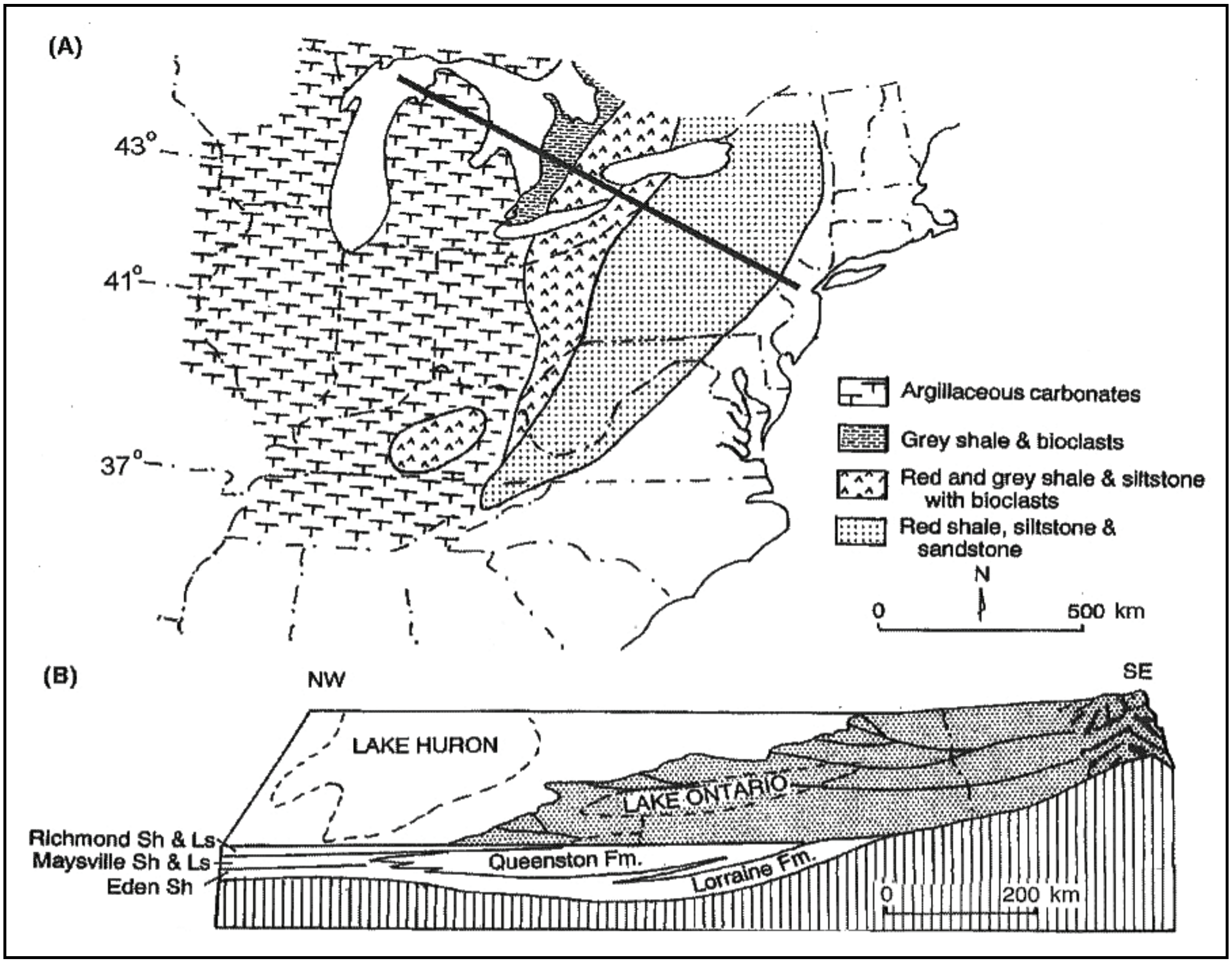
The oldest of the Upper Ordovician shales is the Blue Mountain Formation. The Blue Mountain Formation is characterized by uniform soft and laminated (Hamblin 1999), blue-grey non-calcareous shale with minor siltstone and minor impure carbonate (Johnson et al. 1992). Consistent with the interpretation presented above, the Blue Mountain Formation is interpreted by Churcher et al. (1991) being deposited during this marine transgression and associated clastic sediment input across the Appalachian and Michigan Basins. The facies within the Blue Mountain Formation are primarily open marine (grey shale) with restricted marine facies found only in the lower portion of the formation.

Regionally, the Georgian Bay Formation is composed of blue-grey shale with minor siltstone and limestone interbeds. The facies within this formation are consistent with a shallowing-upward storm-dominated shelf succession (Johnson et al. 1992). The frequency and thickness of carbonate units (impure carbonates) increases towards the top of the unit and to the northwest. Johnson et al. (1992) note that the carbonate-rich portion of the Georgian Bay Formation on Manitoulin Island is referred to as the Kagawong Member. This unit was deposited because carbonate forming conditions were maintained in the northern portion of the Michigan Basin during the Upper Ordovician. Carbonate forming seas would occasionally flood portions of the shale surface resulting in periodic lenses or fingers of carbonate from the northwest extending into both the upper Blue Mountain and the Queenston formations. The limestone interbeds within the Queenston Formation are considered lateral equivalents of the Kagawong Member of the Georgian Bay Formation (Johnson et al. 1992). The carbonate interbeds are confined laterally within the shale, and as noted by Armstrong and Carter (2006), decrease in abundance and thickness to the south and east. Beneath the study area a thick section of the lower middle Queenston Formation includes abundant limestone interbeds within the shale dominated succession.

The Queenston Formation is a shale dominated mixed terrigenous carbonate deposit (Brogly et al. 1998). In general, the Queenston Formation deposits are considered to be non-marine in the southeast (closer to the clastic sediment source) and marine in the northwest toward Manitoulin Island. Northwest of the RSA (beneath Lake Huron) the Queenston Formation and Georgian Bay Formation interfinger (as described above) until the Queenston Formation completely pinches out between the Georgian Bay and Manitoulin Formations (Brogly 1990).

Facies of the Queenston Formation are consistent with depositional settings ranging from:

- Supratidal/Sabkha – red shale, bioclastic siltstone to sandstone to sandy carbonate, to
- Intertidal – interbedded red, grey and green-grey shale, calcareous siltstone sandstone and bioclastic limestone, to
- Subtidal – dark grey shale interbedded with calcareous siltstone and bioclastic limestone.



Note: Figure is from Brogly et al. (1998).

Figure 4.6: Upper Ordovician Taconic Clastic Wedge Facies Model

The subtidal grey-shales and siltstones are found primarily at the base of the Queenston Formation and are transitional with the Georgian Bay Formation. The alternating red-grey shales are found in the middle of the formation and were deposited in the shallower intertidal setting. Finally, the supratidal red-shale facies are found in the upper portion of the Queenston Formation representing a significant marine regression. Consequently, the facies in the upper Queenston Formation are characteristically the least marine to non-marine. It was these non-marine dry arid sabkha conditions that were likely responsibly for the gypsum found with the Queenston Formation, particularly the upper red-shale facies (Brogly et al. 1998). Gypsum is found within the Queenston Formation as thin laminae along bedding planes, fracture filling, and as nodules (Brogly et al. 1998). Further details on the Georgian Bay and Queenston Formations may be found in the synthesis of Hamblin (1999b) and the detailed measured sections of Hamblin (2003).

Figure 4.6 (Brogly et al. 1998) shows the distribution of lithologies of the Taconic clastic wedge (Queenston, Georgian Bay and Blue Mountain formations) from New York through to Michigan as well as an idealized cross-section showing the Queenston Formation shale extending from Western New York to beneath Lake Huron. Previous researchers had considered the Queenston facies assemblages to be formed within a large delta complex, however, work from Brogly et al. (1998) shows that although delta facies exist in parts of the Queenston Formation, the depositional environment is consistent with a broad coastal platform. Modern equivalent depositional environments include the Gulf of California and the western coast of Australia.

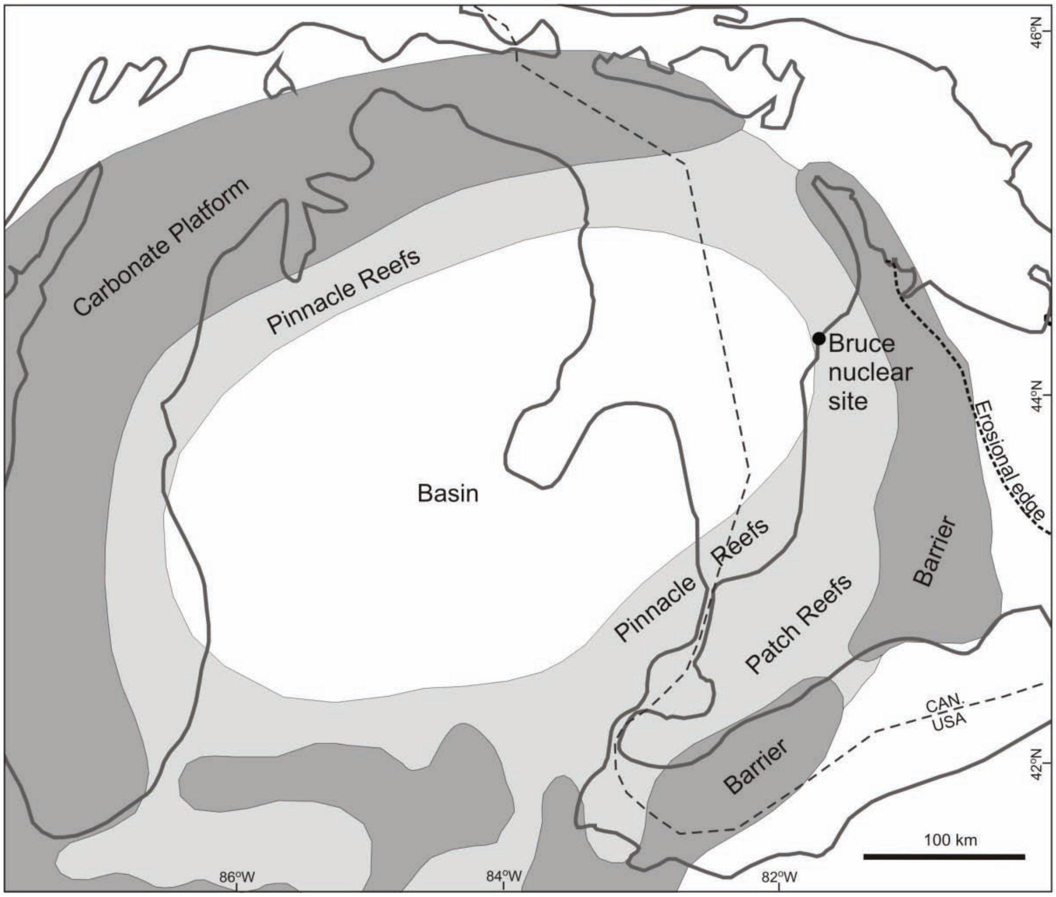
The disconformity at the top of the Queenston Formation is associated with a glaciation in North Africa and a subsequent global eustatic/sea level drop (Hamblin 1999). Desiccation cracks filled with the overlying Whirlpool Formation sandstone (Niagara Peninsula) and Queenston rip-ups within the Manitoulin Formation (Western Ontario and RSA) provide evidence of this erosional surface (Hamblin 1999). Recent works by Hamblin (1999b, 2003) provide detailed measured sections and facies analyses from all of these Lower/Middle Silurian units.

4.2.4 Silurian Carbonates and Shale (Manitoulin, Cabot Head, Fossil Hill, Amabel/Lockport, and Guelph formations)

Within the RSA, the Manitoulin Formation dolostones directly overly the Queenston Formation. Manitoulin dolostones mark a return to carbonate forming conditions during the marine transgression that followed the Queenston disconformity. The Manitoulin Formation is characterized by grey to blue finely crystalline dolomite with grey to blue argillaceous partings (Liberty and Bolton 1971). This formation is found extensively in the subsurface of Southern Ontario and underlies much of the Michigan Basin (Johnson et al. 1992). The Manitoulin Formation also contains bioherms, which are found primarily on Manitoulin Island (Johnson et al. 1992, Anastas and Coniglio 1992). The Manitoulin Formation facies assemblages are interpreted to have been deposited on a southwest-dipping carbonate ramp, similar to that shown in Figure 4.3(A) (Jones and Desrochers 1992).

The overlying Cabot Head Formation records a shallowing upward sequence of non-calcareous shales and minor calcareous sandstone, dolostone and limestone (Johnson et al. 1992). The source of the clastic material is consistent with the Taconic allochthon to the southeast (Sanford 1969a) with a minor craton derived source in the northern portion of the Michigan Basin (Johnson et al. 1992). The environment of deposition ranges from offshore basinal to a marginal marine environment and is consistent with a shallowing (marine regression) and clastic input across the underlying carbonate ramp of the Manitoulin Formation. As a result, the Cabot Head is extensive across southern Ontario and within the RSA. The dolomites of the Fossil Hill Formation disconformably overlie the Cabot Head Formation within the RSA marking a return to carbonate forming conditions.

The top of the Fossil Hill Formation is a regional disconformity and records a regional marine regression during the Middle Silurian. Uplift along the Algonquin Arch is responsible for erosion of the underlying units (Fossil Hill) and development of an angular unconformity moving away from the Algonquin Arch (Johnson et al. 1992).



Note: Figure is adapted from Johnson et al. (1992).

Figure 4.7: Distribution of Middle and Upper Silurian Niagaran Carbonate Facies

The marine transgression that followed this erosion was responsible for the extensive carbonate deposition of the Amabel (Lockport) and Guelph Formations. During this period, the Michigan Basin carbonates are clearly recognizable as being developed within the circular shape and structure that is the familiar form of the Michigan Basin. Deposition of the Amabel/Lockport and Guelph Formation dolostones (Silurian Niagaran Carbonates in Figure 2.5) occurred within a more rapidly subsiding basin centre relative to the margins of the basin (Sears and Lucia 1979). As a result, deeper water basinal facies characterize the Amabel and Guelph Formation in the middle of the Michigan Basin, while the margin and Algonquin Arch are characterized by shallower low energy restricted facies, shallow higher energy facies and reef and inter-reef facies (Armstrong and Goodman 1990). During Guelph Formation deposition, the geometry of the Michigan Basin is clearly marked by the development of pinnacle patch and barrier reefs along “hinge lines” which separate the basin, slopes and platform/arches (Figure 4.7).

West of the Algonquin Arch, the Niagaran deposits are almost entirely carbonates, separated from the terrigenous material derived from the Taconic front. Southeast of the Algonquin Arch in the Appalachian Basin, carbonate and clastic facies are mixed. Within the RSA the

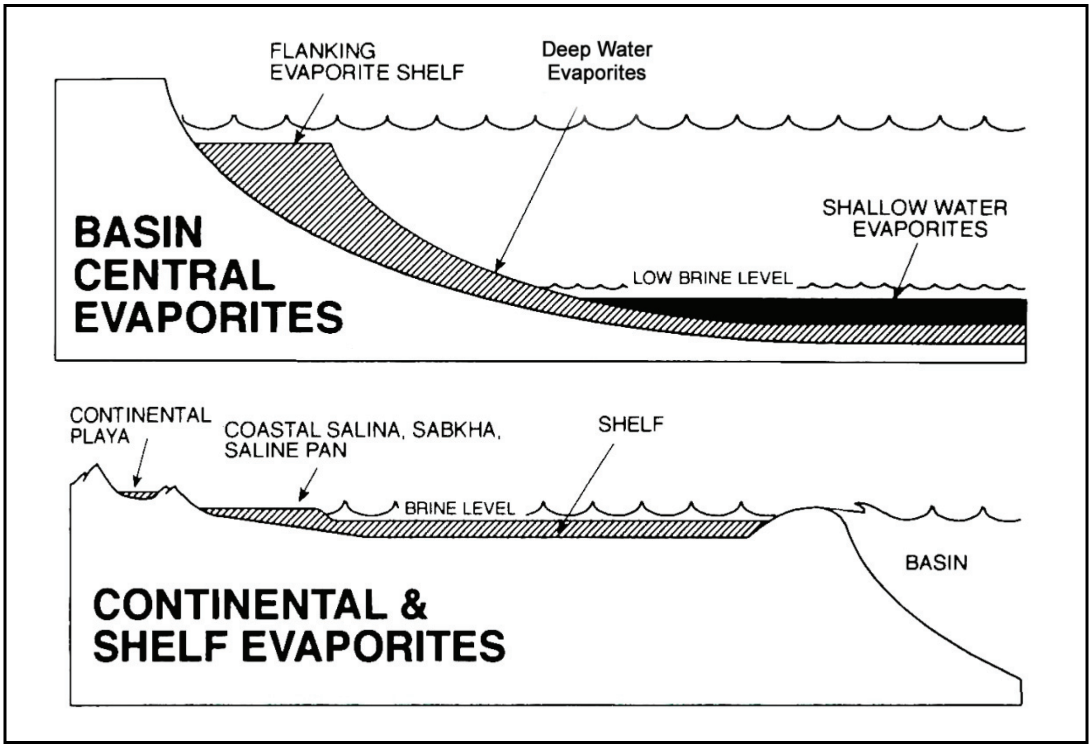
Amabel/Lockport Formation facies are characterized by shallow-moderate to high energy to restricted and locally biohermal, dolomite (Armstrong and Goodman 1990). In the Guelph Formation, the RSA extends from the pinnacle reef belt towards the Algonquin Arch to the barrier reef complex (Figure 4.7). As a result, the Guelph Formation facies range from reefal to inter-reefal dolostones (Armstrong and Goodman 1990). Sanford et al. (1985) suggests that pinnacle reef growth occurred on topographic highs created on the up-thrown side of fault blocks, which were part of a regular and extensive fault network in southern Ontario (Figure 3.3). Liberty and Bolton (1971) suggest that Guelph reefs were formed on topographic highs in the underlying Amabel/Lockport Formation. Examination of borehole well logs within the study area did not suggest the widespread occurrence of fault blocks. As previously noted, the extensive fracture framework conceptualized by Sanford et al. (1985) has not been fully recognized.

4.2.5 Silurian Salina Group (A-0 through G-Unit) and Bass Island Formation

The change from Guelph Formation deposition to Salina deposition marks a significant change in sedimentary environments. This change was the result of arch uplift and rapid basin subsidence caused by the Late Silurian Acadian Orogeny (Sonnenfeld and Al-Aasm 1991, Johnson et al. 1992). The contact of the Guelph and Salina is both conformable and disconformable depending on the location and Armstrong and Carter (2006) describe the contact as complex and poorly understood. It is worth noting that the full Salina Group is conformable with no interpreted breaks in depositions between the individual units (Armstrong and Carter 2006).

Repeating deposition of carbonate, evaporites and argillaceous sediments within both the Appalachian Basin and Michigan Basin characterize the Salina Group. The lithology of the Salina Group units, as encountered in borehole DGR-1, is presented in Figure 5.1. These units include from oldest to youngest the A-0 (carbonate), A-1 (evaporite), A-1 (carbonate), A-2 (evaporite), A-2 (carbonate), B (evaporite), B (carbonate), C (carbonate, shale and evaporite), D (carbonate and evaporite), E (carbonate and shale), F (carbonate, shale, and evaporite) and G (carbonate, shale, and evaporite) units.

The Appalachian Basin deposits are predictably more argillaceous than those in the Michigan Basin. The source of argillaceous (clastic) sediment within the Salina Group of the Michigan Basin is described as mainly craton-derived despite the orogenic activity at the margin of the continent (responsible for Appalachian Basin argillaceous material). The fact that the Michigan Basin was isolated from the Appalachian Basin is supported by the extensive evaporite deposition that occurred within the restricted and isolated Michigan Basin (Mesolella et al. 1974). Shelf evaporites formed as the basin and shelf became increasingly isolated due to lowering sea level and/or barrier reef formation during the Middle Silurian. Basin centre evaporites developed in response to significant periods of marine regression in the Michigan Basin during Upper Silurian. Figure 4.8 (James and Kendall 1992) presents a general shelf and basin centred evaporite forming facies model.



Note: Figure is modified from James and Kendall (1992).

Figure 4.8: Depositional Model for Shelf and Basin Centre Evaporite Formations

Sonnenfeld and Al-Aasm (1991) describe halite formation in the centre of the basin and anhydrite formation at the margin during periods of subsidence. The carbonate and argillaceous facies were deposited during each period of lesser subsidence. Regardless of the subsidence model, it is clear that increasingly restricted marine conditions in the Michigan Basin led to evaporation, brine concentration and precipitation of carbonate, gypsum/anhydrite, halite and sylvite (in order of increasing brine concentration). As a result, sylvite is found only in the centre of the Michigan basin where brine concentrations would have been the greatest. Halite is found only beneath the southwest portion of the RSA, while anhydrite is found beneath the Bruce nuclear site and extending to the basin margin pinching out against the Algonquin Arch. The distribution of salt (Figure 4.9) is interpreted to have been much greater in extent when initially deposited than is presently found. The salt is interpreted (Sanford 1965, Sanford et al. 1985) to have been dissolved over the Algonquin Arch. This dissolution began shortly after salt precipitation and over geological time was responsible for collapse features within the overlying Devonian units (Figure 4.10). Selective dissolution of evaporites also resulted in common breccia facies within the Salina units. The distribution of the Salina Group, based on interpreted petroleum well data, is described in Chapter 6 as part of the geological framework discussion. The presence of salts and their restricted distribution within the southwest portion of the RSA is generally consistent with distribution described in the geological framework.

Periodic inflow or refreshening of the brine (i.e., groundwater input, precipitation, sea water input) combined with the reintroduction of argillaceous sediments (i.e., terrestrial runoff) returns the conditions necessary for the development of the mixed carbonate and argillaceous facies of the Salina Group. Cyclic deposits of the Salina Group are therefore the result of continuous evaporation and refreshening cycles.

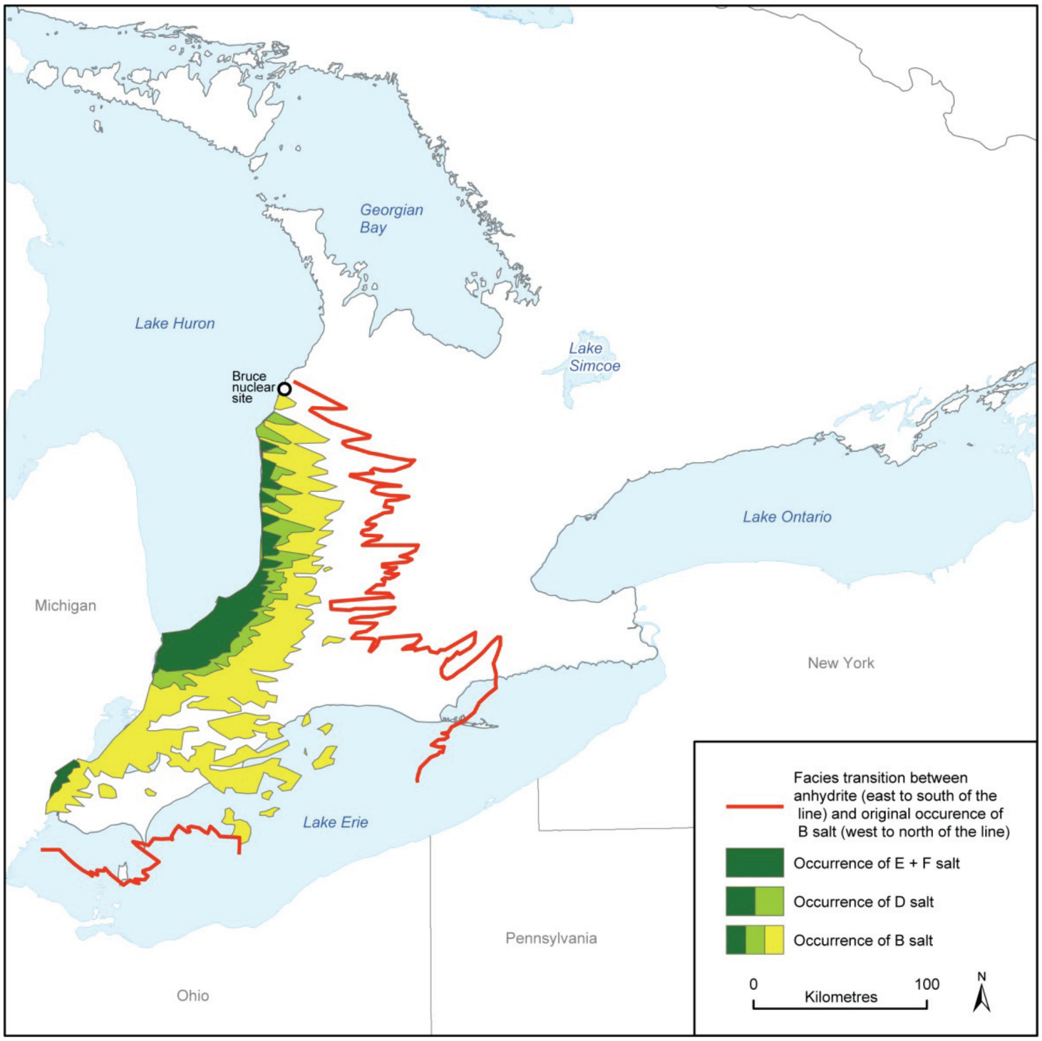
The Bass Islands Formation is a microcrystalline dolostone, commonly bituminous and contains evaporite mineral casts. This formation represents or a return to marine carbonate conditions from the cyclic evaporite, and carbonate forming conditions of the Salina Group. The Bass Islands Formation is interpreted to have been deposited in an intertidal to supratidal setting and marks the final Silurian carbonate depositional period prior to the regional Devonian unconformity separating the Silurian Bass Islands Formation and the overlying Devonian Bois Blanc Formation (Liberty and Bolton 1971, Johnson et al. 1992). The Bass Islands Formation is roughly equivalent in the Appalachian Basin to the Bertie Formation, with the key difference being the increased argillaceous content and more normal marine character of the Appalachian Basin sediments.

4.2.6 Devonian Carbonates (Bois Blanc Formation, Detroit River Group and Dundee Formation)

The Bois Blanc Formation is primarily a cherty dolostone unit within the RSA (Sanford 1968), grading laterally into cherty limestones towards the Michigan Basin centre and interfingering with mixed carbonate clastic units within the Appalachian Basin (Hamilton 1991). Deposition of the Bois Blanc represents a major marine transgression after the long period of subaerial exposure at the end of Silurian deposition (Uyeno et al. 1982). Disconformably overlying the Bois Blanc Formation are the mixed limestones and dolostones of the Detroit River Group (Amherstburg and Lucas Formations).

The Sylvania Formation sandstone unit of the Detroit River Group is limited to southwestern Ontario in the Windsor to Sarnia area (Johnson et al. 1992) and therefore not present within the RSA. Similar to the Bois Blanc, the Amherstburg Formation is primarily limestone towards the basin centre, and locally dolomitized along the Algonquin Arch (Sanford 1968). Local reef development within the Amherstburg is commonly also known as the Formosa Limestone, a descriptions from the Ontario town bearing the same name. The Amherstburg Formation is roughly equivalent to the fossiliferous and cherty limestone of the Onondaga Formation in the Appalachian Basin (Sanford 1968). The Lucas Formation of the Detroit River Group subcrops beneath the study area (Sanford and Baer 1981), where borehole DGR-1, and DGR-2 encountered a thickness of approximately 8 m of this unit below approximately 20 m of Quaternary glacial sediments (overburden). The Lucas Formation conformably overlies the Amherstburg Formation (Johnson et al. 1992) and is characterized by increasing evaporite deposits, mainly anhydrite and gypsum. Sanford (1968) describes the Lucas Formation developing into a primarily anhydrite unit west of the RSA towards the centre of the Michigan Basin and pinching out towards the Appalachian Basin. Appalachian Basin lateral equivalents are primarily limestone.

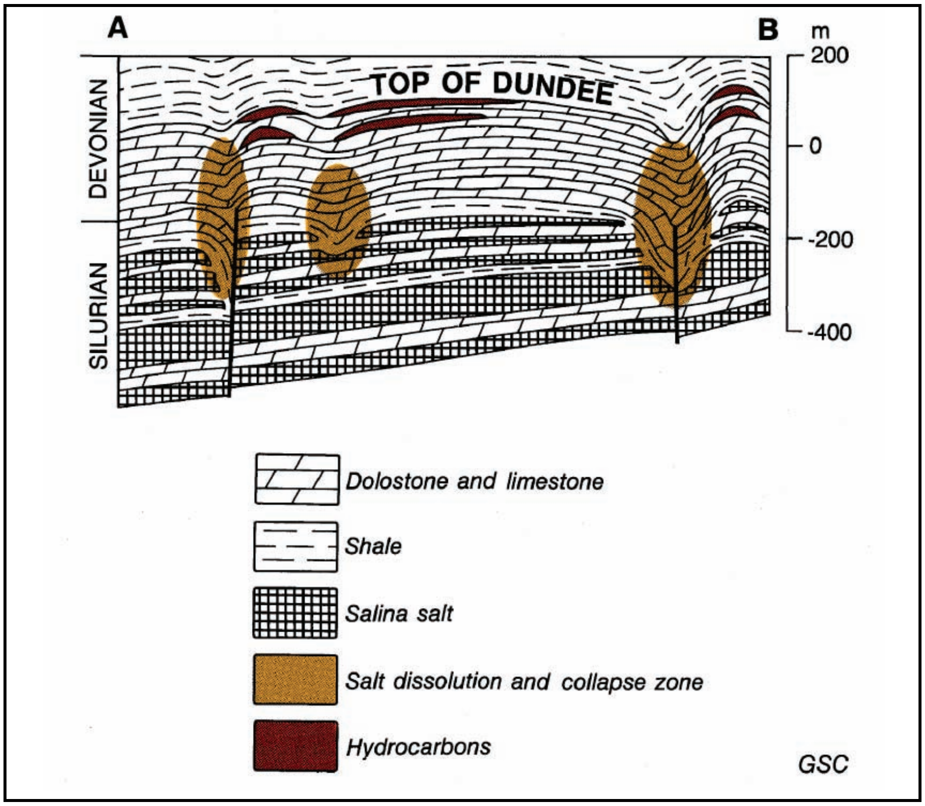
During the late Lower and early Middle Devonian the Michigan and Appalachian Basins were isolated by the Algonquin Arch (Hamilton and Coniglio 1990). As a result of this isolation, the Michigan Basin developed periodic evaporite forming conditions (hypersalinity) while the Appalachian Basin was characterized by normal marine deposition (Hamilton and Coniglio 1990). In the Michigan Basin and within the RSA, the Detroit River Group was predominately deposited in a shallow marine to shallow evaporite setting (Johnson et al. 1992). The Dundee Formation disconformably overlies the Detroit River Group and was deposited during a period of marine transgression across the Algonquin Arch in a shallow lagoonal to open carbonate shelf environment (Hamilton and Coniglio 1990). The freshening of the Michigan Basin during the marine incursion caused a change from the higher salinity (Lucas Formation evaporites) to normal marine conditions.



Note: Figure is adapted from Sanford et al. (1985).

Figure 4.9: Distribution of Salt in the Salina Formation in Southern Ontario

The Devonian strata in southern Ontario are interpreted by Sanford et al. (1985) to have been deformed at the margin of the Michigan Basin as a result of selective salt dissolution with the underlying Salina Salts (B-Salt specifically). Figure 4.9 from Sanford et al. (1985) shows the current and proposed original location of the Salina B salt, interpreted to have largely been dissolved during the Late Silurian. Although salt dissolution likely occurred over millions of years, it is suggested by Sanford et al. (1985) that rapid dissolution was coincident with the Caledonian orogeny and associated fracture reactivation. The interpreted resulting stratigraphy from salt dissolution is presented in Figure 4.10 (Sanford 1993b), which shows a typical Devonian hydrocarbon reservoir geometry from southwestern Ontario.

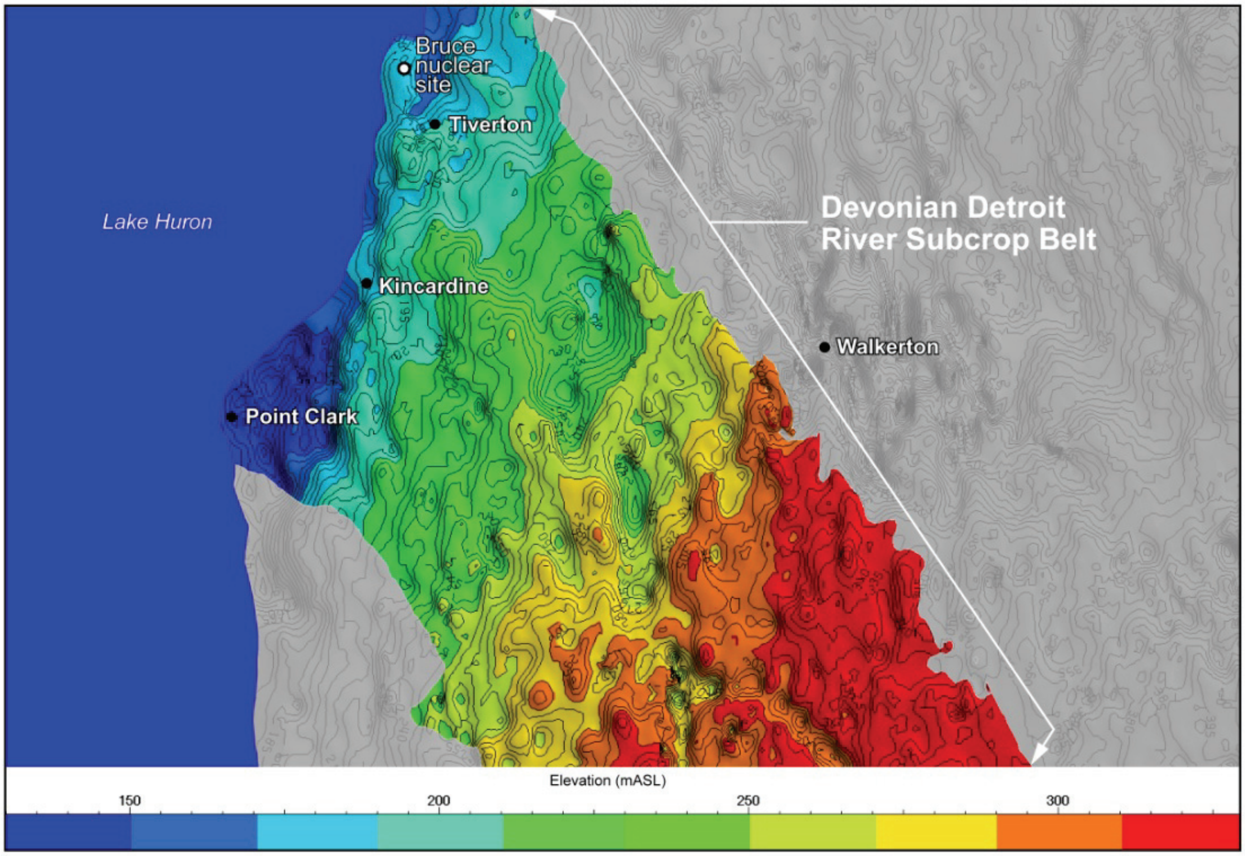


Notes: Section A-B is a NNW-SSE profile across the Petrolia oil field near Sarnia, Ontario. Figure is from Sanford (1993).

Figure 4.10: Illustration of Fault-related Salt Dissolution in the Salina Formation

Figure 4.10 shows the impact of these collapse features from the Devonian to the Upper Silurian (salt source). The result is a fractured and brecciated rock fabric infilled with evaporite, mainly anhydrite and/or gypsum, and late stage carbonate cements. Similar collapse features confined within the Salina Group appear in a few locations within the 3DGF (see Chapter 6).

It should be noted that the potential influence of collapse features and the resulting fracture geometry is confined to the Upper Silurian (source of salt) and younger units. Figure 4.11 presents a colour coded contour bedrock map of the Devonian Detroit River Formation. Interpreted sinkholes are shown as bowl shaped topographic features. Whether, and how many of, these features are related to salt collapse within the Upper Salina Group or whether these are simple erosional features of the glaciated bedrock surface is unclear. A lack of stratigraphic data (borehole records) below “top of bedrock” picks makes it difficult to assess specific units or the root cause of these depressions.



Notes: The bedrock surface elevation ranges from approximately 150 mASL (metres above sea level) at the Lake Huron shore to 300 mASL further inland. Data is derived from OGS digital mapping (MRD207).

Figure 4.11: Bedrock Surface Contour Map of Devonian Detroit River Subcrop Belt

4.3 Summary

The scientific understanding of regional facies models combined with field mapping, outcrop data and borehole data across the Ontario portions of the Michigan and Appalachian Basins allows us to understand facies associations over large distances. In the case of southern Ontario, the Paleozoic stratigraphy is relatively simple and continuous. This geometry was the result of deposition over broad carbonate and clastic shelf and platform settings that extended from the eastern margin of the Appalachian Basin to the centre of the continent. Deposition later in the Paleozoic within the relatively isolated Michigan Basin produced predictable basin-centred facies assemblages. Exceptions to the relatively predictable stratigraphy are the Cambrian deposits and Salina evaporites. Widespread erosion of the Cambrian units during the “Knox” unconformity makes predicting the distribution within the subsurface along the Algonquin Arch, including the RSA, difficult. The Salina evaporite distributions are complicated by selective dissolution within the RSA along the salt dissolution zone described by Sanford et al. (1985).

The Paleozoic geology is well understood, the facies associations and their regional lithologies are predictable, changing in response to well described sediment source locations, and tectonic conditions. The resulting rocks associated with each major facies associations (i.e., Trenton Group) have relatively homogenous litho-structural properties that have resulted from lithification, burial compaction and late diagenesis of marine sediments.

The original hypothesis outlined by Mazurek (2004) that the Paleozoic geology is predicable over large distances and well understood is further confirmed in this investigation.

5. BRUCE NUCLEAR SITE GEOLOGY

The Bruce nuclear site geology encountered during drilling of DGR-1, -2, -3, -4, -5, and -6 boreholes is summarized in Figure 5.1. The information used to compile this figure was provided by Wigston and Heagle (2009), Sterling and Melaney (2011), and INTERA (2011) and was collected as part of the site-specific field investigations as outlined in the Geoscientific Site Characterization Plan (INTERA 2006, 2008). Figure 5.1 shows the relative weathering profile of the individual units/formations encountered with general lithologic descriptions. The interpreted depositional setting derived from the literature review and discussed in Section 4.2 has also been included in Figure 5.1.

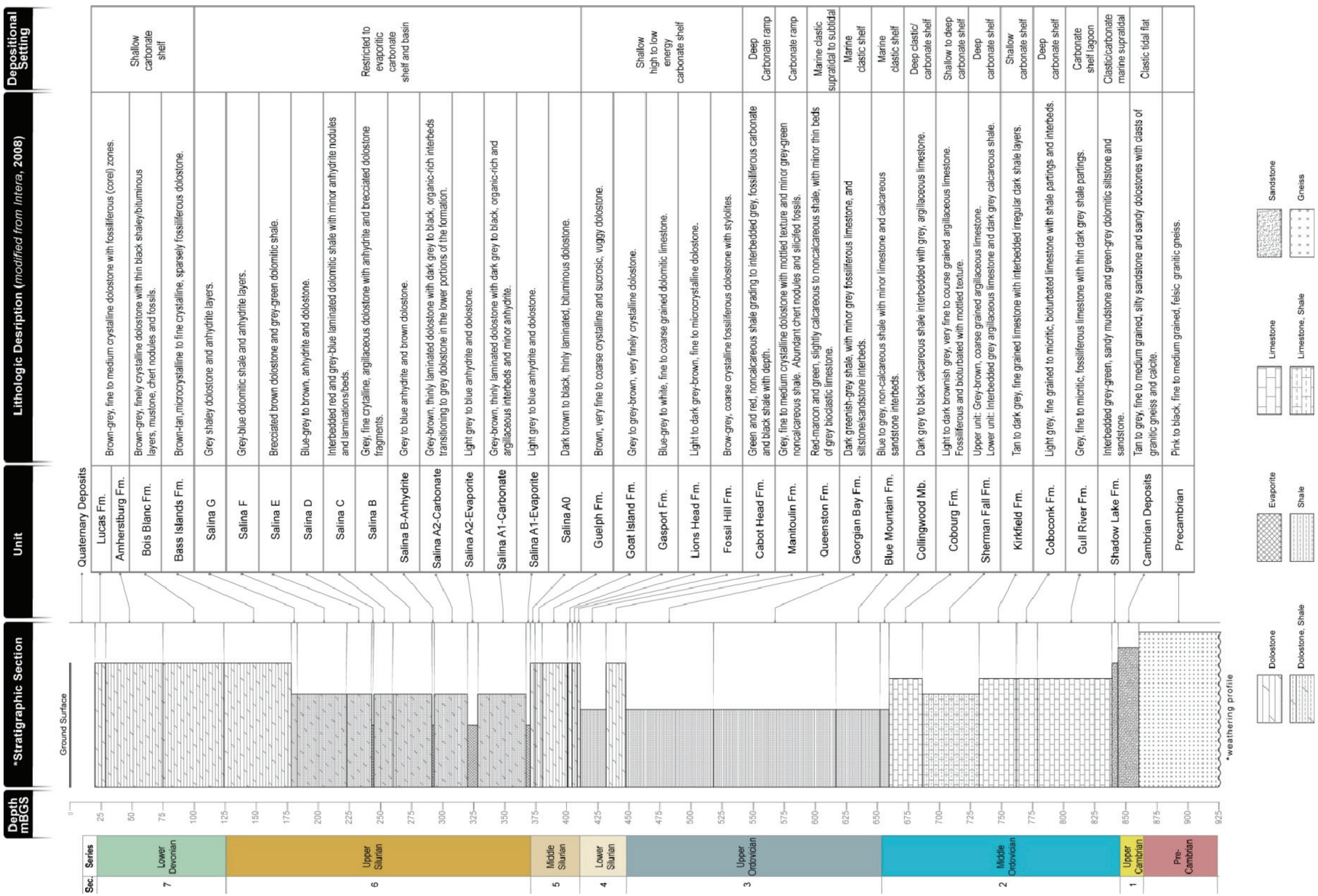
The following discussion compares that the results of the Bruce nuclear site drilling investigations with the information presented in this Regional Geology report using the DGR-2 borehole data as a reference standard for stratigraphy and unit thicknesses.

The work of Bailey Geological Services and Cochrane (1984a), Carter et al*.* (1996), and others suggests that the Bruce nuclear site is within the Upper Cambrian subcrop belt. DGR-2 encountered approximately 17 m of Upper Cambrian sandstone and dolostones (Figure 5.1), a thickness and lithology consistent with the position of the Bruce nuclear site to the west of the Cambrian erosion front against the Algonquin Arch (see Figure 8.5). The Cambrian deposits were unconformably overlying the altered Precambrian granitic gneiss basement rocks (DGR-2 drilled through approximately 1.5 m of basement rock).

DGR-2 intersected approximately 185 m of Middle Ordovician carbonates dominated by limestone and argillaceous limestones. The thickness and lithologies described by INTERA (2011) for the Trenton and Black River units are generally consistent with thickness ranges, lithologies and interpreted facies described by Johnson et al*.* (1992) and Armstrong and Carter (2006) for the subsurface of Southern Ontario.

The Upper Ordovician Georgian Bay, Blue Mountain and Queenston formations comprise approximately 212 m of blue-grey, non-calcareous shale with minor limestone, sandstone interbeds and red/maroon-green calcareous to non-calcareous shales with limestone interbeds. As with the Middle Ordovician carbonates, the Upper Ordovician shale thickness, lithologies and associated facies interpretations are consistent with regional information (Brogly 1990, Johnson et al*.* 1992, Armstrong and Carter 2006). For example, the bioclastic limestone interbeds within the Queenston Formation, which likely represent incursions of the Kagawong Member from the northwest, are predicted from regional information based on the DGR geographic location near the base of the Bruce Peninsula.

The Lower Silurian Manitoulin and Cabot Head formations at the Bruce nuclear site are composed of a total of 37 m of dolostone with minor non-calcareous shale, and non-calcareous shale with minor dolostone, respectively. As predicted from regional information the Lower Silurian Whirlpool sandstone, which commonly overlies the Queenston Formation in Southern Ontario, pinches out at the eastern margin of the RSA, and is therefore not present beneath the site.



Note: Stratigraphic descriptions are from INTERA (2011).

Figure 5.1: Bruce Nuclear Site Stratigraphy

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The Middle Silurian carbonate units are represented by a combined 37 m of predominately dolostone and fossiliferous dolostone units. The relatively thin vertical extent of these carbonate units combined with stratigraphic descriptions, (particularly the Guelph and Gasport-Goat Island formations) confirms that the site occupies an inter-reef position with respect to the Silurian rocks. Silurian reef locations examined in this study commonly intersect >100 m of Silurian dolostones. The absence of the Middle Silurian Rochester shale beneath the Gasport Formation at the site is predicted from regional data (Sanford 1969, Armstrong and Carter 2006) that suggests the Rochester Formation pinches out at the southern margin of the RSA. The Upper Silurian Salina Group beneath the Bruce nuclear site is comprised of approximately 250 m of alternating carbonate, shale and evaporites. The occurrence, thickness, and lithology of the individual units within Salina Group and the Bass Islands Formation at the Bruce nuclear site are consistent with the regional descriptions as summarized in Armstrong and Carter (2006, 2010).

The Lower Devonian Bois Blanc Formation at the Bruce nuclear site is composed of approximately 49 m of cherty and fossiliferous limestone/dolostone. Johnson et al. (1992) suggested a range of 4 m to 50 m thickness for the Bois Blanc, with greater thicknesses towards the Michigan Basin. The Detroit River Group (approximately 55 m) is described by INTERA (2011) as a fossiliferous (coral) dolostone. Approximately 8 m of broken (rubble) Lucas Formation overlies the Amherstburg Formation at the site. Regional descriptions that characterize the Amherstburg Formation as dolostone/limestone with abundant reef building corals (Johnson et al. 1992, Armstrong and Carter 2006, 2010) are consistent with the Bruce nuclear site description.

5.1 Summary

The geology encountered in all DGR boreholes is consistent with the regional geology as described in this report. This interpretation is based on an assessment of lithology and core descriptions. The lithological properties such as shale, evaporite, carbonate and clastic content and dolomite versus limestone distribution are predicted by regional data for a site located at the margin of the Michigan Basin. This provides an illustration of the 3D Geological Framework as a basis for understanding the stratigraphy within the RSA.

6. REGIONAL 3D GEOLOGICAL FRAMEWORK

The primary purpose of the regional 3DGF model was to capture and present the current geological understanding of the Paleozoic sedimentary formations of southern Ontario for a portion of the Michigan Basin (ITASCA CANADA and AECOM 2011). The 3DGF encompasses an area of approximately 35,000 km^2 centred on the Bruce nuclear site (Figures 2.1, 2.6, 6.1 and 6.2). This area also forms the basis for the hydrostratigraphic framework (Figure 6.2) used in the regional hydrogeologic modelling study of Sykes et al. (2011).

In addition to providing the basis for the hydrostratigraphy, the 3DGF model is also designed to provide both context to the site characterization work, and to provide a rationale for extrapolation of site conditions beyond the Bruce nuclear site. The following provides a brief description of a) development tools, b) data sources, c) data verification procedures, d) workflow, and e) limitations of the 3DGF. A complete description of the 3DGF model development and the data set used to build the model can be found in ITASCA CANADA and AECOM (2011) and its accompanying appendices.

6.1 Development Tools

Itasca Consulting Canada Inc. was retained by OPG to work closely with AECOM Canada Ltd. in developing the 3DGF (ITASCA CANADA and AECOM 2011). The framework was designed using GoCAD™ software, an advanced 3D earth modelling and scientific visualization technology. The model coverage extends from the Precambrian basement to the surface topography (Figure 6.1), including watershed features (lakes, rivers), and bathymetry.

6.2 Data Sources

The primary data source for the geologic framework construction was the Oil, Gas, and Salt Resources Library (OGSR) Petroleum Wells Subsurface Database. These data sets include geological formation tops, logging records, and oil/gas/water intervals for tens of thousands of petroleum wells throughout Ontario. The vast majority of these wells are located in southwestern Ontario along the shore of Lake Erie extending towards Sarnia/Lambton County. The RSA contained at total of 341 wells, which were reduced to 299 wells (Figure 6.2) through the data validation process described below. The relative lack of petroleum wells in the RSA reflects a general scarcity of petroleum resources in this area. The wells can be generally grouped, by purpose, into three main categories:

1. Those wells drilled to prove salt resources near the southern portion of the RSA;
2. Oil/gas exploration wells drilled into Silurian strata (primarily reefs); and
3. Oil/gas exploration wells drilled into Ordovician strata.

In addition to the wells within the RSA, a further 57 petroleum Reference Wells (Armstrong and Carter 2006) and 76 petroleum wells from the Michigan State Geological Survey Digital Well Database located outside of the RSA were used (ITASCA CANADA and AECOM 2011 and appendices therein). Other key sources of data also included downhole geophysics (used to verify well contacts/picks), acquired from the OGSR Library for select wells within the RSA, and Ontario Geological Survey (OGS) Open File Report 6191 (Armstrong and Carter 2006), an updated guide to the Paleozoic stratigraphy of southern Ontario. Reference wells were used by Armstrong and Carter (2006) to generate a series of representative geological cross-sections through the subsurface of southern Ontario. These same reference wells were used in the 3DGF as a verification tool and to provide consistency with the accepted Ontario geological nomenclature and understanding. It should be noted that the 3DGF results are consistent with the current state of knowledge on the Paleozoic stratigraphy of southern Ontario at both the regional scale (e.g., Armstrong and Carter 2006, 2010), and the site scale (INTERA 2011). Other important data include:

- 1:50,000 OGS Digital Bedrock Geology of Ontario Seamless Coverage ERLIS Data Set 6;
- Michigan State Geological Survey mapping and Petroleum Well Database;
- OGS Digital Bedrock topography and overburden thickness mapping, Southern Ontario – Miscellaneous Data Release no. 207 (Gao et al. 2006); and
- National Oceanic and Atmospheric Administration (NOAA) digital bathymetry mapping of Lake Huron and Georgian Bay (Great Lakes Bathymetry Griding Project 2007).

The bathymetry mapping was used as a tool to correlate scarp faces within Lake Huron with the stratigraphic data extrapolated from the subsurface well data and bedrock maps. Since no well data exists beneath Lake Huron the State of Michigan geological maps and selected petroleum well data were used to provide some guidance for extrapolating data beneath the lake.

The remaining data sources were published literature, government reports (i.e., MNR and OGS), and consulting reports. These data sources were useful for confirming extent and predictability of geological units across the RSA and as guidance for understanding detailed stratigraphic relationships in the subsurface.

6.3 Data Validation

It should be noted that the 3DGF developed as part of this work program is derived from data acquired from third party sources. As a result, there is some reliance on QA/QC procedures employed by the organizations that have compiled the primary data.

The process of verifying data used for development of the 3DGF involved both geological software modelling methods and the application of “expert” knowledge. The resulting framework is essentially a hybrid geological model where software was used to develop a model or best fit of the source data that was then manually edited, where required, to reflect expert knowledge of the stratigraphy. The geological model software honoured all of the subsurface geological contacts that were deemed to be reliable as determined by the verification procedures outlined below. It should also be noted that advanced three dimensional visualization techniques have been integral in facilitating data validation throughout the entire 3DGF development process.

A process of checking anomalous data to distinguish natural variations in geology versus logging discrepancies, followed by manual correction (where deemed necessary based on a review of factors described below) was required due to the general quality of the well data within the OGSR Database. Many of the well logs grouped various formations together, missed entire formations (apparently dependent on the purpose of the well) or picked contacts inconsistent with current subsurface stratigraphic nomenclature. The OGS reference wells, surrounding well data and downhole geophysics aided in evaluating inconsistent picks. Data verification tools included Database Well Collar Elevations Compared with Digital Elevation Model, Database or Sequence Data Tests, and Geological/Stratigraphic Tests, as described in ITASCA CANADA and AECOM (2011).

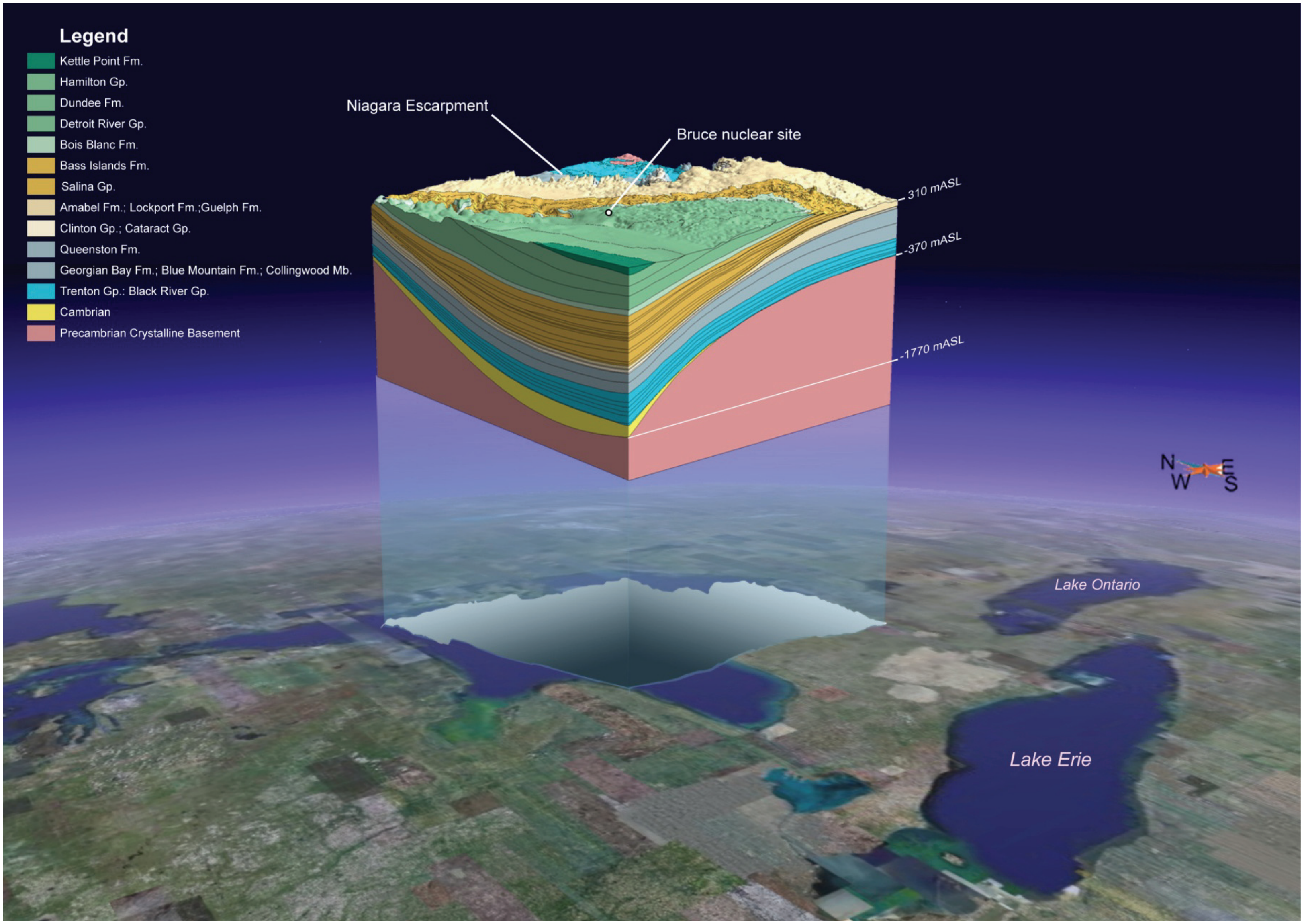
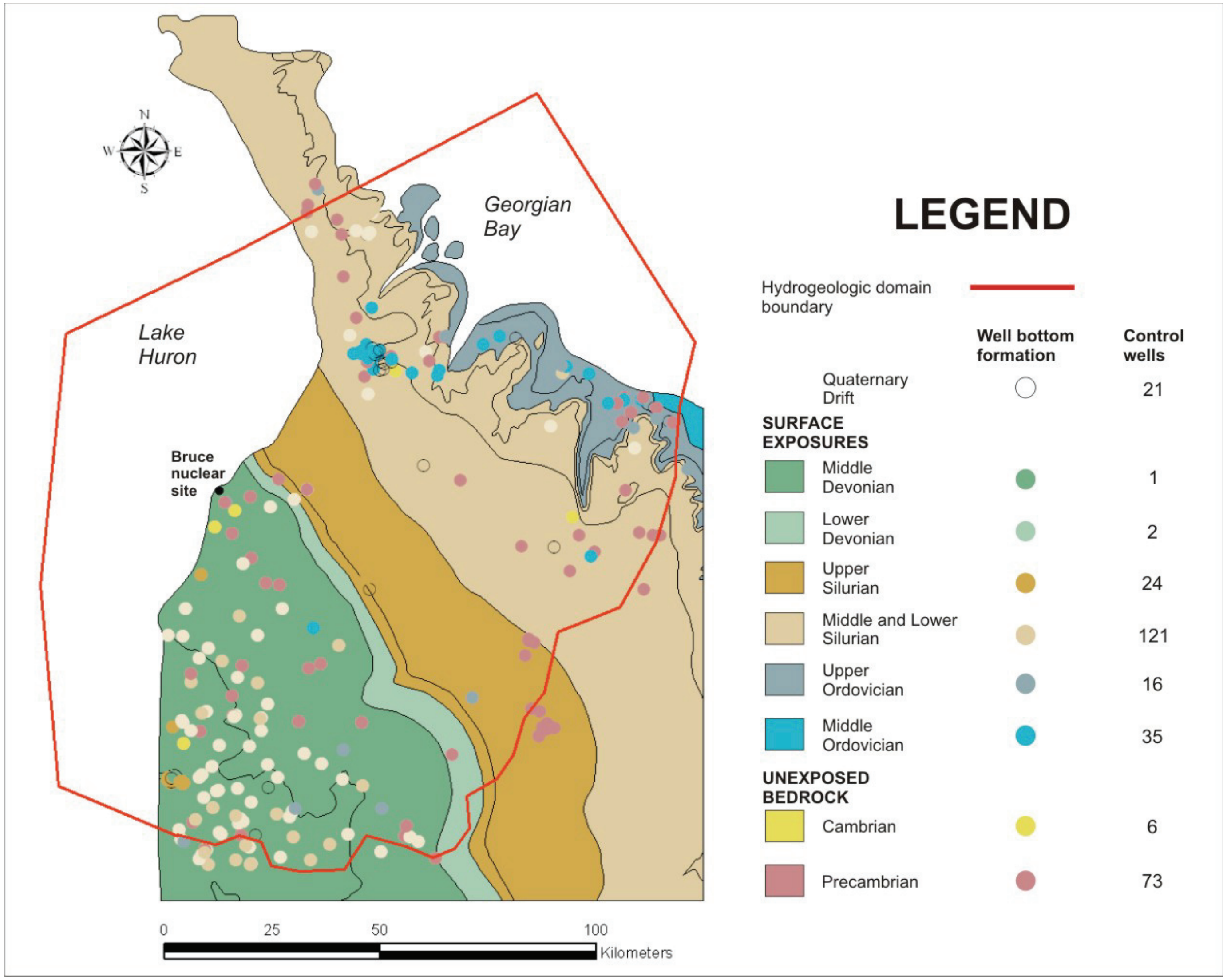


Figure 6.1: 3D Geological Framework Box Diagram of the Regional Study Area



Note: Control (borehole) points are colour-coded by well bottom formation.

Figure 6.2: Paleozoic Geology of the RSA with Well Locations Used for 3DGF Model

Grouping of Geological Formations

The layers represented within the 3DGF represent the maximum number of units/formations/groups that could be reliably interpreted within the study area using the methods applied in this study. Several individual units were not consistently logged within the OSGR database and were primarily grouped within other formations. Where these units were recorded individually in the database, they would be grouped within the 3DGF to avoid apparent lateral pinching in and out affects. The grouping of these units does not diminish the understanding of lateral continuity but rather reflects inconsistent historical geological logging procedures. The grouping in this case provides a more realistic overall representation of the geology. Table 6.1 presents a list of units logged within the study area and their resulting grouping.

Table 6.1: Standard Geological Fields from the OGSR Database and the Revised Geological Framework Grouping

Database Standard Geo_Field	Revised Classification	Notes
Drift	Drift	No change
Dundee	Dundee	No change
Columbus	Detroit River Gp	Lateral equivalent (Carter and Armstrong 2006)
Lucas	Detroit River Gp	The contact between these units cannot be consistently picked on a regional basis (Carter and Armstrong 2006).
Amherstburg	Detroit River Gp	The contact between these units cannot be consistently picked on a regional basis (Carter and Armstrong 2006).
Bois Blanc	Bois Blanc	No change
Bass Islands/Bertie	Bass Islands	Bertie Fm. is the Appalachian Basin lateral equivalent of Bass Islands (Map 2582 in Johnson et al. 1992)
G Unit	G Unit	No change
F Unit	F Unit	No change
F Salt	F Salt	No change
E Unit	E Unit	No change
D Unit	D Unit	No change
C Unit	B and C units	These units are largely dolomitic shales, shaley dolomite (Armstrong and Carter 2006).
B Equivalent	B and C units	Represents a common sequence of anhydrite overlain by salt. The lateral distribution of this Salina sequence is restricted to the southwest portion of the study area.
B Unit	B and C units	Represents a common sequence of anhydrite overlain by salt. The lateral distribution of this Salina sequence is restricted to the southwest portion of the study area.
B Anhydrite	B Anhydrite/Salt	
B Salt	B Anhydrite/Salt	
A-2 Carbonate	A-2 Carbonate	No change
A-2 Shale	A-2 Carbonate	Only recognized as a distinct unit in 2 holes. These shales are commonly found at the base of the A-2 carbonate unit.
A-2 Anhydrite	A-2 Anhydrite/Salt	Represents a common sequence of anhydrite overlain by salt. The lateral distribution of this Salina sequence

Database Standard Geo_Field	Revised Classification	Notes
		is restricted to the southwest portion of the study area.
A-2 Salt	A-2 Anhydrite/Salt	Represents a common sequence of anhydrite overlain by salt. The lateral distribution of this Salina sequence is restricted to the southwest portion of the study area.
A-1 Carbonate	A-1 Carbonate	No change
A-1 Evaporite	A-1 Evaporite	No change
Guelph	Niagaran	Niagaran contacts were not consistently picked in the well logs. This may be partly owing to the distinct differences displayed in Niagaran reef and inter-reef wells.
Eramosa	Niagaran	No change
Goat Island	Niagaran	Lateral equivalent to Fossil Hill in the Michigan Basin (Map 2582 in Johnson et al. 1992)
Gasport	Niagaran	
Irondequoit	Niagaran	
Lions Head	Niagaran	
Wiarton/Colpoy Bay (Amabel)	Niagaran	
Rochester	Niagaran	
Reynales/Fossil Hill	Reynales/Fossil Hill	
Thorold	Reynales/Fossil Hill	
Cabot Head	Cabot Head	No change
Dyer Bay	Cabot Head	Lateral equivalent south of Manitoulin Island (Map 2582 in Johnson et al. 1992)
Grimsby	Cabot Head	Lateral equivalent in Michigan Basin (Map 2582 in Johnson et al. 1992)
Wingfield	Cabot Head	Lateral equivalent south of Manitoulin Island (Map 2582 in Johnson et al. 1992)
Manitoulin	Manitoulin	No change
Whirlpool	Manitoulin	Lateral equivalent in Michigan Basin (Map 2582 in Johnson et al. 1992)
Queenston	Queenston	No change
Georgian Bay/Blue Mtn	Georgian Bay/Blue Mtn	No change
Collingwood	Georgian Bay/Blue Mtn	Although considered a member of the Cobourg Fm., this shale was more likely to have been logged as a member of Blue Mtn Fm.
Cobourg	Cobourg	No change
Sherman Fall	Sherman Fall	No change
Kirkfield	Kirkfield	No change
Coboconk	Coboconk	No change
Gull River	Gull River	No change

Database Standard Geo_Field	Revised Classification	Notes
Shadow Lake	Shadow Lake	No change
Cambrian	Cambrian	No change
Mount Simon/Potsdam	Cambrian	Mount Simon and Potsdam are lateral equivalents from the Michigan Basin and Appalachian Basin respectively (Map 2582 in Johnson et al. 1992)
Precambrian	Precambrian	No change

In contrast to grouping to resolve well logging problems, some formations had to be added to the individual wells in order to more realistically reflect expert knowledge of the subsurface. The addition of contacts was completed primarily for the Ordovician Trenton and Black River Groups. Well logs consistently used the “Group” name rather than the individual formation names. Some wells used the formation name to describe the whole group. Seven wells had minor unit additions other than Trenton and Black River changes. In all cases, these edits were informed and guided with logging data from nearby reference well(s).

Twenty-seven wells were edited to include units not logged with the Trenton/Black River Groups. These database edits were conducted using two different methods. The first and primary method used was interpolation to predict the elevation of missing layers. This was done by generating a surface based on surrounding well data and extending this surface through the well with the missing contact to generate an elevation. The second method used mean unit thickness from surrounding wells, with preference always given to reference wells.

6.4 Limitations

The following is a list of constraints and limitations of the 3DGF.

a) The data used to generate the geological framework is based on historic well logs submitted to the OGSR, which are then added to the database, sometimes with MNR edits. There are distinct variations in the quality of data reported from a large number of different companies, geologists, and technicians that have contributed to this database over nearly 50 years. Despite the verification procedures used to assess the data, the overall quality and completeness of the data cannot be fully verified.

b) The geological framework presents one interpretation of the data used in this study. The geology is interpreted between the boreholes and may vary from that represented in the geological framework.

c) The geological framework presented in this report represents Version 01 for the Geosynthesis project. Subsequent versions of the geological framework may show minor variations based on additional data, input from the scientific community, peer review, and changes in scope, scale, or purpose of the geological framework.

d) The Cambrian distribution in the subsurface as recorded in the geological framework is based both on the distribution as recorded in the consulted literature and the well distribution from the OGSR database. Only a few wells penetrate the full Paleozoic sequence. The actual Cambrian distribution in the subsurface is not well known, as based on descriptions in the literature.

e) The dip of the geological layers represented beneath Lake Huron may vary from that shown in the 3DGF. Data from well picks in Michigan suggest that the dip of the formations increases below the lake. Where this change in dip occurs is subject to interpretation.

f) Scarp faces revealed in bathymetry data in Lake Huron were used to guide and constrain interpreted geological contacts on the lake bed. An assumption made during this process was that there are limited recent sediments draped over the bedrock surface beneath the lake. Assuming limited or no sediment cover within the lake also produced a discrepancy in elevation data in some locations between the bedrock surface digital elevation model and the lakebed bathymetry. The surfaces were stitched together using a qualitative best-fit interpretation.

g) Effort was made to respect all geological contacts in both the subsurface and those mapped at surface, however, this was not always possible. The geological framework represents a best-fit among all data sources, and contacts may vary from that described in the literature and in published mapping. This work represents a new geological map and precise verification to previous work is not an indication of representativeness.

h) For consistency of the geological framework, the Trenton and Black River Groups in many database wells was subdivided according to the known individual formations, even where well data indicated missing units. It should be noted that Ordovician facies may be complicated by Cambrian and Precambrian paleogeographic highs (i.e. Islands) that existed within the Ordovician seas, as a result, it is possible that some units are not well represented in the subsurface.

6.5 Discussion

The 3DGF domain extends from Collingwood, Ontario in the east to the midpoint of Lake Huron in the west, south to Goderich, Ontario and north to the tip of the Bruce Peninsula (Figure 6.1). In the subsurface, the framework is situated at the eastern margin of the Michigan Basin, extending from the Algonquin Arch, west past the Niagaran Pinnacle reef belt and into the deeper portions of the basin below Lake Huron (e.g., Figure 2.6). The framework extends from approximately 500 mASL on the Niagara Escarpment to a depth of approximately 1,000 mBSL (metres below sea level) at the mid-point of Lake Huron.

An oblique view of the 3DGF looking northeast, roughly perpendicular to the Niagara Escarpment, shows the orientation of the stratigraphy from the Precambrian basement through to the Devonian units (Figure 6.1). Table 6.2 shows the mean thickness and standard deviation for all units within the geological framework (based on OGSR well data) and the site unit thickness determined from logging of the DGR boreholes as presented in the Descriptive Geosphere Site Model (DGSM) of INTERA (2011). A discussion of thickness discrepancies and similarities between the predicted and observed is provided for each depositional sequence discussed below. It should be noted that some variability of unit thickness is expected across the RSA given the large distances, changing geometry of the basin, and natural variability in geology due to variations in deposition and erosion. In general, and despite the large distances between many of the wells, the Bruce nuclear site stratigraphy is consistent with the regional data presented in the 3DGF.

Table 6.2: 3D Geological Framework Unit Thickness Compared with Bruce Nuclear Site Average Unit Thickness (DGR-1 to DGR-6) Data

Geological Unit	Samples (n)	Mean Thickness (m)	Std. Deviation (m)	DGR Thickness (m)
Dundee	67	15	8	*
Detroit River	94	103	31	**
Bois Blanc	93	52	19	49.2
Bass Islands	121	50	17	43.9
G Unit	90	9	6	8.4
F Unit	9	46	4	41.9
F Salt	10	15	6	*
E Unit	43	27	7	26.1
D Unit	44	9	3	1.6
B and C Units	88	28	7	42.0
B-Anhydrite/Salt	84	49	31	2.5
A-2 Carbonate	87	33	10	27.5
A-2 Anhydrite/Salt	85	13	11	5.1
A-1 Carbonate	82	36	8	41.1
A-1 Evaporite	82	5	4	4.3
Niagaran	109	55	39	37.8
Reynales/Fossil Hill	105	7	4	2.0
Cabot Head	71	21	12	24.0
Manitoulin	71	11	4	11.8
Queenston	72	85	25	71.5
Georgian Bay Blue Mtn	84	135	50	143.1
Cobourg	76	48	17	27.9
Sherman Fall	73	44	13	28.7
Kirkfield	70	39	11	46.0
Coboconk	73	13	8	23.5
Gull River	77	45	16	52.5
Shadow Lake	26	9	8	4.9
Cambrian	20	7	5	1

Notes: * Not present at site ** Full thickness not present at site. Std deviation of mean unit thickness was calculated using formations tops from all wells used to construct the 3DGF.

Figure 6.3 shows the Precambrian basement structure sloping from the Algonquin Arch and Michigan Basin margin towards the deeper portion of the basin in the southwest. The approximate dip of the Precambrian surface and overlying sedimentary units is 0.5 degrees and increases from the basin margin towards the basin centre. Where this dip changes beneath

Lake Huron and the exact orientation is not well documented in the literature due to the absence of subsurface data within Lake Huron. The version of the geological framework presented in this report relies on the strike and dips generated from the Ontario and Michigan subsurface well data.

The following sections present a discussion of each layer generated within the 3DGF.

6.5.1 Cambrian Sandstones and Carbonates

The interpreted Cambrian distribution is presented in Figure 6.4. The pinch out of the Cambrian carbonates and siliciclastics against the Algonquin Arch is based both on the distribution as presented in accepted literature (i.e., Carter et al. 1996) and the well distribution from the OGSR database. There are additional random petroleum wells east of the contact shown in Figure 6.4 that record Cambrian units. These are interpreted to be discontinuous remnants of eroded Cambrian deposits that once covered the Algonquin Arch (Bailey Geological Services and Cochrane 1984a). The actual Cambrian distribution in subsurface and the specific location of pinch outs is not well known. The absence of data is likely the result of the depth of the Cambrian, scarcity of outcrop information, and limited resource potential in the RSA (few petroleum exploration wells).

DGR-2 was the only borehole to sample the Cambrian unit, intersecting 16.9 m of Cambrian sandstones, and carbonates (Figure 5.1). The mean thickness of the Cambrian in the 3DGF is 7 m (standard deviation of 5 m). The Cambrian is known to be variable in thickness within the RSA, found within a continuous subcrop belt that thickens to the west of the Bruce nuclear site, and pinches out to the east of the site where the Cambrian sediments are interpreted as erosion remnants (Bailey Geological Services and Cochrane 1984a).

6.5.2 Ordovician Carbonates (Black River and Trenton Groups)

The Ordovician units from the Shadow Lake Formation through to the Cobourg Formation are presented in Figures 6.5 to 6.10. These units appear uniform in thickness and lateral extent within the geological framework. This is not surprising given the extensive shelf and ramp depositional environment (Section 4.2) that existed at the passive margin of the continent when these formations were deposited. To test the predictability of units across the RSA a simple statistical analysis was completed. Figure 6.11 shows an analysis of predicted versus the actual subsurface contact for the Sherman Fall Formation. The Sherman Fall Formation was selected because the contact is relatively easy to pick in core and cuttings relative to other Trenton/Black River contacts, and is therefore considered a more reliable pick. For the statistical analysis, 66% of wells were used to generate a surface through the other 33% of wells. When the actual and predicted data were compared the trend line was nearly 1 to 1 with an R^2 value of 0.99. This analysis further confirms the predictability of the Ordovician units.

Erosion of the Ordovician units within Georgian Bay exposes the Precambrian surface in the northeast portion of the study area as shown in Figure 6.10. The location of the eroded sedimentary units coincides with the Ordovician outcrop belt (Figure 3.1). Reported Precambrian islands and shoals in the Ordovician sea (Brookfield and Brett 1988), have not resulted in any significant (i.e. 30 m) promontories/knobs of Cambrian or Precambrian within the 3DGF. The irregular and undulating nature of the erosional Precambrian surface, however, is evident as subtle topographic features that carry up through the Ordovician (Figures 6.5 to 6.10). Only the upper Trenton limestones are exposed in outcrop within the RSA to the east along the base of the Niagara Escarpment.

The total mean thickness of the Ordovician carbonate units in the 3DGF is 198 m, which is relatively consistent with the total thickness of approximately 185 m logged at the Bruce nuclear site. The key differences are the Cobourg Formation and Gull River Formation, which are thinner and thicker respectively than what is predicted from the regional data (Table 6.2) and may simply reflect natural variability. It should be noted however that the approximately 8 m thick Collingwood Member of the Cobourg Formation was grouped with the overlying Blue Mountain Formation shales within the 3DGF.

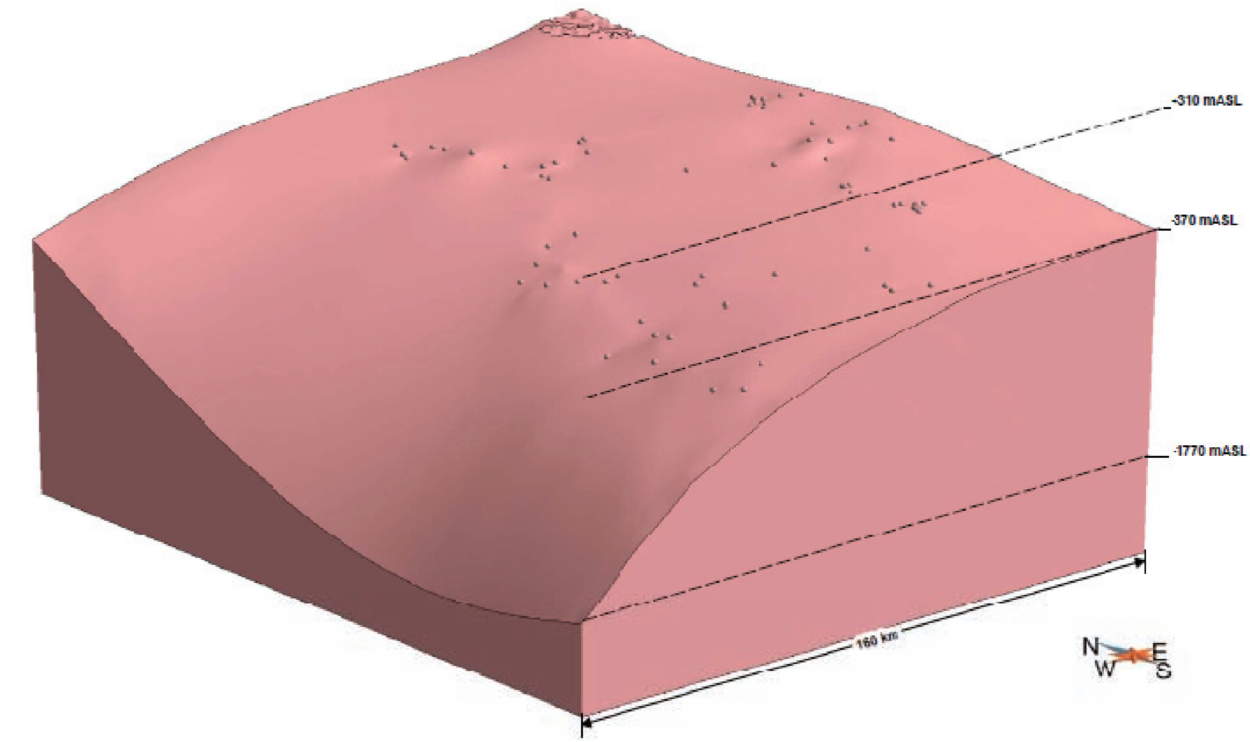


Figure 6.3: Precambrian

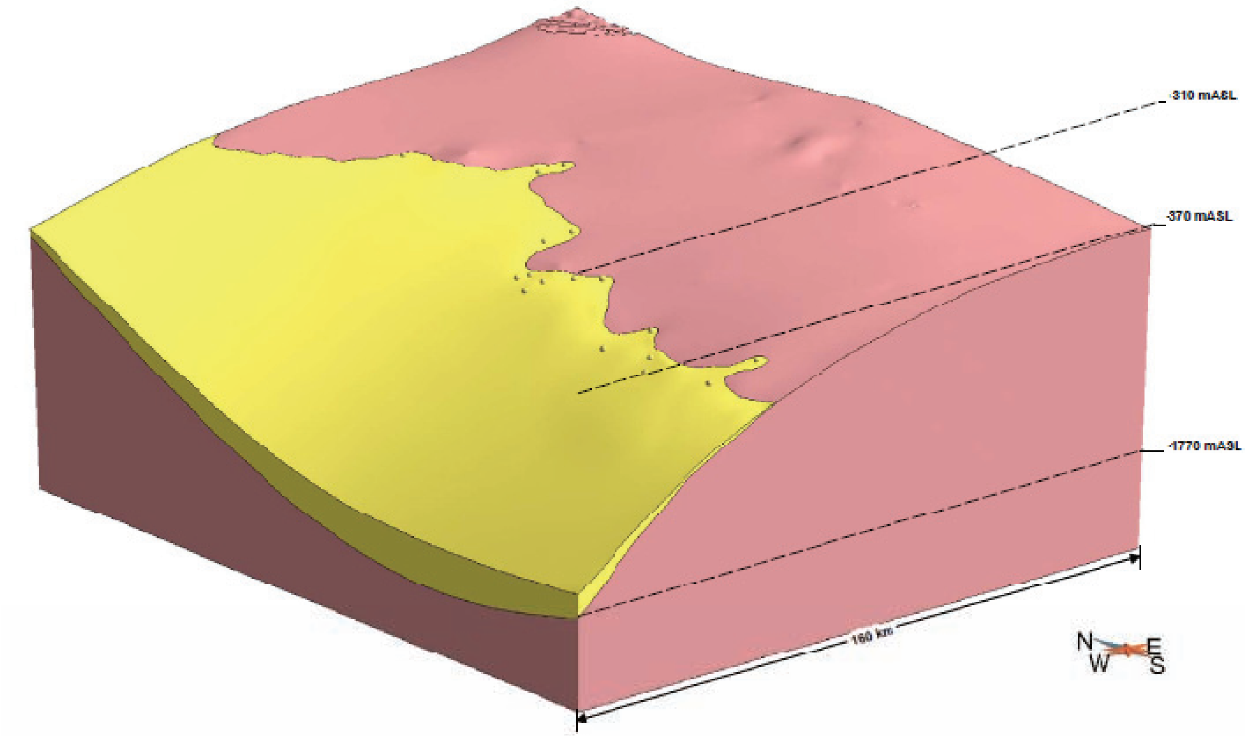


Figure 6.4: Cambrian

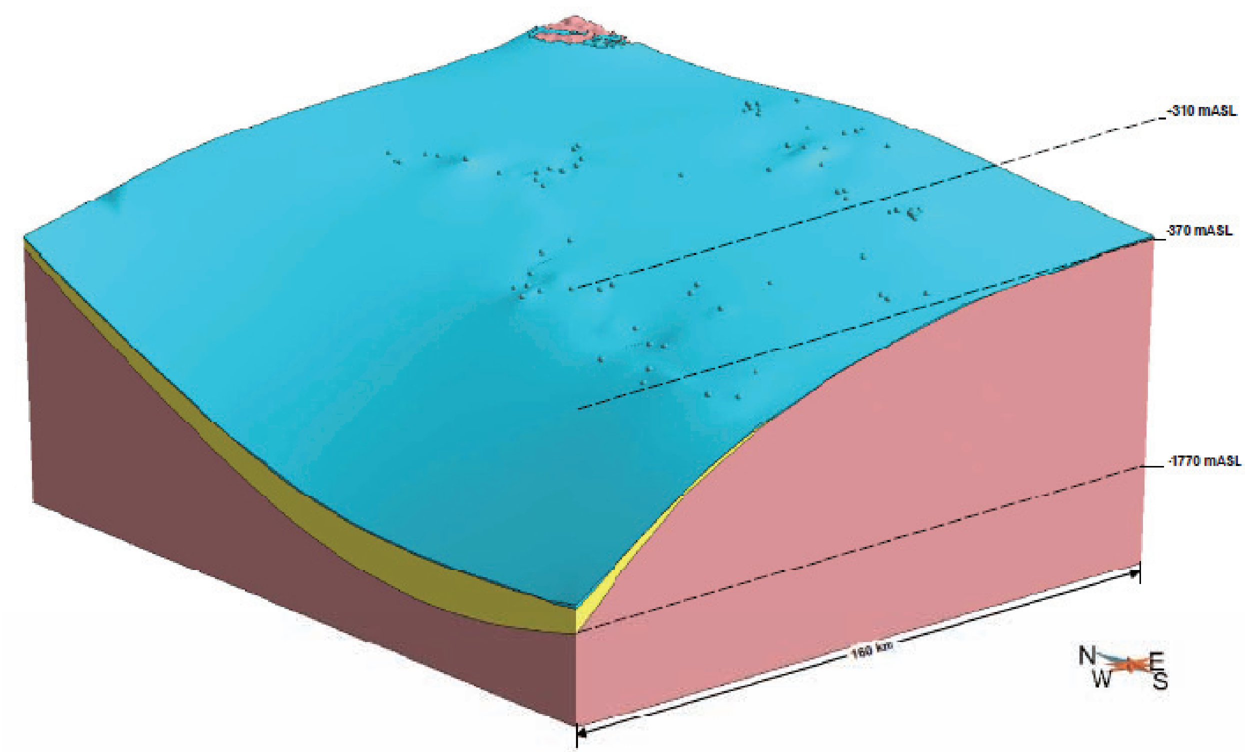


Figure 6.5: Shadow Lake Formation

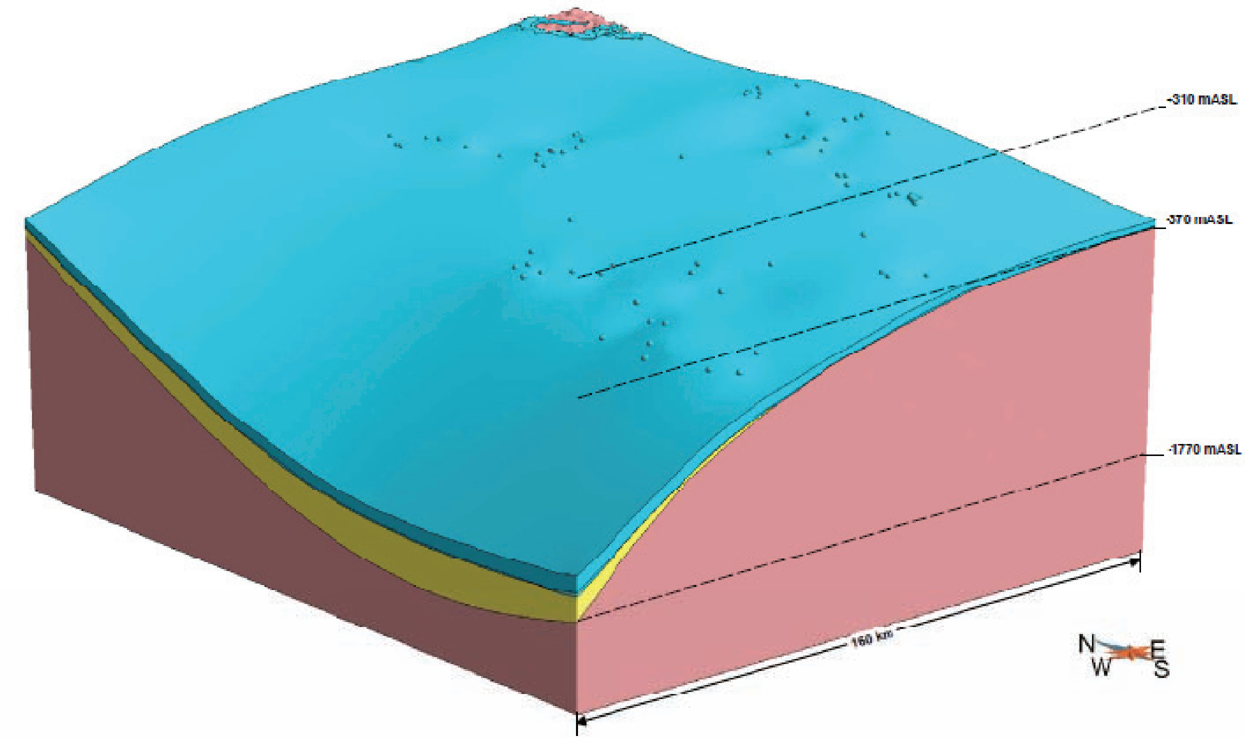


Figure 6.6: Gull River Formation

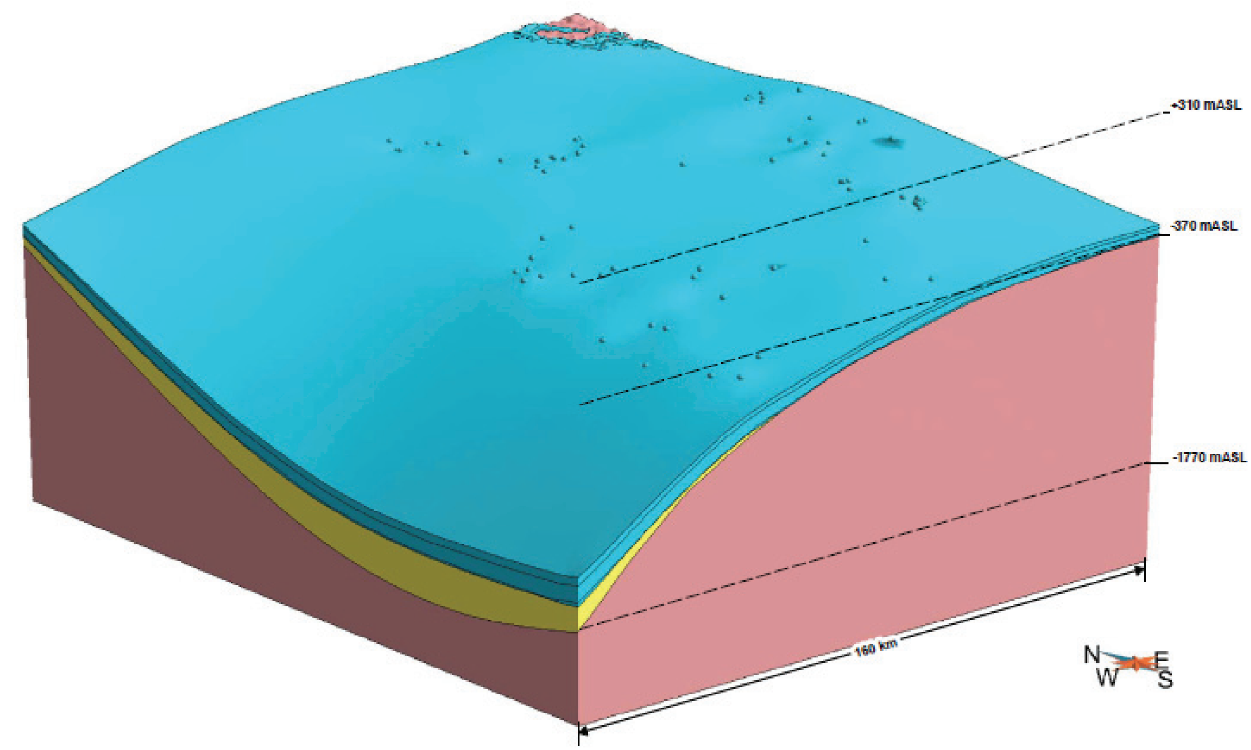


Figure 6.7: Coboconk Formation

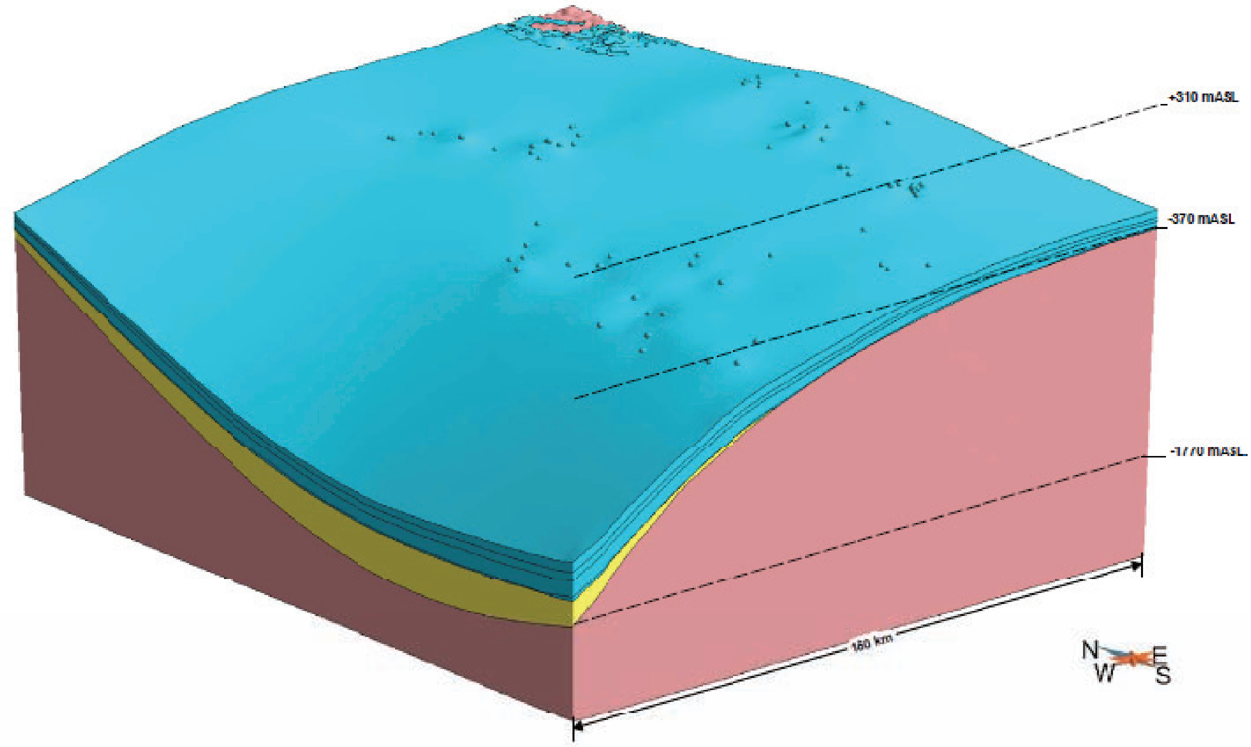


Figure 6.8: Kirkfield Formation

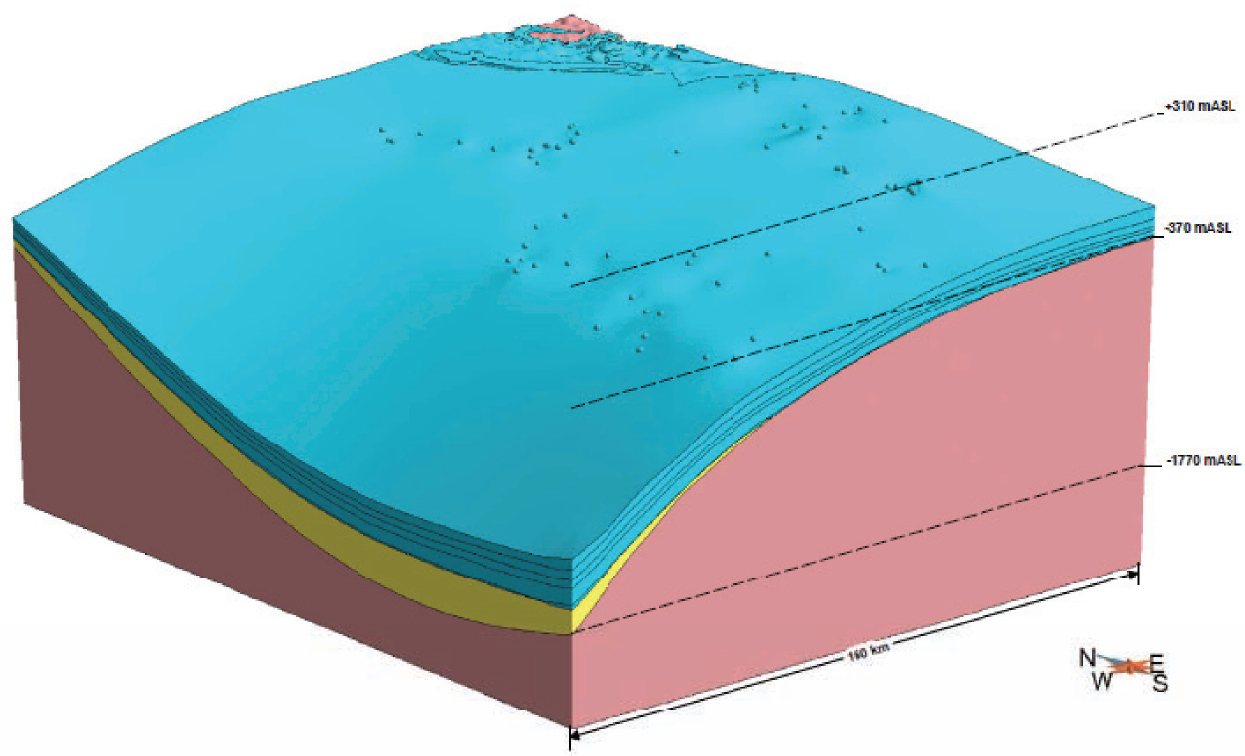


Figure 6.9: Sherman Fall Formation

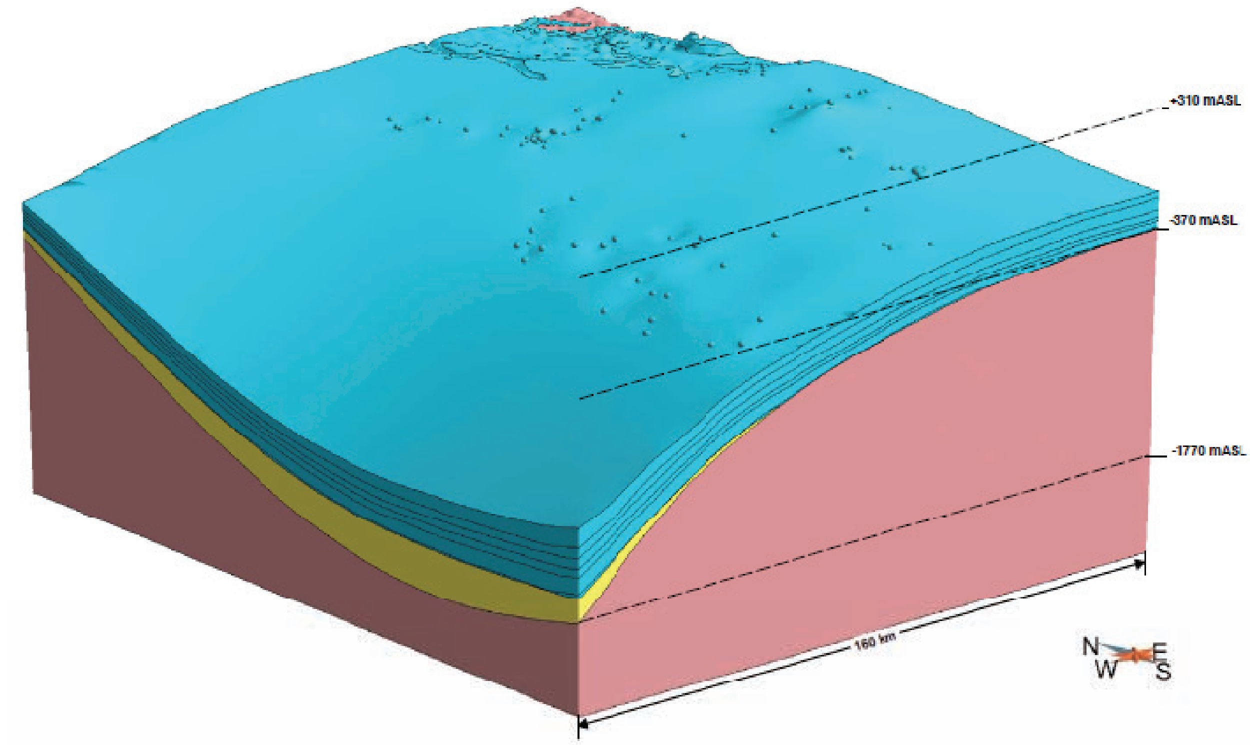


Figure 6.10: Cobourg Formation

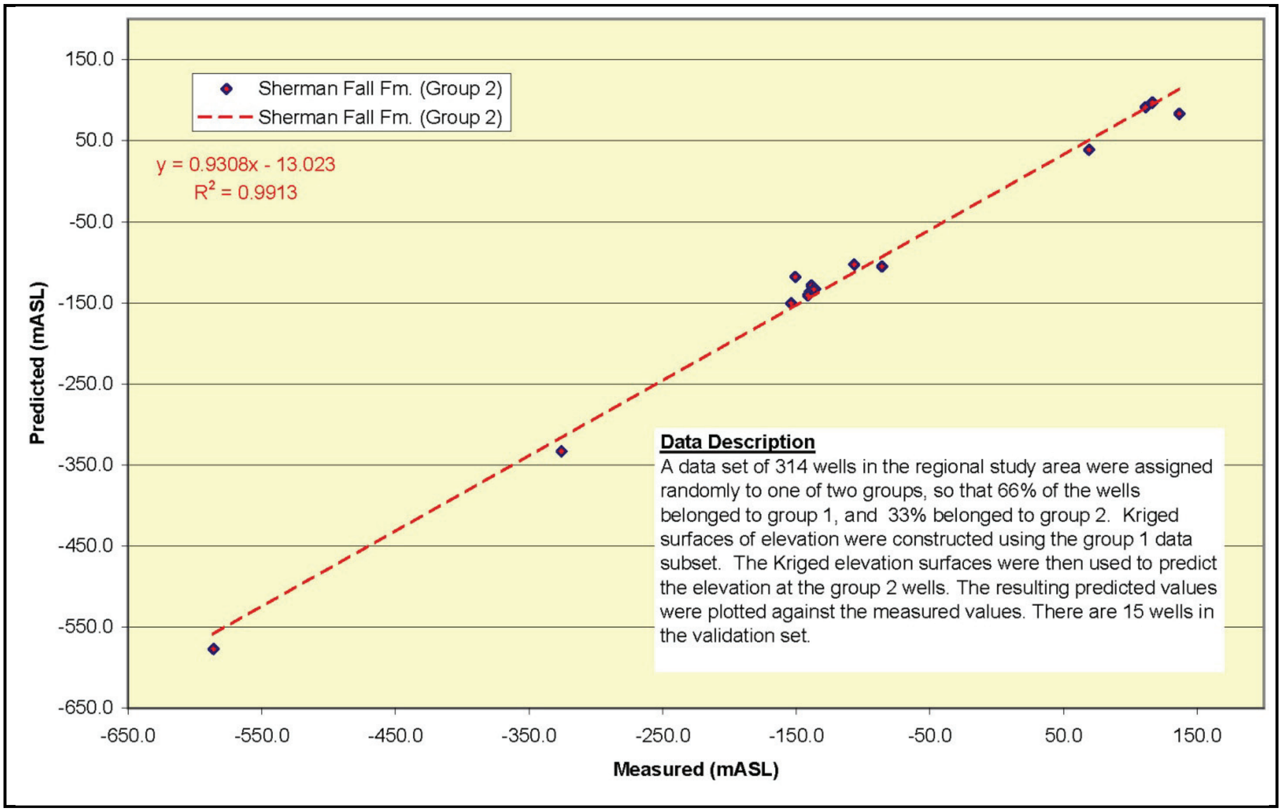


Figure 6.11: Predicted Versus Measured Contact Elevation For Sherman Fall Formation

6.5.3 Ordovician Shale (Queenston, Georgian Bay and Blue Mountain Formations)

The Georgian Bay/Blue Mountain and Queenston Formation surfaces are presented in Figures 6.12 and 6.13. As with the underlying Middle Ordovician carbonate units, these Upper Ordovician shale-dominated units are continuous across the entire RSA. The continuity and significant thickness (approximately 200 m within the RSA) results from the large clastic wedge depositional setting that extended from eastern North America across the Appalachian and Michigan Basins (Section 4.2.3). Although the Queenston Formation is reported to grade laterally into the upper Georgian Bay Formation northwest of the RSA, it is interpreted as a predominately shale unit within the entire RSA. Consistent with this interpretation, the core logs from the DGR boreholes describe the Queenston Formation as a slightly calcareous to noncalcareous shale, with minor thin beds of grey bioclastic limestone (INTERA 2011).

The Ordovician shale units are exposed along the base of the Niagara Escarpment, and are found in the subsurface throughout the remainder of the RSA. The total mean thickness of the Georgian Bay/Blue Mountain and Queenston formations from the OGSR well data are 220 m compared with an average thickness of 215 m in the DGR boreholes at the Bruce nuclear site.

6.5.4 Silurian Carbonates and Shale (Manitoulin, Cabot Head, Fossil Hill, Amabel/Lockport and Guelph Formations)

The Manitoulin and Cabot Head formations are extensive across southern Ontario and within the RSA (Figures 6.14 and 6.15). This is the result of deposition on a broad southwest dipping carbonate ramp (Section 4.2.4). Clastic input from the Taconic allochthon to the east inundated the carbonate ramp, depositing the Cabot Head Shale. These formations outcrop on the Bruce Peninsula along the Niagara Escarpment. Thickness recorded from the Bruce nuclear site for the Manitoulin and Cabot Head formations, 12 m and 24 m respectively, are consistent with mean thickness presented in the 3DGF (11 m and 21 m).

The Fossil Hill/Reynales and Guelph, Amabel/Lockport (Niagaran) formations are extensive across the entire RSA outcropping along the Niagara Escarpment. The Fossil Hill/Reynales is a relatively thin unit with a mean thickness of 7 m within the RSA (Figure 6.16). Approximately 3 m of Fossil Hill was intersected at the Bruce nuclear site (Table 6.2).

The two distinct facies assemblages, reef and inter-reef, complicate thickness comparisons of the overlying Niagaran carbonates. Pinnacle reefs can have up to approximately 130 m of Guelph Formation with inter-reef thickness of less than 10 m (Carter et al. 1994). The complications between reef and inter-reef descriptions are the key reason why the Niagaran carbonates are grouped within the 3DGF. Discrepancies in the database led to problems such as excessively thick Amabel or Lockport units erroneously describing the Guelph Formation reefs. Most of the Niagaran (Lockport, Amabel and Guelph Formation) units display an overlapping range of lithologies dominated by diagenetic dolostone mineralogy. The Niagaran Grouping was completed to prevent erroneous stratigraphic interpretations.

Consistent with accepted Niagaran relationships, (Bailey 1986, Carter et al. 1994, Sanford 1969, Gill 1985, Johnson et al. 1992) the geological framework shows the Niagaran carbonates thinning towards the basin centre, and thickening towards the Algonquin Arch, coincident with the barrier reef complex at the basin margin (Figure 6.17). The pinnacle reefs are represented by prominent Niagaran peaks and are consistent with the known location of the pinnacle reef belt (Figure 4.7). The pinnacle reefs within the reef belt likely continue to the north and west of the RSA beneath Lake Huron. These reefs are not presented in the 3DGF due the absence of borehole data from beneath the lake. DGR-2 intersected approximately 6 m of Guelph Formation and 28 m of Amabel/Lockport Formation. Based on the facies described and thicknesses from the DGR boreholes (Sterling and Melaney 2011, INTERA 2011), the Bruce nuclear site is clearly represented by Niagaran inter-reef facies. Figures 8.12 and 8.13 illustrate the stratigraphic relationships between the Middle Silurian and Upper Silurian units at pinnacle reef and inter-reef locations.

For presentation purposes within the geological framework, and where well data could not define the aerial extent of reefs, pinnacle reefs were given an approximate base of 3 km by 3 km for visualization purposes only (reefs are typically much smaller i.e. < 120 hectares). The resulting Niagaran assemblage within the geological framework has a range of thickness from approximately 20 m in the inter-reef locations, to 125 m within the pinnacle reefs, to 100 m at the basin margin within the barrier reef complex (Figure 6.17).

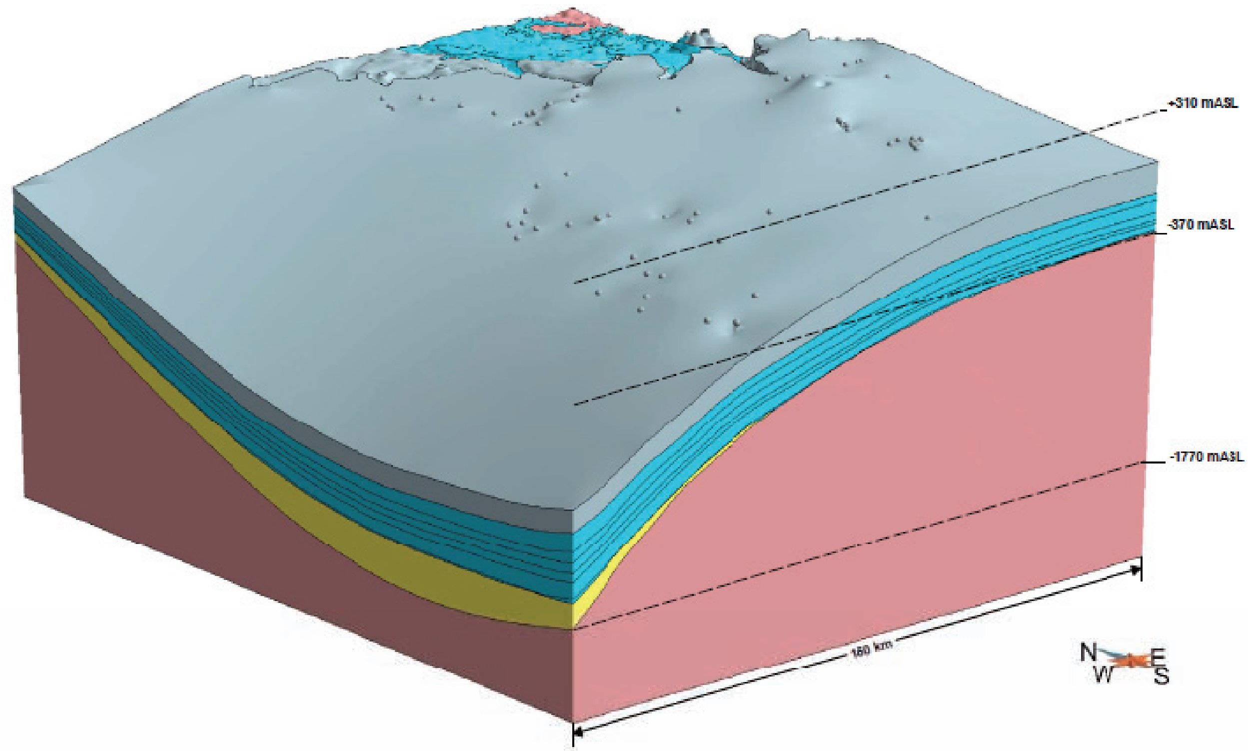


Figure 6.12: Georgian Bay and Blue Mountain Formations

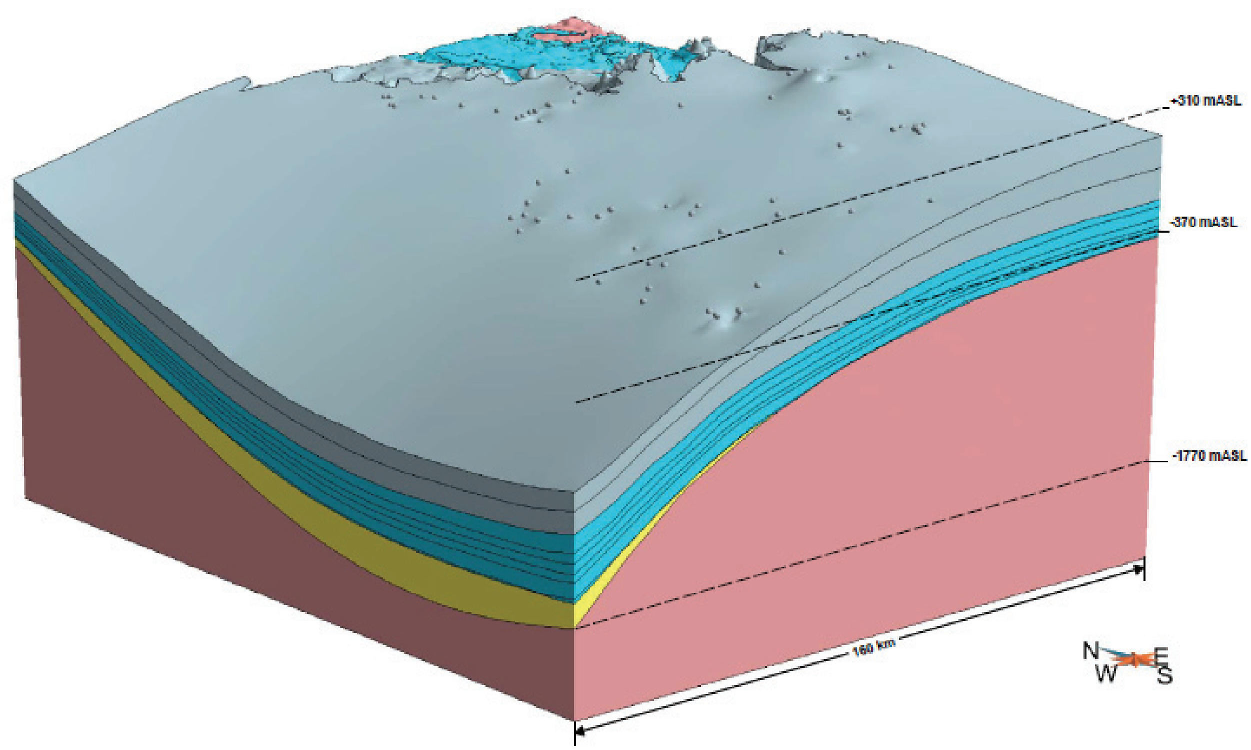


Figure 6.13: Queenston Formation

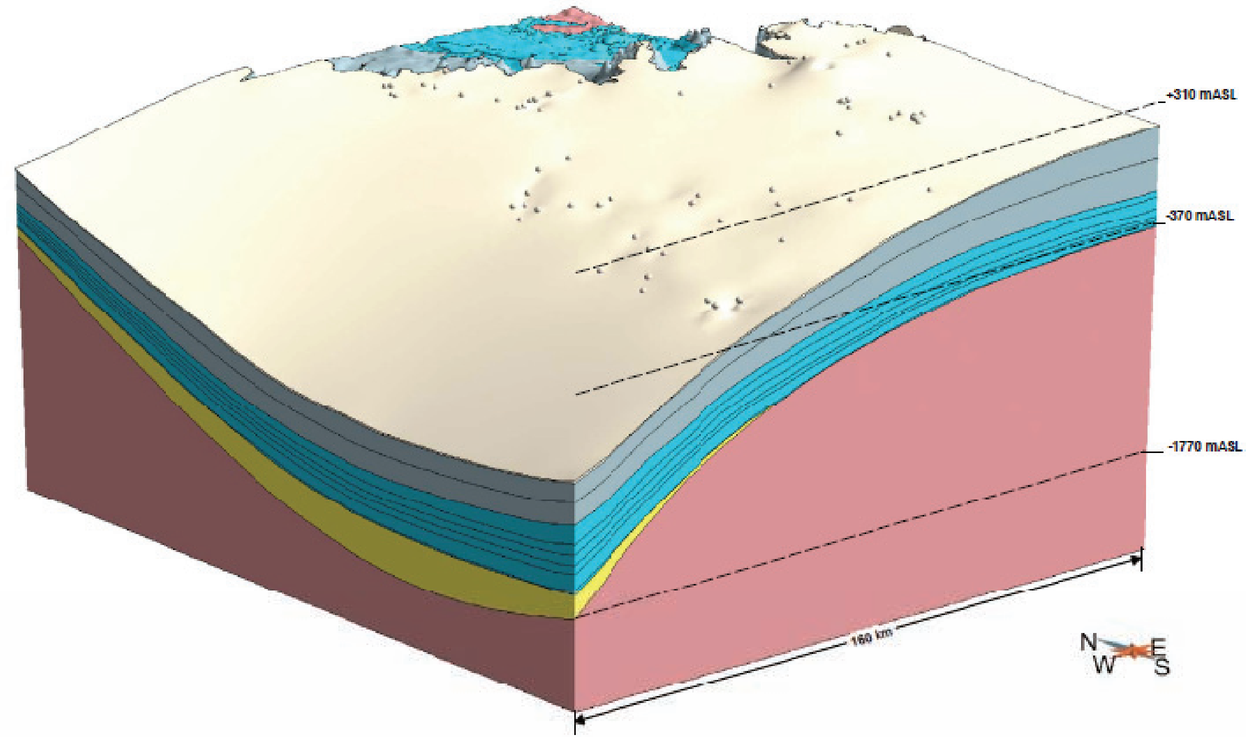


Figure 6.14: Manitoulin Formation

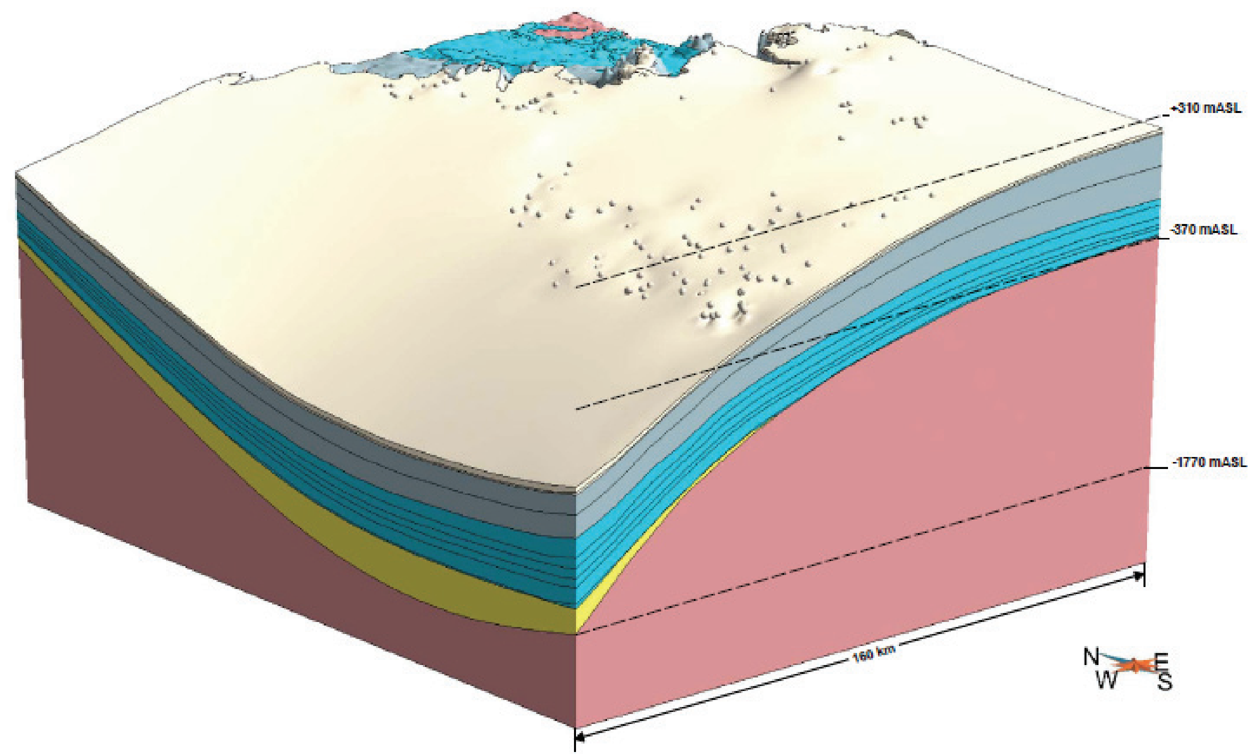


Figure 6.15: Cabot Head Formation

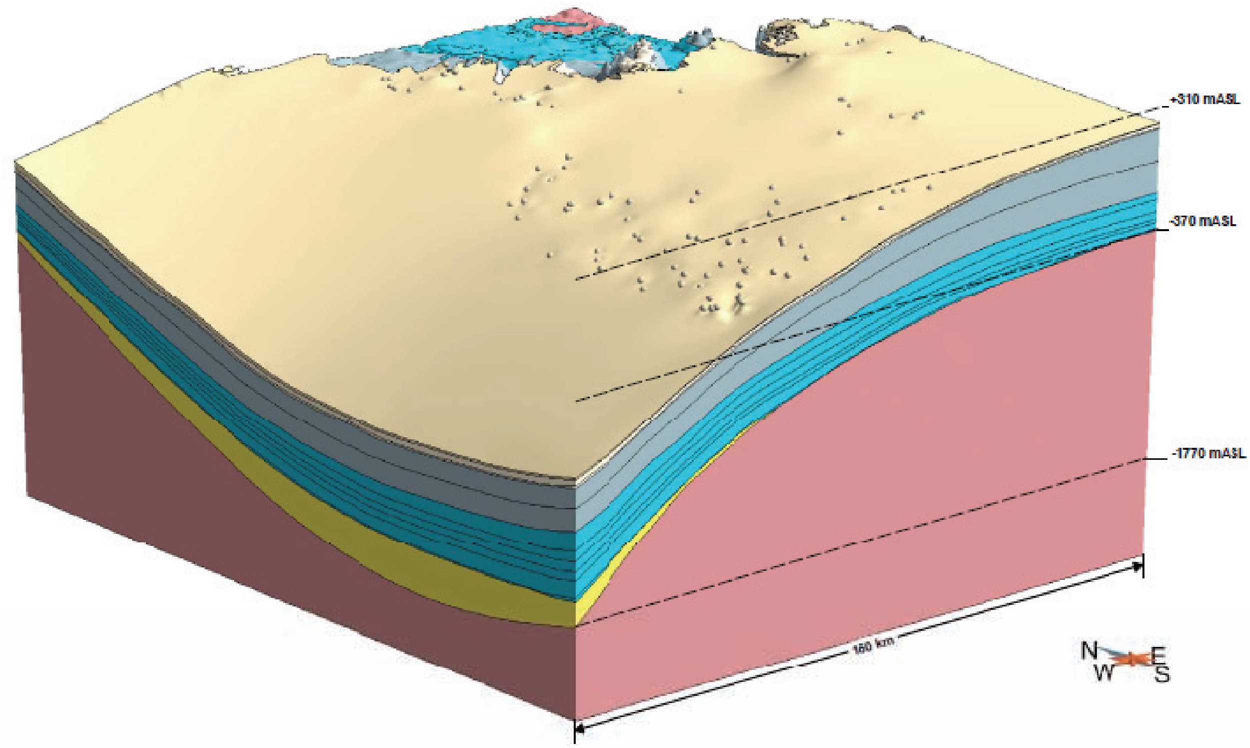


Figure 6.16: Reynales Formation/ Fossil Hill Formation

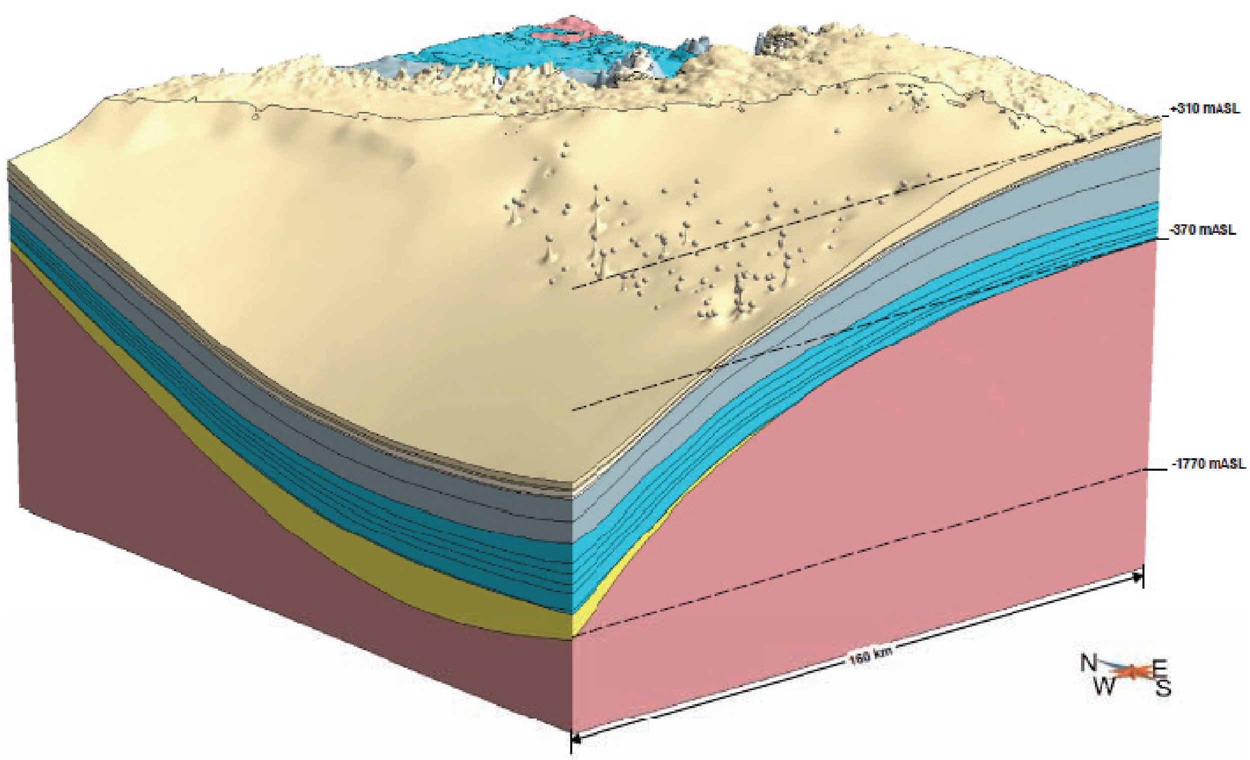


Figure 6.17: Niagaran Group (Guelph/Amabel/Lockport)

6.5.5 Silurian Salina Group (A-0 through G-Unit) and Bass Islands Formation

Alternating deposition of carbonate, evaporites and argillaceous sediments characterize the Salina Group. The distribution of these complicated facies is shown in Figures 6.18 to 6.28 beginning with the A1-Evaporite and ending with Salina G-Unit. The Salina does not appear to outcrop within the RSA and is found only in subcrop. The subcrop contact of the entire Salina Group beneath the Quaternary cover is presented in Figure 6.28.

The A-1 evaporite is composed of anhydrite and dolostone beneath the Bruce nuclear site but likely grades to halite further westward into the Michigan Basin (Section 4.2.5). Figure 6.18 shows the A-1 evaporite flanking the larger pinnacle reefs and pinching out against the Niagaran surface while the A-1 carbonate covers the pinnacle reefs and extends further east onto the Algonquin Arch (Figure 6.19) also pinching out against the Niagaran (Guelph Formation). The relationship between the Salina sequences and the Niagaran reefs is complicated and there remains some controversy on the timing relationships of the formations (Carter et al. 1994). Early work by Sears and Lucia (1979) for the northern Michigan Basin pinnacle reef belt showed a similar relationship of A-1 Carbonates overlapping the reefs. More recent work from southwestern Ontario (Carter 1991, Carter et al. 1994) shows the A-1 Carbonate flanking the reefs, with the A-2 Evaporite overlapping. OGSR wells within the RSA generally described the A-1 carbonate above the Niagaran. The actual relationship is likely to be dependent on factors including reef height and location within the basin.

The A-2 Evaporite and A-2 Carbonate have a similar relationship as the A-1 facies, with the A-2 Evaporite (anhydrite and dolomite) pinching out at the edge of the pinnacle reef belt while the A-2 carbonate extends onto the Algonquin Arch (Figures 6.20 and 6.21).

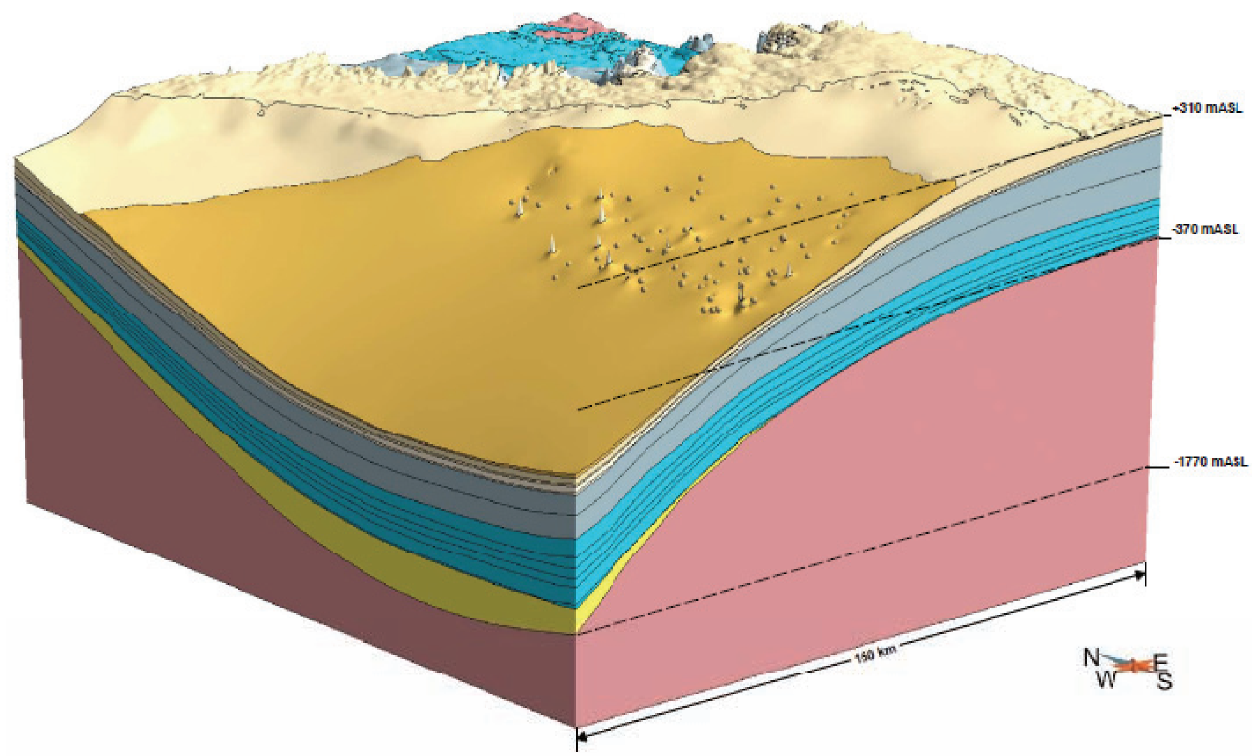


Figure 6.18: Salina A1-Evaporite

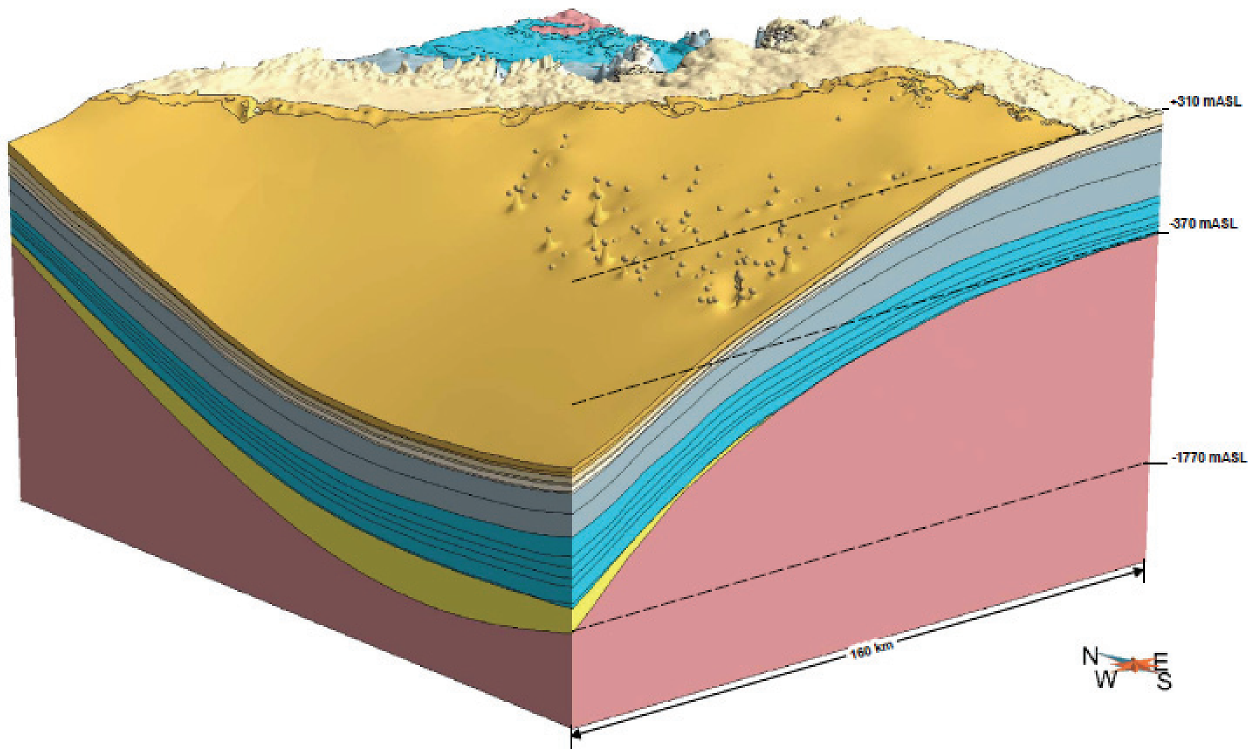


Figure 6.19: Salina A1-Carbonate

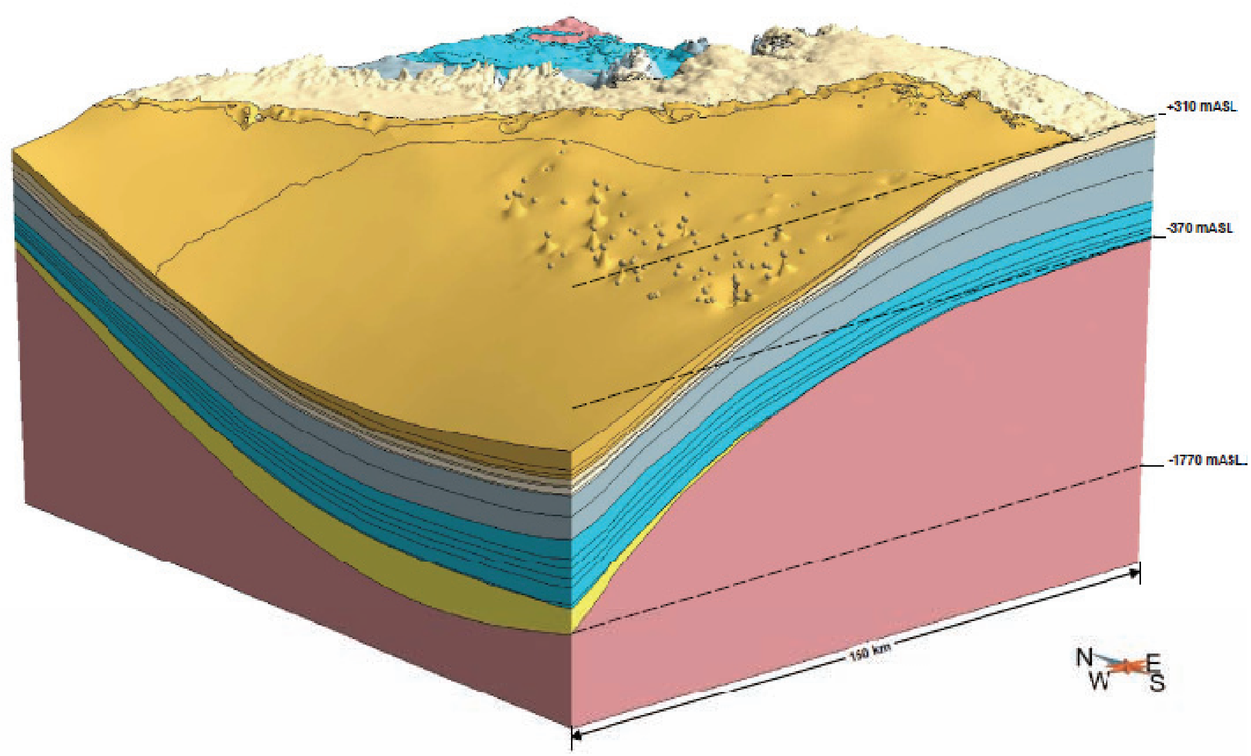


Figure 6.20: Salina A2-Evaporite

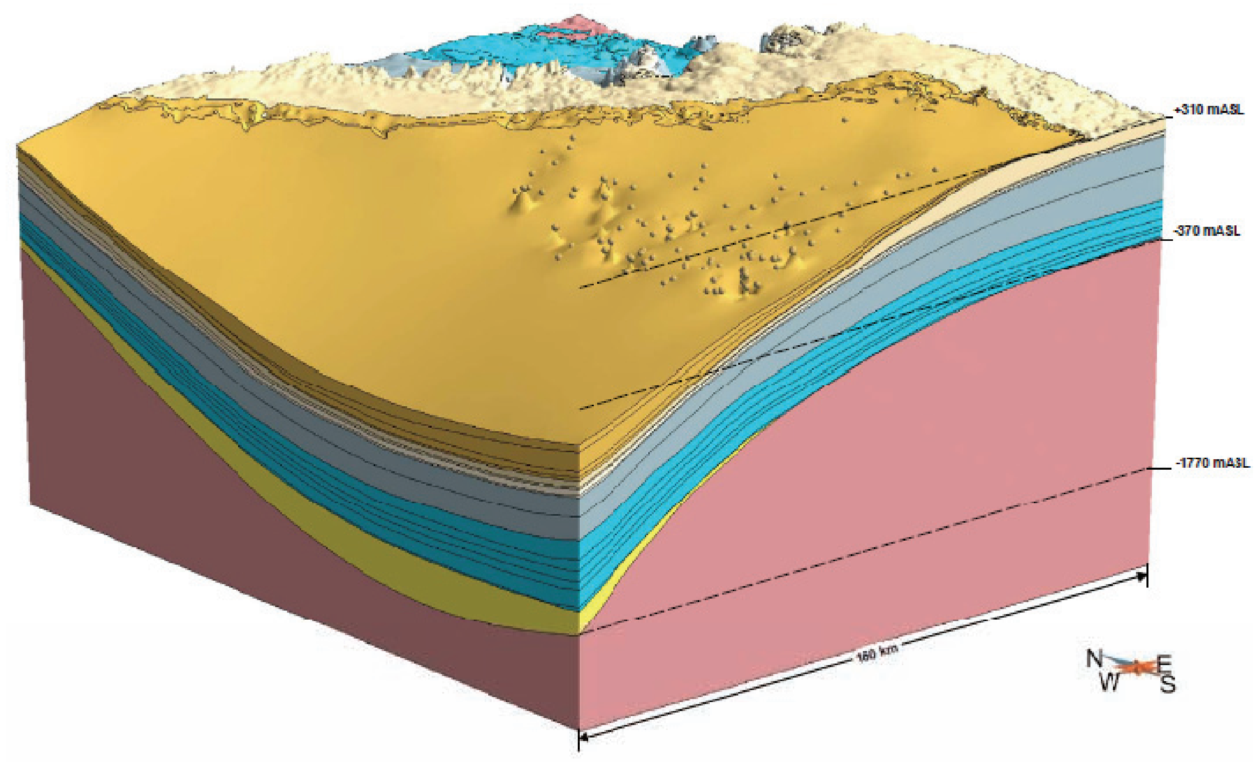


Figure 6.21: Salina A2-Carbonate

The B –Anhydrite (grouped as B-Anhydrite/Salt) is found at the Bruce nuclear site as a thin anhydrite layer. This unit is interpreted as continuous within the subcrop area represented in Figure 6.22. The distribution of corresponding argillaceous dolostones of the combined B and C units is shown in Figure 6.23. The remaining Salina Group units are presented in Figures 6.24 through 6.28. The E-Unit, F-Unit and G-Unit extend to the Salina subcrop belt while the D-unit and F-Salt are confined to the southwest portion of the RSA (Figures 6.24 and 6.26).

The Bass Islands Formation is found beneath the entire RSA, west of the escarpment (Figure 6.29), subcropping adjacent to the Salina G-Unit.

The thickness of the Salina Group carbonates is relatively consistent across the RSA while the evaporite units become thicker towards the basin centre (southwest portion of the RSA). Exceptions to the consistent distribution include the presence of possible collapse features within the Salina Group as evident within the 3DGF. These features may be related to dissolution of salt during the late Silurian as discussed in Sections 4.2.5 and 4.2.6. The thickness of the carbonate units encountered at the Bruce nuclear site is consistent with the mean thicknesses from the RSA well data. The Bass Islands carbonates are interpreted to be relatively uniform throughout the RSA. This unit has a mean thickness of 50 m with 49 m intersected by DGR-2 at the site (Table 6.2).

It should be noted that the A-0 described at the site in DGR-2 is not described in the RSA within the OGSR well database. This is likely because the A-0 was not commonly recognized as a distinct unit in the subsurface. The A-0 would probably have been described as part of the Guelph Formation within most of the OGSR wells.

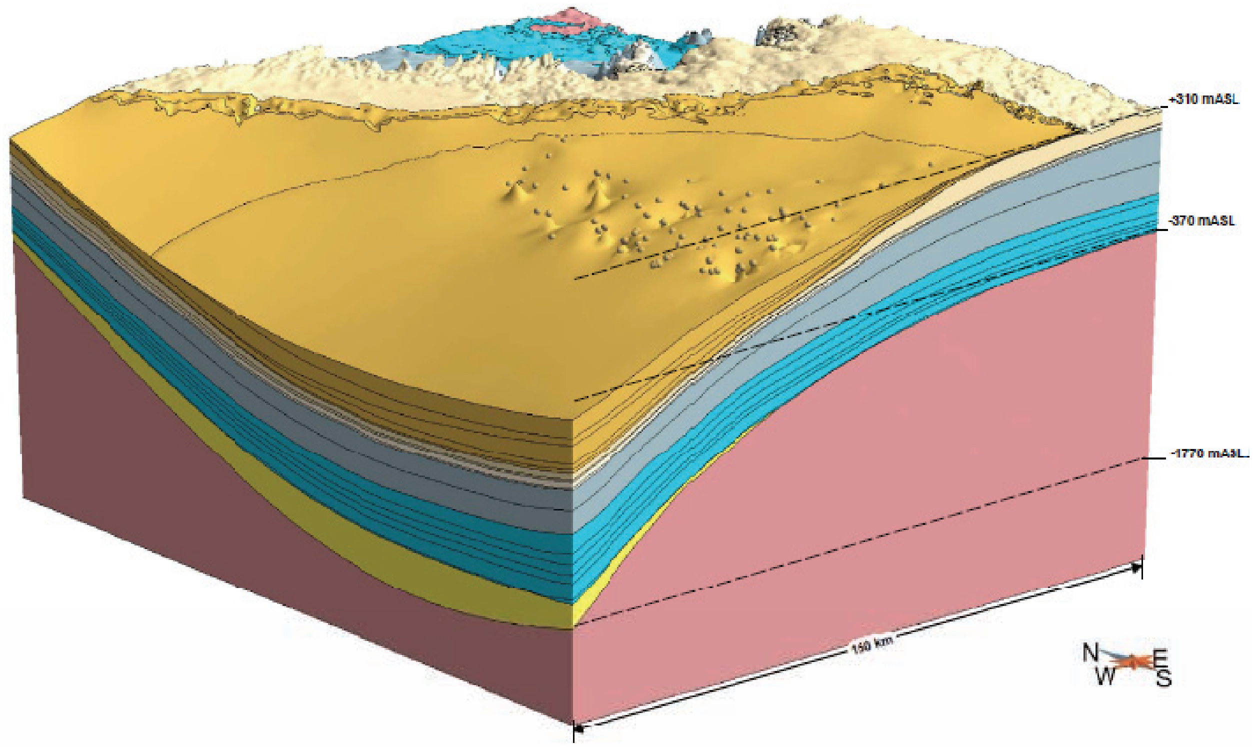


Figure 6.22: Salina B-Anhydrite/Salt

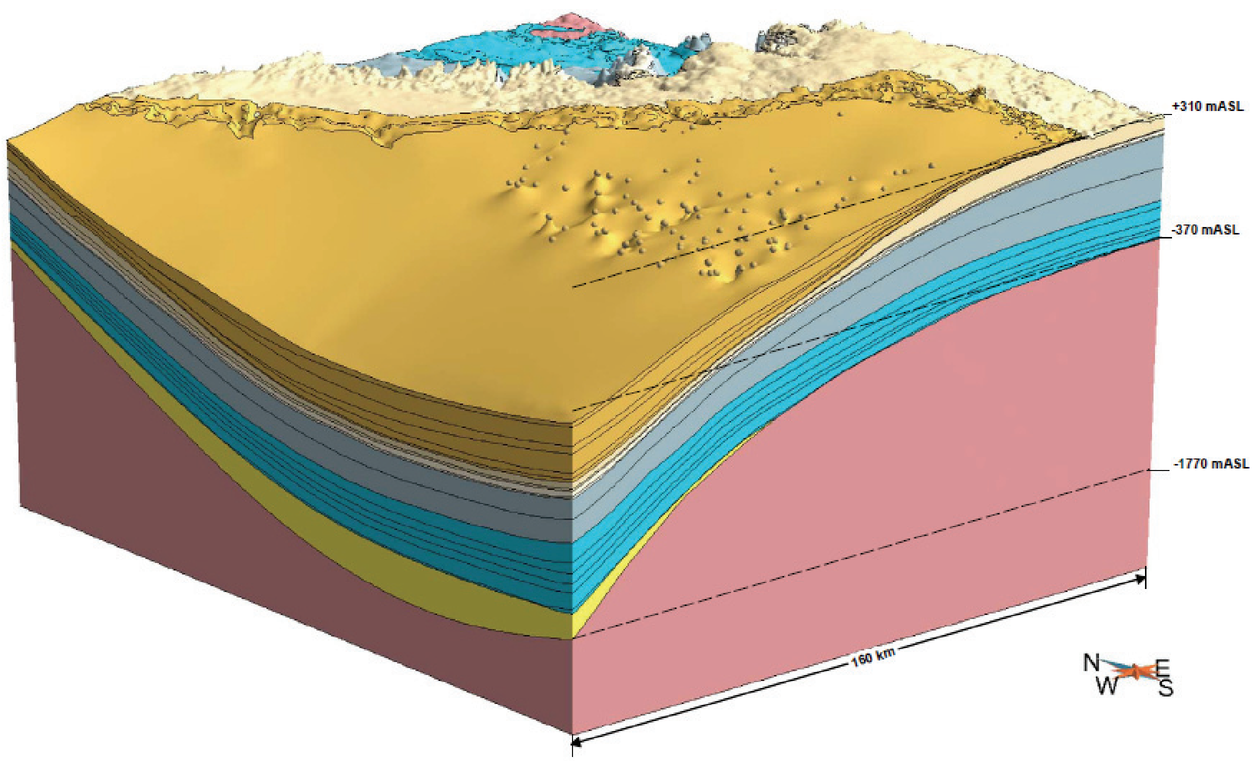


Figure 6.23: Salina B and C Units

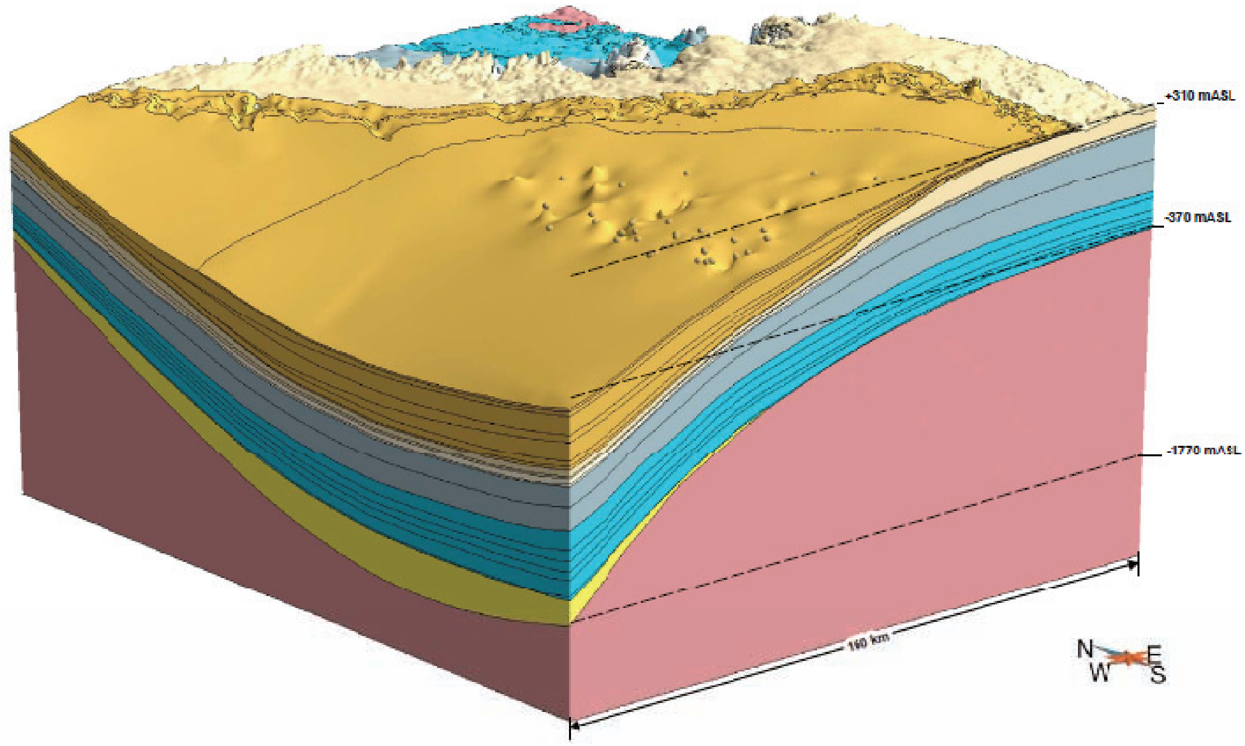


Figure 6.24: Salina D-Unit

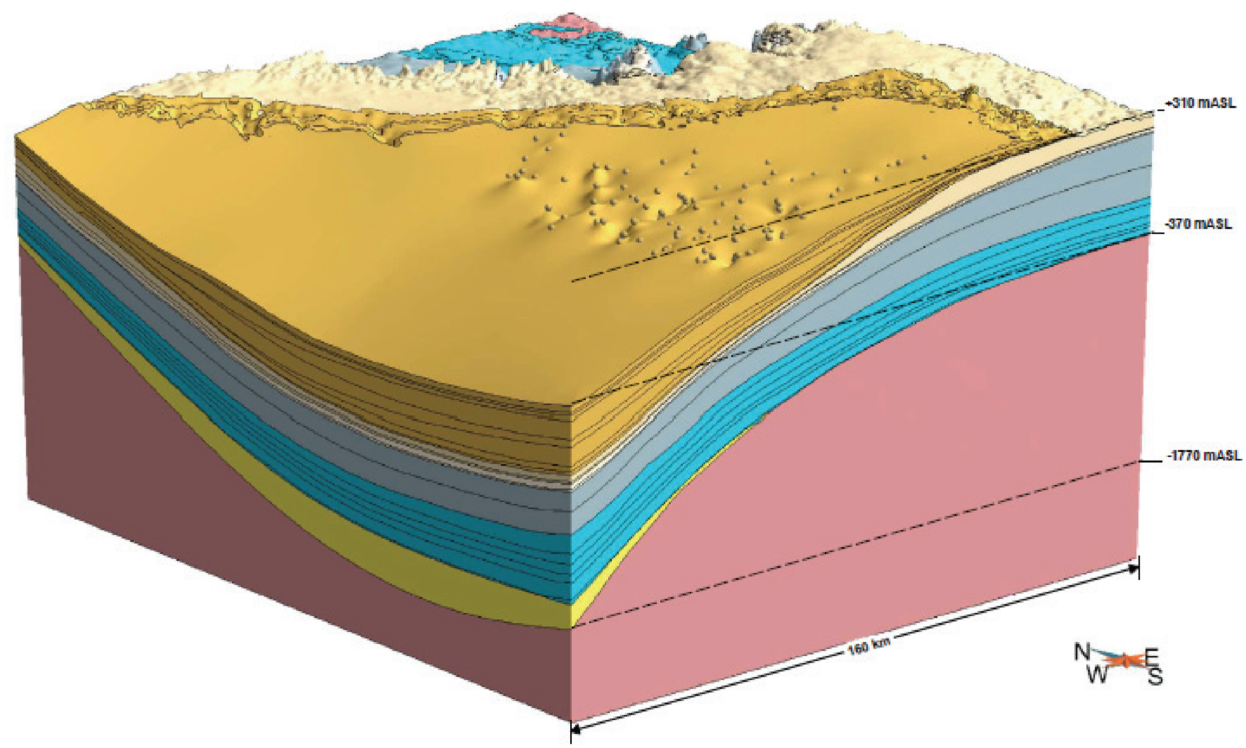


Figure 6.25: Salina E-Unit

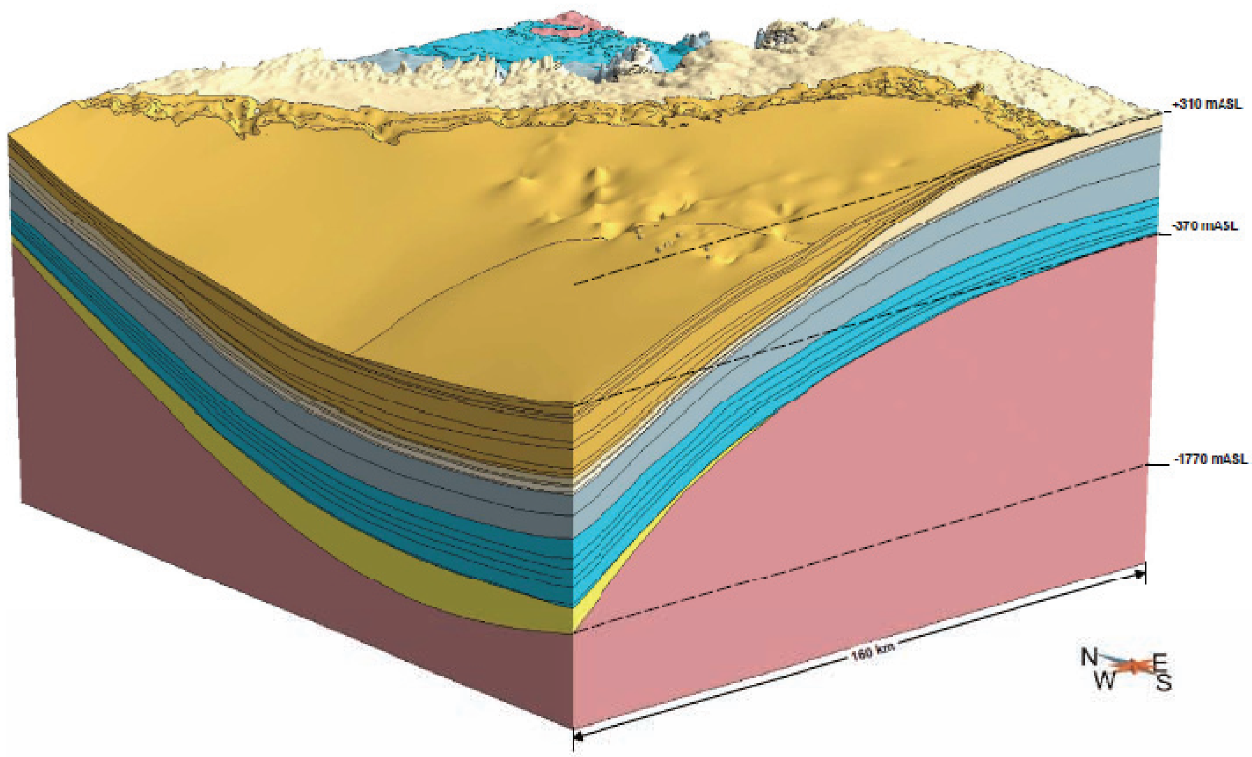


Figure 6.26: Salina F-Salt

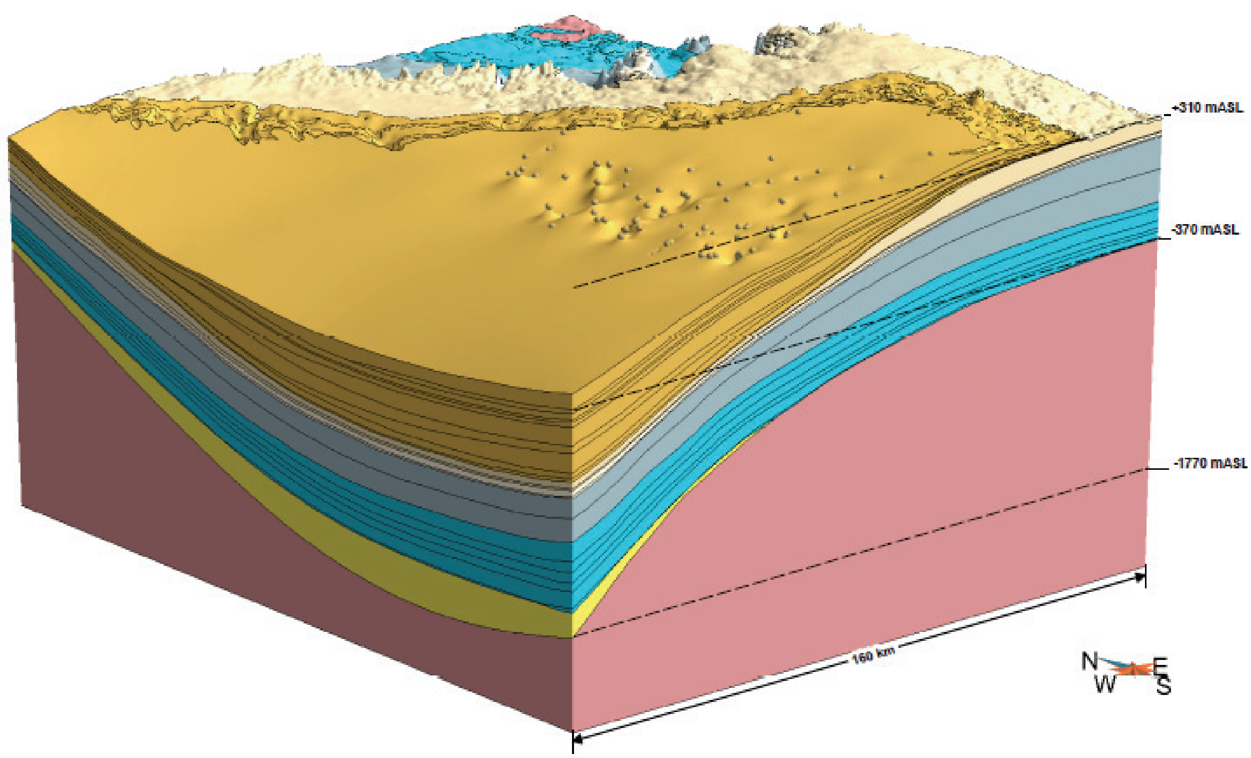


Figure 6.27: Salina F-Unit

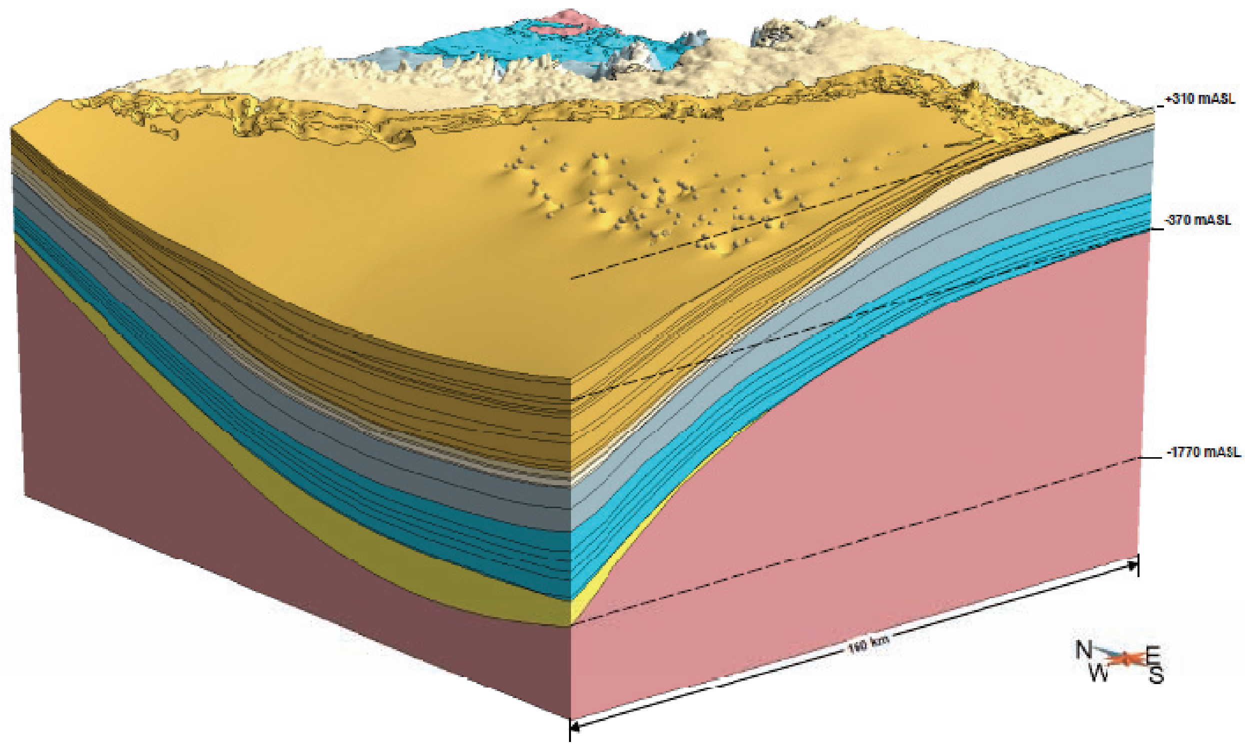


Figure 6.28: Salina G-Unit

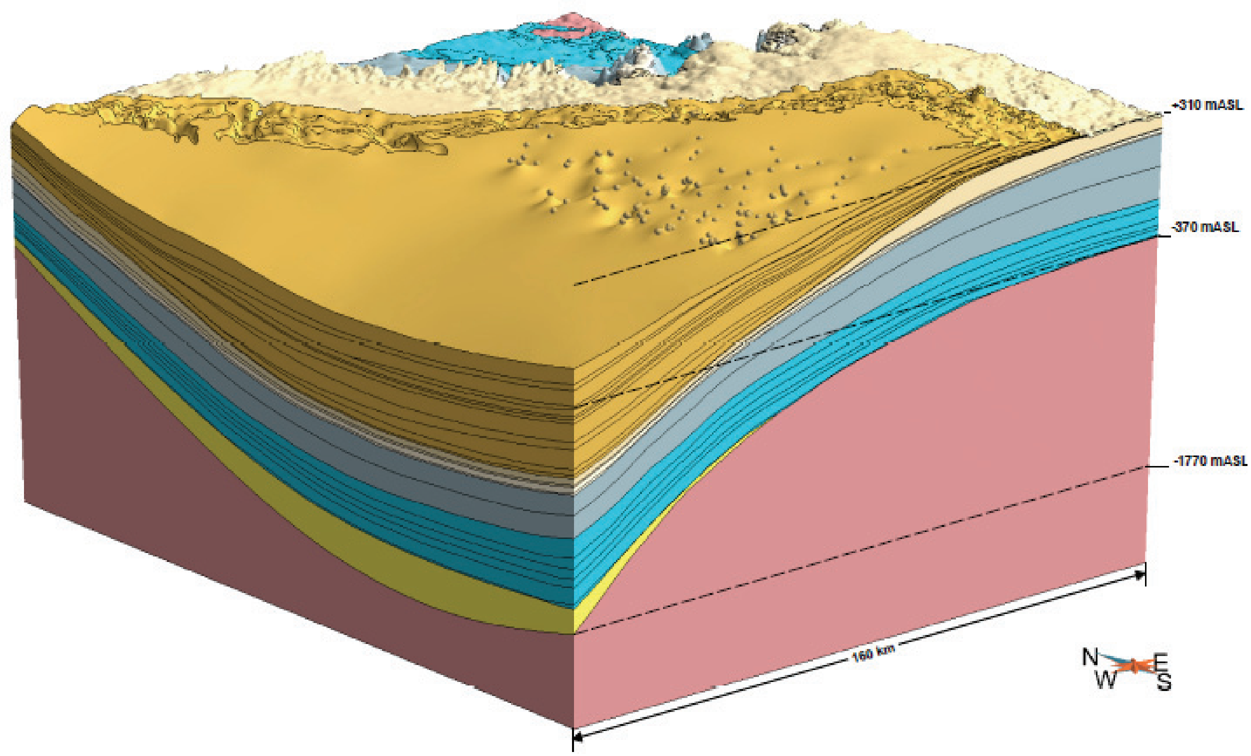


Figure 6.29: Bass Islands Formation

6.5.6 Devonian Carbonates (Bois Blanc Formation, Detroit River Group and Dundee Formation)

The distribution of Devonian units is presented in Figures 6.30 through 6.34, with the younger units progressively outcropping towards the centre of the Michigan Basin. These figures show that the influence of the Niagaran pinnacle reefs is still evident during depositon of the Bois Blanc Formation but is largely gone by the time of Detroit River Group deposition. All Devonian units are shown as continuous and as having relatively uniform thickness. The Lucas Formation of the Detroit River Group is the first Paleozoic units encountered below the Quaternary cover at the Bruce nuclear site (Figure 5.1). Including the underlying Amherstburg Formation yields approximately 55 m of Detroit River Group at the site. The Amherstburg Formation is about 47 m thick compared to the maximum thickness of 60 m described from southwestern Ontario (Johnson et al. 1992).

The collapse features and deformation described within the Devonian as a result of salt dissolution (Sanford et al. 1985) are not represented in the 3DGF other than through the bedrock topography mapping of the outcrop/subcrop. As discussed above, possible collapse features may, however, be present in the Upper Silurian Salina Group within the 3DGF. The location of collapse features in the Devonian was identified based on the presence of interpreted karst topography (sink-holes) expressed at the bedrock surface (Sanford 1975).

The absence of Devonian salt collapse features represented in the 3DGF may be due to the absence of wells drilled directly through these structures combined with the large spacing of petroleum wells, which makes interpreting such structures and associated offsets difficult.

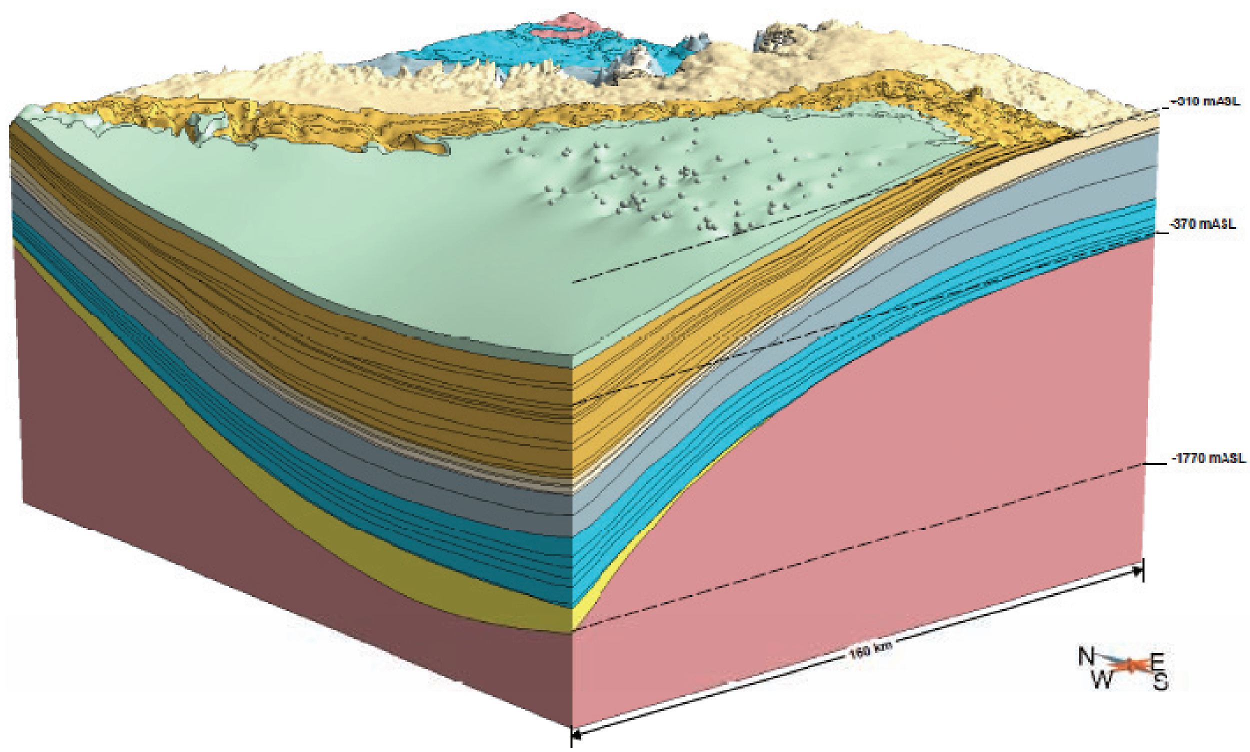


Figure 6.30: Bois Blanc Formation

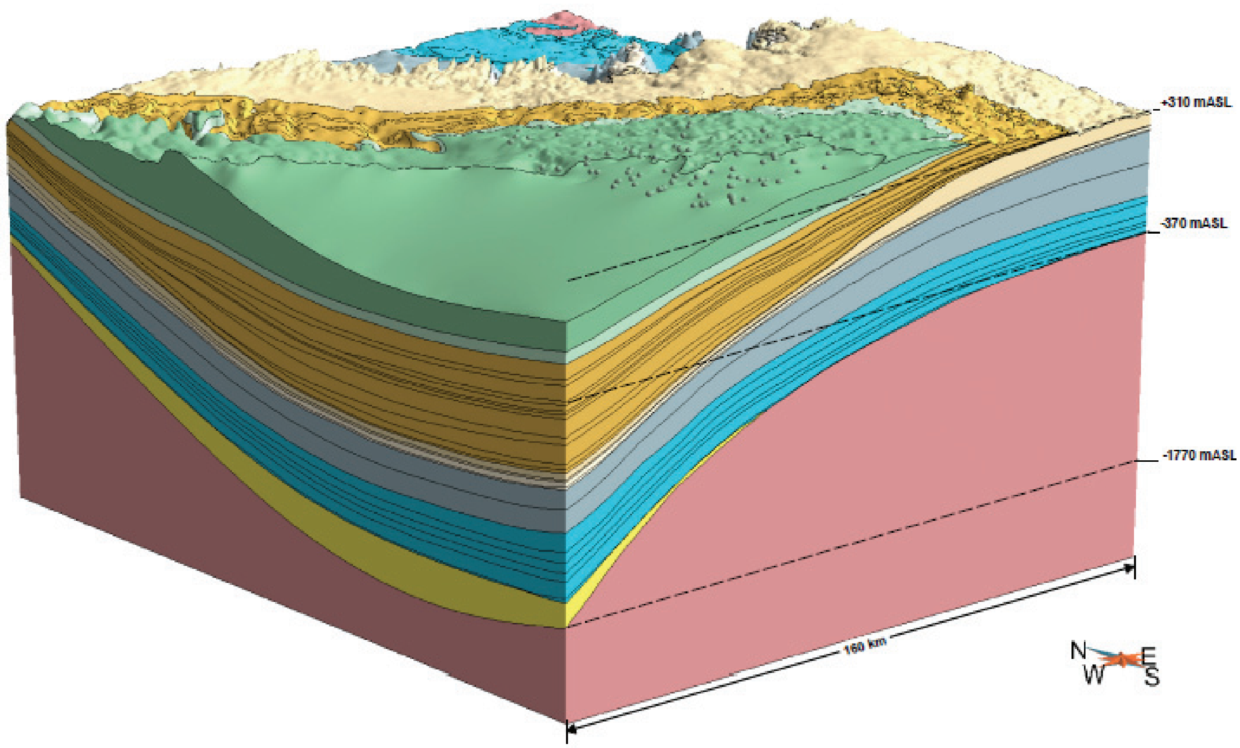


Figure 6.31: Detroit River Group

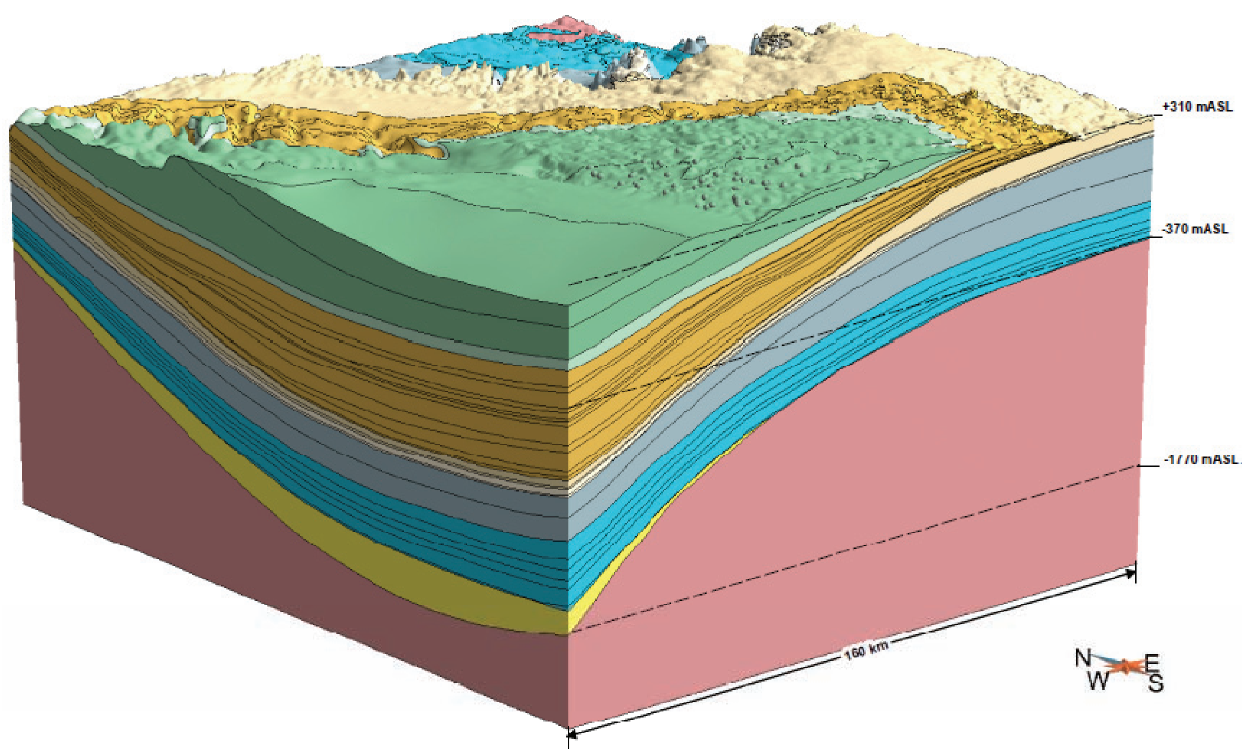


Figure 6.32: Dundee Formation

6.6 Summary

The Regional Geological Framework demonstrates that formation thicknesses are generally predictable over kilometre scale distances and that the primary geological units relevant to demonstrating DGR suitability and safety are continuous throughout the RSA. These key units include the Middle Ordovician Trenton and Black River Groups, and the Upper Ordovician Blue Mountain, Georgian Bay and Queenston Formations, which together represent an approximate 400 m thick sequence of continuous limestone and shale.

7. MICHIGAN BASIN DIAGENESIS

The following sections present an overview of both the thermal history of the Michigan Basin as well as the main diagenetic processes that have influenced the Paleozoic rocks within the basin. Diagenetic processes include dolomitization, clay alteration, oil and gas generation and migration, MVT (Mississippi Valley Type) mineralization, salt dissolution and precipitation of late stage cements. An overview of the thermal history is required to better predict the importance of tectonically (heat source) induced diagenetic events such as hydrothermal dolomitization. It is generally accepted that the thermal history of the Michigan Basin, recorded in fluid inclusions and organic maturation, cannot be readily explained by burial history alone and therefore requires the influence of additional heat sources. These same heat sources provide the mechanism for diagenetic fluid flow.

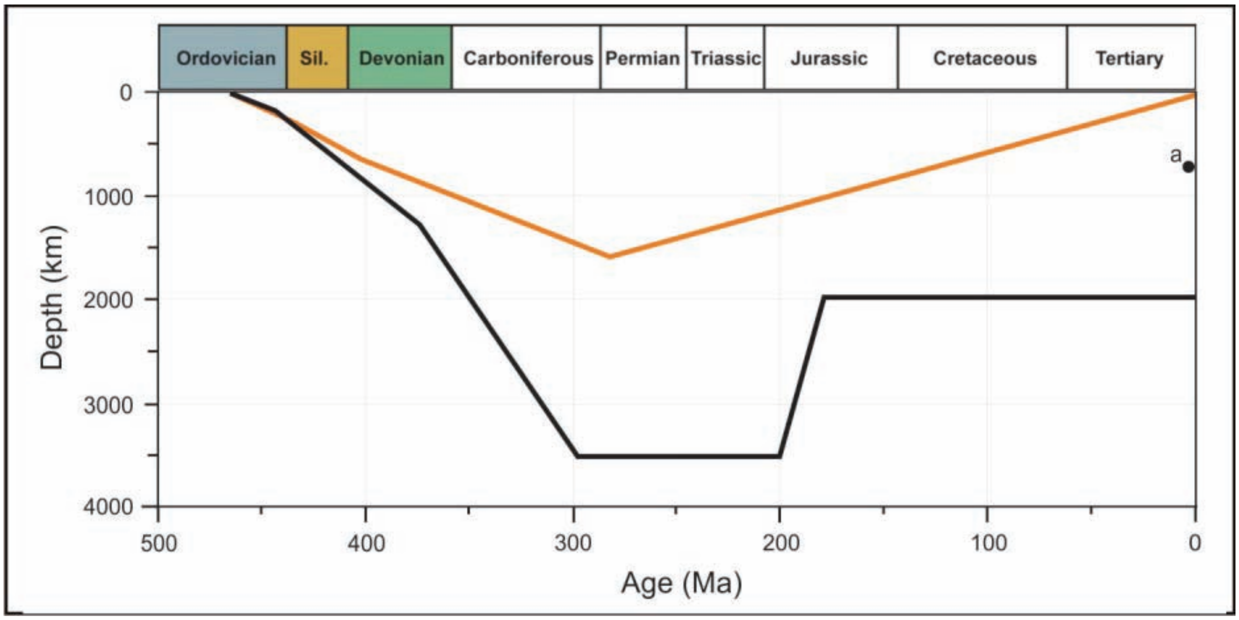
7.1 Thermal History

The Michigan Basin, much like the Appalachian Basin, had a multi-stage subsidence history recording orogenic activity during the Taconic, Acadian and Alleghenian events (Cercone 1984, Reszka 1991). At the onset of the Middle to Upper Ordovician Taconic Orogeny, the Michigan Basin tilted to the east concomitant with deposition of the Ordovician Trenton-Black River group and equivalents (Coakley et al. 1994, Coakley et al. 1995, Engelder 2011). The Paleozoic sedimentary succession in the Michigan Basin reached its maximum thickness during the early Permian Alleghenian Orogeny about 280 Ma.

Figure 7.1 shows maximum burial-erosion curves for rocks of Ordovician age from two different locations within the Michigan Basin. The black curve is based on a regional analysis of apatite fission track dating around the central portion of the Michigan Basin (Wang et al. 1994). The black curve is also constrained by the observation of Mid Jurassic sedimentary rocks overlying an unconformity at the top of the Paleozoic succession in the centre of the basin (Dickinson et al 2010). The black curve indicates a Permo-Carboniferous timing for peak burial during which the Ordovician rocks were covered by approximately a maximum of 3500 m of rock. Subsequent erosion removed approximately 1500 m leaving these rocks buried beneath 2000 m of sediment (Figure 7.1).

The orange curve in Figure 7.1 is from Coniglio and Williams-Jones (1992) who based the interpretation primarily on data from Cercone (1984) and extrapolation of a similar erosion history across a broad location in the east-northeastern region of the basin between Manitoulin Island and Sarnia, Ontario. The orange curve indicates that during the same Permo-Carboniferous peak burial event approximately 1500 m of rock overlaid the present Ordovician bedrock surface that is now exposed at the surface on Manitoulin Island (Coniglio and Williams-Jones 1992). The top of the Ordovician succession exposed at Manitoulin Island is encountered at 450 mBGS at the Bruce nuclear site (INTERA 2011). Given the Bruce nuclear site is located on the periophary of the Michigan Basin it is therefore reasonable to estimate that roughly 1000 m of sedimentary cover has been removed by erosion at the Bruce nuclear site.

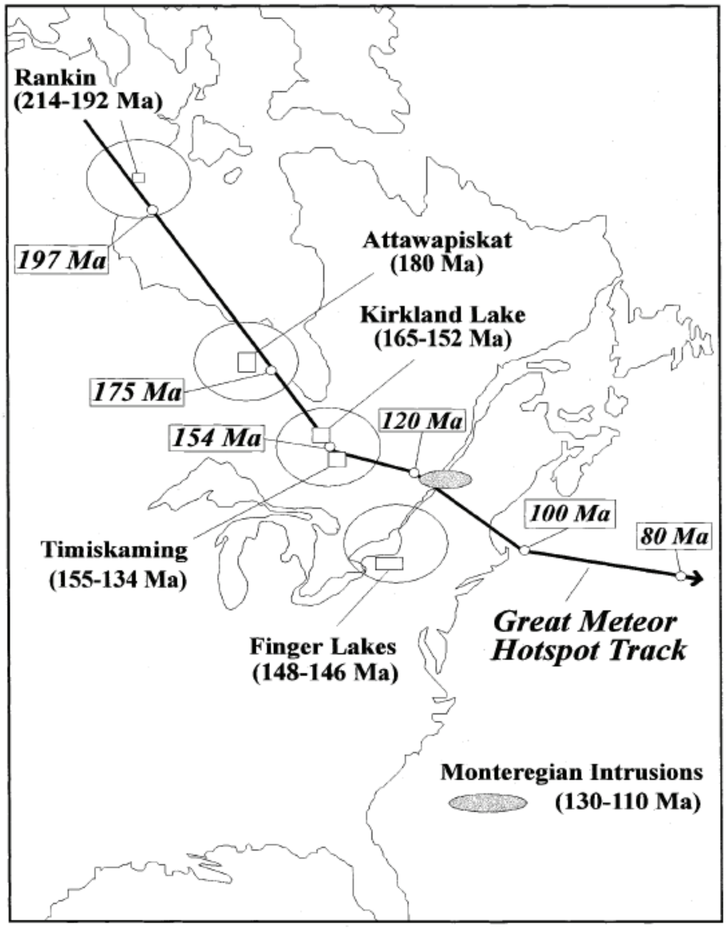
The two burial curves in Figure 7.1 are considered to be suitable for constraining peak burial conditions for rocks within the RSA, including the Bruce nuclear site. They vary, however, in their interpretation of the timing and rate of erosion. While the orange curve depicts a constant erosion rate since peak burial until the present day, the black curve indicates a non-constant erosion rate where a 1500 m thickness of sediments was removed prior to the Mid Jurassic. This timing constraint is justified by the observation of a regional unconformity that separates Mid 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), 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 as a similar amount of rock was removed from elsewhere in the basin. A late Paleozoic to early Mesozoic timing for the majority of the erosion at the Bruce nuclear site coincides with the waning of the Alleghenian stage of the Appalachian Orogeny and the onset of break-up and opening of the Atlantic Ocean.



Notes: Orange curve is based on Coniglio and Williams-Jones (1992) after Cercone (1984). Black curve is based on Wang et al. (1994). (a) Indicates the present day burial depth of approximately 675 m for the middle of the Ordovician sedimentary succession at the Bruce nuclear site.

Figure 7.1: Hypothetical Burial History Curves for Locations within the Michigan Basin

The burial curves in Figure 7.1 are consistent with results from Legall et al. (1981) which characterize two thermal alteration facies in the Paleozoic strata of southern Ontario using primarily a conodont alteration index (CAI). The first, from the top of the Paleozoic to the mid-Ordovician Trenton Group limestones, represents an organically immature to marginally mature facies that attained a maximum temperature of approximately 60°C. The second facies extends from the mid-Ordovician downwards to the base of the Paleozoic sequence. This group would comprise predominantly the Black River Group in the RSA where the Cambrian is very thin or nonexistent. These rocks attained maximum burial temperatures of 60-90°C (Legall et al. 1981). Samples taken approximately 80 km east of the Bruce nuclear site indicate a CAI of 1.5, representing Ordovician burial temperatures of approximately 75-85°C (Legall et al. 1981). Legall et al. (1981) also designate a third maturation facies in eastern Ontario and southern Quebec. Paleozoic sediments in this region attained much higher maximum burial temperatures of 90-120°C as a result of proximity to the path of the Great Meteor Hotspot (Figure 7.2) (Heaman and Kjarsgaard 2000). 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 gradient 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.



Note: From Heaman and Kjarsgaard (2000).

Figure 7.2: Great Meteor Hotspot Track Across North America

In comparison, the present day geothermal gradient of the Michigan Basin was estimated at 19.2°C/km based on a compilation of bottomhole temperature tests (e.g., Vugrinovich 1988). These values allow us to roughly calculate the in situ temperature during peak of burial for the top of the Trenton Group limestones, at the top of the Collingwood Member of the Cobourg Formation (~700 mBGS) assuming no other factors are involved. Given a present day thickness of just less than 900 m of Paleozoic sediments at the Bruce nuclear site, an additional 1000 m would place the Trenton top in situ temperature at approximately 67.5°C using a 25°C/km estimate, and 64.1°C using a 23°C/km estimate, respectively for the geothermal gradient.

Powell (1984) suggests that the alteration facies designation devised by Legall et al. (1981) would indicate a very limited potential for in situ petroleum generation in rocks as deep as the Middle Ordovician Trenton Group in southern Ontario in general. This is consistent with the observation that the same rocks beneath the Bruce nuclear site barely reached the oil window in terms of thermal maturation (e.g., INTERA 2011, their Section 3.7.4.2 and Section 8.5.1 herein).

In contrast to the above discussion, Cercone and Pollack (1991) suggested that organic maturity values throughout the Michigan Basin are too high for such minimal burial rates. They suggest two alternatives to this problem, either we have underestimated the amount of burial that has occurred, or we have underestimated the geothermal gradient of the basin. They further suggest a potential Ordovician geothermal gradient range of 40°C to 60°C/km. Coniglio and Williams-Jones (1992) argue for an alternative solution in the form of a secondary hydrothermal dolomite system. Their analysis of Ordovician limestone samples from Manitoulin Island finds that these rocks host fluid inclusions with homogenization temperatures of up to 210°C in secondary dolomite. The dolomitizing fluid was sourced from dewatering during burial compaction of argillaceous sediments located deeper in the centre of the Michigan Basin.

Coniglio and Williams-Jones (1992) argue that hydrothermal dolomitization may have occurred at the basin scale during the peak of burial conditions in the Michigan Basin. In some cases, this mechanism was associated with the development of large hydrocarbon deposits, generally where a structural control also dominated, for example the fault-related Albion-Scipio hydrocarbon field in southern Michigan (e.g., Hurley and Budros 1990, Davies and Smith 2006). A smaller scale example was observed by Legall et al. (1981) who described a deeper conodont alteration zone that reached a maximum temperature of approximately 90°C. However, the difference in depth for the base of the Black River Group in comparison to the top of the Trenton Group is only a maximum of 300 m disregarding compaction.

Based on the temperature estimates above for the Trenton top at the Bruce nuclear site, which appear to fit in general, the maximum temperature for the Black River Group should therefore reach approximately 71° to 75°C. This model maximum temperature may be lower than that determined by Legall et al. (1981) because the areas they sampled were subjected to a pulse of hydrothermal dolomitization, albeit at a lower temperature that that observed by Coniglio and Williams-Jones (1992) for Manitoulin Island. These studies indicate that when hydrothermal fluids are included as a component of the system wide ranging peak temperature conditions are likely to prevail at the basin scale during burial. In turn this suggests that the extent or volume of hydrothermal dolomitization can also vary along with its morphology. Instances of dolomitization, formed both in situ due to compaction under ambient conditions of burial and/or hydrothermal due to percolation of hot fluids, appear to have developed at all scales in the Michigan Basin. A wrench-faulted, hydrothermal dolomite (HTD) hosted hydrocarbon reservoir (e.g., Davies and Smith 2006) can therefore be offered as an end member type of distributed diagenetic dolomitization that in other cases may exhibit a stronger stratigraphic, rather than structural, control.

7.2 Dolomitization Models

Dolomitization is the most significant diagenetic influence on the Paleozoic strata post lithification and is the result of the conversion of calcite or aragonite to dolomite by the replacement of a calcium ion with a magnesium ion according to the general equation:

$$2CaCO_3 + Mg^{2+} = CaMg(CO_3)_2 + Ca^{2+}$$

Dolomitization is considered important as the process typically increases the rock mass permeability (Morrow 1990).

Dolomite is found in all Paleozoic units represented in southern Ontario. In some cases, units are pervasively dolomitized (Middle Silurian) while in other units dolomitization is associated with fractures (Ordovician hydrothermal dolomite) or other localized dolomitization events. The approximate distribution of dolostone and limestone across the Algonquin Arch in southern Ontario is represented in Figure 2.7. This figure shows the primary mineralogy and does not reflect the significant local variability in degree of dolomitization.

The following provides an overview of the key dolomitization models responsible for alteration of the rocks in southern Ontario. The key point in reviewing the models is that the conditions that led to dolomitization i.e., basinal groundwater flow, fracture related flow, or compaction driven flow, no longer exist within the Michigan Basin, and have not occurred over recent geological time, the last 250 Ma. The primary dolomitization mechanism for rocks in southern Ontario are a) sabkha type, b) mixed-water aquifer, c) seepage reflux, d) burial compaction, and e) hydrothermal (Morrow 1990).

Sabkha type dolomitization occurs shortly after calcite precipitation in response to the shallow seaward migration of groundwater derived from evaporated water in adjacent ephemeral lakes. Dolomitization occurs in the near surface only while a sabkha depositional setting persists.

Mixed-water aquifer dolomitization occurs as seawater is continually circulated through the sediments in response to groundwater flow derived from unconfined aquifers near shore. In this model, dolomitization occurs shortly after calcite precipitation in the zone of groundwater and phreatic seawater mixing. Budai and Wilson (1991) suggest a similar model to explain regional dolomitization of Trenton Group in southwest Michigan.

Seepage reflux dolomitization has been proposed to explain pervasive dolomitization of Middle Silurian carbonates in the Michigan Basin (Cercone 1988). In this model, seawater is driven from the upper platform (Algonquin Arch) down into the lower basin through the underlying carbonate units, resulting in dolomitization. The driving mechanism was interpreted as hydraulic head differences between the upper platform seas and isolated lower seas within basin during the Middle to Upper Silurian. This gravity-driven evaporative drawdown model explains a number of key features of dolomitization observed in the Michigan Basin in southwestern Ontario, particular for the Silurian-aged sediments. These features include: i) incomplete dolomitization of some Silurian-aged pinnacle reefs; ii) partial dolomitization of some lower Silurian strata, and iii) the decreasing extent of dolomitization observed towards the basin centre which remains primarily as limestone (Cercone 1988). This model is compelling because of the vast quantities of seawater required to dolomitize such a large volume of rock. An interesting note is that, with the exception of flow through fractures, the underlying Ordovician carbonates were seemly not impacted by this large-scale basinal groundwater flow system and pervasive dolomitization. The Ordovician shales (post compaction dewatering) appear to have acted as an aquitard during the Silurian dolomitization, isolating the upper flow system from the underlying Trenton/Black River Groups. Localized dolomitization in the Upper Trenton is interpreted to have resulted from fluids derived from compaction of the overlying shale (Coniglio et al. 1994) and not from refluxing Silurian seawater.

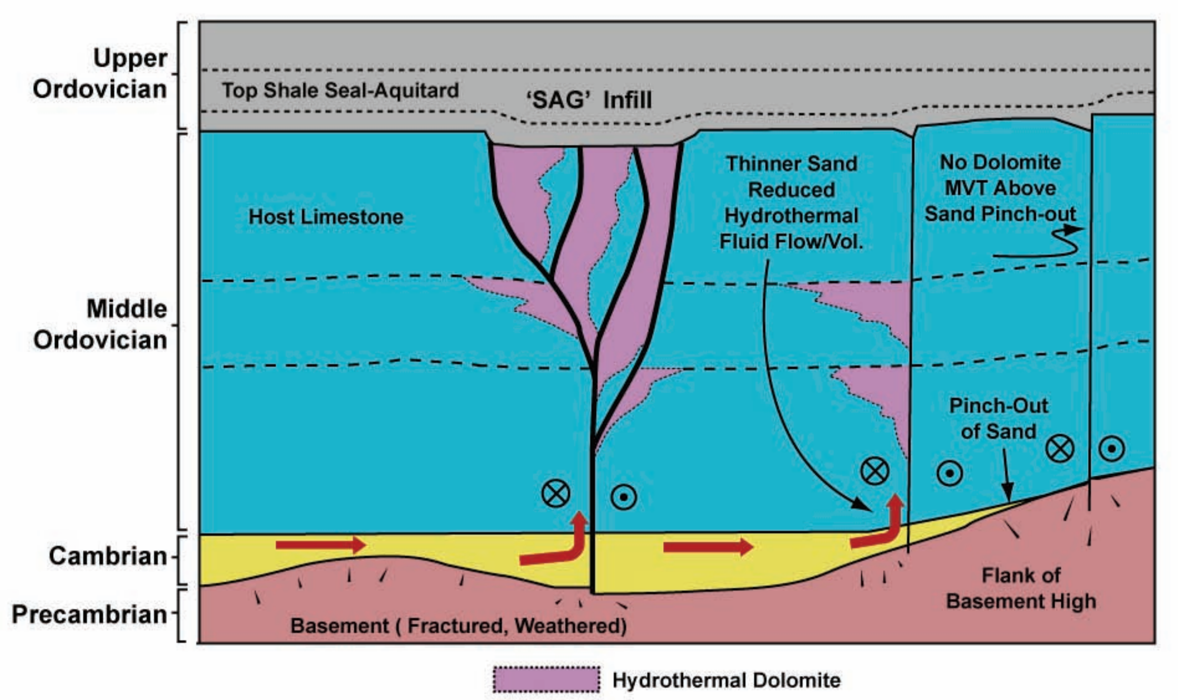
A seawater source for the Silurian dolomitizing fluid is supported by both the $\delta^{13}C$ values (+1.1 to 5.0 ‰ PDB) and the $^{87}Sr/^{86}Sr$ ratios, which range from 0.70845 to 0.70910 (Coniglio et al. 2003), although two dolomite samples had $^{87}Sr/^{86}Sr$ ratios that were more radiogenic. The large range in $\delta^{18}O$ signatures (-5.2 to -9.7 PDB) observed both geographically and stratigraphically in the dolomites is thought to reflect varying degrees of recrystallization due to increasing temperatures during burial or the potential that some fluids were hydrothermal in nature, as suggest by Coniglio et al*.* (1994) for the Ordovician strata in Ontario.

Burial compaction involves the expulsion of magnesium rich pore water from large shale deposits, such as the Ordovician shale's in the Michigan Basin. As the pore water trapped in the shale is released through compaction, this water is circulated through adjacent limestone units, resulting in dolomitization. Burial compaction of the Ordovician shale units is attributed to dolomitization within the Trenton/Black River Groups in Ontario. Given the significant volumes of dolomitizing fluids required for pervasive dolomitization, burial compaction is limited in its application to explain localized dolomitization such as, a) the Trenton cap dolomite (Budai and Wilson 1991), b) adjacent to fractures, and c) within specific beds (Coniglio and Williams-Jones 1992). The Trenton cap dolomite is found at the top of the Trenton Group throughout parts of the Michigan Basin. The ferroan nature of this dolomite is interpreted to have resulted from mixing with fluids derived from the overlying shale units (Coniglio et al. 1994, Budai and Wilson 1991), an interpretation supported by $\delta^{18}O$ values of the dolomite crystals. Budai and Wilson (1991) suggest that cap dolomite occurs because the overlying shales (Utica Shale) also provided an impermeable seal that forced upward moving dolomitizing fluids laterally into the upper Trenton limestone. Importantly, the Trenton cap dolomite is not recognized in the subsurface at the Bruce nuclear site.

The final dolomitization models, and perhaps the most widely discussed due to their relevance to the petroleum industry, are hydrothermal and fracture related dolomitization. Migration and circulation of dense hypersaline brines at depth caused by tectonism is the general mechanism for hydrothermal dolomitization (HTD). In Ontario, the pathway for migration and circulation of the hypersaline brines were permeable units and vertical faults and fractures (Coniglio et al*.* 1994). As a result, hydrothermal dolomite in the Ordovician tends to form long linear reservoirs adjacent to these vertical fractures (Trevail et al*.* 2004). Sanford et al*.* (1985) proposed that reactivation of pre-existing Precambrian fractures related to tectonic activity resulted in many of the Cambrian through Devonian hydrocarbon reservoirs in southwestern Ontario.

Coniglio et al*.* (1994) proposed a mechanism for hydrothermal dolomitization in Ontario where the magnesium bearing fluids are derived from both shale compaction and refluxing Silurian hypersaline fluids (Figure 7.2). The compaction derived magnesium is interpreted to have migrated up-dip from the basin centre. The mechanism for fluid flow in this model is a heat source in the Precambrian basement driving thermal convection cells. The presence of a hydrothermal heat source in the Precambrian is supported by fluid inclusion homogenization temperatures up to 200°C, which cannot be readily explained by burial history alone (as discussed above). The mechanism of brine migration from the Silurian evaporites to the Middle Ordovician limestones as proposed by Coniglio et al*.* (1994) is contradicted by Davies and Smith (2006) who suggest an Upper Ordovician age for HTD reservoir formation. The interpretation presented by Davies and Smith (2006) is based on observations and seismic characteristics of the typical "sag" features associated with HTD reservoirs (see Section 8.5).

Winter et al*.* (1995) identified four separate dolomitizing fluids evolved from seawater that altered the composition of Michigan Basin, Middle Ordovician sandstones during the Paleozoic. One of the fluids proposed was a hot, deep basinal brine which migrated upwards through K-feldspar-rich rocks near the Cambrian-Precambrian boundary. Winter et al*.* (1995) noted that upward cross-formational migration of heated brines was likely confined to local faults, and may have occurred as a result of orogenic events.



Notes: Hydrothermal fluid flow is focused along the basal Cambrian sandstone through strike-slip faults. Fluid flow is decreased as the Cambrian thins and HDT and MVT is absent above the Cambrian pinchout. A similar schematic model applies to Mississippi Valley Type (MVT) deposits (modified from Davies and Smith 2006).

Figure 7.3: Schematic of Ordovician-hosted Fracture Related Hydrothermal Dolomite

Recent work by Davies and Smith (2006) describes the mechanism for hydrothermal fluid flow and dolomitization in the Middle Ordovician as horizontal flow through the basal Cambrian and vertical flow along strike slip faults (Figure 7.2). In this model, the permeable basal sandstone focuses fluids from the fractured basement and/or basinal sources to vertical fractures or fracture damage zones (commonly related to basement highs). The overlying Ordovician shale acts as an aquitard, inhibiting fluid flow. The “sag” feature commonly found above HTD facies (Figure 7.2) is generally interpreted to result from transtensional subsidence along a wrench fault system (Davies and Smith 2006). This structurally controlled model appears consistent with examples of HTD reservoirs from southern Ontario (Davies and Smith 2006, Carter et al. 1996).

7.3 Other Diagenetic Phases

The key post dolomitization diagenetic phases are all volumetrically minor and include late stage calcite cements, MVT mineralization and late stage anhydrite and gypsum (Budai and Wilson 1991, Coniglio et al. 1994). These phases do not include those related to modern surface exposure in the near surface rocks of the Michigan Basin, which are not discussed here. Other diagenetic events include salt collapse features, which impacted Silurian and Devonian stratigraphy and clay alteration at the Precambrian-Paleozoic boundary.

The late stage anhydrite and to a lesser extent gypsum, occurs as fracture filling, pore/vug filling and between dolomite crystals (intercrystalline). Coniglio et al. (1994) notes that the relative order of carbonate and anhydrite is ambiguous; this makes timing relationships for anhydrite difficult. The exact timing of late stage diagenetic events in general is not well defined in the literature. Fluid inclusion data, stable isotopes and other fabric relationships suggest an association with deep burial brines. The migration of these brines is believed to have occurred in response to tectonic events (Alleghenian) beginning in the late Paleozoic or in response to maximum burial depths and compaction in the late Paleozoic, early Mesozoic. Current evidence does not suggest a significant freshwater/meteoric source of these late stage diagenetic minerals.

7.3.1 MVT Mineralization

Mississippi Valley Type (MVT) mineral deposits, named for their classic occurrence in the central United States, are stratabound, carbonate-hosted sulphide deposits of zinc and lead, which occur primarily within sphalerite and galena minerals (Paradis et al. 2006). MVT deposits are diagenetic and are emplaced post lithification originating from saline basinal fluids at temperatures from 75° to 200°C (Paradis et al. 2006).

MVT lead-zinc mineralization occurs in the Middle Silurian dolomites in southern Ontario as a minor diagenetic constituent but is not considered a commercial source of lead and zinc. Although disseminated sulphides (primarily sphalerite, galena, pyrite and marcasite) occur in the dolomites as lenses, veins, linings in vugs and in stylolitic seams, vug infillings are most commonly observed. On the basis of geographic and mineralogical differences, Tworo (1985, after Farquhar et al. 1987) grouped the occurrence of sulphides into two groups; the Bruce District to the north of the Algonquin Arch on the eastern margin of the Michigan Basin, and those of the Niagara District southeast of the Algonquin Arch on the northwestern margin of the Appalachian Basin. Sulphide mineralization is most prevalent in the Niagara District, with only sparse occurrences to the west and north along the Niagara escarpment (Tworo 1985, after Farquhar et al. 1987).

Farquhar et al. (1987) measured lead isotope ratios in galena and whole rock samples from the Middle Silurian Lockport Formation (Eramosa, Goat Island and Gasport members). The majority of galena samples were from the Niagara District, with only one sample from the Bruce District. Comparison with lead isotope analyses for K-feldspars in granite, massive sulphide ores and sedimentary rocks within the Appalachian Basin suggests a common source for Pb within the sediments of the Appalachian Basin and those in galena of the Niagara District. These results are consistent with a conceptual model in which lead from Late Precambrian to Early Paleozoic sediments (~400 Ma) was extracted by brine fluids and mobilized northward from the centre of the basin and into New York state and Pennsylvania during the late Paleozoic – early Mesozoic tectonic thrusting in New York and Pennsylvania. The one sample examined from the Bruce District (Ebel Quarry galena) by Farquhar et al. (1987) had a $^{208}Pb/^{204}Pb$ ratio below the average line observed for the Niagara galena. Both the $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios for the Ebel Quarry galena are consistent with the interpretation that lead in the Michigan Basin galena was derived originally from crustal source beds, and therefore, is from a different source than lead in galena within the Niagara District.

7.3.2 Salt Dissolution

As discussed earlier in Sections 4.2.5 and 4.2.6, the Devonian strata in southern Ontario was deformed/collapsed as a result of selective salt dissolution of the underlying Salina Salts (B-Salt specifically). Hamilton and Coniglio (1990) remark that questions regarding the timing, source, and fluid dynamics of the dissolution remain outstanding and multiple episodes of cross-formation flow during the Paleozoic-Mesozoic with multiple fluid sources have been proposed. These fluid sources include those derived from normal marine waters, Cambrian brines moving upward along regional fractures, Ordovician or Silurian fluids migrating along regional fractures, or groundwater mixing with the Silurian and Devonian strata. Sanford et al. (1985) suggests that salt dissolution occurred primarily during the Late Silurian associated with the Caledonian Orogeny with a second major salt dissolution event in the Mississippian related to the Acadian Orogeny. The dissolution is thought to have occurred in response to tectonically driven fault reactivation and circulation along subsequent fractures.

7.3.3 Clay Mineral Alteration

Ziegler and Longstaffe (2000a) note that regional migration of brines from the Appalachian Basin along the unconformity between the Precambrian basement and the overlying Paleozoic sedimentary rocks may have occurred in response to the Taconic Orogeny. These authors determined the stable isotopic signatures of secondary chlorite and illite, and measured K-Ar dates for secondary K-feldspar and illite in an attempt to determine nature and origin of the fluids, and the timing of alteration.

For secondary chlorite occurring in both the Precambrian basement rocks and in the overlying Cambrian and Ordovician formations, the $\delta^{18}O$ signatures are consistent with precipitation from brines evolved from seawater, at temperatures greater than 150°C
Ziegler and Longstaffe (2000a, b). As the fluid cooled and possibly mixed with meteoric water, secondary potassium-rich feldspar precipitated. Radiometric dates for K-rich feldspar in the uppermost Precambrian rocks in southwestern Ontario range from 453 to 412 Ma, with an average of 444 Ma (Harper et al. 1995). Ziegler and Longstaffe (2000a) proposed a conceptual model in which the regional migration of the brines from which secondary chlorite and K-rich feldspar were precipitated was induced by Taconic orogenic events to the east, which began in the Late Ordovician. In this model, migration of waters of marine origin trapped within Paleozoic formations westward within the Appalachian Basin was focused along the unconformity between the Upper Precambrian crystalline basement and the overlying Paleozoic sedimentary rocks, and was facilitated by faults within the lower part of the sedimentary section.

The available K-Ar dates and the $\delta^{2}H$ and $\delta^{18}O$ signatures of secondary illite suggest that it formed during a second event in the early to mid-Carboniferous from local meteoric waters at temperatures of between 40 and 55°C. Beginning in the Late Devonian-Early Carboniferous (~350 Ma), the uplift of the Findlay-Algonquin Arch in response to the Acadian and Alleghanian orogenic activity along the eastern coast of North America resulted in the erosion of the Paleozoic formations across the top of the arch. Ziegler and Longstaffe (2000a) proposed a conceptual paleohydrogeological model for illite formation in which local meteoric waters infiltrated into Paleozoic sandstone formations and reacted with the K-feldspar alteration assemblage near the unconformity, precipitating secondary illite.

7.4 Timing of Main Diagenetic Events

The timing of the fracture dolomitization and hydrothermal activity is generally accepted as Paleozoic to Early Mesozoic (Coniglio et al. 1994). This diagenetic phase represents the last significant dolomitization event influencing the Ordovician, Silurian and Devonian carbonates of southern Ontario. Earlier dolomitization events are linked to the influence of Ordovician, Silurian or Devonian seawater.

Tectonic compression related to the Alleghanian Orogeny and/or sediment compaction during maximum burial depth in the Michigan Basin is thought to be the driving mechanism for both fracture related dolomitization and hydrocarbon migration within the Michigan Basin. Budai and Wilson (1991) note that there is a close association between hydrocarbon emplacement, fracture dolomites and the presence of Mississippi Valley Type (MVT) mineralization (i.e., barite, anhydrite, fluorite, celestite etc.) within the Ordovician and Silurian strata of the Michigan Basin. The genetic relationship between these diagenetic phases does suggest basinal brine migration likely related to tectonism (Farquhar et al*.* 1987, Budai and Wilson 1991, Coniglio et al*.* 1994) occurring during the Late Paleozoic and Early Mesozoic.

7.5 Summary

Dolomitization is the most significant diagenetic influence on the Paleozoic strata post lithification. All other diagenetic phases/mineralization are volumetrically minor and include late stage calcite cements, MVT mineralization and late stage anhydrite and gypsum. Although the timing and source of diagenetic fluids is not convincingly proven in the literature, the general scientific consensus suggests that most diagenetic events (excluding shallow bedrock diagenesis) occurred during the Paleozoic or early Mesozoic coinciding with large scale tectonic events at the margin of North American and/or to maximum burial depths and compaction. Current evidence does not suggest a significant freshwater/meteoric source for even the late stage diagenetic minerals found within the sedimentary rock record. The tectonic conditions that led to large-scale migration of diagenetic fluids within the Michigan Basin no longer exist and have not existed for millions of years.

8. PETROLEUM GEOLOGY

Since the discovery of crude oil in a shallow well at Oil Springs, Ontario in 1858, over 50,000 wells have been drilled in Ontario in the search for petroleum. Crude oil and natural gas in Ontario have been discovered in commercial quantities in a total of over 300 separate pools or reservoirs. Figure 8.1 illustrates the distribution of oil and gas pools within the RSA and southern Ontario. No documented commercially viable crude oil and natural gas resources have been identified within a 40 km radius of the Bruce nuclear site.

Hydrocarbons have been found in more than a dozen stratigraphic units throughout the Paleozoic sedimentary cover. Early hydrocarbon production was derived from shallow (120 m) Devonian carbonate reservoirs. After more discoveries in shallow Devonian reservoirs, commercial quantities of liquid hydrocarbons were found in deeper Silurian rocks. Current exploration interest is focussed on targets in the southwestern tip of Ontario in Middle Ordovician carbonates and Upper Cambrian sandstones at depths of 800 to 1,000 m (GOLDER 2005). Most exploration is concentrated within the geographic triangle between London, Sarnia and Chatham-Kent in the counties of Essex, Kent, Lambton, Norfolk and Elgin. Production from Ontario's crude oil and natural gas reservoirs accounts for approximately 1% of Ontario's annual domestic consumption of crude oil and 2% of Ontario's annual domestic consumption of natural gas.

8.1 Occurrence and Distribution

Commercial quantities of oil and gas have been discovered in a variety of exploration plays in the subsurface of southern Ontario (e.g., Sanford 1993c). Figure 8.1 illustrates the distribution of active and former producing petroleum pools in Southern Ontario (OGSR 2006). A comparison of commercial production statistics show that most traditional oil production and an increasing proportion of natural gas production within Ontario are derived from Ordovician and Cambrian pools (Carter et al. 1996).

Figure 8.2 illustrates oil and gas occurrences in the stratigraphy of southwestern Ontario for locations at the eastern margin of the Michigan Basin, on the Algonquin Arch and at the western margin of the Appalachian Basin. Hydrocarbon plays in Southern Ontario occur within the stratigraphic and geographical frameworks presented below (Sanford 1993c).

- Cambrian (CAM) sandstone and dolomite structural traps were generated by faulting and tilting (juxtaposition against low-permeability limestones of the Black River Group). Pools have been located mainly along the erosional boundary of the Cambrian along a line connecting Windsor and Hamilton of the Appalachian Basin. No commercially producing Cambrian hydrocarbon reservoirs have been reported on the Michigan Basin side. Although only a limited number of Cambrian wells (20) have been drilled within the RSA, the deep boreholes DGR-2, DGR-3, DGR-4 and the Texaco #6 well 2.9 km away from the Bruce nuclear site all intersected the Cambrian unit and encountered no gas or oil hydrocarbon. The Cambrian plays account for less than 3% natural gas and 6% oil produced cumulatively in Ontario (OGSR 2004).
- Middle Ordovician (ORD) limestones of the Black River and Trenton Groups host petroleum pools in porous and permeable zones in the vicinity of rejuvenated faults along which spatially limited dolomitization took place (permeability pinchout). This type of dolomitization is referred to as hydrothermal dolomite (HTD). Upper Ordovician shales of the Blue Mountain formation may act as caprocks. Reservoirs are primarily found south of the RSA within the Niagara Megablock in southwestern Ontario (London to Windsor area). Studies

have indicated low reservoir potential is expected in the RSA (Bruce Megablock) because of less dense faulting and subsequently more limited dolomitization. Nearly 25% of cumulative oil produced is from the HTD reservoirs of the Ordovician (OGSR 2004). Voluminous dolomite typical of HTD reservoirs was not encountered at the Bruce nuclear site during drilling and only localized traces of oil and gas were found within the Ordovician (INTERA 2011).

- Lower to Middle Silurian (CLI) Sandstones (Whirlpool, Grimsby, Thorold formations) and dolomites (Irondequoit Formation) create reservoirs in permeability pinchouts due to internal heterogeneity of the host formations. Occurrence of the sandstones and most of the production is concentrated in Haldimand, Norfolk and Niagara counties, as well as in the eastern portion of the Canadian sector of Lake Erie (Obermajer et al. 1998). Approximately 20% of Ontario's natural gas is produced from the onshore Lower to Middle Silurian sandstones and dolostones with an additional 50% produced from offshore sandstone pools beneath Lake Erie (Bailey Geological Services and Cochrane 1990, OGSR 2004).
- Upper Silurian Reef (SAL) dolostone of the Guelph Formation, carbonates of the Salina Formation (A-1, A-2) host hydrocarbons in stratigraphic traps related to patch and pinnacle reefs in the Guelph Formation. Reefal reservoirs in Ontario are typically positioned along the eastern edge of the Michigan Basin (from Lake St. Clair north along the shore of Lake Huron). Approximately 25% of cumulative gas produced in Ontario and 17% of the crude oil comes from the Niagaran Reef Reservoirs (OGSR 2004).
- Devonian (DEV) carbonates of the Dundee Formation and Detroit River Group host hydrocarbons in structural traps generated by dissolution of underlying salt of the Salina Group. Devonian reservoirs are typically restricted to southwestern Ontario associated with the Chatham Sag. The Devonian accounts for more than 50% of the cumulative crude oil produced in Southern Ontario (OGSR 2004).

Cumulative Ontario oil production totalled over 13 million m^3 by the end of 2004 (Table 8.1). As of 1996, commercial oil production occurred almost exclusively within Essex, Kent, Lambton and Elgin counties (Obermajer et al. 1998). A 2005 GOLDER study estimated that 85% of the natural gas volume (6,799 x 10^6 m^3) and 43% of the crude oil volume (2,733,296 m^3) contained in the Ordovician remains to be discovered.

Table 8.1: Cumulative Natural Gas and Oil Production in Southern Ontario

Reservoir Geologic Age	No. of Pools	Cumulative Gas Production (1,000 m^3)	% of Cumulative Gas Production	Cumulative Oil Production (m^3)	% of Cumulative Oil Production
Total Cambrian	19	821,201.4	2.3%	822,822.8	6.1%
Total Ordovician	69	1,073,878	3.1%	3,317,142.6	24.7%
Total Silurian Clinton-Cataract (Onshore)	22	6,610,125.2	18.8%	6,862	0.1%
Total Salina-Guelph	163	9,164,078.1	26.1%	2,243,728.8	16.7%
Total Devonian	31	845.7	0.0%	6,999,387.9	52.1%
Total Silurian Lake Erie Offshore	19	17,488,432.4	49.7%	55,822.8	0.4%
Total Ontario	323	35,158,560.8		13,445,766.9	

Note: compiled from OGSR (2006) subsurface dataset.

Hydrocarbons of all ages occur mainly in the southwest edge of southern Ontario and in the area north of Lake Erie. Of more than 21,000 documented wells drilled in Ontario, 27 petroleum exploration wells have been drilled within a 40 km radius of the proposed DGR. Only small occurrences have been found within the RSA and adjacent areas (Figure 8.3). A total of 12 documented active and abandoned petroleum pools were identified within the boundaries of the RSA and are identified in Table 8.2.

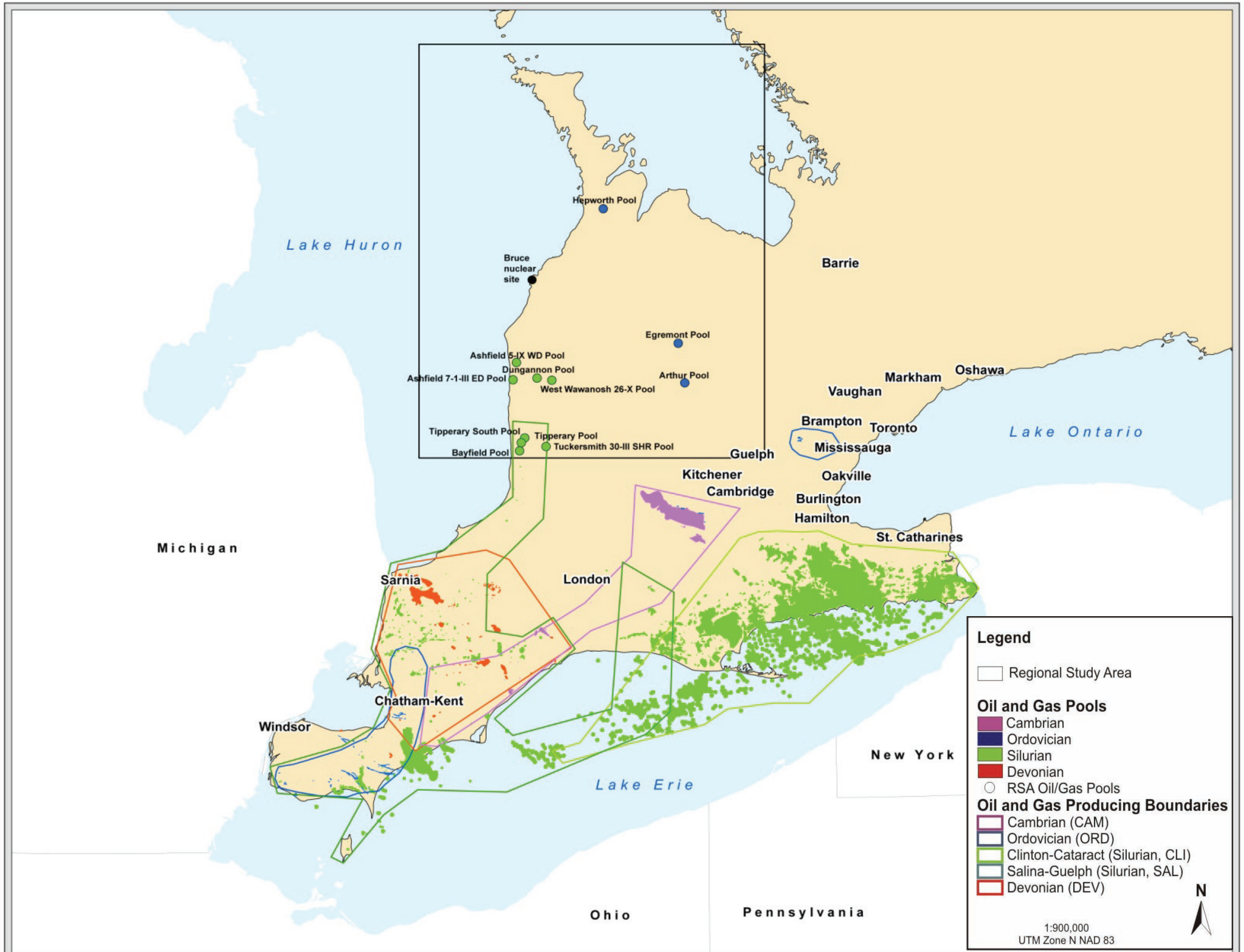
Petroleum production within the RSA has been primarily natural gas from Ordovician hydrothermal dolomite and Silurian reef or carbonate traps. The only actively producing Ordovician pool in the RSA is the Arthur Pool, which has produced 33,871,600 m^3 natural gas between 1968 and 2006 from the Black River Group. Small amounts of crude oil have been produced from the Silurian reef pools within the RSA. Cumulative natural gas production totals amount to approximately 200 million m^3 or less than 0.1% of the cumulative Southern Ontario natural gas production. Crude oil production amounts to a negligible 1,441.7 m^3, or approximately 0.01% of the cumulative production in Ontario.

Since 2000 exploration drilling within the boundaries of the RSA have focussed on the Silurian and Devonian targets south of Goderich. Only five petroleum exploration wells have been completed within the Salina Formation as of August 2008. Natural gas shows were found in three but all have failed to achieve commercially viable volumes. Two wells are officially plugged and abandoned with the others suspended. A single salt solution mining well was active at a depth of 470 m near Goderich as of May of 2003; the current status is unknown. A well intended for natural gas storage in the Salina was complete to a depth of 1,066 m in December 2007; its status is currently listed as suspended.

8.2 Shale Gas

The term “Shale Gas” refers to natural gas resources contained in fine grained, organic-rich, low permeability reservoirs in which thermogenic or biogenic gases (typically methane) are stored within the matrix or fracture porosity, or as adsorbed/dissolved gas on the organics and/or clays (Hamblin 2006). A recent Geological Survey of Canada (GSC) report (Hamblin 2006) documented all the prospective sources of natural gas from shale strata in Canada. The best potential for shale gas in Ontario occurs in the shales of the Upper Ordovician Collingwood and Blue Mountain Formations; the late Middle Devonian Marcellus Formation and the Upper Devonian Kettle Point Formation where they are overlain by glacial till (Hamblin 2006, 2008). Currently there is no production from any of these strata, however, the bituminous Collingwood Formation shales were quarried near Craigleith for lamp oil in the late 1800s.

However, because neither the Marcellus, nor the Kettle Point formations occur at the Bruce nuclear site, there was an absence of natural gas shows during the drilling of DGR-1 and DGR-2, the moderate degree of thermal maturity and depth of occurrence of 600-675 m of the Collingwood and Blue Mountain Formations, the probability of commercial shale gas resources beneath the Bruce nuclear site is considered low. Obermajer et al. (1996) concluded based on vitrinite reflectance that the thermal maturity of the Collingwood Member and Blue Mountain Formation in the Georgian Bay area was close to the onset of oil generation. As a result, hydrocarbons would be expected to occur only as oil within these units.



Notes: Base map is from Ontario Ministry of Natural Resources Pool data supplied by the Oil, Gas and Salt Resources Library and Ministry of Natural Resources. All pool boundaries are accurate as of October 2006. Pool boundaries are interpretive and approximate. Production boundaries are modified from Carter (1990).

Figure 8.1: Oil and Natural Gas Pools and Production Boundaries in Southern Ontario

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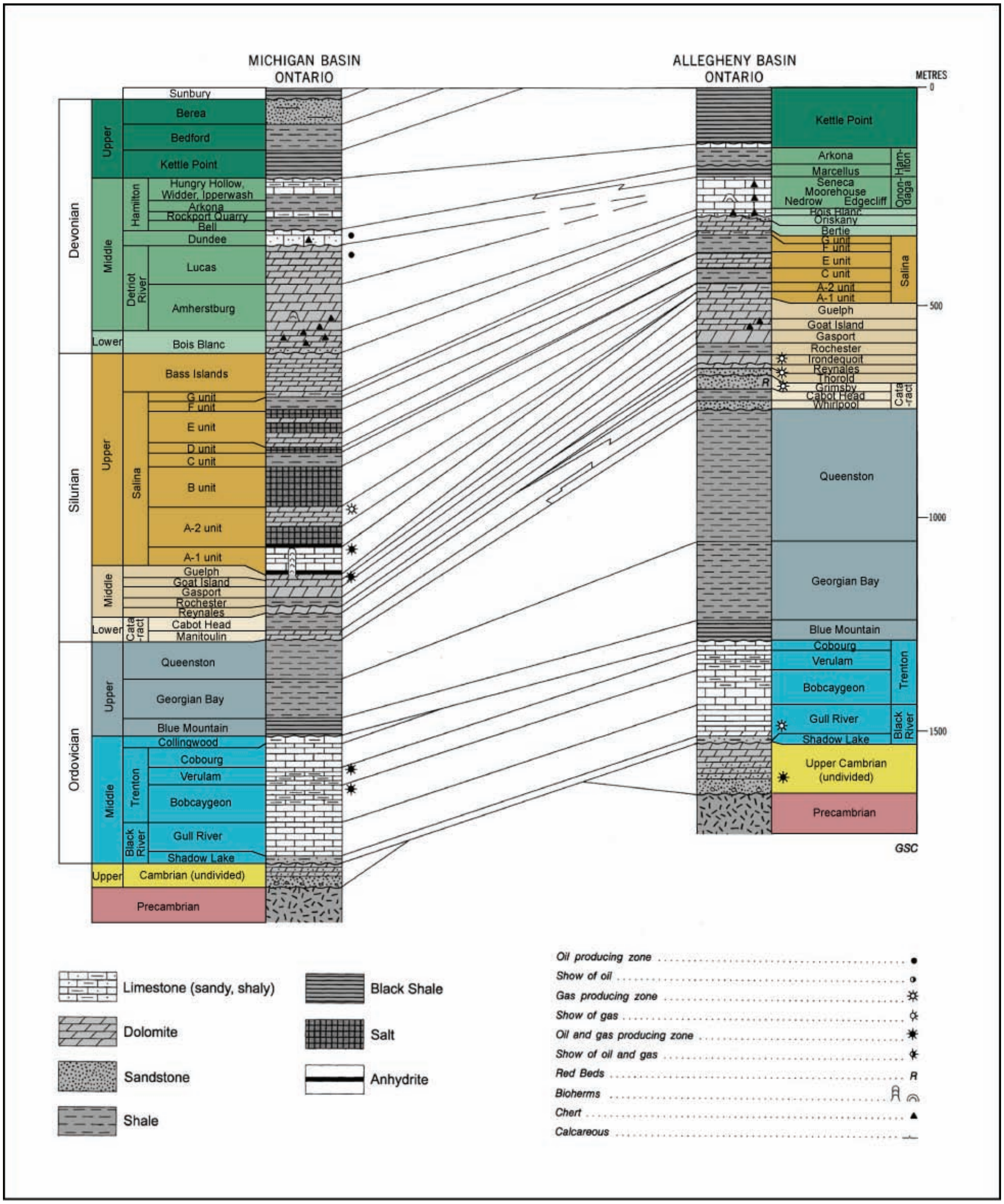

Notes: The equivalent units for both the Michigan and Appalachian basins are shown (from Mazurek 2004; as adapted from Sanford 1993b).

Figure 8.2: Stratigraphic Section Showing All Formations and Oil and Gas Producing Units

Table 8.2: Active and Abandoned Petroleum Pools Identified in the RSA

Name	Type	Mode	Geological Age	Area (m^2)	Township	Discovery Date	Depth (m)	Producing Formation	Cumulative Gas Production (1,000 m^3)	Cumulative Oil Production (m^3)
Hepworth Pool	Gas Pool	Abandoned	Ordovician	1,788,257.5	Amabel	1900	428	Trenton, Black River	708.2	0.0
Egremont Pool	Gas Pool	Abandoned	Ordovician	31,370.6	--	--	--	--	--	--
Egremont Pool	Gas Pool	Active (no production)	Ordovician	212,710.9	Egremont	1966	666	Black River	0.0	0.0
Arthur Pool	Gas Pool	Active	Ordovician	729,558.5	Arthur	1968	700	Shadow Lake, Black River	33,871.6	0.0
Tuckersmith 30-III SHR Pool	Gas Pool	Active	Silurian - Salina-Guelph	74,129.8	Tuckersmith	10/6/1998	490	Guelph	2,008.0	0.0
Tipperary Pool	Gas Pool	Active	Silurian - Salina-Guelph	352,104.4	Goderich	8/9/1969	571	Guelph	14,716.0	1,273.7
Tipperary South Pool	Gas Pool	Active	Silurian - Salina-Guelph	339,439.5	Goderich	11/17/1979	537	Guelph	12,963.8	168.0
Bayfield Pool	Gas Pool	Active	Silurian - Salina-Guelph	250,427.9	Stanley	10/8/1956	530	Guelph	67,770.2	0.0
Ashfield 5-IX WD Pool	Gas Pool	Active	Silurian - Salina-Guelph	320,867.6	Ashfield	2/28/1979	556	Guelph	5,459.4	0.0
Ashfield 7-1-III ED Pool	Gas Pool	Active	Silurian - Salina-Guelph	230,759.3	Ashfield	3/5/1979	582	Guelph	20,613.4	0.0
Dungannon Pool	Gas Pool	Active	Silurian - Salina-Guelph	621,129.7	West Wawanosh	8/29/1958	510	Guelph	38,907.4	0.0
West Wawanosh 26-X Pool	Gas Pool	Active	Silurian - Salina-Guelph	183,530.0	West Wawanosh	10/4/1968	509	Guelph	3,832.4	0.0
Note: Compiled from OGSR (2006) subsurface dataset.								***Cumulative Petroleum Production totals from the RSA:***	**200,850.4**	**1,441.7**

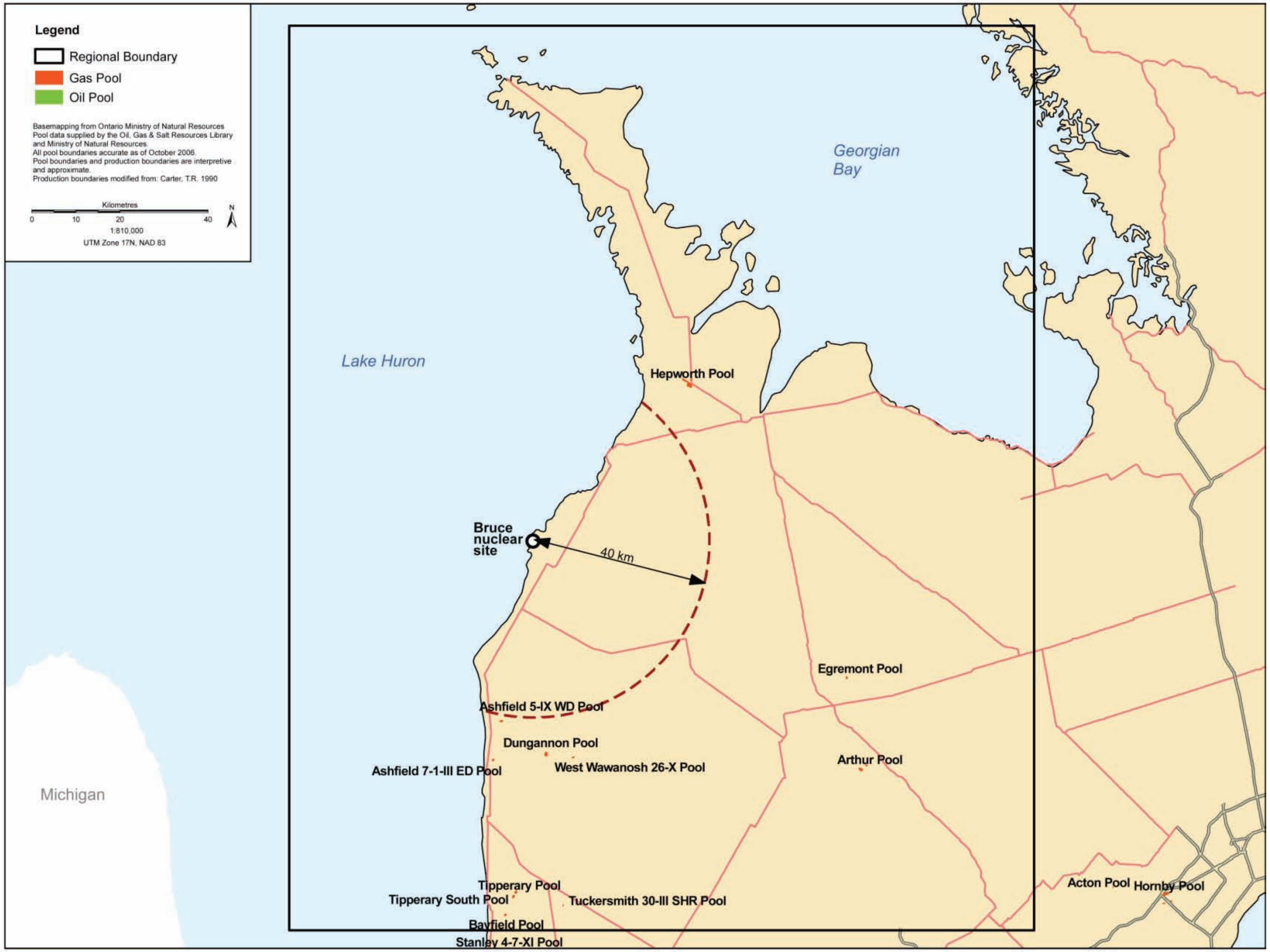

Figure 8.3: Distribution of Oil and Gas Pools within the Regional Study Area

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8.3 Tectonic Controls on Hydrocarbon Distribution

The tectonic regime and associated basement controls on fractures and structural trapping is a key component of understanding the distribution of hydrocarbons. Structural mapping of the Precambrian basement, surface features, and petroleum industry seismic data indicate that the Paleozoic fracture network (Figure 3.3) may be largely inherited from a system of pre-existing basement faults and fractures that propagated into overlying cover strata during cratonic uplift phases (Sanford et al. 1985, Carter et al. 1996). Additionally, it is thought that reactivation of a pre-existing Precambrian fracture framework played a major role in the migration of hydrocarbons throughout the Paleozoic Michigan and Appalachian basins (Carter et al. 1996).

Various researchers have documented faults in the subsurface of southern Ontario by classic subsurface structure contour and isopach mapping of data from oil and gas wells (Brigham 1971; Sanford et al. 1985; Bailey Geological Services and Cochrane 1984a, b, 1986; Carter et al. 1996). Seismic data can also aid in identification of fault structure and location and is widely used by the oil and gas industry in Ontario for this purpose. A synthesis by Carter et al. (1996) demonstrated that many oil and gas reservoirs are bounded by Paleozoic fault systems that originate in and displace the underlying Precambrian basement (e.g., the Dawn and Electric faults). They further identified from aeromagnetic data that many oil and gas pools are elongated parallel with the local direction of magnetic strike. Within southern Ontario the Ordovician and Cambrian hydrocarbon reservoirs show the most direct association with faults and fractures (Carter et al. 1996). Despite exploration attempts few commercially exploitable tectonically associated oil and gas reservoirs have been identified within Sandford et al.’s (1985) Bruce Megablock.

8.4 Controls on Fluid Movement

Groundwater movement in the sedimentary sequence of southern Ontario was active during deposition and burial diagenesis, which extended throughout the Paleozoic, possibly into the early Mesozoic. The main migration pathways are fractures and faults or zones affected by dolomitization. Research has suggested that the fracture framework played a major role in migration of hydrocarbons and the formation of many of the hydrocarbon reservoirs found in southwestern Ontario (Carter et al. 1996, Coniglio et al. 1994, Sanford et al. 1985).

The generation of oil and gas from thermally mature sediments of the Michigan Basin is likely related to maximum burial diagenesis occurring in the late Paleozoic to early Mesozoic (Mazurek 2004, Cercone and Pollack 1991, Coniglio and Williams-Jones 1992).

The precise time at which hydrocarbon migration occurred is not well constrained. Middleton et al. (1993) and Coniglio et al. (1994) concluded on the basis of textural evidence and on fluid-inclusion data that migration may have been coeval with mineral formation during the late stages of burial diagenesis (late Paleozoic). An overview of the geochemical relationship between the diagenetic phases of the Michigan Basin and their link to thermal history and/or tectonic activity is presented in Chapter 7 of this report.

The following sections provide a general overview of fluid and hydrocarbon movement in the Cambrian, Ordovician, Silurian and Devonian aged strata of Southern Ontario.

8.4.1 Cambrian

It has been suggested that diagenetic fluid/brines had migrated through the underlying Cambrian sandstones in the Michigan and Appalachian basins throughout the Paleozoic (Sanford et al. 1985, Middleton et al. 1990, Davies and Smith 2006). Cambrian aged units typically have relatively high porosity and permeability values compared with the surrounding limestone (Dollar et al. 1991).

Alteration minerals such as secondary K-feldspar, chlorite and illite have been identified in Cambrian sediments of southern Ontario and in the rocks above and below the Precambrian-Paleozoic unconformity at the base of many Paleozoic sedimentary basins (Ziegler and Longstaffe 2000b). K/Ar dating of K-feldspar by Ziegler and Longstaffe (2000b) found ages of 412-453 Ma which are consistent with the Taconic orogeny during the Upper Ordovician to Lower Silurian times. The authors also indicated that secondary chlorite alteration might have been caused by regional migration of basinal brines from the Appalachian Basin (and possibly the Michigan Basin) along the unconformity also during the Taconic Orogeny. In comparison, the secondary illite dated 365–321 Ma (Upper Devonian - Upper Carboniferous) largely postdates the Acadian Orogeny, and the illite-forming fluids have stable isotopic compositions typical of meteoric water. This suggests that basement arches beneath southern Ontario were reactivated by the Acadian Orogeny, which facilitated introduction of meteoric water.

Similar clay mineral alteration in underlying Precambrian rocks showed that fluid flow was focused along the unconformity during an Ordovician brine migration event, as well as during the localized Mississippian introduction of fresh water (Ziegler and Longstaffe 2000b).

A study of natural gases from Ordovician and Cambrian strata by Sherwood-Lollar et al. (1994) concluded that only the hydrocarbons to the southeast of the Algonquin Arch/Cambrian pinch-out boundary, display elevated thermal maturities, which would support migration from the Appalachian Basin. Hydrocarbon reservoirs to the northwest, which would coincide with migration from the Michigan Basin, do not display such elevated maturities. The authors concluded that the dominant migration pathways for oil and gas (and hydrothermal fluids) within the Chatham Sag were structurally and/or lithologically controlled by the nature of the Cambrian strata, or by the nature of the contact between the Cambrian and Precambrian basement geology in the southeastern portion of the Algonquin Arch, or a combination of both.

Cambrian hydrocarbon reservoirs are capped by low permeability limestones of the Middle Ordovician Black River and Trenton Groups (Bailey Geological Services and Cochrane 1984b). A number of studies concerning the Ordovician of the Michigan Basin have discussed the possible role of upwardly migrating brines along faults in dolomitizing Trenton and Black River group limestones (Middleton et al. 1990, Middleton 1991). It has been suggested that these brines were sourced and migrated through the underlying Cambrian sandstones (Middleton et al. 1990, Davies and Smith 2006). The presence of fault-related high porosity and permeability hydrothermal dolomite (HTD) traps throughout the Ordovician indicates that cross-formational fluid movement between the Cambrian and Ordovician likely occurred. This is supported by research from Obermajer et al. (1998) indicating that oil within Cambrian and Ordovician reservoirs is likely of the same source because oils from reservoirs within these formations cannot be distinguished.

8.4.2 Ordovician

Two major types of Ordovician dolomite diagenesis were identified by Coniglio et al. (1994). The first is a widespread ferroan 'cap' dolomite that occurs in the upper 1 to 3 m of the Trenton sequence. The cap dolomite formed by dewatering of the overlying Blue Mountain shale as a result of compaction during burial diagenesis (Coniglio et al. 1994).

The second major dolomite type is fracture-related hydrothermal dolomite (HTD), occurring in proximity to fractures or faults within the Trenton-Black River Group limestones and can host hydrocarbon reservoirs. Coniglio et al. (1994) observed that core which contains widespread fracture-related dolomite do not preserve a clearly identifiable cap dolomite, suggesting that the hydrothermal dolomite has over-printed the cap dolomite, and therefore, post-dates the ferroan cap dolomite.

Fracture-related hydrothermal dolomitization and hydrocarbon migration in the Michigan Basin likely occurred during the Late Paleozoic to Early Mesozoic (Prouty 1989, Hurley and Budros 1990, Budai and Wilson 1991). The observation of solid hydrocarbons coating saddle dolomite and late stage calcite cement supports hydrocarbon migration into the Ordovician reservoir rocks during these late-stage diagenetic phases (Coniglio et al. 1994). Coniglio and Williams-Jones (1992) attributed the dolomitizing fluid source of the Ordovician limestones to burial diagenesis, most likely triggered by compaction-derived brines that travelled up dip from the deeper parts of the Michigan Basin. Dollar (1988) and McNutt et al. (1987) noted the strontium isotopes of the brines and the fracture-filling precipitates to be slightly radiogenic, suggesting either a clastic or basement influence.

According to Sanford (1993b), the potential for fluid entrapment is low in the Ordovician units of the Bruce Megablock north of Sarnia due to the limited extent of fault reactivation and dolomitization.

There is some evidence of interaction, and a relationship between the Ordovician and Silurian diagenetic fluids, as discussed by Obermajer et al. (1999). These authors indicate that there is evidence of cross-formational flow between the Ordovician and Silurian units (e.g., Mosa reservoir) and possibly some relationship between the overlying Devonian oils and the Ordovician source rocks, but emphasize that no clear evidence exists that links those cross-formational fluids to the Silurian dolomitization events.

8.4.3 Silurian

Hydrocarbon emplacement in the Michigan Basin, via migration through the pervasively dolomitized units to the Silurian traps, was estimated to have occurred prior to evaporite dissolution during the late Paleozoic (Coniglio et al. 2003). The organic-rich laminated dolomites of the younger Salina A-1 Carbonate and underlying Eramosa Formation have been indicated as potential sources of oil in the Guelph Formation by Obermajer et al. (1998, 2000) on the basis of biomarker studies. The younger Salina A-1 carbonate is presumed to be the most likely source of southern Ontario Silurian oils (Obermajer et al. 2000).

8.4.4 Devonian

Devonian rocks in southwestern Ontario are either immature or marginally mature according to Powell et al. (1984), in a study of southern Ontario oils. As a result, it is suggested that potential source formations for Devonian oils occur down-dip in the Michigan Basin from a more mature regime. Powell et al. (1984) suggested that Devonian oils likely migrated from the Kettle Point, Dundee and Marcellus formations located down-dip within the Michigan Basin to the west during the Acadian orogenic event. A migration pathway to stratigraphically lower reservoirs from these formations was not postulated. Research published in 1998 by Obermajer et al. on genetic sources for Devonian oil pools indicated that source rocks were deposited deep in either the Michigan or Appalachian basins depending on their proximity to the dividing axis of the Algonquin Arch, however the pathways for transport were unconstrained.

Two major phases of diagenetic fluid migration resulted in extensive dissolution of the Silurian Salina salt beds and is interpreted to have caused the formation of collapse features and an extensive fracture network in the Middle Devonian units (Bailey Geological Services and Cochrane 1985, Sanford et al. 1985, Figure 4.10). Diagenetic events resulted from the rejuvenation of faults and fractures during the Caledonian (Early Devonian) and Acadian orogenies (Late Devonian) allowing for the periodic migration of diagenetic fluids and later hydrocarbons along these structures (Middleton 1991).

8.5 Hydrocarbon Sources

8.5.1 Oil Source and Formation

Geochemical characterization (Powell et al. 1984, Obermajer et al. 1998, 1999a) of oil shales and hydrocarbons within the sedimentary formations in southwestern Ontario has identified three geochemically distinct oil families. Differentiation is based on gross composition, n-alkane distributions, pristane to phytane ratios, carbon isotope composition of the saturate and aromatic fractions, distribution of gasoline-range hydrocarbons and ring distributions in the aromatic fractions. Each oil family had a distinctive organic geochemical composition, enabling clear separation of the different types:

- Cambro-Ordovician oils, which are typical of oils derived from marine organic matter;
- Silurian oils, which show the greatest diversity in geochemical characteristics, and are typical of oils occurring in hypersaline carbonate-evaporite (Salina) type environments and open marine (platform) settings; and
- Devonian oils, which are typical of oils derived from marine organic matter.

The Ordovician Collingwood Member of the Lindsay (Cobourg) Formation, Middle Silurian Eramosa Formation and the Devonian Kettle Point Formation were considered to be potential hydrocarbon source rocks (Powell et al. 1984).

Obermajer et al. (1998) identified that the geochemical character of the Cambro-Ordovician family is typical for oils derived from Ordovician-aged marine clastic source rocks deposited in a dysoxic (chemofacies with <1.5 wt% total organic carbon) paleo-environment. The earlier geochemical study by Powell et al. (1984) had identified the Collingwood member of the Lindsay (Cobourg) Formation as the only potential Ordovician source rock for Cambro-Ordovician oils. However the possibility of a separate source, either Ordovician or Cambrian, for the thermally mature Cambrian oils was indicated by Obermajer et al. (1998). Furthermore, it was indicated that the source rock intervals may occur within the Black River-Trenton (Middle Ordovician) sequence based on variability in gasoline and biomarker parameters (Obermajer et al. 1998).

The Silurian oils are chemically the most distinctive having characteristics typical of oils occurring in carbonate-evaporite environments such as low pristane-to-phytane ratios, (<1), high contents of acyclic isoprenoids, uneven distributions of n-alkanes, and distinctive isotopic and aromatic compositions (Powel et al. 1984). Slight geochemical variations define at least two subfamilies of Silurian oil (Obermajer et al. 1998) thought to indicate differences in source rock deposition conditions.

A possible source for Middle Silurian reef-hosted oils (patch and pinnacle reef reservoirs) is the Middle Silurian Eramosa Formation, an organic-rich dolomite unit occurring in inter-reef positions between the Lockport and/or Guelph Formation. McMurray (1985) postulated that the, Silurian Salina A-1 carbonate, which has a similar facies to the Eramosa Member and is located in close proximity to the Silurian reservoirs, is a better candidate as a source of the Silurian oils. Subsequent biomarker work by Obermajer et al. (2000) suggested that the organic-rich laminated dolomite of the younger Salina A-1 Carbonate is a more likely primary source of oil in the Guelph Formation than the Eramosa Formation.

Two anomalous oil reservoirs were identified by Powell et al. (1984) in the Chatham-Kent area on the basis of the distinct compositions of oils. The Silurian-aged (A-1 Carbonate) Fletcher reservoir was geochemically identified as having Cambro-Ordovician family oil, and the Silurian (A-1 Carbonate) Mosa reservoir was also found contain a mixture of Cambro-Ordovician and Silurian oils. The presence of Cambrian-Ordovician oils in Silurian reservoirs suggests that at least locally, some paleo cross-formational flow of hydrocarbons between reservoirs has occurred.

Devonian oils were found to have the most consistent geochemical character however small differences likely resulting from small variability in the geography, maturity and composition of source kerogen (Obermajer et al. 1998). Powell et al. (1984) were not able to identify a source formation for Devonian oils, because the Devonian rocks in southwestern Ontario are either immature or marginally mature. The authors suggested potential sources down-dip in the Michigan Basin including the Kettle Point, Dundee and Marcellus Formations.

A number of hypotheses have been proposed to account for the maturities of the Michigan Basin oils and gases based on geochemical and isotopic characteristics of the possible source rocks (see Section 7.1). These include:

- A high Paleozoic geothermal gradient that was significantly higher than the current average of 22°C/km (Cercone and Pollack 1991, Speece et al 1985, Cercone 1984);
- Insulating sediments such as coal, which were deposited during the Late Paleozoic. These sediments were subsequently eroded during the Mesozoic (Cercone and Pollack 1991); and
- A thermal anomaly, geothermal activity in the underlying basement resulted in an influx of high temperature fluids into the base of the sedimentary column, resulting in an increased thermal maturity of the surrounding sediments (Coniglio et al. 1994).

A combination of the geothermal gradient and erosion models are often used together to account for the observed maturities in the Ordovician through Devonian oil and gas (Section 7.1).

8.5.2 Gas Source and Formation

Examinations of the major hydrocarbon fractions of natural gases from reservoirs in Upper, Middle and Lower Silurian formations (Barker and Pollock 1984), as well as Middle Ordovician and Cambrian formations have characterized natural gases using isotopic and compositional indicators (Barker and Pollock 1984, Sherwood-Lollar et al. 1994).

Barker and Pollock (1984) found on average that methane comprises 90% of the hydrocarbon fraction with the dominant non-hydrocarbon gas being nitrogen. Gases from the Michigan and Appalachian Basins are very similar and can be distinguished only through a ratio obtained by dividing the ethane/propane ratio by the isobutane/normal butane ratio revealing some subtle differences on either side of the trend of the Algonquin Arch. Most of the chemical and isotopic maturation indicators of the natural gases showed a very mature to over-mature source maturation level. As commented on previously, the enclosing rocks are only immature to marginally mature suggesting that much of the natural gas has been generated outside the sedimentary sequence of southern Ontario.

Sherwood-Lollar et al. (1994) indicated that the Cambrian and Ordovician gases are thermogenic in origin, and do not show evidence of bacterial CH_4 contributions. This is consistent with the elevated temperatures in excess of 75°C expected at the postulated burial depths of the Cambrian and Ordovician sediments since bacterial methane production can take place only in conditions below this temperature. Additionally, Cambrian and Ordovician gas samples from wells where the sedimentary rocks are in direct contact with the Precambrian basement strata had substantially elevated helium values with respect to the average concentration in the samples from all other producing zones in the region. Sherwood-Lollar et al. (1994) suggested that a possible explanation for the elevated helium values is a mixing process between in situ produced gas in the Cambrian and Ordovician strata, and an end-member enriched in helium that was derived from deep within the Precambrian basement.

Barker and Pollack (1984) provided similar explanations to account for the discrepancy in thermal maturities of gases compared to the potential sedimentary source rocks. They suggested that the maturity of CH_4 in the natural gases was the result of the lateral migration of CH_4 into southwestern Ontario from more mature source rocks in the Michigan and Appalachian Basins, or due to an upward migration of CH_4 from an overly mature Precambrian basement source.

8.6 Hydrocarbon Plays and Trapping Mechanisms

According to the Geological Survey of Canada, a “play” refers to a group of petroleum deposits (pools) that share a common history of hydrocarbon generation, migration, reservoir development and trap configuration. A play is geographically and stratigraphically delimited, where a specific set of geological factors exist in order that petroleum may be provable in commercial quantities. Such geological factors include reservoir rock, trap, mature source rock and migration paths, and the trap must have been formed before termination of the migration of petroleum. Generally a trap requires three elements: a porous reservoir rock to accumulate the oil and gas, an overlying impermeable rock to prevent the oil and gas from escaping and a source for the oil and gas. A summary of hydrocarbon exploration plays in southern Ontario is provided in Table 8.3. Further details on the exploration history, source rocks, maturity, reservoir characteristics, traps and diagenesis of the plays discussed below are given by Hamblin (2008).

Figure 8.1 illustrates the approximate boundaries of the principal oil and gas plays in southern Ontario. Hydrocarbons of all ages occur mainly in the southwest edge of southern Ontario and in the Niagara Megablock north of Lake Erie. However historical exploration data indicates that only small occurrences have been found in the Bruce Megablock. As noted in Section 8.1.1, only small commercial pools in the Ordovician and Silurian (Guelph) have been identified within the geographical framework of the RSA.

Table 8.3: Hydrocarbon Exploration Plays in Southern Ontario

Play	Reservoir rocks	Trapping mechanism	Geographic distribution
Cambrian (CAM) See Figure 8.4	▶ Sandstones, dolomites	▶ Pools controlled by faulting and tilting (juxtaposition against low-permeability limestones of the Black River Group) or as permeability pinch outs	▶ Mainly along the erosional boundary of the Cambrian along a line connecting Windsor and Hamilton. No active economic reservoirs known on the Michigan Basin side.
Middle Ordovician Hydrothermal Dolomite (ORD) See Figure 8.7	▶ Hydrothermal dolostones within the Black River and Trenton Groups	▶ Pools in porous and permeable zones in the vicinity of rejuvenated faults along which spatially limited dolomitization took place (permeability pinch-out). Upper Ordovician shales act as caprocks	▶ Southwest end of southern Ontario (London - Windsor area). Limited potential (not exploited) in the whole Niagara Megablock, low potential in the Bruce Megablock (3 small gas pools known; low density of reservoirs expected because of less dense faulting and/or more limited dolomitization).
Lower to Middle Silurian Sandstones (CLI) See Figure 8.11	▶ Sandstones (Whirlpool, Grimsby, Thorold Formations) and dolomites (Irondequoit Formation)	▶ Permeability pinch-out due to internal heterogeneity of the host formations (spatially variable cementation)	▶ Occurrence of the sandstones and pools mainly along the north shore of Lake Erie (Appalachian Basin, Niagara Megablock)
Upper Silurian (Niagaran) Reefs (SAL) See Figure 8.11	▶ Reef limestones of the Guelph Formation, carbonates of the Salina Formation (A1, A2)	▶ Related to patch and pinnacle reefs in Guelph Formation	▶ Along the edge of the Michigan Basin (from Lake St. Clair north along the shore of Lake Huron)
Devonian (DEV) See Figure 8.15	▶ Carbonates of Dundee Formation and Detroit River Group	▶ Structural traps generated by dissolution of underlying salt	▶ Southwestern Ontario (Chatham Sag)

Note: Modified from Mazurek 2004, Sanford 1993c, Carter (ed.) 1990.

8.6.1 Cambrian

Cambrian (CAM) aged hydrocarbon traps in southern Ontario occur as either stratigraphic traps or fault-related structural traps. Both trapping styles are strongly influenced by the basement tectonics and geology. Pools are located mainly along the erosional boundary of the Cambrian along a line connecting Windsor and Hamilton of the Appalachian Basin. No commercially producing hydrocarbon reservoirs have been reported on the Michigan Basin side, however, areas with good thicknesses of Cambrian sandstone are considered economic from the standpoint of CO_2 or waste fluid sequestration. The Cambrian plays account for less than 3% natural gas and 6% oil produced in Ontario (OGSR 2004). It should be noted that DGR-2 did not encounter any hydrocarbons within the Cambrian unit beneath the Bruce nuclear site (INTERA 2011).

Reservoirs

Typical Cambrian reservoir rocks occur as fine to medium crystalline dolostone, sandy dolostone, argillaceous dolostone, and fine to coarse sandstone located along the onlapping erosional boundary of the Cambrian along the Algonquin Arch in a line connecting Windsor and Hamilton (Johnson et al. 1992, Figure 8.4).

Cambrian sandstones and dolostones in Southern Ontario formerly blanketed a wide segment of the craton, however, rejuvenation of the Algonquin Arch, triggered by an Early Ordovician phase of the Taconian Orogeny, resulted in widespread uplift, fracturing and subaerial erosion of Upper Cambrian and Lower Ordovician strata from the crest and flanks of the arch (Sanford et al. 1985, Carter et al. 1996). This has left a horseshoe shaped ring of porous Cambrian sediments pinching out updip against the Pre-Cambrian surface, as illustrated in Figure 8.5, except where isolated patches are preserved in down faulted grabens in the Pre-Cambrian surface (Bailey Geological Services and Cochrane 1984a).

Along the southern flank of the Algonquin Arch (Niagara Megablock) the Upper Cambrian consists of porous, well-rounded and sorted, quartz sandstones (Carter et al. 1996). The quality of the Mount Simon Formation and Eau Claire Formations as reservoirs is relatively unknown within the Bruce Megablock, north of the Algonquin Arch (Bailey 2005).

Trapping Mechanisms

The Cambrian traps occur as either:

- Stratigraphic traps occurring as permeability pinchouts involving porous Cambrian sediments pinching out updip against the Precambrian surface sealed by low permeability shales; or as
- Basement-controlled structural traps by faulting and tilting causing juxtaposition against low-permeability limestones of the Black River Group, both within and without recognized anticlinal trends (Figure 8.6).

Either trapping styles are strongly influenced by the basement tectonics and geology (Sanford et al. 1985, Carter et al. 1996).

Stratigraphic Traps

Cambrian stratigraphic traps appear to be controlled by paleo-depressions on the basement surface with variations in pay thickness controlled by basement paleo-topography (Carter and

Trevail 1993). The best examples of southern Ontario Cambrian stratigraphic traps in are the Innerkip gas pool and Gobles oil pools, located north of Woodstock. These porous stratigraphically trapped pools were formed in re-entrants on the southern flank of the Algonquin Arch that were filled with porous, well-rounded and sorted, quartz sandstones of Upper Cambrian age. The sandstones are unconformably overlain by shales and sandy shales of the Middle Ordovician Shadow Lake Formation that pinch out laterally (Carter and Trevail 1993).

At Innerkip and Gobles, the reservoirs are associated with thickening of porous Cambrian sandstones (up to 12 m) deposited directly on the deeply eroded Precambrian surface in a north- to northwest-trending paleo-depression, which is conformable with magnetic strike (Carter and Trevail 1993, Carter et al. 1996). Local thickening and thinning of the sandstone within the depression is controlled by northeast-striking normal faults and/or paleo-topographic ridges of the Precambrian surface (Bailey Geological Services and Cochrane 1984a).

Recent work on the Cambro-Ordovician hydrocarbon potential have suggested that the some of the basal sandy facies in some the Cambrian stratigraphic traps may represent a lateral heterogeneity of the Middle Ordovician Shadow Lake formation (e.g., Innerkip pool, Bailey 2003). In 2008, the OGS Petroleum Resources Centre (Sangster et al. 2008) indicated that there also may be potential for trapping of natural gas in sandy facies lenses of the Shadow Lake Formation in depressions over the crest of the Algonquin Arch.

Structural Traps

The major recognized trap style for Cambrian reservoirs in Ontario is structural traps created by tilted fault-blocks that were initially formed in the Early Ordovician and reactivated in Late Ordovician, Middle and Late Silurian, and several stages of Devonian and Late Paleozoic (Sanford et al. 1985). Several Cambrian oil and gas pools in fault traps have been discovered on the Appalachian Basin side of the Algonquin Arch near the erosional edge of the Cambrian strata (Sanford et al. 1985, Carter and Trevail 1993).

The Cambrian structural trap is formed by porous Cambrian sandstones in the crest of a horst block sealed by overlying shales of the Shadow Lake Formation and laterally by limestones of the Gull River Formation (Bailey Geological Services and Cochrane 1984a, Carter and Trevail 1993, Figure 8.6). The bounding faults extend down into and displace the Precambrian.

An example exists in Clearville where the structural trap exists as a horst (aeromagnetic low) flanked by two elliptical aeromagnetic highs. The bounding faults are marginal to the magnetic highs (Carter and Trevail 1993, Bailey Geological Services and Cochrane 1984a). In comparing the Clearville and other Cambrian producing structures discovered to date in Ontario with the regional stratigraphic and structural framework, Sanford et al. (1985) identified similar potential trapping configurations in regionally identified lineaments. Most of the potential prospects were confined to the Niagara Megablock.

Aeromagnetic maps, determination of the Precambrian lithology (particularly the presence or absence of magnetite), and structural mapping of the Precambrian surface are the principal basement mapping tools relevant to identification of Cambrian hydrocarbon traps in southern Ontario (Carter et al. 1996).

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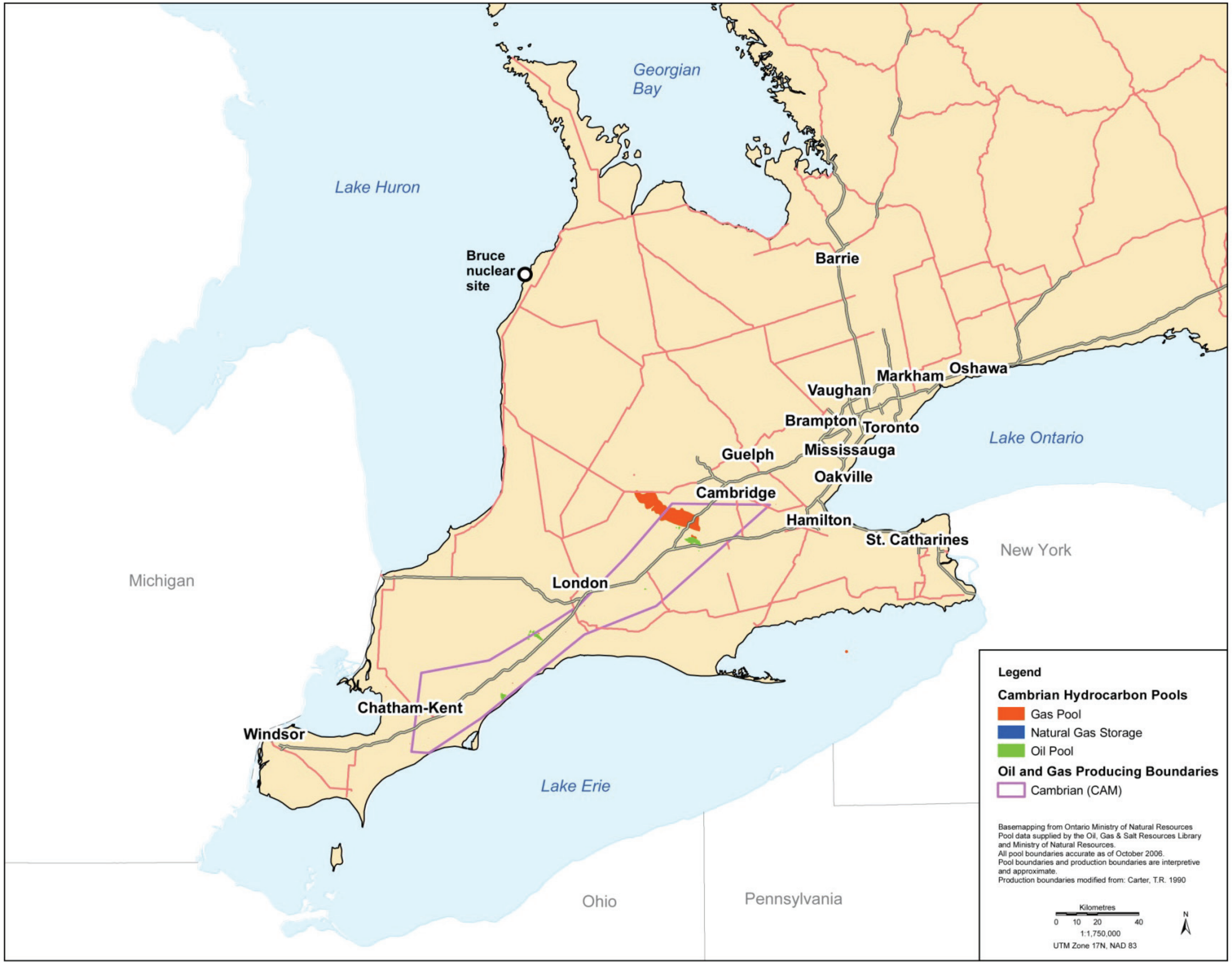

Figure 8.4: Cambrian Aged Oil and Gas Reservoirs of Southern Ontario

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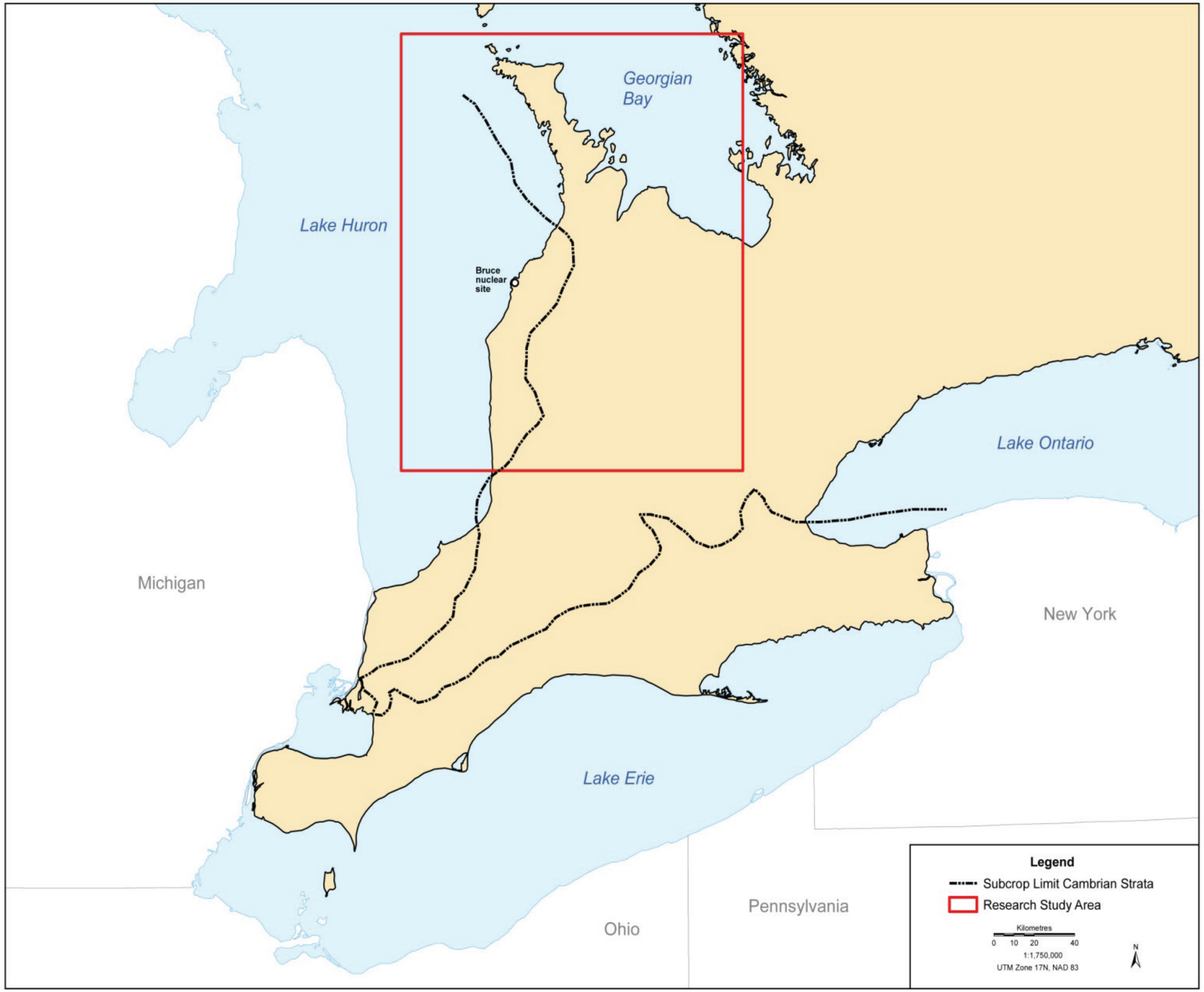

Note: Figure is modified from Carter et al. (1996) and Trevail (1990).

Figure 8.5: Cambrian Subcrop Erosional Boundary

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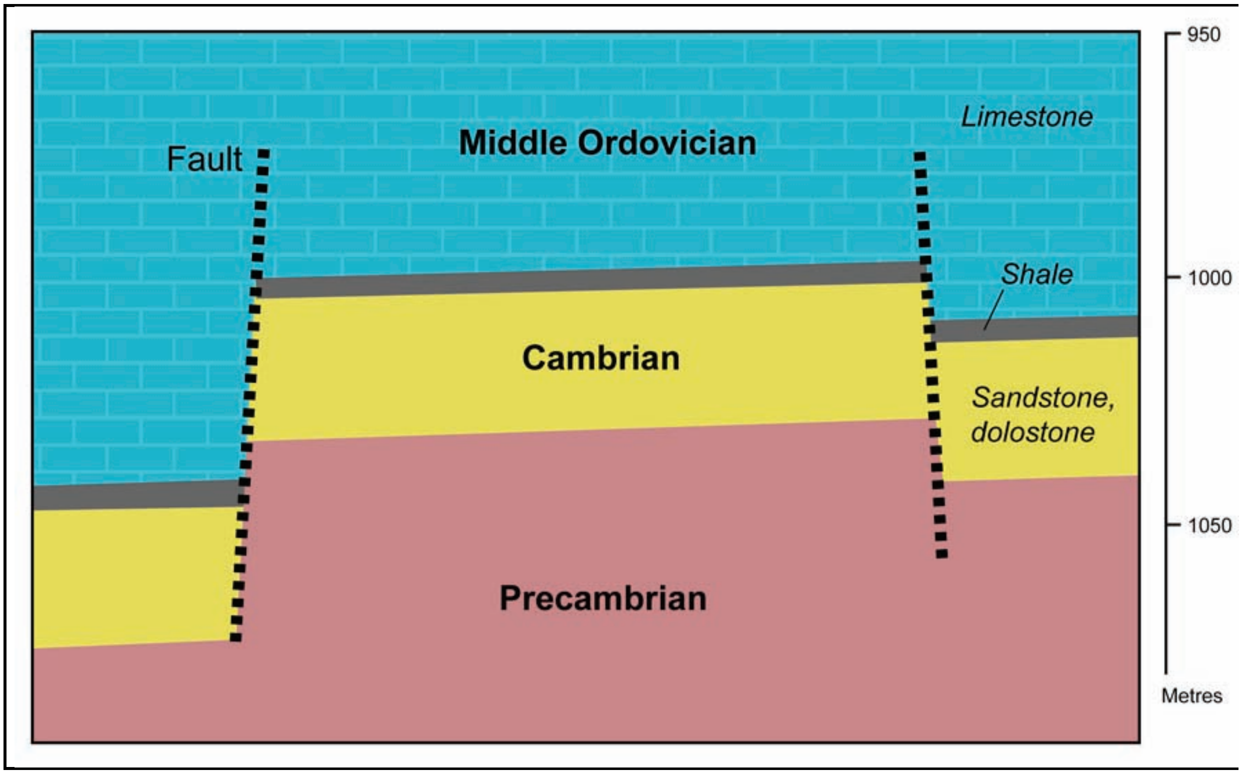


Note: Figure is modified from Carter and Trevail (1993), Bailey Geological Services and Cochrane (1984b).

Figure 8.6: Schematic Geometry of a Cambrian Fault Trap

<u>Resource Potential Within the RSA</u>

Although the presence of Cambrian traps in Bruce Megablock (RSA in particular) is possible, the region has not been the subject of significant exploration. Commercial hydrocarbon reservoirs of Cambrian age near the proposed DGR in the RSA are unlikely for the reasons listed below.

- Most Cambrian oil and gas accumulations are associated with or controlled in some manner by faults and fractures (Sanford et al. 1985). The RSA is located within a structurally simple part of southern Ontario, no major fault systems such as those described in southwestern Ontario have been identified;
- There is a lack of demonstrated adequate reservoir rocks on the western side of the Algonquin Arch and although the Mount Simon and Eau Claire Formations have been identified in core, Bailey (2005) speculated that within the study area these would tend to be quite thin and the resulting porosity too sporadic; and
- No oil or gas shows were reported during the drilling of the Cambrian sections of DGR-2 (INTERA 2011).

No commercial Cambrian hydrocarbon accumulations have been identified north of the Electric Fault, which cross-cuts the Chatham Sag, in Ontario and no commercially viable hydrocarbon reservoirs have been identified elsewhere in the Michigan Basin to date.

8.6.2 Ordovician Hydrothermal Dolomite

The Trenton-Black River play is characterized by hydrocarbon accumulations in stratigraphic traps in fault-related hydrothermal dolomite (HTD) reservoirs within the Upper and Middle Ordovician Trenton and Black River Groups in southern Ontario. Since the application of seismic techniques after 1983, new oil pool discoveries have tripled Ontario's annual oil production (GOLDER 2005). An overview of HTD reservoirs, dolomitization and HTD reservoir relations to structural controls is presented by Davies and Smith (2006). Additionally, a resource assessment and discussion of future potential of the Trenton-Black River HTD play of Ontario was produced by GOLDER in 2005.

The HTD play is found in areas of southern Ontario underlain by Trenton and Black River rocks bounded by the Canada-United States international border and the edge of the Black River outcrop belt (Figure 2.1). The play includes the largest field in the Michigan Basin, the Albion-Pulaski-Scipio trend, as well as the production in Ohio, Indiana, Pennsylvania, West Virginia and New York. Most Ordovician pools discovered in Ontario to date are located in the southwest end of southern Ontario in Essex County and southern Kent County (Figure 8.7).

<u>Reservoirs</u>

Fracture-related HTD reservoirs are recognized to occur in western Canada, Saudi Arabia, Australia, northeastern United States and southern Ontario (GOLDER 2005, Davies and Smith 2006). HTD hydrocarbon reservoirs were created in low porosity Ordovician limestones through fracturing and faulting, in particular strike-slip faults. Dolomitizing fluids flowing through these fractures resulted in localized dolomitization of the adjacent limestone and the subsequent increase in porosity (e.g., Carter et al. 1996, Coniglio et al. 1994, Middleton et al. 1993, Carter 1991, Sanford et al. 1985). Dolomitization as saddle dolomite in both replacement and void-filling modes is a characteristic of HTD reservoirs (Davies and Smith 2006). Hydrothermal dolomite in the Ordovician tends to form long linear localized reservoirs adjacent to fractures (Trevail et al. 2004). In Ontario, oil and gas pools of this type are long narrow features 400 to 1,200 m in width and up to several kilometres length covering an area up to 900 ha (Trevail et al. 2004).

Reservoirs preferentially occur within the Sherman Fall Formation of the Trenton Group or the Gull River-Coboconk Formations of the Black River Group (GOLDER 2005). Local occurrences within the Cobourg Formation of the Trenton Group have been documented. The reservoir thickness averages between 10 to 20 m and is found at depths averaging 800 m below surface.

The porosity, and hence the hydrocarbons, are found only in fracture-related HTD dolomite including the fractured cap. Typically the dolomitized zones have intercrystalline, vuggy, and/or fracture porosity, which has subsequently trapped oil and natural gas, and generally in narrow linear trends cut vertically through the involved formations, localized along fault and fracture trends. In some intervals, vugs, fractures, and even caverns are abundant. Average reservoirs display porosities of 6 to 8%, with permeabilities of 0.01 to 10,000 mD (GOLDER 2005). The reservoir seal is provided by the original limestones, the ferroan cap dolomite or the overlying Blue Mountain shales.

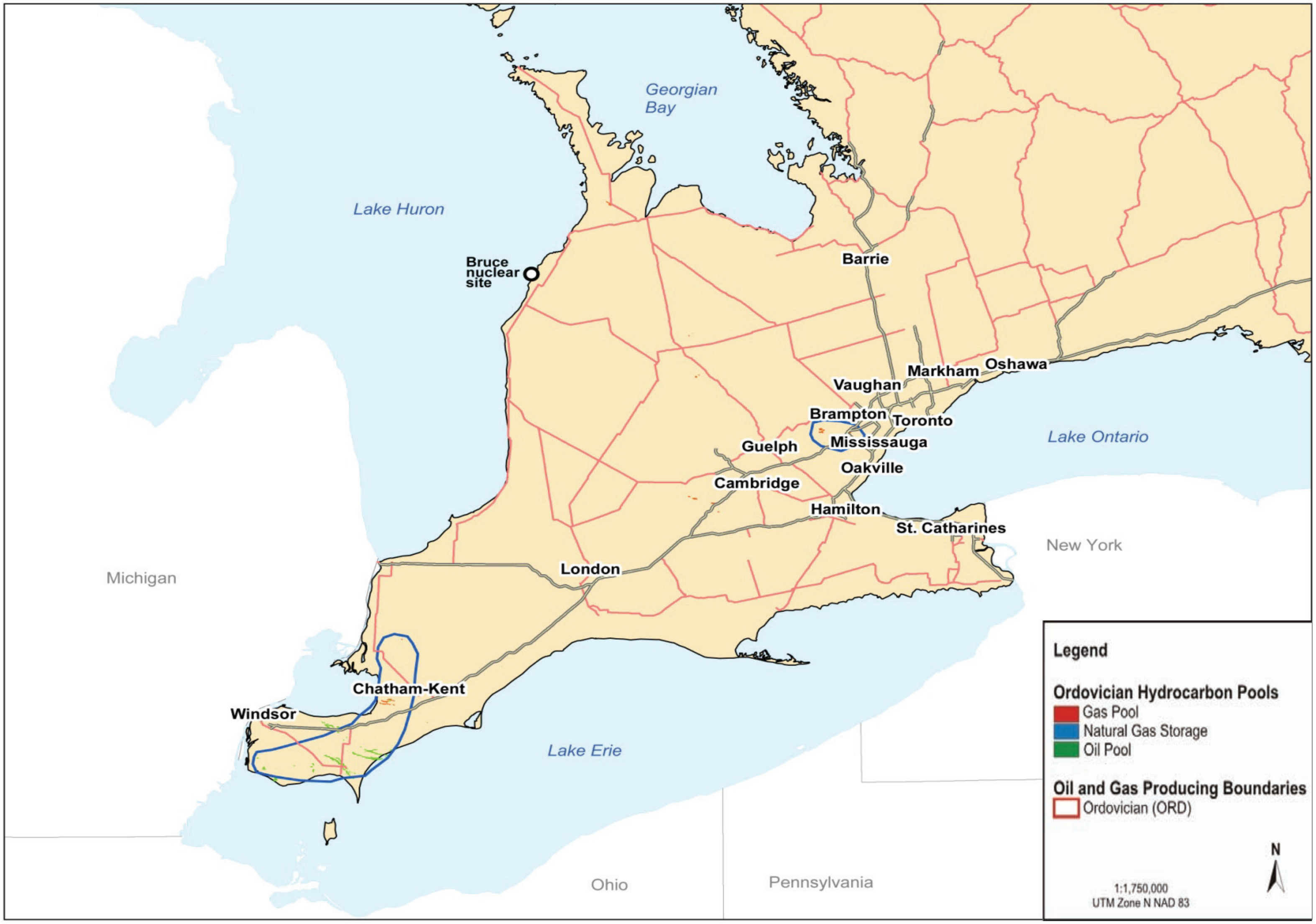
The mature portion of the Ordovician HTD play occurs in southwestern Ontario (e.g., Essex and Kent Counties) where production is primarily oil with lesser amounts of solution gas. Production data gathered indicate that the gas/oil ratios in HTD reservoirs increase steeply to the northeast of Essex and southern Kent, with the pools north of Dover primarily producing natural gas with lesser amounts of oil (GOLDER 2006).

Traps

The porosity of the hydrothermal dolomite is vertically confined beneath the thick nonporous shales of the Blue Mountain Formation and it is laterally confined by non-porous Trenton/Black River limestone, forming a reservoir or pool (Davies and Smith 2006, GOLDER 2005).

Trenton-Black River HTD reservoir zones are typically adjacent to vertical faults or fractures that extend from the Precambrian basement to the top of the Trenton Group (Carter et al. 1996, Middleton et al. 1993). The relationship of faulting or fracturing and selective hydrothermal dolomitization is illustrated schematically in Figure 8.8. Figure 8.9 (Sagan and Hart 2006) shows a fractured hydrothermal system from Ohio interpreted from seismic data. In this fracture system, a series of *en echelon* faults are propagated through the Ordovician limestones and into the overlying shales (Figure 8.9, left). The Ordovician reservoir is created within the dolomitized zone between the two fractures (Figure 8.9, right). Note that compressional forces that caused the faulting, have also produced positive, upward concave flower structures, which are known to be potential petroleum reservoirs. Extensional forces (transtensional) create negative flower structures. The Dover field of southwest Ontario, as recognized by Sanford (1961) and Sanford et al. (1985) is known as a classic structurally controlled HTD reservoir. Productive wells have a high correlation to sags identified at the top of the Trenton (Davies and Smith 2006). Sandford et al. (1985) interpreted that the structural control relates to the down-dropped side of rotated structural blocks propagated from the Precambrian basement.

Figure 8.10 shows a seismic profile of a Trenton-Black River HTD reservoir in Ontario that is located adjacent to several fractures cutting through the Trenton/Black River. The hydrothermal dolomite found within the “sag” in the seismic data along the fault trends (Figure 8.10) and within the boundaries of individual oil and gas pools is typically heterogeneous (GOLDER 2005). Due to the porosity of the HTD reservoir, the accepted industry practice is to indicate the hydrocarbon pool margins to the identified edges of the dolomitized zone until proven to be unproductive by drilling (GOLDER 2005).



Notes: Base map is from Ontario Ministry of Natural Resources Pool data supplied by the Oil, Gas and Salt Resources Library and Ministry of Natural Resources. All pool boundaries are accurate as of October 2006.Pool boundaries are interpretive and approximate. Production boundaries are modified from Carter (1990).

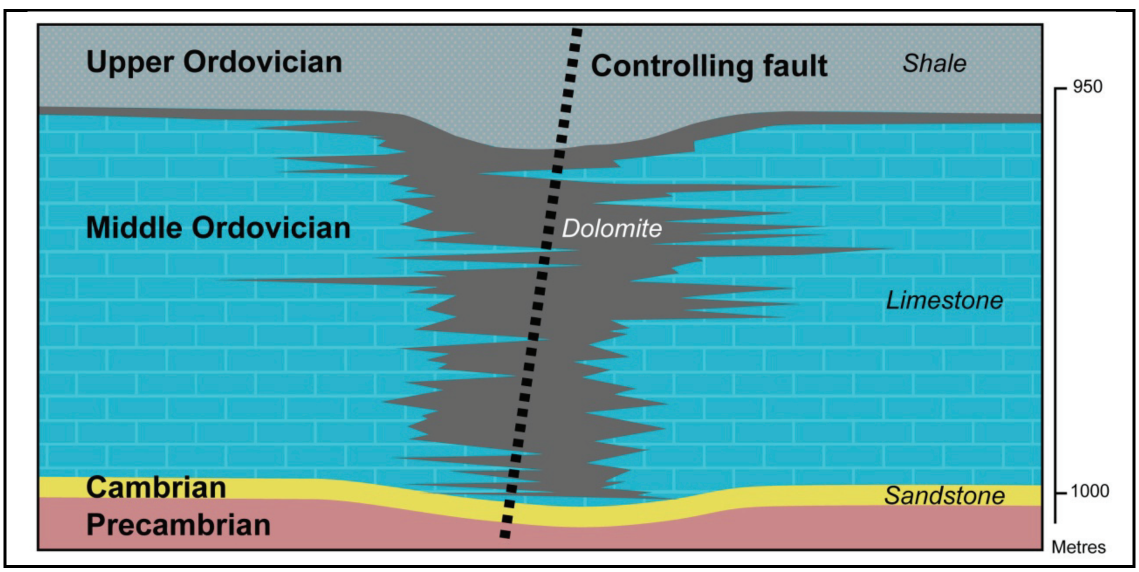
Figure 8.7: Ordovician Aged Oil and Gas Reservoirs of Southern Ontario

Exploration Status

Favoured drilling sites for HTD reservoirs typically occur as transtensional sags above negative flower structures on wrench faults (Davies and Smith 2006). Within the Michigan Basin, HTD reservoirs hosted in the Trenton-Black River Groups have typically been identified using geophysical means such as 2-D seismic surveys, to identify displacements along faults and fractures, and aeromagnetic methods to identify perturbations in the underlying crystalline basement. Displacements on vertical faults extending from the Precambrian basement to the top of the Trenton Group adjacent to Trenton-Black River HTD reservoir zones typically do not extend far into units overlying the Trenton and are readily visible on industry seismic lines (Figure 8.10, Carter and Trevail 1993).

In addition to industry seismic lines defining the fault locations for these pools the reservoirs are seismically characterized as follows:

- A seismically recognizable structural depression of less than 10 m of relief on the Trenton Group surface generally coincides with the zone of greatest hydrothermal dolomitization (Carter et al. 1996). Preferred drilling sites are often located on these depressions;
- Thickening of the potential seismic scattering points (isochrons) between the seismic markers for the Rochester Member and Trenton Group (GOLDER 2005);
- The basement surface appears as a low or appears to be disappearing due to faulting (GOLDER 2005); and
- Diffraction anomalies delineate the transition from porous reservoir dolomite to regional low permeability limestone (GOLDER 2005).



Note: Figure is modified from Carter and Trevail (1993).

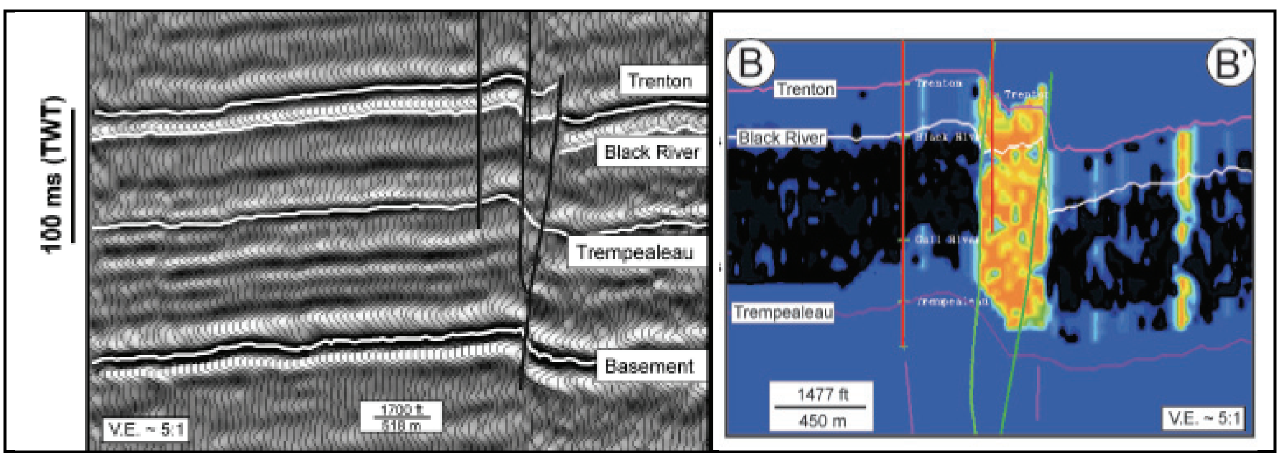
Figure 8.8: Schematic of a Trenton-Black River Ordovician HTD Petroleum Trap

Literature suggests that basal Cambrian sandstones overlying the Precambrian basement rocks contribute to hydrothermal flow systems and HTD emplacement into Ordovician hosts in the Michigan Basin (Davies and Smith 2006, Colquhoun and Trevail 2000). Bailey (2005) speculated that without the presence of the porous Cambrian sandstone underlying the tight and impermeable Ordovician limestones, the probability of developing a hydrothermal reservoir in those rocks would be poor. This is because the dolomitizing fluids were thought to have potentially migrated through the Cambrian units. Bailey (2005) noted that the best prospecting for Ordovician hydrothermal traps in Ontario should occur south of the Mount Simon subcrop edge, on the southeastern side of the Algonquin Arch. GOLDER (2005) supported this interpretation, indicating that the play has a significant potential for undiscovered recoverable hydrocarbon resources between Essex-Kent and the eastern most point of the Niagara Peninsula; an area south of the Late Cambrian Mount Simon Formation erosional line (Bailey 2005).

The areas along the arch subject to widespread erosion and complete removal of the Lower Ordovician strata and much of the Cambrian strata (Bailey and Cochrane 1984a) are very poor petroleum prospects.

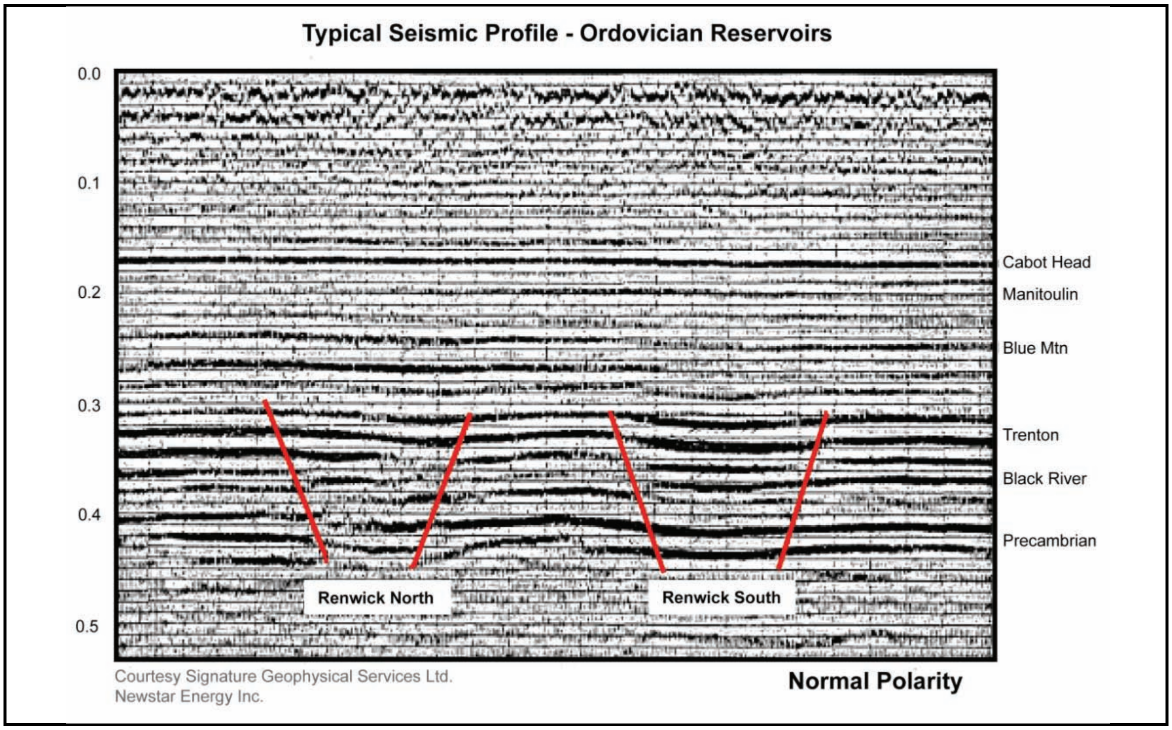
Resource Potential Within the RSA

HTD reservoirs have been shown to occur as porous and permeable zones in the vicinity of rejuvenated faults with intersecting fracture systems. These reservoirs have typically been identified using geophysical means such as 2-D and 3-D seismic surveys, to identify displacements along faults and fractures, and aeromagnetic methods to identify perturbations in the underlying crystalline basement. In addition it has been demonstrated that HTD reservoirs have an association with the presence of underlying Cambrian sediments that have facilitated the transport and migration of the dolomitizing fluids to the fault and fracture systems. On the northwestern (Michigan Basin) side of the Algonquin Arch (and within the RSA) Cambrian units are thinner and heterogeneous and only provide fair HTD pool prospecting (Bailey 2005). Hydrothermal dolomite reservoirs rocks were not encountered within the DGR boreholes (INTERA 2011).



Notes: The faults overlap to form concave-upward positive “flower” structures interpreted from seismic data (Left). Extrapolation of enhanced relative porosity from the same seismic survey showing highest porosity values are concentrated in the areas of intense faulting, especially where the faults overlap and meet at depth (Right) (Sagan and Hart 2006).

Figure 8.9: Example of En Echelon Faults in the Trenton/Black River of Saybrook, Ohio



Notes: HTD reservoir is adjacent to vertical faults that extend from the Precambrian and through Trenton Group. Figure is modified from Carter and Trevail (1993).

Figure 8.10: Example Seismic Profile of Trenton-Black River HTD Reservoir Zones

8.6.3 Silurian

The Silurian strata of southern Ontario are perhaps the most studied rocks in the region. This is due, in part, to their excellent exposure along the Niagara Escarpment and to the considerable oil and gas resources within several Silurian units in the subsurface (Sanford 1969, Bailey Geological Services and Cochrane 1986, Figure 8.11).

Silurian pools in Southern Ontario fall into two main stratigraphic reservoir categories.

- Upper Silurian reef (Niagaran) dolostone of the Guelph Formation and the Salina Formation (A1, A2) host hydrocarbons in stratigraphic traps.
- Lower to Middle Silurian sandstones (Whirlpool, Grimsby, Thorold Formations) and dolomites (Irondequoit Formation) create reservoirs in permeability pinchouts due to internal heterogeneity of the host formations. Occurrence of the sandstones and associated hydrocarbon pools are restricted to the Niagara Peninsula and areas beneath Lake Erie (Appalachian Basin). No Silurian sandstone hosted hydrocarbons are expected within the RSA and are not discussed further in this report.

Reservoirs

As described above in the regional Silurian geology (Section 4.2.4), three concentric rings of Guelph reef developed from the basin centre outwards they are, the Pinnacle Reef Belt, the Patch Reef Complex, and finally the Main Reefs, or the Barrier Reef Complex (Bailey 1986). The majority of

Southern Ontario's Silurian reef reservoirs occur within a well defined "pinnacle reef belt" primarily in Lambton County and Huron County (Figure 4.7 and Figure 8.11). Pinnacle and incipient reefs developed on the basin slope forming a belt or trend approximately 50 km in width below most of the eastern shore of Lake Huron and the St Clair River, and extending into Michigan.

The Middle Silurian (Niagaran) reservoirs consist of oil and gas accumulations trapped in pinnacle and incipient reefs (illustrated in Figure 8.12). In Ontario the pinnacles have heights up to 128 m above the regional inter-pinnacle surface (McMurray 1985). They occur only in the subsurface, at depths ranging from 450 to 700 m. Typically, reservoir rocks within the reefs are dolomitized and have both intercrystalline and vuggy porosity averaging about 8 percent. Pay thickness averages about 20 m, but varies greatly (Bailey Geological Services and Cochrane 1990). Incipient reefs, much smaller than the pinnacle reefs, typically have less than 50 m of relief above the inferred regional inter-reef surface (Carter et al. 1994). Incipient reefs have been found to have also occurred on the basin slope within the pinnacle reef trend. Most of the productive Middle Silurian reefal reservoirs are about 16 to 120 ha in area and have more than 50 m of relief.

Accumulations of oil or gas are also occasionally found in the overlying and adjacent carbonates of the Salina A-1 Carbonate and A-2 Carbonate Units where these carbonates have been dolomitized (Figure 8.13) (Bailey Geological Services and Cochrane 1990). They are usually associated with dolomitized zones along faults, such as the Dawn Fault in Lambton County, or occur within structural closures of variable origin (Figure 8.14) where the A-1 Carbonate is principally limestone with a regional dolomite content of less than 10% (Carter et al. 1994).

Trapping Mechanisms

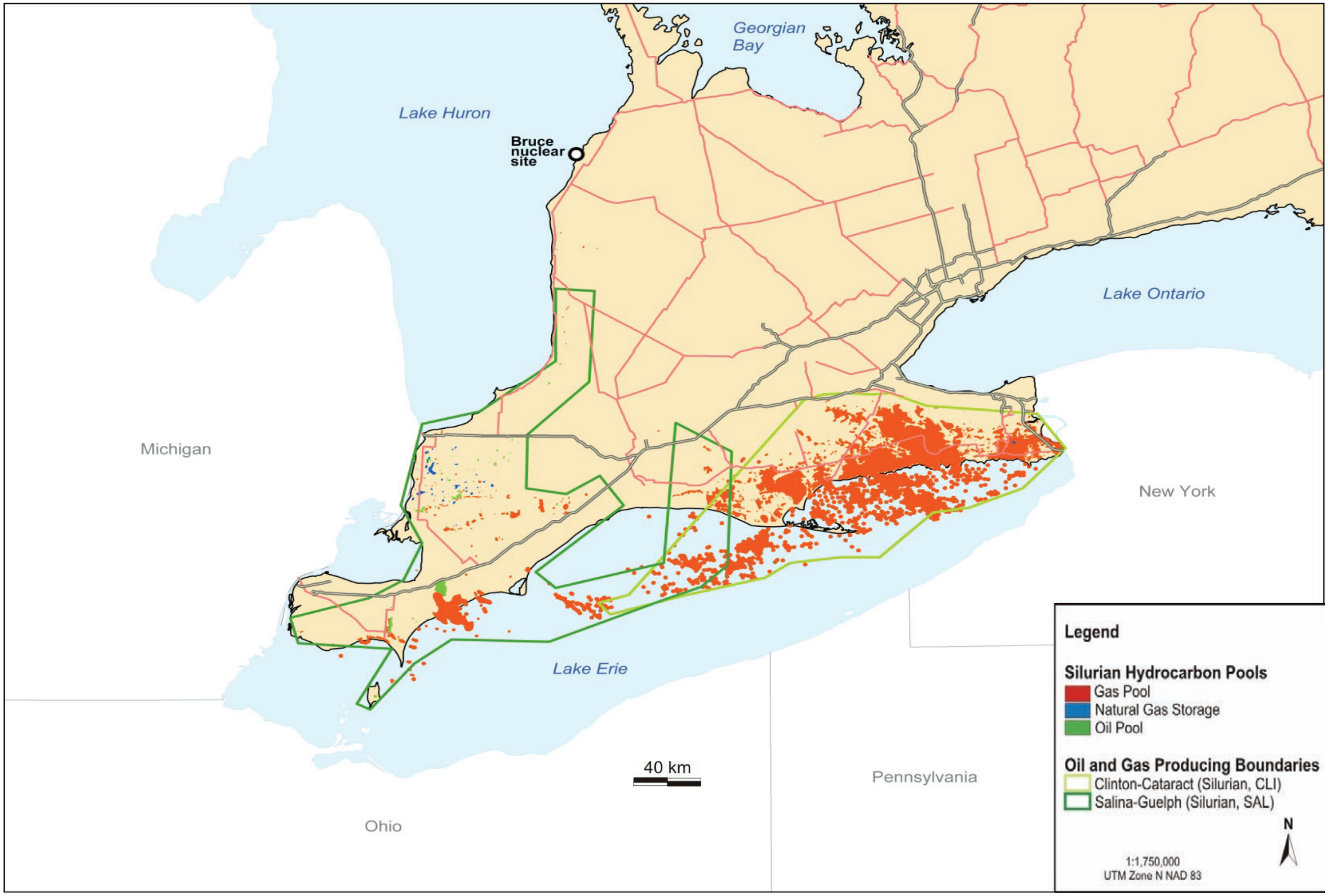
Major types of trapping mechanisms have been recognized in the Middle to Upper (Niagaran) Silurian Reef complexes (Carter et al. 1994, Bailey Geological Services and Cochrane 1990):

- Stratigraphic trapping in the Pinnacle, Incipient and Platform Reefs of the Middle Silurian Guelph Formation; and
- Structural trapping within the Salina A-1 Carbonate and A-2 Carbonate units.

Accumulations of oil and gas are found within porous and permeable dolostones and limestones of the reef, sealed vertically by evaporites of the Salina A-2 Unit, and laterally by non-permeable evaporites and limestones of the Salina A-1 and A-2 units.

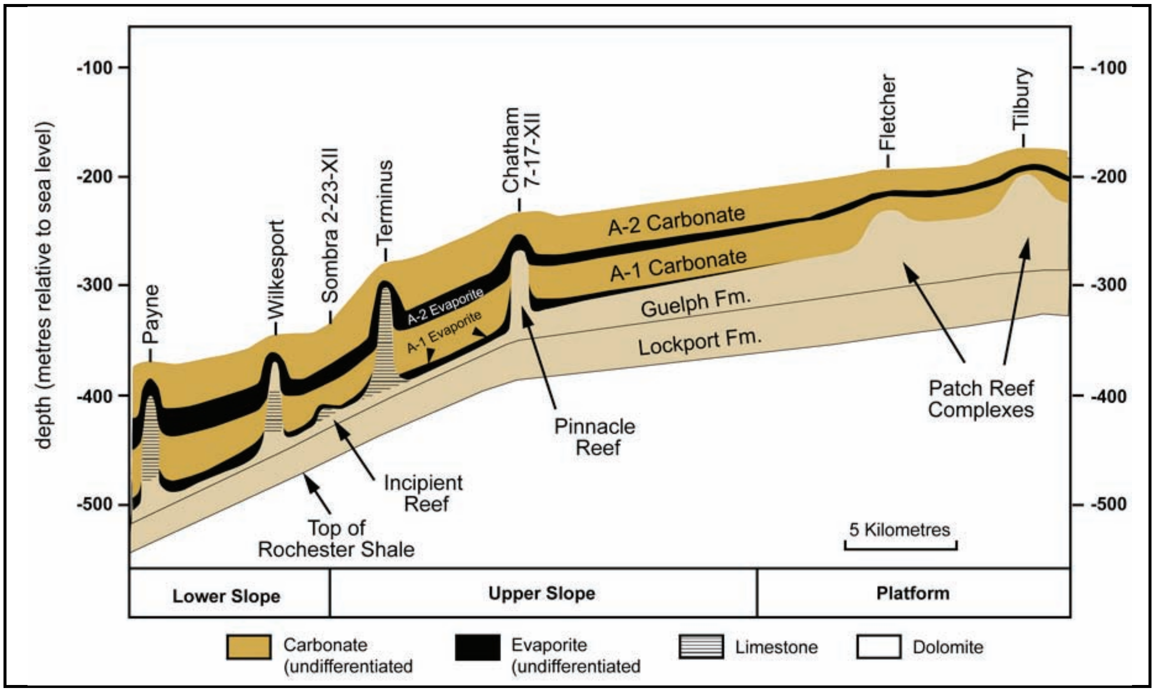
Platform reef traps occur in a large bank complex of coalesced reefs underlying the western and west central parts of Lake Erie, or as separate patches on the platform between the bank complex and the pinnacle belt (Figure 4.7). Platform reefs occur within the Guelph Formation and the underlying Lockport Formation (Carter et al. 1994) and are sealed also vertically by evaporites of the Salina A-2 Unit, and laterally by non-permeable evaporites and limestones of the Salina A-1 and A-2 units.

Structural traps occur within the Salina A-1 Carbonate and A-2 Carbonate units and within the underlying Guelph Formation. The reservoir in this pool type is formed by porous dolomite in the Salina A-1 Carbonate or A-2 Carbonate Units on the up-thrown side of the faults (Figure 8.14). The porous dolomite is sealed by non-porous salt, shale, limestone, and anhydrite of the Salina A-1, B, and C Units.



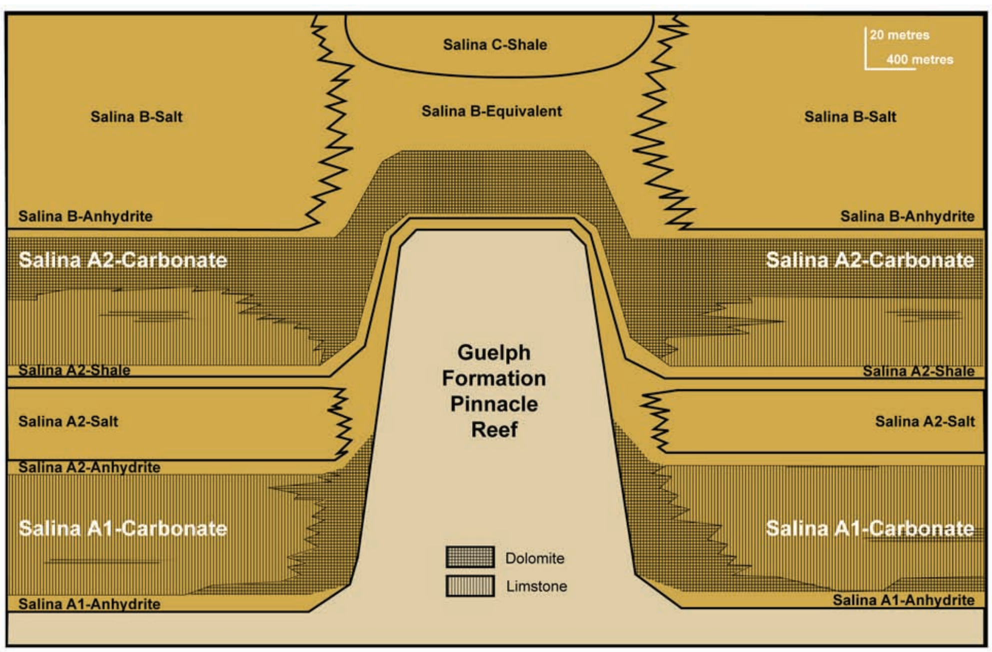
Notes: Base map is from Ontario Ministry of Natural Resources Pool data supplied by the Oil, Gas and Salt Resources Library and Ministry of Natural Resources. All pool boundaries are accurate as of October 2006. Production boundaries are modified from Carter (1990).

Figure 8.11: Silurian Aged Oil and Gas Reservoirs of Southern Ontario



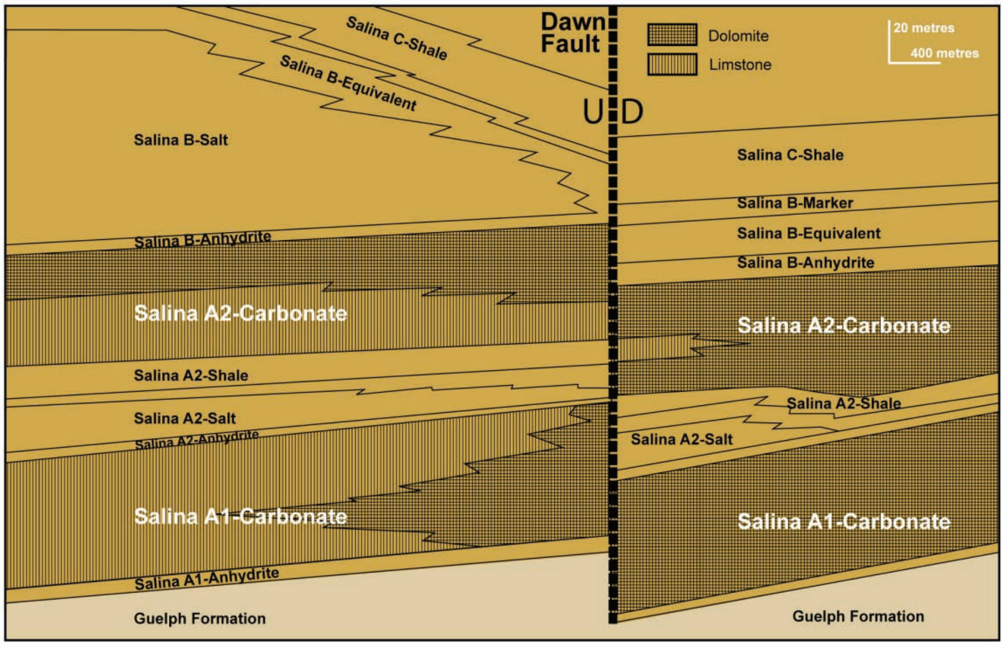
Note: Cross-section displays facies distributionsm, lithologies and its relationship with overlying units of the Salina A Group (modified from Coniglio et al*.* 2003).

Figure 8.12: Regional Structural Cross-section of the Silurian Guelph Formation



Note: This model is based on pinnacle reefs in the Salina A1 and A2 Carbonate Units in Sombra County (modified from Carter (1991).

Figure 8.13: Schematic Distribution of Dolomitization near Pinnacle Reefs



Note: Potential hydrocarbon traps occur in porous dolomite in both the Salina A-1 and A-2 Carbonate units on the up-thrown side of the Dawn Fault in Sombra Township, Ontario (modified from Carter et al. 1994).

Figure 8.14: Schematic Summary of a Silurian Fault Trap

Examples of this type of trap occur along the up-thrown side of the east-west trending Dawn and Electric Faults in Kent County as a string of small oil and gas pools. These faults also form the northern boundary of the Chatham Sag. The Electric Fault is clearly visible on seismic profiles and subsurface maps and extends down into and displaces the Grenville basement (Sanford et al. 1985).

Exploration Status

The most active area for current exploration is the Michigan Basin slope area underlain by the pinnacle reef belt (Figure 4.7) of the Middle Silurian Guelph Formation (Carter et al. 1994) in Lambton and Huron Counties. The large pinnacle reef reservoirs are the most attractive targets for exploration due to their size, relative ease of identification in seismic surveys and usability for hydrocarbon storage after depletion. The reefs, which are clearly visible in the 3DGF (Chapter 6), are interpreted based on the petroleum exploration wells that targeted these features. The lack of commercial discoveries in these reefs may be related to the absence of a well-developed fault and fracture framework or due to pervasive salt plugging (Bailey 1996).

Salt plugging is commonly noted, particularly throughout the Northern Pinnacle Belt (Armstrong and Goodman 1990). Supersaturated brines, from partial dissolution of overlying bedded halites of the Salina A-1 and A-2 Evaporites, invade reef porosity and reduce the reservoir potential (Armstrong and Goodman 1990, Bailey 2000).

Resource Potential Within the RSA

Historically, the highest probability of identification of potentially commercial resources of Middle and Upper Silurian carbonate-hosted hydrocarbons within the RSA lies within Huron County between Bluewater (south of Goderich) to Southampton along the Lake Huron shore. Eight small historical Silurian natural gas pools have been identified within the RSA from depths of 490 to 580 m: Tuckersmith 30-III SHR Pool, Tipperary Pool, Tipperary South Pool, Bayfield Pool, Ashfield 5-IX WD Pool, Ashfield 7-1-III ED Pool, Dungannon Pool and West Wawanosh 26-X Pool.

From 2000 to 2008 Silurian exploration drilling within the RSA has consisted of five well completions in the Goderich area. Natural gas shows were found in three wells but not of sufficient quantities to be commercial. Two wells are officially plugged and abandoned with the others suspended (Table 8.2). Commercial oil and gas accumulations may be trapped by Niagaran pinnacle reefs within the offshore part of the reef trend below Lake Huron (Figure 4.7).

8.6.4 Devonian

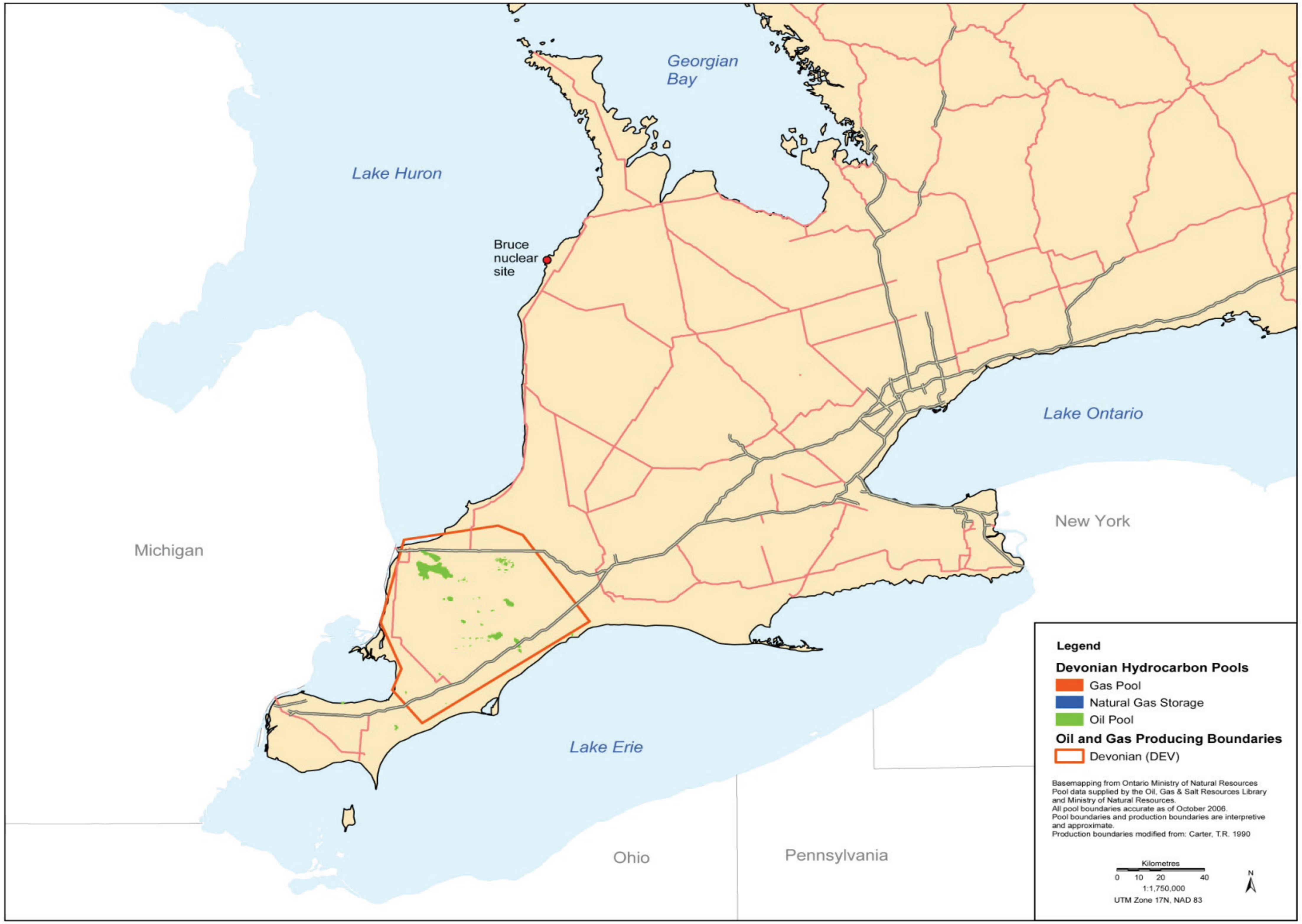
The Middle Devonian Carbonate (DEV) Play in southwestern Ontario (Figure 8.15) consists of hydrocarbon accumulations controlled by stratigraphic and diagenetic variations within Middle Devonian rocks, specifically the Dundee Limestone, and Detroit River Group (Bailey Geological Services and Cochrane 1985, Hamilton 1991). The majority of the Middle Devonian reservoirs are structurally controlled resulting largely as a result of selective dissolution of the underlying Silurian Salina “B” salt along fractures (Sanford et al. 1985), and to a lesser extent by differential compaction over Silurian pinnacle reefs (Hamilton 1991). The Devonian accounts for more than 50% of the cumulative crude oil produced in Southern Ontario (OGSR 2004).

Reservoirs

Production comes from two main types of reservoirs within the Devonian (Bailey Geological Services and Cochrane 1985):

- High porosity zones in the sandy facies of the Anderdon Member (often termed “Columbus” or “oil sand” by the oil industry), particularly at the interfingering of this facies with the remainder of the Anderdon Member; and
- Carbonate traps in the fractured Dundee Formation crinoidal limestones, porous Lucas Formation dolomites and Rockport Quarry formations.

Both of these traps are associated with fractures and structural highs or anticlines caused by regional warping or differential salt solution (Bailey Geological Services and Cochrane 1985). The carbonate traps are always located on structural highs, but not always on the crest of these features. It is apparent that, although there are some patches of intergranular porosity, the bulk of the production is from fractures. The limestones of the Dundee group are not porous in the subsurface and production could only have come from fractures within that zone (Bailey Geological Services and Cochrane 1985).



Notes: Base map is from Ontario Ministry of Natural Resources Pool data supplied by the Oil, Gas and Salt Resources Library and Ministry of Natural Resources. All pool boundaries are accurate as of October 2006. Pool boundaries are interpretive and approximate. Production boundaries are modified from Carter (1990).

Figure 8.15: Devonian Oil/Gas Pools

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Trapping Mechanisms

In southern Ontario the trapping mechanism within the Middle Devonian is structural, related to the pattern of salt dissolution in the underlying Silurian Salina Formation, and to regional tectonics. The overlying Devonian shales, anhydrites, and/or dense carbonate rocks provide the stratigraphic seal (Bailey Geological Services and Cochrane 1985). Salt dissolution creates a typical southwestern Ontario Devonian hydrocarbon reservoir geometry, with a series of anticlinal structures, as illustrated in Figure 4.10. Extensive salt leaching is interpreted to have occurred along northwest and east-west trending faults, which has resulted in local reversal of the northwest regional dip to form domal structures over the thicker salt beds preserved between the fault traces ultimately leading to the migration and entrapment of hydrocarbons in the Middle Devonian reservoirs (Sanford et al*.* 1985).

Exploration Status

In southern Ontario, all oil production from the Devonian lies west of the City of London, where the Dundee-Detroit River carbonates are overlain by the Hamilton Group (see Figure 2.1). To date, oil production from Devonian units has been largely restricted to the Dundee and Lucas Formations. Minor amounts of oil and gas have been found in the overlying Hamilton Group carbonate beds, although this unit primarily acts as a top seal for the Dundee-Lucas reservoirs. No potential natural gas reserves have been assigned to the Devonian because commercial quantities of gas have not been found to this date.

The remaining potential in new Devonian onshore pool oil reserves has been predicted to be low (Bailey Geological Services and Cochrane 1985). The offshore areas (Lake Erie; Lake Huron) appear to have the best potential for significant discoveries of oil in the Devonian (Bailey Geological Services and Cochrane 1985). Approximately 8.97 million m^3 or 82.6% of the remaining potential oil reserves were estimated to lie offshore, with 6.51 million m^3 in Lake Erie and 1.81 million m^3 in Lake Huron (Bailey Geological Services and Cochrane 1985). However, at the present time, exploratory drilling for all hydrocarbons is not permitted in Lake Huron, Lake St. Clair and Lake Ontario, and oil production is not permitted on Lake Erie.

Resource Potential Within the RSA

The potential for Devonian hydrocarbon resources to occur throughout the RSA is low and likely restricted to the southwest quadrant where the oil hosting Dundee and thicker exposures of Lucas Formations occur in subcrop. The absence of overlying Hamilton Group limestones and shales to provide an adequate seal for the trap makes commercial hydrocarbon reservoirs unlikely.

A small probability exists that where the Dundee Formation is found in subcrop, the Lucas Formation dolomite and the Columbus sandstone could host hydrocarbon traps (Bailey Geological Services and Cochrane 1985). The shallow reservoir depths and corresponding low formation pressures, however, would result in low volumes of natural gas and low recovery factors for oil (Bailey Geological Services and Cochrane 1985).

8.7 Summary

Current commercial oil production in Ontario occurs almost exclusively within Essex, Kent, Lambton and Elgin Counties in southwestern Ontario. Historical exploration data indicates that 12 small pools were documented within the boundaries of the RSA. These resources consisted primarily of natural gas from Ordovician and Silurian carbonates with very small amounts of crude oil. The only currently active reservoir is the Ordovician aged Arthur natural gas pool in the southeast of the RSA. Presently, no documented commercially viable crude oil and natural gas resources have been identified within a 40 km onshore radius of the proposed Bruce nuclear site. Furthermore, the literature suggests that the RSA geology generally does not lend itself to be a prospective target for significant oil and/or gas plays.

The recorded cumulative production of natural gas to the end of 2006 from all pools within the boundaries of the RSA has amounted to approximately 21 million m^3 or less than 0.1% of the cumulative southern Ontario natural gas total. Crude oil production has amounted to approximately 1,440 m^3, or approximately 0.01% of the cumulative crude production in Ontario.

Since 2000, exploration drilling in the RSA has focused on Silurian and Devonian targets in Huron County south of Goderich. Two petroleum well completions have been made within the Salina Formation to the end of 2006. Natural gas shows were found in both but failed to achieve commercially viable quantities and both wells have been abandoned and /or plugged.

From an evaluation of existing literature, the probability of future identification of potential economic oil and/or gas resources associated with major structures adjacent the proposed Bruce nuclear site is low. All Ontario hydrocarbon trapping styles are associated with or controlled in some manner by faults and fractures. Cambrian and Ordovician hydrocarbon reservoirs show the most direct association. Few faults have been identified to date within the RSA (e.g., Figure 3.4).

Although porous Cambrian sediments have been identified in core within the RSA, no oil or gas shows have been encountered. The Cambrian play is likely restricted to south of the northern limit of the Mount Simon deposition, on the southeastern side of the Algonquin Arch.

Ordovician HTD reservoirs have been shown to occur in porous and permeable zones in the vicinity of rejuvenated major faults with intersecting fracture systems. DGR-2 borehole encountered no evidence of an Ordovician HTD reservoir. It is expected that future onshore exploration potential for commercially viable HTD traps within the RSA is low. Presently, industry exploration for Trenton-Black River HTD traps is focussed almost exclusively in Essex and Kent Counties in the Niagara Megablock.

Silurian natural gas pools have been identified within this area of the RSA at depths of 490 to 580 m, however, none of the reefs adjacent to the DGR, as shown in the 3DGF, encountered commercially viable resources. In addition, the Bruce nuclear site is located within an inter-reef zone.

The potential for Devonian hydrocarbon resources to occur throughout the RSA is low and restricted to the southwest quadrant where the oil hosting Dundee and Lucas Formations occur and are underlain by Salina evaporites. The probability of commercial quantities of hydrocarbons occurring northeast of the Kincardine-Wingham area is substantially reduced because of the absence of overlying Hamilton Group Limestones and shales to provide an adequate seal.

9. QUATERNARY GEOLOGY

Glaciations during the Quaternary Period have played a major role in shaping and creating the landscape of Ontario. The last period of glaciation in southern Ontario occurred from approximately 23,000 to 10,000 years ago, during the Wisconsinan Substage of the Pleistocene Epoch. During this time, the Laurentide Continental Ice sheet advanced out of the Great Lakes basins (Lake Huron, Lake Erie and Lake Ontario) to cover southern Ontario (Chapman and Putnam 1984). Figure 9.1 shows the distribution of Quaternary sediments within the RSA. A summary of the glacial periods, from youngest to oldest, and the Quaternary deposits that result from them, is presented in Table 9.1.

The RSA was covered by two ice lobes, namely the Huron and Georgian Bay ice lobes. These ice lobes advanced from the west and north, respectively, during the last glaciation (Chapman and Putnam 1984, Sharp et al. 1997). The locations of the ice lobes and their margins fluctuated until the final retreat of the glaciers, which started approximately 10,000 years ago. The resulting surficial geology is highly varied across the RSA (Figure 9.1). The unconsolidated materials deposited on bedrock in a glaciated region such as southern Ontario consist mainly of the following; (a) ground moraine or glacial till laid down directly by the ice; (b) glaciofluvial deposits, the sand and gravel deposited by water from the melting glacier; (c) glaciolacustrine deposits, the clays, silts, and sands deposited in glacial lakes; and (d) ice contact deposits formed at the margin of the glacier.

Table 9.1: Summary of Quaternary Deposits and Events in the RSA

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).

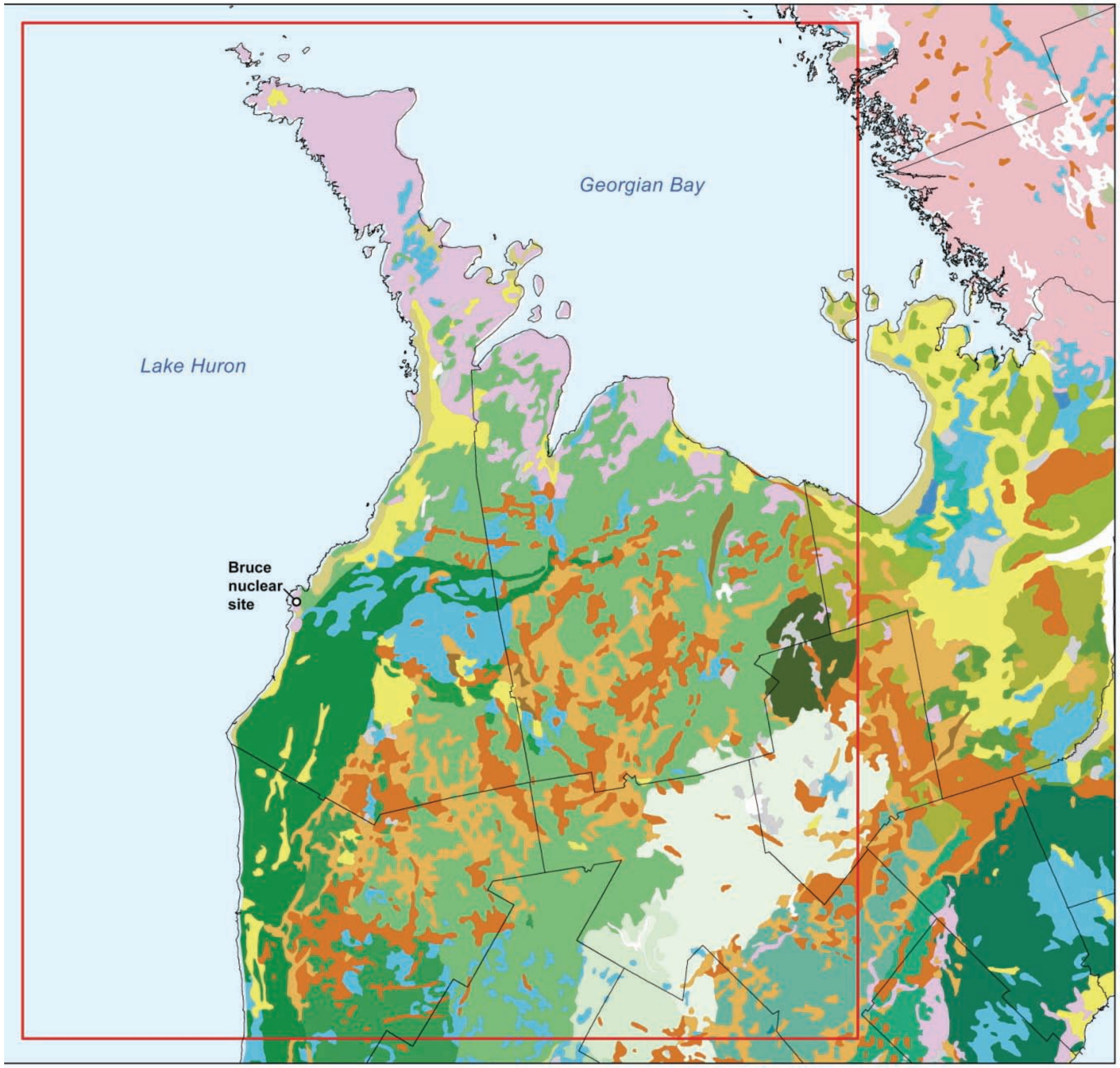

Figure 9.1: Quaternary Geology Map of the Regional Study Area

The Catfish Creek Till is the oldest till in the RSA. It was deposited during the Nissouri Stadial as ice advanced from the north, approximately 20,000 to 18,000 years ago. At the beginning of the Port Bruce Stadial, approximately 16,000 to 15,000 years ago, the climate cooled and a series of smaller ice lobes moved radially out of the Great Lake basins into southern Ontario. Grey and Bruce Counties, which sit between Lake Huron and Georgian Bay, were overridden by the Huron-Georgian Bay lobe of the Laurentide Ice Sheet.

During this stadial, the ice lobe deposited the Elma Till and the Dunkeld Till. The Elma Till occurs as ground moraine and in drumlins of the Teeswater drumlin field. It is associated with the Singhampton moraine (formerly the Saugeen Kames) and is overlain by glaciofluvial sand and gravel, glaciolacustrine silts and younger tills. The Elma Till ranges in thickness between 2 and 15 m. It was deposited during the latter part of the Port Bruce Stade, but deposition of this till probably continued during the following Mackinaw Interstade (Barnett 1992). The Dunkeld Till occurs as ground moraine within the Saugeen River valley and is in the core of the Walkerton Moraine. Dunkeld Till is the product of a minor re-advance of the ice margin over glaciolacustrine silts of glacial Lake Saugeen. The Elma Till is probably both older and younger than the Dunkeld Till (Barnett 1992). The Mornington Till occurs as flat and weakly fluted ground moraine varying between 1 and 3 m in thickness over much of the southeast of the RSA.

Following the Port Bruce Stadial, temperatures warmed and the ice sheet rapidly retreated during the Mackinaw Interstadial, approximately 15,000 to 13,000 years ago depositing extensive outwash sands and gravels from meltwater rivers draining southward from the ice front. Glaciolacustrine clay and silt are present south of the RSA in the Lake Ontario South Slope. At the beginning of the Port Huron Stadial, approximately 13,000 to 12,000 years ago, the climate cooled again and the Huron-Georgian Bay ice lobe re-advanced and deposited the St. Joseph Till in the area. A halt in the retreat of the Huron-Georgian Bay lobe margins in the northern portion of Wellington County is marked by extensive deposits of ice-contact stratified drift and outwash sand and gravel. These ice-contact deposits form a large area of hummocky topography known as the Saugeen Kames (Chapman and Putnam 1984).

The St. Joseph Till occurs in the Wyoming Moraine, the Williscroft Moraine and the Banks Moraine, which parallel the Lake Huron and Georgian Bay shorelines, and roughly defines the extent of the ice lobe advance. It can be overlain by outwash sand and gravel and glaciolacustrine gravel, sand and silt (Barnett 1992). After the Post Huron Stadial, the Laurentian Ice Sheet receded northward during the Two Creeks Interstadial, approximately 12,000 to 10,000 years ago, and deposited lacustrine silts and clays, and ice-contact and outwash sands and gravels.

9.1 Physiography

The dominant surficial features of the study area (Figure 9.1) are presented below, and are based on the Physiography of Southern Ontario (Chapman and Putnam 1984).

- The dominant geomorphic feature in the RSA is the northwest-trending Niagara Escarpment extending from the northwest to the southeast corners of the study area. In the northern portion of the RSA, on the Bruce Peninsula, the escarpment forms steep bluffs (up to 100 m high) along the Georgian Bay shoreline with exposed rock strata gently dipping to the southwest into Lake Huron. Further south, the Niagara Escarpment is less prominent and follows the Georgian Bay shoreline to the southeast. Karst features are present throughout the Niagara Escarpment, having a major impact on surface water and groundwater hydrology. Deep, dissolution-enhanced joints characterize karst development in the thick-bedded dolostones on the topographically higher eastern part of the peninsula. Karstic cave systems are known southeast of Tobermory and in very fossiliferous biohermal dolostones near Mar (Cowen and Sharpe 2007).

- The Bruce Peninsula consists largely of gently rolling and irregular exposed dolostone plains, with a thin veneer of Quaternary deposits. Soils are shallow, and are classified as Breypen series in the Ontario Soil Survey. The irregular topography of the bedrock surface results in many wet swampy basins and small lakes throughout the Peninsula.
- Coarse-textured glaciolacustrine deposits make up the sand plains of the Huron Fringe. This area comprises wave-cut terraces of glacial Lakes Algonquin and Nippissing along the Lake Huron shore, with minor sand plains also occurring along the Georgian Bay shoreline.
- Shale plains, known as the Cape Rich Steps, are located between Owen Sound and Nottawasaga Bay. This area consists of Paleozoic bedrock overlain by shallow overburden, with the plain being incised by the Beaver Valley (in the Thornbury area) and the Bighead Valley (in the Meaford area).
- The Port Huron Moraine system, consisting of glaciofluvial and ice-contact stratified deposits (kames), extends south-southwest from the head of the Beaver and Bighead Valleys to run parallel to the shoreline below Goderich covering the southcentral to southwestern part of the RSA. Meltwater stream deposits and spillways also occur throughout this physiographic region, as do drumlins in the vicinity of Dornoch. Huron clay loam is a common soil type on the moraine ridges.
- The southeast part of the RSA, extending to the southern tip of Beaver Valley and east to the Niagara Escarpment, consists mainly of drumlinized till plains, with a small drumlin field in the area of Dundalk. The till is a stone-poor, carbonate-derived silty to sandy deposit.
- At the base of the Bruce Peninsula is the Arran drumlin field. The ground moraine is thin with many of the drumlins located directly on the bedrock of the Silurian Guelph and Amabel Formations.
- The Stratford Till Plain lies east of the Port Huron Moraine system and adjoins the Teeswater Drumlin Field to the north. This physiographic region is a rolling to flat till plain that is divided by three major moraines. Eskers occur frequently in the Stratford Till Plain, and the eastern part of the Teeswater Drumlin Field. They generally trend to either the south or the east, reflecting the general flow directions of the Georgian Bay and Huron ice lobes respectively.
- Immediately south of the Arran drumlin field is an area of fine-textured, glaciolacustrine deposits of the Saugeen Clay Plain. It is underlain by deep stratified clay deposits. The Saugeen River, Teeswater River and Deer Creek have cut valleys through the clay up to 38 m deep.
- West of the Saugeen Clay Plain, and extending south along the Lake Huron shore to Goderich, is an area of silty to clayey till of the Huron Slope. The till is generally up to 3 m thick, and overlies stratified clay. The clay matrix of the till is likely reworked material from the underlying clay beds.

The Bruce nuclear site is located within the Huron Fringe and Huron Slope physiographic regions. The thickness of overburden across the site is generally less than 4.5 m increasing to thicknesses in excess of 20 m in a localized area within the central eastern area (GOLDER 2003, INTERA 2011). Borehole DGR-1 at the Bruce nuclear site intersected 20 m of overburden and fill, including approximately 3 m of gravel fill overlying approximately 17 m of native overburden comprised of clayey silt tills with a gravel base (INTERA 2011).

To the northwest and southwest of the Bruce nuclear site, thin heterogeneous deposits of sand, gravel and boulders left from beach deposits typically overlies the bedrock along the present Lake Huron shoreline between Sarnia and Tobermory (Chapman and Putnam 1984).

9.2 Post Wisconsin Isostacy

Vertical loading of the crust of southern Ontario during the growth of the Wisconsin ice sheet depressed the surface by up to 500 m resulting in a build up of the neotectonic stress field (NWMO and AECOM 2011, Peltier 2011). After recession of the ice sheet the earth's crust rebounded, uncovering these lowlands and tilting the beaches of the glacial lakes upward toward the northeast. The upper level of submergence under seawater north of Ottawa is indicated by a beach containing marine shells at Kingsmere, north of Ottawa, in the Province of Quebec at 210 mASL. In the Lake Huron region the tilting of the ancient, abandoned shorelines amounted to as much as 180 m (Chapman and Putnam 1984).

Subsequent retreat also caused the release of stored elastic energy as the formation of pop-up structures appeared. Although no major post-glacial faults are observed in southern Ontario the latter resulted in the formation of numerous open field pop-up structures and linear ridges on the floor of Lake Ontario that are mostly oriented at a high angle to the present maximum horizontal in situ stress direction (Section 3.1.4).

10. AGGREGATE RESOURCES

The potential aggregate resources of the DGR Research Study Area (RSA) in Grey County were assessed by evaluating provincial government and county aggregate resource publications, and published geological maps and reports.

Mineral aggregates, which include bedrock-derived crushed stone as well as naturally formed sand and gravel, constitute the major raw material in Ontario's road building and construction industries. Mineral aggregates are characterized by their high bulk and low unit value so that the economic value of a deposit is a function of its proximity to a market area as well as its quality and size.

10.1 Surficial Sand and Gravel Resources in the RSA

Throughout the RSA sand and gravel pits have been identified in Huron, Grey, Wellington, Perth and Bruce counties. Most of these are situated in esker, glaciofluvial outwash, ice-contact and glaciolacustrine beach deposits (Figure 9.1). A number of areas have been identified by the Ontario Geological Survey and Ministry of Natural Resources as containing primary significant resources of sand and gravel.

Primary sand and gravel deposits are defined as those with a minimum of 35% gravel and the proven or inferred presence of crushable (>26.5 mm) gravel in commercial quantities (approximately 20% or more). The materials are of mineable size and thickness, exhibit reasonable textural consistency, contain moderate to low quantities of fines (< 8%), and have the proven or inferred ability to meet medium to high physical quality standards as determined by the Ministry of Transportation (MTO).

The sand and gravel resources in the RSA have been organized around the physiographic regions identified by Chapman and Putnam (1984).

- The Huron Slope, a flat to undulating plain, is composed chiefly of the low-stone content St. Joseph Till. Glaciolacustrine and beach sand or sand and gravel occur as thin beds or low ridges on the plain. The aggregate material is shallow and generally does not exceed 6 m in thickness. This feature runs parallel to Lake Huron from the Bruce Peninsula to the base of the RSA. In the past, the beach material was extensively extracted for aggregate in southern Huron County.
- The Port Huron Moraines physiographic region extends in a north-northeast trending belt parallel to the shore through the RSA and contains the most significant concentration of primary aggregate deposits. Large, drainage spillway or meltwater channels occur within the moraines, particularly in northern and west-central Huron County (Wyoming and Wawanosh Moraines), and the largest aggregate resource in Grey County, the Singhampton Moraine in the northern portion of Grey County. The network of spillway outwash deposits are commonly 10 to 15 m in thickness. Outwash aprons of significant size are also located adjacent to the Gibraltar and Banks Moraines in Grey County near Owen Sound. Singhampton Moraine outwash gravel deposits also occur as belts of braided outwash between ridges of moraine deposits in the northern portions of Wellington County. The gravels range for the most part from 2 to 6 m in thickness although more than 15 m has been reported locally.
- The Teeswater Drumlin Field in the central portion of the RSA (northeastern part of Huron County and southeast Bruce County) contains drumlins that are composed primarily of sandy to silty Elma Till, which has a moderate to high stone content with a large distribution

of outwash sand and gravel. As a result, this section of Bruce and Huron Counties contain some of the richest aggregate deposits in the RSA.

Because of their importance as aggregate sources, many of the large eskers have been mined intensively within the RSA and are nearing depletion. However, small eskers occur frequently in the Stratford Till Plain, the Moraine fields southwest of Owen Sound and the eastern part of the Teeswater Drumlin Field. Numerous eskers are found in northeastern Huron County and Grey County.

Near the DGR, thin beds of beach sand or sand and gravel occur parallel to the Huron Shore as low elongated ridges overlying the St. Joseph Till in the Municipalities of Kincardine and Port Elgin to the southwest and northeast of the DGR respectively. No primary sand or gravel resources have been identified within 20 km of the Bruce nuclear site.

10.2 Bedrock Geology Resources in the RSA

Primary Bedrock Resources are identified by the Ontario Geological Survey as those with little to moderate overburden cover (<8 m), occurring in mineable thicknesses. Removal of overburden greater than 8 m is considered prohibitive, unless there are unusual circumstances. Most bedrock extraction operations are developed in areas where the overburden thickness is 3 m or less. DGR-1 and DGR-2 encountered approximately 20 m of overburden at the site.

The following Table 10.1 summarizes the various rock units contained in the RSA. Current quarrying activities in the RSA are almost exclusively limited to Middle Silurian dolostones, which are extracted for building stone, landscaping stone, and aggregate. The massive dolostones of the Wiarton-Colpoy Bay Member of the Amabel Formation is currently actively quarried on or near the Niagara Escarpment in Albemarle and Sydenham Townships in Bruce County. Economically the most important bedrock resource in the RSA is the Eramosa Member of the Guelph Formation where the thinly bedded bituminous dolostone is quarried in numerous localities in Bruce and Grey Counties primarily for building and landscaping stone. The dolomitic limestones of the Manitoulin Formation are quarried intermittently along the Niagara Escarpment in St. Vincent and Sarawak Townships for aggregate. The Georgian Bay and Queenston Formation shales have been used in the past for brick making.

10.2.1 Bedrock Resource Potential in the RSA

Currently the rock units of significant potential economic interest are the Wiarton-Colpoy Members of the Amabel Formation and the Eramosa Member of the Guelph Formation on or near the Niagara Escarpment in Bruce County particularly in the Bruce Peninsula. Drift thickness over much of the peninsula area mapped as rock dominated is usually less than 1 m. Drift thickness is typically less than 15 m in thickness but in isolated locations it may exceed 30 m. Small portions of the Guelph Formation are under less than 8 m of drift in the northeast of Wellington County and are considered a primary resource.

The Wiarton/Colpoy Bay Member of the Amabel Formation is currently quarried for aggregate and dimension stone products at quarries in the southern and central Bruce Peninsula (Derry et al. 1989). The Eramosa Member of the Guelph Formation is currently quarried for a variety of building stone products from numerous quarries in the southern and central Bruce Peninsula (Armstrong and Meadows 1987). A number of presently abandoned Eramosa quarries also exist in the northwest (Bruce County) portion of the RSA.

Table 10.1: Summary of Economic Bedrock Units in the RSA

Age	Group/Formation	Type	Potential Usage	Location in RSA	Quarried in RSA?
Mid Upper Ordovician	Lindsay Formation (Collingwood Member)	Calcareous shale	Oil Shale	Collingwood Area	past producer
U. Ordovician	Blue Mountain Formation	Noncalcareous shale	Structural clay products, pottery	Collingwood- Georgian Bay	No
U. Ordovician	Georgian Bay Formation	Limestone and shales	Manufacture of bricks	Collingwood area – Georgian Bay shore	Past Producer
U. Ordovician	Queenston Formation	Shale	Brick Making	Bruce Penn./ Base of Niagara Esc.	Past Producer
L. Silurian	Whirlpool Formation	Sandstone	Building stone	Niagara Esc.	No
L. Silurian	Manitoulin Formation	Dolomitic limestone	Landscaping and building stone, aggregate	Niagara Esc. St. Vincent and Sarawak Counties	Yes
L. Silurian	Cabot Head Formation	Shales	Aggregate potential/brick, tile	Niagara Esc.	No
M. Silurian	Dyer Bay Formation	Dolostone	None	N. Bruce Penn.	No
M. Silurian	Wingfield Formation	Shale/ dolostone	None	N. Bruce Penn.	No
M. Silurian	St. Edmund Formation	Dolostone	Fill, crushed stone, asphalt and concrete suitable	N. Bruce Penn.	No
M. Silurian	Wiarton/Colpoy Bay Member of the Amabel Formation	Massive dolostone	Industrial mineral use (glass manufacturing), dimension stone, dolomitic lime, crushed stone, concrete aggregate and building stone	On or near Niagara Esc to end of Bruce Penn. (Grey County, Bruce County - Albemarle Twp., Sydenham Twp.)	Yes
M. Silurian	Guelph	Thickly bedded dolostone	Dolomitic lime, crushed stone, concrete aggregate and building stone	Manitoulin Island, Bruce County – Amabel Twp.	Yes
M. Silurian	Guelph (Eramosa Member)	Thinly bedded bituminous dolostone	Building and landscaping stone (flag, paving, ashlar, and polished dimension stone)	Bruce County – Albemarle Twp., Amabel Twp. – Grey County – Keppel Twp.	Yes
U. Silurian	Salina Formation	Evaporite	Salt, brine	Southwestern ON: Windsor, Goderich, Sarnia, North Wellington Cty. Only in subsurface.	Yes
M. Devonian	Detroit River Group (Amherstburg (Formosa Reef) and Lucas Formations)	Limestone	Cement manufacture, high purity and used by the steel, cement and chemical industries	Southern Grey and northern Wellington Counties	No
M. Devonian	Anderdon Member limestone of the Lucas Formation	Limestone	Aggregate, building stone, armour stone, lime and cement	Southwest quadrant	No

The lower Silurian Manitoulin Formation has been intermittently quarried for aggregate in the past and is of secondary resource potential in the RSA. Potential shale resources are very limited in the northern Bruce Peninsula as the shale units (i.e., Queenston and Cabot Head Formations) are poorly exposed in a narrow outcrop belt at the base of the Niagara Escarpment.

The upper Silurian Salina Formation is characterized by dolomite, shale, gypsum and salt. This formation has little value as a source for crushed stone aggregate but salt is extracted to the south of the RSA at Goderich. Rock salt has been mined continuously since 1959 at depths approaching 500 m. The Salina salt has been dissolved and removed over most of the RSA and beneath the Bruce nuclear site through natural geologic processes.

The limestones of the middle Devonian Detroit River Group (Amherstberg and Lucas Formations) occur in the southwestern corner of the RSA. The Formosa Reef Limestone, which has a thickness of up to 26 m of high-purity limestone, is a member of the Upper Middle Devonian Amherstburg Formation and subcrops in the southwest of the RSA.

The majority of the southern portion of the RSA (e.g., Huron County, south Grey County) bedrock is covered by 10 to 50 m of drift and exhibits wide variations in aggregate quality. Only in limited areas, mainly in the river valleys (e.g., Maitland River in Huron County) and their branches, is the drift less than 8 m thick (OGS 2004). No further potential bedrock resources were identified in this area.

Sphalerite (MVT deposits) occurrences within the Bruce Peninsula have attracted some base metal exploration interest over the years. Evidence of historical exploration (e.g., shafts, trenches) exists on the peninsula, however, no commercial MVT deposits have been found within Ontario.

11. CONCLUSIONS

The purpose of the regional geology study, in conjunction with the other geosynthesis supporting technical reports, is to present the current understanding of the deep sedimentary formations surrounding the DGR. The following summarizes the key findings of this report.

The characteristics of the Paleozoic rocks within the RSA were the result of deposition and burial history within two paleo-geological sedimentary basins. These basins are the Appalachian Basin to the east of the Bruce nuclear site and the Michigan Basin where the Bruce nuclear site is located. These basins are separated by the Algonquin Arch, a basement topographic feature that trends in a northeast / southwest direction. The current scientific understanding of regional facies models combined with field mapping, outcrop data and borehole data across the Ontario portions of the Michigan and Appalachian Basins make it possible to predict the geology over large distances. The Paleozoic stratigraphy of southern Ontario is relatively simple, extremely shallowly dipping, and continuous. This geometry was the result of deposition over broad carbonate and clastic shelf and platform settings that extended from the eastern margin of the Appalachian Basin to the centre of the continent. As a result, stratigraphic formation thicknesses and lithologies are generally predictable over kilometre scale distances and the primary geological units relevant to demonstrating DGR suitability and safety are continuous throughout the RSA. These units include the Middle Ordovician limestones (approximately 200 m in thickness), Upper Ordovician shales (approximately 200 m in thickness) and Upper Silurian argillaceous dolostones and evaporites (approximately 190 m in thickness).

The geology encountered in boreholes DGR-1 to DGR-6 is consistent with the regional geology as described in this report (Armstrong and Carter 2006, Armstrong and Carter 2010). The lithological properties such as shale, evaporite, carbonate and clastic content and dolomite versus limestone distribution are predicted by regional data for a site located at the margin of the Michigan Basin. Facies assemblages characterizing the limestones and dolostones found within southern Ontario are relatively homogenous with respect to rock properties. The diagenetic process of lithification and burial compaction to form limestone and dolostone progressively and significantly reduces the variability in the original sediments.

A discussion of the structural geology of southern Ontario suggests that the study area can be characterized as one of the more structurally simple parts of southern Ontario. Paleozoic strata dip gently towards the centre of the Michigan Basin and contain two principle fracture (joint) sets in surface exposures whose orientations are consistent with those elsewhere in southern Ontario. The fracture and joint patterns primarily reflect tectonic loading during Paleozoic orogenic events. There are no known active faults within the Paleozoic rocks in the study area, an assessment supported by the low level of seismicity in the Bruce Megablock.

The general scientific consensus from the literature suggests that major diagenetic events (excluding shallow bedrock diagenesis) including petroleum migration occurred during the Paleozoic or early Mesozoic coinciding with large scale tectonic events at the margin of the North American plate and to maximum burial depths and compaction within the Michigan and Appalachian Basins. Current evidence does not suggest a significant freshwater/meteoric source for even the late stage diagenetic minerals found within the sedimentary rock record. The tectonic conditions that led to large-scale migration of diagenetic fluids within the Michigan Basin no longer exist and have not existed since Mesozoic times.

A petroleum geology assessment based on a review of existing literature indicated that the probability of future identification of potential economic oil and/or gas resources adjacent to the proposed Bruce nuclear site is low. Drilling at the Bruce nuclear site did not encounter significant oil and gas resources. Currently, there is no petroleum production within 40 km of the Bruce nuclear site and only minor petroleum resources are extracted within the RSA.

An assessment of Quaternary geology and aggregate resources shows that the Bruce nuclear site is located within the Huron Fringe and Huron Slope physiographic regions with approximately 20 m of fill and Quaternary sediments, mainly till, over the Paleozoic basement. The bedrock immediately beneath the site is the Detroit River Group (Lucas and Amherstburg formations) dolostone, which is not considered an economic resource at or adjacent to the Bruce nuclear site.

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13. ABBREVIATIONS AND ACRONYMS

3DGF	3D Geological Framework
CAI	conodont alteration index
CMBBZ	Central Metasedimentary Belt Boundary Zone
DGR	Deep Geological Repository
DGSM	Descriptive Geosphere Site Model
GFTZ	Grenville Front Tectonic Zone
GSC	Geological Survey of Canada
HS Unit	Hydrostratigraphic Unit
HTD	hydrothermal dolomite
mBSL	metres below sea level
MNR	Ministry of Natural Resources
MVT	Mississippi Valley Type
NOAA	National Oceanic and Atmospheric Administration
OGS	Ontario Geological Survey
OGSRL	Ontario Oil, Gas and Salt Resources Library
OPG	Ontario Power Generation
RSA	Regional Study Area