OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Supporting Technical Report

Phase I Regional Geology, Southern Ontario

November 30, 2008

Prepared by:
Gartner Lee Limited

OPG 00216-REP-01300-00007-R00

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EXECUTIVE SUMMARY

The Regional Geology Geosynthesis Study presented in this report represents one of six Supporting Technical Reports that comprise the Phase I Geosynthesis Program for the proposed Deep Geological Repository located near Tiverton, Ontario. The five other Phase I studies include; Regional Hydrogeochemistry, Hydrogeologic Modelling, Regional Geomechanics, Long-term Climate Change (Bruce Site), and Long-term Cavern Stability. 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 DGR as it relates to long-term stability of the sedimentary sequence and its ability to isolate and contain Low and Intermediate Level Radioactive Waste. For the Regional Geology Report 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 regional geology report was compiled from existing data, and is a synthesis of the current scientific understanding of the Paleozoic rock within the Regional Study Area, an area of approximately 35,000 km^2 surrounding the DGR site. A key component of the synthesis of geological information was the development of a Three Dimensional Geological Framework of the Regional Study Area, which captures and presents the current geological understanding of the Palaeozoic sedimentary formations and their stratigraphy. This framework was also used to construct the Regional Hydrogeological Model Domain (Sykes *et.al*., 2008). The primary data sets used to construct the Three Dimensional Geological Framework were the Ontario Oil, Gas and Salt Resources Library Petroleum Well Database, boreholes from the DGR site and published maps.

The synthesis of geological information as presented in the Regional Geology Report suggests the following:

a) In southern Ontario the Paleozoic stratigraphy is flat lying and continuous. 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 Regional Study Area. The geometry of the sedimentary units was the result of deposition over a broad carbonate and clastic shelf and platform paleo-environments, which extended from the eastern margin of the Appalachian Basin to the centre of the continent.

b) The geology encountered in boreholes DGR-1/2 cored as part of Phase I site investigations is consistent with the regional geology as described 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 DGR site displays approximately 400 m of continuous 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.

c) The Regional Study Area 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 events throughout the Paleozoic.

d) 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.

e) An evaluation of existing literature and results from DGR-1/2 drilling suggest that the probability of future identification of potential economic oil and/or gas resources associated with major geological structures adjacent to the proposed DGR site is low. The scarcity of petroleum resources within the regional study area and absence of commercial petroleum extraction within 40 km of the DGR site supports this assessment.

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A. 3D Geological Framework

1. INTRODUCTION

The Regional Geology Geosynthesis Study presented in this report represents one of six Supporting Technical Reports that comprise the Phase I Geosynthesis Program for the proposed Deep Geological Repository located in Tiverton, Ontario. The five other Phase I studies include; Regional Hydrogeochemistry, Regional Hydrogeologic Modelling, Regional Geomechanical Review, Glaciation Scenario (Bruce Site), and Long-term DGR Geomechanical Stability.

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 DGR. For the Regional Geology Report, 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 being undertaken as part of the Geoscientific Site Characterization Plan, and provides a framework for extrapolation of site conditions beyond the DGR 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 Geosynthesis Report (Sykes *et al.*, 2008). The RSA boundary and the boundary used to develop the Three Dimensional Geological Framework (*Section 6*) 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 3D Geological Framework (3DGF) as part of this study was the Ontario Oil, Gas and Salt Resources Library (OGSRL) Petroleum Well Database. A full methodology is provided in Section 6 describing how the Geological Framework was developed and verified. The Geosynthesis Regional Hydrogeological model uses the 3D geological layers derived from this geological framework.

The final interpretations of the regional geology as presented in this report are therefore based on the combined literature review and geological framework derived from the petroleum well database. In addition, the results of the DGR site Phase 1 drilling program are integrated into this geologic interpretation. The interpretations and reporting of the Paleozoic stratigraphy are based on published facies models and sedimentology processes.

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 Deep Geological Repository 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:

a) the Paleozoic geology is predicable over large distances;
b) geological unit/formation thicknesses are uniform and also predictable over distances of kilometres;
c) litho-structural properties are understood and homogenous at scales relevant to DGR safety;
d) there are multiple low permeability geologic barriers;
e) there is a stable regional stress regime; and
f) the origin and general processes of diagenesis, including dolomitization, are understood.

The Regional Geology Geosynthesis 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 (Figure 2.1). Figure 2.1 shows progressively younger sedimentary units outcropping/subcropping from the Canadian Shield margin towards southwestern Ontario.

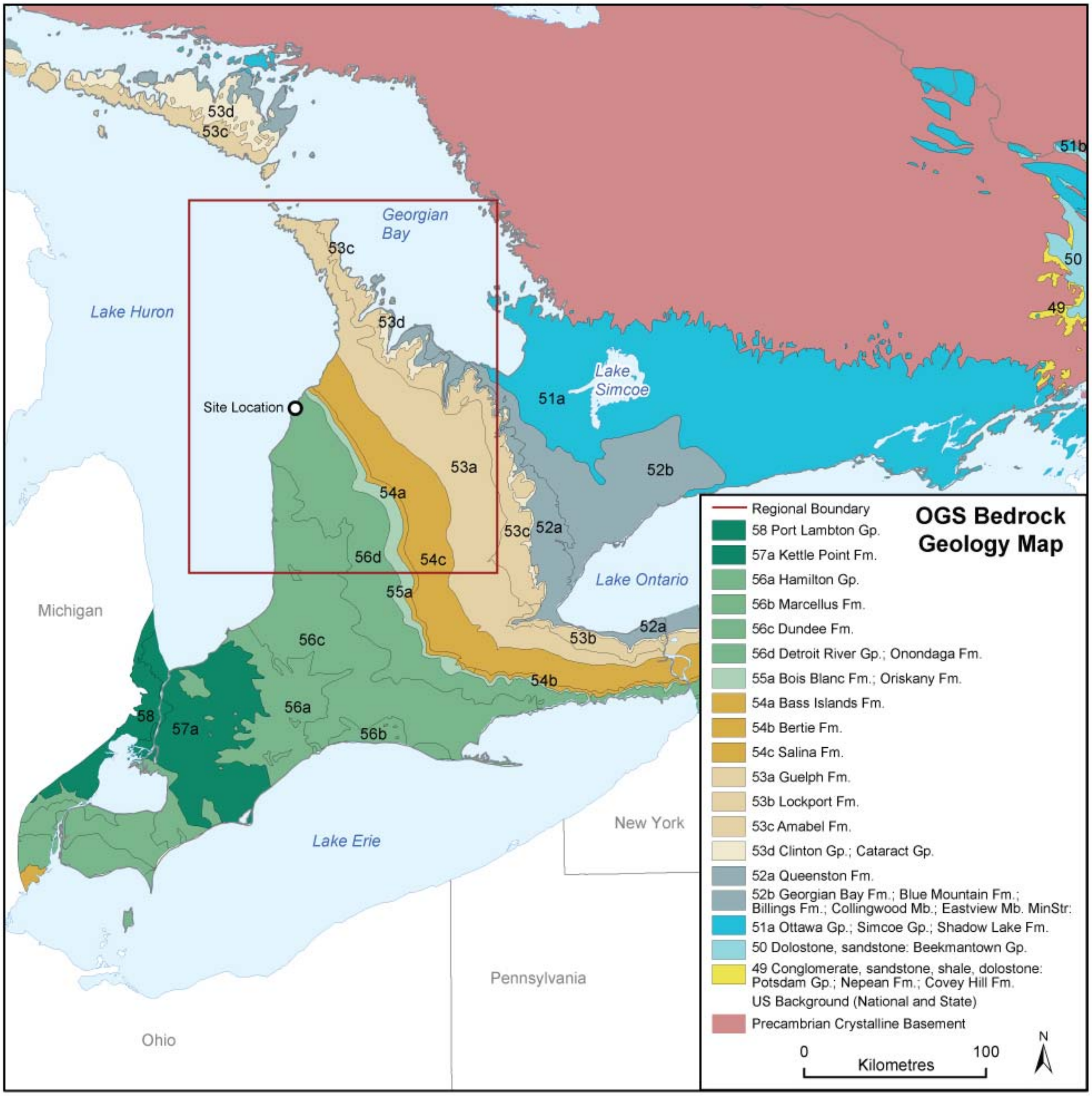


Figure 2.1 Geologic Map of Southern Ontario

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 at ca. 1100 Ma 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).

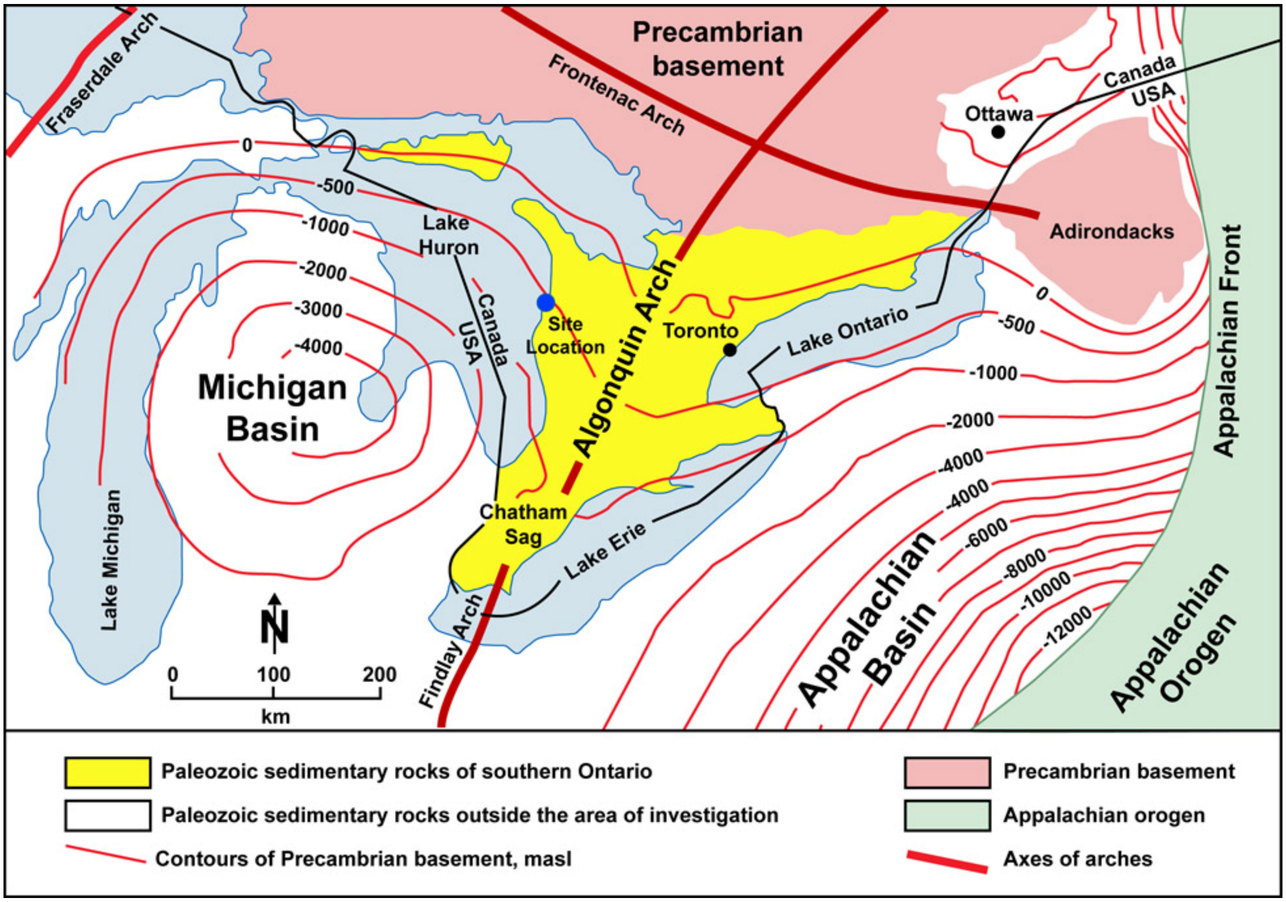


Figure 2.2 Large-scale Tectonic Elements in Southern Ontario (Mazurek, 2004 after Johnson *et al.* 1992)

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 and Howell and van der Pluijm, 1999).

2.1.1 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).

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, G. deV., and Hsui, A.T. 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, Sleep and Nunn, 1980, Nunn et. el, 1984).

More recent studies by Howell and Van der Pluijm (1990) and Howell and Van der Pluijm (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 2.4 shows the major tectonic influences on eastern North America through time (Sanford, 1993b). The Taconian 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).

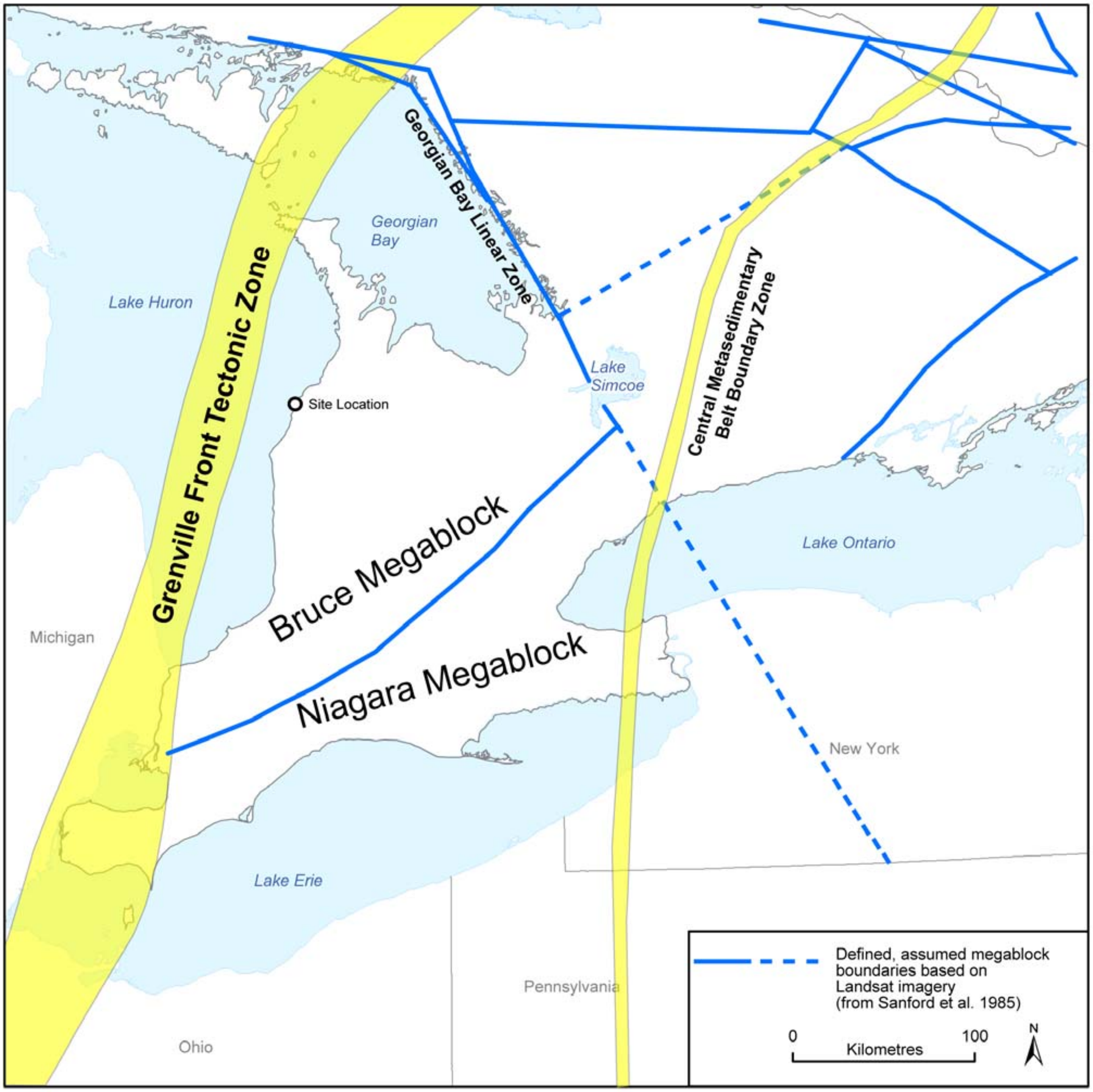


Figure 2.3 Major structural boundaries of Southern Ontario and interpreted tectonic block boundaries derived from Landsat imagery by Sanford et al., (1985).

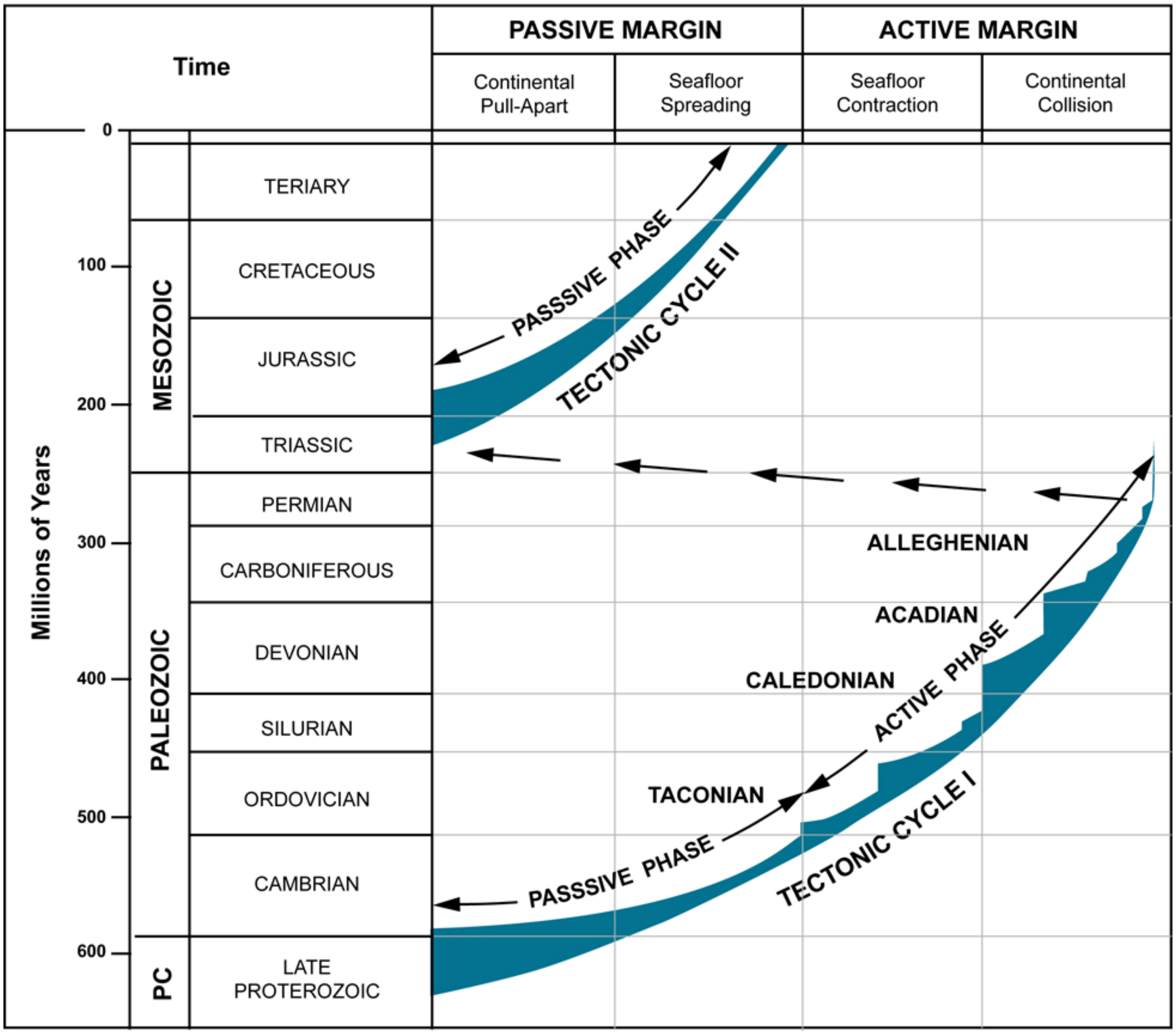
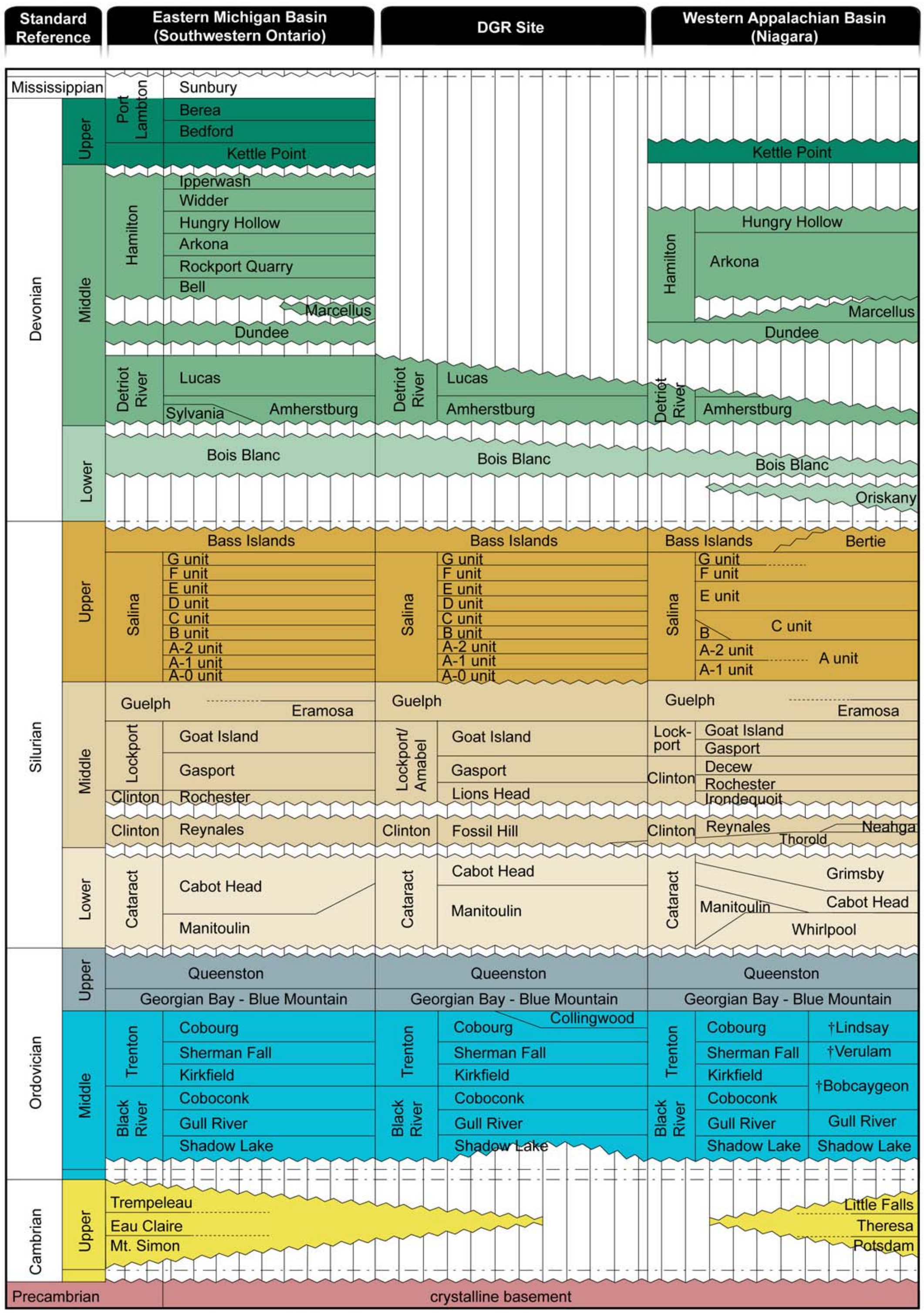


Figure 2.4 Phanerozoic Tectonic Cycles with band widths representing relative tectonic intensity (Sanford, 1993)

2.1.2 Paleozoic Geology

The characteristics of the Paleozoic rocks within the Regional Study Area (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 RSA, the Michigan Basin where the RSA is located, and 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 DGR site and at the western margin of the Appalachian Basin.



*modified from Armstrong and Carter (2006) after Winder and Sanford (1972)
†outcrop nomenclature for Southern and Eastern Ontario

Figure 2.5 Paleozoic Stratigraphy of Southwestern Ontario from locations in the Michigan Basin, Algonquin Arch and Appalachian Basin (modified from Armstrong and Carter, 2006)

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.

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 DGR 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 described in Section 6.0 is also shown on Figure 2.6.

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).

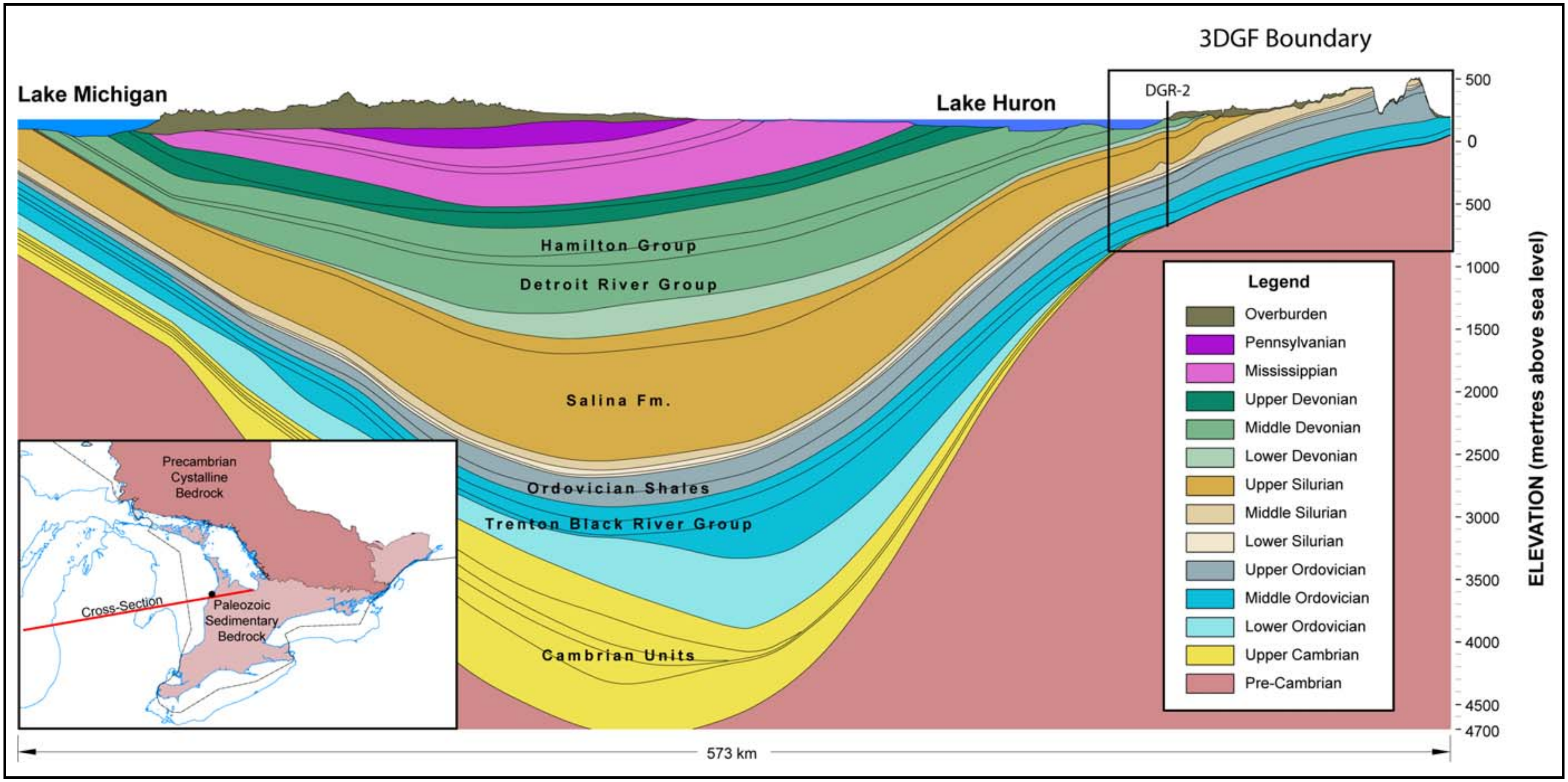


Figure 2.6 Geological Cross-section of the Michigan Basin with the boundary of the regional 3D Geological Framework is shown at the eastern margin of the basin (note: DGR-2 offset from geological cross-section).

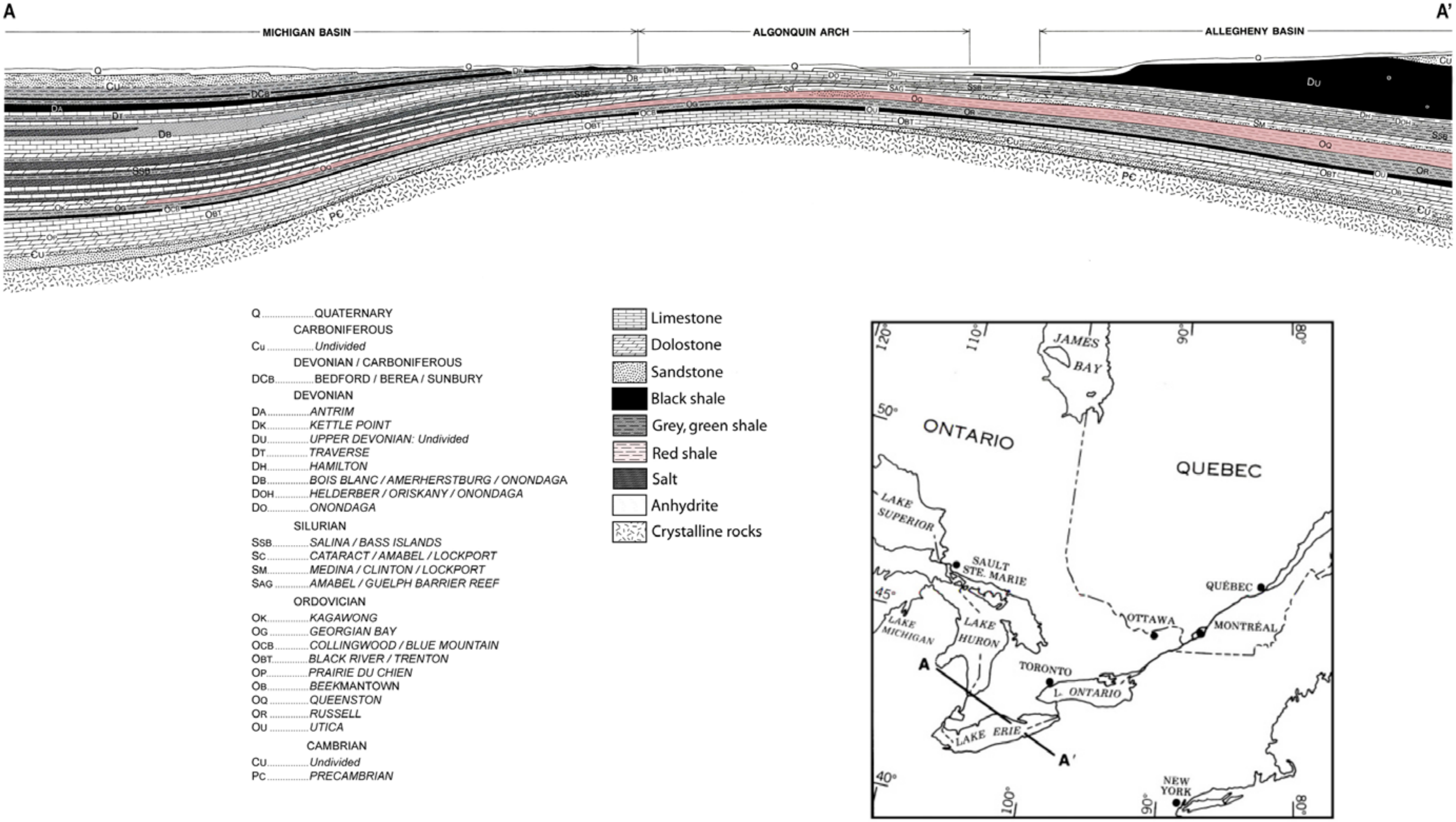


Figure 2.7 Geological Cross-section from Allegheny (Appalachian) to Michigan Basin across the Algonquin Arch (Sanford, 1993). Cross-section location is shown as A-A'.

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 & 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 OPG and GLL, pertinent to the study area was also made available.

This section 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 DGR 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:

a) an analysis of the structure and tectonic history of the Proterozoic basement;

b) determination of the mechanism and tectonic controls acting on the development of the Michigan and Appalachian Basins and the intervening Algonquin Arch, and;

c) 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 site is located just east of the Grenville Tectonic Front within the Central Gneiss Belt. 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;

a) local deformation events associated with the break up of the Atlantic which resulted in Mesozoic rifting and volcanism in eastern Canada and the USA;

b) localized deformation associated with the development of Cordillera in the west (Laramide event); and,

c) some domains of recent faulting and seismicity that remain poorly understood (e.g., New Madrid Seismic zone/Reelfoot Rift, Missouri and Tennessee, Saguenay Rift, St. Lawrence lowlands).

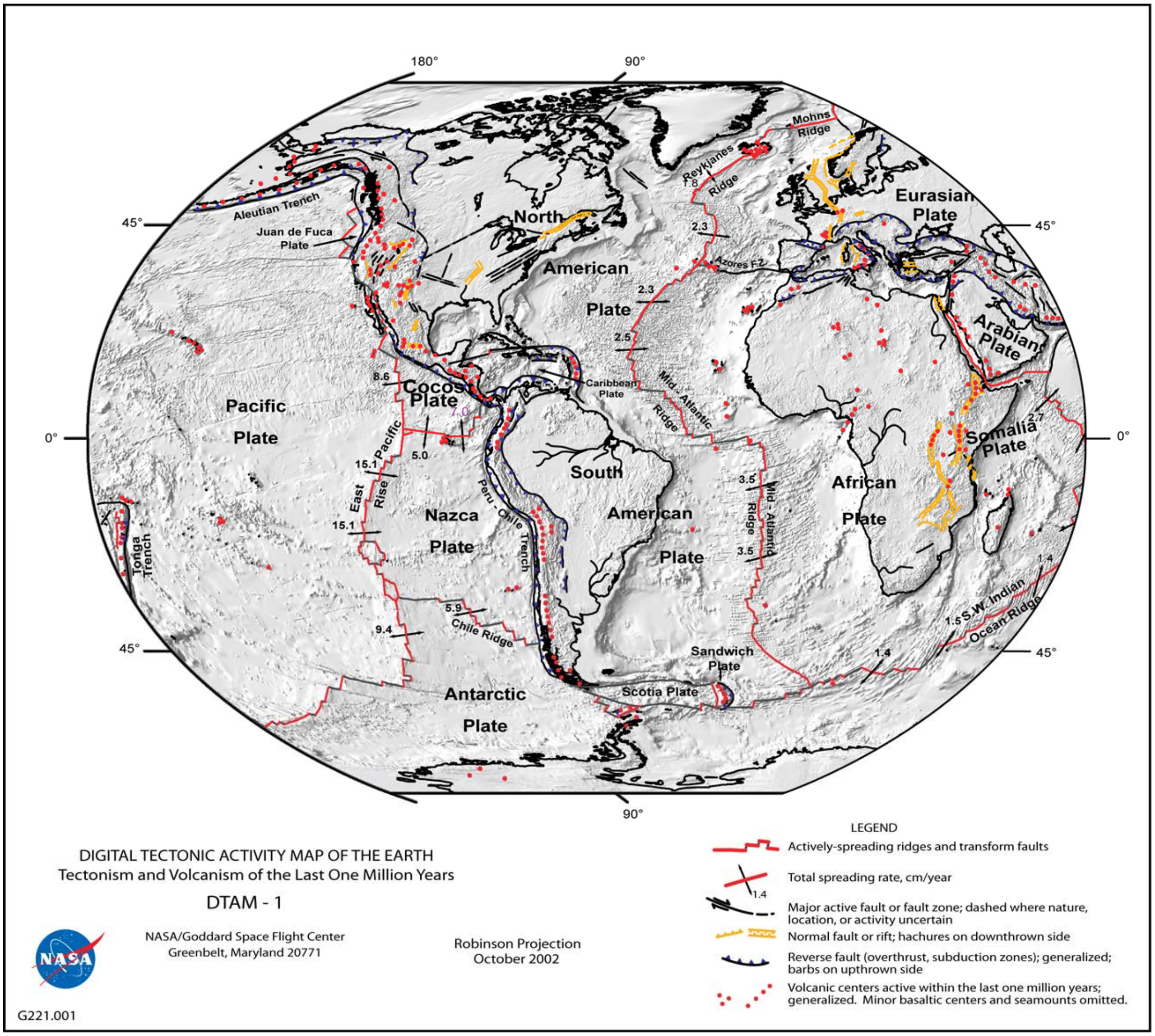


Figure 3.1 **Digital Tectonic Activity Map of the Earth indicating locations of plates, plate boundaries and regions of active faulting and volcanism over the last 1 Ma (NASA 2002 *http://denali.gsfc.nasa.gov/dtam/*)**

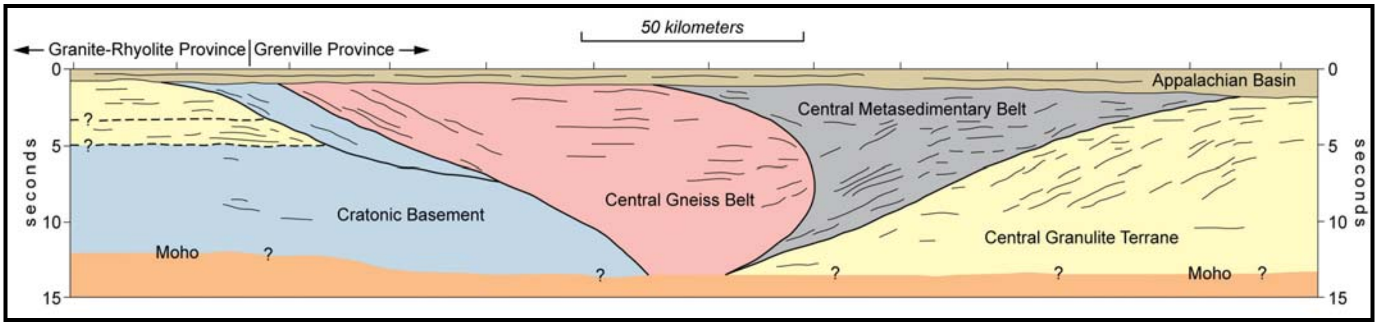


Figure 3.2 **Speculative Interpretation (NW-SE) of Deep Seismic Lines of the Grenville Province COCORP (adapted from Culotta *et al.* 1990)**

Sanford *et al.* (1985) subdivided Southern Ontario south of the Canadian Shield into a number of tectonic blocks (megablocks) based upon the characteristics of basement structures, subsurface faults and surface lineaments (Figure 2.3). The two megablocks most relevant to the DGR are the Bruce and Niagara Megablocks. The study area, located in the Bruce Megablock, occurs in a triangular region bound to the west by the Grenville Front Tectonic Zone, the Algonquin Arch to the south, and approximately at the Georgian Bay Linear Zone (Wllach, 1990) to the east. Sanford *et al.* (1985) further refined and evaluated the block model by introducing a conceptual fracture framework for southwestern Ontario based on contouring of selected Silurian unit isopachs and structure contours on the top of the Silurian Rochester Formation. Figure 3.2 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 simple structure with regularly spaced, ESE to EW faults with down to the south normal displacements that 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 & Harrison 2002), although their spacing is significantly closer. Sanford *et al.*, (1985) further suggest that dissolution of salt was focused along regional fracture patterns resulting in an interpreted distribution of Salina Salt 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.

Given the importance of the block model proposed by Sanford *et al.* (1985) for this study it is useful to comment on this work in light of more recent research. It is difficult to evaluate the block model because primary data on surface lineaments are not reported by the authors. The block model is based on surface lineament patterns derived from low resolution Landsat imagery and compilation of major basement structures. The use of lineaments derived from low resolution satellite imagery as a structural criterion in the Bruce-Niagara region is questionable because of the thickness of Quaternary surficial deposits, which tend to mask near surface faults (should they be present) and fractures compared to the regions of Precambrian exposure to the north, which typically have very thin or 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 & 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). 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 & Engelder 1991; Andjelkovic *et al.* 1996, 1997, 1998).

Johnson *et al.* (1992) note that although such a fracture-framework may exist, the extensive fracture framework conceptualized by Sanford *et al.* (1985) has not been recognized.

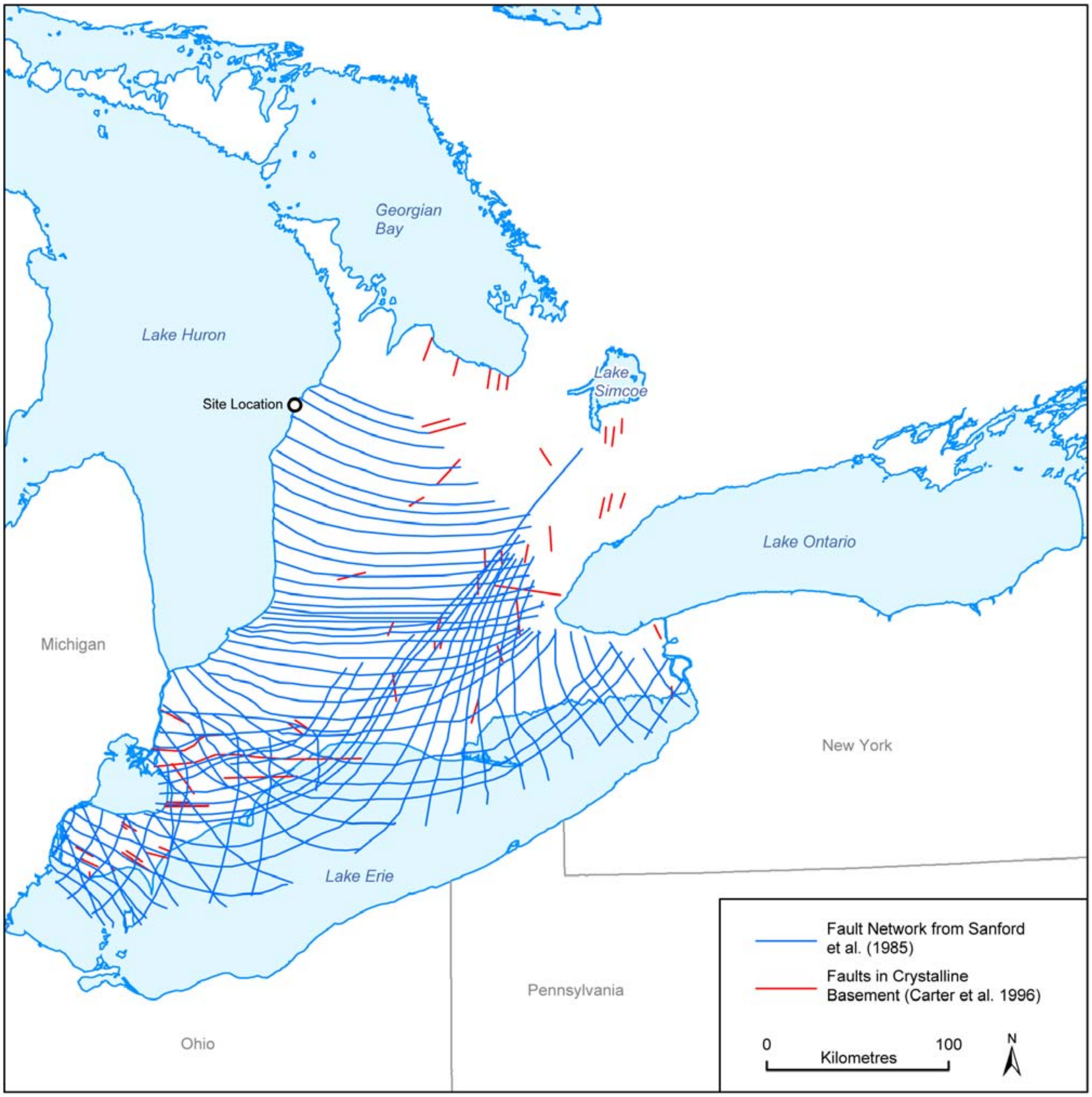


Figure 3.3 Proposed Fracture Framework and Mapped Faults of Southern Ontario (Sanford et al., 1985) that displace the Paleozoic-Precambrian unconformity surface (from Mazurek 2004, after Sanford et al. 1985; Carter et al. 1996).

Although the existence of the Bruce Megablock cannot be validated, it never-the-less presents a useful geographical boundary for comparison, of seismicity and underlying basement structure, with adjacent areas and in providing a convenient basis for discussion. Present data support the interpretation that the Regional Study Area is characterized by a relatively simple basement structure and very low historical seismicity compared to adjacent tectonic blocks (Gartner Lee Ltd., 2008). From this context, the Bruce Megablock may extend further east than that defined by Sanford *et al.*, (1985). The Georgian Bay Linear Zone is not a structural feature that delimits a block, rather it is a surficial expression of the basement rocks, coincident with the water level in Georgian Bay. It is more likely that the block extents to the east and north up to the edge of the Ottawa-Bonnechere-Nippissing graben (e.g., Kumarapeli 1976), continuing to be bound by the Algonquin Arch to the south. Based on this interpretation, that the block represents a geographic zone of stable, low seismicity rock, it is concluded that use of the geographical boundaries of the Bruce Megablock as originally defined by Sanford *et al.* (1985) is acceptable to use for this assessment.

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 line 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 Orogen 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, 1993, 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 (Regional Geomechanics Report, Gartner Lee, 2008) in southern Ontario 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 & 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.

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	Subsidance of Michigan Basin and Arch Uplift (episodic)	NNE	Howell and Vander Pluijm, 1999; Sanford *et al.*, 1985
458 – 431	Taconic Orageny ➤ 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	Alleghanian 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, 1986, 1985
50 – Present	➤ post-glacial uplift ➤ NE-SW compression (from ridge push)	ENE	Barnett, 1992

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. 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:

a) vertical surface motions driven by thermal or density forces in the lithosphere;
b) mantle flow; or
c) subsidence and uplift related to horizontally transmitted principle tectonic stresses.

A detailed analysis of the subsidence history of the Michigan Basin by Howell & 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 & Carter 1995; Carter *et al.* 1996). Figure 3.4 (modified from Boyce and Morris, 2002, and Carter, 2006) 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 tectonic 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 data images these structures, which dip gently to moderately to the east (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 of these subdivisions is the Huron domain, which coincides with the Bruce Megablock that is characterized by a relatively featureless gravity and aeromagnetic anomaly patterns (Figure 3.5). Figure 3.5 (Wallach *et al*., 1998) presents three maps of southern Ontario, these include i) a gravity map, ii) an aeromagnetic map and iii) the resulting interpretive map, which shows the interpreted gravimetric and magnetic lineaments. Wallach *et al.* (1998) have characterized the eastern boundaries of the structurally featureless domain (including the Regional Study Area) 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's interpretation, as published in a report for the Atomic Energy Control Board (Wallach, 1990), Roest (2005) 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.* (1995) is marginal. A similar lack of correspondence can be noted when structure contours on the unconformity are compared with the fracture framework model. Likewise, the fracture framework model is difficult to reconcile with regional studies of jointing in southern Ontario (Gartner Lee Limited, Regional Geomechanics, 2008).

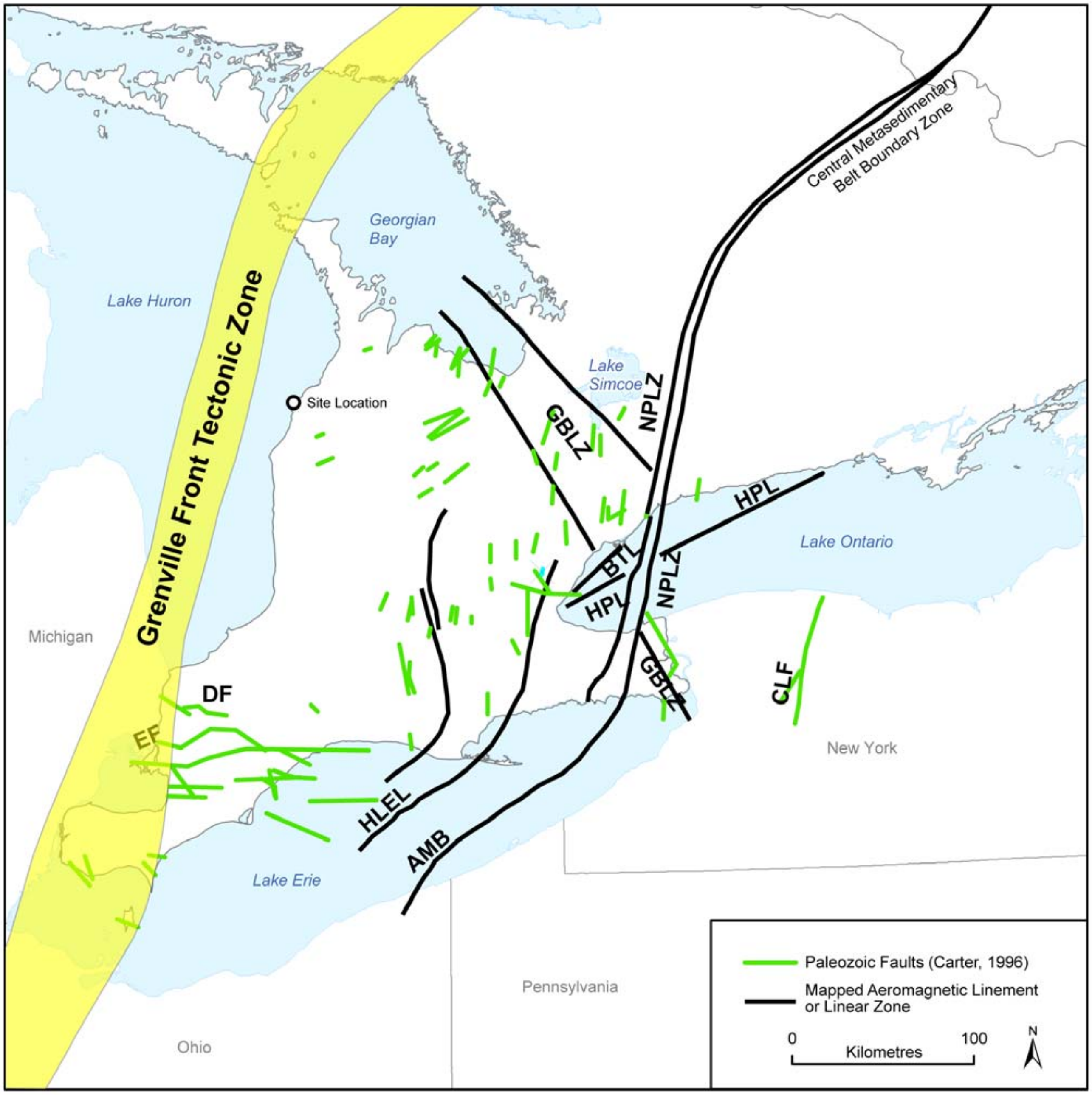


Figure 3.4 **Structural Subdivisions of Precambrian Basement with faults (Carter et al., 1996, and Carter, 2006), aeromagnetic lineaments and lithotectonic domain boundaries (after Carter and Easton, 1990; Easton and Carter, 1995; Wallach et al., 1998; Jacobi and Fountain, 1993). CMBBZ: Central Metasedimentary Belt Boundary Zone; AMB: Akron Magnetic Boundary; NPLZ: Niagara–Pickering Linear Zone; HLEL: Hamilton– Lake Erie Lineament; BTL: Burlington–Toronto Lineament; HPL: Hamilton– Presqu’ile Lineament; GBLZ: Georgian Bay Linear Zone; EF: Electric fault; DF: Dawn fault; CLF: Clarendon – Linden fault (modified from Boyce and Morris, 2002).**

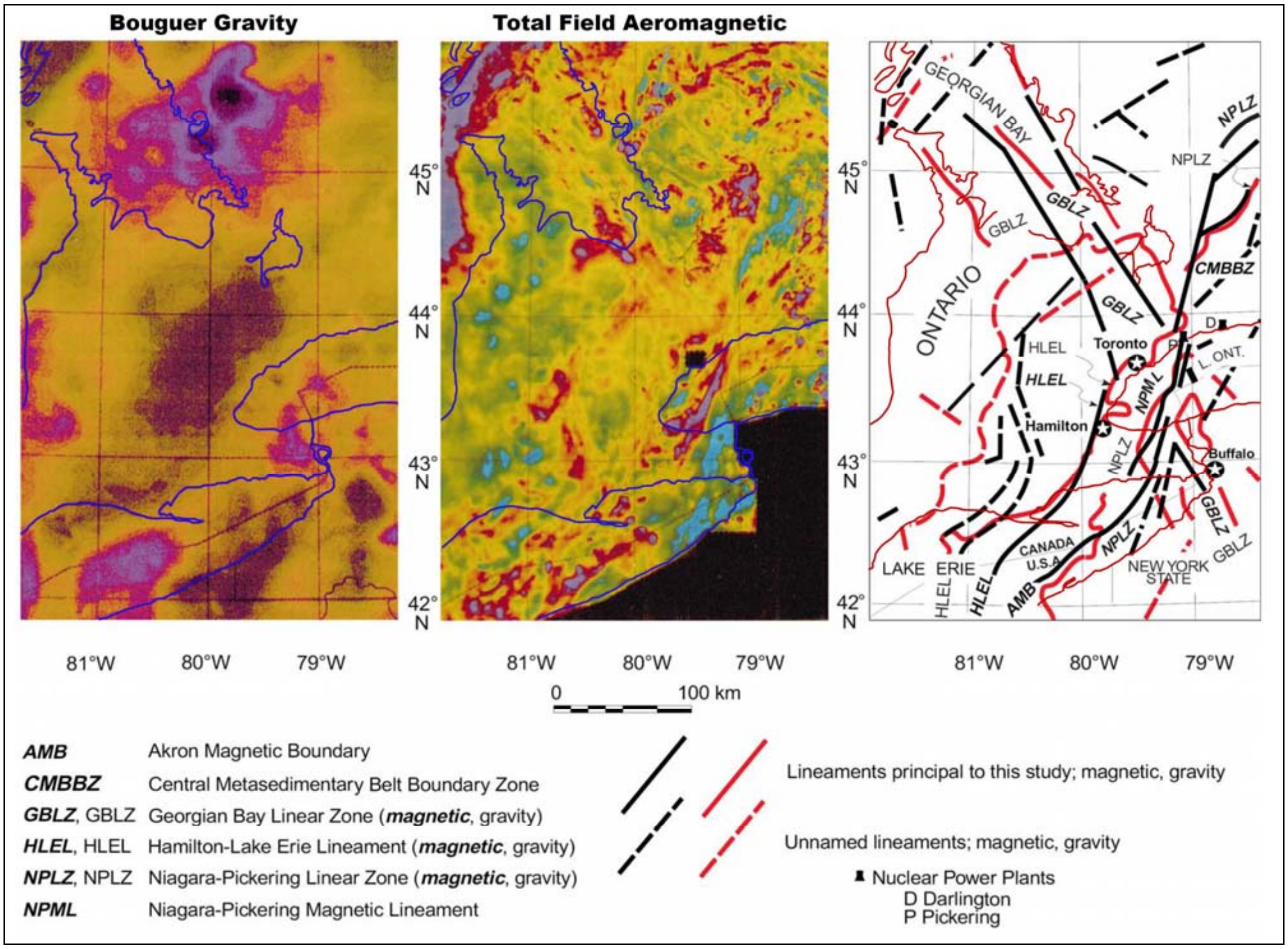


Figure 3.5 Southcentral Ontario Bouguer Gravity and Total-field Aeromagnetic Map (left and centre) with the interpretive map showing the magnetic and gravimetric lineaments on the right. Different shading reflects different densities on the gravity map and different intensities on the magnetic map (adapted from Wallach et al. 1998).

Given this brief description of lineaments and blocks, consideration is now given to the use of the Bruce Megablock as a useful context for this geosynthesis. If anything, the Bruce Megablock extents further east than that defined by Sanford *et al.*, (1985). The Georgian Bay Linear Zone is not a structural feature that delimits a block, rather it is a surficial expression of the basement rocks, coincident with the water level in Georgian Bay. It is more likely that the block extents to the east and north up to the edge of the Ottawa-Bonnechere-Nippissing graben (e.g., Kumarapeli 1976), continuing to be bound by the Algonquin Arch to the south. Based on this interpretation, that the block is just as stable and probably more extensive, it is concluded that use of the Bruce Megablock as originally defined by Sanford *et al.* (1985) is acceptable to use for this assessment.

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. The majority of fractures observed in Southern Ontario are joints. The Regional Geomechanics Report (Gartner Lee Limited, 2008) 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:

a) during vertical compaction under conditions of high pore fluid pressure;
b) during tectonic loading events:
    i) compressional = horizontal maximum stress + horizontal minimum stress;
    ii) extensional = vertical maximum stress + horizontal minimum stress; and
c) unloading and isostatic rebound (horizontal maximum stress + vertical minimum stress).

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

Figure 3.6 shows a generalized map of joint orientations derived from a variety of sources (Andjelkovic *et al.* (1996, 1997, 1998), Gartner Lee (1996), Ontario Power Generation (2007), and others). The “propeller plots” shown on Figure 3.6 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.

Andjelkovic *et al.* (1996, 1997, 1998) measured ~7,000 fracture orientations from outcrops and quarries between Georgian Bay and Kingston (Figure 3.7). 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 & 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 year) 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.

Figure 3.6 Joint Orientations of Southcentral Ontario plotted as Gausian contoured and smoothed rose diagrams for the Paleozoic cover and Precambrian basement (Regional Geomechanics, GLL, 2008).

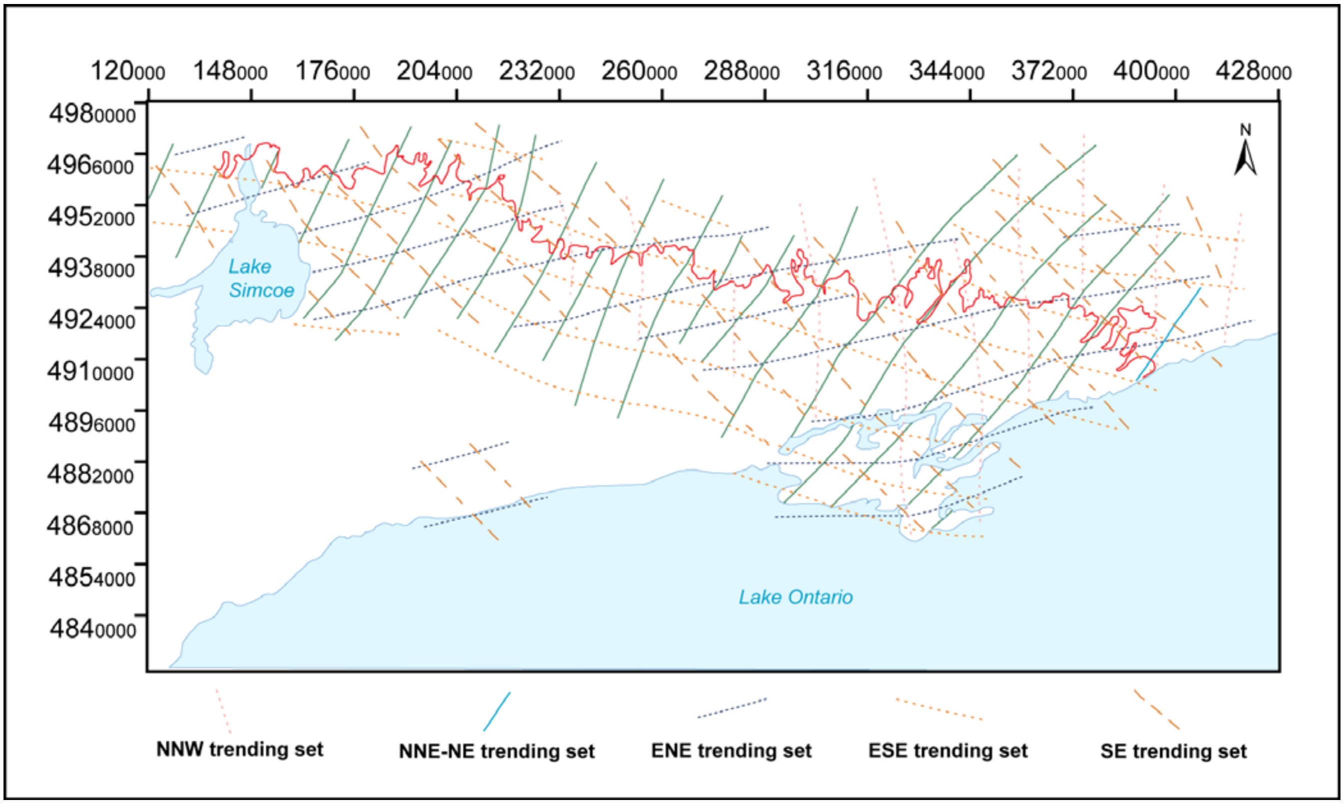


Figure 3.7 Trajectories of Peak Joint Orientations in Southcentral Ontario (Andjelkovic et al. 1997)

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, 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 3.6) is also apparent in the major joint set at each point.

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

1. that topographic lineaments are controlled by fractures in the underlying rocks (i.e., lineaments are a good proxy for characterizing bedrock fractures);
2. that fractures in the Paleozoic rocks retain a remarkable consistency orientation across the region (i.e., they are *systematic*); and
3. that 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.

Of some interest are the Ordovician strata, which under the Bruce site may host the 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 (Figures 3.6 and 3.7).

Andjelkovic *et al.* (1996, 1997, 1998) have proposed the following scenarios for the formation of the major systematic vertical joint sets in South central Ontario (Figure 3.7), in chronological order.

a) ***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 (a) above).

b) ***SE-trending set***: most likely formed due to high in-plane stresses transmitted into the foreland of the Appalachian orogeny (i.e., Mechanism (b) above).

c) ***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 (b) above).

d) ***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 (b) above).

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) indicate 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 (Gartner Lee Limited, 2008b).

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 formation of rift structures in eastern North America (St. Lawrence, Ottawa-Bonnechere-Nipissing, 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, the latter resulted in the formation of numerous near surface pop-up structures mostly oriented at a high angle to the present maximum horizontal in situ stress direction. Some ENE trending joints may have also occurred at this time, although precise timing criteria are lacking.

4. PALEOZOIC STRATIGRAPHY AND SEDIMENTOLOGY OF SOUTHERN ONTARIO

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.

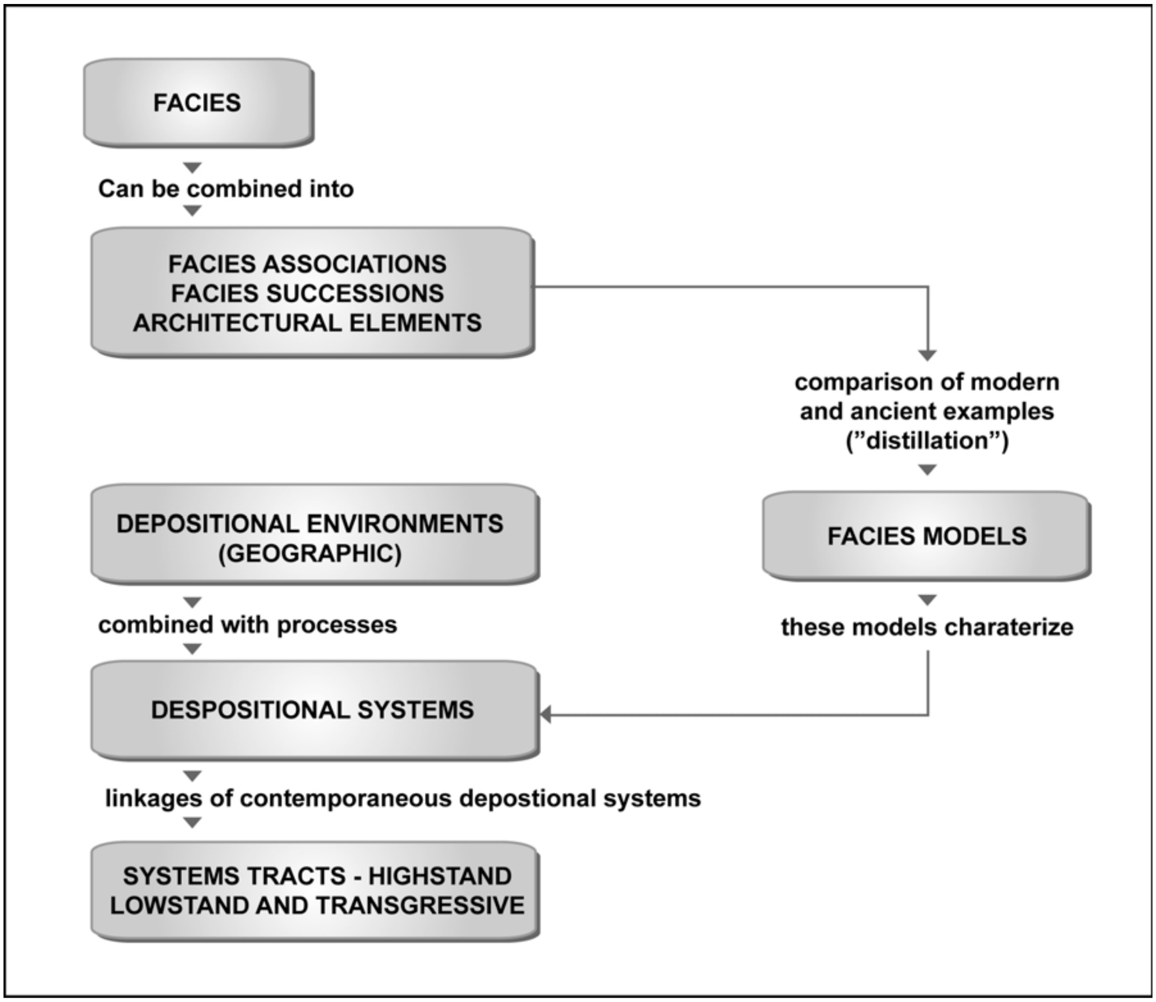


Figure 4.1 Facies Models Flow Chart (modified from Walker, 1992)

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 association (comprised of similar and predictable small scale facies) influences 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.

4.2 Discussion

The following descriptions are generally organized according to the main sequence stratigraphic associations in southern Ontario.

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 by Bailey Geological Services and Cochrane (1984a) to have been the result of arch rejuvenation and uplift during Early Paleozoic times. Well log records obtained from the OGSRL 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 in Section 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, 1999). In some locations, including the DGR 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, 1999). 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, 1999, Johnson *et al.*, 1992, and 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).

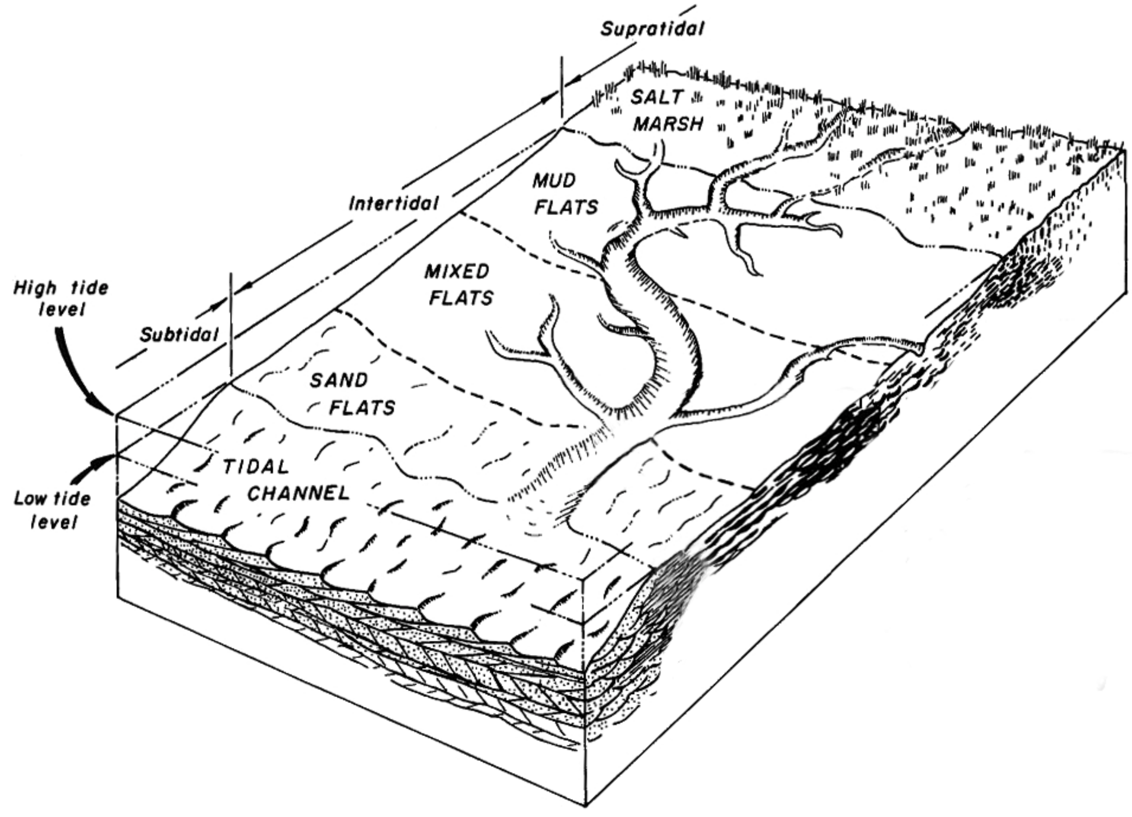


Figure 4.2 Cambrian Depositional Facies Model showing setting and structures of siliciclastics deposits. The tidal flats fine toward the high-tide level, passing gradationally from sand flats, through mixed flats, to mud flats and salt marshes (Dalrymple, 1992)

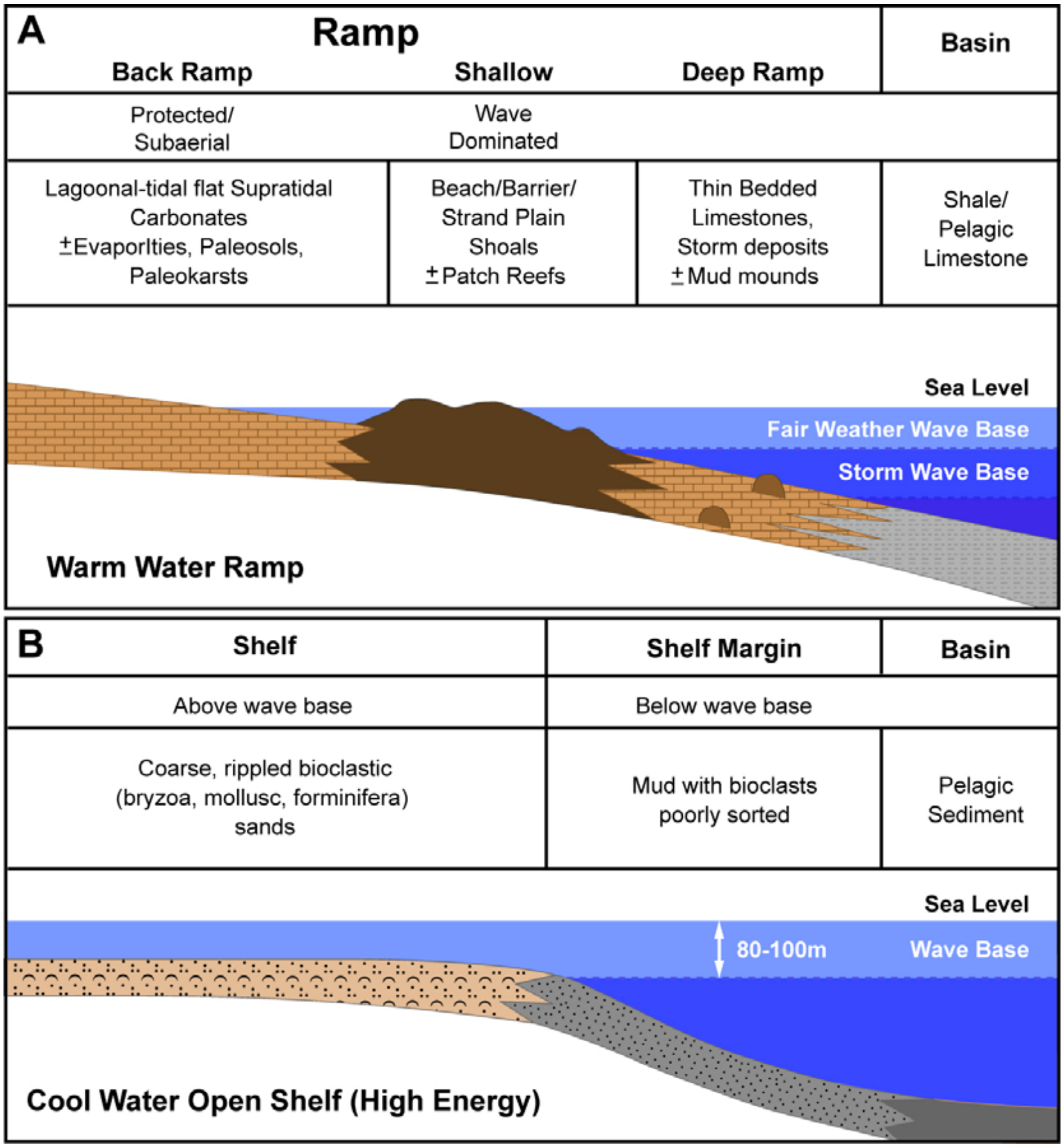


Figure 4.3 Facies Models for Unrimmed Shelves (A) warm water ramps; (B) cool water open unrimmed shelf - high energy (Jones and Desrochers, 1992).

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 described in Section 6 of this report shows the resulting distribution of Cambrian deposits in the Regional Study Area (RSA). A period of marine transgression during the Ordovician was responsible for the subsequent Black River Group, which was deposited over the unconformity.

4.2.2 Ordovician Carbonates (Black River and Trenton Groups)

In the subsurface of southwestern Ontario, including the DGR site, the Middle Ordovician carbonates are divided into two groups, the Black River and Trenton groups. 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 (Figure 2.5). 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 was responsible for the sequence of Black River and Trenton facies assemblages that characterize a succession from supratidal and tidal flat clastics/carbonates to lagoonal carbonates and offshore shallow water and deep shelf carbonates (Coniglio *et al.* 1990). During deposition of the Blackriver and Trenton groups 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). During this period of time the Algonquin and Frontenac Arches had very subdued relief unlike the geometry seen today, which has resulted from subsidence in the Appalachian and Michigan Basins. 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 Formations. 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.

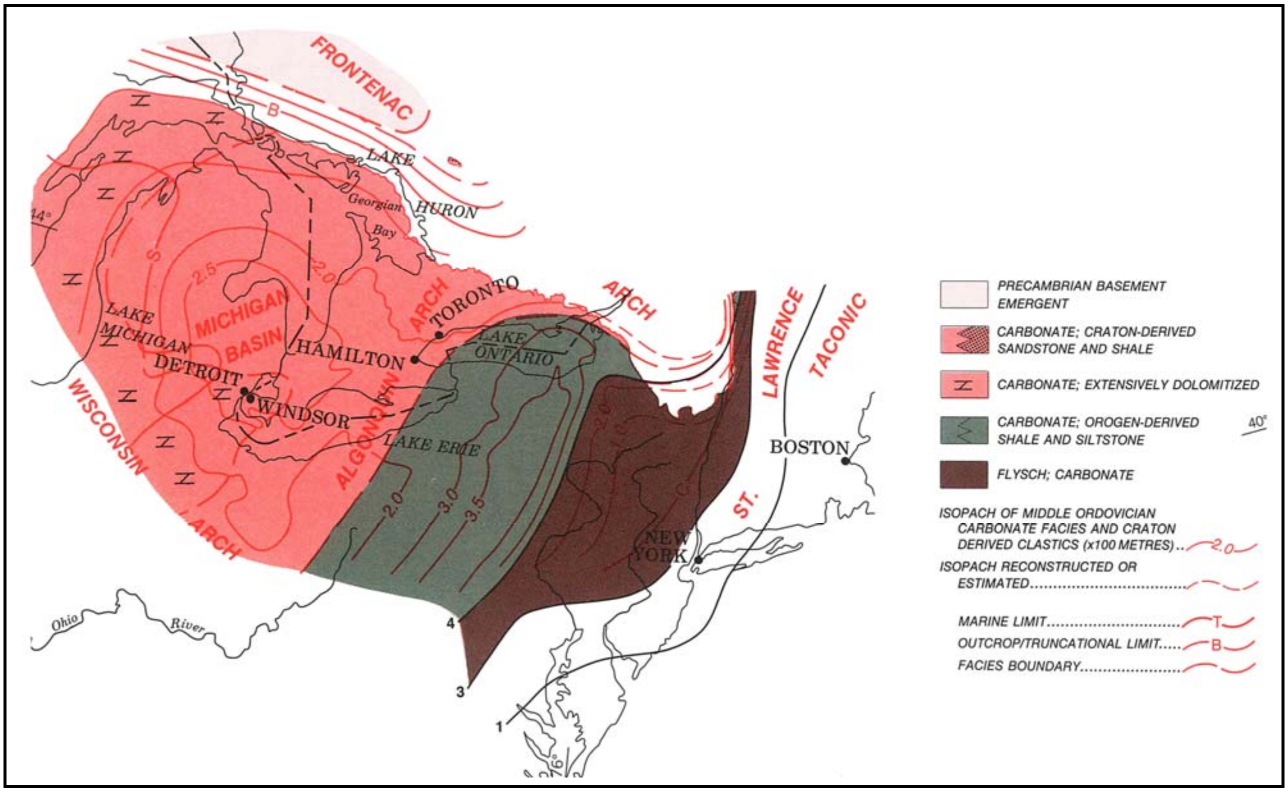


Figure 4.4 Middle Ordovician Depositional Sequence and Isopach Thickness (Sanford, 1993b)

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.

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. Coniglio (pers. comm., 2007) noted that 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).

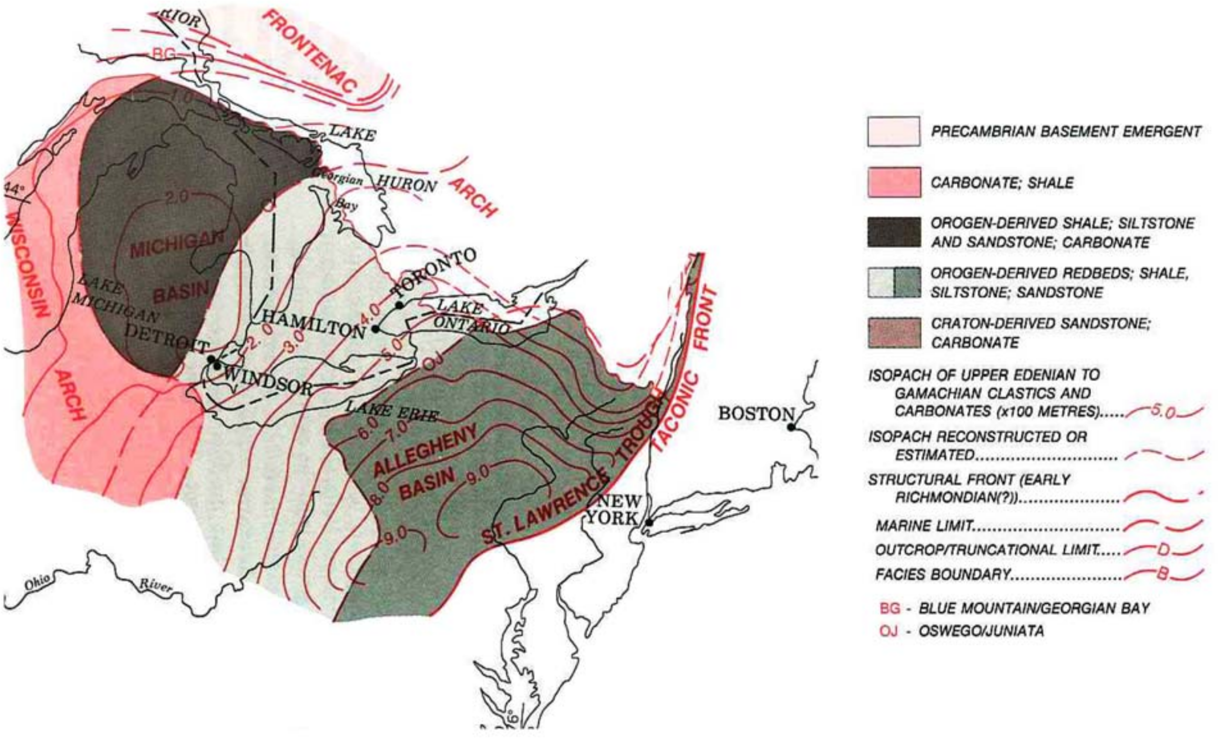


Figure 4.5 Upper Ordovician Depositional Sequence and Isopach Thickness (Sanford, 1993)

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.).

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) and is 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 site stratigraphy shown in Figure 5.1 (Intera, 2008) derived from the DGR Site-Characterization program describes the characteristic lithologies and specific depositional environment of the Shadow Lake Formation through to the Collingwood member of the Cobourg Formation. The Ordovician 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 sequence from the Sherman Fall Formation through the Cobourg Formation represents a gradual deepening or marine transgression across the broad carbonate shelf. Hamblin (1999) suggests that the Collingwood Member was deposited in relatively shallower water based on the presence of storm deposit facies. Work by Melchin *et. al*. (1994), however, describes the Collinwood Member as a deep shelf deposit occurring at the peak of the marine transgression, which preceded the influx of the overlying Ordovician Shales.

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.

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, 1993) 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 only minor limestone interbeds are described within the Queenston Formation (*Section 5*). The absence of limestone interbeds is the result of the site paleo-geography, which was well south of the main carbonate source, the Kegawong Member.

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:

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

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).

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.

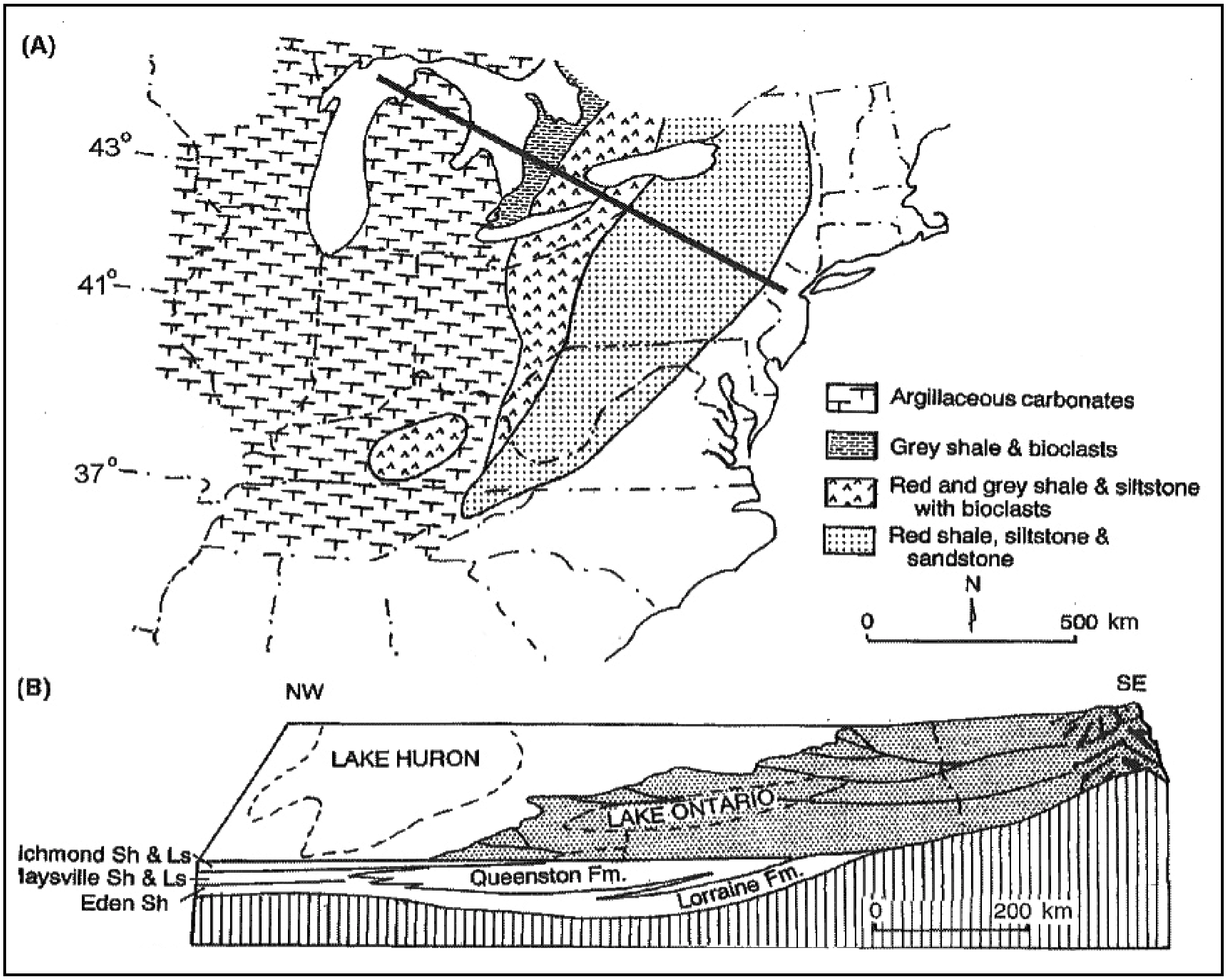


Figure 4.6 Upper Ordovician Taconic Clastic Wedge Facies Model (Brogly et al., 1998).

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

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 Regional Study Area) provide evidence of this erosional surface (Hamblin, 1999).

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) and are 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 overly 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).

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 (Niagaran Carbonates) 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 carbonate, 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 4.8). 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 Sandford *et al*., (1985) has not been fully recognized.

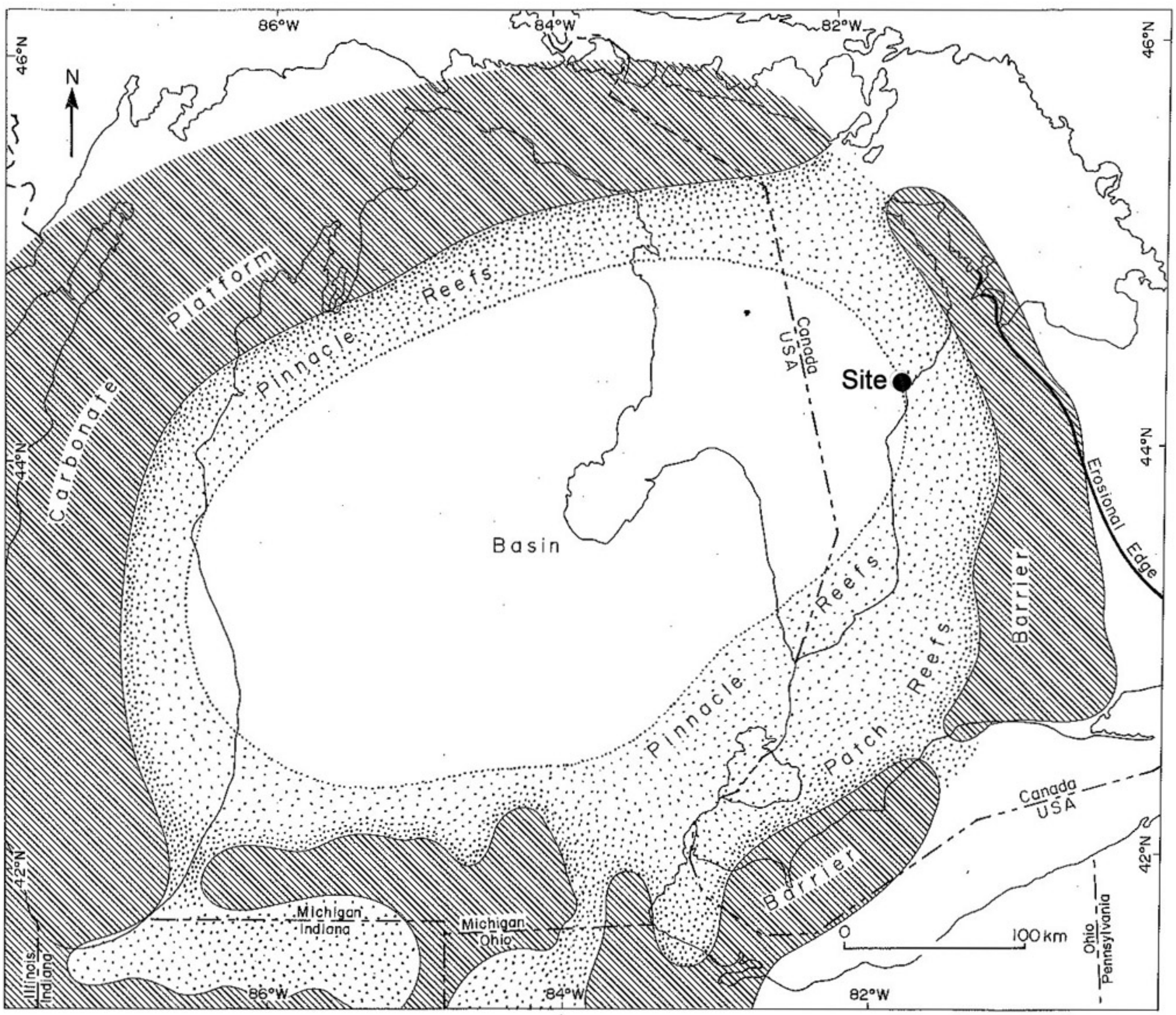


Figure 4.7 Distribution of Middle and Upper Silurian Niagaran Carbonate Facies (Johnson et al., 1992).

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 and 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.

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 DGR site and extending to the basin margin pinching out against the Algonquin Arch. The distribution of salt is interpreted to have been much greater in extent when initially deposited than is presently found. The salt is interpreted (Sanford, 1965, and 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. 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 are described in Section 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.

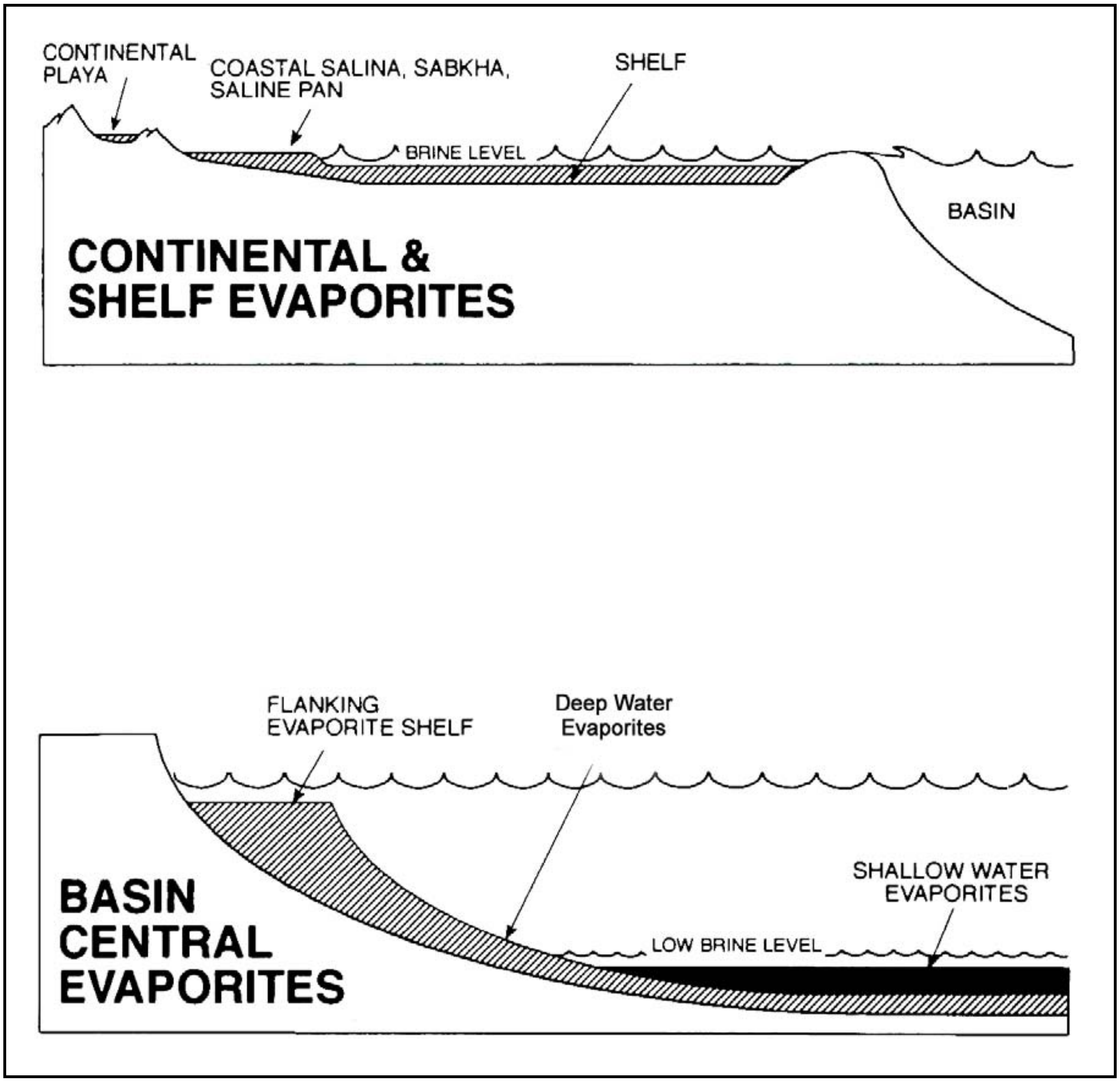


Figure 4.8 Depositional Model for Shelf and Basin Centre Evaporite Formations (James and Kendall, 1992)

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 Amhurstburg Formation is roughly equivelent 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 overlyies 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.

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. 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 Section 6).

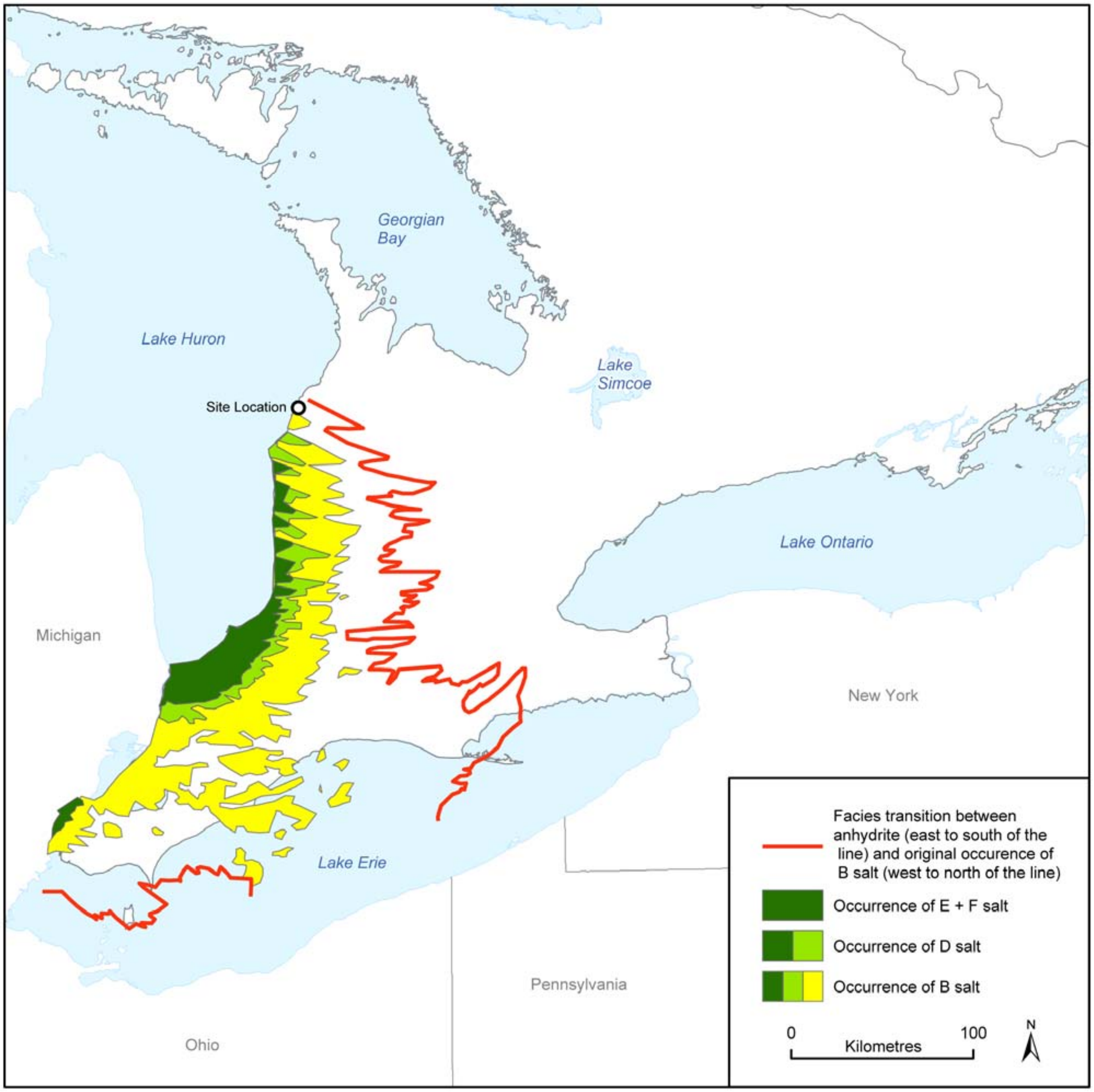


Figure 4.9 Distribution of Salt in the Salina Formation in Southern Ontario (Sanford *et al.* 1985)

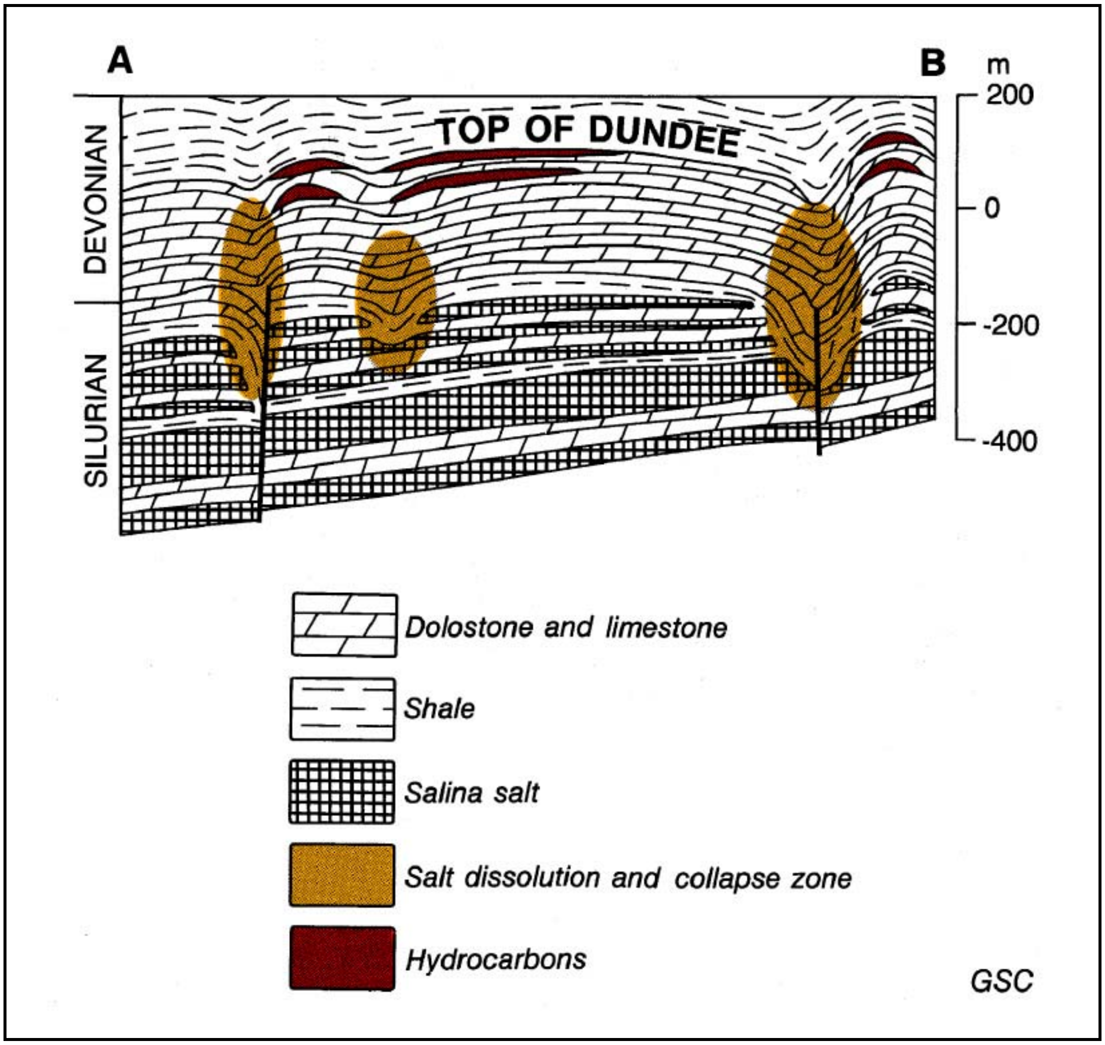


Figure 4.10 Illustration of Fault-related Salt Dissolution in the Salina Formation NNW-SSE profile across the Petrolia oil field near Sarnia (Sanford, 1993).

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 deprssions.

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, flat lying 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.

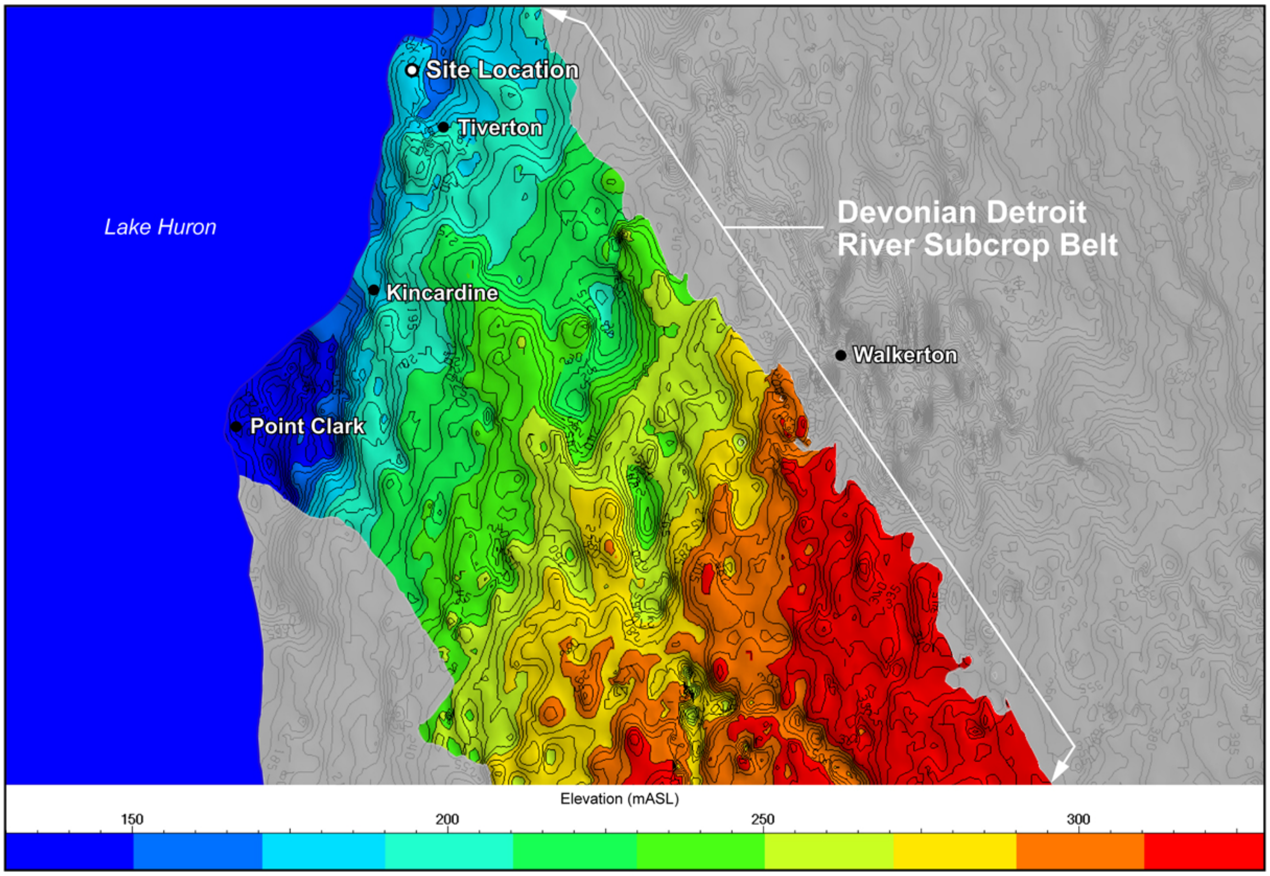


Figure 4.11 Bedrock Surface Contour Map of Devonian Detroit River subcrop belt derived from OGS digital mapping (MRD207). The bedrock surface elevations ranges from approximately 150 mASL at the Lake Huron shore to 300 mASL further inland.

5. DGR SITE GEOLOGY

The DGR site geology encountered during drilling of DGR-1 and DGR-2 is summarized in Figure 5.1. The information used to compile this figure was provided by Intera (2008) and was collected as part of the Phase I site-specific field investigations as outlined in the Geoscientific Site Characterization Plan (Intera, 2006). 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 on Figure 5.1.

The following discussion compares that the results of the DGR site drilling investigations with the information presented in this Regional Geology report.

The work of Bailey Geological Services and Cochrane (1984a), Carter et. al., (1996) and others suggests that the DGR site is within the Upper Cambrian subcrop belt. DGR-2 encountered approximately 17 m of Upper Cambrian sandstone and dolostones, a thickness and lithology consistent with the sites position 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 (2008) 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, and Armstrong and Carter 2006). For example, minor bioclastic limestone interbeds within the Queenston Formation, which likely represent incursions of the Kegawong 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 DGR 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.

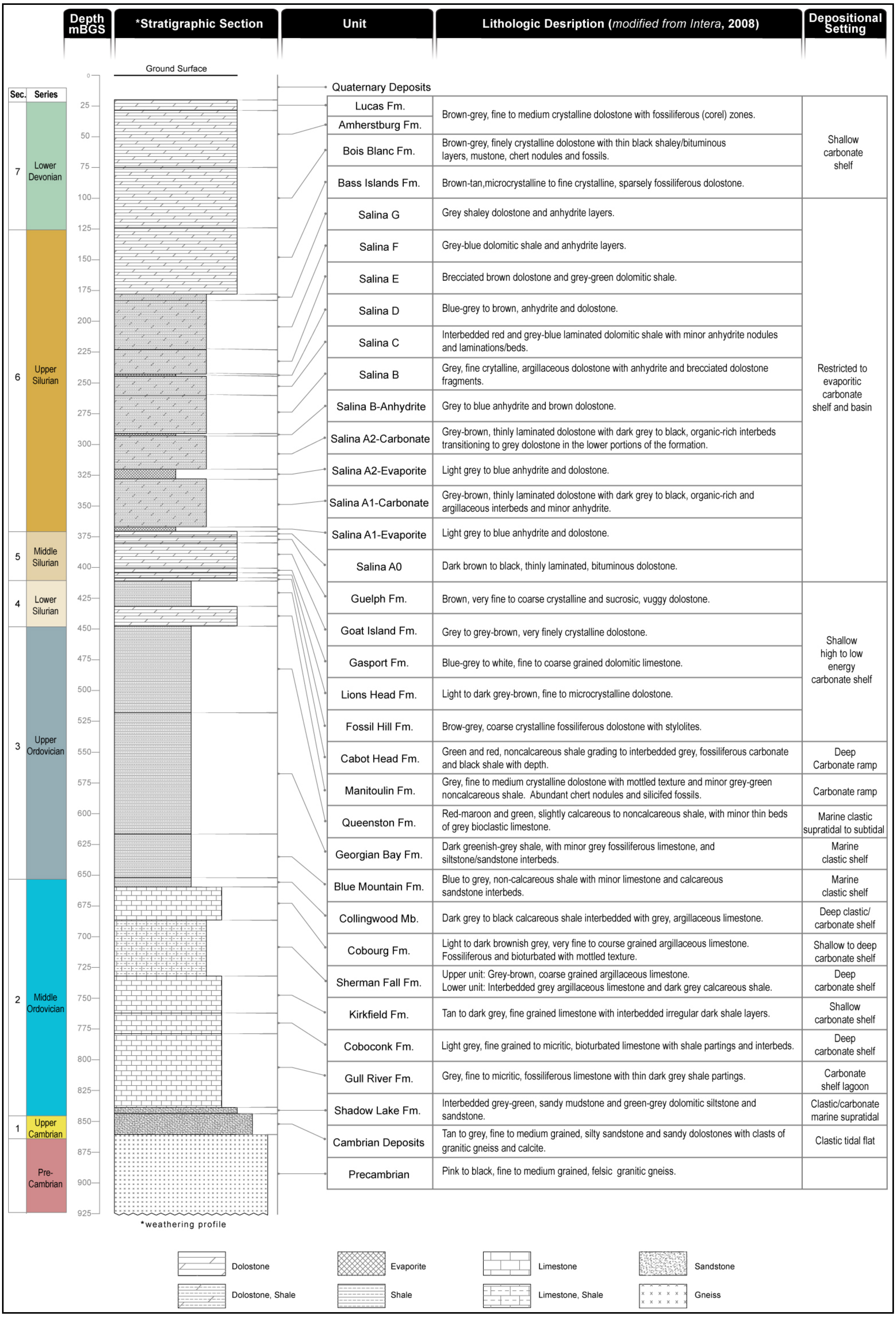
The Middle Silurian carbonate units are represented by a combined 37 m of predominately dolostone and fossiliferous dolostone units. The relatively thin vertical extent of these carbonate units combined with stratigraphic desciptions, (particularly the Guelph and Gasport-Goat Island formations) confirms 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, 1969a and 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 DGR 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 DGR site are consistent with the regional descriptions as summarized in Armstrong and Carter (2006).

The Lower Devonian Bois Blanc Formation at the DGR 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 (2008) 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, and Armstrong and Carter, 2006) are consistent with the DGR site description.

5.1 Summary

The geology encountered in boreholes DGR-1 and DGR-2 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.



Unit	Lithologic Desription (*modified from Intera*, 2008)	Depositional Setting
Lucas Fm. Amherstburg Fm.	Brown-grey, fine to medium crystalline dolostone with fossiliferous (corel) zones.	Shallow carbonate shelf
Bois Blanc Fm.	Brown-grey, finely crystalline dolostone with thin black shaley/bituminous layers, mustone, chert nodules and fossils.	
Bass Islands Fm.	Brown-tan,microcrystalline to fine crystalline, sparsely fossiliferous dolostone.	
Salina G	Grey shaley dolostone and anhydrite layers.	Restricted to evaporitic carbonate shelf and basin
Salina F	Grey-blue dolomitic shale and anhydrite layers.	
Salina E	Brecciated brown dolostone and grey-green dolomitic shale.	
Salina D	Blue-grey to brown, anhydrite and dolostone.	
Salina C	Interbedded red and grey-blue laminated dolomitic shale with minor anhydrite nodules and laminations/beds.	
Salina B	Grey, fine crytalline, argillaceous dolostone with anhydrite and brecciated dolostone fragments.	
Salina B-Anhydrite	Grey to blue anhydrite and brown dolostone.	
Salina A2-Carbonate	Grey-brown, thinly laminated dolostone with dark grey to black, organic-rich interbeds transitioning to grey dolostone in the lower portions of the formation.	
Salina A2-Evaporite	Light grey to blue anhydrite and dolostone.	
Salina A1-Carbonate	Grey-brown, thinly laminated dolostone with dark grey to black, organic-rich and argillaceous interbeds and minor anhydrite.	
Salina A1-Evaporite	Light grey to blue anhydrite and dolostone.	
Salina A0	Dark brown to black, thinly laminated, bituminous dolostone.	
Guelph Fm.	Brown, very fine to coarse crystalline and sucrosic, vuggy dolostone.	Shallow high to low energy carbonate shelf
Goat Island Fm.	Grey to grey-brown, very finely crystalline dolostone.	
Gasport Fm.	Blue-grey to white, fine to coarse grained dolomitic limestone.	
Lions Head Fm.	Light to dark grey-brown, fine to microcrystalline dolostone.	
Fossil Hill Fm.	Brow-grey, coarse crystalline fossiliferous dolostone with stylolites.	
Cabot Head Fm.	Green and red, noncalcareous shale grading to interbedded grey, fossiliferous carbonate and black shale with depth.	Deep Carbonate ramp
Manitoulin Fm.	Grey, fine to medium crystalline dolostone with mottled texture and minor grey-green noncalcareous shale. Abundant chert nodules and silicifed fossils.	Carbonate ramp
Queenston Fm.	Red-maroon and green, slightly calcareous to noncalcareous shale, with minor thin beds of grey bioclastic limestone.	Marine clastic supratidal to subtidal
Georgian Bay Fm.	Dark greenish-grey shale, with minor grey fossiliferous limestone, and siltstone/sandstone interbeds.	Marine clastic shelf
Blue Mountain Fm.	Blue to grey, non-calcareous shale with minor limestone and calcareous sandstone interbeds.	Marine clastic shelf
Collingwood Mb.	Dark grey to black calcareous shale interbedded with grey, argillaceous limestone.	Deep clastic/ carbonate shelf
Cobourg Fm.	Light to dark brownish grey, very fine to course grained argillaceous limestone. Fossiliferous and bioturbated with mottled texture.	Shallow to deep carbonate shelf
Sherman Fall Fm.	Upper unit: Grey-brown, coarse grained argillaceous limestone. Lower unit: Interbedded grey argillaceous limestone and dark grey calcareous shale.	Deep carbonate shelf
Kirkfield Fm.	Tan to dark grey, fine grained limestone with interbedded irregular dark shale layers.	Shallow carbonate shelf
Coboconk Fm.	Light grey, fine grained to micritic, bioturbated limestone with shale partings and interbeds.	Deep carbonate shelf
Gull River Fm.	Grey, fine to micritic, fossiliferous limestone with thin dark grey shale partings.	Carbonate shelf lagoon
Shadow Lake Fm.	Interbedded grey-green, sandy mudstone and green-grey dolomitic siltstone and sandstone.	Clastic/carbonate marine supratidal
Cambrian Deposits	Tan to grey, fine to medium grained, silty sandstone and sandy dolostones with clasts of granitic gneiss and calcite.	Clastic tidal flat
Precambrian	Pink to black, fine to medium grained, felsic granitic gneiss.	

Figure 5.1 DGR Site Stratigraphy

6. 3D REGIONAL GEOLOGICAL FRAMEWORK

The primary purpose of the 3D Geological Framework (3DGF) was to capture and present the current geological understanding of the Palaeozoic sedimentary formations of Southern Ontario for a portion of the Michigan Basin. The 3DGF encompasses an area of approximately 35,000 km^2 centred on the DGR site (Figures 6.1, 6.2 and 2.6). This area was selected to encompass the Regional Hydrogeological Study boundary and forms the basis for the hydrostratigraphic modelling framework.

In addition to providing the basis for the hydrostratigraphy, the 3DGF is also designed to provide both context to the site characterization work, and to provide a rationale for extrapolation of site conditions beyond the DGR site. The following provides a description of, a) development tools, b) data sources, c) data verification procedures, d) workflow, and e) limitations of the 3D geological framework.

6.1 Development Tools

Itasca Consulting Canada Inc. was retained by OPG to work closely with Gartner Lee Limited in developing a three-dimensional Geological Framework model (3DGF). The framework was designed using Gocad^{TM} software, an advanced 3D earth modelling and scientific visualization technology. The base of the model extends from the Precambrian basement to the surface topography, including watershed features (lakes, rivers), and bathymetry (Figure 6.1). A discussion of the development tools is presented in Appendix A1. The 3DGF presented in this report represents Version 01.

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 Regional Study Area contained at total of 341 wells, which were reduced to 302 wells (Appendix A2) 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 purpose of the wells can be generally grouped into three main categories:

a) those wells drilled to prove salt resources near the southern portion of the RSA;
b) oil/gas exploration wells drilled into Silurian strata (primarily reefs); and
c) oil/gas exploration wells drilled into Ordovician strata.

In addition to the wells within the RSA, a further 57 petroleum Reference Wells (Open File Report 6191, Armstrong and Carter, 2006) (Appendix A4) and 76 petroleum wells from the Michigan State Geological Survey Digital Well Database located outside of the RSA were used (Appendix A3). Figure A1 (Appendix A) shows the location of all wells used in the construction of the 3DGF. Other key sources of data also included downhole geophysics (used to verify well

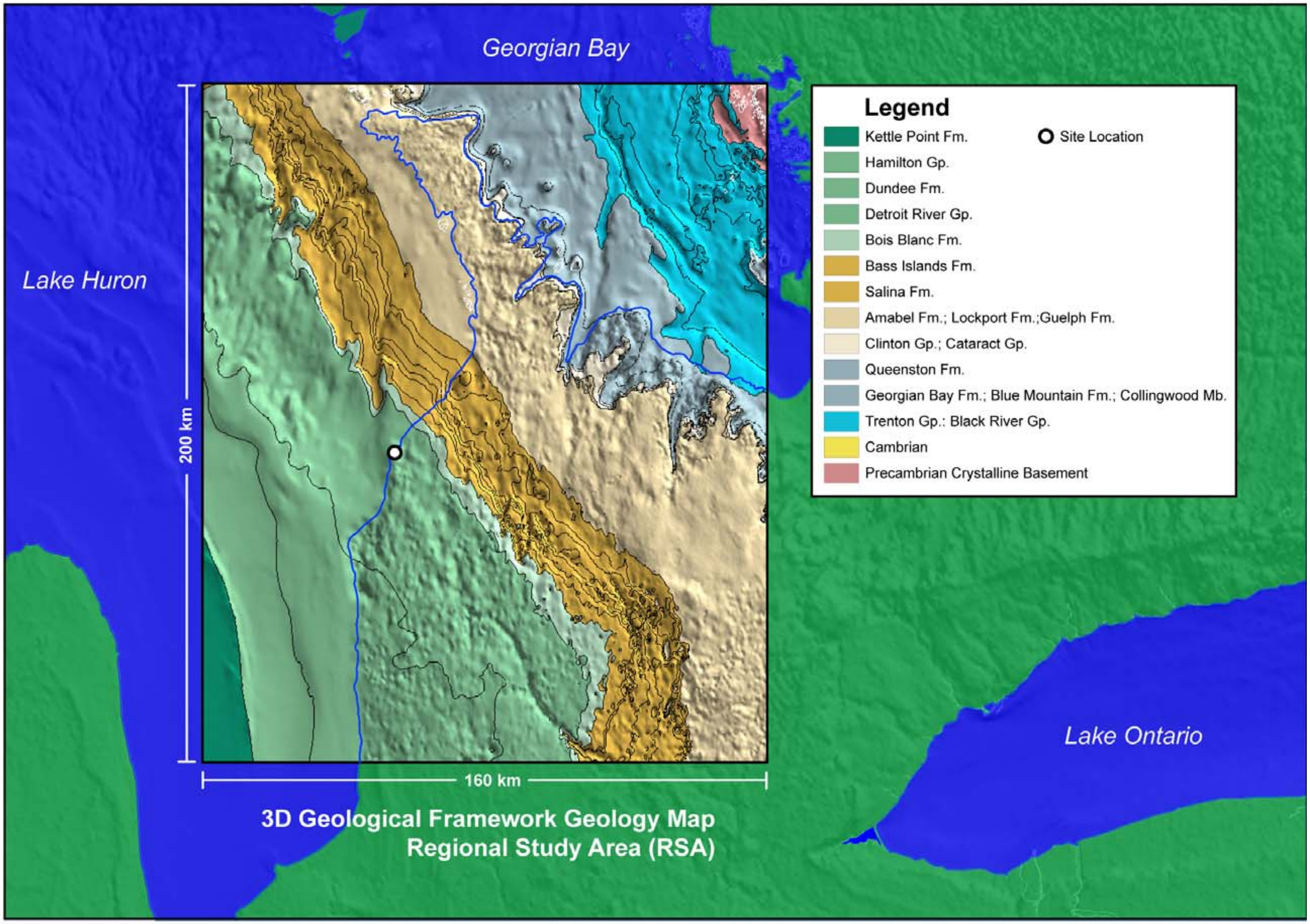


Figure 6.1 3D Geological Framework Study Boundary with Paleozoic Geology Derived from 3D Model

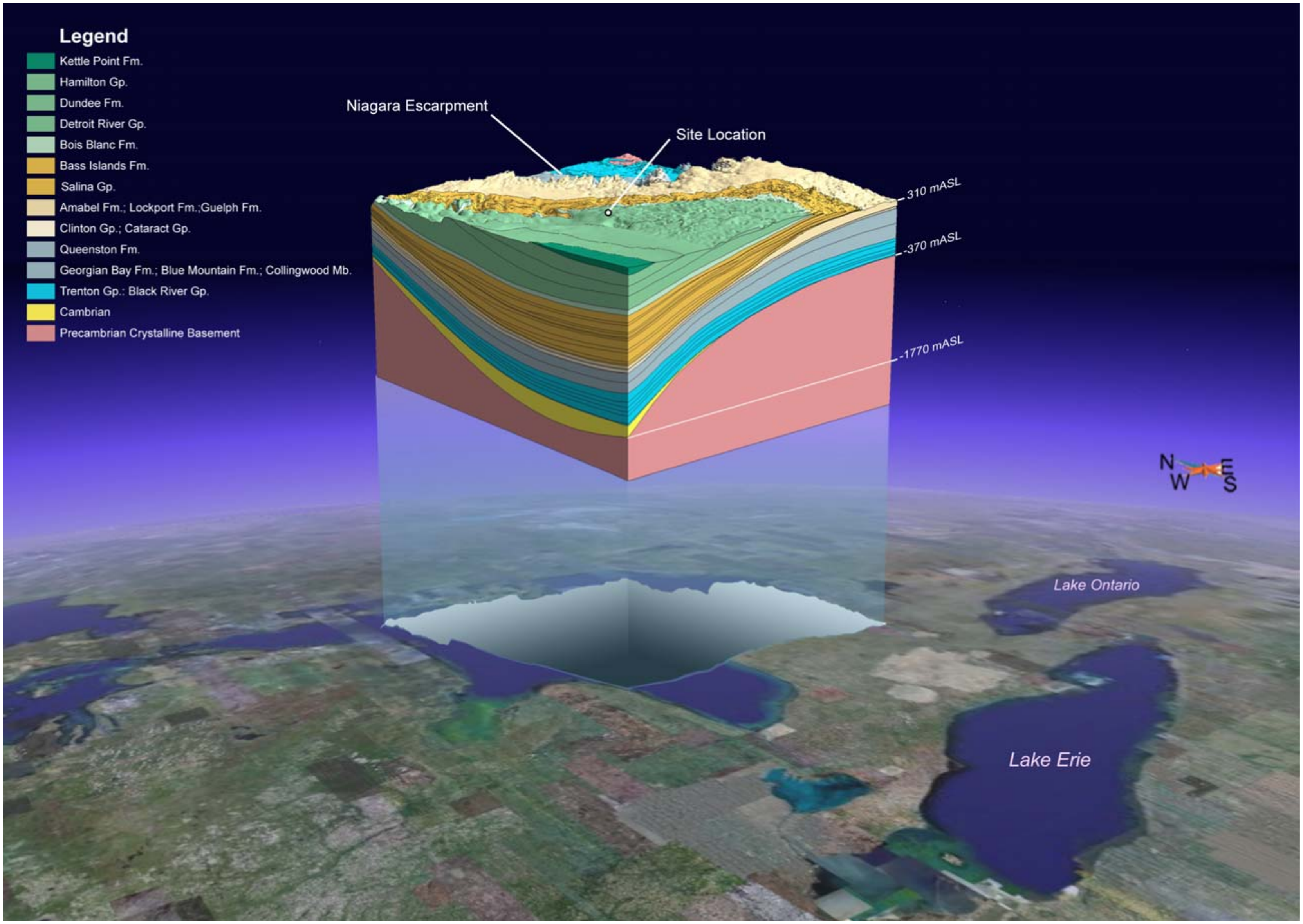


Figure 6.2 3D Geological Framework Box Diagram of the Regional Study Area

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.

Other important data includes:

a) 1:50,000 OGS Digital Bedrock Geology of Ontario Seamless Coverage ERLIS Data Set 6;
b) Michigan State Geological Survey mapping and Petroleum Well Database;
c) OGS Digital Bedrock topography and overburden thickness mapping, Southern Ontario – Miscellaneous Data Release no. 207 (Gao *et al.*, 2006); and
d) 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. Note that no well data exists within Lake Huron, as a result, the State of Michigan geological mapping 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 3D 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, Geological/Stratigraphic Tests. A description of these methods is described in Appendix A1.

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 OSGRL 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
Antrim	Antrim	Equivalent to Kettle Point Formation
Traverse Group	Traverse Group	Equivalent to Hamilton Group
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, GOO, 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	
B Unit	B and C units	
B Anhydrite	B 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.
B Salt	B 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-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.

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

Database Standard Geo_Field	Revised Classification	Notes
A-2 Anhydrite	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-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	
Goat Island	Niagaran	
Gasport	Niagaran	
Irondequoit	Niagaran	
Lions Head	Niagaran	
Wiarton/Colpoy Bay (Amabel)	Niagaran	
Rochester	Niagaran	
Reynales/Fossil Hill	Reynales/Fossil Hill	No change
Thorold	Reynales/Fossil Hill	Lateral equivalent to Fossil Hill in the Michigan Basin (Map 2582, GOO, 1992)
Cabot Head	Cabot Head	No change
Dyer Bay	Cabot Head	Lateral equivalent south of Manitoulin Island (Map 2582, GOO, 1992)
Grimsby	Cabot Head	Lateral equivalent in Michigan Basin (Map 2582, GOO, 1992)
Wingfield	Cabot Head	Lateral equivalent south of Manitoulin Island (Map 2582, GOO, 1992)
Manitoulin	Manitoulin	No change
Whirlpool	Manitoulin	Lateral equivalent in Michigan Basin (Map 2582, GOO, 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
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, GOO, 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 Workflow Development

One of the key elements in the development of the 3DGF was to devise a workflow to ensure a consistent approach to modelling each of the formation surfaces. The workflow used to develop the 3DGF is presented in Appendix A.1. The workflow sets out how data is acquired, validated and used to construct geological surfaces within the framework.

6.5 Limitations

The following is a list of constraints and limitations of the 3D Geological Framework.

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 described 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 (ie. Islands) that existed within the Ordovician seas, as a result, it is possible that some units are not well represented in the subsurface.

6.6 Discussion

The three dimensional geological framework (Figure 6.1), 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. 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 (Figure 2.6). The framework extends from approximately 500 mASL on the Niagara Escarpment to a depth of approximately 1,000 mBSL 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 6.2). 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 thickness derived from the DGR boreholes as presented in Figure 5.1 (Intera, 2008). 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 site is well described by the regional data presented in the 3DGF.

Table 6.2 3D Geological Framework Unit Thickness Compared with DGR Site 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
Bass Islands	121	50	17	54
G Unit	90	9	6	5
F Unit	9	46	4	40
F Salt	10	15	6	*
E Unit	43	27	7	20
D Unit	44	9	3	2
B and C Units	88	28	7	47
B-Anhydrite/Salt	84	49	31	2
A-2 Carbonate	87	33	10	27
A-2 Anhydrite/Salt	85	13	11	8
A-1 Carbonate	82	36	8	39
A-1 Evaporite	82	5	4	8
Niagaran	109	55	39	34
Reynales/Fossil Hill	105	7	4	3
Cabot Head	71	21	12	21
Manitoulin	71	11	4	16

Table 6.2 3D Geological Framework Unit Thickness Compared with DGR Site Data

Geological Unit	Samples (n)	Mean Thickness (m)	Std. Deviation (m)	DGR Thickness (m)
Queenston	72	85	25	70
Georgian Bay Blue Mtn	84	135	50	142
Cobourg	76	48	17	27
Sherman Fall	73	44	13	46
Kirkfield	70	39	11	30
Coboconk	73	13	8	17
Gull River	77	45	16	60
Shadow Lake	26	9	8	5
Cambrian	20	7	5	17

*Note: * Not present at site*
***Full thickness not present at site*

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.

6.6.1 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 described in literature. The absence of data are likely the result of the depth of the Cambrian, scarcity of outcrop data, and limited resource potential in the RSA (few petroleum exploration wells).

DGR-2 intersected approximately 17 m of Cambrian sandstones, and carbonates (Figure 5.1) and 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 DGR 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).

6.6.2 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.

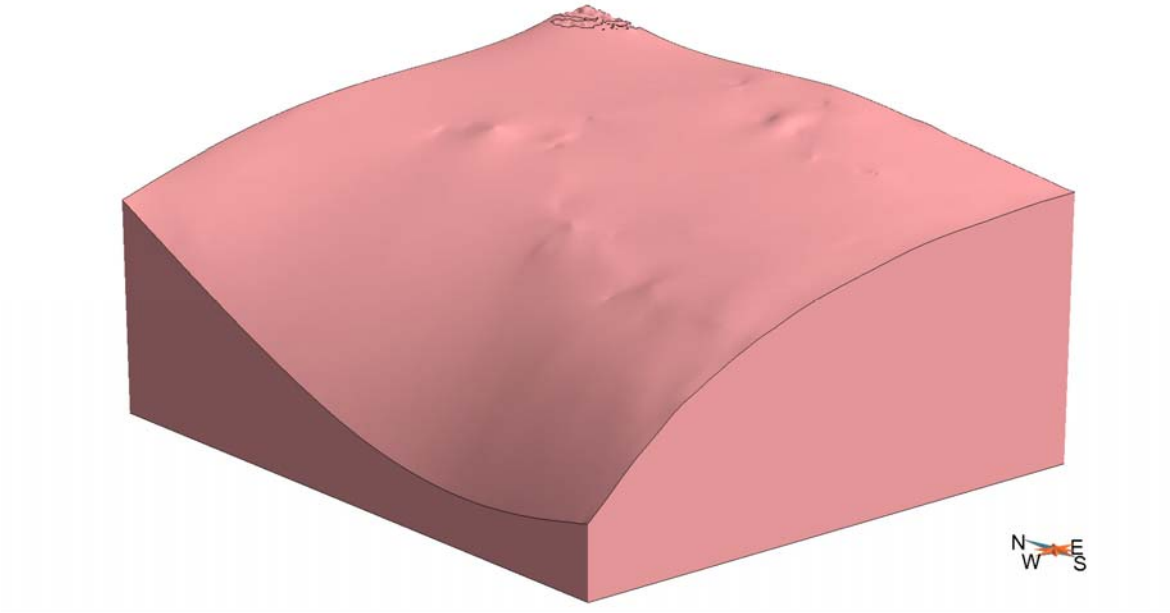


Figure 6.3 Precambrian

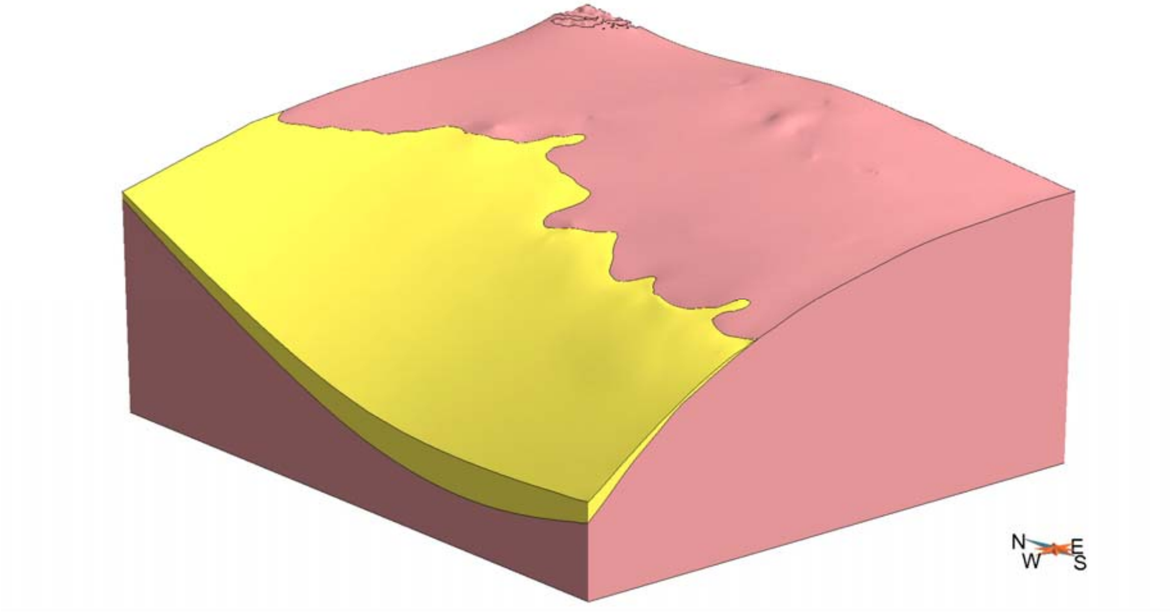


Figure 6.4 Cambrian

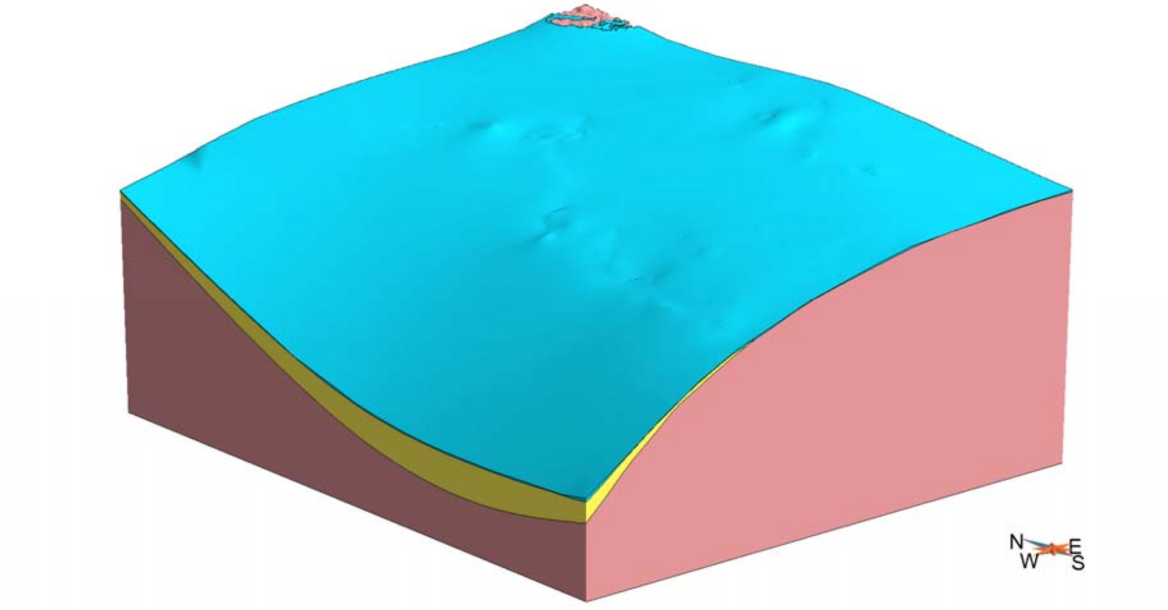


Figure 6.5 Shadow Lake Formation

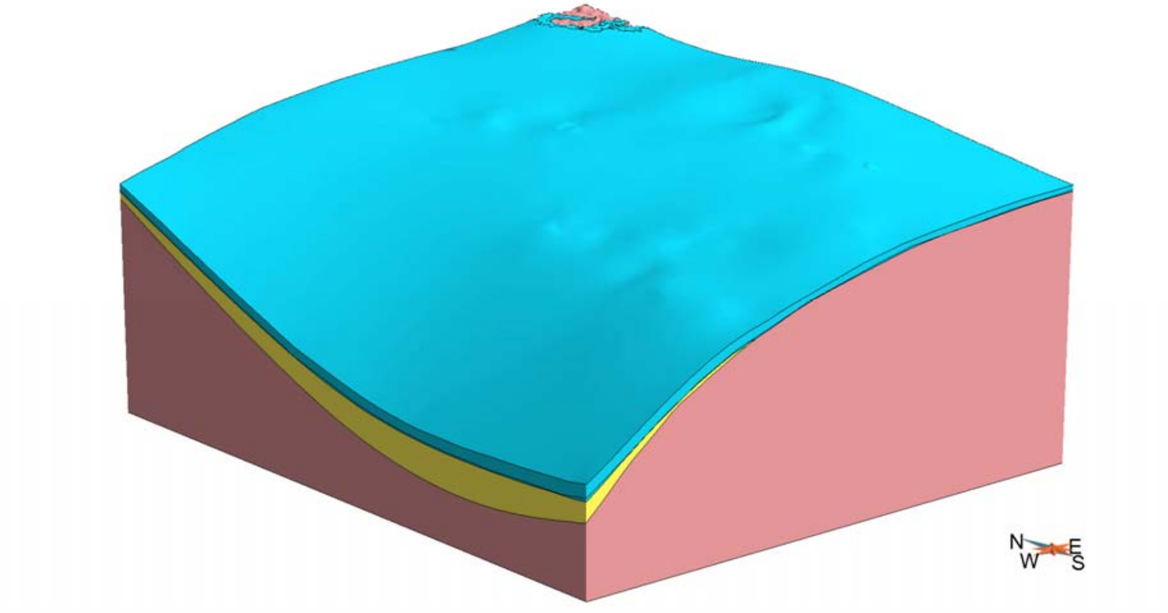


Figure 6.6 Gull River Formation

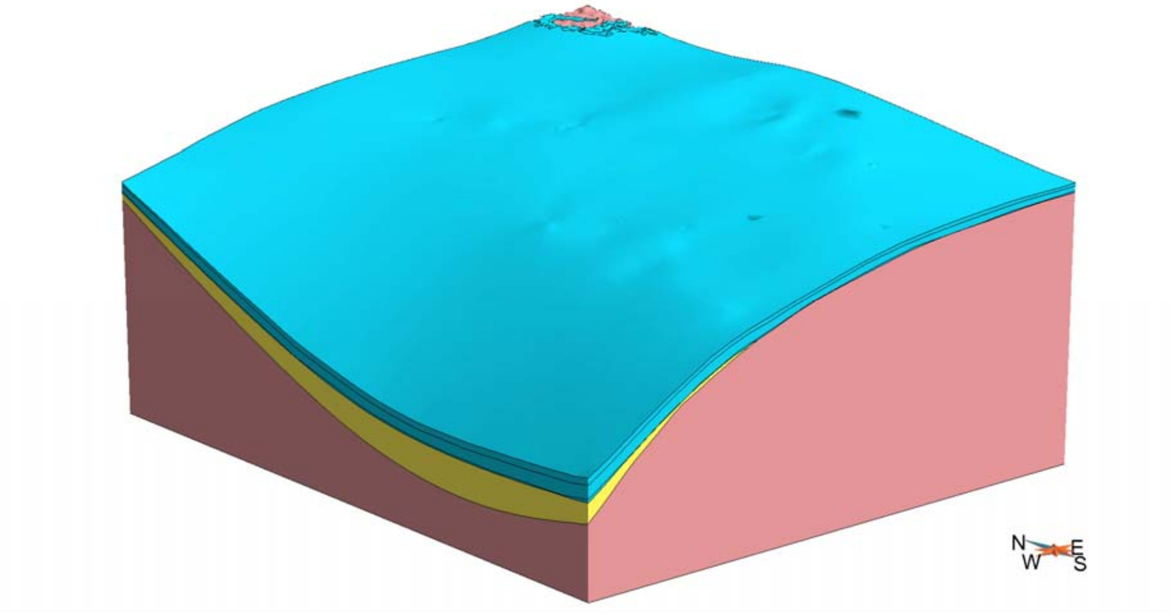


Figure 6.7 Coboconk Formation

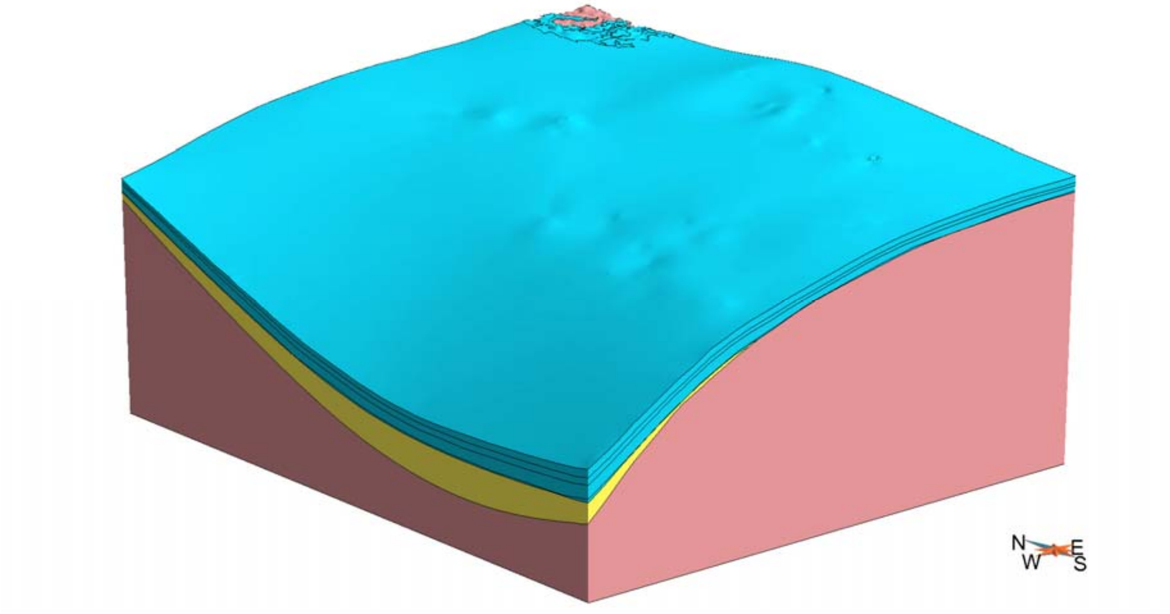


Figure 6.8 Kirkfield Formation

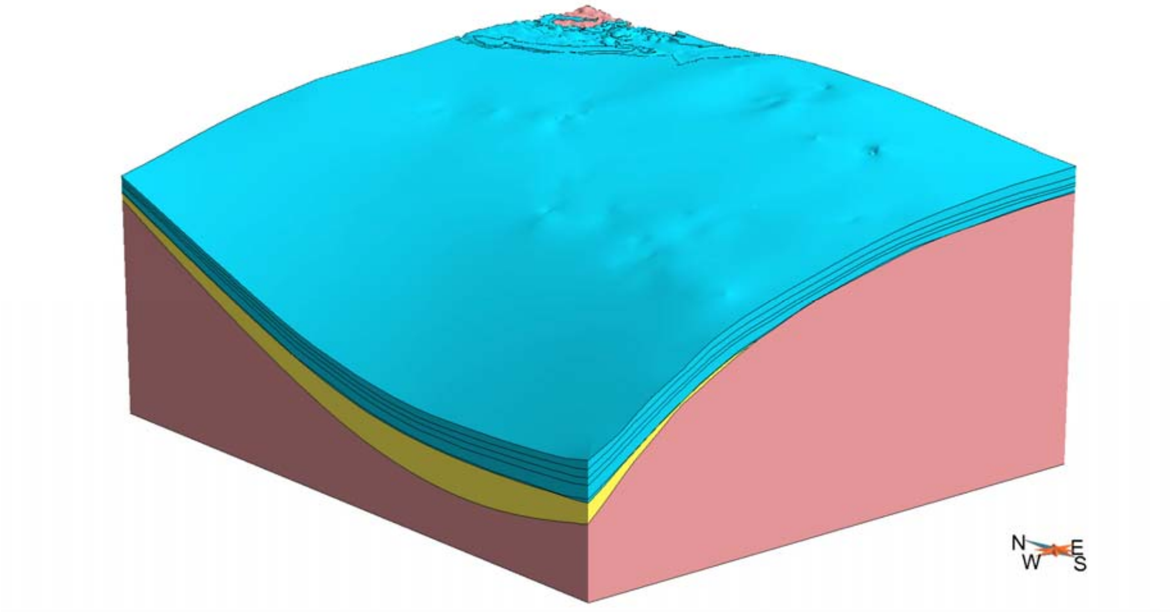


Figure 6.9 Sherman Fall Formation

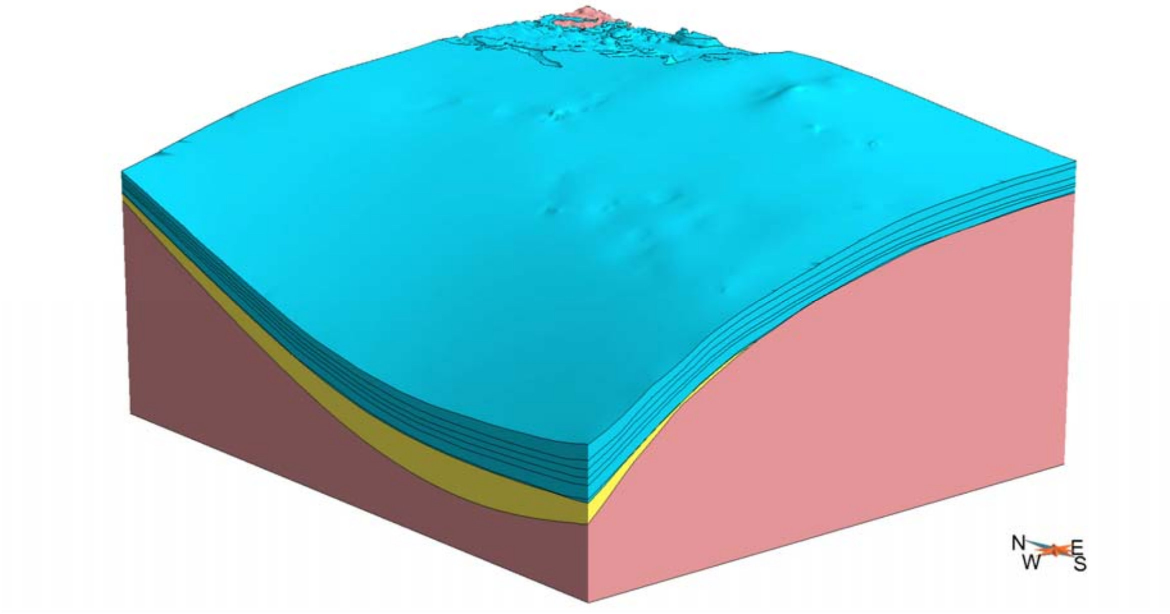


Figure 6.10 Cobourg Formation

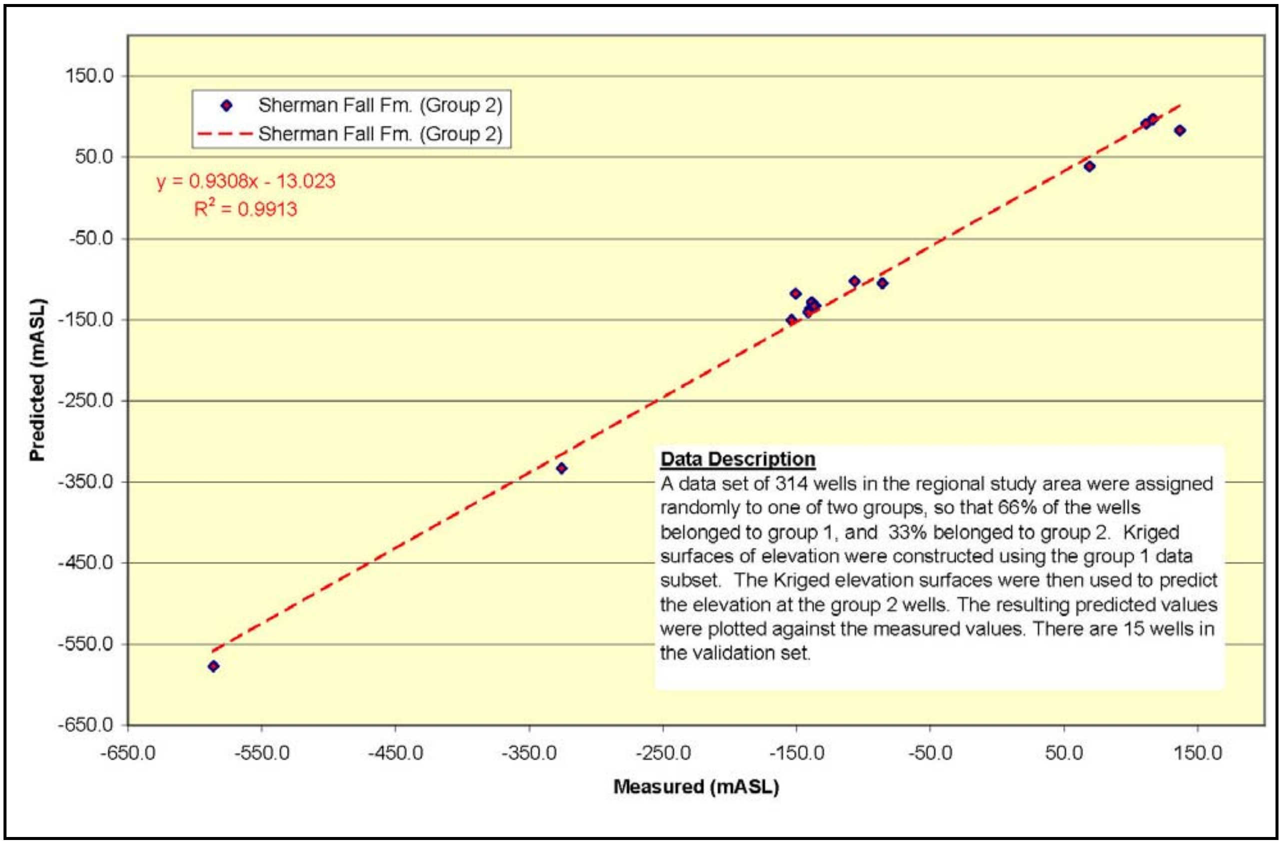


Figure 6.11 Predicted Versus Measured Contact Elevation For Sherman Fall Formation

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 (ie. 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 199 m, which is relatively consistent with the total thickness of approximately 185 m logged at the DGR site. The key differences are the Cobourg Formation and Gull River Formation, which 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 that the Collingwood Member of the Cobourg Formation was grouped with the overlying Blue Mountain Formation.

6.6.3 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 Ordovician carbonate units, the shale 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). 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 log from the DGR-2 describes a slightly calcareous to noncalcareous shale, with minor thin beds of grey bioclastic limestone (Figure 5.1).

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 a thickness of 212 m recorded at the DGR site.

6.6.4 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 depositing the Manitoulin Formation (Section 4.2). 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 DGR site for the Manitoulin and Cabot Head formations, 16 m and 21 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 DGR 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 dominanted by diagenetic dolostone mineralogy. The Niagaran Grouping was completed to prevent erroneous stratigraphic interpretations.

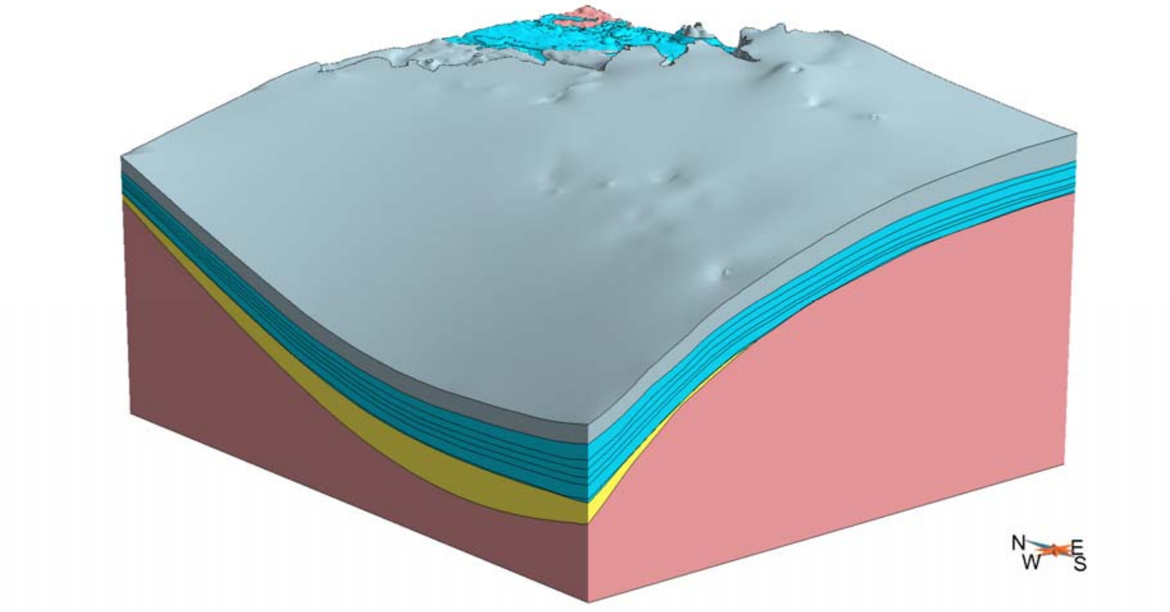


Figure 6.12 Georgian Bay and Blue Mountain formations

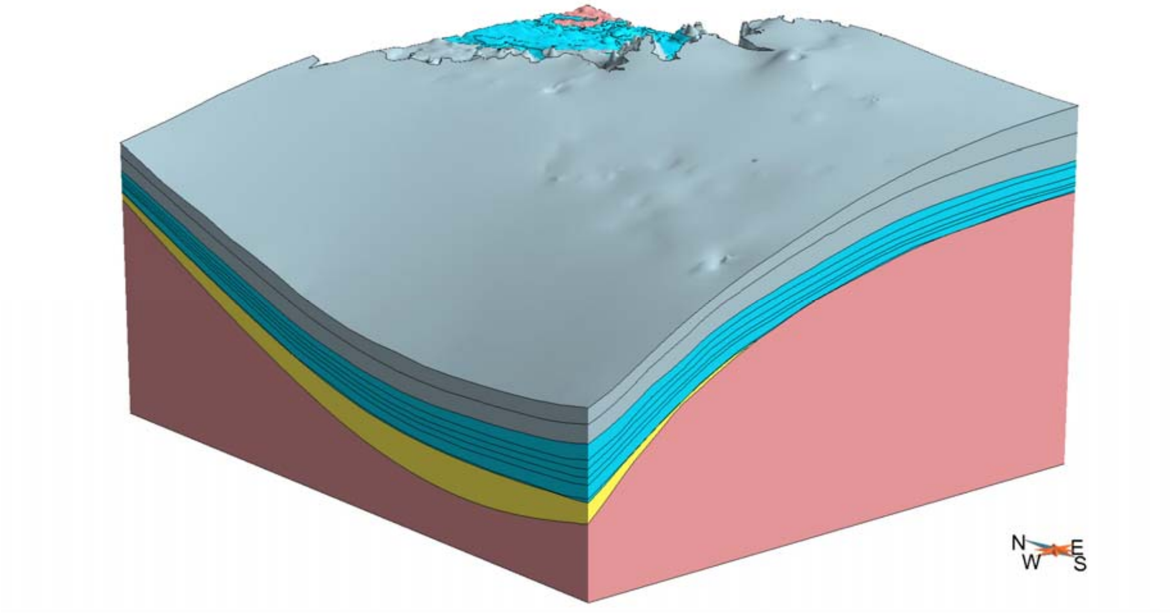


Figure 6.13 Queenston Formation

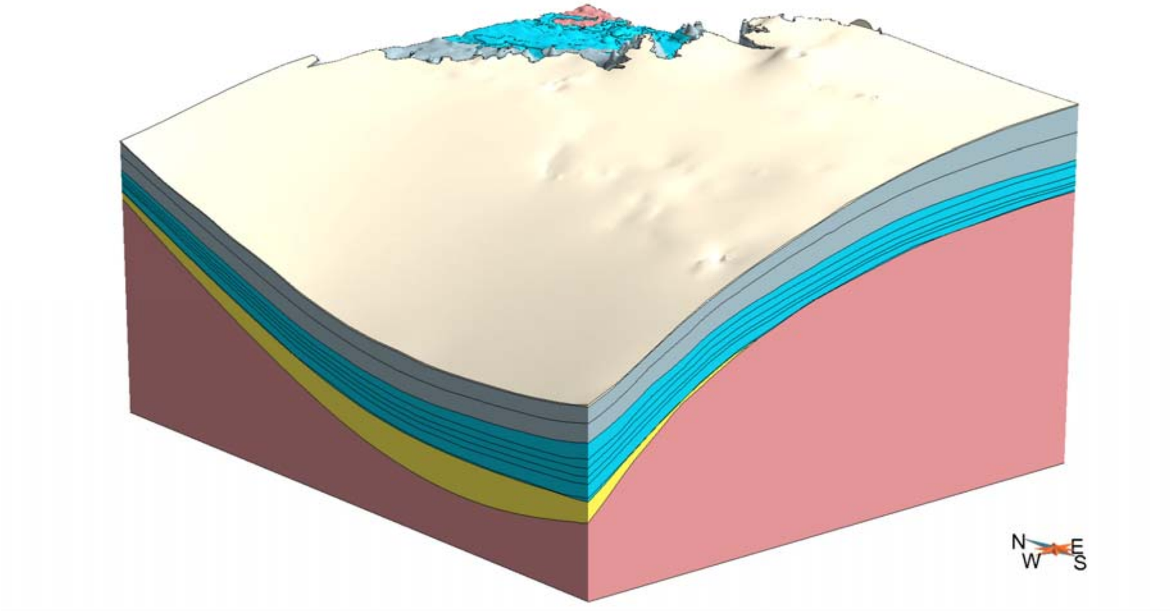


Figure 6.14 Manitoulin Formation

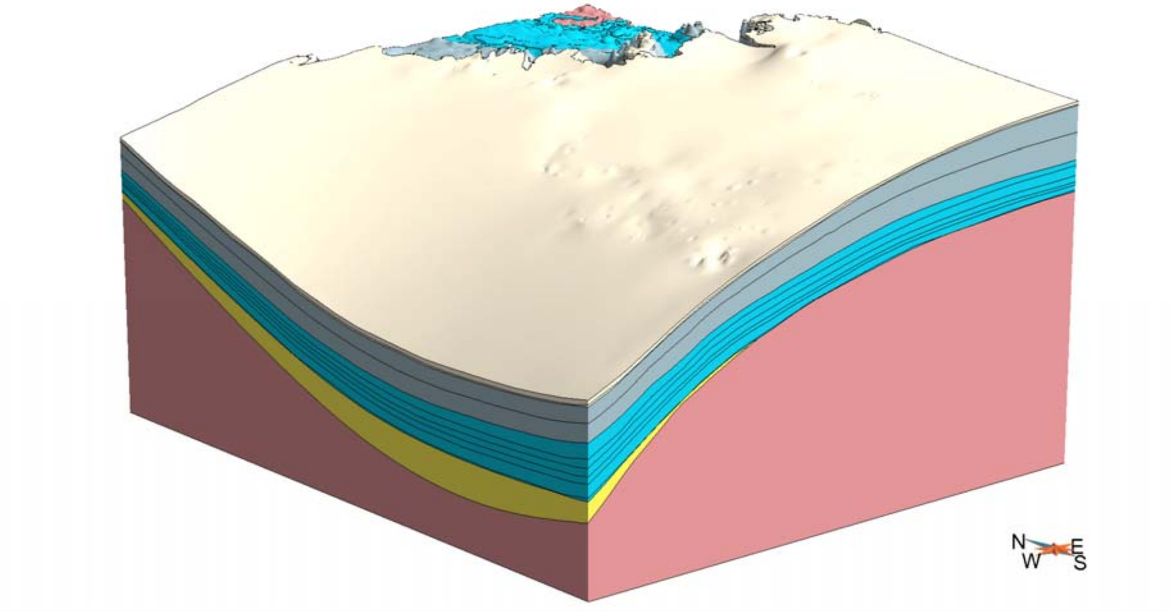


Figure 6.15 Cabot Head Formation

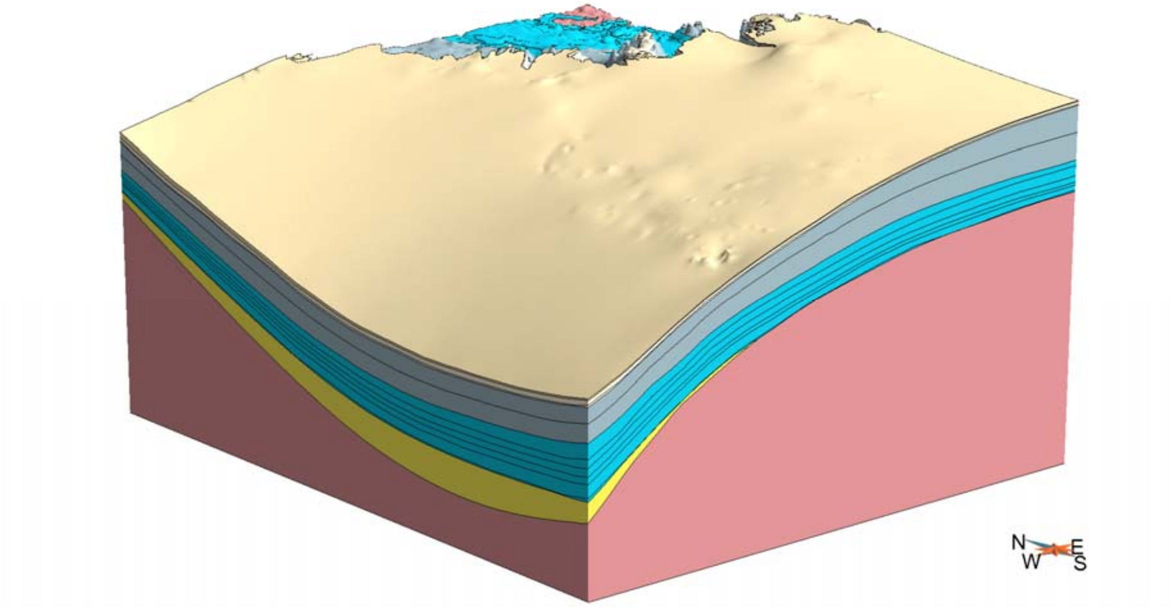


Figure 6.16 **Reynales Formation/ Fossil Hill Formation**

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-2 (Intera, 2008), the DGR 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).

6.6.5 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.

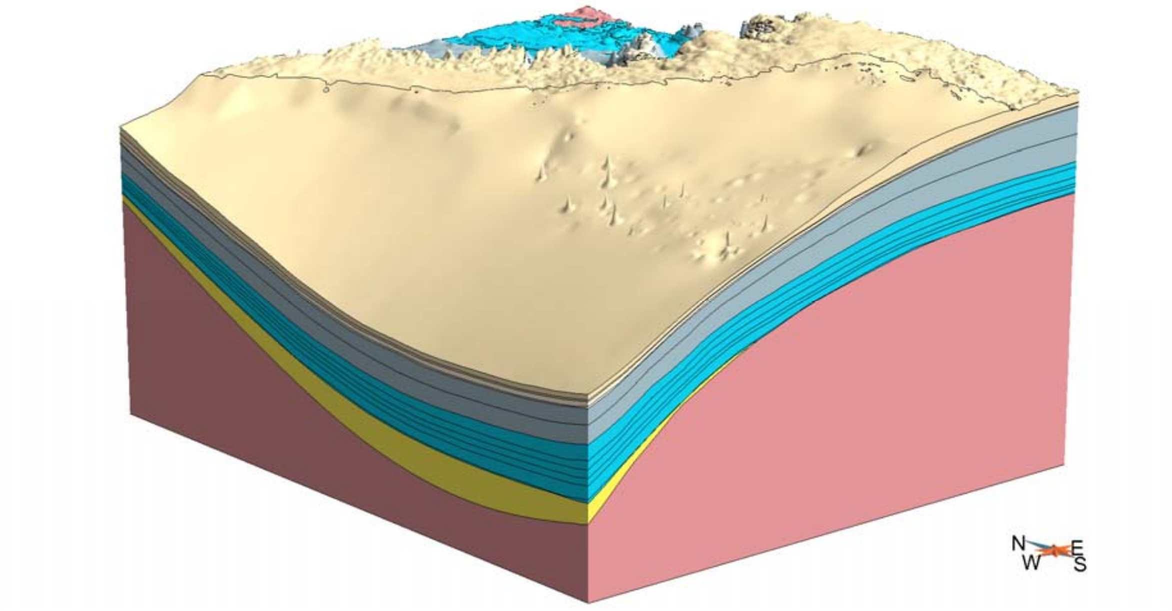


Figure 6.17 Niagaran Group (Guelph/Amabel/Lockport)

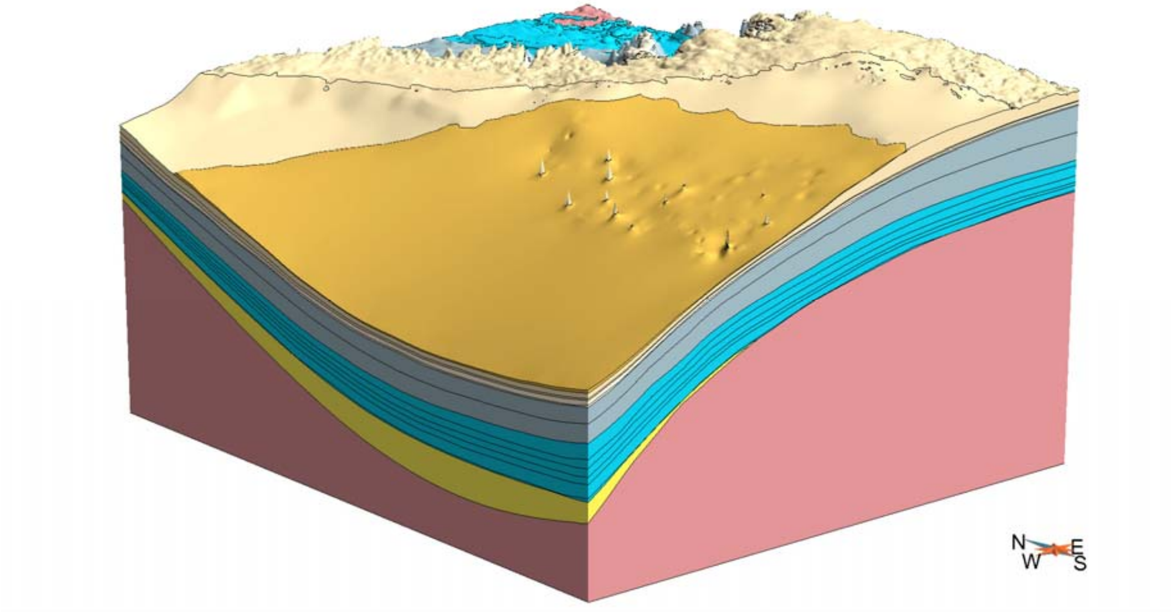


Figure 6.18 Salina A1-Evaporite

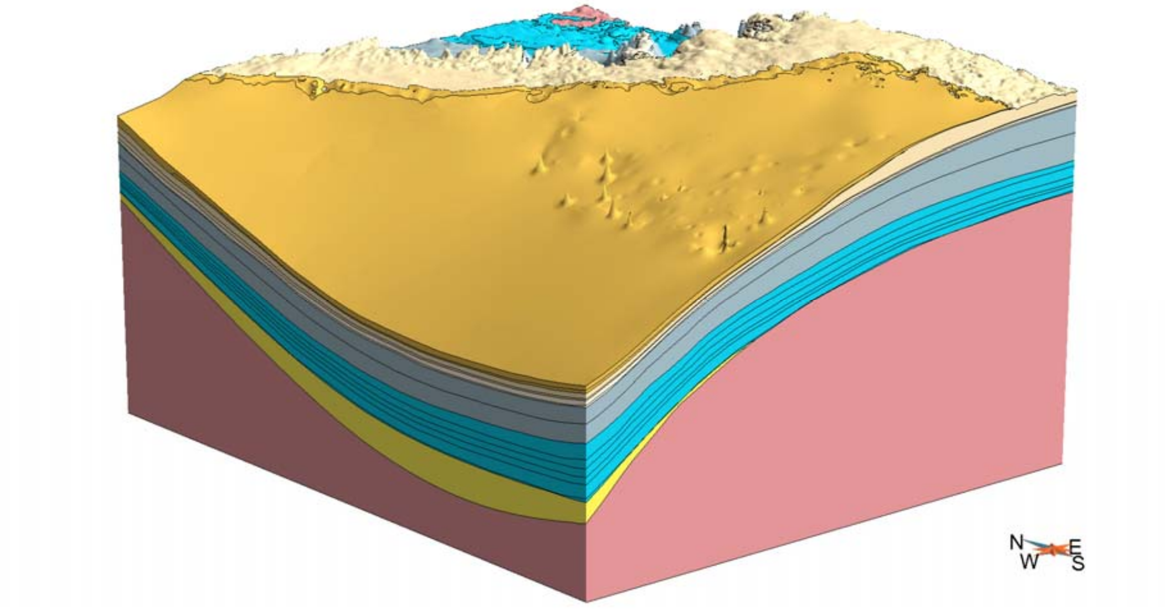


Figure 6.19 Salina A1-Carbonate

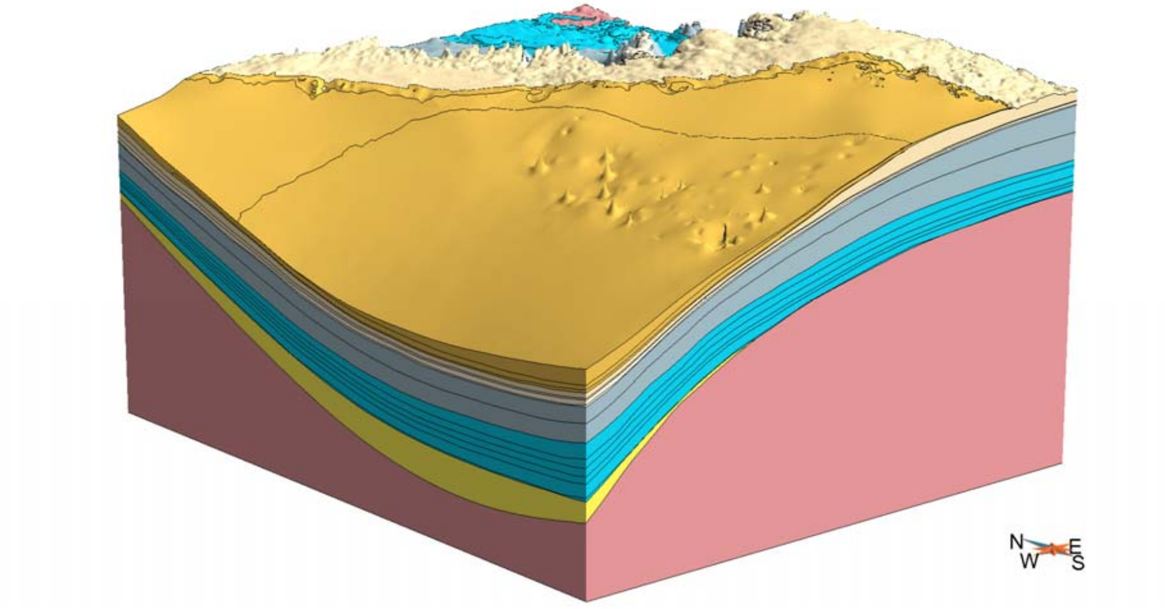


Figure 6.20 Salina A2-Evaporite

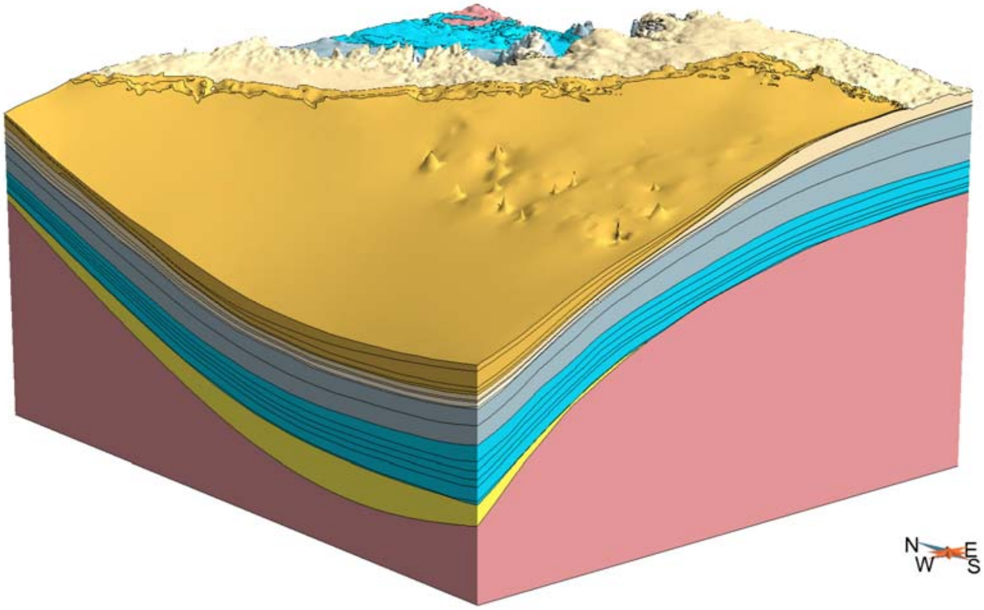


Figure 6.21 Salina A2-Carbonate

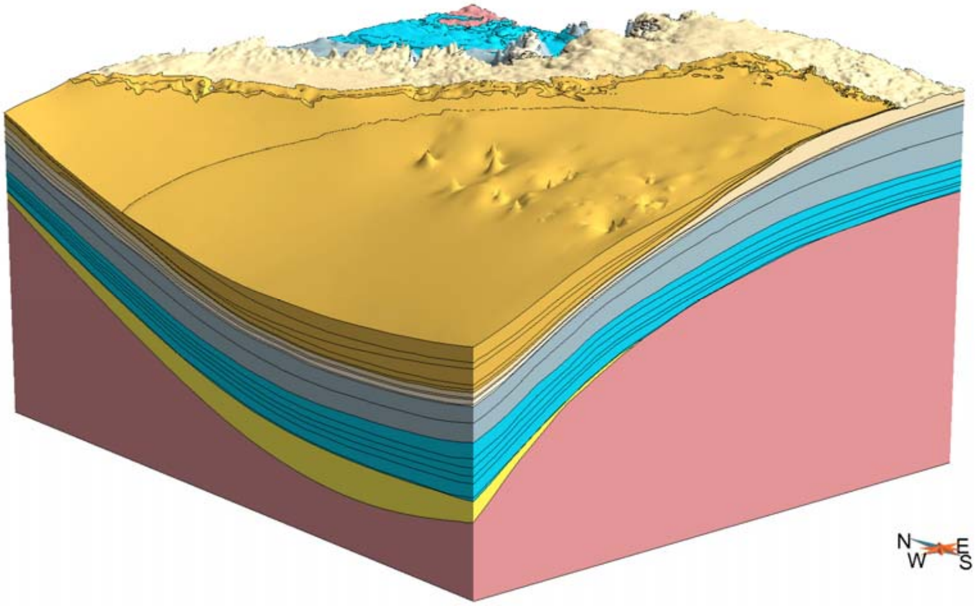


Figure 6.22 Salina B-Anhydrite/Salt

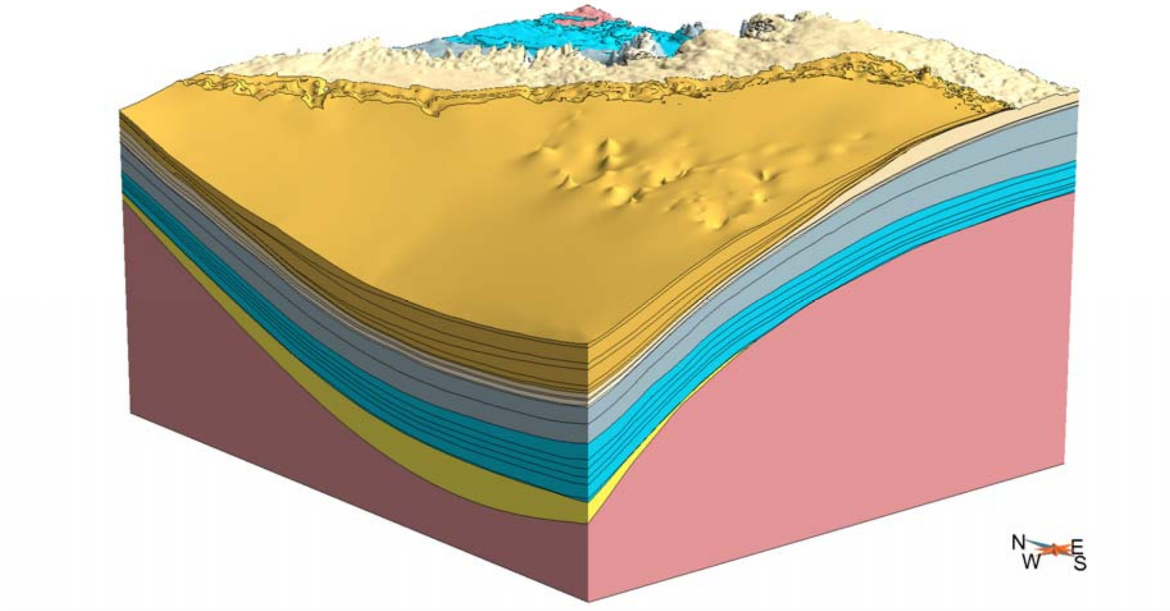


Figure 6.23 Salina B and C units

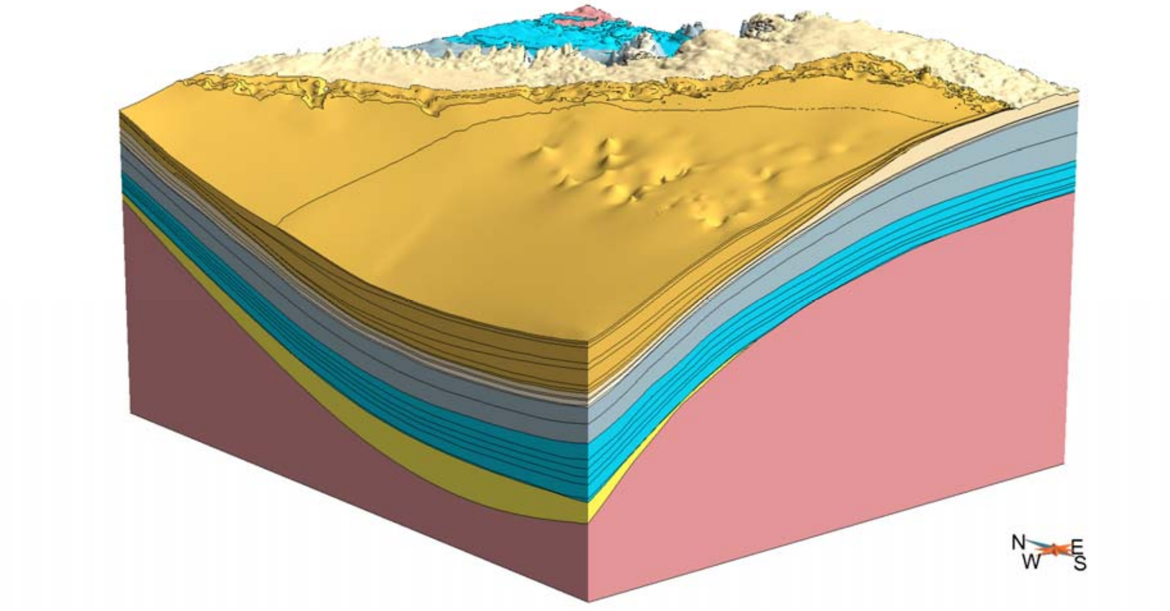


Figure 6.24 Salina D-Unit

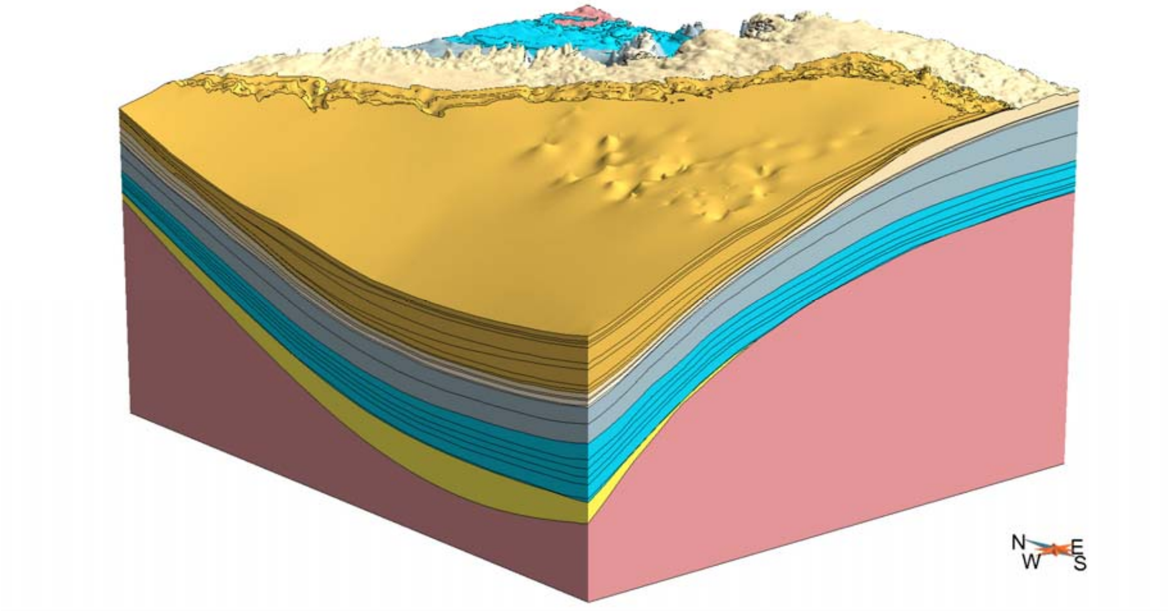


Figure 6.25 Salina E-Unit

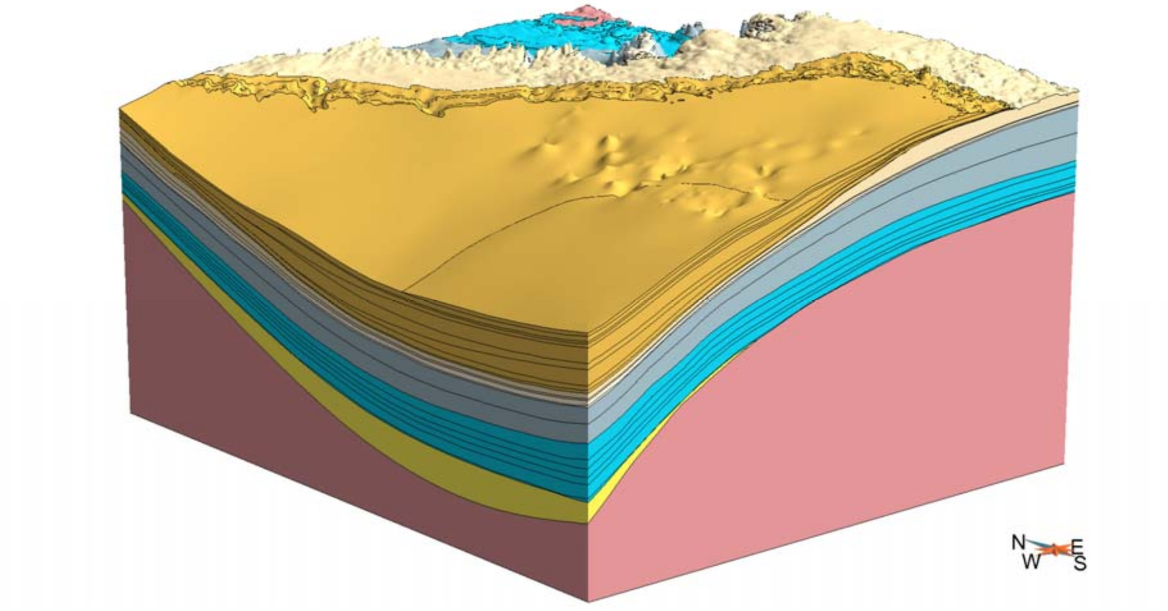


Figure 6.26 Salina F-Salt

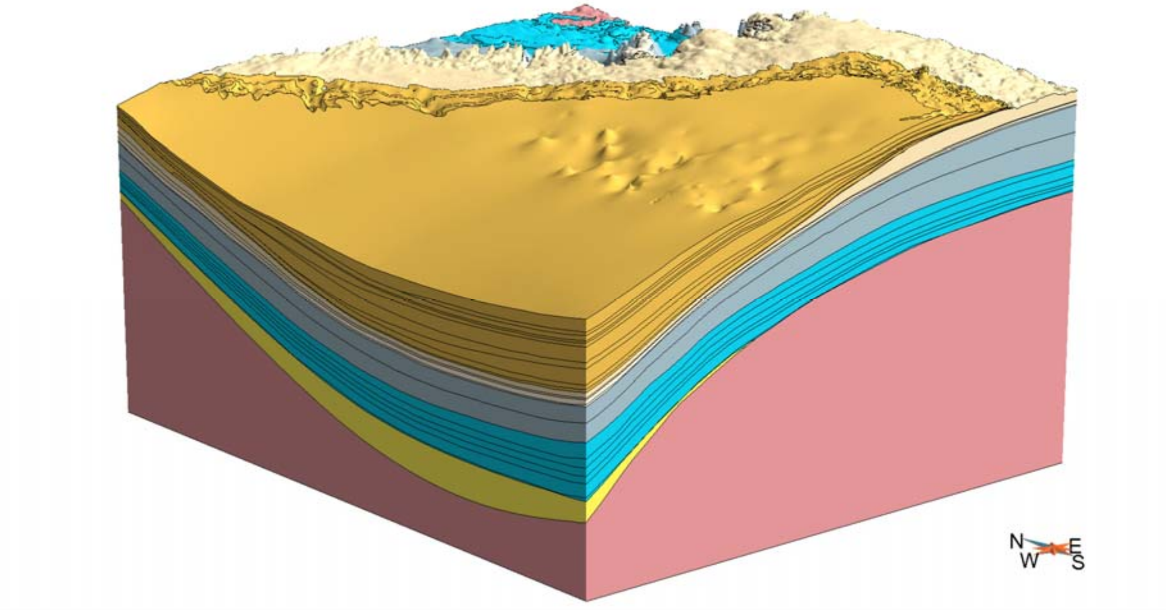


Figure 6.27 Salina F-Unit

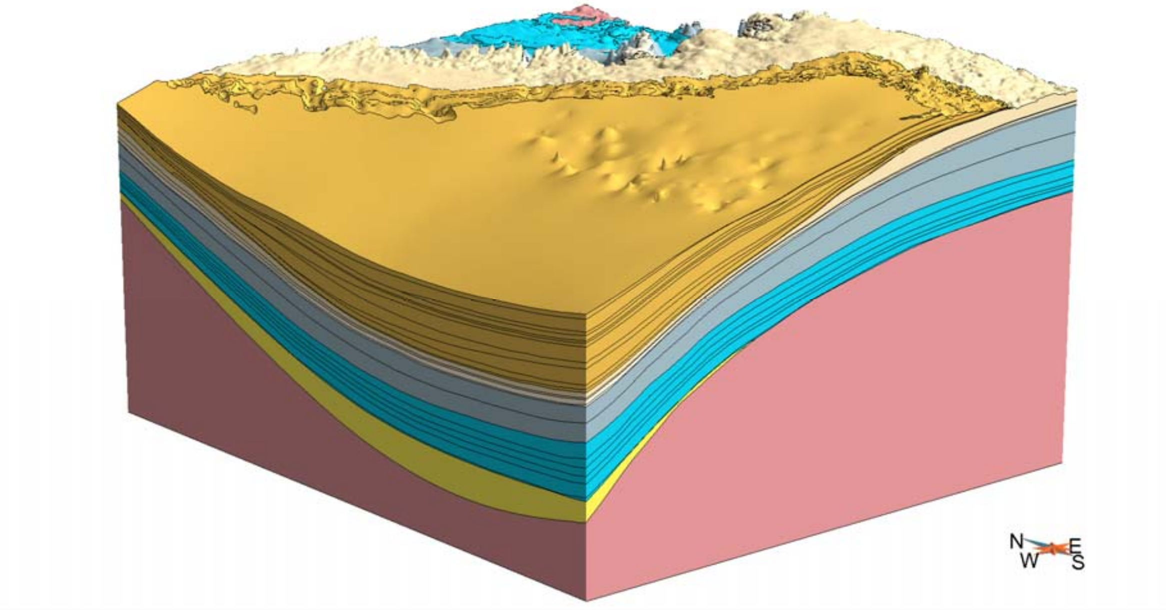


Figure 6.28 Salina G-Unit

The A-1 evaporite is composed of anhydrite and dolostone beneath the DGR site but likely grades to halite further westward into the Michigan Basin (Section 4.2). 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 (Figure 6.20 and 6.21).

The B –Anhydrite (grouped as B-Anhydrite/Salt) is found at the DGR 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 are 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 Section 4.2. The thickness of the carbonate units encountered at the DGR 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 OGSR wells within the RSA. 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.

6.6.6 Devonian Carbonates (Bois Blanc Formation, Detroit River Group, Dundee Formation, Hamilton Group and Antrim/Kettle Point)

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 largely gone by the time of Detroit River deposition. All Devonian units are shown as continuous and as having relatively uniform thickness. The Lucas and Amherstburg Formations of the Detroit River Group are the first Paleozoic unit encountered at the DGR site (Figure 5.1). Approximately 55 m of these formations are intersected 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).

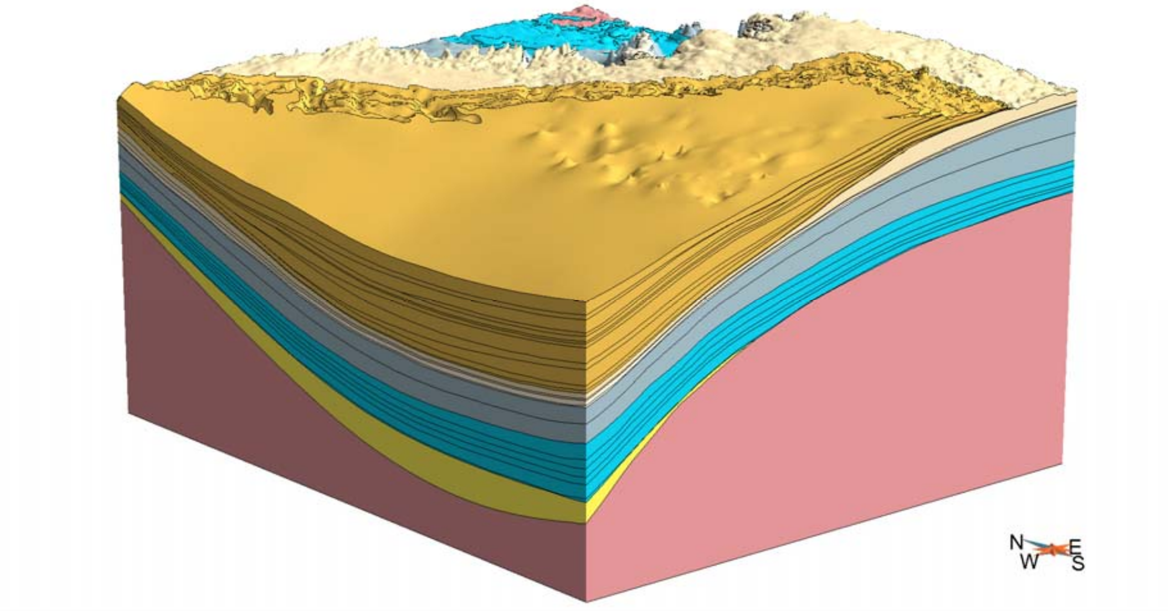


Figure 6.29 Bass Islands Formation

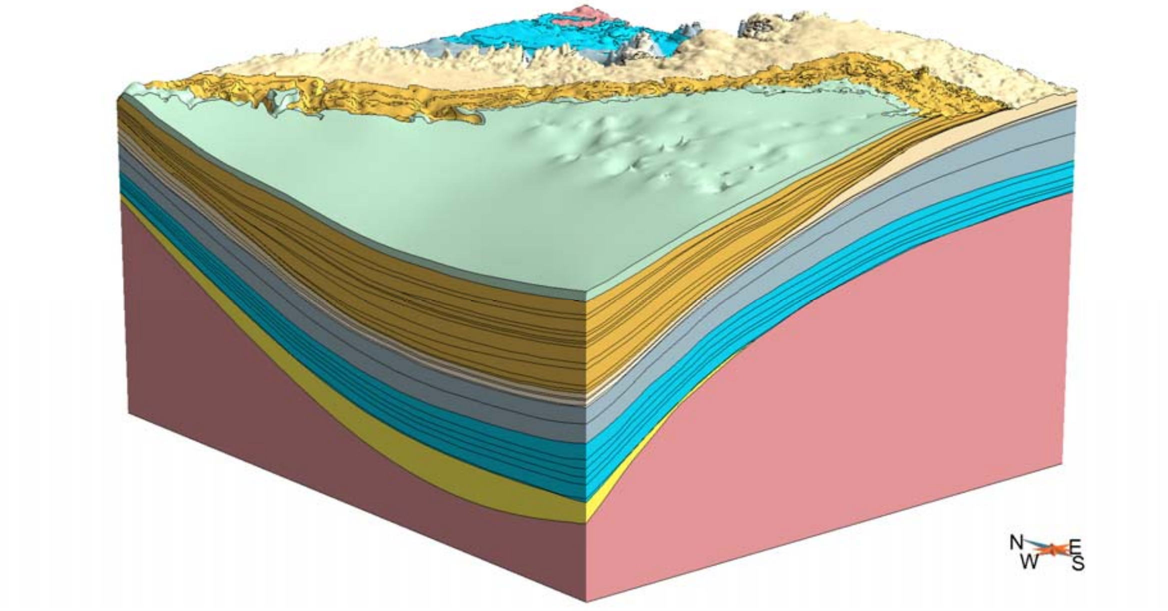


Figure 6.30 Bois Blanc Formation

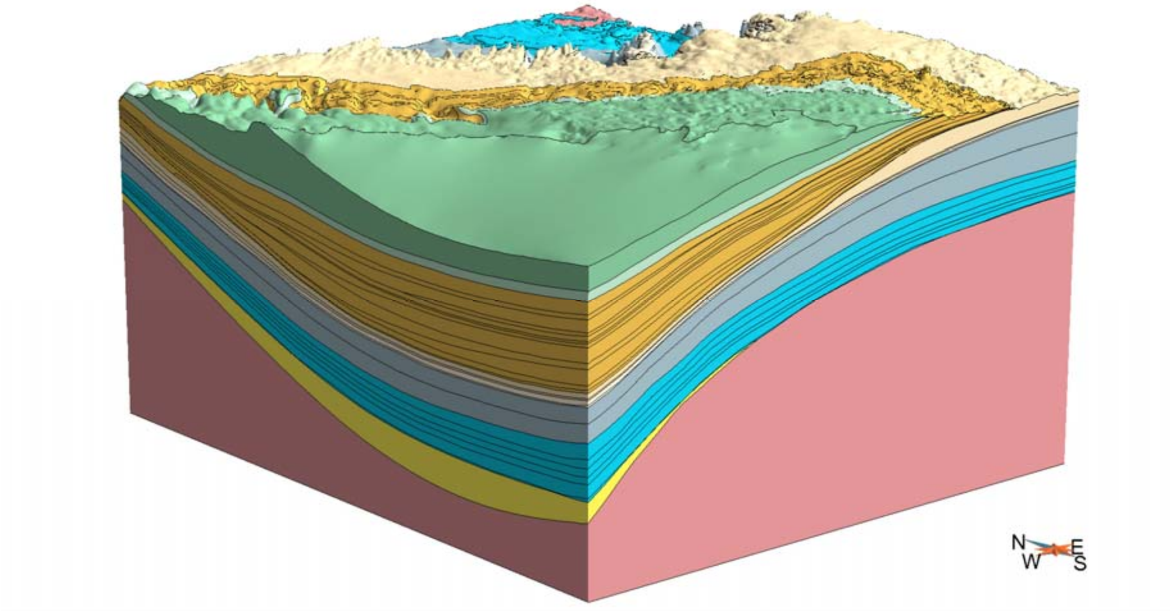


Figure 6.31 Detroit River Group

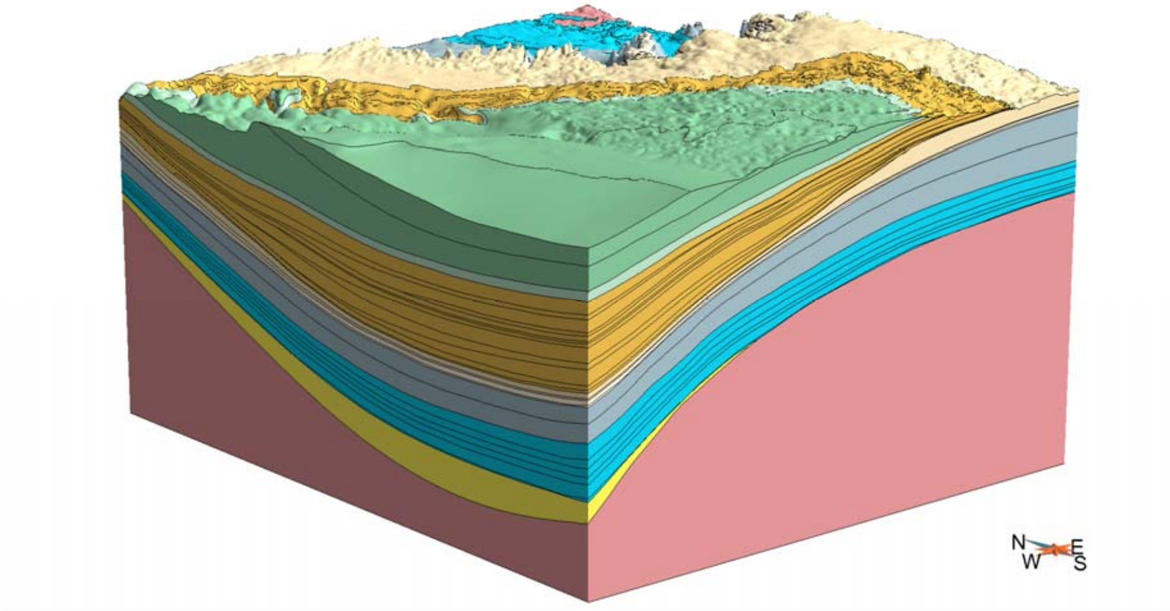


Figure 6.32 Dundee Formation

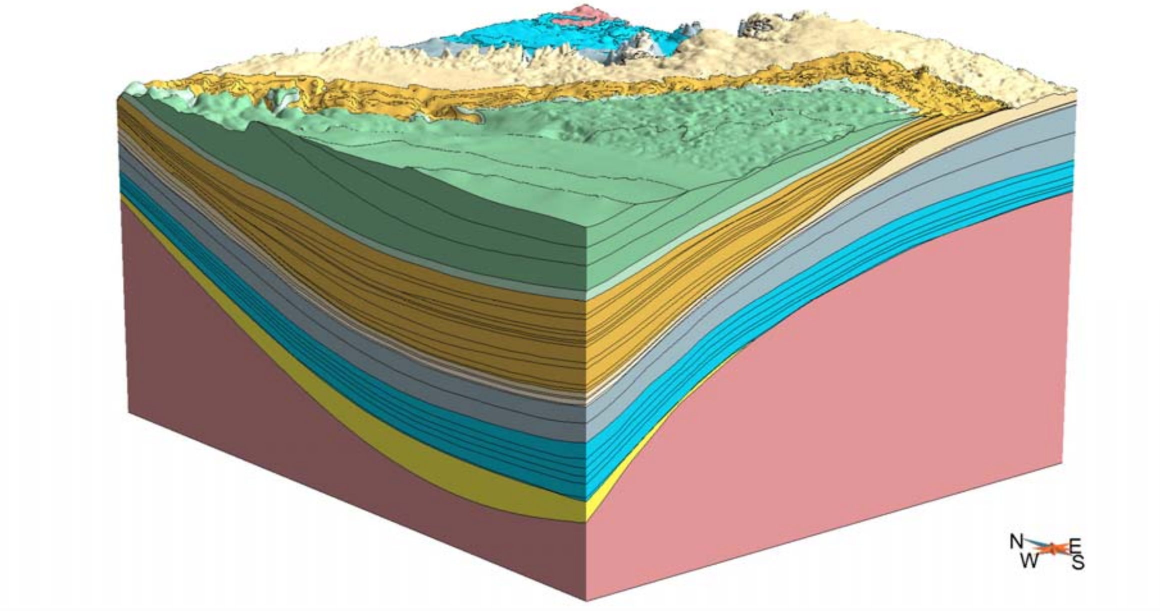


Figure 6.33 Hamilton/Traverse Group

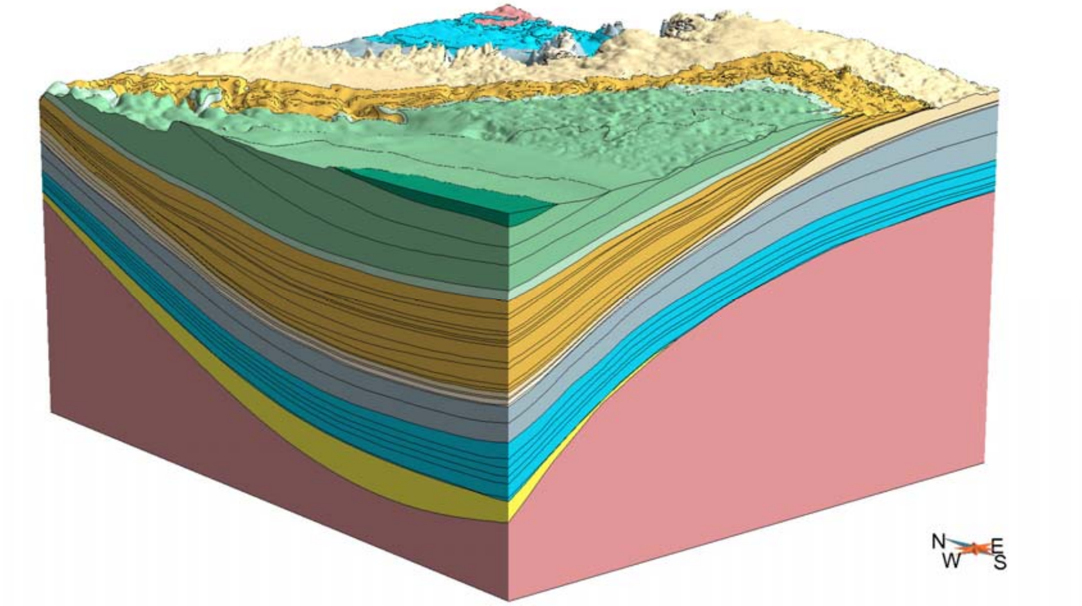


Figure 6.34 Kettle Point/Antrim Formation

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.

It should be noted that the Kettle Point Formation (Antrim Formation using Michigan nomenclature) distribution is extrapolated from OGS bedrock geology mapping contacts out to Lake Huron scarp face distributions as no well data exists in Lake Huron.

6.7 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 regional study area. 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 section presents an overview of both the thermal history of the Michigan Basin as well as the main digenetic 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) formation, 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 diagentic 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 diagentic fluid flow.

7.1 Thermal History

The Paleozoic rocks of the Michigan Basin are characterized by moderate to high levels of organic maturity. The cause of this thermal organic maturity continues to be a subject of academic debate due to a scarcity of vitrinite in organic matter and conflicting estimates from using different maturity parameters.

On the eastern margin of the basin, organic maturity appears to increase to the southeast, with the Collingwood Member at Georgian Bay being less thermally mature for example than the equivalent unit in Toronto (Obermajer *et al.* 1996). Similarly in the Lower Michigan Peninsula, observed maturity in the Salina C Formation suggests that the southern margin is more mature than the north (Cercone 1984). Organic maturity in the centre of the basin is greater than that at the basin margin (Cercone 1984).

A prevailing model for the formation of the basin (Nunn *et al.* 1984) suggests an Ordovician thermal anomaly resulted in contraction and subsidence of the basin. It predicts that the thermal anomaly would have elevated temperatures to the hydrocarbon generation stage in Cambrian, Ordovician, and Lower Silurian rocks, but not in younger rocks (Nunn *et al.* 1984). This trend is observed in the southern margin of the basin, however, it does not hold true for the entire basin.

To explain the maturity of the younger Devonian strata, Cercone (1984) suggested that the thermal maturity of the Michigan Basin is the result of deep burial by Carboniferous and Permian sediments, which have since eroded. Evidence for deposition during this interval can be seen where Carboniferous (some Permian) strata are up to approximately 2,000 m thick in adjacent Illinois and Appalachian basins (Cercone, 1984). Extrapolation of the present erosional surface of the basin also supports significant erosion, estimating at least 1,000 m of eroded sediment at the basin margins. The erosion of approximately 1,000 m of Carboniferous sediments also corresponds with estimates of early Paleozoic basin-centre accumulation rates (Cercone, 1984).

Cercone (1984) modelled the thermal evolution of the Michigan Basin suggesting that at least 2,300 m of overlying sediment would have been required to generate the observed organic maturity, assuming a geothermal gradient of 23°C/km. This suggests an exceptional period of uplift and erosion. The estimate of overburden thickness was revised by Cercone and Pollack (1991) by applying different geothermal gradients to each lithology, based on the thermal conductivity of the unit. Their model suggests that 1,000 m of overburden and a 40°C to

60°C/km geothermal gradient in that overburden would account for the organic maturity of the Michigan Paleozoic rocks. Insulating units such as coal and organic rich shale could produce the low thermal conductivities required to generate a higher geothermal gradient (Cercone and Pollack, 1991).

Ordovician dolomites on the northeast basin margin, analyzed by Coniglio and William-Jones (1992) and Coniglio *et al.* (1994), indicate that hydrothermal events have also occurred in the basin history. Fluid inclusions in dolomites of Manitoulin Island and southwestern Ontario were identified with homogenization temperatures of up to 200°C. Estimated burial depths of even 2,000 m would only have produced peak temperatures of 66°C, therefore burial history alone cannot explain the elevated fluid inclusion temperatures (Coniglio *et al.* 1994). Coniglio *et al.* (1994) therefore suggest that the high and variable temperatures imply hydrothermal activity and may also provide a mechanism of dolomitization.

Figure 7.1 (Coniglio and William-Jones, 1992) shows the hypothetical burial history of Ordovician carbonates from Manitoulin Island. Figure 7.1 shows maximum burial during the late Carboniferous of approximately 1,500 m of rock over the present bedrock surface. The 1,500 m of material has been eroded since the Carboniferous times and re-exposed the Ordovician units.

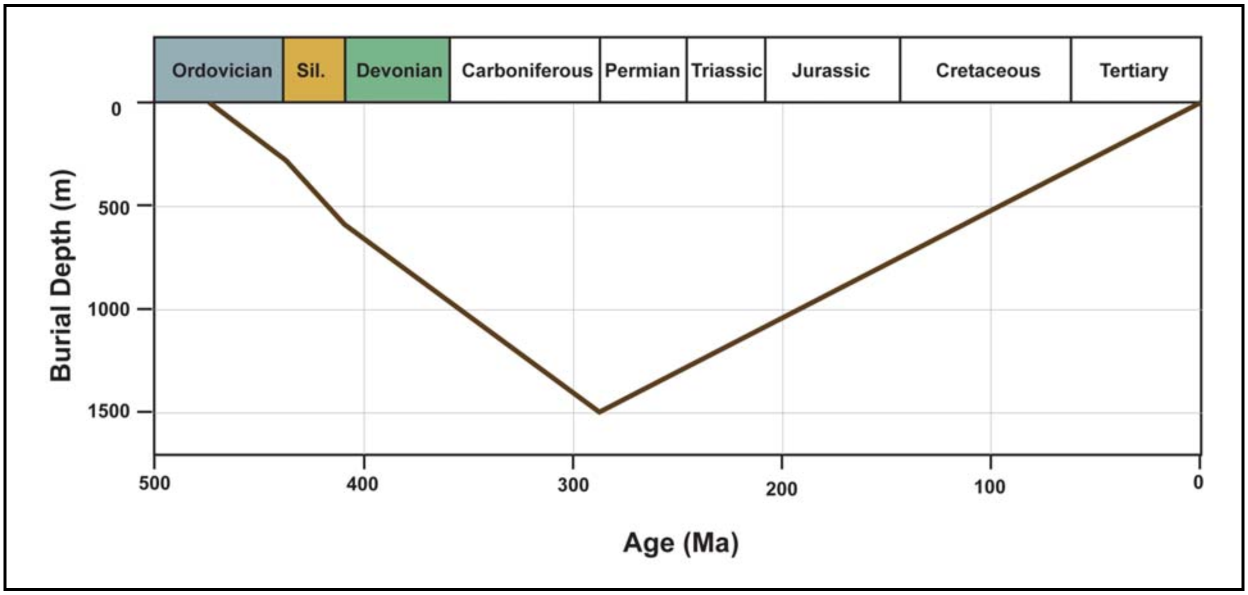


Figure 7.1 Hypothetical Burial History Diagram for the Manitoulin Island area, Ontario (Coniglio and William-Jones, 1992 after Cercone, 1984)

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 distribution of dolostone and limestone throughout Southern Ontario is represented approximately within Figure 2.7 (Sanford, 1993) across both basins. This figure shows the primary mineralogy and does not reflect the significant local variability in 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 following models are summarized from Morrow (1990).

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.

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 in this model 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 shale’s (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 δ^{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 δ^{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 commonly found at the top of the Trenton Group throughout the Michigan Basin. The ferroan nature of this dolomite is interpreted to have resulted from mixing with fluids derived from the overlying shale units (Conglio *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.

The final dolomitization models, and perhaps the most widely discussed due to its relevance to the petroleum industry, are *hydrothermal and fracture* related dolomitization (HTD). Migration and circulation of dense hypersaline brines at depth caused by tectonism is the general mechanism for hydrothermal dolomitization. In Ontario, the pathway for migration and circulation of the hypersaline brines were permeable units and vertical faults and fractures (Conglio *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.

Congilio *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 HDT 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 heated, 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.

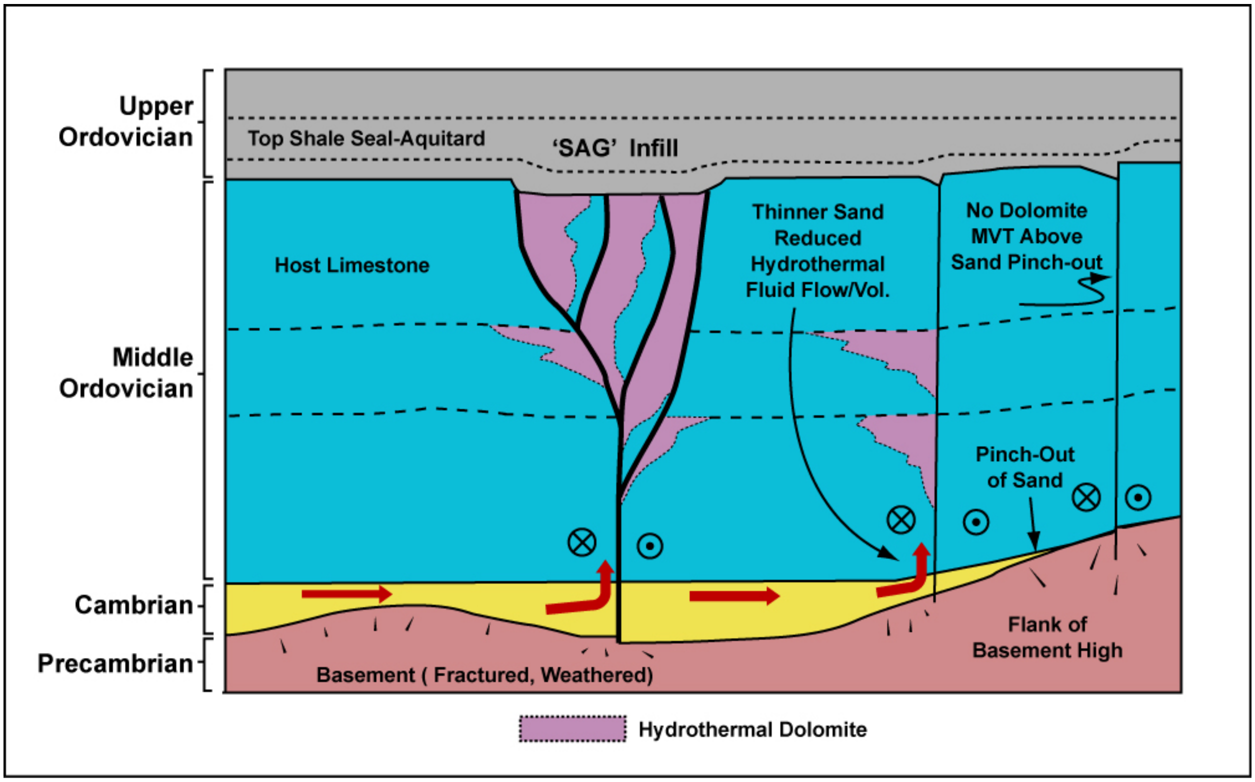


Figure 7.2 Schematic Representation of the origin of fracture related hydrothermal dolomite (HDT) or MVT deposits within the Ordovician sequences of Ontario. Hydrothermal fluid flow is focused along the basal Cambrian sandstone through strike-slip faults. Fluid flow is decreased as the Cambrian thins and HDT and MVT is absent above the Cambrian pinchout (modified from Davies and Smith, 2006).

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 HDT facies (Figure 7.2) is generally interpreted to result from transtentional subsidence along a wrench fault system (Davies and Smith, 2006). This structurally controlled model appears consistent with examples of DHT reservoirs from southern Ontario (Davies and Smith, 2006, and Carter *et al.,* 1996 and Bailey 1995).

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 (Alleghanian) 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 diagentic minerals (pers. com., Coniglio, 2007).

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 galenas 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 galenas. 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.

Salt Dissolution

As discussed earlier, 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.

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 million years BP. (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 paleohydrogeogical 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 Southern Ontario and identifies the regional study area (RSA) of this report. No documented commercially viable crude oil and natural gas resources have been identified within a 40 km radius of proposed Deep Geologic Repository (DRG).

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 Associates, 2005). The majority of exploration is concentrated within the geographic triangle between London, Sarnia and Chatham-Kent in the counties of Essex, Kent, Lambton, Norfolk and Elgin.

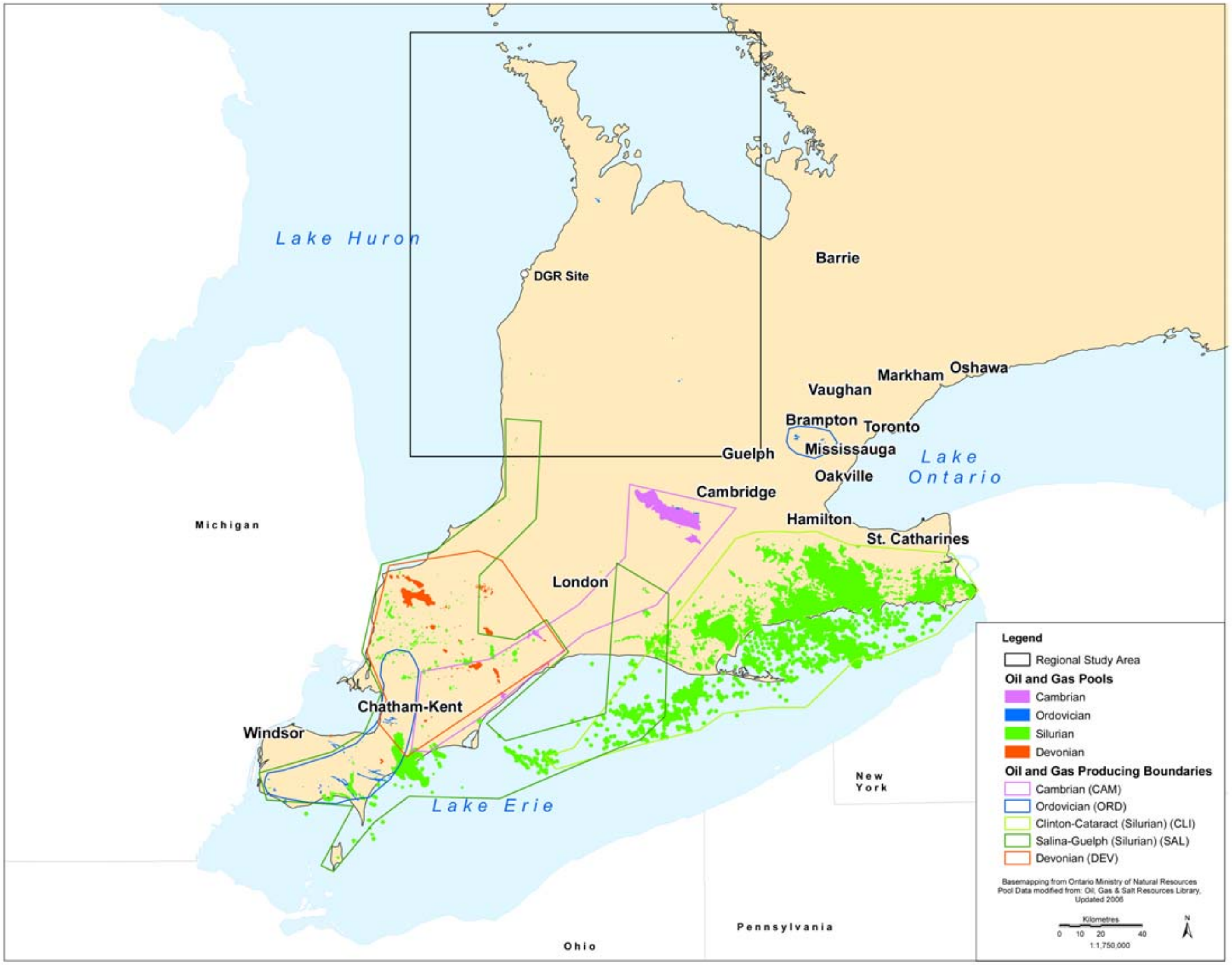
Production from Ontario’s crude oil and natural gas reservoirs accounts for approximately 1% of Ontario’s annual domestic consumption of crude oil and 2% of Ontario’s annual domestic consumption of natural gas.

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, Rose *et al.*, 1970). Figure 8.1 illustrates the distribution of active and former producing petroleum pools in Southern Ontario. 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 (Allegheny) Basin. Hydrocarbon plays in Southern Ontario occur within the following stratigraphic and geographical frameworks (Sanford, 1993c):

a) Cambrian (CAM) sandstone and dolomite structural traps have been 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. The Cambrian plays account for less than 3% natural gas and 6% oil produced cumulatively in Ontario (Oil, Gas and Salt Resources Library, 2004);



Basemapping from Ontario Ministry of Natural Resources
Pool Data modified from: Oil, Gas & Salt Resources Library,
Updated 2006

Figure 8.1 Map Showing Oil, Natural Gas and Natural Gas Storage Pools in Southern Ontario approximate boundaries of Principal Oil and Gas producers (past and present) in Southern Ontario (modified from Oil, Gas and Salt Resources Library data, 2004 and Carter, T.R. (ed) 1990).

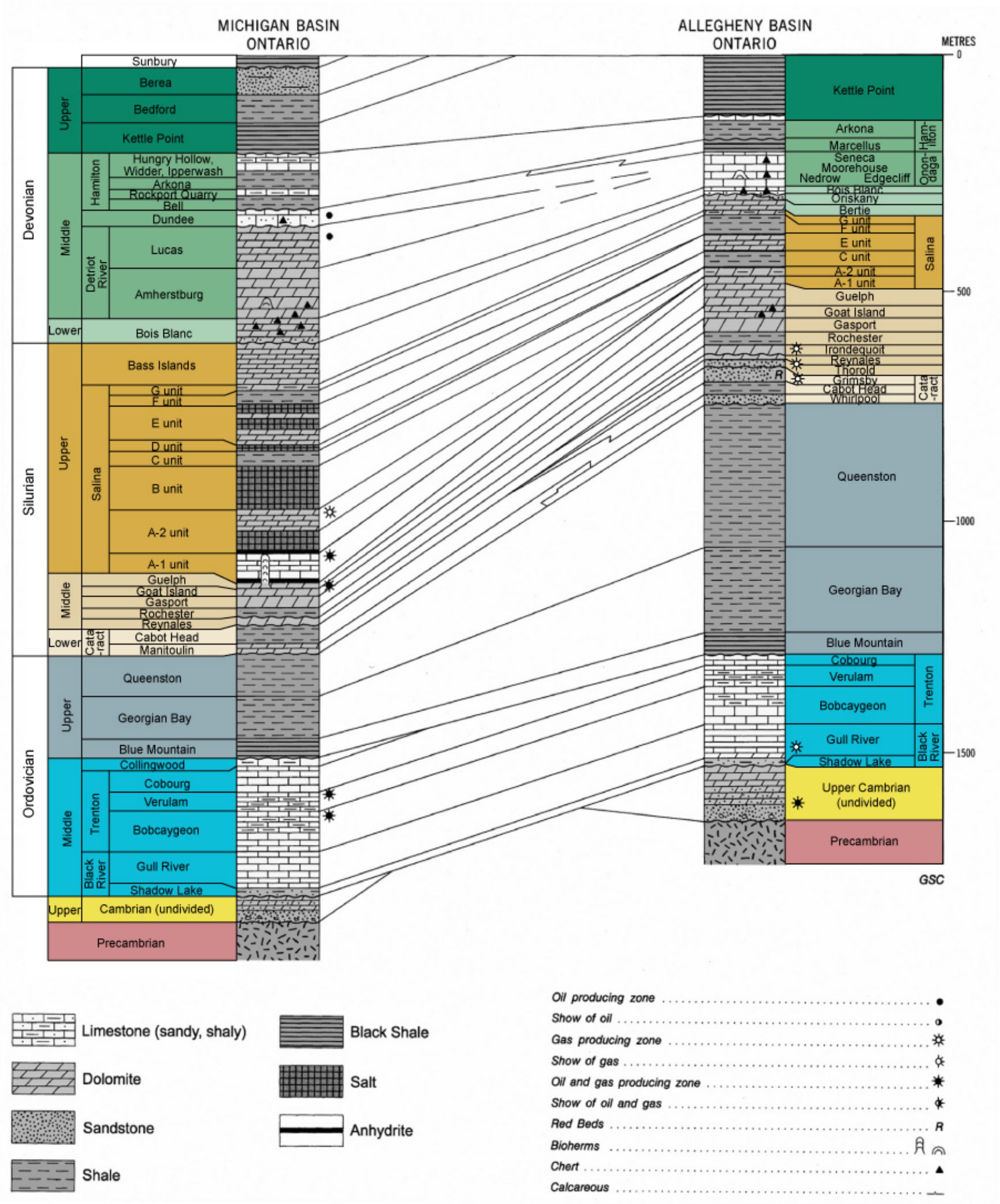


Figure 8.2 Stratigraphic Section Showing Formations, Ages and Oil and Gas Producing Units. The equivalent units for both the Michigan and the Appalachian (Allegheny) basins are shown (From Mazurek, 2004; as adapted from Sanford 1993).

b) 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 (Oil, Gas and Salt Resources Library, 2004). HTD was not encountered at the DGR site when drilled and only localized traces of oil and gas were found within the Ordovician (Intera, Pers. Com. 2007);

c) 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; Oil, Gas and Salt Resources Library, 2004);

d) 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 (Oil, Gas and Salt Resources Library, 2004); and

e) 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 (Oil, Gas and Salt Resources Library, 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 Associates study estimated that 85% of the natural gas volume ($6,799 \times 10^6$ 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: To end 2006 (compiled by GLL from Oil, Gas and Salt Resources Library, 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.

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 occur 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.

Basemapping from Ontario Ministry of Natural Resources
Pool data supplied by the Oil, Gas & Salt Resources Library and Ministry of Natural Resources.
All pool boundaries accurate as of October 2006.
Pool boundaries and production boundaries are interpretive and approximate.
Production boundaries modified from: Carter, T.R. 1990

Figure 8.3 Distribution of Oil and Gas Pools within the Regional Study Area (RSA)

Table 8.2 Active and Abandoned Petroleum Pools Identified in the RSA

Name	Type	Mode	Geological Age	Area (m^2)	Township	Disc. 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
								Cumulative Petroleum Production totals from the RSA:	**200,850.4**	**1,441.7**

Note: Compiled by GLL from Oil, Gas and Salt Resources Library 2006 subsurface dataset.

The probability of commercial shale gas resources beneath the DGR site is considered low due to the absence of natural gas shows during drilling of DGR-1 and DGR-2 and the moderate thermal maturity of the Collingwood and Blue Mountain Formations. 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 as oil, within these units.

8.2 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, 1984ab, 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 in the Sandford *et al*.'s (1985) Bruce Megablock.

8.3 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 Section 7 or this report.

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

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 by Longstaffe *et al.*(1990) reasoned that structural and tectonic features might have facilitated the movement of brines from the south-southwest into southwestern Ontario Cambro-Ordovician sandstones using large fracture systems and/or basement highs as conduits. The brines would then have mixed with pre-existing formation waters across most units, beginning with the Ordovician carbonate sequence to the southwest, moving through Cambrian and Silurian sandstones and into Silurian carbonate reefs near Lake Huron. The origin of the brine remains uncertain; dissolution of Salina salt beds is one possibility, but a source farther to the south, perhaps near the termination of the Findlay Arch, is noted as plausible.

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, and 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 are likely of the same source because oils from reservoirs within these formations cannot be distinguished.

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.

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).

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).

8.4 Hydrocarbon Sources

8.4.1 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:

a) Cambro-Ordovician oils, which are typical of oils derived from marine organic matter;

b) 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

c) 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 models 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). Models include:

a) the existence of a geothermal gradient in the basin sometime during the Paleozoic that was significantly higher than the current average of 22°C/km (Cercone and Pollack, 1991; Speece, 1985, Cercone, 1984);

b) late Paleozoic sediments, including potential coal layers, had previously contributed to the overburden pressure and acted as an insulating cap, allowing the thermal maturity of the sediments to increase. These sediments were subsequently eroded during the Mesozoic (Cercone and Pollack, 1991; and

c) 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).

8.4.2 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 (Barker and Pollock, 1984; Sherwood-Lollar *et al.* 1994) and Cambrian formations (Barker and Pollock, 1984; Sherwood-Lollar *et al.* 1994) have characterized natural gases using isotopic and compositional indicators.

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.

8.5 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.

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.

8.5.1 Cambrian

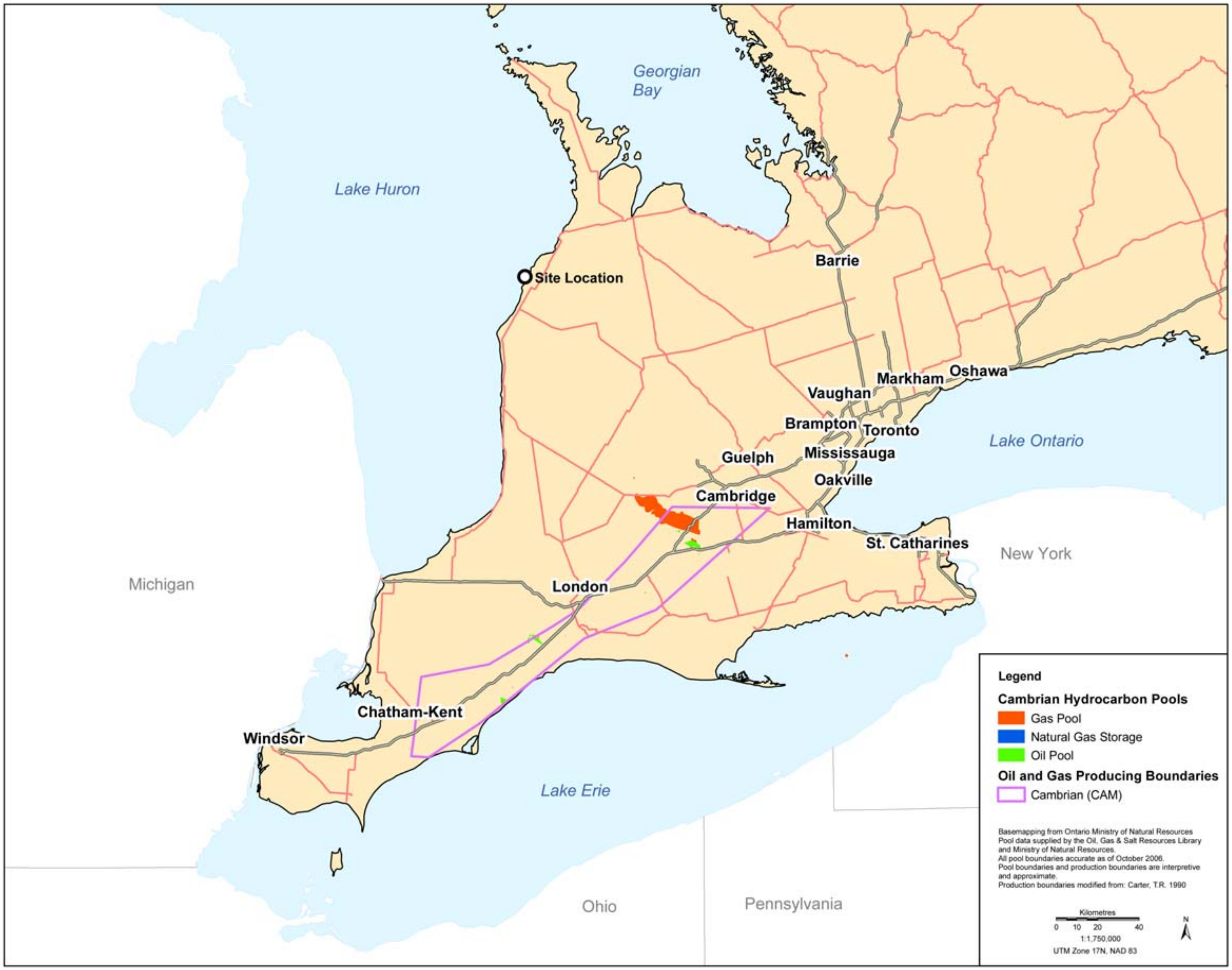
Cambrian (CAM) aged hydrocarbon traps in southern Ontario occur as either stratigraphic traps or fault-related structural traps. Both trapping styles are strongly influenced by the basement tectonics and geology. Pools are located mainly along the erosional boundary of the Cambrian along a line connecting 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 (Oil, Gas and Salt Resources Library, 2004). It should be noted that DGR-2 did not encounter any hydrocarbons within the Cambrian units beneath the DGR Site (Intera, Pers. Com. 2007).

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).



Basemapping from Ontario Ministry of Natural Resources
Pool data supplied by the Oil, Gas & Salt Resources Library and Ministry of Natural Resources.
All pool boundaries accurate as of October 2006.
Pool boundaries and production boundaries are interpretive and approximate.
Production boundaries modified from: Carter, T.R. 1990

Figure 8.4 Cambrian Aged Oil and Gas Reservoirs of Southern Ontario

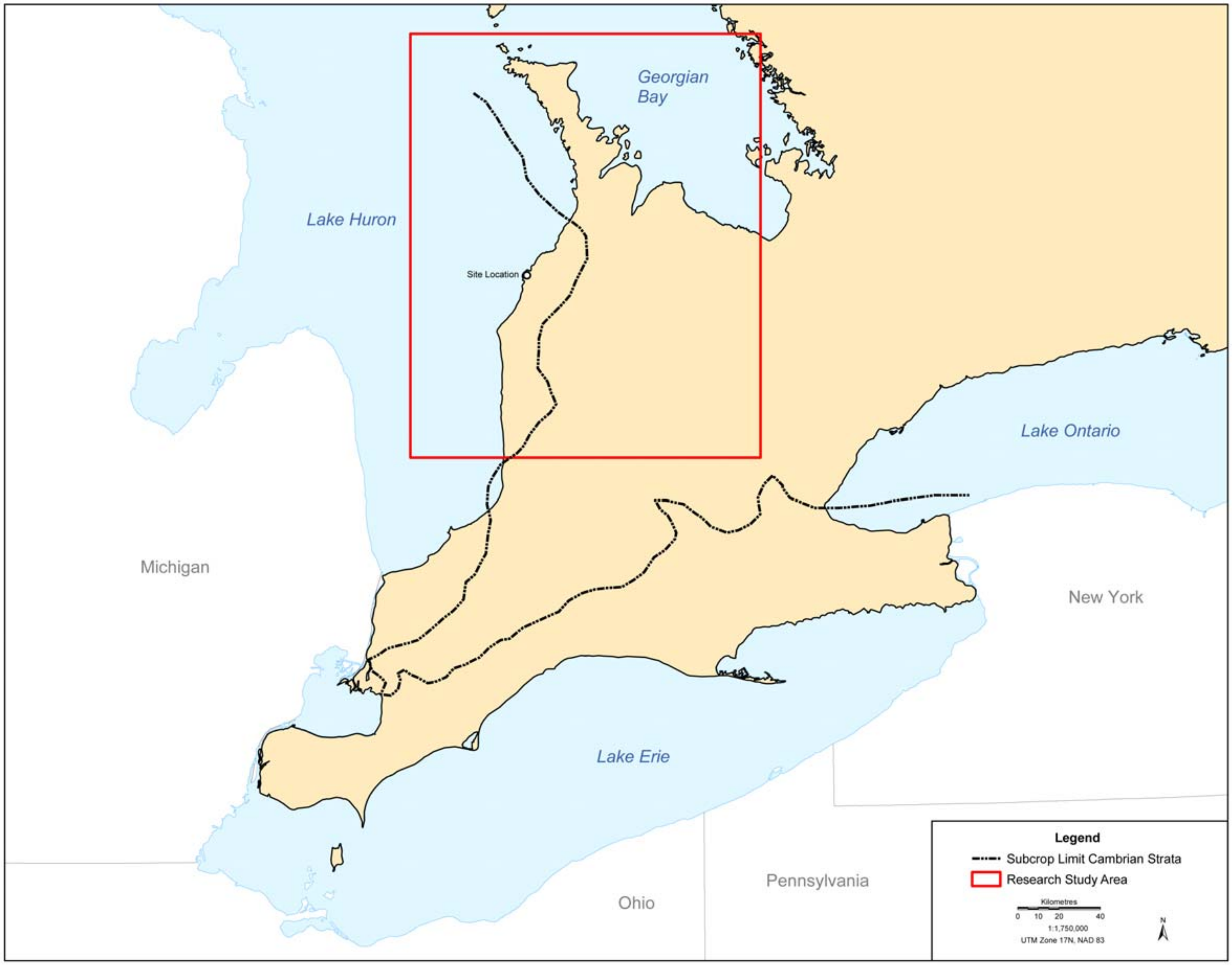


Figure 8.5 Cambrian Subcrop Erosional Boundary (modified from Carter et al., 1996; Trevail, 1990; Sanford and Quinlan, 1959)

Trapping Mechanisms

The Cambrian traps occur as either:

a) stratigraphic traps occurring as permeability pinchouts involving porous Cambrian sediments pinching out updip against the Precambrian surface sealed by low permeability shales; or as

b) 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.

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 et al., 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 trappped 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 et al., 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 *et al.,* 1996, 1993). 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 *et al.,* 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 *et al.,* 1993; Figure 8.6). The bounding faults extend down into and displace the Precambrian.

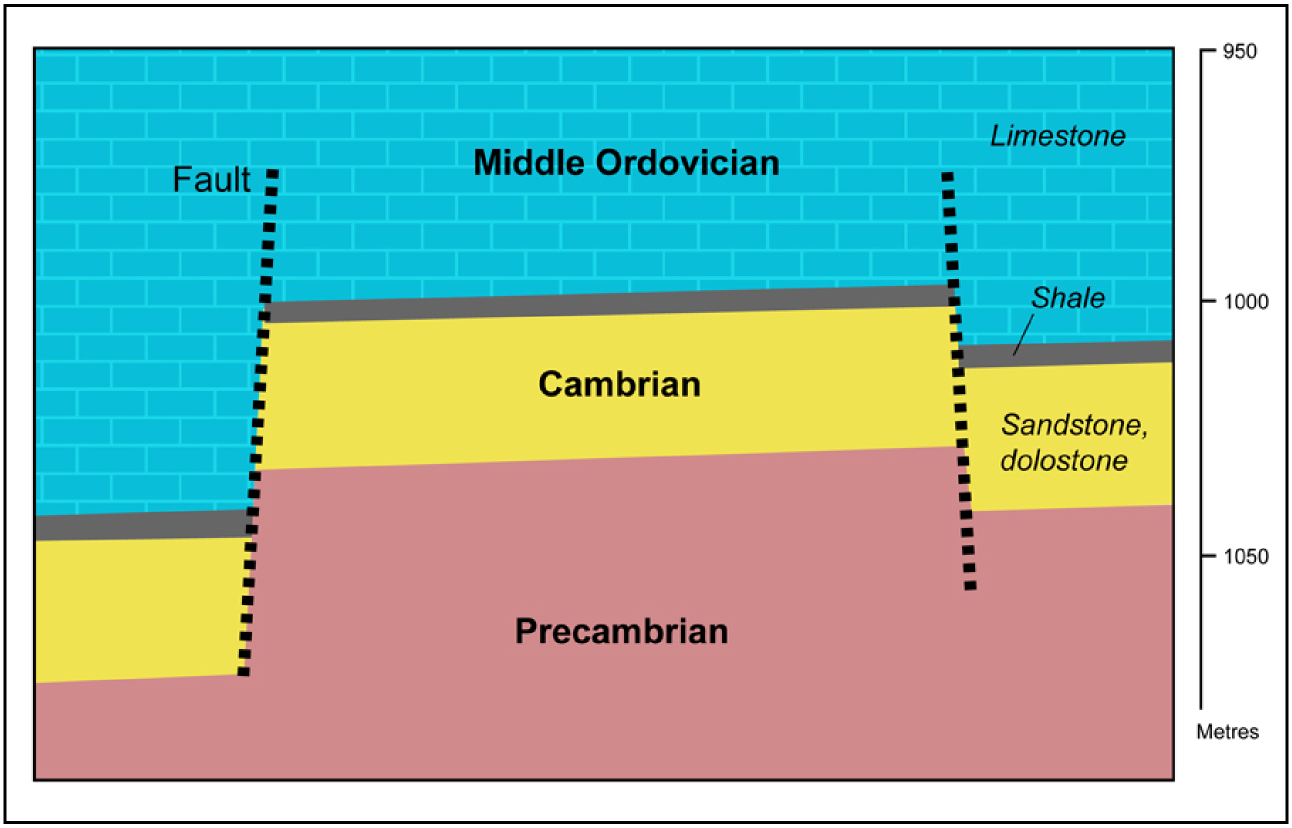


Figure 8.6 Schematic Summary of the Geological Relationships of a Cambrian Fault Trap such as the Clearville oil pool. (Modified from Carter et al., 1993; Bailey and Cochrane, 1984b)

Exploration Status

Exploration for Cambrian hydrocarbon traps in southern Ontario is focussed on two major features:

a) the presence of Cambrian sediments in the subsurface (Bailey, 2005); and
b) structural mapping of the Precambrian surface (Carter *et al.,* 1996).

At present the only Cambrian production in the Michigan Basin is from Kent County on or near the axis of the Algonquin Arch at the eastern edge of the basin.

The pinchout edge of the Cambrian is present in Ontario on both sides of the Algonquin Arch (Figure 8.5; Bailey Geological Services and Cochrane 1984a). Those same rocks bordering the Michigan Basin side of the arch, however, have virtually no shows and no commercial fields. Bailey (2005) has suggested that the shape of the arch was not symmetrical during Cambrian time with the Michigan Basin side being much steeper than the Appalachian Basin side hence, on the Michigan Basin side, the Cambrian sediments were mostly abutting against a steep slope, whereas on the Appalachian Basin side they were able to onlap much farther up the sides and farther inland.

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 *et al.,* 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).

<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 following reasons:,

a) 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;

b) 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

c) no oil or gas shows were reported during the drilling of the Cambrian sections of DGR-2 (Intera, Pers. Com. 2007).

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.

8.5.2 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 Associates*,* 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 Associates 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).

Reservoirs

Fracture-related hydrothermal dolomite reservoirs (HTD) are recognized to occur in western Canada, Saudi Arabia, Australia, northeastern United States and southern Ontario (Golder Associates, 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 replacive 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 Associates, 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.

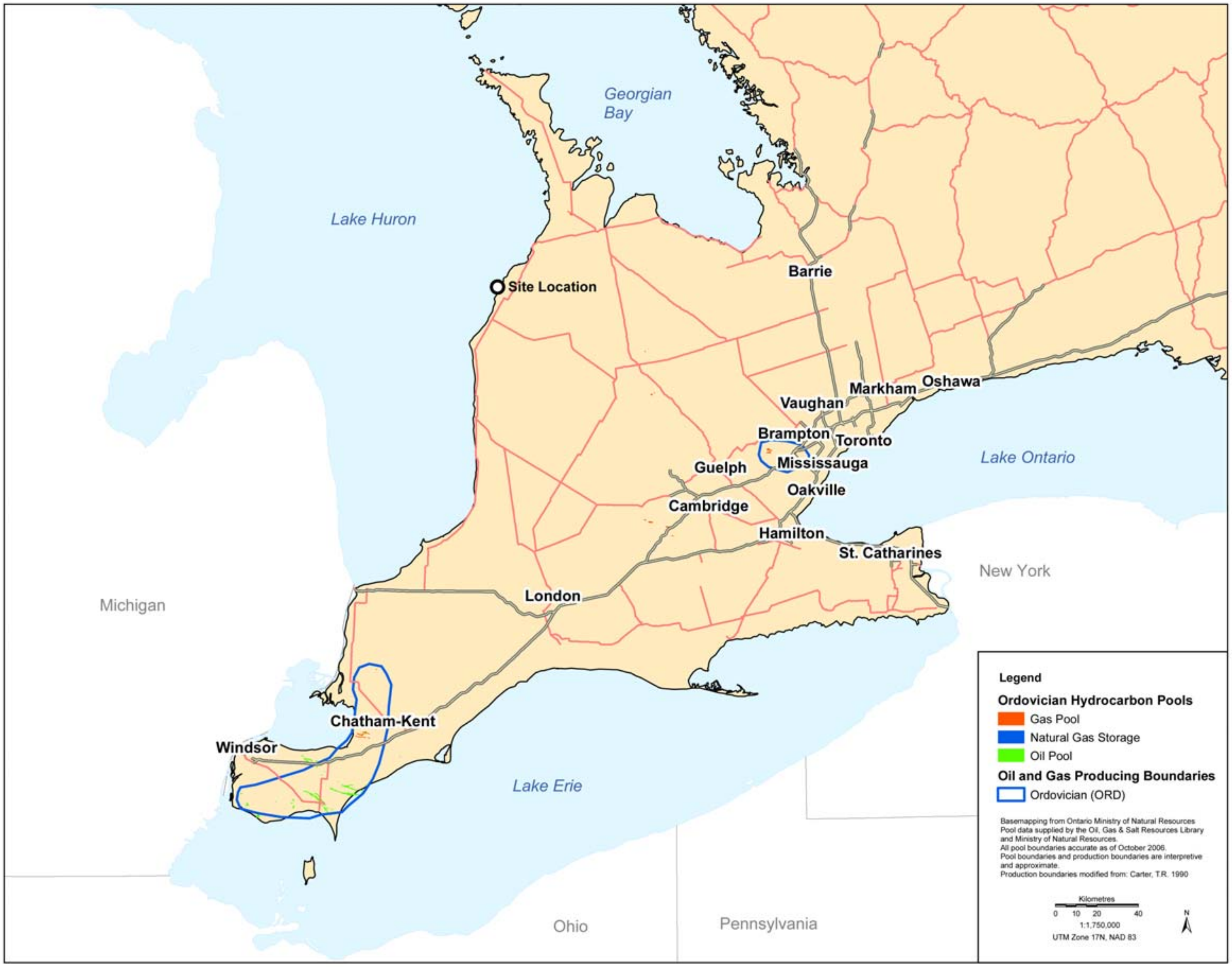
The porosity, and hence the hydrocarbons, are found only in fracture-related HTD dolomite including the fractured cap. Typically the dolomitized zones have intercrystalline, vuggy, and/or fracture porosity, which has subsequently trapped oil and natural gas, and generally in narrow linear trends cut 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 Associates, 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 Associates, 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, and Golder Associates, 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)



Basemapping from Ontario Ministry of Natural Resources
Pool data supplied by the Oil, Gas & Salt Resources Library and Ministry of Natural Resources.
All pool boundaries accurate as of October 2006.
Pool boundaries and production boundaries are interpretive and approximate.
Production boundaries modified from: Carter, T.R. 1990

Figure 8.7 Ordovician Aged Oil and Gas Reservoirs of Southern Ontario

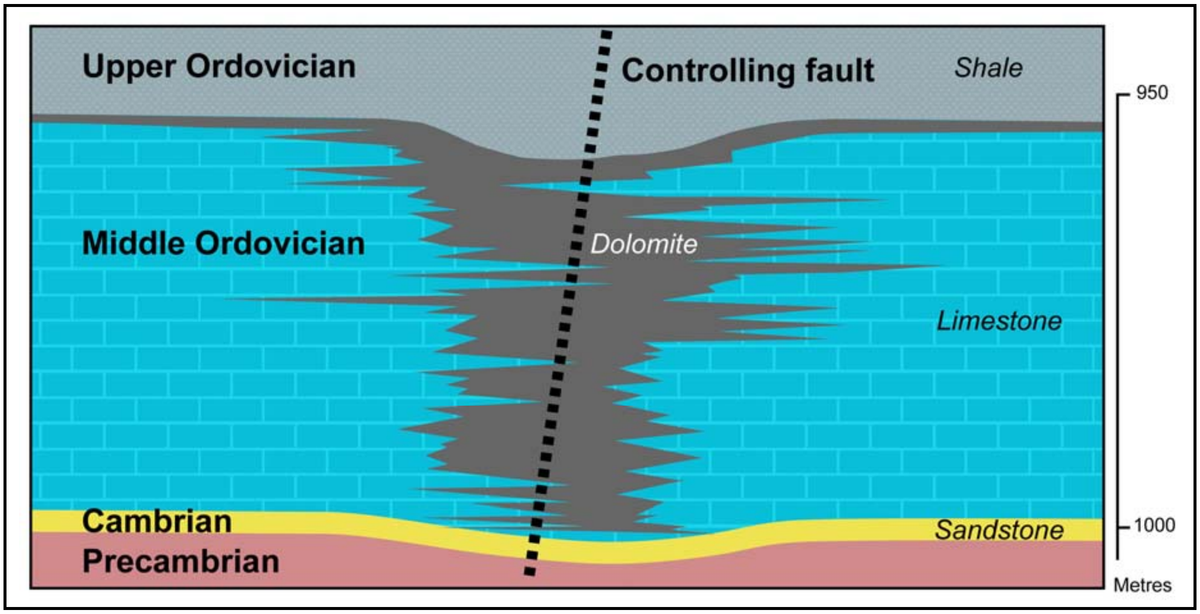


Figure 8.8 Schematic Summary of the Geological Relationships of a Trenton-Black River Ordovician HTD Petroleum Trap modified from Carter et al., 1993

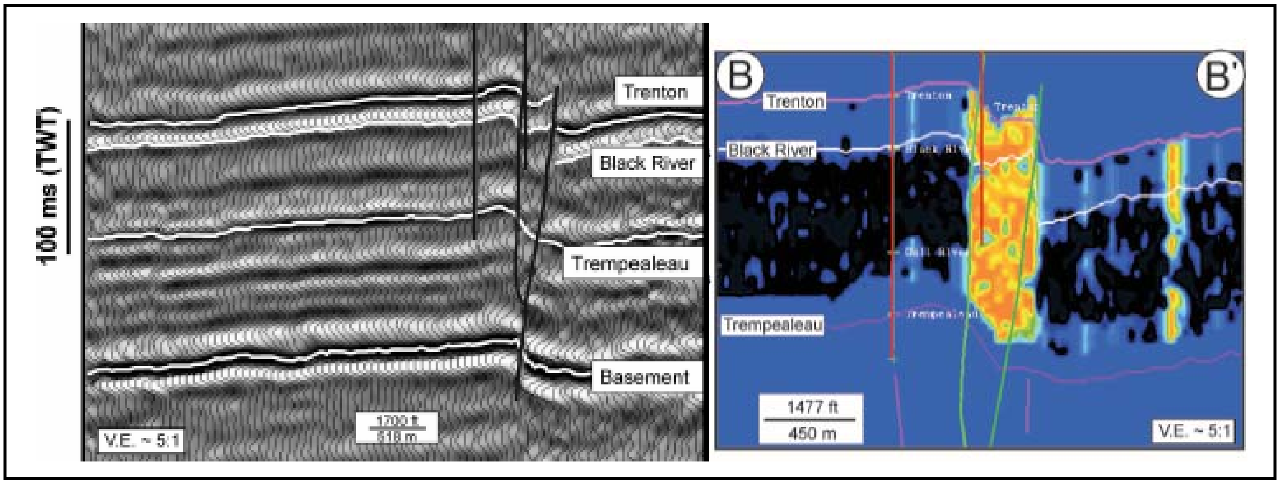
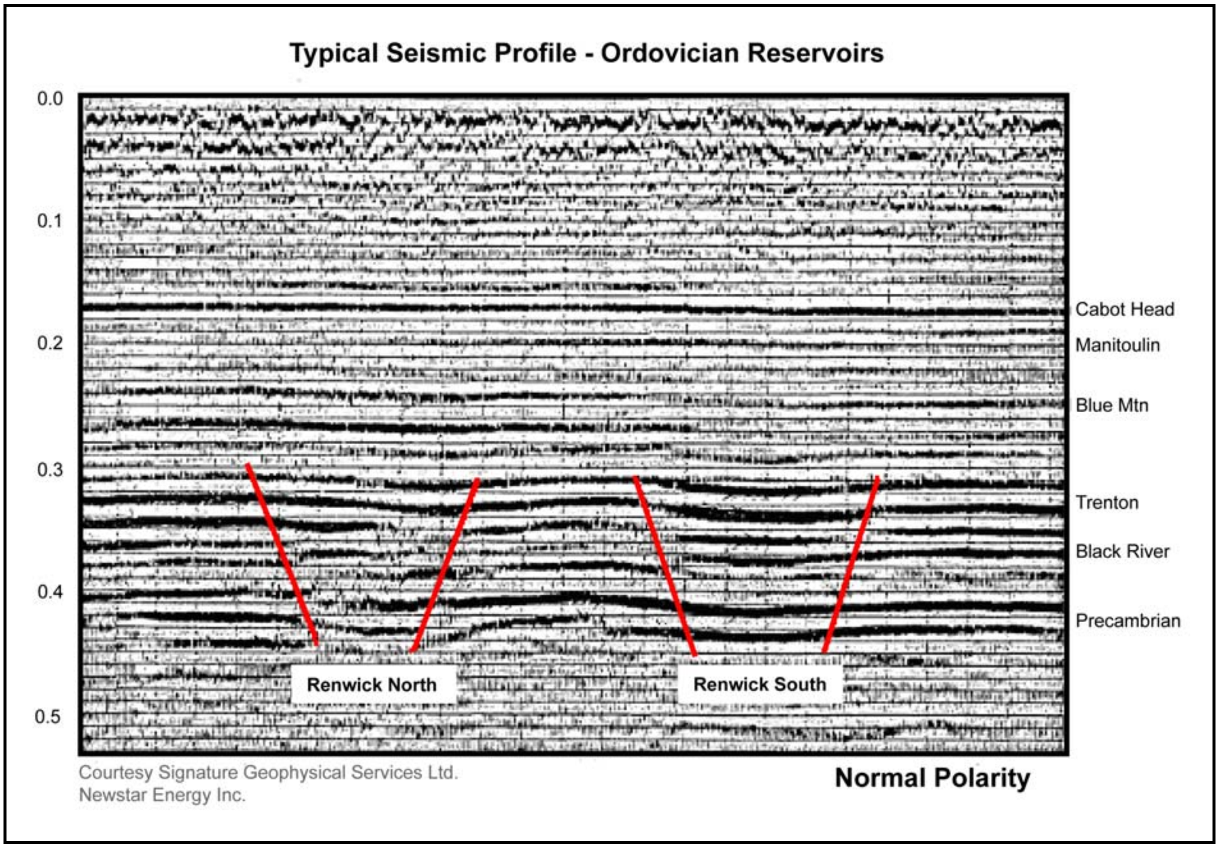


Figure 8.9 Example of en echelon faults in the Trenton/Black River of Saybrook, Ohio interpreted from seismic data (Left). The faults overlap to form concave-upward positive "flower" structures. Extrapolation of enhanced relative porosity from the same seismic survey showing highest porosity values are concentrated in the areas of intense faulting, especially where the faults overlap and meet at depth (Right) (Sagan and Hart, 2006).

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 downdropped 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 Associates, 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 Associates, 2005).



Courtesy Signature Geophysical Services Ltd.
Newstar Energy Inc.

Figure 8.10 Seismic Profile Showing Trenton-Black River HTD Reservoir Zones (Renwick North and South) adjacent to vertical faults or fractures that extend from the Precambrian basement to the top of the Trenton Group (modified from Carter et al., 1993).

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 usually typically do not extend to units overlying the Trenton and are readily visible on industry seismic lines (Figure 8.10; Carter *et al.*, 1993).

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

a) 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;

b) thickening of the potential seismic scattering points (isochrons) between the seismic markers for the Rochester Member and Trenton Group (Golder Associates, 2005);

c) the basement surface appears as a low or appears to be disappearing due to faulting (Golder Associates, 2005); and

d) diffraction anomalies delineate the transition from porous reservoir dolomite to regional low permeability limestone (Golder Associates, 2005).

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 Associates (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. 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 DGR-2 (Intera, 2008).

Structurally the RSA resides within the stable area of the Bruce Megablock with few faults and no major regional fault systems (such as those found in southwestern Ontario) currently identified. In addition, no major magnetic anomalies or perturbations in the magnetic signature of the Precambrian basement have been recorded (Figure 3.5) to date.

8.5.3 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:

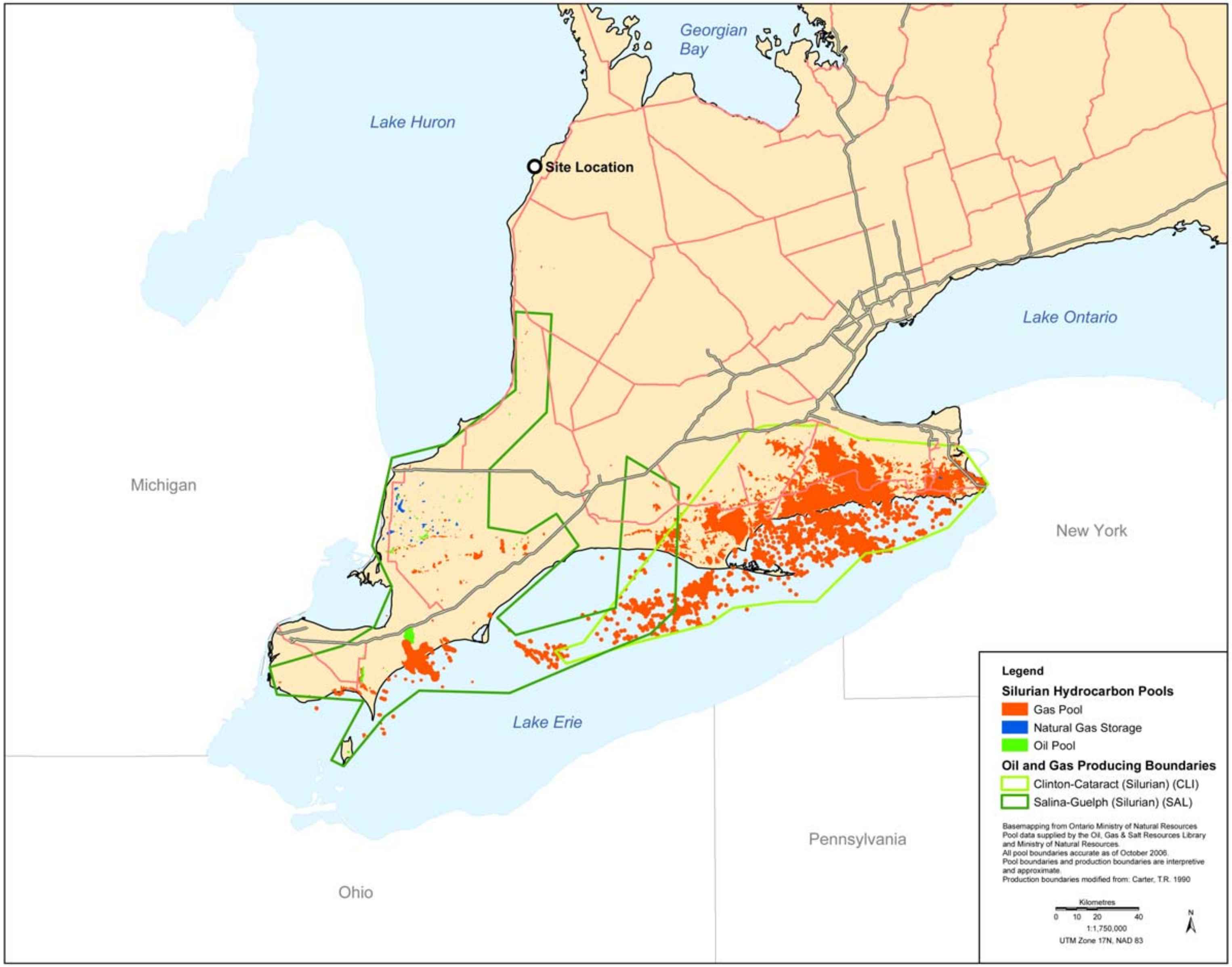
a) Upper Silurian reef (Niagaran) dolostone of the Guelph Formation and the Salina Formation (A1, A2) host hydrocarbons in stratigraphic traps; and

b) 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 4.24), 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.



Basemapping from Ontario Ministry of Natural Resources
Pool data supplied by the Oil, Gas & Salt Resources Library and Ministry of Natural Resources.
All pool boundaries accurate as of October 2006.
Pool boundaries and production boundaries are interpretive and approximate.
Production boundaries modified from: Carter, T.R. 1990

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

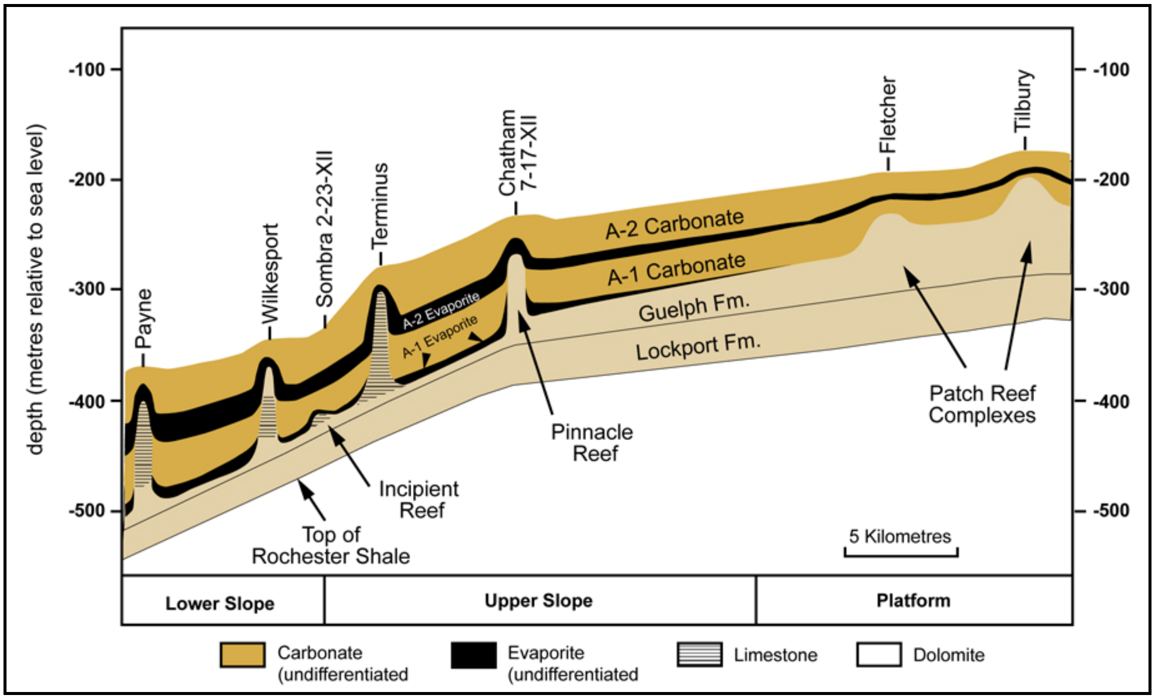


Figure 8.12 **Regional Structural Cross-section Showing the Distribution of Facies and Lithologies in the Guelph Formation. The relationship between the Guelph Formation and overlying units of the Salina A Group (modified from Coniglio et al., 2003).**

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):

a) Stratigraphic trapping in the Pinnacle, Incipient and Platform Reefs of the Middle Silurian Guelph Formation; and
b) 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.

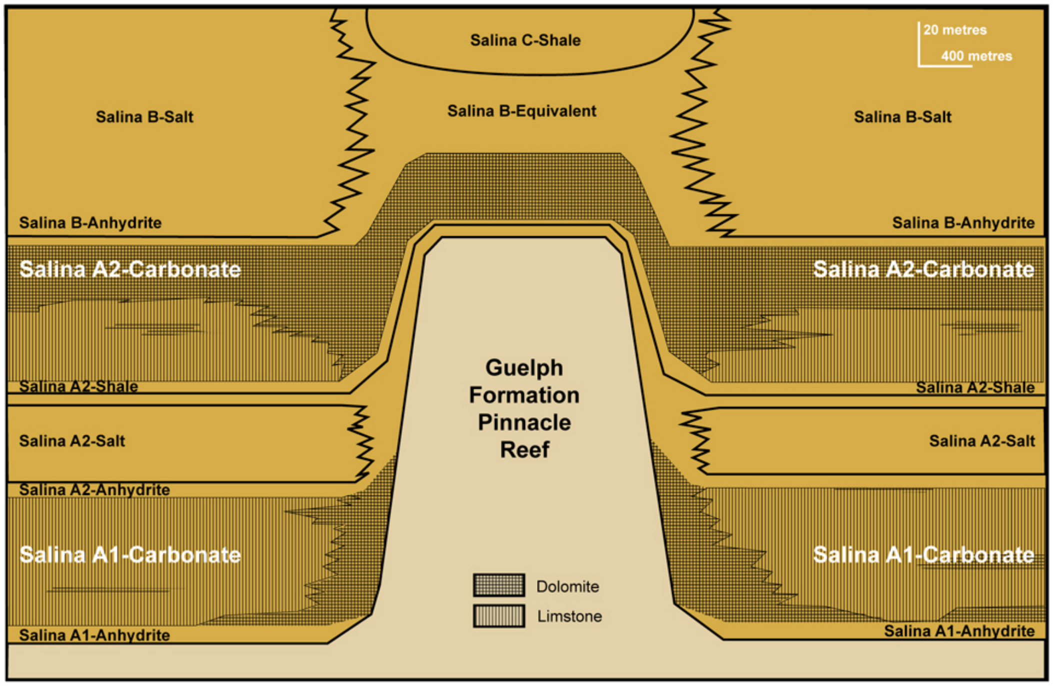


Figure 8.13 Schematic Summary of Dolomitization Patterns in the Salina A-1 and A-2 Carbonate Units in the vicinity of pinnacle reefs in Sombra County (modified from Carter et al., 1991).

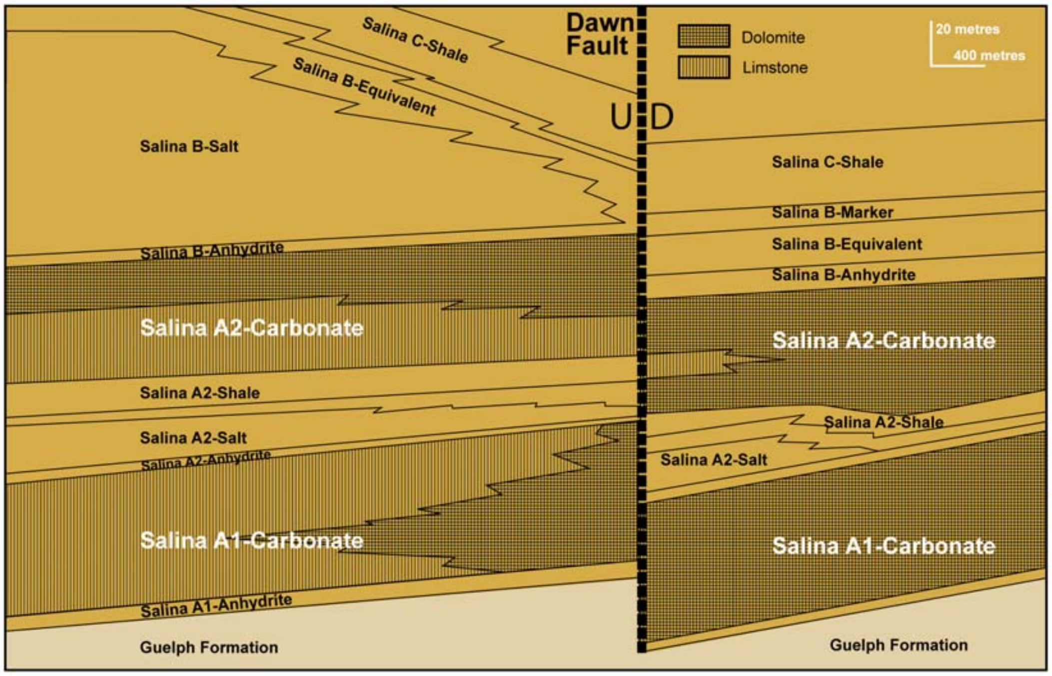


Figure 8.14 Schematic Summary of a Silurian Fault Trap in the Salina A-1 and A-2 Carbonate Units along the Dawn Fault in Sombra Township, Ontario. Potential hydrocarbon traps occur in porous dolomite in both the A-1 Carbonate and A-2 Carbonate on the up-thrown side of the fault (modified from Carter et al., 1994).

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.

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 (Section 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 with 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).

8.5.4 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 Library Pool data, 2004).

Reservoirs

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

1. 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
2. Carbonate traps in the fractured Dundee Formation crinoidal limestones, porous Lucas Formation dolomites and Rockport Quarry formations.

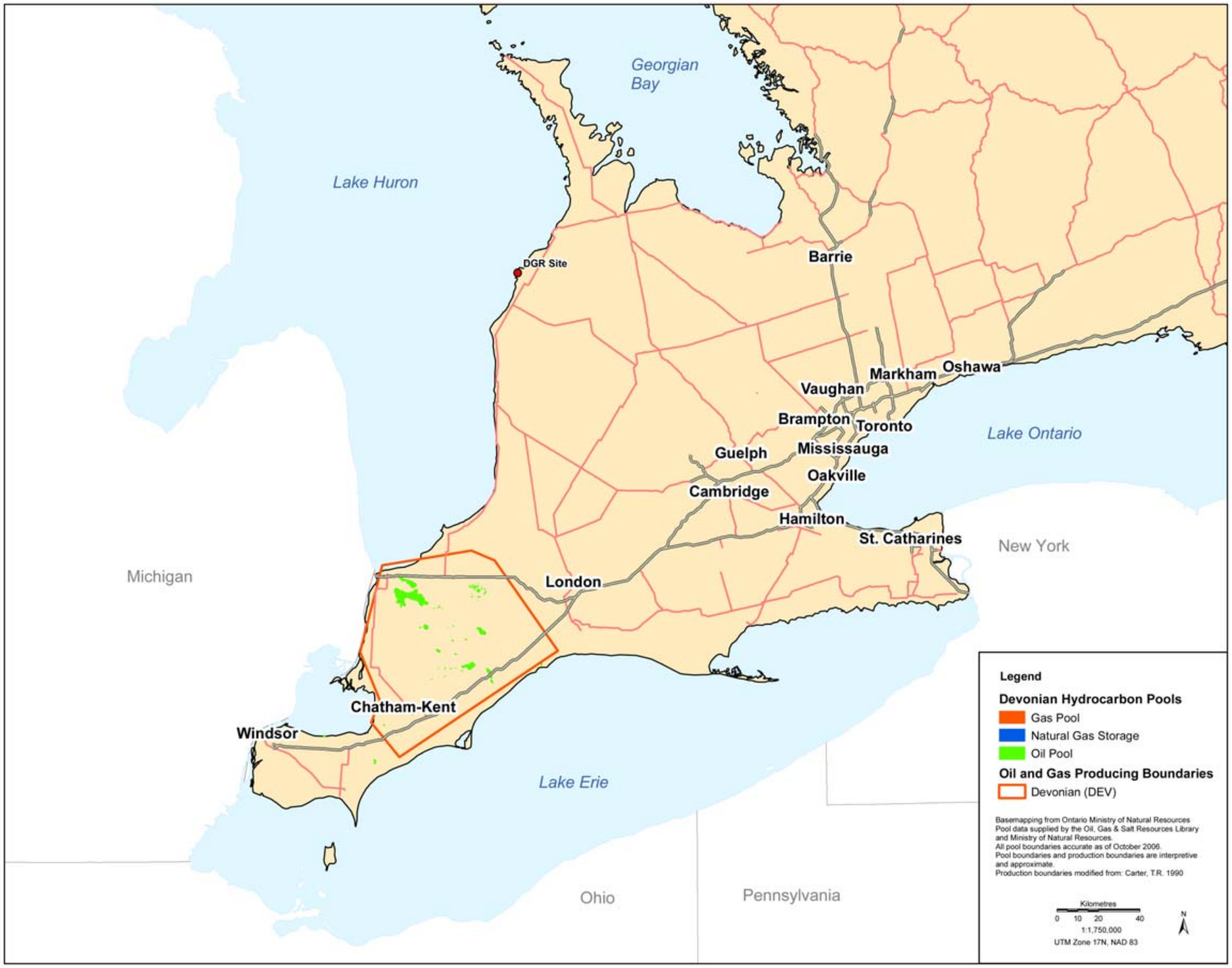
Both of these traps are associated with fractures and structural highs or anticlines caused by regional warping or differential salt solution. (Bailey Geological Services and Cochrane, 1985).

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).

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. Overlying Devonian shales, anhydrites, and/or dense carbonate rocks provide the stratigraphic seal (Bailey Geological Services and Cochrane, 1985).

The resulting stratigraphy from salt dissolution creating a typical Devonian hydrocarbon reservoir trapping geometry within southwestern Ontario is illustrated in Figure 4.10, which shows a series of anticlinal structures. 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).



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Pool data supplied by the Oil, Gas & Salt Resources Library and Ministry of Natural Resources.
All pool boundaries accurate as of October 2006.
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Production boundaries modified from: Carter, T.R. 1990

Figure 8.15 Devonian Oil/Gas Pools

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).

8.6 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 Regional Study Area (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 DGR 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 within the boundaries of the RSA have focussed on the Silurian and Devonian targets in Huron County south of Goderich with two petroleum well completions 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 DGR 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 (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 hydrothermal Ordovician dolomite. 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 DGR 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.

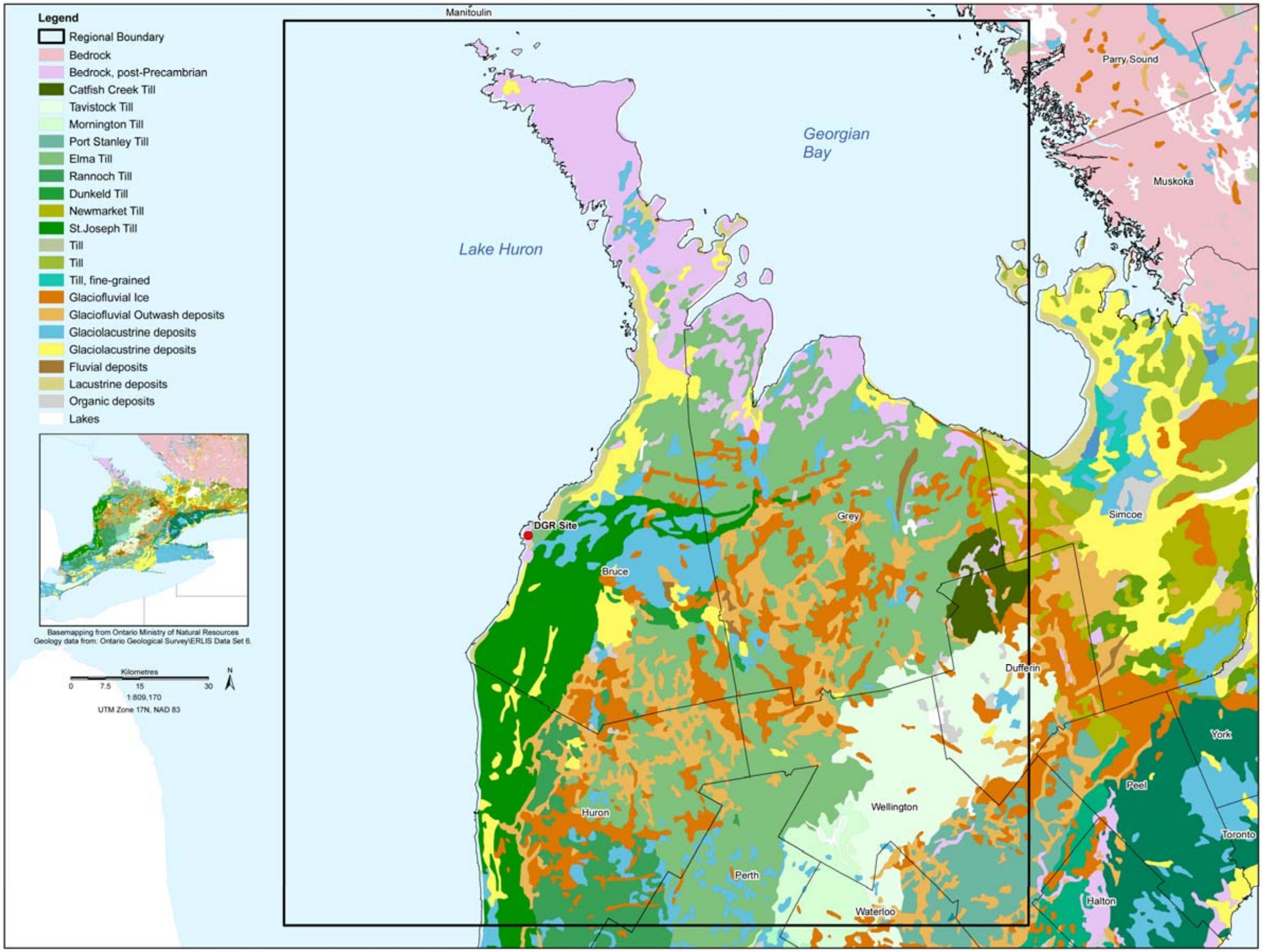
The RSA was covered by two ice lobes, namely the Huron and Georgian Bay ice lobes. These ice lobes advanced from the west and north, respectively, during the last glaciation (Chapman and Putnam 1984, Sharp *et al.*, 1997). The locations of the ice lobes and their margins fluctuated until the final retreat 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. A summary of the glacial periods, from youngest to oldest, and the Quaternary deposits that result from them, is presented in Table 9.1.

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

The Catfish Creek Till is the oldest till in the Regional Study Area. 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,



Basemapping from Ontario Ministry of Natural Resources
Geology data from: Ontario Geological Survey\ERLIS Data Set 6.

Figure 9.1 Quaternary Geology Map of Regional Study Area 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 readvance 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 readvanced 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):

1. 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 (Cowell, 2007).

2. 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.

3. 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.

4. 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).

5. 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.

6. 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.

7. 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.

8. 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.

9. 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; and,

10. 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 proposed DGR site is located within the Huron Fringe and Huron Slope physiographic regions.

The thickness of overburden throughout 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 of the site (Golder Associates, 2003). Overburden and fill thickness at the DGR site (DGR-1) is approximately 20 m (Intera, 2008). Approximately 3 m of gravel fill overlies approximately 17 m of native overburden comprised of clayey silt tills with gravel.

To the northwest and southwest of the DGR, 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 (Peltier, 2008) and resulted in a build up of the neotectonic stress field (Gartner Lee Limited, 2008). 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).

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 Overview of 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):

a) 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 occurs 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.

b) 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 morainic 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.

c) 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 DGR site.

10.2 Overview of 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 brickmaking.

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.

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 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 Michener Booth and Wahl, and Ontario Geological Survey, 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.

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 DGR 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 RSAs (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 (ARIP177, 2004). No further potential bedrock resources were identified in this area.

Sphalerite (MVT deposits) occurrences within the Bruce Peninsula have attracted some interest by base metal explorationists 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. REPORT SUMMARY

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 Regional Study Area 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 DGR site, the Michigan Basin where the DGR site is located, and the Algonquin Arch, the basement topographic feature that separates the two basins. 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 the geology over large distances. The Paleozoic stratigraphy of southern Ontario is relatively simple, flat lying 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 Regional Study Area. These units include the Middle Ordovician limestones (approx. 200 m in thickness), Upper Ordovician shales (approx. 200 m in thickness) and Upper Silurian argillaceous dolostones and evaporites (approx. 190 m in thickness).

The geology encountered in boreholes DGR-1 and DGR-2 is consistent with the regional geology as described 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. 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 exists 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 DGR site is low. Drilling at the DGR site did not encounter significant oil and gas resources. Currently, there is no petroleum production within 40 km of the DGR site and only minor petroleum resources are extracted within the Regional Study Area.

An assessment of Quaternary geology and aggregate resources shows that the DGR 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 (Lucas/Amhurstburg Formation) dolostone, which is not considered an economic resource at or adjacent to the DGR site.

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Appendix A

3D Geological Framework

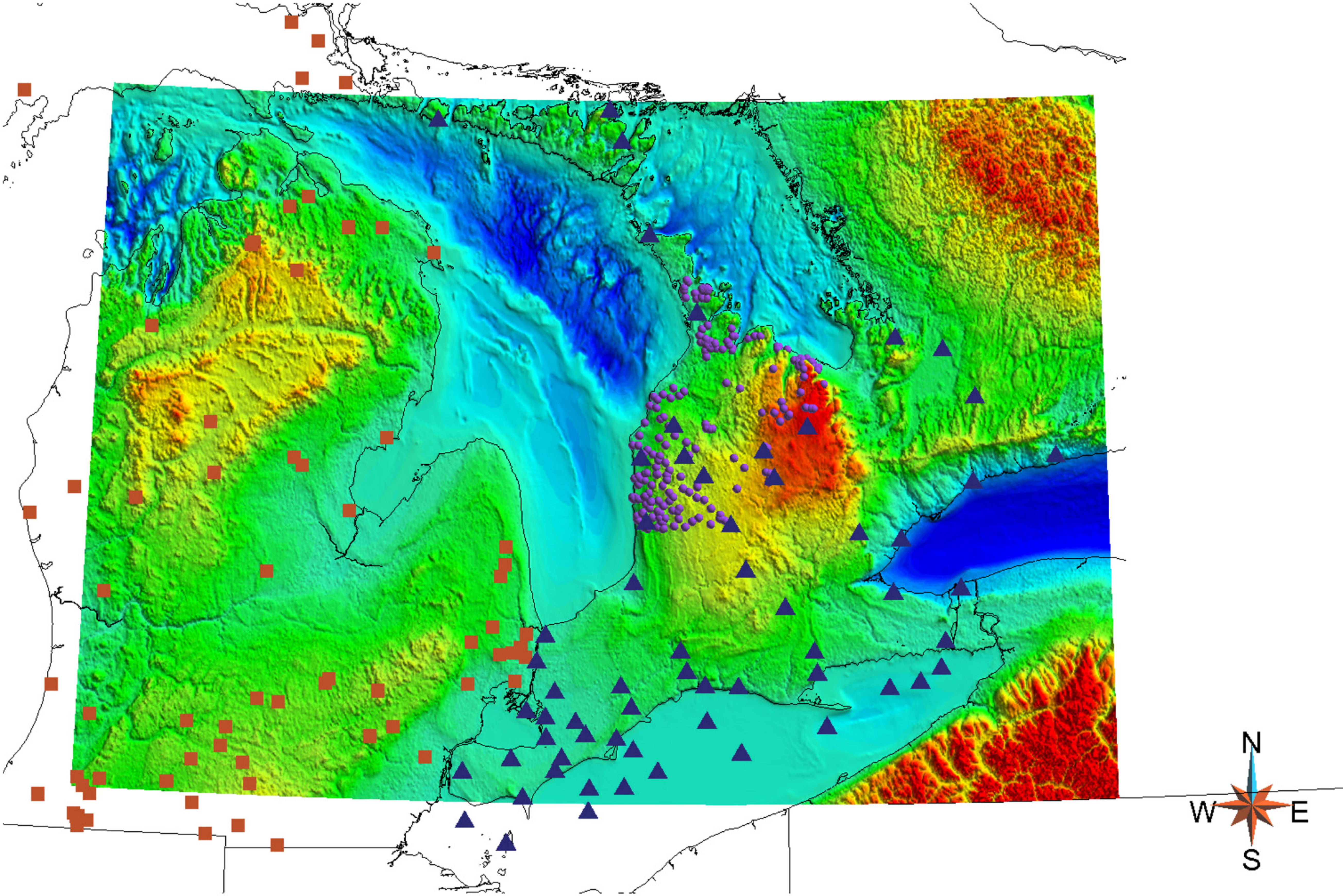

Figure A1. Digital Elevation Map With 3D Geological Framework Well Locations

Appendix A.1

3D Geological Framework Methodology

1. Development Tools

1.1 Data Integration, Validation and Geological Modelling – Earth Decision/Paradigm's Gocad^{TM}

Gocad^{TM} was selected as the primary tool for the development of the 3DGF. This software was developed for the oil and gas industry, however, it has a wide range of applications in other geoscientific-related fields such as geophysics, geomechanics, geochemistry and mining. Gocad^{TM} has also been used in Ontario Power Generation's Deep Geological Research Technology Program during the last five years. Gocad^{TM} is a true "topological" 3D earth modelling environment supporting 3D vector and raster data overlays, spatial queries, and sophisticated earth model decision analysis. This software also provides governance tools that help support quality programs through process control frameworks and audit trail capabilities.

At the heart of the Gocad^{TM} engine is a mathematical tool capable of interpolating the physical properties and the location (x,y,z) of nodes defining a 3D geological object. Object geometry and object properties may be interpolated by the Discrete Smooth Interpolation (DSI) method, which is an iterative method. The DSI method was developed because traditional computer aided design tools, are not capable of properly representing the complex nature of the data encountered in the geosciences. Details of the DSI method are discussed below.

1.2 Co-ordinate Transformation – Blue Marble's Geographic Calculator

The datasets being used for this study come from various sources and for various data/project specific reasons, and therefore many have unique co-ordinate systems. For this reason, Blue Marble's Geographic Calculator, an industry-standard co-ordinate transformation tool was selected to handle all co-ordinate system transformations.

1.3 DSI Method GoCAD®

In essence, the goal of the DSI is to create a smooth result. Note however, that it is possible to force the DSI to honour hard constraints imposed on the geometry or properties, such as measured data, e.g., a well contact or a measured downhole property. If geology is interpolated with no constraints or control nodes, DSI will try to reduce the relief and size of the object until it collapses. If a property is interpolated with no constraints or property control nodes, DSI will try to move the property values toward the mean until the property becomes a constant. If some constraints are set on the object, DSI will try to modify the object to fit the imposed constraints. Once assigned, the "constraints" are locked in and the DSI will NOT modify these points, hence "constraining" your model. Therefore, it is good practise to set additional constraints or control nodes to maintain the geometry or property values in the area of the object that you do not want to be modified. During an interpolation, DSI can move every node that is not a control node to fit the constraints and to accomplish its original goal of reducing the relief of the geometry or property. It should be noted that this technique has been specifically designed for modelling natural objects, i.e. geological contacts.

The main advantages of using the DSI (modified after Mallet, 1989):

a) DSI can easily account for discontinuities, i.e. faults
b) DSI is very efficient for interactive modelling since it requires very few iterations to be solved
c) The main disadvantages are:
d) Unlike DSI, classical methods do not require the data to be located at the nodes of the grid.
e) Unlike Kriging, DSI does NOT provide a point estimation of the precision of the interpolation, i.e. error estimate

The DSI should not be used to replace classical methods such as Kriging, however, DSI may be seen as a complimentary tool to get an approximation of values of classical interpolation techniques. This allows the user to quickly identify potential trends in the data, without the exhaustive overhead required by classical methods. The method is a hybrid approach to geological modelling combining traditional interpretation techniques along with an advanced interpolation method. For a detailed explanation of the DSI, the reader is referred to Mallet (1989).

2. Data Validation

2.1 Database Well Collar Elevations Compared with Digital Elevation Model

This simple test was used to verify whether geological contacts consistently offset from neighbouring wells were related to errors in the recording of well collar elevations. A comparison with the DEM model could be used when the difference between the two elevation data points was greater than the standard measurement error of the DEM, typically +/- 5 to 10m.

2.2 Database or Sequence Data Tests

Database and data sequence tests were largely designed to check for errors in the database itself. These validations included:

a) checking if formations were simply not logged in the database;
b) identifying anomalous well formation intervals; and
c) identifying formations that were recorded out of sequence. For example, older formations above younger formations.

2.3 Geological/Stratigraphic Tests

These validations involved identifying geological or stratigraphic anomalies within the geological framework. These validations included:

a) verifying whether the geophysical logs (e.g., gamma ray) match the geological picks selected. Geophysical logs were compared with standard geophysics recorded in the OGS reference wells (Armstrong and Carter, 2006);
b) verifying that the stratigraphic relationships, as recorded in the data, are valid;
c) verifying if offsets in adjacent formation elevations provided evidence of geological structure such as faulting or reefs;
d) comparing whether the logged geological units coincide with outcrop mapping; and
e) verifying that the geological model layers reflect the current scientific understanding of the subsurface stratigraphy.

3. Workflow Development

1. Acquire primary data and perform preliminary QA/QC operations.
2. Import OGSR wells into Gocad^{TM}. Perform secondary QA/QC operations, i.e., collar checks, qualitative visual inspection, etc.
3. Once validated by the geologist, create 3D pointset from the “tops” of the formation well markers.
4. Create a coarse wireframe surface (mesh) from the 3D pointset created in step 3.
5. Set “hard” constraints on the surface, derived from the well markers, to ensure the surface honours the well data.
6. Densify the mesh surface.
7. Enhance the mesh by making triangles equilateral and running a DSI (all the while honouring the constraints imposed in step 5).
8. Compute the formation thickness from the well intercepts of a given formation.
9. Transfer these thicknesses’ to the surface directly below the formation surface in question.
10. Run the DSI on the thickness property to propagate the values across the entire surface. This creates a “thickness map” that will be used to constrain the thickness of the formation (see next step).
11. Set a thickness constraint on the surface in question.
12. Run DSI on the formation surface to impose the thickness constraint, i.e., this will move the surface up or down to try and match the prescribed thickness computed in step 10.
13. Check resulting geometry and locally remove any “crossing” between surfaces that is artificial.
14. Manual intervention from geologist may be required to interpret and correct geological relationships.
15. Final geological review.

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
DGR_1	454239.78	4907753.24	185.71	462.00
DGR_2	454208.92	4907720.30	185.84	862.00
H000015	551300.84	4887646.92	503.30	611.50
N000256	554186.39	4926978.57	232.25	49.68
T001892	466525.78	4913076.19	235.31	770.50
T002636	456347.03	4905796.19	228.90	881.50
T002713	530430.01	4855695.71	435.90	716.28
T004767	485863.04	4856905.01	342.30	865.94
T004881	473529.80	4869343.45	294.10	882.70
T006056	481621.08	4959855.36	196.00	446.50
T007544	446247.27	4868248.11	219.90	1100.00
F011909	460307.89	4824403.87	288.65	551.69
F011928	449485.93	4826945.60	280.72	643.13
F011941	449937.55	4827428.68	276.15	629.11
F011953	459780.23	4828115.44	284.99	548.03
F011962	478538.38	4828801.03	338.94	438.30
F011965	443873.49	4829975.73	205.13	619.35
F011968	461192.82	4830800.42	297.48	60.35
F011969	495901.03	4830643.74	357.84	883.92
F011970	457823.81	4830924.08	299.62	1076.25
F011973	457284.16	4833588.63	284.07	563.88
F011974	446766.24	4833839.51	254.51	1128.98
F011975	457688.06	4834080.31	292.30	567.23
F011976	458300.40	4834132.00	295.96	563.88
F011977	457694.35	4834693.35	288.04	562.36
F011978	469036.93	4835202.11	323.09	518.16
F011981	469780.42	4836309.35	324.31	504.44
F011982	470316.34	4837011.10	327.36	551.99
F011983	482653.36	4831105.85	349.91	430.99
F011984	490433.34	4837044.23	359.36	451.41
F011985	451441.87	4837290.36	284.68	610.21
F011986	460163.77	4838578.82	294.44	549.55
F011987	449251.39	4839546.89	244.45	611.73
F011988	452697.14	4841323.12	288.65	624.84
F011989	457162.60	4841796.12	293.52	570.28
F011993	441626.93	4842977.95	206.04	569.37
F011997	441539.71	4843225.29	178.00	537.06
F011998	441606.54	4843224.71	178.49	256.64
F011999	440983.35	4843601.17	179.59	543.46
F012000	441565.23	4843657.14	181.51	540.41
F012001	440717.41	4843850.11	179.16	548.94
F012002	441232.72	4843937.74	178.77	542.85
F012003	441680.12	4843996.01	177.70	344.73
F012004	442240.23	4844052.23	180.75	586.74
F012005	442240.50	4844083.33	178.00	585.06
F012006	441659.19	4844088.39	178.16	233.78
F012008	466347.35	4844140.29	344.12	542.54
F012009	440966.25	4844217.77	179.10	545.90
F012010	448188.24	4844164.43	252.37	618.74
F012011	448754.77	4844857.57	267.31	633.98
F012013	464072.89	4847133.18	323.10	533.40
F012014	476523.42	4847388.67	336.80	441.35

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
F012015	498939.77	4829467.55	360.27	346.25
F012016	472540.57	4849662.97	337.41	469.70
F012017	452831.03	4851698.26	265.80	590.40
F012018	444529.92	4852039.95	218.54	1111.00
F012021	481722.72	4850624.36	336.80	435.86
F012022	497128.79	4830473.17	358.44	348.08
F012025	448371.41	4854801.37	238.96	1083.56
F012026	446305.05	4854953.25	226.47	622.10
F012027	462479.53	4855138.84	328.88	551.69
F012040	471211.96	4857171.14	323.10	975.06
F012042	462578.05	4857930.56	319.43	542.54
F012047	456656.90	4858617.43	297.18	577.60
F012048	449790.86	4859452.19	245.67	601.98
F012059	457070.15	4867346.04	291.08	556.87
F012061	458057.08	4870138.73	295.96	1021.38
F012062	476381.32	4870517.77	316.70	870.20
F012063	453514.93	4871110.98	260.30	568.76
F012066	450275.88	4874071.35	235.61	566.93
F012068	480626.26	4874752.36	318.20	323.09
F012077	474716.16	4878798.63	282.90	726.60
F012078	457446.65	4881565.40	264.87	507.49
F012088	489695.02	4887137.36	294.40	79.30
F012089	491066.41	4887416.36	285.30	26.82
F012090	487527.60	4887708.68	289.99	64.01
F012093	486916.75	4890231.19	274.00	35.05
F012102	451703.61	4901991.01	184.10	890.90
F012117	486555.50	4936704.83	212.18	525.50
F012119	488651.07	4938415.89	216.70	511.50
F012120	488014.53	4940107.68	226.20	449.90
F012121	487192.65	4940161.46	212.80	526.70
F012122	487262.53	4940997.76	212.80	452.00
F012123	489403.88	4941595.95	218.80	439.52
F012124	487158.73	4941858.83	207.85	436.50
F012125	489271.97	4941934.96	218.50	453.20
F012126	488555.79	4941982.84	215.20	438.90
F012127	487489.89	4942059.24	210.90	455.70
F012128	485637.11	4942111.97	200.92	457.20
F012129	489342.93	4942154.78	217.90	525.80
F012130	487391.28	4943555.69	210.00	457.20
F012131	485468.17	4942464.47	192.30	460.20
F012132	489327.60	4942481.39	215.50	430.99
F012133	489255.45	4942497.06	215.20	429.50
F012134	489338.79	4942533.58	215.80	502.92
F012135	488930.08	4942849.73	214.00	458.70
F012136	488407.91	4943116.13	214.00	442.00
F012137	488491.62	4942918.26	213.40	438.90
F012139	486945.05	4944065.33	212.80	448.40
F012141	484603.30	4950304.38	208.50	501.40
F012142	488214.24	4952579.51	198.70	396.20
F012144	489058.22	4941713.16	217.30	442.00
F012148	481129.79	4969515.63	196.90	450.80
F012149	475772.22	4979889.20	185.32	96.01

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
F012151	475019.57	4981206.28	199.90	461.80
F013544	484444.24	4969996.62	224.65	155.40
F013547	488832.58	4942879.89	213.97	428.24
F013549	483926.85	4942048.23	195.36	457.20
F013552	448547.66	4891082.63	180.97	342.90
F013975	487107.93	4969521.93	213.50	14.53
F013976	487064.51	4969535.35	213.30	1.37
F013977	486965.93	4969604.42	217.00	12.24
F013978	487037.20	4969697.59	216.03	22.60
F013979	487075.14	4969715.28	212.40	11.38
F014094	561490.87	4915469.47	462.50	98.07
F014095	530394.65	4897466.03	473.77	46.94
F014194	503190.65	4950731.13	236.00	5.90
F014195	503234.22	4950731.15	236.00	6.10
F014196	500601.19	4942498.16	248.00	21.70
F014197	532457.86	4937549.75	218.00	7.60
F014199	529606.45	4925229.47	426.00	50.90
F014200	556946.89	4926360.10	220.48	16.76
F014201	553640.22	4929569.00	231.77	49.68
H000007	488837.75	4941735.75	217.90	527.30
H000008	488090.92	4943242.23	213.70	0.00
H000022	534865.48	4904382.77	425.20	570.90
H000023	536271.09	4900088.41	475.18	579.12
H000024	539752.00	4896252.02	490.73	596.00
H000025	554344.83	4929519.31	190.80	196.60
H000026	547432.35	4931499.10	184.71	227.69
H000027	546911.34	4931799.68	190.68	192.02
H000028	546858.62	4931508.26	193.85	167.64
H000029	522829.77	4897482.00	390.14	598.02
H000030	489714.77	4942058.65	218.85	452.60
H000031	493661.62	4937961.40	221.75	492.90
H000032	492710.63	4941351.45	240.18	497.43
H000033	501616.93	4940342.27	239.57	472.44
H000034	489832.57	4942818.26	217.93	463.91
H000037	547006.77	4910401.47	470.92	548.94
H000038	534100.28	4891959.39	475.49	701.95
H000039	503895.24	4938239.39	181.66	382.20
H000040	503988.11	4938211.68	170.99	0.00
H000041	503961.98	4945892.85	222.50	416.40
H000042	505162.94	4945893.70	218.54	402.34
H000043	505422.89	4945958.34	217.30	368.20
H000051	514003.22	4944103.97	224.72	353.60
H000052	517853.33	4945970.74	268.53	353.90
N000050	488835.40	4941754.64	217.32	435.86
N000053	489199.87	4942460.49	217.00	432.82
N000055	488374.66	4942708.52	215.33	441.96
N000058	488181.73	4974472.07	254.52	82.30
N000059	487319.46	4974242.66	250.22	20.42
N000060	487274.50	4974650.43	242.02	24.38
N000061	488029.41	4974892.25	252.32	27.43
N000062	486364.80	4974760.06	246.52	13.11
N000063	487134.80	4975036.18	249.02	13.41

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
N000064	487876.29	4975296.90	257.22	28.04
N000065	488722.76	4975609.72	256.50	18.59
N000066	485093.37	4974726.23	247.82	22.25
N000067	485812.98	4975026.75	250.22	27.74
N000068	486995.12	4975421.93	253.92	21.95
N000069	487730.25	4975682.64	247.78	21.95
N000070	484942.79	4975124.27	246.52	21.95
N000071	486849.13	4975805.48	243.92	22.56
N000072	487597.65	4976066.15	247.52	24.08
N000073	485964.02	4975890.67	244.72	24.08
N000074	484812.66	4975491.17	246.52	20.42
N000075	484673.12	4975871.42	236.82	22.86
N000076	473168.04	4974718.45	185.00	486.77
N000250	538958.32	4895250.90	475.18	579.12
N000252	503457.87	4936872.87	195.99	438.91
N000253	549093.54	4920150.92	484.63	35.97
N000254	548961.59	4924993.15	462.70	78.50
N000255	557328.32	4924045.09	261.50	80.01
N000257	545544.56	4929115.05	263.80	117.34
N000258	548028.95	4930438.19	226.50	55.90
N000259	550646.33	4931391.19	183.80	32.08
N000261	547865.73	4931235.68	223.70	57.63
N000262	546535.58	4931350.42	219.30	63.70
N000263	550980.41	4931851.48	191.11	217.02
N000264	538629.33	4937301.46	218.76	80.85
N000266	489881.58	4938149.48	226.16	499.87
N000267	490709.12	4938523.69	221.89	243.84
N000268	490994.21	4939796.26	226.16	0.00
N000269	490217.26	4940223.94	224.33	437.08
N000270	492608.45	4940090.80	225.55	471.83
N000271	489918.25	4942834.79	218.54	438.30
N000273	533203.77	4939143.12	181.72	54.96
N000274	532167.87	4939361.17	183.15	22.96
N000276	521379.51	4945675.97	304.00	42.06
N000277	500032.64	4916284.85	274.32	298.70
N000556	464073.27	4841823.10	329.20	370.33
N002809	511480.74	4862737.52	382.50	289.56
T000084	451199.52	4846689.65	259.38	589.48
T000085	453206.40	4831212.42	267.61	590.70
T000382	469936.19	4830428.95	325.53	507.80
T000857	474075.04	4825240.62	324.92	481.28
T001092	466192.98	4835746.77	314.60	525.78
T001182	459938.10	4824141.74	286.21	544.68
T001720	473226.72	4910799.29	239.88	315.47
T001720A	473240.24	4910793.68	239.88	722.38
T001807	548212.35	4928426.70	360.58	391.36
T001817	546173.00	4926467.93	314.55	355.70
T001825	545039.70	4930625.60	224.94	259.38
T001877	508633.01	4912733.93	322.63	558.40
T001896	550139.78	4900781.88	527.00	610.21
T001925	460322.04	4894758.70	274.93	912.90
T001942	455764.31	4900536.09	233.17	897.90

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
T002001	553461.50	4900198.30	524.90	596.50
T002046	555118.42	4900165.37	525.20	581.90
T002229	524520.60	4876198.93	432.80	667.51
T002235	456309.83	4858495.31	285.30	560.83
T002238	459943.53	4909022.22	234.70	850.40
T002250	455945.86	4858492.16	289.56	1053.08
T002275	484513.26	4970453.01	220.54	60.96
T002284	524673.13	4875688.57	438.61	672.08
T002306	558130.16	4926092.85	218.80	215.00
T002347	525182.97	4860023.14	427.30	718.72
T002380	456156.79	4858315.27	290.47	577.60
T002433	529044.36	4856068.25	442.00	726.95
T002470	464081.62	4861102.16	314.55	526.69
T002478	527739.31	4855269.65	435.90	731.82
T002556	462327.73	4857854.22	320.04	543.50
T002613	523661.93	4872321.68	422.45	677.57
T002627	525961.39	4875339.20	449.58	679.70
T002663	444273.45	4876779.52	210.31	608.69
T002730	467410.51	4883088.07	277.10	429.46
T002731	449436.49	4827241.41	277.98	77.11
T002731A	449437.32	4827137.00	277.37	626.67
T002754	526986.28	4853659.42	434.90	743.41
T002783	481402.40	4843921.40	345.03	420.01
T002842	449609.99	4827342.28	280.11	616.92
T003126	528368.75	4855815.43	442.57	800.40
T003298	528469.41	4855204.99	434.90	730.91
T003350	464778.80	4906776.16	249.00	393.80
T003387	470293.45	4908300.53	247.50	335.89
T003535	444998.43	4883101.51	203.00	583.69
T003553	461679.92	4877089.85	295.05	511.45
T003563	444608.95	4842964.75	228.60	498.35
T003588	458400.89	4893570.97	268.83	481.89
T003607	456629.81	4835277.71	278.60	540.72
T003625	490214.88	4827080.14	358.44	401.73
T003632	458881.80	4828485.18	288.04	92.05
T003632A	458884.25	4828488.50	288.04	536.45
T003656	440912.77	4877016.46	189.59	643.13
T003661	486101.21	4842407.27	349.00	390.14
T003684	448245.77	4871845.44	241.10	612.34
T003785	449582.31	4827632.37	279.20	624.84
T003895	444461.29	4842833.80	228.60	495.30
T004315	528883.43	4856669.53	440.70	773.58
T004433	529087.34	4855429.80	433.70	762.00
T004545	527690.33	4855837.00	438.30	730.00
T004604	461635.39	4865950.74	307.24	528.52
T004730	496269.41	4833006.89	357.84	873.25
T004848	528475.19	4855544.88	435.90	739.14
T004849	446275.59	4866199.67	222.00	564.50
T004851	455710.69	4862979.88	272.80	1037.23
T004853	442104.37	4855920.41	201.80	573.00
T004854	466865.51	4888668.88	289.30	894.00
T004864	444245.76	4857280.52	213.70	639.00

Appendix A.2 3D Geological Framework Wells Within Regional Study Area (OSGRL)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
T004869	527186.15	4859432.39	431.80	726.60
T004910	463643.92	4889056.88	282.20	909.00
T004918	444373.03	4857029.54	213.30	625.00
T004985	503007.25	4825709.87	363.60	875.10
T005051	459873.27	4851355.51	305.90	594.00
T005124	466979.14	4825797.11	311.70	525.00
T005131	448788.04	4859000.01	236.20	573.40
T005166	448977.95	4826279.71	272.80	644.00
T005177	528373.59	4855809.89	438.30	883.90
T005182	456649.60	4825120.66	271.90	545.00
T005326	452932.30	4831467.57	264.50	601.00
T005397	442309.73	4844360.41	180.00	259.00
T005404	452247.84	4841008.67	292.50	625.50
T005478	442309.73	4844360.41	180.00	95.00
T005652	506804.04	4849489.88	391.30	809.30
T005778	497561.63	4937527.77	251.10	478.50
T005779	441659.46	4844119.48	177.70	91.30
T006251	443499.82	4832166.93	211.50	623.80
T006332	542931.03	4930580.21	219.30	95.70
T006341	444686.37	4829333.66	214.55	632.80
T006346	448905.34	4826391.33	269.50	635.70
T006364	449451.27	4827487.86	278.55	1134.00
T006629	473339.26	4976415.15	200.10	486.40
T006737	492812.24	4940700.40	240.00	451.50
T007014	480160.14	4972912.24	194.20	579.40
T007179	450366.47	4824195.69	252.50	598.00
T007469	474245.21	4970183.88	185.80	79.90
T007586	487360.02	4932813.22	226.90	106.40
T007587	483154.33	4946326.82	205.80	91.10
T007591	487252.57	4969578.29	220.10	34.40
T007594	487728.14	4970045.04	224.30	34.90
T008657	460223.98	4824278.87	286.60	539.00
T008843	448232.46	4825294.71	253.42	623.00
T008915	444578.18	4842945.01	220.68	455.68
T009126	444090.22	4843337.83	193.30	470.00
T009355	444347.90	4843143.52	216.70	477.60
T010054	447294.19	4834523.96	256.00	665.00
T010686	449347.77	4826823.36	279.70	639.50
T011156	504962.63	4868851.44	365.10	55.20
T011523	443891.54	4843077.37	223.60	408.10
T011524	443798.86	4843164.79	224.30	408.10
T011525	443889.13	4843172.91	223.80	408.10

Appendix A.3 3D Geological Framework Wells Michigan State (MSGS)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
21005351860000	73207.92	4726075.80	205.13	1828.80
21007256900000	314979.22	4998537.35	208.48	1944.62
21011428580000	285239.48	4882063.74	179.53	4728.67
21017377790000	261834.07	4835671.13	180.75	4446.73
21021235450000	64869.73	4656818.64	238.96	905.26
21021235450100	64869.73	4656818.64	238.96	905.26
21023297790000	145709.30	4664778.08	266.70	1655.67
21023299690000	146510.17	4664880.48	267.00	1668.78
21023330190000	170821.58	4631951.44	307.24	1412.14
21023380450000	161948.13	4651435.43	288.04	1639.21
21025304680000	183350.40	4699468.56	295.05	1828.80
21025360010000	180348.60	4687456.75	296.27	1686.46
21025396470000	161545.42	4678965.96	280.42	1492.61
21025404170000	158853.31	4703408.41	284.38	1901.95
21027229130000	89680.03	4637088.12	258.47	1005.84
21027343040000	90068.29	4643038.86	292.00	1173.78
21027343670000	92999.17	4662152.57	291.69	1219.20
21027347630000	89455.01	4667617.72	264.57	1219.20
21027347730000	97647.43	4656884.58	295.96	1219.20
21027354590000	95799.94	4640167.16	268.83	1158.24
21027359670000	89234.19	4642272.37	278.59	913.79
21027369850000	87253.02	4644991.47	252.07	1219.50
21027375360000	103936.44	4666568.96	268.53	1188.72
21029348240000	201645.48	5005539.16	345.03	2712.72
21029362600000	200114.51	5003888.95	359.66	2447.54
21031306820000	235970.36	5033951.86	240.49	1753.51
21031350600000	224230.07	5028288.34	243.23	1810.51
21033078520000	242092.47	5132709.25	211.53	178.31
21033290220000	225075.15	5144269.83	201.17	397.76
21033346780000	259348.48	5106282.40	227.08	361.49
21035347900000	176216.63	4859979.35	336.19	3969.11
21035357810000	173748.23	4892240.72	350.22	3524.40
21041007290000	56507.44	5101850.65	190.50	353.57
21045291170000	203133.49	4717323.88	260.91	2109.83
21051335590000	226787.35	4869516.26	224.33	702.56
21051350900000	232128.90	4864532.51	214.88	4833.82
21051350900100	232128.90	4864532.51	214.88	4833.82
21055342920000	136769.41	4952809.82	274.62	3358.90
21057297390000	209526.24	4797364.45	227.08	5323.64
21057297390100	209526.24	4797364.45	227.08	5321.81
21059270240000	216097.68	4624283.90	265.79	1212.19
21059404140000	198778.08	4663243.55	333.76	1803.50
21059532680000	191471.33	4637127.18	335.58	1483.16
21065286070000	216844.27	4714743.64	282.24	2397.56
21075271370000	194220.54	4676668.53	307.54	1809.29
21093404380000	249002.00	4729844.74	282.24	2270.76
21093437270000	246701.06	4726943.89	274.93	2278.68
21093540210000	279576.59	4722001.21	308.76	2296.67
21097426710000	232146.02	5109189.83	290.47	749.81

Appendix A.3 3D Geological Framework Wells Michigan State (MSGS)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
21099337370000	356729.71	4744953.48	221.59	1645.92
21099398590000	336437.20	4726040.21	191.11	1532.23
21123398560100	126528.46	4844360.19	328.57	3108.96
21127331340000	59951.00	4834594.18	225.25	2206.75
21127416550000	87794.85	4850935.67	259.38	2414.02
21137351130000	228790.91	4987636.50	413.92	2654.81
21139348850000	106487.80	4785143.86	267.00	2208.28
21141293720000	282789.26	5014706.33	231.95	2053.74
21141350850000	261333.35	5014822.09	271.27	2032.10
21147303760000	366403.82	4728078.90	180.14	1386.84
21147389640000	339086.50	4752626.72	240.18	2040.94
21147389650000	352575.66	4762247.58	240.18	1923.29
21147422970000	370370.05	4748981.09	189.59	1502.66
21147422970100	370370.05	4748981.09	189.59	1584.96
21147422970200	370370.05	4748981.09	189.59	1483.46
21147426330000	373175.08	4742843.46	188.37	1421.89
21147433790000	369767.24	4749331.30	191.41	1478.58
21147435260000	370593.35	4749342.36	190.50	1488.64
21147444430000	364877.46	4746147.36	199.64	1533.14
21147552310000	373456.45	4757617.29	196.60	1554.78
21151309740000	360839.16	4812890.68	235.00	2735.58
21151339990000	357513.33	4794326.28	229.82	2594.15
21151357790000	359960.96	4801450.43	232.26	2384.76
21159162340000	97793.71	4707882.64	208.18	402.03
21161342230000	274893.97	4693347.31	283.16	1920.24
21161416710000	289605.25	4699423.89	287.73	1795.27
21163556620000	309405.85	4680068.50	191.41	1395.68

Appendix A.4 3D Geological Framework Regional Wells (MNR Ref Wells)

Well ID	Easting (m)	Northing (m)	Ground Elevation (m)	Total Depth (m)
T002843	334763.21	4639023.50	173.74	936.04
F012058	708443.64	4870001.43	142.00	328.90
T005473	563855.11	4698541.87	174.60	1427.00
T004907	638819.84	4752515.61	176.00	1008.80
T007844	537449.72	4773721.61	269.44	896.00
T004497	456787.43	4669941.97	174.70	1435.60
T004772	412820.86	4644795.30	174.65	1330.45
T004754	413474.11	4659312.35	174.65	1274.06
T002887	636135.34	4735913.57	0.00	155.75
T003071	373643.06	4708449.35	176.20	1211.60
T006539	371298.64	4653939.81	177.00	1062.00
T006912	395942.78	4678684.10	190.20	1155.00
T006878	475188.53	4733152.30	218.90	1119.00
T006814	441205.82	4683509.73	173.70	1340.00
T006818	487930.79	4701607.06	173.70	1269.00
T006815	435516.51	4660085.22	174.70	1436.00
T004105	441568.56	4789105.52	191.10	1153.97
T006960	433415.80	4723951.33	212.10	1158.50
T001536	471221.01	4746082.42	242.60	1088.14
T007162	391884.03	4670671.15	190.54	1101.00
T002012	648491.00	4786141.94	92.40	687.90
T008556	385809.06	4756225.17	184.90	1495.00
T002033	605820.51	4783360.65	195.70	739.10
F012155	451585.73	5009019.29	205.44	492.25
T008079	360940.05	4624857.49	174.30	926.00
T002613	523661.94	4872321.69	422.45	677.57
T006044	380263.32	4739840.69	190.80	1380.70
T006305	426605.67	5087948.05	281.90	222.92
T006045	411110.69	4693401.65	180.80	1180.00
T006078	486775.35	4724268.04	211.40	1168.50
T006120	584144.79	4820731.86	304.80	637.64
T006102	610756.71	4817042.99	94.42	429.00
T006124	656187.27	4853327.52	88.16	251.50
T006883	318015.18	5081992.63	192.43	521.00
T007726	657324.26	4907127.78	265.83	180.23
T007968	636835.31	4936867.94	219.90	53.79
T007979	606829.34	4944183.80	204.30	46.94
T007395	404824.36	4701397.36	183.90	1202.10
T006621	385762.84	4704539.05	176.30	1203.00
T008111	363950.62	4678220.93	181.60	1102.00
T007714	386131.53	4691590.07	175.10	1132.00
T004854	466865.52	4888668.88	289.30	894.00
T008230	430618.23	4690768.99	182.90	1284.00
T008512	509733.34	4681682.36	174.40	1464.50
T004985	503007.26	4825709.87	363.60	875.10
T006965	391652.08	4720494.52	178.30	1186.00
T002327	434384.50	5068009.67	195.07	252.40
T006364	449451.27	4827487.87	278.55	1134.00
F005446	557709.52	4732254.95	214.60	1711.80
T001021	555927.57	4745856.43	221.38	1036.62
T007191	333168.82	4670299.30	180.20	1119.00
T009793	512451.83	4797383.29	356.90	917.00
T010044	603500.22	4722943.96	174.40	1290.00
T010043	622949.92	4726901.82	174.40	1302.00
T010456	507857.55	4723438.17	204.10	1185.00
T010520	440029.68	4710653.80	215.70	1241.00
F013651	832300.47	4896321.03	81.30	107.60