OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Supporting Technical Report

Phase I Geosynthesis

November 30, 2008

Prepared by:
Gartner Lee Limited

OPG 00216-REP-01300-00010-R00

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DOCUMENT HISTORY

Title:	Phase I Geosynthesis	
Subtitle:	OPG's Deep Geological Repository for Low and Intermediate Level Waste	
Client:	Ontario Power Generation Inc.	
Document Number:	OPG 00216-REP-01300-00010-R00	
Revision Number:	0	**Date:** November 30, 2008
Prepared by:	Gartner Lee Limited	
Reviewed by:	Monique Hobbs, Tom Lam, Rob Frizzell, Branko Semec, M. Mazurek	

Approved by: ______________________________
Robert Leech

Accepted by: ______________________________
Mark Jensen

EXECUTIVE SUMMARY

Ontario Power Generation (OPG) is proposing the development of a Deep Geologic Repository (DGR) at the Bruce site, near Tiverton, Ontario for the long-term management of Low and Intermediate Level Radioactive Waste (L&ILW). This proposal envisions the excavation of a repository at a depth of approximately 680 m in a limestone formation overlain by 200 m of low permeability shale. This report describes the Phase 1 Geosynthesis Project completed as part of a stepwise geoscientific characterization program that is supporting an ongoing Environmental Assessment and preparation of a Preliminary Safety Report for submittal in 2011.

This Phase 1 Geosynthesis document provides an interim assessment of the Bruce site with respect to its geologic suitability for implementation of the DGR concept. This assessment is supported, in part, by the preparation of six (6) studies that provide a reasoned and peer reviewed basis to establish regional geoscientific characteristics of the Bruce site as relevant to DGR safety and performance. The six (6) studies are:

- Phase I Regional Geology, Southern Ontario (Gartner Lee Limited, 2008a)
- Phase I Regional Hydrogeochemistry, Southern Ontario (Hobbs et al., 2008)
- Phase I Regional Geomechanics, Southern Ontario (Gartner Lee Limited, 2008b)
- Phase I Hydrogeologic Modelling (Sykes et al*.,* 2008)
- Phase I Long-Term Climate Change Study (Peltier, 2008)
- Phase I Long-term Cavern Stability (Itasca, 2008)

In addition to these studies, the Phase I Geosynthesis has been informed by the preliminary results of Bruce site geoscientific site characterization activities to assess coincidence with regional geologic knowledge. The Phase II Geosynthesis that will present a complete integration with site specific site characterization data will be completed in fall 2010.

As described by Intera (2006), a conceptual geosphere model of the Palaeozoic sedimentary sequence beneath the Bruce site listed characteristics and attributes of the sedimentary geologic setting that would be favourable for implementation of the DGR concept. From these characteristics and attributes were drawn seven (7) geoscientific tenets that were directly relevant to establishing the long-term safety and performance of the DGR. The validity of these geoscientific tenets are examined in this report. The tenets and their supporting geoscientific evidence are described below.

- **Predictable: horizontally layered, relatively undeformed sedimentary shale and limestone formations of large lateral extent:**

  - Reconstruction of the regional bedrock stratigraphy using over 300 historical oil and gas well records within a 35,000 km^2 Regional Study Area (RSA) surrounding the Bruce site defines a sedimentary sequence with a near horizontally layered, relatively undeformed predictable 'layer cake' geometry.

  - Coring of Phase I deep boreholes DGR-1 and DGR-2 confirms that the Bruce site is underlain by 34 bedrock formations comprised of layered carbonate/shale/ evaporite/ sandstone units with a total thickness of about 840 m above the Pre-Cambrian crystalline basement. This stratigraphy is consistent with the RSA stratigraphic model.

- Predictions of bedrock formation thicknesses from the RSA stratigraphic model are within metres of that observed during coring of deep boreholes DGR-1 and DGR-2.
- It is confirmed that there is over 200 m of low permeability formations dominated by shale directly overlying the Cobourg Formation that is proposed to host the DGR.

■ **Multiple Natural Barriers: multiple low permeability bedrock formations enclose and overlie the DGR**

- The DGR repository horizon is under- and overlain by multiple low permeability bedrock ($\approx 10^{-19}$ to 10^{-21} m^2) formations of Silurian and Ordovician age. Within the deep groundwater regime there is over 200 m of low permeability shale directly overlying limestone of the host Cobourg Formation and 150 m of low permeability carbonates below.
- The intermediate groundwater regime comprised of Silurian age sediments contains laterally extensive low permeability, carbonate, shale and anhydrite layers.
- Observed environmental hydraulic heads indicate a convergent hydraulic gradient field on the Ordovician sediments. Transient groundwater simulations reveal that such conditions could persist for 1 Ma.
- Observed abnormal under- and over-pressure hydraulic heads particularly within the Ordovician sediments require extremely low formation scale permeabilities ($k_v \approx 10^{-21}$ m^2) to persist.
- Observed vertical hydraulic head gradients indicate that transmissive vertical or sub-vertical faulting does not exist in the deep or intermediate groundwater regimes.
- Evidence based on rock core retrieved during drilling and in situ borehole testing has provided no evidence for the existence of hydrothermal dolomitized faults.

■ **Contaminant Transport is Diffusion Dominated: deep groundwater regime is ancient showing no evidence of glacial perturbation or cross-formational flow**

- Hydraulic straddle packer testing of deep boreholes DGR-1 and DGR-2 within the intermediate and deep groundwater regimes indicate low bedrock permeabilities that are consistent with a diffusion dominant regime.
- Numerical modelling of the regional and local scale groundwater system predicts formation scale vertical formation permeabilities ($\approx 10^{-21}$ m^2) necessary to maintain observed hydraulic gradients; a factor of 10 to 100 lower than horizontal permeabilities.
- Numerical modelling using Base Case, sensitivity and paleohydrogeologic simulations indicates that despite uncertainty groundwater velocities of 0.0001 m/a, consistent with a diffusion dominant regime persist. Estimated Mean Life Expectancies (time to discharge) for solutes at the repository horizon exceed 8 Ma in the Base Case simulation.
- Within the Michigan Basin the regional hydrogeochemistry and isotopic systematics reveal pore waters within the intermediate and deep groundwater domains represent either evaporated seawater or evaporated seawater subject to diagenetic alteration. These waters have resided in the sediments since at least the Mesozoic (~200 Ma).

- **Seismically Quiet: comparable to stable Canadian Shield setting**
  - The Bruce site is located within the tectonically stable interior of the North American continent. The stable interior region of North America is characterized by low rates of seismicity. In particular, the Bruce region experiences sparse seismic activity, with no apparent concentrations of activity that might delineate regional seismogenic features or active faults.
  - The seismicity record shows that there has not been an event exceeding M5 in the RSA in 180 years of record.
- **Natural Resource Potential is Low: commercially viable oil and gas reserves are not present**
  - The results of petroleum well drilling, the coring and testing of the deep boreholes on Bruce Site coupled with knowledge of the geologic setting strongly suggest that viable commercial oil and gas reserves within 40 km of the Bruce site do not exist.
  - Commercially viable base metal deposits have not been identified in the study area.
  - There are no commercially viable aggregate resources at the Bruce site.
- **Shallow Groundwater Resources are Isolated**
  - Groundwater resources in the vicinity of Bruce site are obtained from shallow overburden or bedrock wells extending to depths of approximately 100 m. The bedrock wells intersect the permeable Devonian carbonates.
  - Regionally, the hydrogeochemistry of the Michigan Basin defines two distinct groundwater regimes: i) a shallow bedrock system at depths above 200 m; and ii) an intermediate to deep saline system characterized by elevated TDS (>200 g/L) and discrete isotopic signatures.
  - The hydrostratigraphy of the Bruce site provides multiple low permeability, thick (10 to 100’s m), horizontally layered bedrock formations that act as aquitards or aquicludes isolating the repository horizon from shallow groundwater resources. This includes bedrock formations within both the intermediate and deep groundwater domains.
  - Observed abnormal vertical hydraulic heads and gradients in the Ordovician and Silurian sediments at the Bruce site strongly suggest that vertical connectivity across bedrock aquitards/aquicludes does not exist.
  - The proposed DGR repository horizon in the Cobourg Formation is overlain by 200 m of Ordovician shales that are of low permeability ($\sim 10^{-19} - 10^{-21}$ m^2). Mass transport in the Ordovician shales is diffusion dominant.
- **Geomechanically Stable: selected DGR limestone formation will provide stable, virtually dry openings**
  - Construction experience with the excavation of underground openings in the Cobourg Formation indicates that excavated openings in either the Ordovician shale or Ordovician limestone could be dry and stable.

- The low permeability of the Cobourg Formation and enclosing formations as determined through field testing and numerical groundwater analyses, strongly suggest that the DGR openings will be virtually dry.
- Numerical simulation of repository openings in the Cobourg Formation that considered internal (i.e., gas pressure) and external perturbations (i.e., glaciations; seismicity) during a 100 ka timeframe provide quantitative evidence that the unsupported excavations do not sustain major collapse. Both internal and external loading simulations are superimposed on the long-term strength degradation of the rock.
- Geomechanical modelling of the DGR opening in the Cobourg Formation considered several different perturbations e.g., seismic shaking, glacial loading. The results of this work demonstrated that the maximum damage zone around the room openings was about 7.5 m under the long-term strength degradation case and the maximum horizontal fracture propagation of 16 m under the gas generation scenario. None of the scenarios modelled created potential pathways to the biosphere.
- Geomechanical testing on site specific core samples of the Cobourg Formation limestone indicates a mean Unconfined Compressive Strength of ≈109 MPa. Whereas the mean strength determined from the regional rock strength database is about 72 MPa.

ACKNOWLEDGEMENTS

The Phase 1 Geosynthesis has benefitted from the contributions of many. Technical supporting documents were prepared through the co-ordinated efforts of Rob Frizzell (Gartner Lee), Mario Coniglio (UofW), Luigi Cotesta (Itasca), Jon Sykes (UofW), Ed Sudicky (UofW), Eric Sykes (UofW), Stefano Normani (UofW), Young-Jin Park (UofW), Yong Yin (UofW), Monique Hobbs (OPG), Shaun Frape (UofW), Tom Lam (OPG), Branko Semec (OPG), Steve Usher (Gartner Lee), Sandy Cruden (UofT), Dick Peltier (UofT), Dave Eaton (UWO), Gail Atkison (UWO) and Branko Damjanac (Itasca). Technical peer reviews of the supporting technical reports were conducted by Tom Al (UNB), Derek Armstrong (OGS), Terry Engelder (Penn State), Leslie Smith (UBC), Dennis Bottomley, Dougal McCreath (Laurentian University) and Martin Mazurek (University of Bern). Interim review and guidance on preparation of the Geosynthesis was provided by the Geoscience Review Group including Joe Pearson (Ground-Water Geochemistry), Andreas Gautschi (Nagra), Derek Martin (UofA) and Jacques Delay (Andra).

LIST OF ABBREVIATIONS

CMBBZ ......Central Metasedimentary Belt Boundary Zone
DEM ....digital elevation model
DGR ....Deep Geologic Repository
EDZ ....excavation damage zone
GFTZ..........Grenville Front Tectonic Zone
GMWL ....Global Meteoric Water Line
Gocad™ ....an advanced 3D earth modelling and scientific visualization software technology
GSCP ....geoscientific site characterization plan
ILW.............intermediate level waste
L&ILW ....low and intermediate level radioactive waste
LLW............low level waste
MNR...........Ministry of Natural Resources
MVT ....Mississippi Valley-type deposits
OGS ....Ontario Geological Survey
OGSRL ......Ontario Oil, Gas and Salt Resources Library
OPG........... Ontario Power Generation
PQP ....project quality plan
RSA............regional study area
TDS............Total dissolved solids
WWMF ....Western Waste Management Facility
3DGF .... three dimensional geological framework

SYMBOLS

Ga ....billon years
g/L ....grammes per Litre
Ma ....million years
Ma b. p. ......million years before present
mASL ....metres above sea level
mBSL ....metres below sea level
mg/L ....milligrams per Litre

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1. INTRODUCTION

1.1 Background

Ontario Power Generation (OPG) is proposing the development of a Deep Geologic Repository (DGR) for the long-term management of Low and Intermediate Level Radioactive Waste (L&ILW) from OPG owned nuclear generating facilities (Figure 1.1). An Environmental Assessment for the proposed DGR is currently underway in accordance with the Canadian Environmental Assessment Act. Beneath the Bruce site, situated 225 km northwest of Toronto on the eastern shore of Lake Huron, is an 840 m thick sedimentary sequence of Cambrian to Devonian age near horizontally bedded, weakly deformed shales, carbonates and evaporites of the Michigan Basin. Within this sedimentary pile, the proposed DGR would be excavated within the low permeability limestone Cobourg (Lindsay) Formation at depth of 680 m, which is overlain by 200 m of upper Ordovician shale formations.

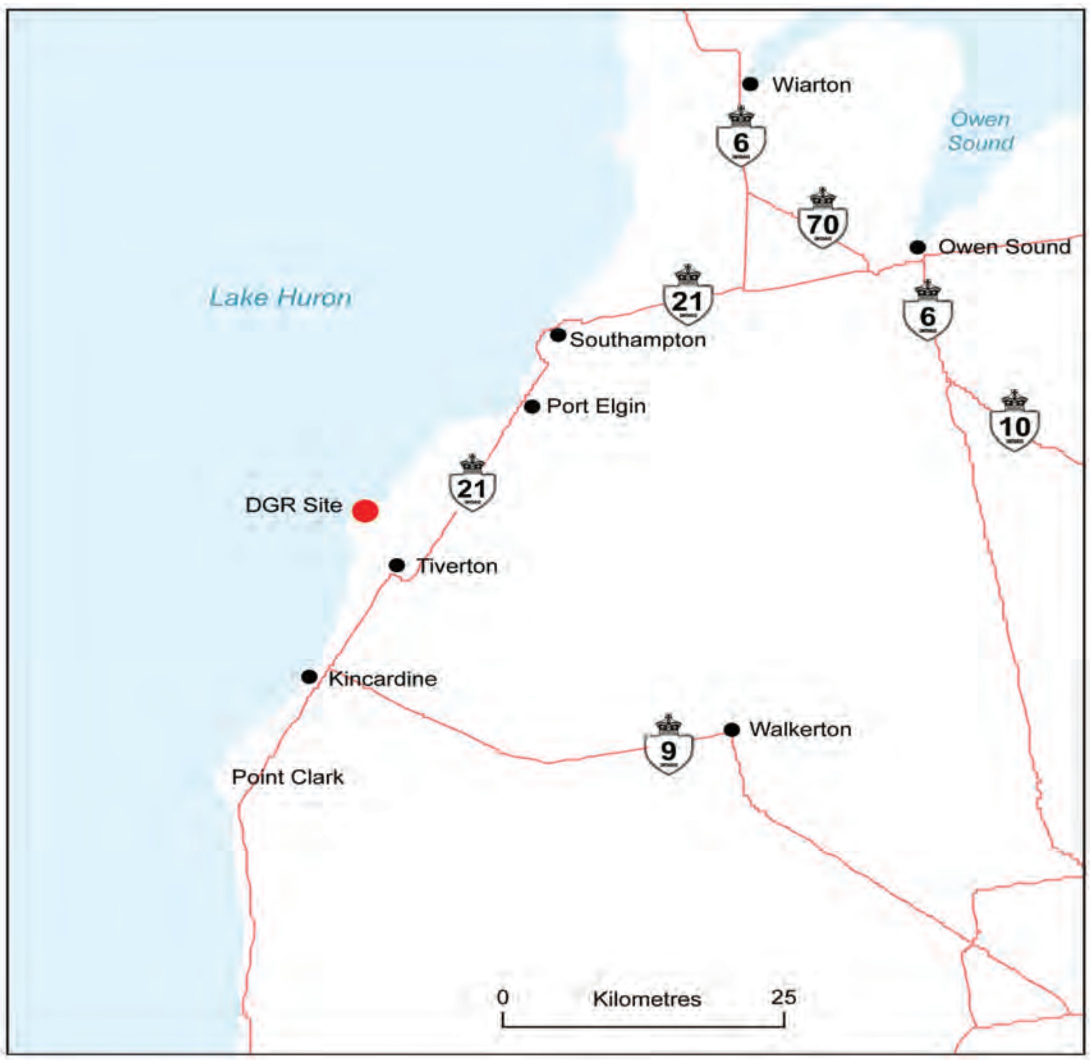

Figure 1.1 Bruce Site (DGR) Location

A key aspect of the DGR Safety Case is the integrity and long-term stability of the sedimentary sequence to isolate L&ILW at timeframes of 1Ma. Early in the project, geoscientific studies that considered regional and site-specific public domain data sets indicated favourable geologic conditions for implementation of the DGR concept (Golder, 2003; Mazurek, 2004). In 2005, OPG initiated the process of developing a Geoscientific Site Characterization Plan (GSCP) to support an Environmental Assessment for the project (Intera, 2006) and the preparation of a Preliminary Safety Report for submittal in 2011.

Within the GSCP site-specific field and laboratory investigations have been established to further develop and test the existing geoscientific knowledge of sub-surface conditions as they relate to geosphere stability and evolution, engineered repository systems design, and long-term repository safety. These investigations, which will eventually support regulatory submissions, are providing the first opportunity for on-site characterization of the sedimentary sequence and underlying Precambrian crystalline bedrock. The GSCP represents a stepwise multi-year, two-phase program of geoscientific investigations. Phase 1 program activities were initiated in fall 2006.

In summer 2005, OPG initiated a process that culminated in the preparation of the GSCP for the proposed DGR. The GSCP provides a comprehensive and internationally peer-reviewed basis for DGR-related geoscientific studies. In this capacity, the GSCP describes surface and sub-surface site characterization activities necessary to:

a) assess and reaffirm the technical suitability of the proposed DGR concept;
b) provide evidence on the geoscientific basis for repository safety at timeframes of 100,000 years or beyond (i.e., stable rock formations; diffusion dominant transport regime);
c) yield information to support development of a site-specific engineered repository design;
d) provide a geoscientific basis for the post-closure safety assessment; and
e) contribute to the development of an integrated DGR Safety Case describing the expected long-term safety and potential impacts of the DGR.

The activities described in the GSCP are intended to support two key deliverables:

1. a **Descriptive Geosphere Model**, which is an integrated, multi-disciplinary, geoscientific description and explanation of the undisturbed subsurface environ as it relates to site-specific geologic, hydrogeochemical, hydrogeologic and geomechanical characteristics and attributes; and
2. a **Geosynthesis**, which is a geoscientific explanation of the overall understanding of site characteristics, attributes and evolution (past and future) as they relate to demonstrating long-term DGR performance and safety.

A project as complex and important as the DGR has several major components, of which Geosynthesis is only one. Figure 1.2 shows how the geoscientific studies, including the geosynthesis, relate to the overall DGR project from inception to approval. The geoscientific studies are divided into two main activities, namely; Site Characterization and Geosynthesis. Site Characterization includes drilling deep boreholes from surface to the Precambrian basement, detailed geological logging, geophysical logging, hydraulic testing, geomechanical testing, groundwater sampling and surface geophysics (2D seismic). The output from the site characterization program is a Descriptive Geosphere Site Model for the Bruce site. The site characterization program is described by Intera (2006). The Geosynthesis program provides detailed descriptions of the regional geosciences as described in more detail in the following section.

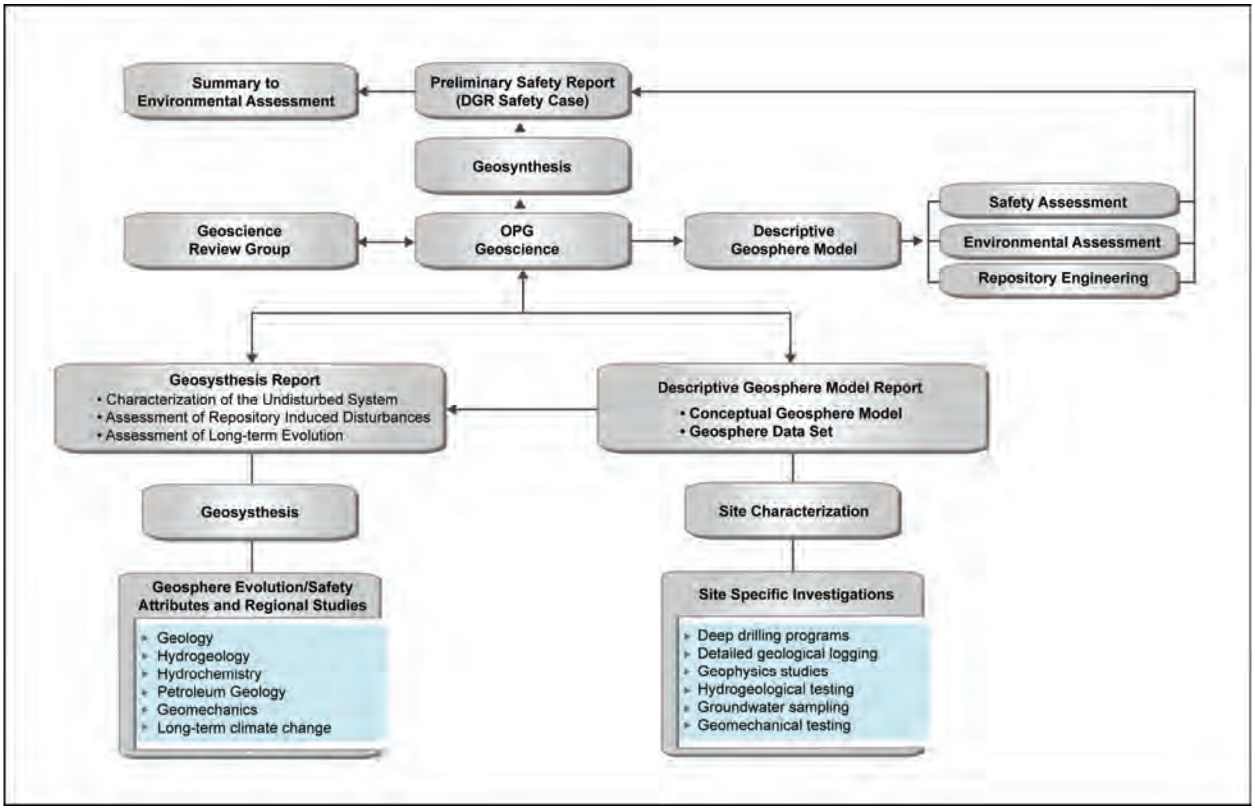

Figure 1.2 Organization and Project Interfaces within DGR Geoscientific Work Program

The results of the site characterization and Geosynthesis programs are peer reviewed by a number of respected geoscientists from Canada and internationally. In addition, OPG has established a Geoscience Review Group of eminent international geoscientists to assist in formulating the geoscience programs and to monitor progress in achieving objectives. The results from both the site characterization and geosynthesis programs are then input to the repository engineering, environmental assessment and safety assessment programs. Together all of these programs roll up into a DGR safety case that forms the basis for seeking regulatory approval to commission the DGR.

1.2 Deep Geological Repository Concept

The proposed DGR will be located at a depth of 680 m below the surface of the Western Waste Management Facility (WWMF) at the Bruce site. The repository is located within the Cobourg Formation, a low permeability limestone overlain by more than 200 m of low permeability shales. The repository, accessed via two vertical shafts, would require the excavation of nearly 500,000 m^3 of rock to accommodate an emplaced L&ILW volume of 200,000 m^3 within an approximate 28 ha repository footprint. For the past 30 years the wastes have been stored in engineered above and below ground storage structures at the WWMF. At present there is approximately 70,000 m^3 of L&ILW stored at the WWMF with annual waste arisings of between 2,000 m^3 to 3,000 m^3 following volume reduction (5,000 m^3 to 7,000 m^3 before volume reduction). The WWMF storage structures have a minimum design life of 50 years and are suitable for the interim storage of L&ILW. Although current storage practices are safe, these wastes will eventually need to be transferred to a long-term management facility as some of the wastes remain hazardous for thousands of years

Figure 1.3 shows a conceptual diagram of the DGR facility below the Bruce site with surface and belowground features. The waste received at the surface facilities will be placed into appropriately sized containers and lowered down the main shaft. Once the waste is received at the DGR level it will be transported to a storage room for final disposal. Once a room is filled with waste it will be sealed from the delivery drift and further waste will be stored in the next room. OPG (2005) describes in detail the proposed DGR facilities and waste management systems.

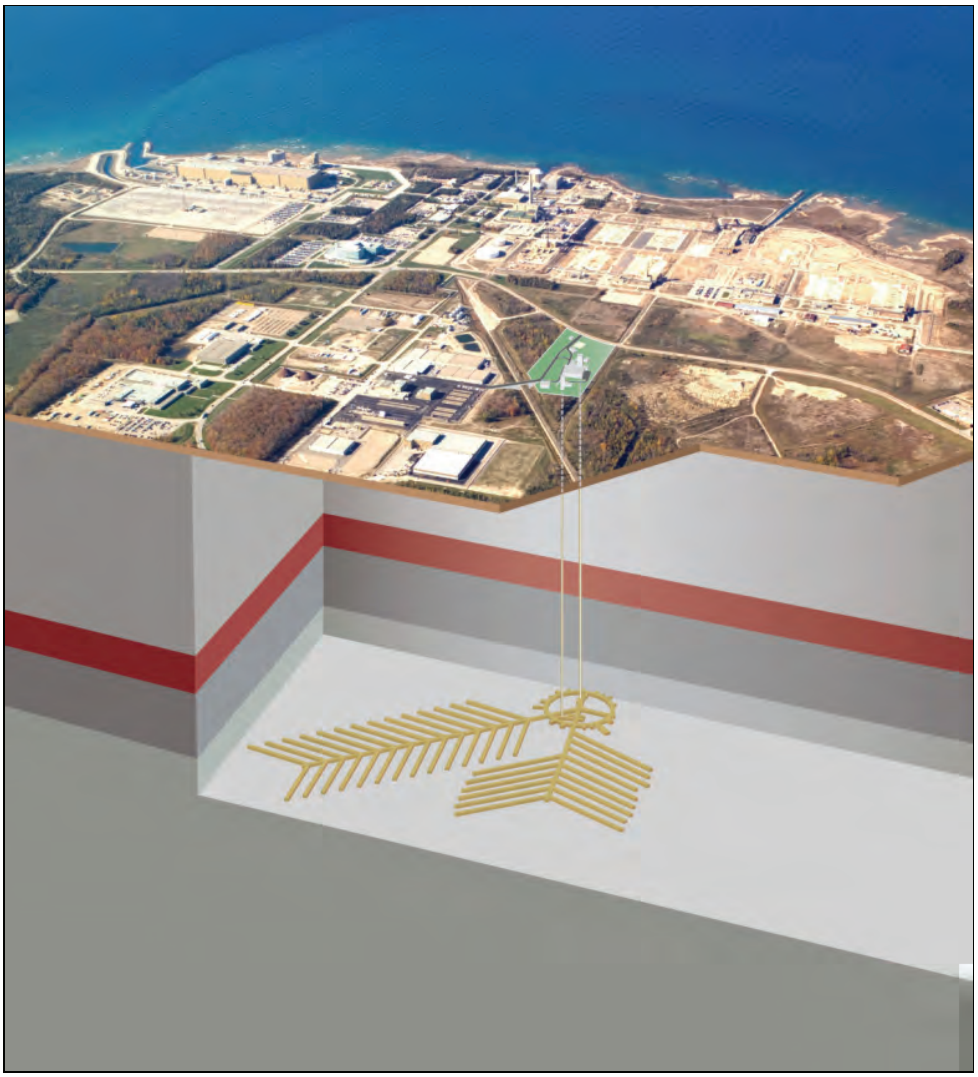

Figure 1.3 Conceptual Layout of the DGR Below the Bruce Site

The surface facilities will comprise several buildings for receiving, processing and preparing waste for disposal. These buildings will be associated with the current WWMF buildings and infrastructure. Head frames for the shafts will also be placed within the OPG retained lands. In addition, land will be prepared for the storage of waste rock produced during excavation of the shafts and underground openings. It is estimated that the surface work will take one year to prepare prior to commencing construction of the shafts.

It is estimated that the main shaft and ventilation shafts will take about two years to complete. Approximately 50,000 m^3 of waste rock will be produced and stored on site in an engineered facility. The main and ventilation shafts will have finished diameters of 6.5 m and 4.5 m, respectively. Following shaft completion the underground excavation work will begin. It is estimated that a period of five years will be required to complete this work before waste is received in the repository.

It is anticipated that further approvals and licences will be required during the life span of the DGR to adjust to changed conditions and during the preparations for decommissioning and post operational monitoring. Precise timing for post operations monitoring and institutional controls are not possible at this time, but the times assigned are likely reasonable.

1.3 Report Structure

This report is divided into eight (8) chapters the details of which are summarized below:

a) **Chapters 1 and 2** provide an introduction to the geosynthesis and background on work program scope;

b) **Chapter 3** presents a discussion of the development of the regional geologic framework. The geological history of the Bruce Megablock area is described from Precambrian times to the present. Particular emphasis is directed to barrier formations that host and overlie the repository. Economic Geology and Long-term Climate Change as it relates to future glaciation is discussed.

c) **Chapter 4** presents a review and summary of regional geomechanical properties for the sedimentary sequence as it occurs in the Appalachian and Michigan basins. A description of seismicity and long-term stability of the DGR repository openings is provided.

d) **Chapter 5** presents a summary and interpretation of existing regional hydrogeochemical and isotopic data within the Appalachian and Michigan Basins. Preliminary Bruce site data are presented for comparison.

e) **Chapter 6** presents a numerical groundwater system analysis at regional and Bruce site scales. The simulations performed examine issues surrounding parameter uncertainty, boundary condition uncertainty and realizations, variable groundwater density, glaciation, and site-specific analogues (i.e., abnormal hydraulic heads).

f) **Chapter 7** provides findings and conclusions that result from the geosynthesis work program, in part, informed by preliminary data derived from Phase 1 site characterization activities.

g) **Chapter 8** cited references.

2. GEOSYNTHESIS PROJECT SCOPE

2.1 Geosynthesis Overview

This section outlines the Phase 1 Geosynthesis and introduces the geoscientific principles that are relevant to demonstrating the long-term performance and safety of the Deep Geologic Repository concept as implemented within the sedimentary sequence underlying the Bruce site. The primary goal of the Geosynthesis is to provide an integrated geoscientific understanding of geosphere or far-field evolution as it relates to its capacity to contain and isolate the Low and Intermediate Level Radioactive waste at timeframes of 1Ma and beyond.

In this role the Geosynthesis provides a reasoned integration of all available geoscience information at regional and site-specific scales to construct a comprehensive understanding of the geosphere. The geoscience information can be qualitative and quantitative, and involve disciplines such as geochemistry, geophysics, hydrogeology, lithography, paleohydrogeology, isotopic analysis, tectonics, structural lithography, climate change and glaciation. Geosynthesis in support of a deep geologic repository should yield a model from which predicted geosphere behaviour and performance can be extracted with a measure of confidence.

The DGR concept envisions a shaft accessed repository excavated at a depth of approximately 680 m in the low permeability Ordovician Cobourg Formation. A focus has been placed on examining the multiple lines of geoscientific evidence that allow the authenticity of the following site-specific attributes to be understood. These fundamental attributes or tenets are:

a) **Predictability**: horizontally layered, relatively undeformed sedimentary shale and carbonate formations of large lateral extent;

b) **Multiple Natural Barriers**: multiple low permeability bedrock formations enclose and overlie the DGR;

c) **Contaminant Transport is Diffusion Dominated**: deep groundwater regime is ancient showing no evidence of glacial perturbation or cross-formational flow;

d) **Seismically Quiet**: comparable to a stable cratonic region;

e) **Natural Resource Potential is Low**: commercially viable oil and gas reserves are not present;

f) **Shallow Groundwater Resources are Isolated**: near surface groundwater aquifers isolated; and

g) **Geomechanically Stable**: selected DGR limestone formation will provide stable, virtually dry openings.

The information presented in this report is derived from the Phase 1 geoscientific work program. In order to provide context for understanding site-specific suitability a description of the regional geologic, geomechanical, hydrogeochemical and hydrogeologic setting, its evolution and current state is provided.

The Phase 1 Geosynthesis Program comprised a series of investigations directed at understanding the regional context of the geoscientific information. These studies relied heavily upon existing data in agency databases and on the professional experience of the authors, many of whom have spent considerable time on their research in southern Ontario. The reference studies contributing to the Phase 1 Geosynthesis are:

a) Phase I Regional Geology, Southern Ontario (Gartner Lee Limited, 2008a)

b) Phase I Regional Hydrogeochemistry, Southern Ontario (Hobbs et al., 2008)

c) Phase I Regional Geomechanics, Southern Ontario (Gartner Lee Limited, 2008b)

d) Phase I Hydrogeologic Modelling (Sykes et al*.,* 2008)

e) Phase I Long-Term Climate Change Study (Peltier, 2008)

f) Phase I Long-term Cavern Stability (Itasca, 2008)

The geoscientific data of southern Ontario varies considerably by discipline and geographically. Therefore no specific study area was identified for the geosynthesis program. Rather the authors of the reference studies identified the regional context in which their work was completed. For example, the regional geologic framework had a geographic area covering the Alleghany and Michigan Basins, thus all of southern Ontario and much of the northeast and central United States. On the other hand, the site specific hydrogeological modelling covered an area of less than 400 km^2 around the Bruce site. Figure 2.1 provides an appreciation of the scales of the component geosynthesis studies.

The Regional Geologic study provides a detailed description of the Palaeozoic geology in southern Ontario. The Bruce site is located on the eastern flank of the Michigan Basin. Therefore this work relied heavily on the large amount of stratigraphic information in the Ontario Oil, Gas and Salt Resources Library. There is an extensive database of geologic information in southern Ontario describing the host rocks at the Bruce site. The regional geologic report also discusses in detail the geological history, tectonic influences, depositional environments (i.e., facies models) and diagenetic processes during the Palaeozoic Era. This report also provides a description of the petroleum geology showing the known extent of the various oil/gas fields.

Regional Hydrogeologic Modelling of the Michigan Basin sequence was completed for an area of 18,000 km^2 from the Niagara Escarpment and Algonquin Arch in the east to Georgian Bay to the north, Lake Huron to the west and a watershed divide some 60 km south of the Bruce site. The geological basis for the model honoured the regional geology from the regional geologic study. Modelling was completed using FRAC3DVS-OPG based on the FRAC3DVS model developed by Therrien *et al.* (2004). The model simulates the groundwater system in this part of the Michigan Basin and includes a base case using existing data, followed by a series of sensitivity analyses and 'what-if'scenarios to test the hydrogeologic uncertainty and robustness of predictions.

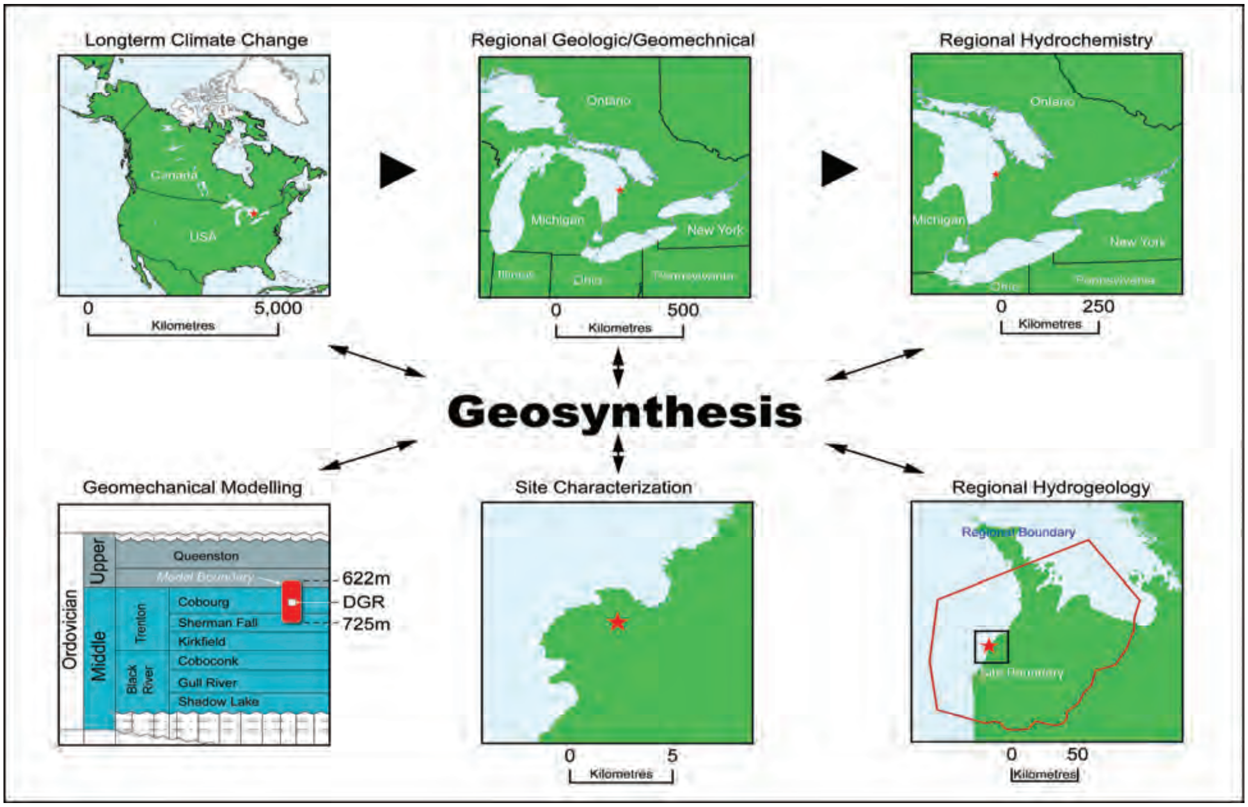

Figure 2.1 Geosynthesis Reference Studies Geographic Scope

A second component of the hydrogeological modelling was completed at a local scale to more accurately understand the groundwater regime at the Bruce site and to put context to the site characterization results from boreholes DGR-1 and DGR-2 (Intera, 2008). The local model was established as a refinement of the regional model with improved discretization for numerical simulation of solute transport. The model was used to assess the effects of variable groundwater density, hydromechanical and hydrogeochemical perturbations during a glacial event, and structural discontinuities in the geologic sequence.

The Regional Hydrogeochemistry work assembled a database of deep groundwater quality analyses from the stratigraphic sequence in southern Ontario. More than 200 groundwater samples, selected from a larger database by applying quality assurance criteria, formed the information base on which the assessment was completed. The preponderance of deep Paleozoic groundwater data are located in the Niagara Block area adjacent to Lake Erie. Nevertheless, this information can be used to predict groundwater quality elsewhere in the basin.

The Regional Geomechanical assessment gathered rock property information from all available sources across southern Ontario. Most of the data are confined to projects completed in Paleozoic rocks in central Ontario around Lake Ontario. Major structural features are described, as well as, variations in regional jointing and stress fields. Site characterization work provides the most reliable local information for this work.

Geomechanical Modelling was completed at a site scale to assess perturbations caused by natural events on the DGR repository over a 100,000 year time horizon. Events considered were time-dependent degradation of the rock adjacent to the opening, gas pressure build-up from decay of emplaced waste, glacial loading and seismic shaking.

A Long-term Climate Change study was performed using the peer reviewed University of Toronto Glacial Systems Model. The purpose of this work was to predict the potential for future glacial events. The model is calibrated against past glacial history by considering the time dependence of ice thickness, normal stress regime associated with the ice load, and the temperature at the base of the ice sheet among other factors. No unique solution can be calculated for future glacial events, however, based on the constraints of past glacial events the modelling results are sufficiently broad to encompass the characteristics of any similar future event.

2.2 Site Conceptual Model

Based on a review of existing data, Golder (2003) developed an initial site conceptual model. This model consisted of the Paleozoic sequence and a division of the groundwater regime into three domains: shallow, intermediate and deep. The results from the above Phase 1 Geosynthesis reference studies and the Phase 1 Site Characterization program has provided evidence re-affirming the original site conceptual model and allowed refinement to the geology and hydrogeology aspects of the model (Figure 2.2). Further refinement of the model will take place in subsequent phases of the work programs. The model shows the major geological units and three divisions of the groundwater regime below the site. The geology shown is consistent with both the regional (Gartner Lee Limited, 2008a) and site (Intera, 2008) descriptions. The right hand side of the model shows the low permeability (aquitard) formations protruding from the figure and to the left the three groundwater systems.

The conceptual model shows that the DGR is overlain by multiple low permeability formations, including 280 m of low permeability limestone, shale and dolostone before the first permeable formation (Guelph Formation). Above the Guelph Formation are further low permeability shale and anhydrite units within the Silurian deposits. The DGR and overlying cap rocks are located in the deep groundwater system that is dominated by old, highly saline groundwater (300 g/L). The intermediate system includes all Silurian formations above the Queenston Formation. This zone has mixed permeability formations (e.g., high permeability Guelph Formation and low permeability shale/anhydrite beds in the Salina Formation) with groundwater salinity ranging from saline to brackish. The Devonian and Quaternary formations represent the shallow groundwater system. The lower Devonian Formations contain brackish groundwater that becomes fresh towards the top of the Devonian and within the unconsolidated Quaternary deposits. It is this zone, some 500 m above the DGR, from which local groundwater supplies are taken.

During the first workshop of the Geosynthesis program in February 2007, the contributing authors of the reference reports and site characterization program met to develop a set of geoscience tenets, that would, if met, confirm the ability of the natural attributes at the Bruce site and surrounding area to protect human health and the environment over the design life of the DGR. The seven tenets were subsequently confirmed by OPG and are documented above in Section 2.1. The Geosynthesis reference reports and the balance of this summary report provide an interim assessment of the geoscientific basis to test the validity of the tenets and, in so doing, the favourable geological and hydrogeological attributes at the Bruce site for implementation of the DGR concept.

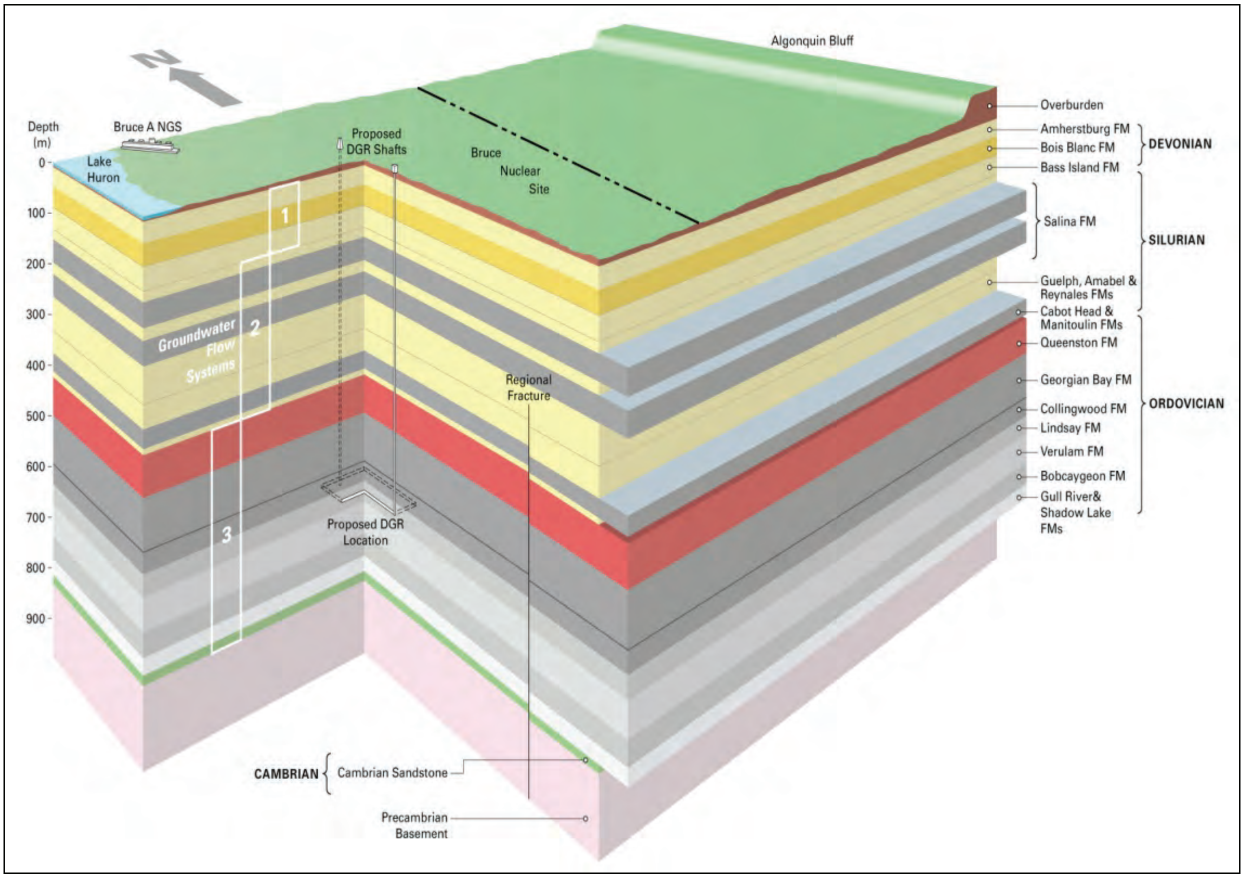

Figure 2.2 Bruce Site Conceptual Geosphere Model

2.3 Data Sources

For a project of this nature and broad scope there is not a single authority to house all the data required to demonstrate the fundamental tenets for the geosynthesis interpretation. The deep experience of the reference report authors and their affiliated institutions, together with government databases, house much of the information required for this work. Table 2.1 summarizes the major databases and literature sources used by the reference report authors. More detailed descriptions are provided in the individual reference reports.

The data sources described in Table 2.1 are based on literature searches that cover the past 100 years of geoscience research in Ontario. In addition, the reference report authors have met with the relevant scientists and agencies including the Ontario Geological Survey, the Geological Survey of Canada, and the Ontario Ministry of Natural Resources. Their contribution to this work is gratefully acknowledged. In addition, US state agencies, universities and consulting firms have also contributed to the data used in the geosynthesis work programs.

Table 2.1 Overview of Referenced Databases Contributing to the Geosynthesis Project

Reference Study	Data Sources
Regional and Petroleum Geology	➤ Oil, Gas, and Salt Resources Library (OGSR) - Petroleum Wells Subsurface Database ➤ Regional Study Area contained at total of 341 wells, including ▸ those wells drilled to prove salt resources near the southern portion of the study area ▸ oil/gas exploration wells drilled into Silurian strata (primarily reefs); and ▸ oil/gas exploration wells drilled into Ordovician strata ➤ Ontario Geological Survey (OGS) Digital Bedrock Geology of Ontario Seamless Coverage ERLIS Data Set 6 ➤ Michigan State Geological Survey mapping and Petroleum Well Database ➤ OGS Digital Bedrock topography and overburden thickness mapping, Southern Ontario – Miscellaneous Data Release no. 207 ➤ National Oceanic and Atmospheric Administration (NOAA) digital bathymetry mapping of Lake Huron and Georgian Bay ➤ 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 study area and as guidance for understanding detailed stratigraphic relationships in the subsurface
Geomechanics	➤ National Earthquake Database of the Geological Survey of Canada ➤ In situ stress measurement data were compiled from several published works that were conducted in the Michigan and Appalachian Basins ➤ OPG and consultant reports related to major energy generating projects in Ontario ➤ The remaining data sources were published literature, government reports, and consulting reports
Hydrogeology	➤ Stratigraphic sequence from the Regional Geology and Site Characterization programs ➤ Hydraulic properties from published literature and Site Characterization (OPG, 2008)
Long-term Climate Change	➤ Multiple world wide studies are referenced in this work
Hydrogeochemistry	➤ Research conducted at the University of Waterloo over a period of 25 years on formation fluids from within the sedimentary sequence underlying southwestern Ontario have been combined into a single database ➤ Over 90 percent of all samples are from producing oil and gas wells ➤ The remaining data sources were published literature, government reports, and consulting reports

3. REGIONAL GEOLOGY

3.1 Introduction

The Regional Geology presented in this report is a summary of the more detailed Regional Geology, Southern Ontario Supporting Technical Report prepared for the Phase I Deep Geological Repository Geosynthesis Program (Gartner Lee Limited, 2008a). The purpose of the Regional Geology study is to present an understanding of the deep sedimentary formations enclosing and surrounding the DGR based on a review and assessment of current published literature. In particular, this study describes the regional geologic setting surrounding the Bruce site in context of its structural geology, tectonics, basin history, formation sediment source areas, sedimentology, formation thermochronology, depth of burial, economic resources, and glacial history. A key outcome of this work was the development of the regional Three Dimensional Geological Framework (3DGF) for an area of approximately 35,000 km^2 surrounding the DGR, an area defined as the Regional Study Area (RSA). The RSA boundary (Figure 3.1) was delineated in order to fully encompass the Regional Hydrogeologic Modelling domain (Sykes *et al.*, 2008) as the 3DGF provides the geometric framework for numerical simulations of groundwater migration and mass transport within the sedimentary sequence.

3.1.1 Site Characterization Activities

Phase I site-specific geoscientific studies at the Bruce site were initiated in fall of 2006. These studies, described by Intera (2006) consisted primarily of the coring, in situ and laboratory testing and instrumentation of two deep (460 and 860 m) vertical boreholes (DGR-1 and DGR-2), the refurbishment and monitoring of the mostly pre-existing shallow (<100 m) US-series of boreholes and the completion of a 2-dimensional seismic reflection study. Phase I investigations are scheduled for completion in fall-2008. Phase 2 work was initiated in April 2008 with the addition of two deep (860 m) vertical boreholes (DGR-3 and DGR-4) and will continue in 2009 with two deep inclined (930 m) boreholes (DGR-5 and DGR-6). These studies are intended to complement Phase I results in obtaining additional detailed borehole information to test the understanding in the context of the aforementioned site attributes or tenets. The work presented in this section has been informed by the interim results of the Phase I and partially completed Phase 2 site characterization programs. Full integration of regional and site-specific data is planned for early 2010.

3.2 Geological Setting

The sedimentary rocks of Southern Ontario rest on the southern margin of the Canadian Shield. The crystalline basement is composed of metamorphic rocks of the Proterozoic Grenville Province. Figure 3.1 shows progressively younger Paleozoic sedimentary units outcropping/subcropping from the Canadian Shield margin in central Ontario towards southwestern Ontario. These sedimentary units range in age from the upper Cambrian to upper Devonian and were deposited in two paleo-sedimentary basins, the Appalachian and Michigan basins (Figure 3.2). The RSA boundary used to construct the 3DGF (described below) is shown as a red box within Figure 3.1

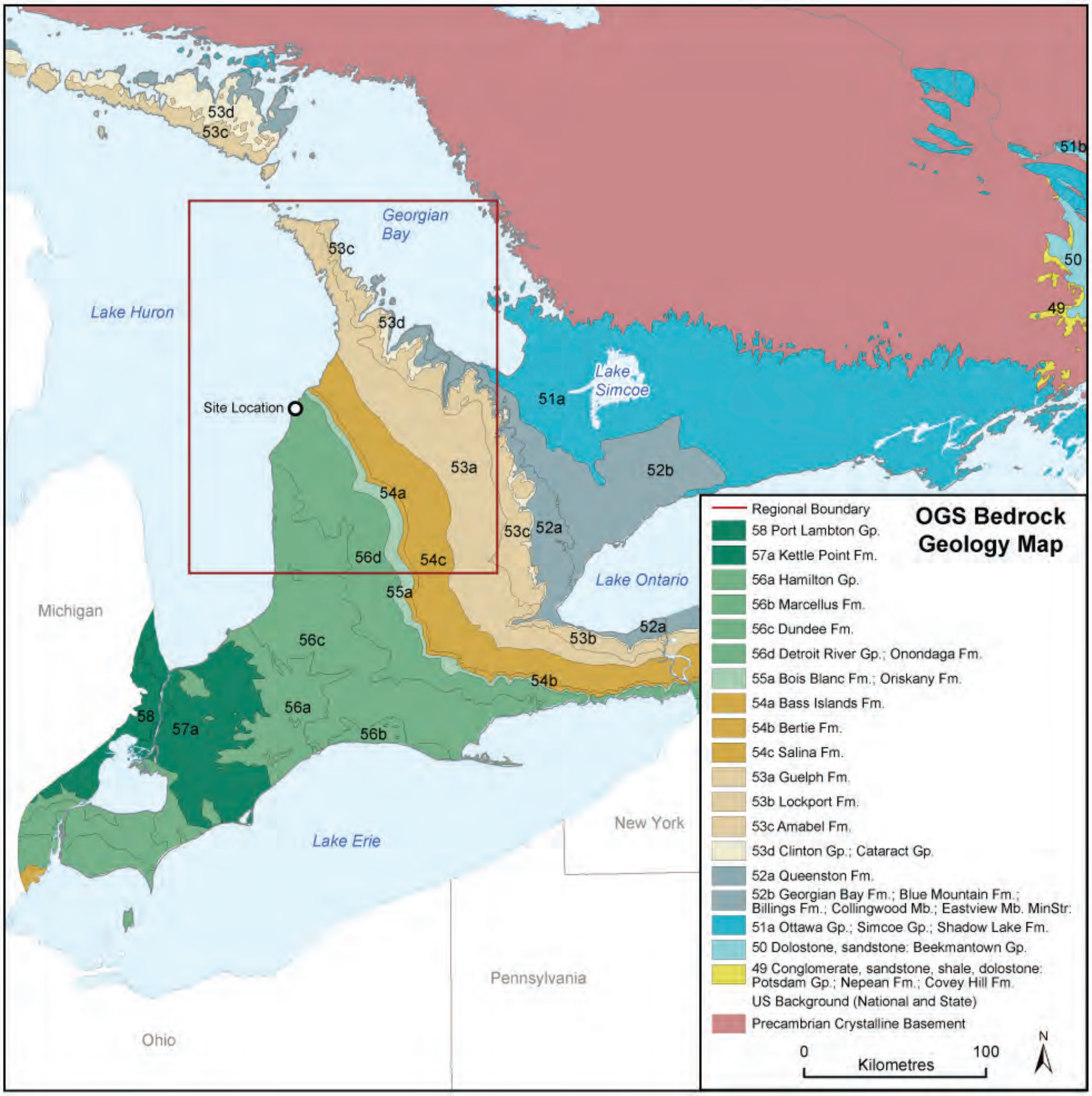

Figure 3.1 Geologic Map of Southern Ontario

Studies of the exposed Paleozoic-Precambrian unconformity 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 3.2). The Michigan Basin, centred over northern Michigan, 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. Paleozoic strata in the Appalachian Basin shallow to approximately 850 m over the Algonquin Arch (Sanford, 1993b).

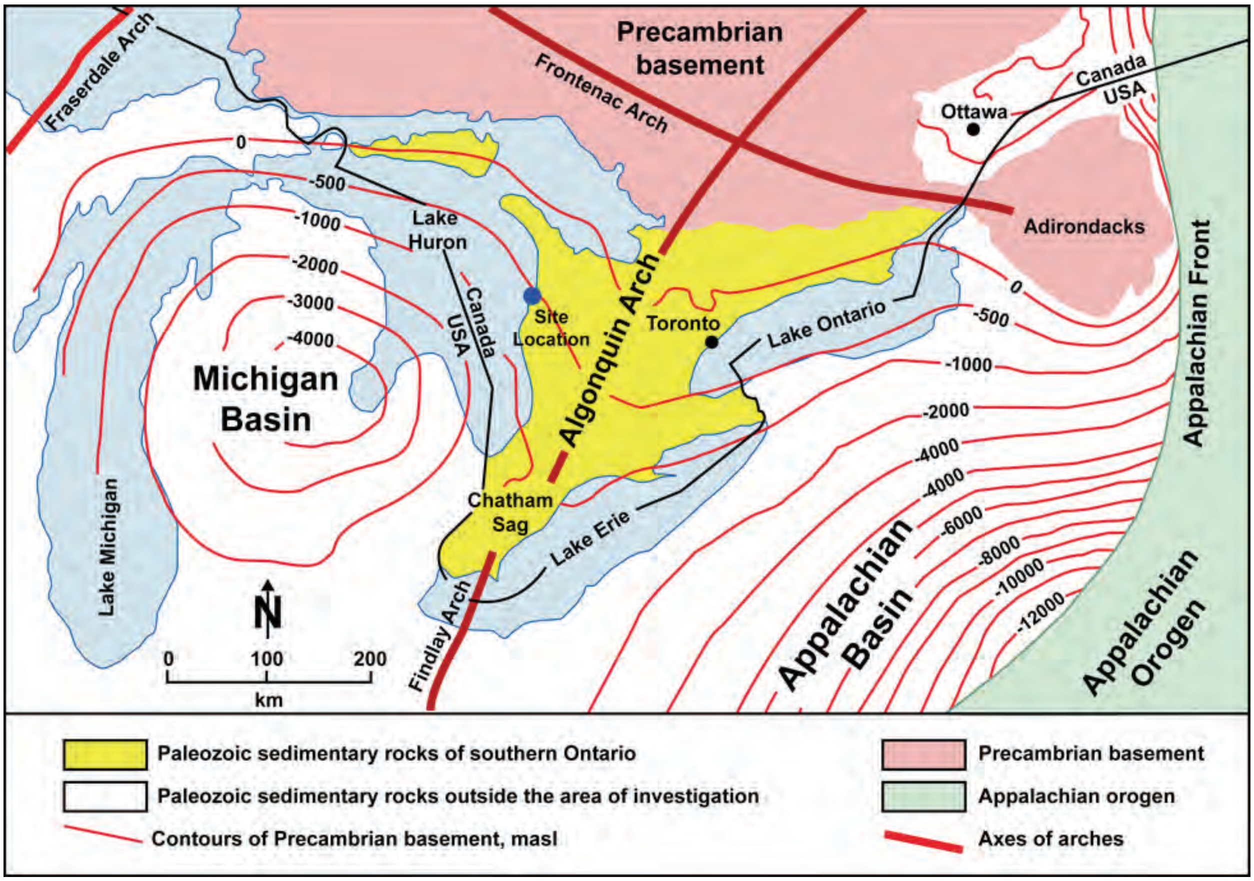

Figure 3.2 Large-scale Tectonic Elements in Southern Ontario (Mazurek, 2004 after Johnson et al. 1992).

Sedimentation in the Michigan Basin continued beyond the Mississippian 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).

The DGR Site is located near the eastern edge of the Michigan Basin (Figure 3.2, Figure 3.3). Figure 3.3 presents a geological cross-section through the Michigan Basin from Collingwood, Ontario in the east to Lake Michigan in the West. The Niagara Escarpment at Georgian Bay truncates the eastern edge of Figure 3.3 and the erosional valley located immediately west of the escarpment is the Beaver Valley. The basin deposits are 860 m thick at the Bruce site (Intera, 2008) and consist generally of dolostones, limestones, shales, sandstones and evaporites. The proposed DGR stratigraphic location is the Middle Ordovician Cobourg Formation at a depth of approximately 680 m.

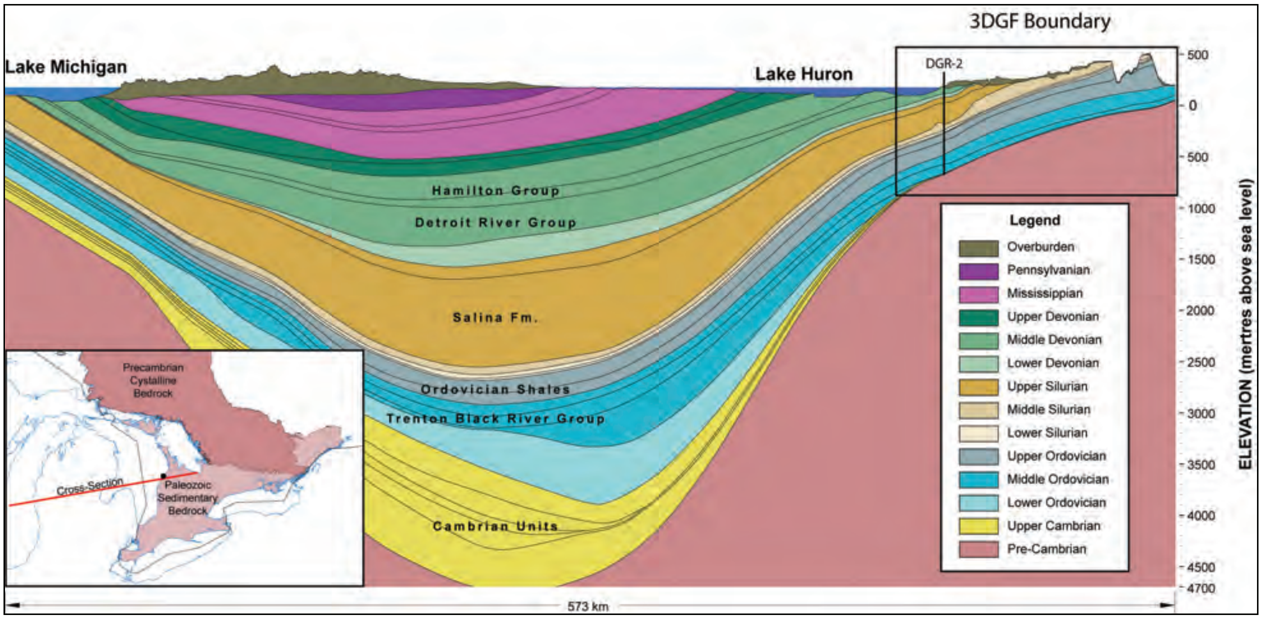

Figure 3.3 Geological cross-section through the Michigan Basin with approximately 45x vertical exaggeration (note: DGR-2 well is offset from cross-section).

3.2.1 Structural Geology and Tectonics

This section reviews the structural geology and tectonic history of Southern Ontario. The sedimentary rocks lie unconformably on a crystalline basement that formed during the Grenville Orogeny in Proterozoic times. The main regional structural features are discussed, as well as, the tectonic events that influenced the region.

3.2.1.1 Arches and Basins

The land area of southwestern Ontario forms a shelf separating two depositional basins, the Appalachian Basin and the Michigan Basin, with a broad northeasterly trending high in the Precambrian Basement called the Algonquin Arch (Johnson *et al*., 1992). The Chatham Sag represents a drop in elevation along this Precambrian high and separates the Algonquin Arch in Canada from its extension, the Findlay Arch, in the United States (Figure 3.2). The crest of the Algonquin Arch gradually decreases in elevation in a south-westerly direction, from about 300 mASL north of Lake Simcoe to -1,000 mASL at the Chatham Sag (Carter *et al*., 1996). Since the two basins were structurally active at different times in the past, the crest of the arch migrated back and forth between the basins (Howell and van der Pluijm, 1999).

3.2.1.2 Major Precambrian Structures

Two major NNE oriented structures that occur in the Precambrian basement are the Grenville Front Tectonic Zone (GFTZ) and the Central Metasedimentary Belt Boundary Zone (CMBBZ) (Figure 3.4). Both are major ductile shear zones, several kilometres wide consisting of strongly deformed rocks (Carter and Easton, 1990ab). The GFTZ forms the northwestern boundary of the Grenville province, where it meets the Superior and Southern provinces. The CMBBZ occurs along the boundary between two major subdivisions of the Grenville province, the Central Gneiss Belt on the west side and the Central Metasedimentary Belt on the east side. The Grenville province is considered to have remained tectonically stable for the last 1.0 Ga, since the end of the Grenville orogeny, when a Himalayan style mountain range and plateau existed on the Grenville (Percival and Easton, 2007). Subsequent erosion levelled the Precambrian landscape to a peneplane prior to the deposition of the Cambrian sandstones and Ordovician limestones.

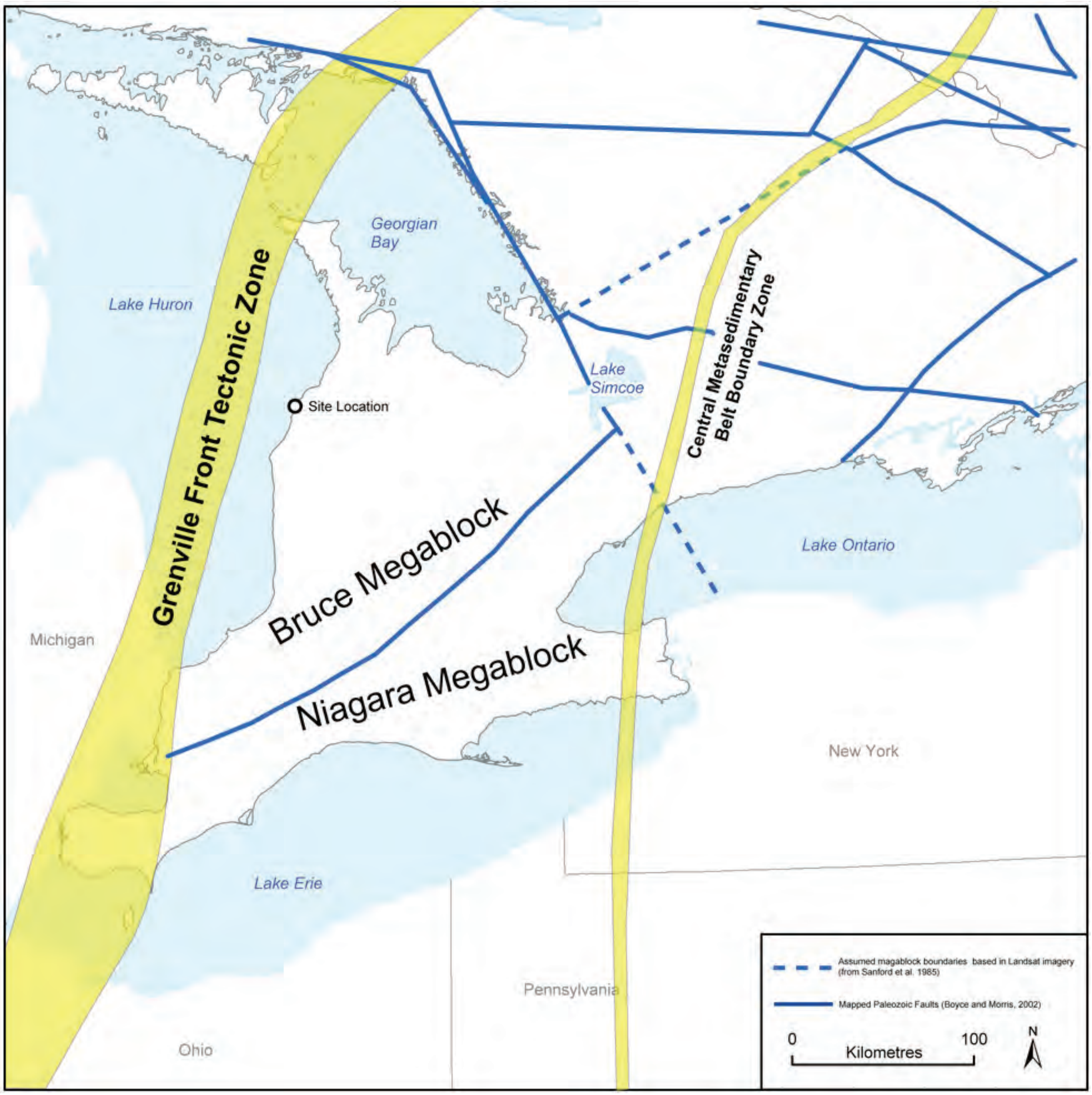

Figure 3.4 Major structural boundaries of Southern Ontario (Easton, 1992) and interpreted tectonic block boundaries by Sanford *et al.*, (1985).

The Midcontinent Rift cuts across the state of Michigan in a roughly northeasterly direction. The rift formed about 1.1 Ga and, where exposed, consists of basalts overlain by sandstones, shales and conglomerates. Carter and Easton (1990) proposed the extension of the Midcontinent Rift into Essex County, east of the Grenville Front into Ontario, based on lithologic, aeromagnetic and gravity data.

3.2.1.3 Paleozoic Structures

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 3.4). The two megablocks most relevant to the DGR are the Bruce and Niagara Megablocks. It is difficult to evaluate the block model because primary data on surface lineaments are not reported by Sanford *et. al*., 1985. 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.

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 roughly the Georgian Bay Linear Zone to the east. Sanford *et al.* (1985) introduced a conceptual fracture framework for southwestern Ontario based on hand contouring of selected Silurian unit isopachs and structure contours on the top of the Silurian Rochester Formation. This work suggested that Silurian units contain ENE- to EW-trending normal faults with ~10 km spacing. Figure 3.5 illustrates the Sanford *et al.* (1985) conceptual fracture distribution combined with the known basement faults as described by Carter *et al.* (1996). Sanford *et al.* (1985) postulated that the fractures (faults) in the Paleozoic cover initiated from the reactivation of pre-existing Precambrian basement faults. 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 3.5, 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 and Engelder, 1991; Andjelkovic *et al.,* 1996, 1997; Andjelkovic and Cruden, 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.

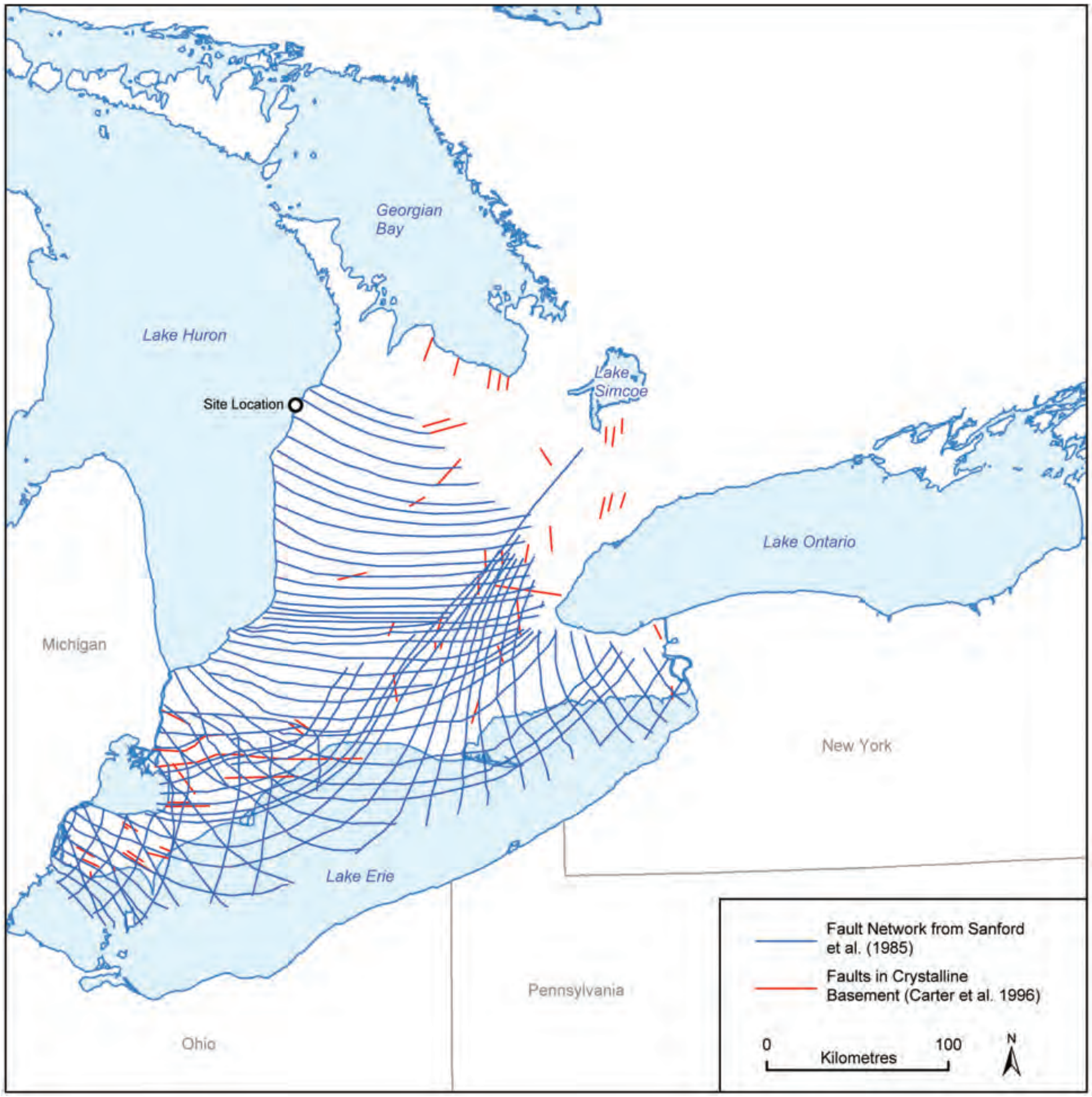

Figure 3.5 Proposed Fracture Framework and Mapped Faults of Southern Ontario (Sanford et al., 1985) that displace the Paleozoic-Precambrian unconformity surface (from Mazurek 2004, after Sanford et al. 1985; Carter et al., 1996).

3.2.1.4 Tectonic History

The geological evolution of southern Ontario as we know it today has occurred over a period of about 1.3 Ga. The first half of this period recorded the development of the basement metamorphic Proterozoic rock. During this period a series of tectonic events; structural uplift, erosion, burial, faulting and intrusion occurred. This early history formed the rocks that we now refer to as the Precambrian basement of the Canadian Shield. From Cambrian times (approx. 550 Ma) through to the Devonian period basin subsidence and arch uplift occurred to form the Michigan Basin. Table 3.1 summarizes the major tectonic activities over geologic time that have defined the geology of southern Ontario.

Table 3.1 Timetable of Tectonic Events

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

Figure 3.6 shows the major tectonic influences on eastern North America through time (Sanford, et. al., 1985). 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 3.6).

The Alleganian Orogeny was the last active orogeny to provide significant sediment deposition through the Carboniferous, Permian and likely early Mesozoic times. Evidence for deposition during this period is extrapolated from similar thick sequences that exist to the southwest in the United States. Cercone (1984) estimates that over 2 km of Late Paleozoic to Early Mesozoic sediments must have existed to introduce sufficient burial pressure and temperature to explain the thermal history of the Michigan Basin. These sediments have since been eroded in the Ontario portion of the Michigan Basin.

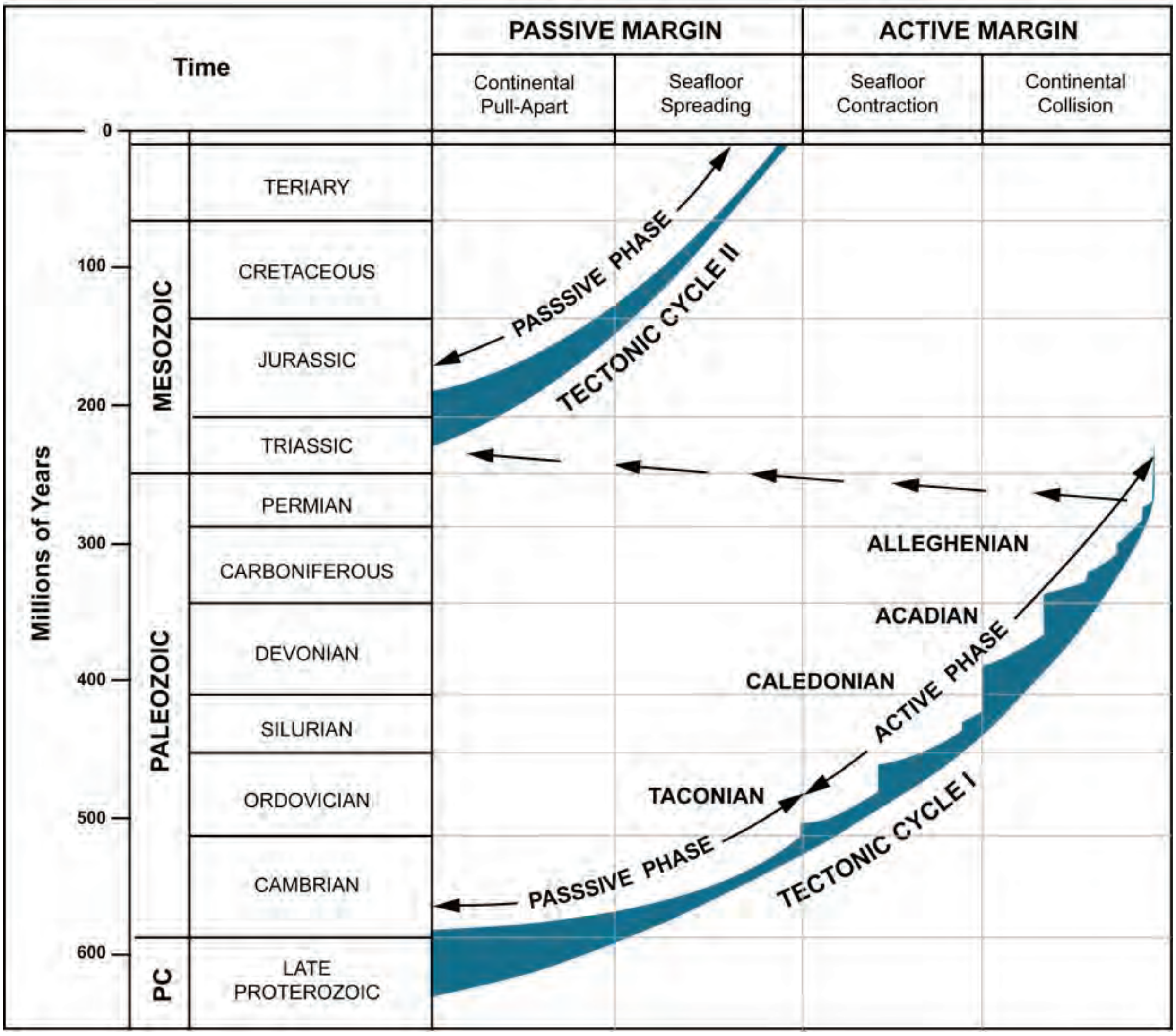

Figure 3.6 Phanerozoic Tectonic Cycles with band widths representing relative tectonic intensity (Sanford, 1985)

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 attributed to the formation of ESE trending faults and systematic regional joints in Paleozoic cover rocks (Gartner Lee Limited, 2008a).

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.

From Permian times (250 Ma) to the present southwestern Ontario has been above sea level and subjected to passive tectonic forces and erosion (Gartner Lee Limited, 2008a). Over this long period of time the Paleozoic sequence has been stable and unaffected by major tectonic events.

3.2.2 Regional Stratigraphy

In 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-centered facies assemblages. The broad scientific understanding of sedimentary environments from modern and ancient examples combined with field mapping and borehole data allow geologists to predict the stratigraphy over large lateral distances with confidence. Figure 3.7 illustrates the Paleozoic stratigraphy of southern Ontario, at locations in the Appalachian Basin, the DGR site and the Michigan Basin in southwestern Ontario.

The following descriptions of the Paleozoic geology beneath the RSA are generally organized according to the main sequence stratigraphic associations in southern Ontario and are based on regional descriptions primarily from Johnson *et al*. (1992) and Armstrong and Carter (2006).

Precambrian

The nearest outcrops of Precambrian basement occur approximately 150 km to the northeast of the site, along the north shore of Georgian Bay. The Bruce site is underlain by the Huron domain of the Central Gneiss Belt in the Grenville Province and generally consists of gneisses of granite to monzonite composition (Carter and Easton, 1991). Carter and Easton (1990) noted the altered zone of the Precambrian basement rocks extended on average 2 to 5 m beneath the Precambrian/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

The lithology of the Cambrian units ranges from fine to medium crystalline dolostone, sandy dolostone, argillaceous dolostone to fine to coarse quartzose sandstone (Hamblin, 1999). In southwestern Ontario they are dominated by white to grey quartzose sandstone (Armstrong and Carter, 2006), which are often described as porous. 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, 1984).

In general, the Cambrian deposits are considered to be a succession of marine sandstone and dolostone 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).

Middle Ordovician Carbonates

In the subsurface of southern Ontario, including the DGR site, the Middle and Upper Ordovician Carbonates are divided into the Black River and Trenton groups. The Black River Group includes three formations in ascending order, 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 3.7).

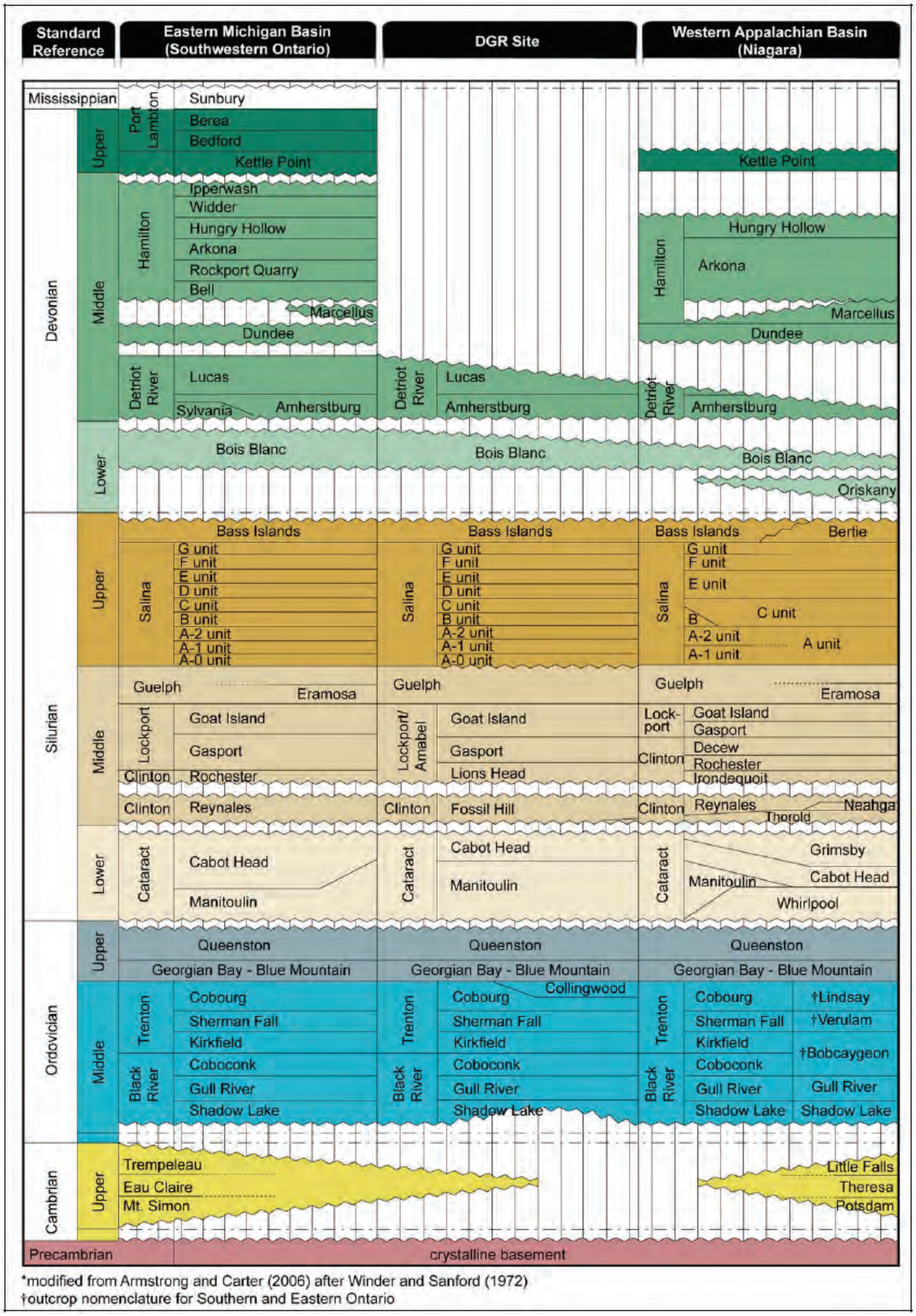

Figure 3.7 Paleozoic Stratigraphy of Southwestern Ontario from locations in the Michigan Basin, Algonquin Arch and Appalachian Basin (modified from Armstrong and Carter, 2006)

A major marine 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 (Figure 3.8) 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 3.8 from Sanford (1993b) presents the interpreted depositional setting with isopach thickness of the Middle Ordovician units, prior to the formation of the Michigan Basin.

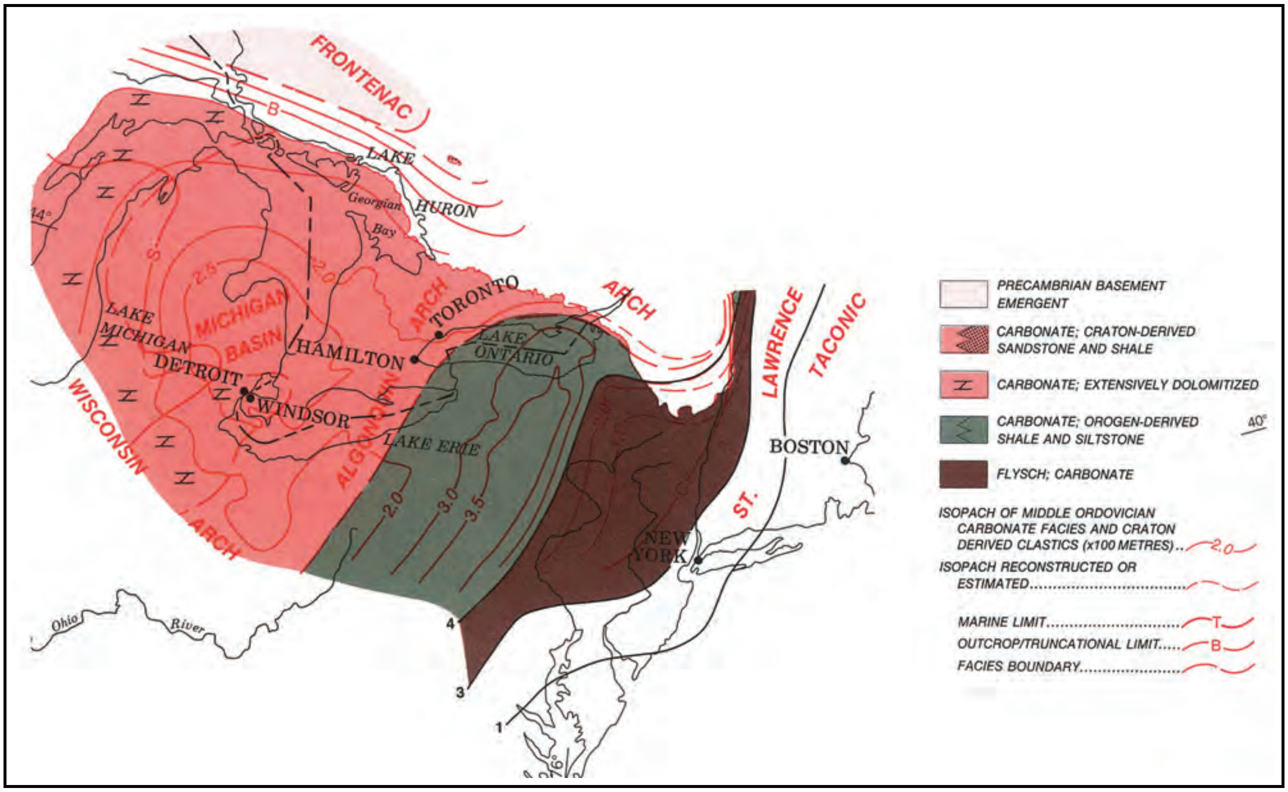

Figure 3.8 Middle Ordovician Depositional Sequence and Isopach Thickness (Sanford, 1993b)

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 assemblages within the Ordovican rocks. This lateral extent is confirmed by outcrop and well data across Ontario. Brookfield and Brett (1988) describe the Arabian (Persian Gulf) and Sahul (Southeast Asia) shelves as two modern examples closest to the Trenton seas.

The rock types described for the succession of Ordovician carbonates in Ontario range from coarse-grained bioclastic carbonates to carbonate mudstone with interbedded calcareous and non-calcareous shale. Individual facies demonstrate variability vertically and laterally: however, the facies assemblages that comprise these Ordovician carbonates are predictable and well described regionally (Gartner Lee Limited, 2008a

The Shadow Lake Formation lies at the base of the Black River Group and is characterized by poorly sorted, red and green sandy shales, argillaceous and arkosic sandstones, minor sandy argillaceous dolostones and rare basal arkosic conglomerate (Armstrong and Carter, 2006).

The Gull River Formation consists mainly of light grey to dark brown limestones and the upper part of the formation is very fine grained (lithographic). Thin shale beds and partings may be present (Armstrong and Carter, 2006). The Coboconk Formation lies at the top of the Black River Group and is composed of light grey-tan to brown-grey, medium to very thick bedded, fine to medium grained bioclastic limestones.

The Kirkfield Formation (Trenton Group) is characterized by fossiliferous limestones with shaly partings and locally significant thin shale interbeds. The Sherman Fall Formation ranges in lithology from dark grey argillaceous limestones, found lower in the formation, to grey to tan bioclastic, fossiliferous limestones that characterize the upper portions of the unit.

The lower member of the Cobourg Formation, the host rock for the DGR, is described as bluish-grey to grey-brown, very fine to coarse grained, fossiliferous limestones and argillaceous limestones with a nodular texture (Intera, 2008). The upper member of the Cobourg Formation, the Collingwood Member, consists of dark grey to black, calcareous shales with organic content. 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 underlying Cobourg Formation due to its calcareous content, while the overlying Blue Mountain Formation shales are distinctly non-calcareous.

Upper Ordovician Shales

Formation of the Middle Ordovician Trenton carbonates ceased in response to the collision of the passive margin with an island arc system that occurred during the Taconian Orogeny (Figure 3.6). 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 Upper Ordovician orogen-derived clastic sediments (Hamblin, 1999). 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) largely incorporating it, as well as the Algonquin Arch into the Appalachian Basin (Figure 3.9). Figure 3.9 (Sanford 1993) illustrates the interpreted structural/tectonic setting and depositional sequences during the Upper Ordovician. It is the broad platform tectonic setting that allowed for the deposition of the Upper Ordovician clastic sedimentary wedge which is pervasive across the RSA. Modern equivalent depositional environments include the Gulf of California and the western coast of Australia.

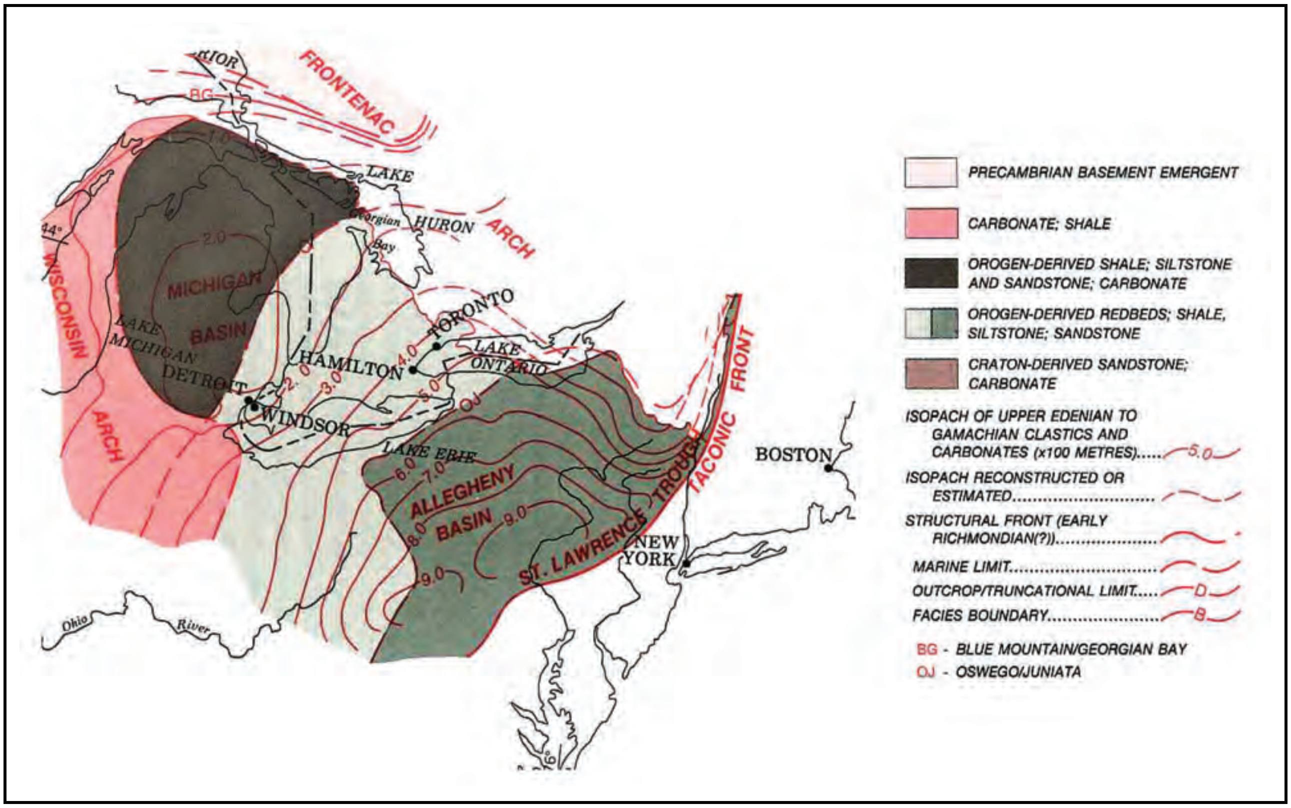

Figure 3.9 Upper Ordovician Depositional Sequence and Isopach Thickness (Sanford, 1993)

The extensive Upper Ordovician shale sequences are comprised of the Blue Mountain, Georgian Bay and Queenston formations, which underlie southern Ontario and the Bruce site. 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). 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. 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 Queenston Formation is characterized by maroon, with lesser green, shale with varying amounts of carbonate. The carbonate content increases regionally to the northwest. Gypsum is found locally as small nodules and thin subhorizontal fracture in-fillings. 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 until the Queenston Formation completely pinches out between the Georgian Bay and Manitoulin Formations (Brogly, 1990).

Lower Silurian Carbonates and Shales

The Lower Silurian Manitoulin Formation, which unconformably overlies the Queenston Formation shales, consist of grey argillaceous dolostone and minor grey-green shale and also contains bioherms. The Manitoulin was deposited in a shallow carbonate ramp setting (Armstrong and Carter, 2006).

The overlying Lower Silurian Cabot Head Formation is described as grey to green to maroon, noncalcareous shales that may contain some sandstone and carbonate interbeds (Armstrong and Carter, 2006). The depositional environment ranged from offshore basinal to a marginal marine environment.

Middle Silurian Carbonates

The Middle Silurian rocks beneath the DGR consist of the Fossil Hill, Lions Head, Gasport, Goat Island and Guelph formations.

The Fossil Hill Formation is composed of thin to medium bedded, very fine to coarse grained fossiliferous dolostone. 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 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 Lions Head, Gasport, Goat Island 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. The resulting depositional facies across the basin are shown in Figure 3.10.

The Lions Head is light grey to grey-brown, finely crystalline, thin to medium bedded, sparingly fossiliferous dolostone with minor chert nodules. The Gasport Formation is blue-grey, fine to coarse grained, thick bedded to massive dolostone which may contain some dolomitic limestone. The Goat Island is lithologically very similar to the Lions Head but is more argillaceous and may contain vugs filled with gypsum, calcite or fluorite. Deeper water basinal facies characterize the Middle Silurian Carbonates in the Michigan Basin, while the margin of the basin and Algonquin Arch are characterized by shallower low energy restricted facies and shallow higher energy facies (Armstrong and Goodman, 1990).

The Guelph Formation is variable due to its depositional environment, where pinnacle, patch and barrier reefs occur in separate zones within the basin (Figure 3.10). In the RSA, the Guelph Formation extends from the basinward pinnacle reef belt to the barrier reef complex at the margin of the Michigan Basin. As a result, the Guelph Formation facies range from reefal to inter-reefal dolostones (Armstrong and Goodman, 1990). The widespread inter-reefal dolostones are typically sucrosic, dark brown to black dolomudstones with pebble size fragments lithologically similar to the underlying Goat Island Member (Armstrong and Carter, 2006).

Upper Silurian Carbonates, Shales and Evaporites

The Upper Silurian Formations are comprised of the Salina Group and the Bass Islands formations. 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 beneath the DGR site include 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. Salina units vary cyclically in lithology, grading upwards from basal carbonates to anhydrites to halite (evaporites), with the tops of each evaporite cycle often being marked by shaly strata (Armstrong and Carter, 2006)

The Bass Islands Formation is a microcrystalline dolostone, commonly bituminous and contains evaporite mineral casts. This formation represents a change back to marine carbonate conditions away from the cyclic evaporite, and carbonate forming conditions of the Salina Group. The contact with the overlying Devonian carbonates marks a major unconformity characterized by subaerial exposure (Uyeno *et al.*, 1982).

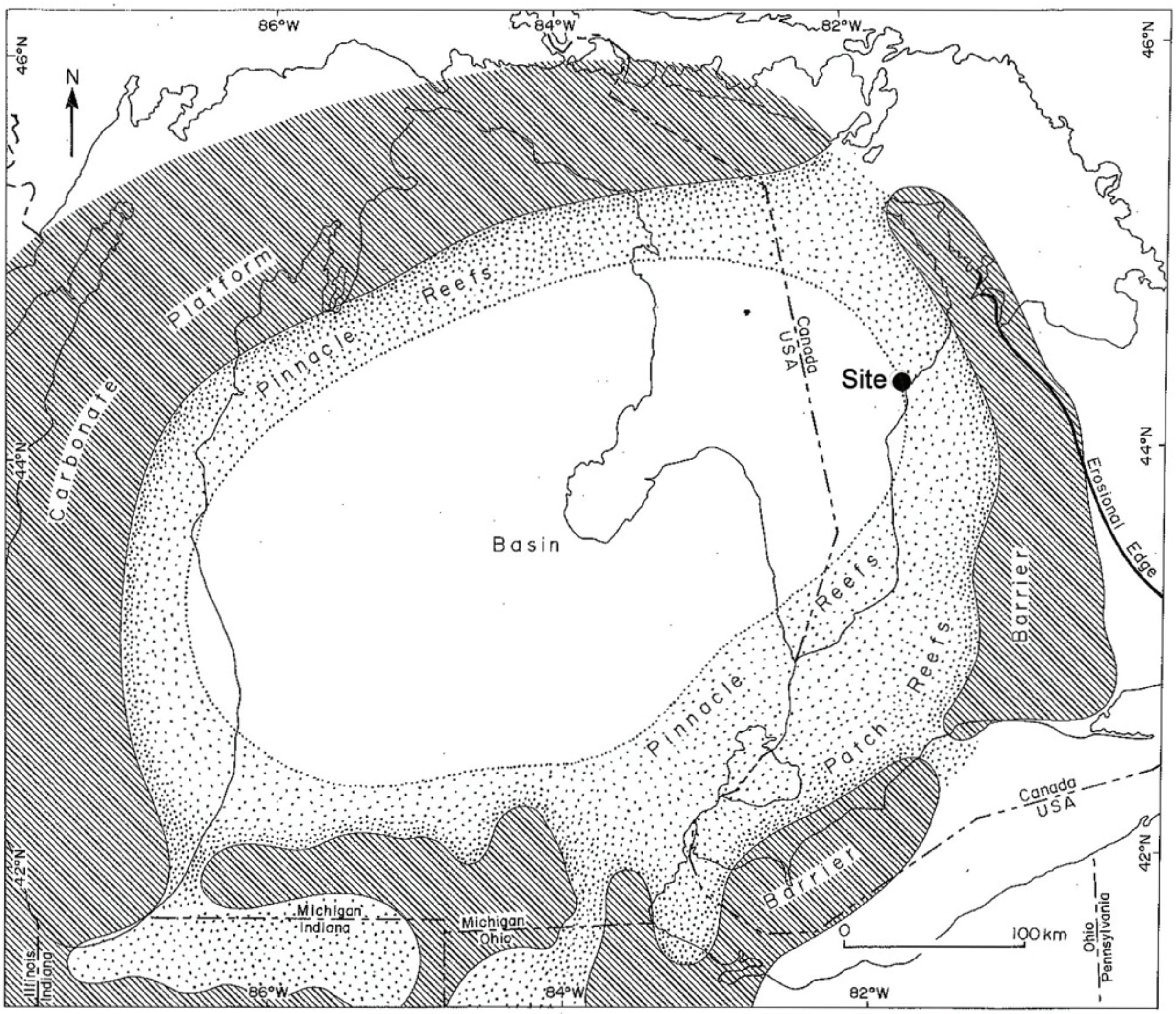

Figure 3.10 Distribution of Middle and Upper Silurian Carbonate Facies (Johnson et al., 1992).

Devonian Carbonates

The Bois Blanc Formation is primarily a cherty dolostone unit within the regional study area, grading laterally into 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 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). Similar to the Bois Blanc, this unit 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, based on descriptions from the Ontario town bearing the same name. The Lucas Formation conformably overlies the Amherstburg Formation (Johnson *et al.*,

1992) and is characterized by fine grained dolostone and limestone. The Lucas and Amherstburg are found along the bedrock surface beneath the overburden at the Bruce site and the Lucas outcrops extensively along the shoreline.

3.2.3 3D Geological Framework

Itasca Consulting Canada Inc. was retained by OPG to work closely with Gartner Lee Limited in developing the Three-Dimensional Geological Framework (3DGF) model (Gartner Lee Limited, 2008a). The framework was designed using Gocad^{TM} software, an advanced 3D earth modelling and scientific visualization technology. The model is capable of displaying the three-dimensional configuration of individual stratigraphic layers, as well as partial or entire stratigraphic sequences. It can also be used to predict the depths and elevations of stratigraphic units at new proposed borehole locations and to prepare geological cross sections where required. The geological framework also forms the basis of the hydrostratigraphic model domain used for the Phase I Hydrogeological Modelling. A map view of the Geological Framework within the Regional Study Area boundary is provided in Figure 3.11. The framework extends from Collingwood, Ontario in the east to the midpoint of Lake Huron in the west, south to Goderich, Ontario, and north to the tip of the Bruce Peninsula (Figure 3.11). An oblique view of the 3D Geological Framework looking NE is presented in Figure 3.12, which also shows the location of the DGR relative to the surrounding stratigraphy.

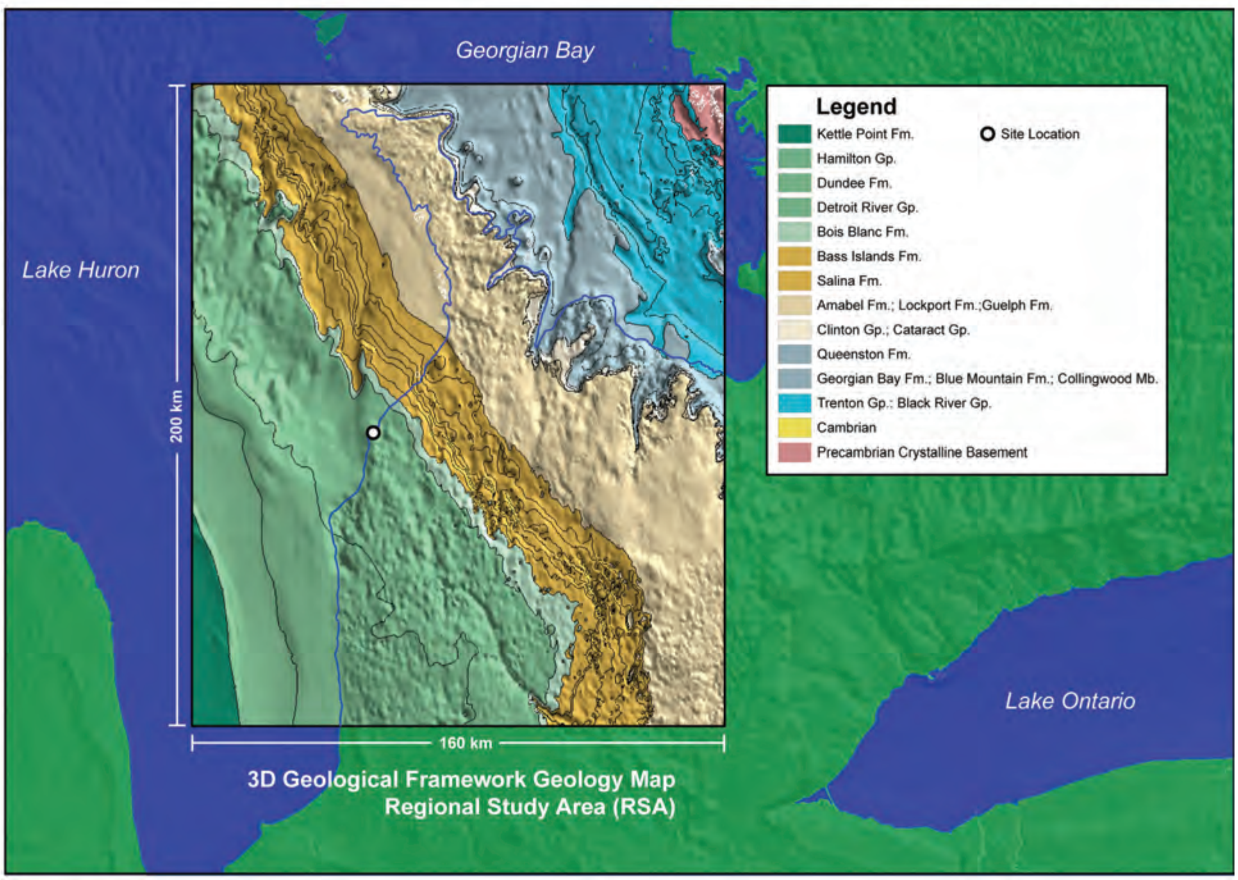

Figure 3.11 3D Geological Framework Study Boundary with Paleozoic Geology Derived from the 3DGF model.

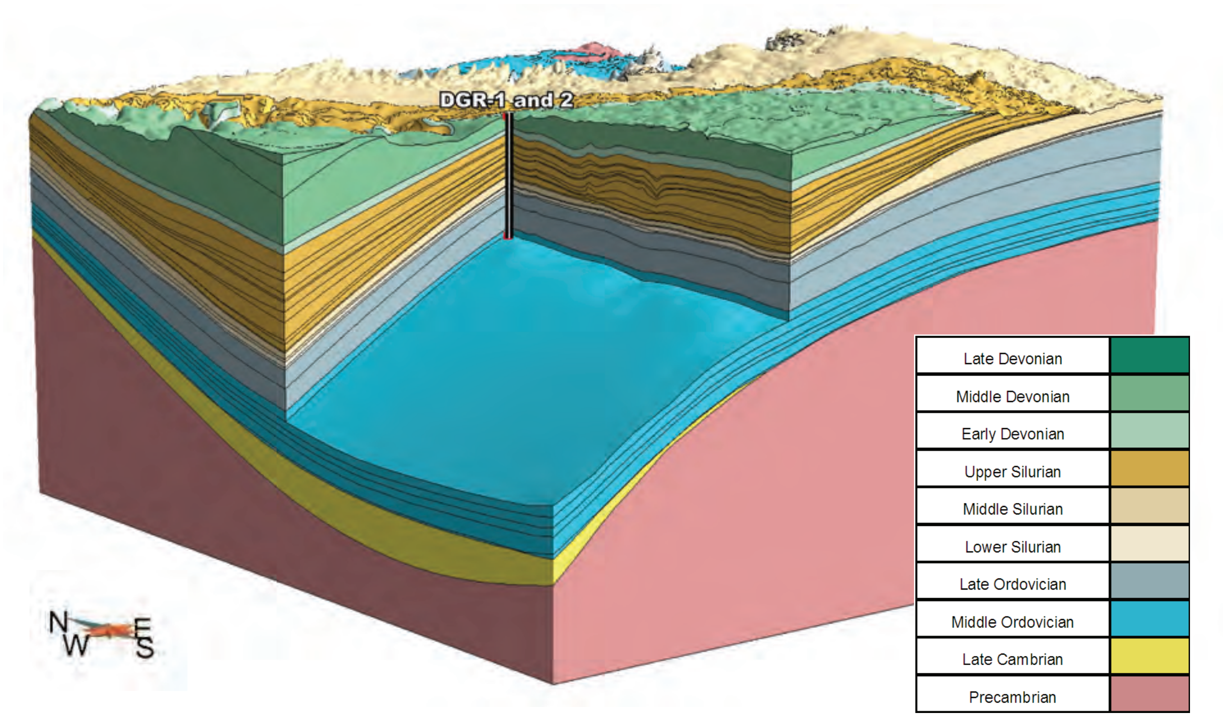

Figure 3.12 3D Regional Geological Framework and the Location of the DGR beneath the Bruce Site (approx. 40X vertical exaggeration).

In the subsurface, the geologic framework is situated at the eastern margin of the Michigan Basin, extending from the Algonquin Arch, west past the Silurian pinnacle reef belt (Figure 3.10) and into the deeper portions of the Michigan Basin below Lake Huron (Figure 3.13). The base of the framework extends from the Precambrian basement located approximately 1,000 mBSL at the mid-point of Lake Huron to the surface topography at a maximum elevation of approximately 500 mASL on the Niagara Escarpment (Figure 3.13).

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 (RSA) contained at total of 341 wells, which were reduced to 302 wells through a data validation process described in the Regional Geology Supporting Technical Report (Gartner Lee Limited, 2008a). 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.

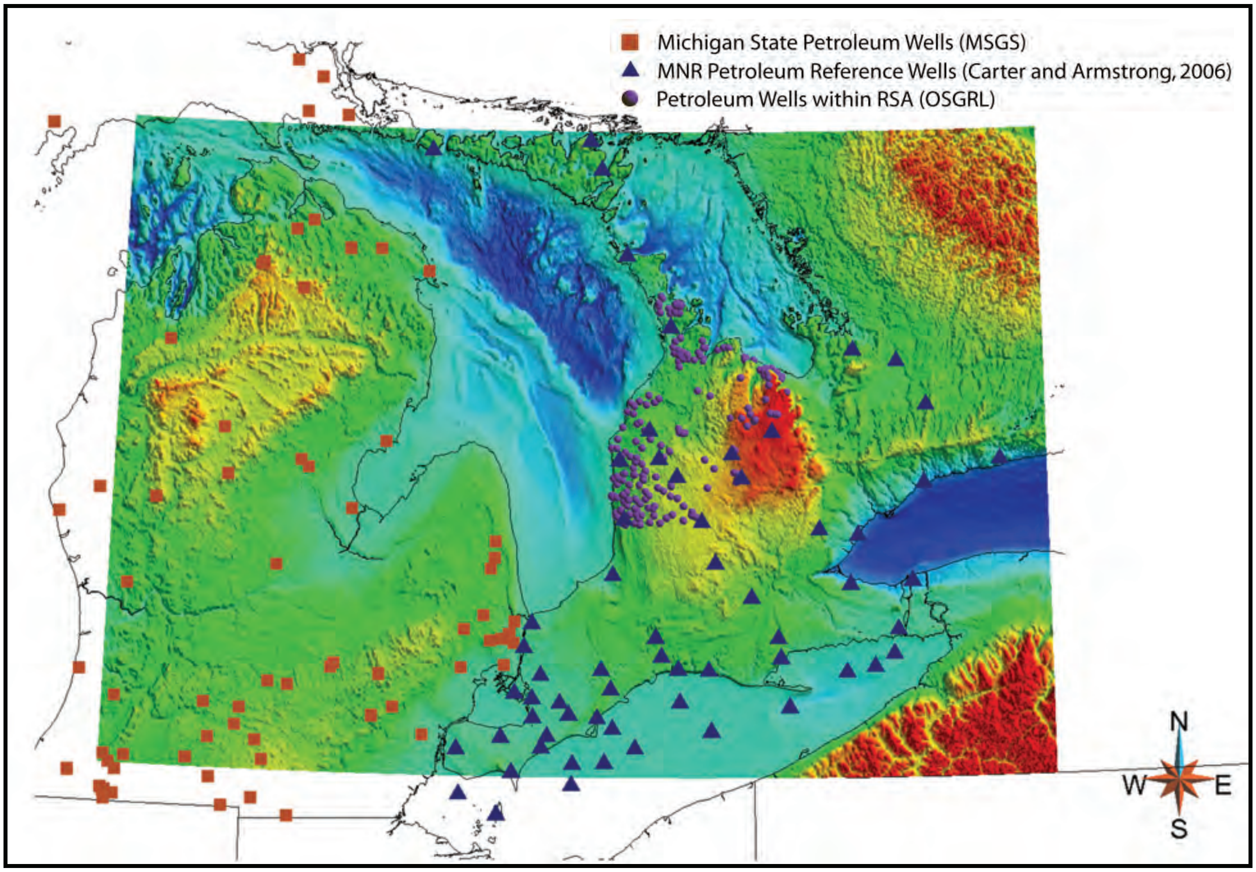

Figure 3.13 Digital elevation map (higher elevations shown in red) with the location of wells used to construct the 3DGF.

Key sources of data also included downhole geophysics (used to verify well contacts/picks), acquired from the OGSR Library for select wells within the RSA, and Ontario Geological Survey (OGS) Open File Report 6191 (Armstrong and Carter, 2006), "An updated guide to the Paleozoic stratigraphy of southern Ontario". Reference wells were used by Armstrong and Carter (2006) to generate a series of representative geological cross-sections through the subsurface of southern Ontario. These same reference wells were used in the 3DGF as a verification tool and to provide consistency with the accepted Ontario geological nomenclature and understanding.

Other important data used to constrain the geological layers within the 3DGF included:

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.

3.2.4 DGR Site Stratigraphy

A detailed stratigraphic section with general lithologic description of each formation encountered in boreholes DGR-1 and DGR-2 is shown in Figure 3.14 (Intera, 2008). The following discussion compares the core logging results of the Phase I DGR drilling investigation with a regionally based stratigraphic understanding presented by Gartner Lee Limited (2008a).

The work of Bailey and Cochrane (1984), Carter et. al., (1996) and others suggests that the DGR site was 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 site's position west of the Cambrian erosion front against the Algonquin Arch.

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 Groups are 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).

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 descriptions, (particularly the Guelph and Gasport-Goat Island formations) confirms that the site occupies an inter-reef position with respect to the Silurian rocks. Silurian reef locations examined in this study commonly intersect >100 m of Silurian dolostones. The absence of the Middle Silurian Rochester shale beneath the Gasport Formation at the site is predicted from regional data (Sanford, 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).

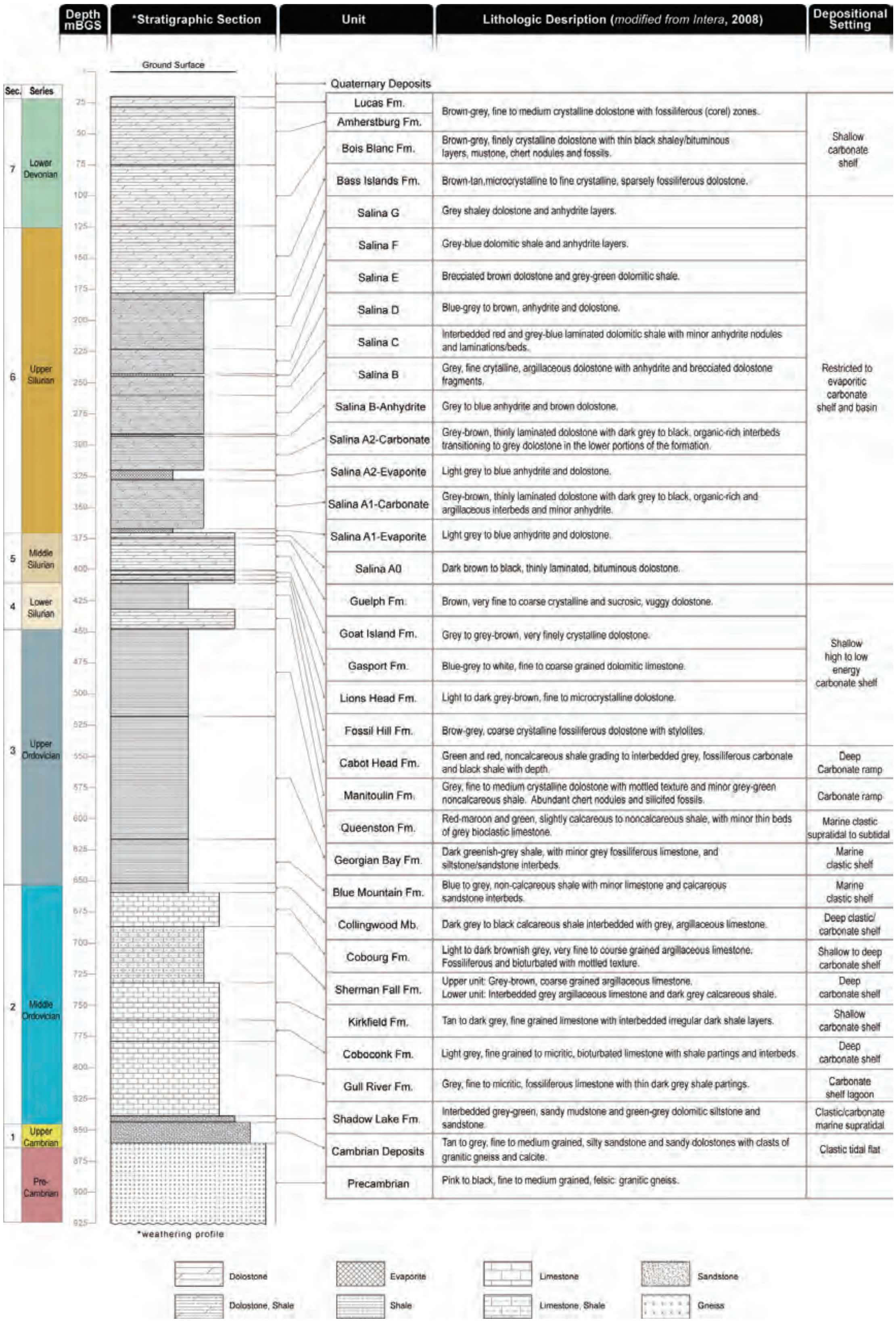

Figure 3.14 Phase I Deep Drilling Program: DGR-series boreholes – Stratigraphy

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 to 50 m thickness for the Bois Blanc, with greater thicknesses towards the Michigan Basin center. The Detroit River Group (approximately 55 m) is described by Intera (2008) as a fossiliferous (coral) dolostone. Approximately, 10 m of Lucas Formation overlies the Amherstburg Formation at the site an DGR-1. 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.

3.2.5 Diagenesis

A number of diagenetic processes have influenced or altered the Paleozoic rocks of southern Ontario since Cambrian times. 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 calcium with magnesium. The primary dolomitization mechanism (Morrow, 1990) for rocks in Southern Ontario are reportedly: a) sabkha type, b) mixed-water aquifer, c) seepage reflux d) burial compaction, and e) hydrothermal. The timing of these events ranged from during or shortly after marine carbonate deposition (*a* and *b*) to the Late Paleozoic/Early Mesozoic and/or/ corresponding to maximum burial compaction (*c*, *d, and e*). Hydrothermal dolomitization selectively altered the Paleozoic rocks along and adjacent to discrete fracture systems in response to tectonic events throughout the Paleozoic and Early Mesozoic. The conditions that led to dolomitization i.e., basinal groundwater flow, fracture related flow and hydrothermal dolomitization no longer exist within the Michigan Basin, and have not occurred over recent geological time, the last approximately 250 Ma (Figure 3.6).

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 dissolution and subsequent collapse features (Upper Silurian and Devonian stratigraphy), clay alteration at the Precambrian-Paleozoic boundary, and hydrocarbon migration and emplacement.

Groundwater movement in the sedimentary sequence of southern Ontario occurred during deposition and burial diagenesis, which extended throughout the Paleozoic, possibly into the early Mesozoic. The main migration pathways were fracture and fault zones similar to those affected by dolomitization. Sanford *et al.*, (1985) suggest that dissolution of Upper Silurian evaporites (mainly salt) was focused along regional fracture patterns resulting in the present distribution of Salina Group evaporites. Dissolution of salt was also interpreted (Sanford et al., 1985) to have created collapse features in the overlying Upper Silurian and Devonian sediments.

Research has suggested that faults and fractures played a 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 and migration of oil and gas from thermally mature sediments of the Michigan Basin is likely related to maximum burial conditions and tectonics 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) conclude on the basis of textural evidence and on fluid-inclusion data that migration was coeval with mineral formation during the late stages of burial diagenesis (late Paleozoic).

3.3 Quaternary Geology and Glaciation

The Quaternary Period represents the last two million years of geologic history. During the later half of this period the North American continent has endured nine glacial events occurring on a nominal timescale of 100,000 ka (Peltier, 2008). The resulting Quaternary sediments in the DGR study area are shown in Figure 3.15 and described in Gartner Lee Limited (2008a). The unconsolidated materials 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.

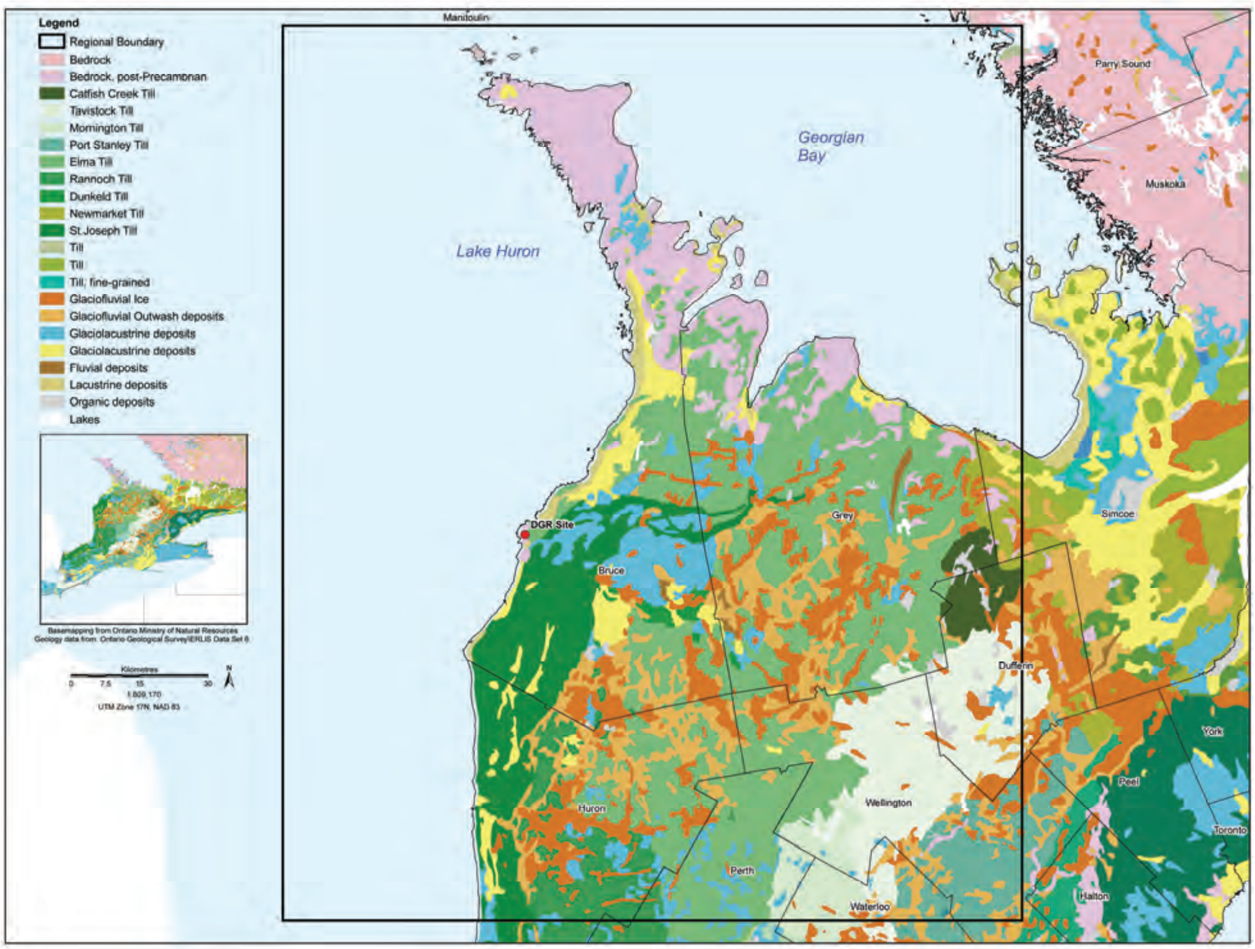

Figure 3.15 Quaternary Geology in the Regional Study Area around the DGR site.

Quaternary sediment thicknesses vary across the Bruce site from about 1 m at the lakeshore to 20 m in the southeastern part of the site. Overlying the Paleozoic rocks at the DGR-1/2 drill site are approximately 20 m of Quaternary aged sediments (Intera, 2008). These recent sediments comprise surficial glaciolacustrine sands, and sand and gravel overlying silt, fine sand and clay glacial tills. Given the shallow depth of overburden along the lake and under much of the site, combined with the small map scale, the Quaternary Geology map presented in Figure 3.15 shows the DGR site located directly on bedrock.

The past glacial events, which markedly altered the landscape and physiography of southern Ontario, created significant external perturbations on the sedimentary sequence and regional groundwater flow systems. Peltier (2008) provides a detailed account of the glacial process and a series of constrained numerical simulations using the University of Toronto Glacial Systems Model to predict future glacial conditions as they may affect the Bruce site.

The Late Pleistocene Laurentide ice sheet that developed in the Arctic and advanced over most of Canada into the United States began approximately 120 ka ago (Peltier, 2008). At last glacial maximum, approximately 20 ka ago, the Laurentide ice sheet approached 4 km in thickness over the most glaciated regions of the continent (Figure 3.16). Within the Great Lakes region, as the ice sheet retreated 14 ka ago glacial melt waters from the retreating ice filled erosional depressions that evolved into the modern day Great Lakes. The weight of the ice sheet depressed the surface of the earth by approximately 600 m (Peltier, 2008). After the ice retreated the earth's surface has rebounded. This process is known as isostacy and is still occuring today. In the Great Lakes area the continental isostacy contour represents zero with increasing up lift to the north of about 1.5 mm/a and subsidence to the south at about the same rate, thus indicating that the continent is tilting slightly upward in the north (Peltier, 2008).

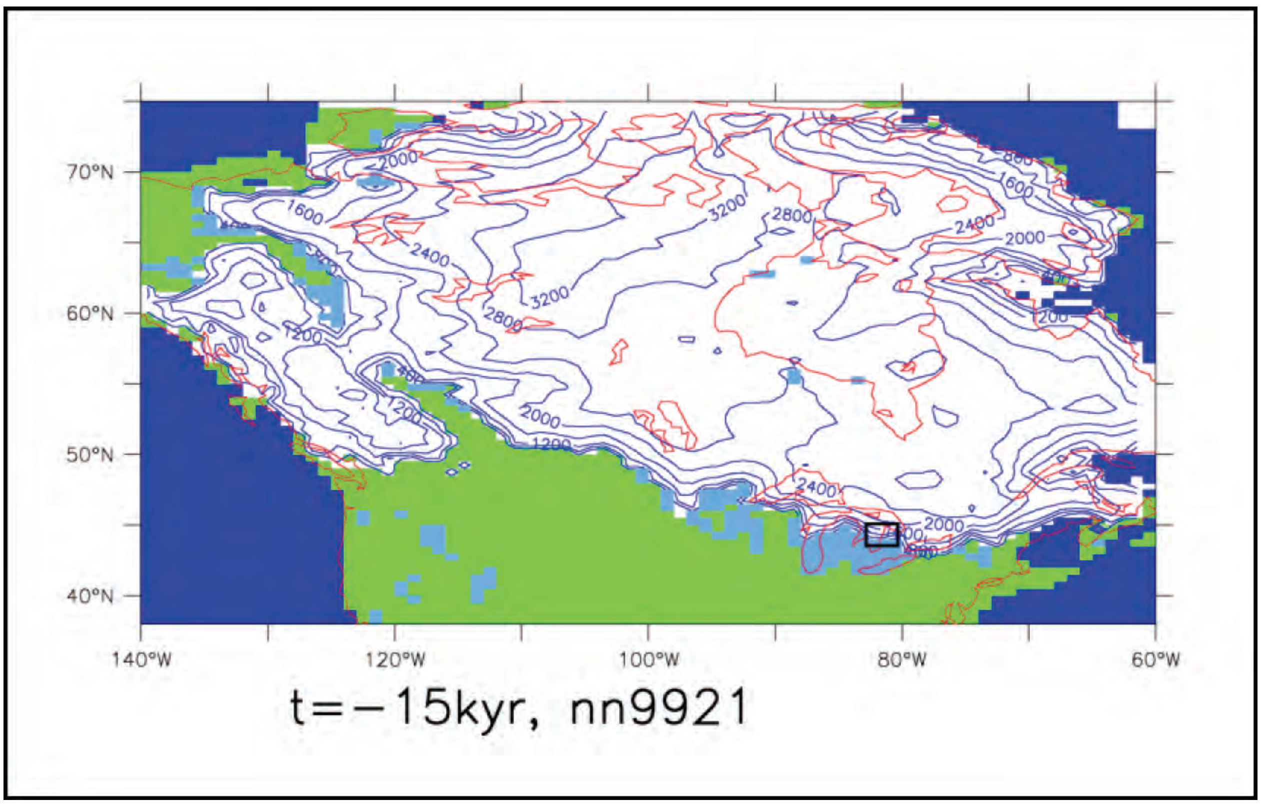

Figure 3.16 Laurentide Ice Sheet Thickness at the Glacial Maximum (from Peltier, 2008)

Evidence for the multiple glacial periods is derived, in part, from isotopic analysis of undisturbed deep-sea cores. The determination of relative concentrations of ^{16}O and ^{18}O in pore fluids at different depths within the cores yields a high resolution quality proxy for understanding continental ice-sheet volume. The lighter $\delta^{16}O$ isotope is evaporated preferentially and precipitated to build up the northern ice sheets; confirmation is obtained from ice cores collected in modern day glaciers. Another source of evidence includes relative sea level histories that provide a direct measure of the transfer between the ocean to land ice. Figure 3.17 shows the relative sea level changes over the past 120 ka based on coral evidence in the Caribbean (Peltier and Fairbanks, 2006; Peltier, 2008).

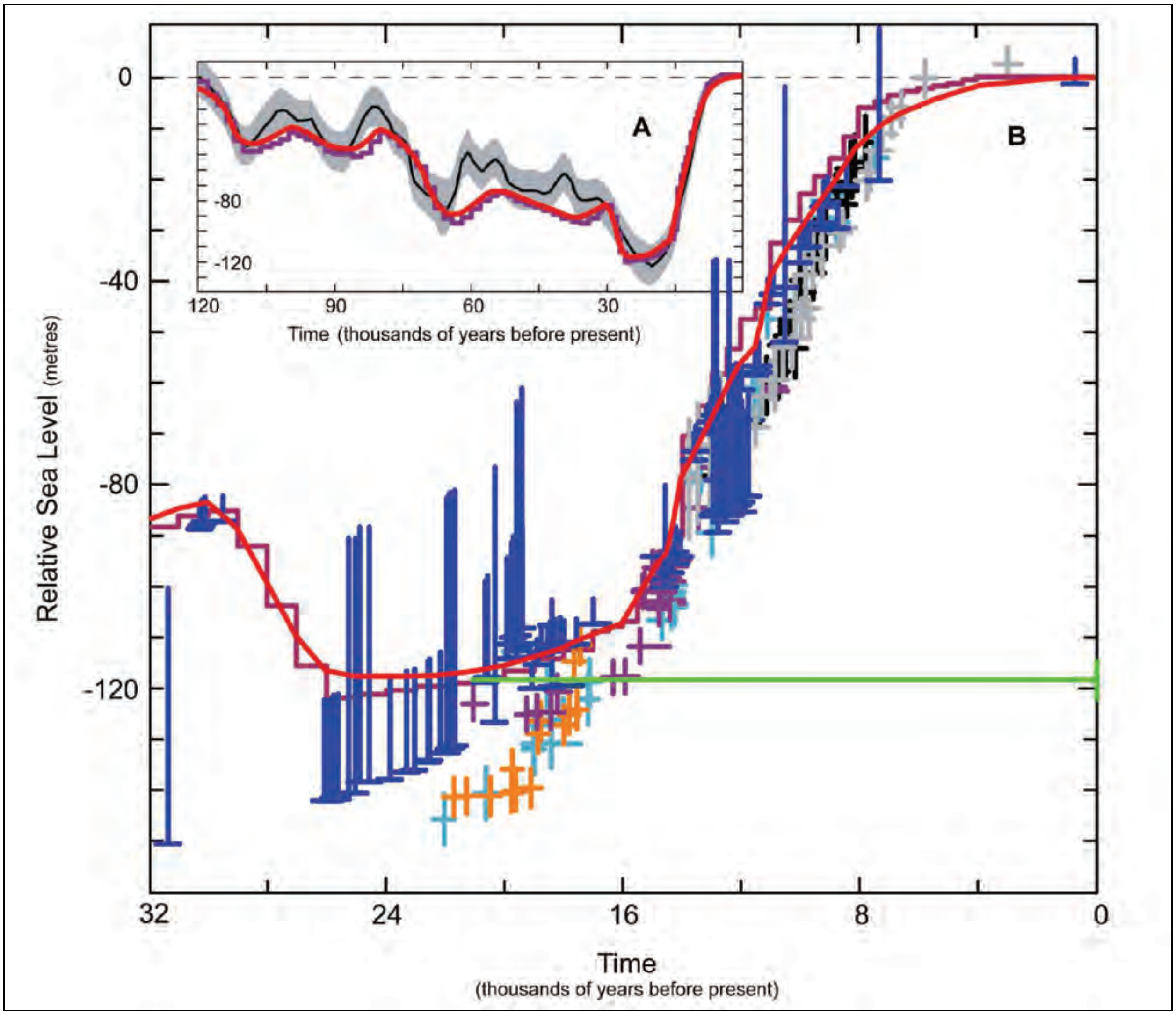

Figure 3.17 Relative sea level changes in the late Quaternary based on coral analysis in the Caribbean Sea. Red line represents ICE-5G(VM2) model predictions (Peltier, 2008)

The University of Toronto Glacial Systems Model (Peltier, 2008) was applied to simulate glacial ice-sheet and ground surface conditions at Bruce site during the last Laurentide glaciation. Among other states, GSM provided time series prediction of normal stress (ice-sheet thickness), permafrost depth, basal ice-sheet temperatures, crustal depression and uplift, and glacial meltwater production. It is evident from the simulations that three periods of glacial advance and retreat across the Bruce region occurred with maximum ice thicknesses approaching 2.5 km at last glacial maximum approximately 24 ka ago. The model has been calibrated against multiple data sets including relative sea level curves, ground surface uplift rates and radiocarbon dated ice-sheet margins during retreat to yield a series of plausible glaciation scenarios. Further discussion of the glacial scenario is provided in section 6.3.3.7 on explicitly coupling the GSM results to transient simulations of groundwater system response and perturbation to glacial events. It is noteworthy, that the accumulation of greenhouse gases in the atmosphere has created uncertainty with respect to the timing of the next glacial onset. Regardless, the GSM predictions provide a conservative basis to understand glacial induced perturbations on the repository and groundwater system necessary to demonstrate repository safety.

3.4 Economic Geology

Natural economic geological resources in the Bruce area fall into two broad categories: petroleum resources and industrial minerals. Commercial petroleum production is almost exclusively located in Essex, Kent, Lambton and Elgin counties (OGSR, 2004). Industrial minerals referred to in this report include aggregate resources (sand and gravel, and rock) and salt. Aggregate resources are widely distributed and are exploited close to the need, whereas the salt resources are mined further to the south (Goderich and Windsor) where the resources are commercial.

3.4.1 Petroleum Resources

The Paleozoic formations of southwestern Ontario locally contain commercially viable oil and gas deposits. The genesis of these deposits is not fully known (Gartner Lee Limited, 2008a), however, it is thought that the hydrocarbons migrated to southern Ontario from deeper in the basin via porous dolomitized zones or faults and fractures. Notwithstanding the uncertainty of the origin of these deposits, it is known that they have been in place for hundreds of millions of years confined by the extremely low permeability overlying cap rocks.

Crude oil and natural gas in Ontario have been discovered in commercial quantities in a total of over 300 separate pools or reservoirs, primarily located in southwestern Ontario. Figure 3.18 illustrates the distribution of oil and gas pools within the regional study area (RSA). No documented commercially crude oil and natural gas extraction is currently identified within a 40 km radius of proposed Deep Geologic Repository (OGSR, 2004).

Historical exploration data indicates that 12 small pools were documented within the boundaries of the Regional Study Area (RSA) (Gartner Lee Limited, 2008a). 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. 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 (OGSR, 2006).

Recent exploration in the Bruce area has found no commercially viable pools. In addition, the DGR boreholes confirmed the results from Texaco #6 some 3 km distant that there are no significant oil or gas shows in the Paleozoic sequence at the Bruce site. From an evaluation of existing literature (Gartner Lee Limited, 2008a), the probability of future identification of potential economic oil and/or gas resources adjacent the proposed DGR site is low.

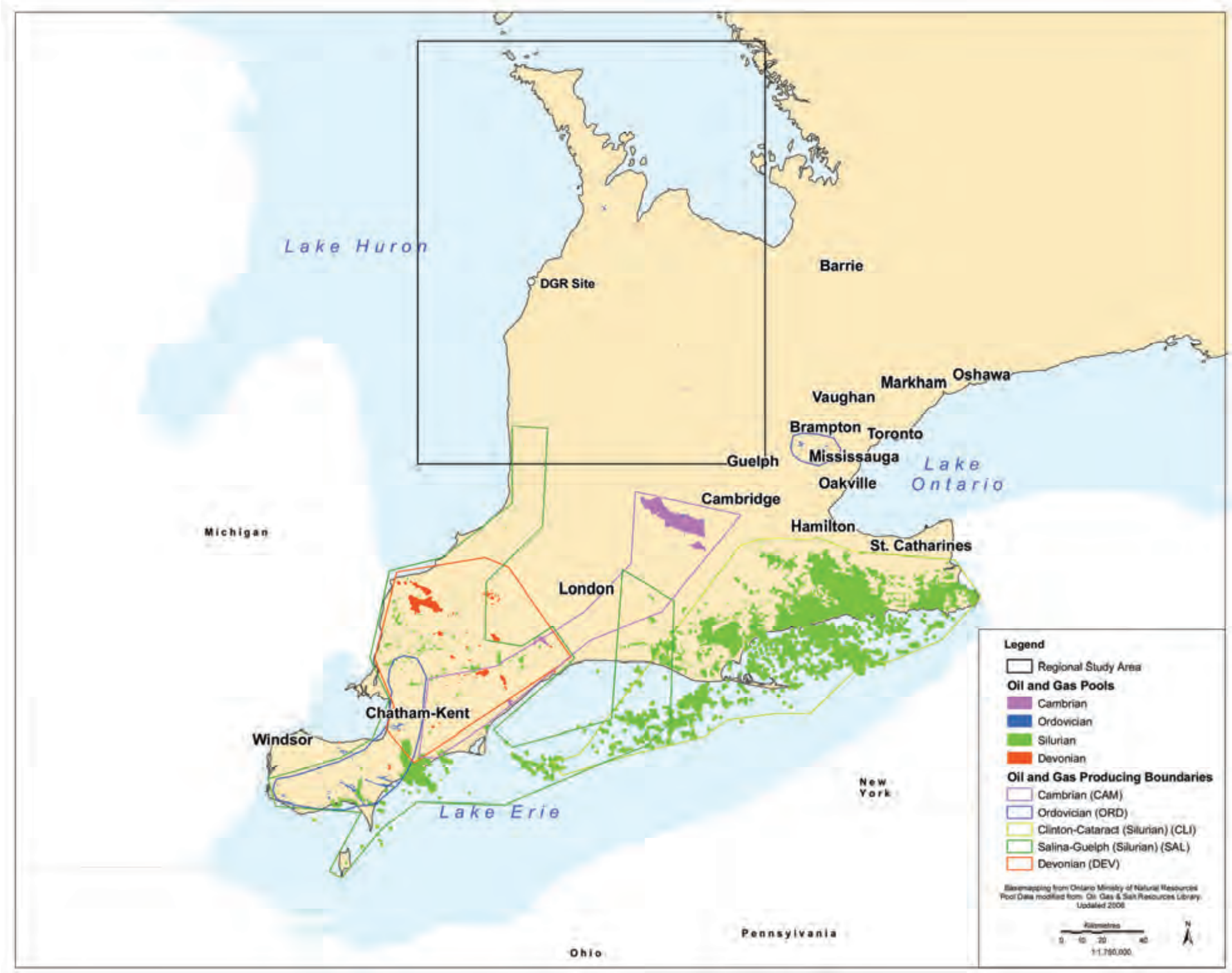

Figure 3.18 Map Showing Oil, Natural Gas and Natural Gas Storage Pools in Southern Ontario approximate boundaries of Principal Oil and Gas producers (past and present) in Southern Ontario (modified from Oil, Gas and Salt Resources Library data, 2004 and Carter, T.R., (ed) 1990).

3.4.2 Industrial Minerals

The Regional Geology Report (Gartner Lee Limited, 2008a) a companion report to this Geosynthesis summarizes the aggregate resources of the Bruce area. These resources comprise sand and gravel from glacial outwash and esker deposits. Near the DGR, thin beds of beach sand or sand and gravel occur parallel to the Lake Huron shore as low elongate 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 (OGSR, 2004).

Many of the Paleozoic rocks identified at the Bruce site have been exploited elsewhere in Ontario for their aggregate potential, for landscaping rock, and brick manufacture. Generally for these industries to be economic the rock source must be close to the surface, less than 8 m and be of mineable thickness. Therefore most of the rock aggregate is extracted in quarries along the Niagara Escarpment or areas of shallow overburden in Bruce County. The DGR site is considered to have a low aggregate resource extraction potential.

The upper Silurian Salina Formation is characterized by dolomite, shale, gypsum and salt. Salt from this formation 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 naturally dissolved and removed over most of the RSA and beneath the DGR site where the Salina Formation is typically represented by anhydrite deposits.

3.5 Summary

The synthesis of geological information, as presented in the Regional Geology Supporting Technical Report (Gartner Lee Limited, 2008a) and summarized here, suggests:

a) In southern Ontario the Paleozoic stratigraphy is generally 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 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 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, an assessment supported by the low level of seismicity in the Bruce Megablock.

c) The geology encountered in boreholes DGR- and DGR-2 drilled at the site is consistent with the regional geology as described in this report and presented in the Three Dimensional Geological Framework (Section 3.2.3). 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.

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 and DGR-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.

4. REGIONAL GEOMECHANICS REVIEW

4.1 Introduction

This section provides a regional overview and summary of the geomechanical properties of the Paleozoic sedimentary formations occurring beneath the Bruce site and or relevance to the DGR concept (Gartner Lee Limited, 2008a). A key purpose is to document existing geomechanical knowledge and construction experience as it relates to regional joint set patterns, material properties, regional ground stress distribution and seismicity. Where possible the regional data sets are compared with interim site-specific data gathered during Phase I site characterization activities at Bruce site. Further, the results of analyses to assess long-term cavern stability and DGR performance at time frames of 100 ka are presented (Itasca, 2008).

4.2 Regional Joint Set System

There are consistent sets of joints observed at outcrops of the Precambrian, Ordovician, Silurian and Devonian rocks located across southern Ontario. Mapping has demonstrated that at any one location there may be one or two major and minor joint sets. Up to five distinct sets are found in some locations. Figure 4.1 shows a compilation of joint orientations taken from Andjelkovic et al., 1997; Gartner Lee Limited, 1996; Holst, 1982, among others, from across southern Ontario and the Great Lake States. It is based on data from many authors, comprised of measurements taken on surficial joints on bedrock exposures in quarries and at outcrops. Most jointing is vertical to near vertical within the studied area sedimentary sequence. There are also many subvertical joints (or those that are inclined from the vertical) that occur when the sedimentary sequence is draped over irregular basement structures of the underlying Precambrian Shield.

4.2.1 Joint Orientation

In determining patterns that might be useful in predicting what may lie below the Bruce site, the orientation of vertical joints has been examined on a formational and geographic basis. Table 4.1 has been compiled from all sources for southern Ontario, Michigan, Ohio and New York states. It provides a general understanding of regional joint orientation relative to the sedimentary sequence. This table has been compiled from surficial joint sets and does not necessarily imply that these joint sets will be consistent with depth at any one location.

In Table 4.2, the data have been compiled geographically from the same sources of surficial joint sets for southern Ontario as Table 4.1 above. Examination of this table reveals several key patterns. Of most interest is the fact that the SE joint orientation is consistent across Ontario, New York, Ohio and Michigan. In most places it is a major set, regardless of formation. A second pattern that is apparent in Table 4.2, is that southern Michigan, New York and Ohio closely resemble the patterns seen in Ontario. Compilation of the joint data in Figure 4.1 reveals that jointing in the Cambrian to Mississipian Formations in northern Michigan appears to have a slight rotation of 15^{o} counter clockwise (Gartner Lee Limited, 2008b). This is shared by the Silurian rocks on Manitoulin Island based on Holst (1982).

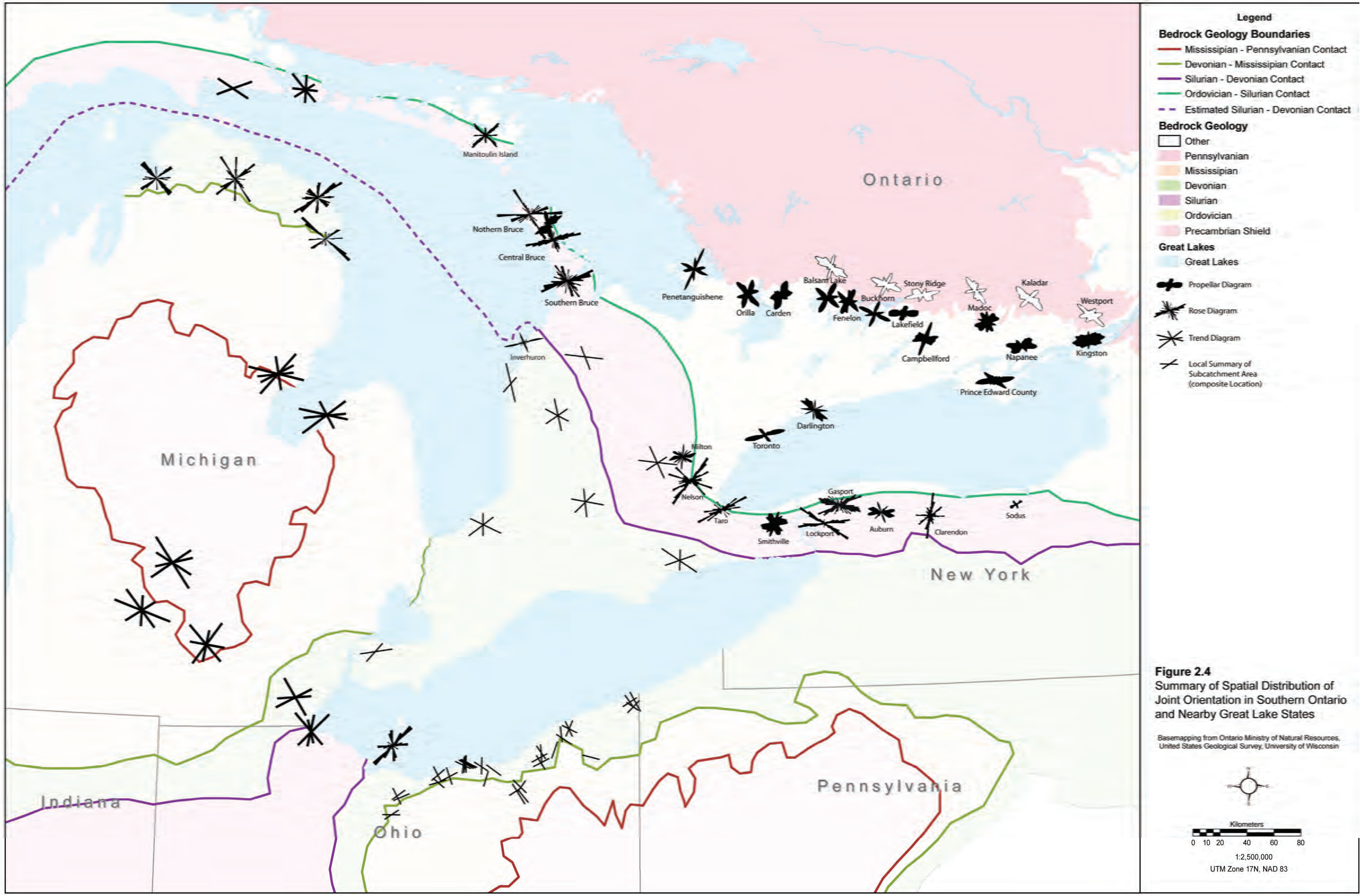

Figure 4.1 Summary of Spatial Joint Orientation in Southern Ontario and nearby Great Lake States (Gartner Lee Limited 2008b).

Table 4.1 Major Joint Orientation by Formation in Ontario (Gartner Lee Limited, 2008b)

Age	Location	N-S	NNE	NE	ENE	E-W	ESE	SE	SSE	Reference
Precambrian	Ontario	m	**M**	m	**M**		**M**	**M**		1, 2, 3 and 11
Cambrian	Ontario		m	**M**		m		**M**		1, 2, 3 and 11
	Michigan Basin	m		**M**		m		**M**		7 and 8
Ordovician	South of Canadian Shield	m	**M**		**M**			**M**		1,2 and
	Lake Ontario north shore	m			**M**			**M**		1,2, and 13
	Michigan Basin	m		**M**		m		**M**		8
Silurian	New York				**M**		**M**	m	m	6
	Ontario (Niagara)		**M**		**M**			m	**M**	6 and 5
	Milton		**M**		**M**		m			
	Bruce Peninsula				**M**				**M**	
	Manitoulin Island	m		**M**		**M**		**M**		8
	Michigan Basin	m		**M**		m		**M**		8 and 12
Devonian	Ontario			**M**	m		**M**		**M**	4
	Inverhuron				**M**				**M**	14
	Michigan Basin	m		**M**		**M**		**M**		8,9 and 12
	Ohio						m	**M**	m	10
Mississippian	Michigan Basin	m		**M**				**M**		14
Pennsylvanian	Michigan Basin		**M**	m	m		**M**	**M**		14

Notes: ***M** = Major joint set*
m = Minor joint set

Table 4.2 Major Joint Orientation by Location in Ontario (Gartner Lee Limited, 2008b)

Location	Area	Age	N-S	NNE	NE	ENE	E-W	ESE	SE	SSE	Reference
Ontario	Precambrian-Palaeozoic contact	Precambrian	m	**M**	m	**M**		**M**	**M**		1, 2, 3 and 11
	South of Canadian Shield	Cambrian		m	**M**		m		**M**		1,2,3 and 11
	South of Canadian Shield	Ordovician	m	**M**		**M**			**M**		1,2 and 14
	Lake Ontario north shore	Ordovician	m			**M**			**M**		1,2, and 13
	Niagara	Silurian		**M**		**M**			m	**M**	5 and 6
	Milton	Silurian		**M**		**M**		m			14
	Bruce Peninsula	Silurian				**M**				**M**	14
	Manitoulin Island	Silurian	m		**M**		**M**		**M**		8
	Inverhuron	Devonian				**M**				**M**	14
	Southwestern Ontario subcatchments	Devonian			**M**	m		**M**		**M**	4
Michigan Basin	Northern Michigan Basin	Cambrian	m		**M**		m		**M**		7 and 8
	Northern Michigan Basin	Ordovician	m		**M**		m		**M**		8 and 9
	Northern Michigan Basin	Silurian	m		**M**		m		**M**		8, 9 and 12
	Northern Michigan Basin	Devonian	m		**M**		**M**		**M**		8,9 and 12
	Southern Michigan Basin and Saginaw Bay	Mississippian	m		**M**				**M**		12
	Southern Michigan Basin	Pennsylvanian		**M**	m	m		**M**	**M**		12
New York	South of Lake Ontario	Silurian				**M**		**M**	m	m	6
Ohio	South of Lake Erie	Devonian						m	**M**	m	10

Notes: ***M** = Major joint set* *References: Same as for Table 2.1*
m = Minor joint set

4.2.2 Jointing in DGR Host and Barrier Formations

The orientations of joints measured along and to the south of the contact of middle Ordovician rocks and the Precambrian, show three major sets trending NNE, ENE and SE with minor sets striking ESE and N-S (Andjelkovic *et al.,* 1997). The measurements along the northern shores of Lake Ontario show the prominence of the ENE and SE sets. Again the pattern persists with the SE set being a major set, but in this case accompanied by a stronger presence of the ENE and NE sets.

The Ordovician rocks of the northern Michigan Basin show four sets. Similar to the Cambrian to the north, the major sets are NE and SE, and the minor sets are NS and EW. This differs on a consistent basis from the orientation to the east in Ontario. Figure 4.2 is a histogram of the Michigan Ordovician joint sets derived from the available data in the literature. The equivalent joint sets from Ontario have been shown for comparison. As described in the previous section, there appears to be a 15^{o} clockwise rotation in at least three sets. The major NE set in Michigan is oriented ENE in Ontario. The minor EW set in Michigan is oriented in ESE in Ontario and is a major set there. The minor NS in Michigan is oriented NNE in Ontario and is also a major set.

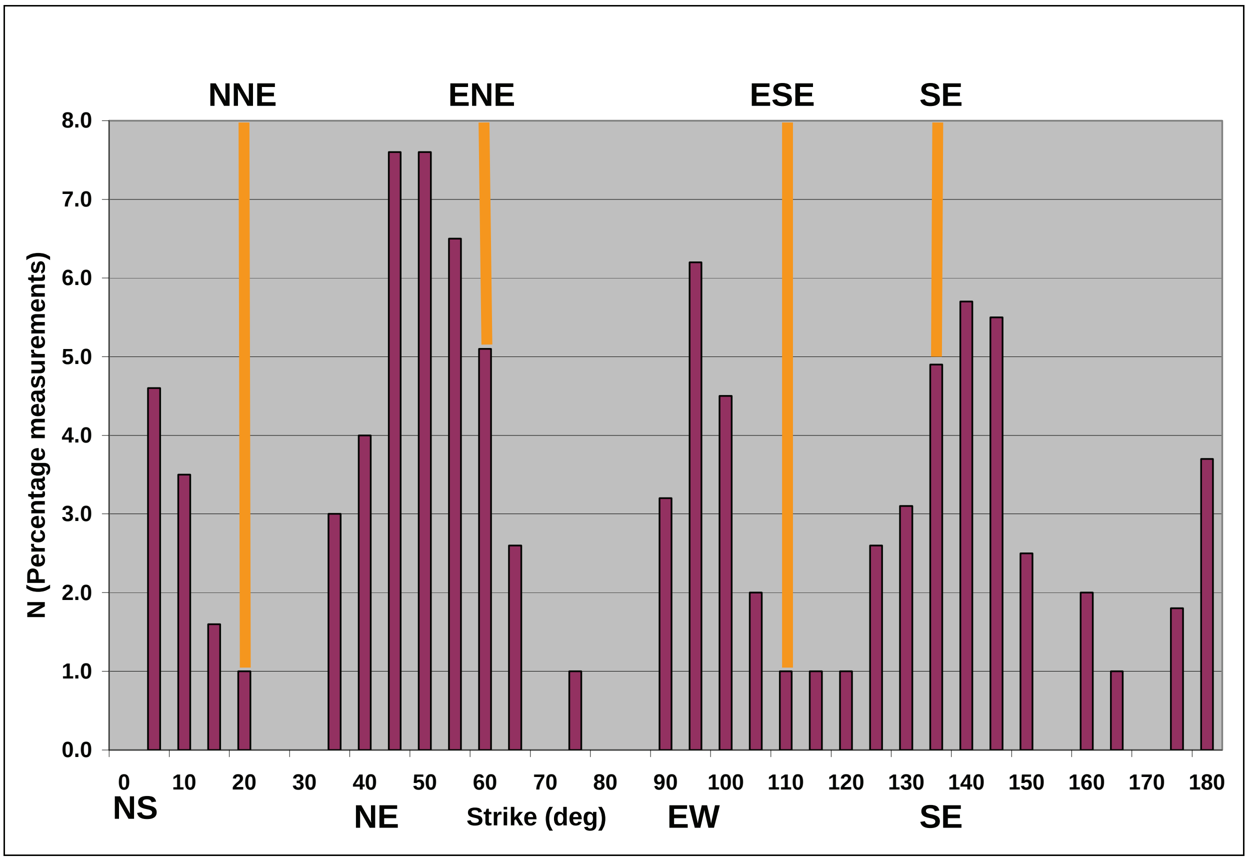

Figure 4.2 Comparison of Joint Orientations in Michigan (histogram) and Ontario (yellow). Major sets labelled in black and minor set in grey (Gartner Lee Limited, 2008b).

4.2.3 Joint Distribution with Depth

Several studies have examined joint distribution with depth, either in shallow quarry excavations, or in borehole logs. Hill, *et al.* (2002) examined the Devonian shales in New York in three boreholes extending to 1,171 m in depth. Their data indicates a consistent EW joint set ranging from ENE to ESE in the upper 300 m. At greater depth, the NE-ENE trend became more consistent. A SSE set was present below 760 m. In general, the NE-ENE was present across all depths, but other minor joint directions showed no discernable pattern.

Four major sub-vertical joint sets have been mapped at 142 outcrop sites situated on the northern Michigan Basin rim. As described by Holst (1982), the orientation of these joint sets appears consistent regardless of bedrock formation age. It was observed in the deep boreholes at Darlington Generating Station (where the ENE joint set persists throughout the Paleozoic sequence and into the Precambrian; Semec, 1978 and 1985), as well as by Engelder (1982) on the jointing of western New York State. On the other hand, Cruden and Usher (Gartner Lee Limited, 1996) found that within the Silurian on the Niagara Escarpment that there was a subtle joint orientation shift with depth.

4.3 Geomechanical Properties: Rock Strength and Deformation

An understanding of the geomechanical properties of rock is necessary to allow the prediction of the current and long-term behaviour of the proposed facility. As part of the site characterization work (Intera, 2006), information regarding the in-situ and regional geomechanical properties of the sedimentary formations which host the DGR was assembled and reviewed. This information was integrated with the regional data (Gartner Lee Limited, 2008b, 2008) to establish preliminary input parameters for conceptual engineering analyses of the DGR facility. The data will also serve as a supplementary data set for the ongoing site-specific field and laboratory investigations.

The regional data comprise over 700 test results from 29 sites as described in the public domain literature and laboratory reports (Gartner Lee Limited, 2008b). The database contains a wide range of information on bedrock formations of interest to the DGR project ranging in age from Devonian to Ordovician. Except for southwestern Ontario OPG sites and an anonymous site south of the Bruce facility, all sites are located along the shore or in the vicinity of Lake Ontario. The following paragraphs are mainly focused on the DGR host rock, the Cobourg argillaceous limestone of middle Ordovician age (Trenton Group). Only brief descriptions of the overlying rocks are included. Table 4.3 summarizes the general geomechanical properties of the formations overlying the Trent group formations. Although the following discussion focuses on the intact rock strength obtained from uniaxial compressive tests, the table also presents the elastic modulus, Poisson’s ratio, and tensile test results where data exist. Results on other types of testing, such as triaxial tests, cross anisotropic tests, free and semi-confined swelling test and long-term strength degradation tests, are documented in Gartner Lee Limited, (2008b).

For the upper *Ordovician shale* barrier layers, for which the greatest number of test results exists, both the Queenston and Georgian Bay shales show moderate strength with estimated mean values of 44 MPa and 35 MPa, respectively. Figure 4.3 shows histograms of the UCS data for both the Queenston Shale and Georgian Bay Shale. The outliers in the Georgian Bay data likely represent test results from carbonate, siltstone, and sandstone interbeds in the Georgian Bay Formation (“hardlayers”). The mean UCS of the Georgian Bay shale could reduce to 23 MPa if the test results of the hardlayers are excluded. The majority of the test data for the Georgian Bay Shale are from published sources whereas that of Queenston Shale were mainly obtained from OPG studies on the Niagara Tunnel Development Project.

Table 4.3 Summary of Geomechanical Properties of Rock Units Overlying the Trenton Group (Gartner Lee Limited, 2008b)

Rock Formation		UCS (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio
Amherstburg Dolostone	Mean	63 (4)		27 (6)	
	Range	33 – 113		8 – 40	
Amherstburg Limestone	Mean	74 (9)		31 (11)	
	Range	23 – 182		12 – 66	
Eramosa	Mean	118		63	0.4
Goat Island	Mean	210 (10)		67 (6)	0.3 (6)
	Range	137 – 282		58 – 81	0.2 – 0.4
Gasport	Mean	142 (26)		57 (12)	0.3 (13)
	Range	27 – 255		25 – 70	0.1 – 0.5
Decew	Mean	107 (5)	5	54 (5)	0.4 (4)
	Range	74 – 174		43 – 57	0.3 – 0.4
Irondequoit	Mean	105 (11)		60 (11)	0.4 (11)
	Range	60 – 185		50 – 78	0.1 – 0.5
Reynales	Mean	107 (13)		33 (11)	0.4 (3)
	Range	53 – 141		22 – 49	0.2 – 0.5
Cabot Head	Mean	73 (7)	9 (22)		
	Range	20 – 127	5 – 14		
Queenston	Mean	44 (50)	10 (4)	15 (47)	0.4 (48)
	Range	12 – 118	1 – 15	7 – 34	0.1 – 0.5
Georgian Bay	Mean	35 (63)		9 (49)	0.3 (39)
	Range	3 – 206		1 – 58	0.1 – 0.5

Note: (n) = number of data

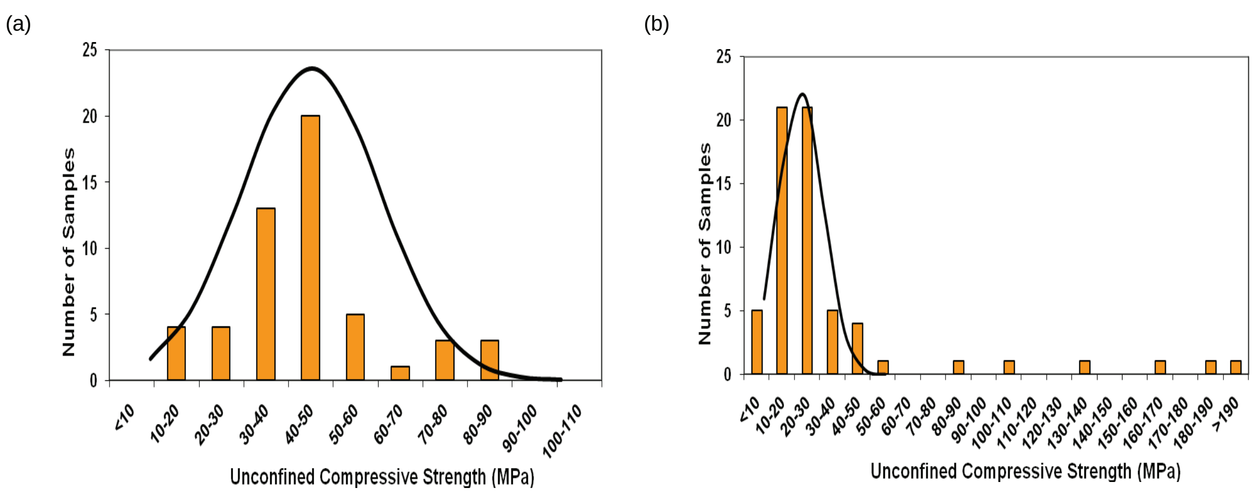

Figure 4.3 Unconfined Compressive Strength of; (a) Queenston and (b) Georgian Bay Shales (Gartner Lee Limited, 2008b)

For strength determination of the Cobourg Formation (which is an argillaceous limestone), results from 94 samples subjected to uniaxial compressive loading were used. These specimens were retrieved from sites at Mississauga, Pickering, Bowmanville, Wesleyville and

Port Hope, Ontario. Despite a large data range from 22 to 140 MPa, a well-defined distribution of strength measurements is shown on Figure 4.4. The large range in data is likely attributed to rock composition variations between sampling sites, as well as the different sample preparation and testing arrangements. The arithmetic mean of the uniaxial compressive strengths is 72 MPa. Figure 4.5 also illustrates a histogram of the corresponding elastic modulus of the limestone. It has a mean elastic modulus of 31.5 GPa.

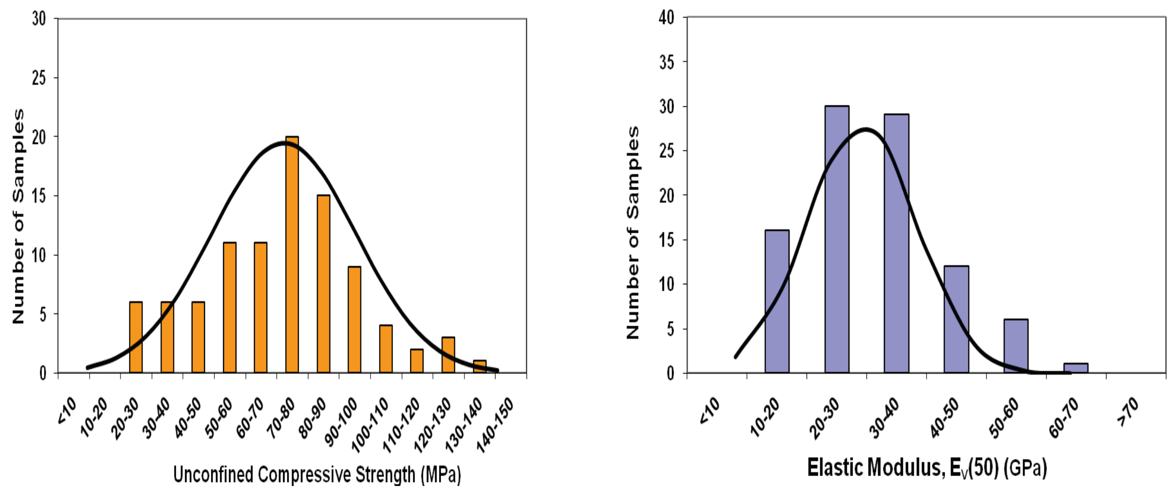

Figure 4.4 Unconfined Compressive Strength and Elastic Modulus of the Cobourg Formation (Gartner Lee Limited, 2008b)

The drilling of DGR-1 and DGR-2 at Bruce site provides an opportunity to further characterize the rock formations. The results of uniaxial compression testing and the corresponding elastic modulus and Poisson's ratios on samples obtained from these holes down to about 750 m depth are shown in Figure 4.5 (Intera, 2008b). Also shown on Figure 4.5 are results of the Brazilian or split tension tests and the dynamic deformation parameters determined from retrieved samples.

The strength of the intact rock from DGR drill holes generally lies within the data range of those compiled from the regional study except for the Cobourg Limestone where site specific results showed a stronger rock. Figure 4.6 shows a comparison between the UCS of the Cobourg host rock determined on samples from DGR-2 (Intera, 2008b) and those from the regional study. The plot reveals that the average strength value is considerably higher than the average UCS of 72 MPa. This strength increase is favourable for stability of deep underground excavations.

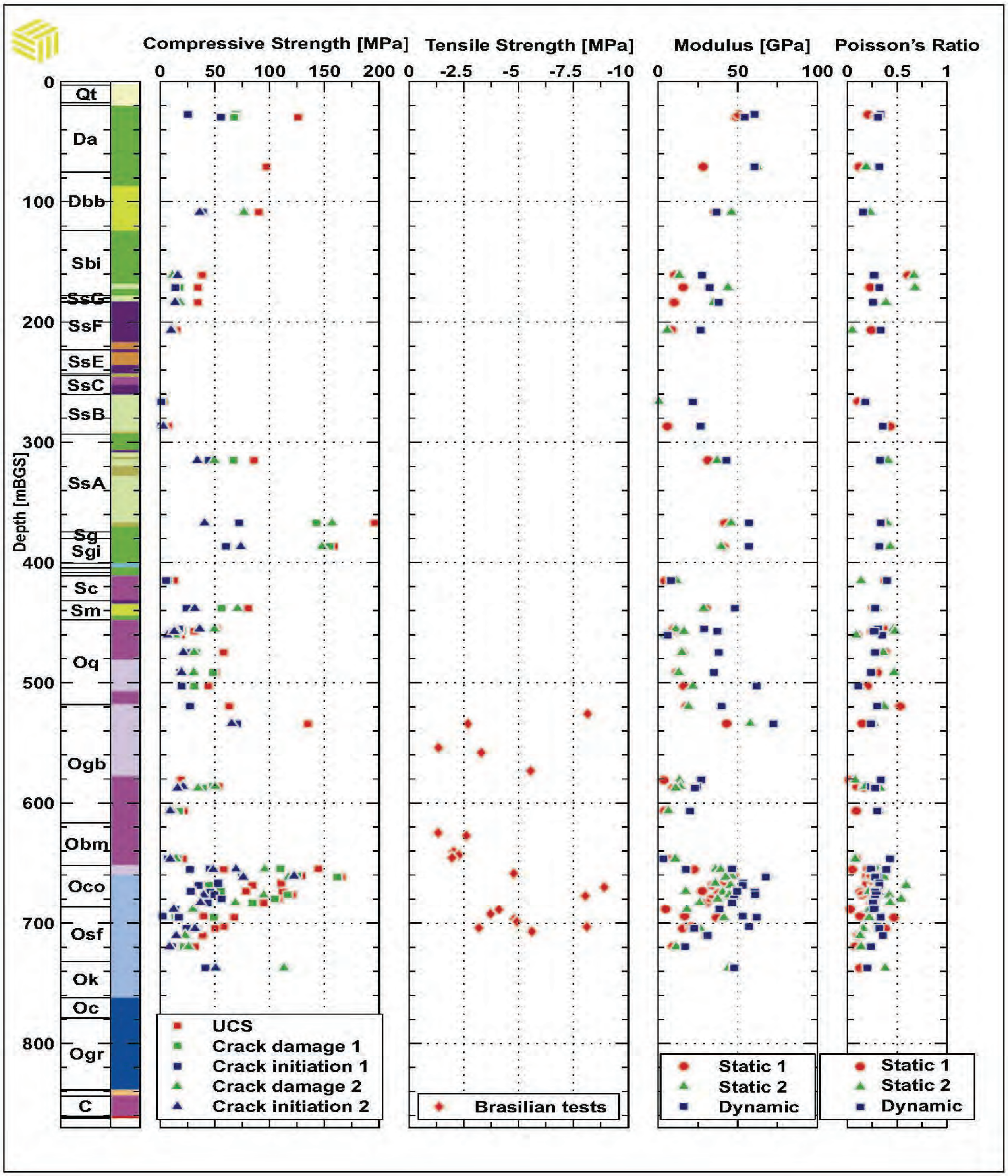

Figure 4.5 Strength and Elastic Properties measured on DGR-1 and DGR-2 Cores (Intera, 2008b)

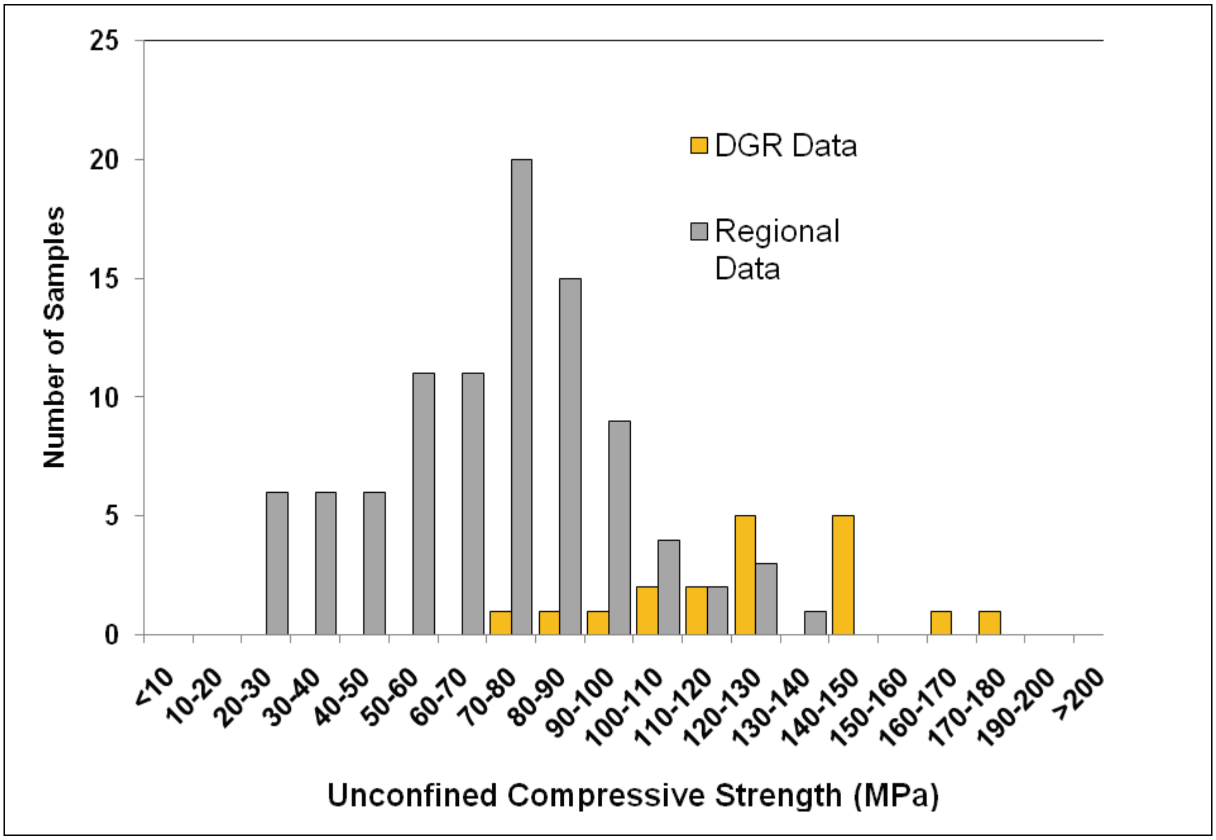

Figure 4.6 UCS Measurements from DGR-2 (Intera 2008b) and Regional data (Gartner Lee Limited, 2008b)

4.4 Geomechanical Properties: In-situ Stresses

Most of the available in-situ stress data in Paleozoic rock (Gartner Lee Limited, 2008b) have been obtained from over 20 sites in the Great Lake region. Figure 4.7 shows a plot of the maximum and minimum horizontal stresses (σ_H & σ_h) as a function of depth. The diamond symbol indicates the magnitude of the maximum stress at a given horizon and the square symbol corresponds to the minimum horizontal stress. The coloured symbols represent measurements from hydraulic fracturing tests, whereas the open symbol represent results obtained from overcoring tests. The stress measurements for shallow bedrock were made using the overcoring method while virtually all of the deeper measurements were conducted using the hydrofracture technique. Except for Norton Mine in Ohio, measurements at about the 700 m level (Bauer et al., 2005), the overcoring stress measurements are limited to the upper 100 m depth. There is a large scatter in both hydraulic fracture and overcoring measurements, particularly in the shallow zone above 200 m and in the deeper zone below 700 m from these many sites. Haimson (1982, 1978a-c) and Evans et al. (1989) conducted several studies on in situ stress measurement at various sites in the Appalachian and Michigan basins using the hydraulic fracturing technique. The bulk of these measurements were from Ordovician and Silurian limestone, dolostone and shale to a depth of approximately 1000 m. One of these studies (Haimson, 1978a) was conducted in the deepest sedimentary rock formations located in the Michigan Basin, providing stress measurements to a depth of about 5,100 m.

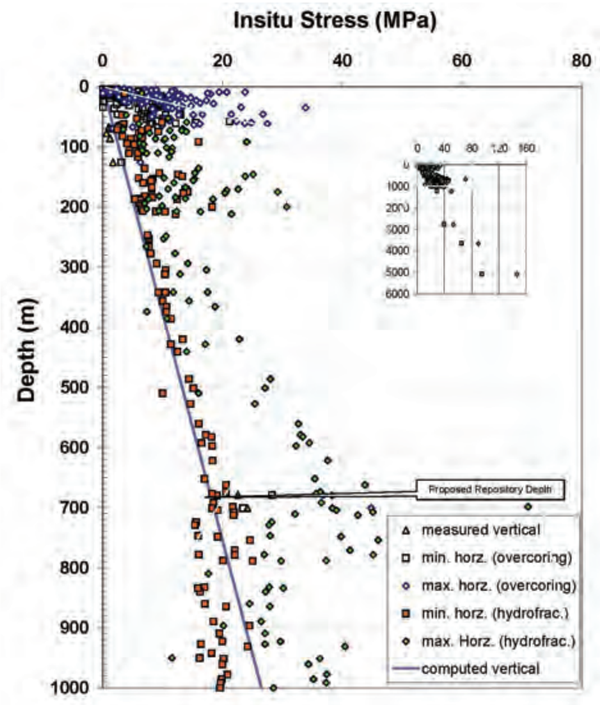

Figure 4.7 Distribution of principal stress with depth in the Appalachian and Michigan Basin. Included are both hydro-fracturing and overcoring results (Gartner Lee Limited, 2008b)

4.4.1 In-situ Stress Magnitude

As described above, there are only a few deep boreholes with in-situ stress measurements drilled within a few hundred kilometres of the Bruce site. One of these is at Darlington GS in Bowmanville, southern Ontario, where a deep vertical borehole (UN-1) was drilled into Precambrian basement (Semec, 1978). A total of ten measurements were conducted to determine the state of in situ stress using the hydraulic fracturing method (Haimson, 1978b). Six of these were completed in the Ordovician limestone between 45 and 208 m depth and four others in the Precambrian gneissic bedrock between 228 and 300 m depth. Based on these measurements, the **minimum horizontal stresses**, σ_h, vary between 8.3 and 9.5 MPa within the Ordovician Formations (75 – 208 m). The stress increases by about 20% and stays within a narrow range of 10.5 MPa to 11.3 MPa in the Precambrian basement. The **maximum horizontal stress**, $\sigma_{H,}$ for the two rock types was determined to vary between 10.6 MPa and 15.4 MPa in the Ordovician rock and between 17.2 MPa and 19.6 MPa in shield rock (Haimson and Lee, 1980).

In situ stress measurements were conducted recently at the Norton Mine, slightly west of Akron, Ohio, by means of the overcoring method at a depth of about 700 m (Bauer *et al.,* 2005). This study yielded average maximum and minimum horizontal stresses of 36.7 MPa and 28 MPa, respectively. A higher maximum horizontal stress was measured using the same method (σ_H = 44.7 MPa and σ_h = 23.4 MPa) at the southern portion of the mine in a 1960's study (Obert, 1962). The stress value is consistent with earlier hydraulic fracturing measurements (Bauer et al., 2005), where an average σ_H of 44.6 MPa and σ_h of 23.2 MPa were reported for the southern portion of the mine.

Analysis of the supporting data and calculated stress ratios allow an estimation of the approximate range in stress ratios at repository depth at the Bruce site. This has been done over the interval of 650 to 715 m bracketed evenly around the 680 m repository depth. At the repository horizon σ_H / σ_v will likely vary from 1.7 to 2.5; σ_h / σ_v from 1.0 to 1.2; and $\boldsymbol{\sigma_H / \sigma_h}$ from 1.5 to 2.1 (Gartner Lee Limited, 2008b). The scatter in data at these depths is observed in Figure 4.7. The variability of results from these depths is attributed to the fact that these results are taken from sites from across the study area and in different lithological strata.

4.4.2 Orientation

In general, the current in situ stress regime in the Appalachian and Michigan basins is oriented in an ENE direction and is similar to that in the North American continent as defined in the world Stress Map (Figure 4.8). This stress regime is most likely the result of continental drift. This direction also is consistent with the stress orientation measurements within the Ordovician limestone in a deep borehole at the Darlington Generation Station (N70°E; Haimson and Lee, 1980) and recent measurements at 670 m depth in the Norton Mine at the southwest tip of Appalachian Basin (N75°E; Bauer *et al.,* 2005).

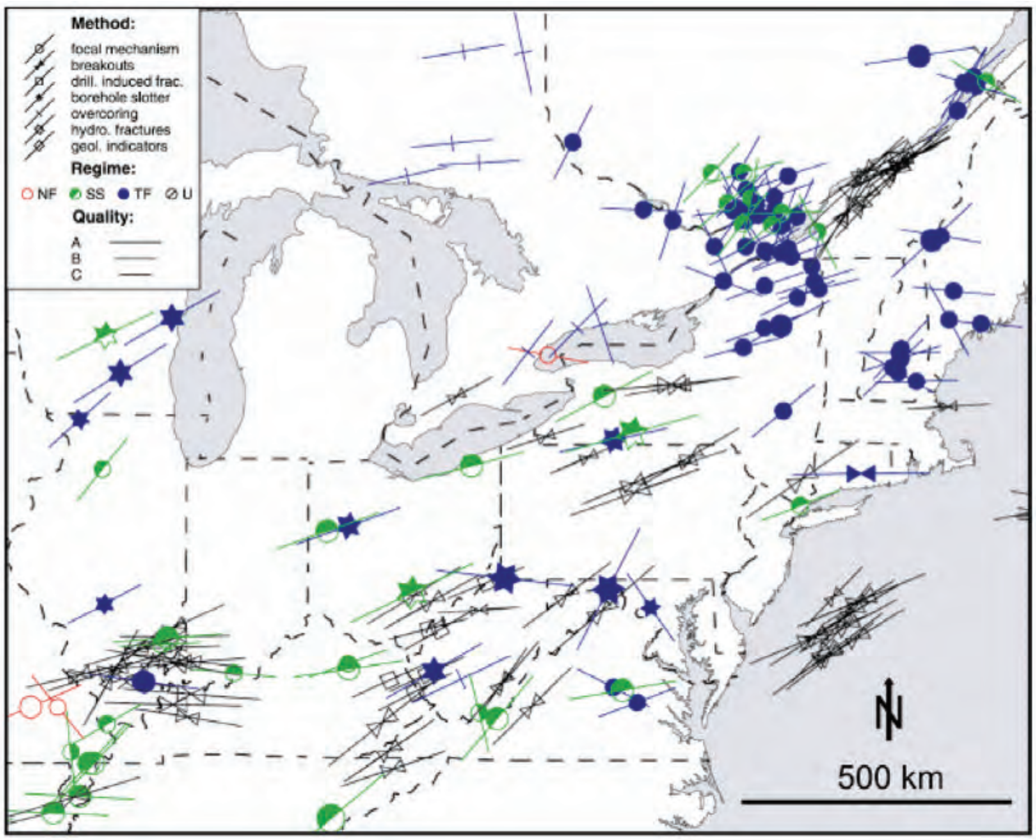

Figure 4.8 Stress map of greater study area, based on Reinecker et al., 2004, as reproduced from Mazurek, 2004. NF = normal fault regime, SS = strike-slip regime, TF = thrust fault regime, and U= regime unknown

Currently, there is a lack of site specific information on in situ stresses. Only one set of overcoring stress measurements was carried out in the Amherstburg and Bois Blanc Formations between 41 and 62 m at Bruce site (Figure 4.9) in 1989 (McKay and Williams, 1990). The in situ stress data that has been assumed in conceptual engineering is based on far-field measurements within the Michigan and Appalachian basins (Gartner Lee Limited, 2008b). There are also severe limitations and uncertainties associated with carrying out accurate in situ stress measurements in deep boreholes (Martin et al., 2001 and Martin, 2007). In situ stress estimation relying on bounding limits obtained from the observations of core disking, borehole breakouts and spalling in DGR1 and DGR2 was carried out (Intera, 2008). This approach (Valley and Evan, 2007) provides valuable information on the stress regime at the site. Figure 4.9 shows the consistency between results obtained from previous stress measurements in the Salina Formation, stress characterization results of DGR1 and DGR2 and the σ_H/σ_v stress ratio profile established based on far-field regional data using the moving median technique.

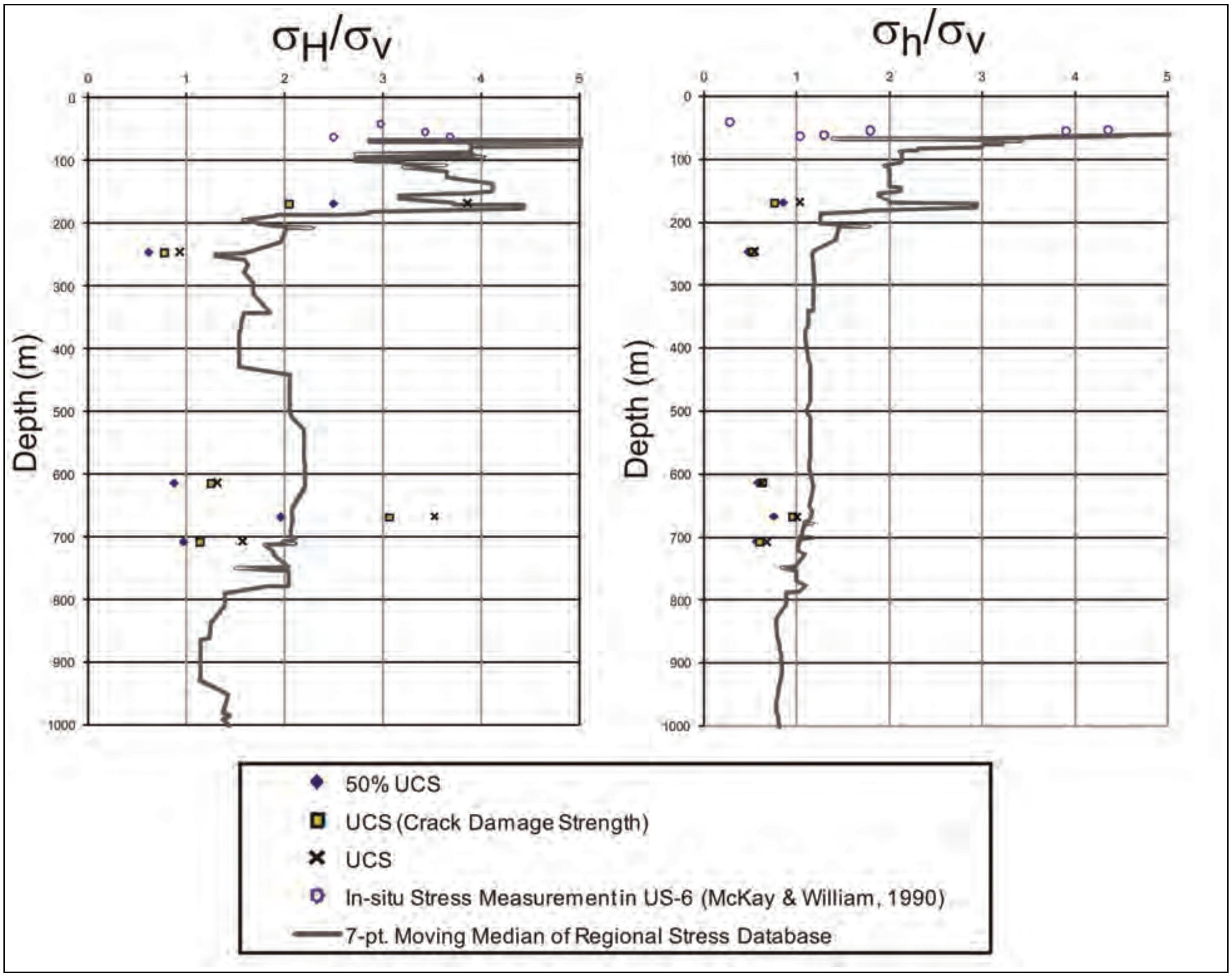

Figure 4.9 Comparison of stress constraints and overcoring stress measurements at the Bruce Site with regional data. Grey solid line is the moving median in-situ stress ratio derived from regional data at 20 sites (Gartner Lee Limited, 2008b).

4.5 Regional Seismicity

Southwestern Ontario and the Bruce region lie within the tectonically stable interior of the North American continent, which is characterized by low rates of seismicity. All recorded events in the

Bruce region have magnitude less than 5. Magnitude in this report is presented on the moment magnitude scale, **M**, which is similar to the Richter magnitude, but a more direct indication of earthquake fault size.[1] In general, earthquakes in stable interior regions such as the Bruce region, occur at depths of 5 to 20 km in the Precambrian basement.

Figure 4.10 shows all known earthquakes in the region up to 2007; the event locations and magnitudes were obtained from the National Earthquake Database of the Geological Survey of Canada (www.seismo.nrcan.gc.ca). Catalogue magnitudes as reported by the Geological Survey of Canada on various magnitude scales were also converted to moment magnitude for this report, using empirical relations such as that given by Atkinson and Boore (1995). From the figure, it can be seen that the Bruce region has experienced sparse seismic activity, with no apparent concentrations of activity that would be an indication of regional seismogenic features or active faults. Most recorded events have a magnitude of less than M3 with only one occurrence[2] of a larger event within a 150 km radius from Bruce facility.

In the Bruce area, events as small as M<3 have been reported since the early part of the twentieth century, though the record may not be complete or accurate at this level until the 1960s. It has become more complete at lower magnitudes over the last 10 years, with the installation of the Southern Ontario Seismographic Network and recently the POLARIS network (www.polarisnet.ca). The sparse station density of seismographic stations in the Bruce region may be responsible for the relative lack of small events (M < 3) on the map (Figure 4.10). To improve the local pattern of low-level seismicity, three highly sensitive borehole seismometer stations were installed by OPG within a 50 km radius of the Bruce facilities in 2007. Another objective of this new array is to capture microseismic events in the immediate area for the identification of seismogenic features deep in the Precambrian bedrock. Despite lowering the monitoring threshold to M>0.6 (monitoring magnitude (m_N) of greater than 1), there has been one M1.6 (m_N2.1) event at 51 km away since the implementation of the new array and nine smaller events within a radius of 150 km since 2000.

In general, it is difficult to correlate seismicity with specific faults. Earthquakes in eastern Canada typically occur at depths of 5 to 20 km in the Precambrian basement, on faults that have no surface expression. Furthermore, faults mapped on the surface in eastern Canada were formed hundreds of millions of years ago, and may bear little relation to current seismic activity. Thus there is no clear-cut relationship between observed faults and seismicity. This is certainly the case in the Bruce region, particularly as the seismic activity would generally be occurring in the underlying Precambrian basement, which begins at a depth of about 860 m beneath the Bruce site (borehole DGR-2).

The focal depths for most of the events plotted on Figure 4.10 are unknown. For the 76 events in this region with known focal depth, the average depth is 7 km. The depth distribution is as follows:

a) 38% of the events occurred at depths less than 5 km;
b) 43% occurred in the depth range from 5 to 10 km;
c) 16% were at depths of 10 to 15 km; and
d) 2% were at depths of 15 to 20 km.

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1. The moment magnitude scale was calibrated such that moment magnitude equals Richter magnitude in most cases

*2 This **M**4 event was the 2005 earthquake at a depth of > 2 km in the Precambrian rock under Georgian Bay, some 90 km from the site.*

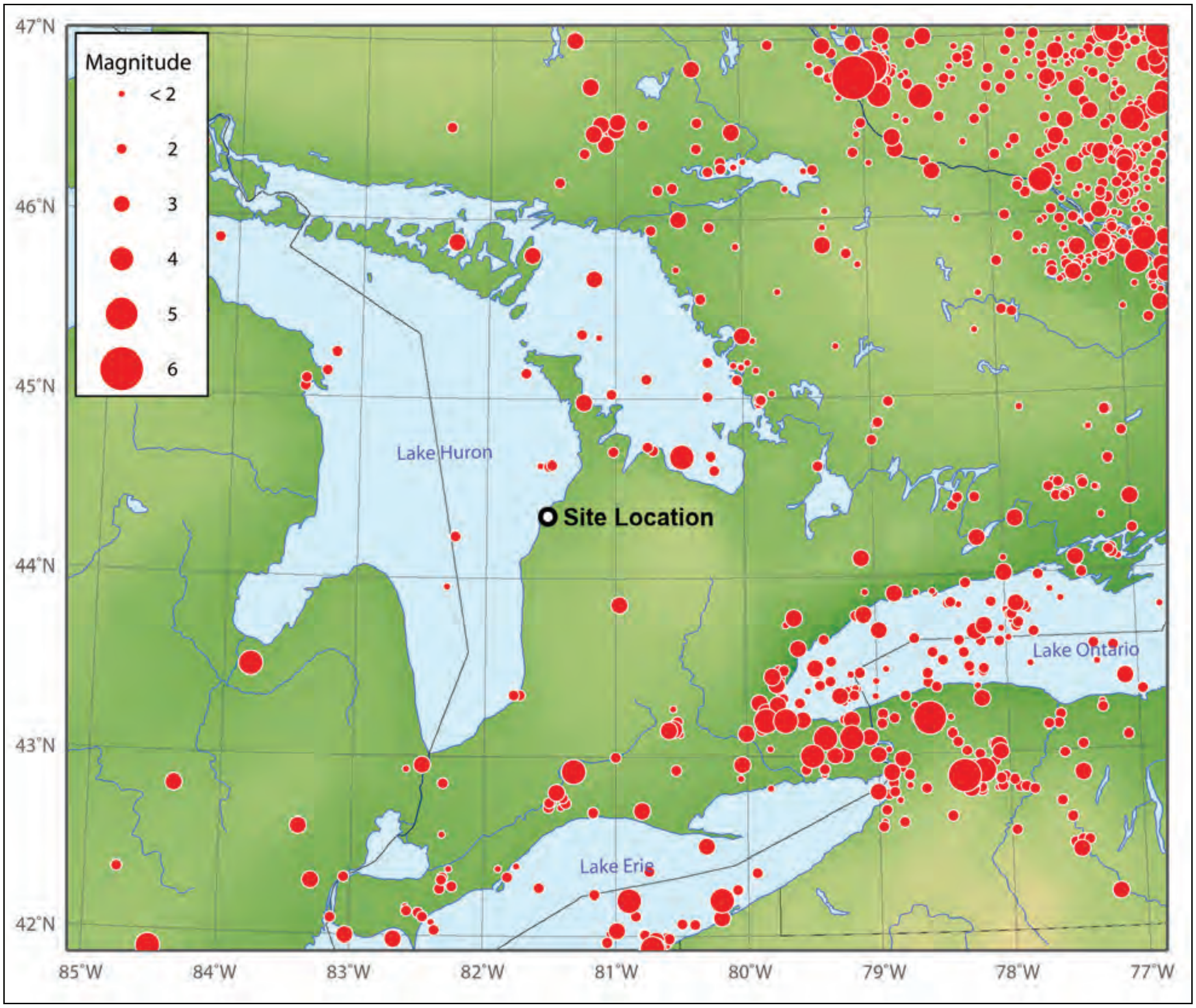


Figure 4.10 Seismicity in the Bruce region to 2007 (Gartner Lee Limited, 2008b).

This is consistent with the earthquake focal depth distribution determined for western Lake Ontario and Niagara seismic zones by Dineva *et al.* (2004) using the Joint Hypocentre Determination Method. Hence, about 80% of the seismicity is distributed randomly over the top 10 km, with the remainder gradually tapering off with depth. Maximum focal depths are likely to be about 25 to 30 km, based on the deepest known events within the eastern North American crust (such as the 1988 Saguenay earthquake in Quebec, at 28 km).

With respect to the more shallow Paleozoic rocks that will host the DGR, a review of the data where the focal depths are known provides an initial indication of focal depths not in the Paleozoic sequence. In fact none of the events depicted have a focal depth in the Paleozoic sequence. Only three events were found to occur at less than 1 km depth and these were all in the Precambrian basement rocks over 200 km away from the site. In addition, there are no known surficial expressions of large scale faults existing in the shallow Paleozoic, at least in the Bruce Region.

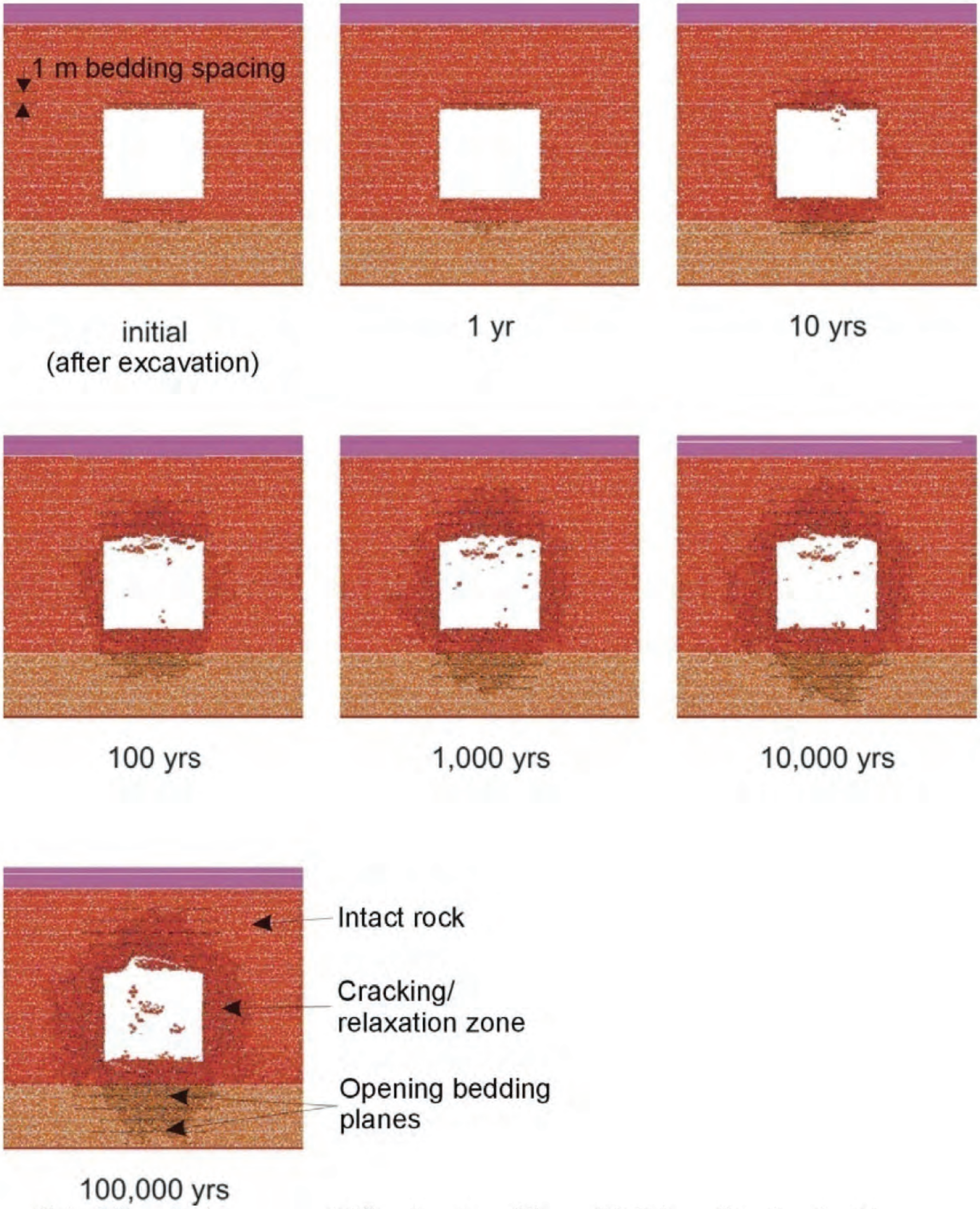
A recent study of seismicity rates in the Canadian craton by Atkinson and Martens (2007) reports a Canadian craton rate of M > 6 events of <0.001 pa per 10^6 km^2 with a variability (standard deviation) of about a factor of three. This density of seismicity (where density is the rate of activity per unit area) is applicable to the Bruce region. To put this in context, this means that an event of M ≥ 6 would be expected somewhere within a 20 km radius of the Bruce Site roughly once in 800,000 years (with an uncertainty of a factor of 3 on this return period). The rate could potentially be altered under future glaciation cycles which lead to vertical stress changes that may temporarily increase seismicity rates (Adams, 1989) – but the rate is clearly very low in any case.

A preliminary seismic hazard analysis (SHA) was performed for the Bruce region to estimate bedrock ground motions that are expected for probabilities of 10^{-3} to 10^{-5} per annum (Atkinson, 2007). The results are summarized in the following table.

Table 4.4 Summary of Seismic Hazard Analysis Result (based on Atkinson 2007)

Event (Prob. of exceed. p.a.)	**Peak Ground Acceleration**	
	(cm/s^2)	**(%g)**
4×10^{-3} (1/**2500**)	22	2.2
10^{-4} (**1/10,000**)	60	6.1
10^{-5} (**1/100,000**)	260	26.5

Ground shaking hazard is one of the greatest threats to surface facilities, and forms the basis for seismic design. For an underground facility, it is generally known that adverse earthquake effects to underground workings are rare. Dowding and Rozen (1978) demonstrated using 71 tunnel damage cases during earthquakes and concluded that there is a strong dependence of these effects to peak velocity response of the ground motion (PGV). Based on the results of the preliminary SHA adverse effects are highly unlikely in the repository even under 10^{-5} annual probability events as the responses of the ground motion generated are well below the damage threshold (Itasca 2008). This was further confirmed by numerical analysis of a cavern subjected to seismic ground motions at the same probability level (Itasca 2008). Detailed description of the seismic analysis is presented in the following section.



Note: Different colors represent different regions of the model. Cobourg limestone is pink; Cobourg limestone discretized into Voronoi blocks is red; weak Sherman Fall limestone discretized into Voronoi blocks is brown. Black lines represent location of the fractures.

Figure 4.11 Time-Dependent Strength Degradation around the Cavern Outline (Itasca, 2008)

4.6 DGR Cavern Stability

4.6.1 Tunnelling Case Histories in Similar Rock Formations

The previous sections provided an assessment of the regional and site specific geomechanical properties of the rock material at a laboratory scale, as it relates to the Bruce site. In this section, the condition of rock mass at the field scale will be examined through previous tunnelling case histories in Ontario and in Ohio as insight into the type of rock conditions that may be encountered beneath Bruce site.

In practice, the strength of a rock mass cannot be solely assessed based on rock matrix strength as generally defined by uniaxial compressive strength described above. It also depends on the degree of interlocking within the system of the state of stress and the hydraulic conditions. Rock mass classification systems, such as Bieniawski's (1976) Rock Mass Rating (RMR_{76}); Barton's (1974) NGI Tunnelling Quality Index (Q) have been created to quantify the rock mass parameters, so that media can be systematically classified. In this way it allows previous design experience to be transferred from one engineering project to another.

Golder (2003) compiled existing rock mass information from shallow tunnelling projects in rock of the same type as the host and cap rock at the Bruce site. Based on the measurements from the site investigation work at the Darlington Generating Station, the Cobourg argillaceous limestone was classified to be **good quality** with RMR and Q values of 72 and 32, respectively. The integrity of the rock mass was demonstrated by two precedent 8 and 10.4 span tunnels excavated in this formation: the Darlington cooling water intake tunnel; and the oil storage cavern access tunnel at Wesleyville Generating Station. The Darlington tunnel is completely located in the Cobourg Formation, whereas the Wesleyville tunnel straddles the Cobourg and underlying Sherman Fall Formations. Drill and blast techniques were used to construct both tunnels. No significant construction problems related to rock stability were encountered in either project. Also, there was no sign of seepage inflow from the rock units and the tunnels were completely dry, demonstrating the low hydraulic conductivity of these formations at depths of about 44 m.

Similarly, the rock mass classification for the Queenston Shale also yields **good quality** rock with ratings of 66 and 11 for RMR and Q values, respectively. A good example of tunnels constructed in this formation is demonstrated by the 13.5 m diameter enlargement of the Niagara Falls Sir Adam Beck tunnel development's test adit. Mechanical excavation was employed by means of a road header. There was no major instability of the rock following excavation except some slabbing at the crown and on the sidewalls. This surficial spalling only occurred at areas where primary bedding planes existed (Acres Becthel Canada, 1993). Also, it is known that the shale tends to be susceptible to swelling upon exposure. Rock reinforcement was required to control slabbing and slaking. Despite this condition, the rock encountered was of better quality than was anticipated. The tunnel was essentially dry except at local bedding planes where minor seepage was observed (Golder, 2003).

The Georgian Bay Formation is shale with minor interbedded siltstone and limestone layers. The thicknesses of the shale beds are generally much thinner than that of Queenston Formation above. Also the uniaxial compressive strengths of the rock from the southern Ontario database (Table 4.3) average only 35 MPa, however, a large variation in UCS results was observed due to the interbedded nature of shale and carbonate in the rock unit. Based on these rock characteristics, the RMR_{76} of the shale is classified as **fair quality** with an estimated rating of about 54, which is less than that of the Queenston Shale. Despite a fair rock mass rating, numerous municipal service tunnels have been excavated in this formation without any stability problem during construction. These tunnels have a relatively small diameter when compared to those mentioned above (Golder, 2003).

Rock mass properties are primarily governed by the strength of the intact rock and by the presence of discontinuities in the rock mass. Because of the lack of discontinuities and an increase in confinement, which results in overall strength increase, the quality of the rock mass at repository depth is anticipated to be stronger and in a less disturbed state with a much higher rock mass rating than that at shallow depths. Preliminary findings on the host rock (Cobourg Formation) and cap rock (Ordovician shales) from boreholes DGR1 and DGR2 appear to confirm this trend. This observation is supported by the high RQD and massive bedding (except for the Georgian Bay Formation) encountered in these drill holes.

4.6.1.1 Numerical Analysis on Cavern Stability

Numerical analyses on cavern (DGR) stability (Itasca, 2008) were carried out to study the following four plausible cases:

1. time-dependent strength degradation (base case);
2. strength degradation with additional effects of gas pressure build-up;
3. strength degradation with additional effects of seismic ground shaking; and
4. strength degradation with additional effects of glacial loading.

A simple 2D configuration of the DGR with the invert of the repository at 683 mbgs was utilized in the analysis. Rock mass properties used are from the laboratory test results conducted on rock cores retrieved from DGR-2 (Itasca, 2008). The cavern geometry, rock support, waste storage content, rock mass behaviour and in situ stress condition assumed for these initial analyses were as follows:

a) DGR cavern is considered to be 8.1 x 7.5 m and unsupported with no backfill;

b) all waste packages are excluded from the analyses i.e., the rooms are empty;

c) static fatigue test data from Lac du Bonnet granite were adopted for the long-term strength degradation analysis;

d) no minimum strength degradation threshold was set for the Cobourg limestone;

e) a bedding plane spacing of 1 m was assumed;

f) the vertical seismic ground motion was assumed to be equal to that of the horizontal component;

g) critical damping of rock material of 0.03% was used in dynamic simulations of seismic shaking; and

h) the horizontal in situ stress in the analysis is assumed to be a factor of two greater than the magnitude of vertical stress (Gartner Lee Limited, 2008b).

The results of these analyses are discussed in the following paragraphs.

CASE 1 **Time-Dependent Strength Degradation**

Time-dependent strength degradation is a measure of how the rock will perform over a period of time under existing stress conditions after the cavern has been excavated. The results from a discrete block model indicate the most conservative damage, assuming that long-term strength for the Cobourg Formation will eventually degrade to zero; after a period of 100,000 years the damage zone extended to about 6 m above the cavern and about 4 m into the adjacent pillars (Figure 4.11). This in turn results in about 2.5 m of overbreak of the cavern crown. If the long-term strength threshold of the Cobourg Formation is limited to be 40% of the unconfined compressive strength the extent of the damage is considerably reduced to 3.5 m from the cavern crown with only 0.5 m of overbreak. Minimal damage to the pillars is also anticipated. Further site specific testing is currently being conducted to define the long-term strength threshold. For the results of the remaining loading cases, the zero long-term strength assumption is adopted.

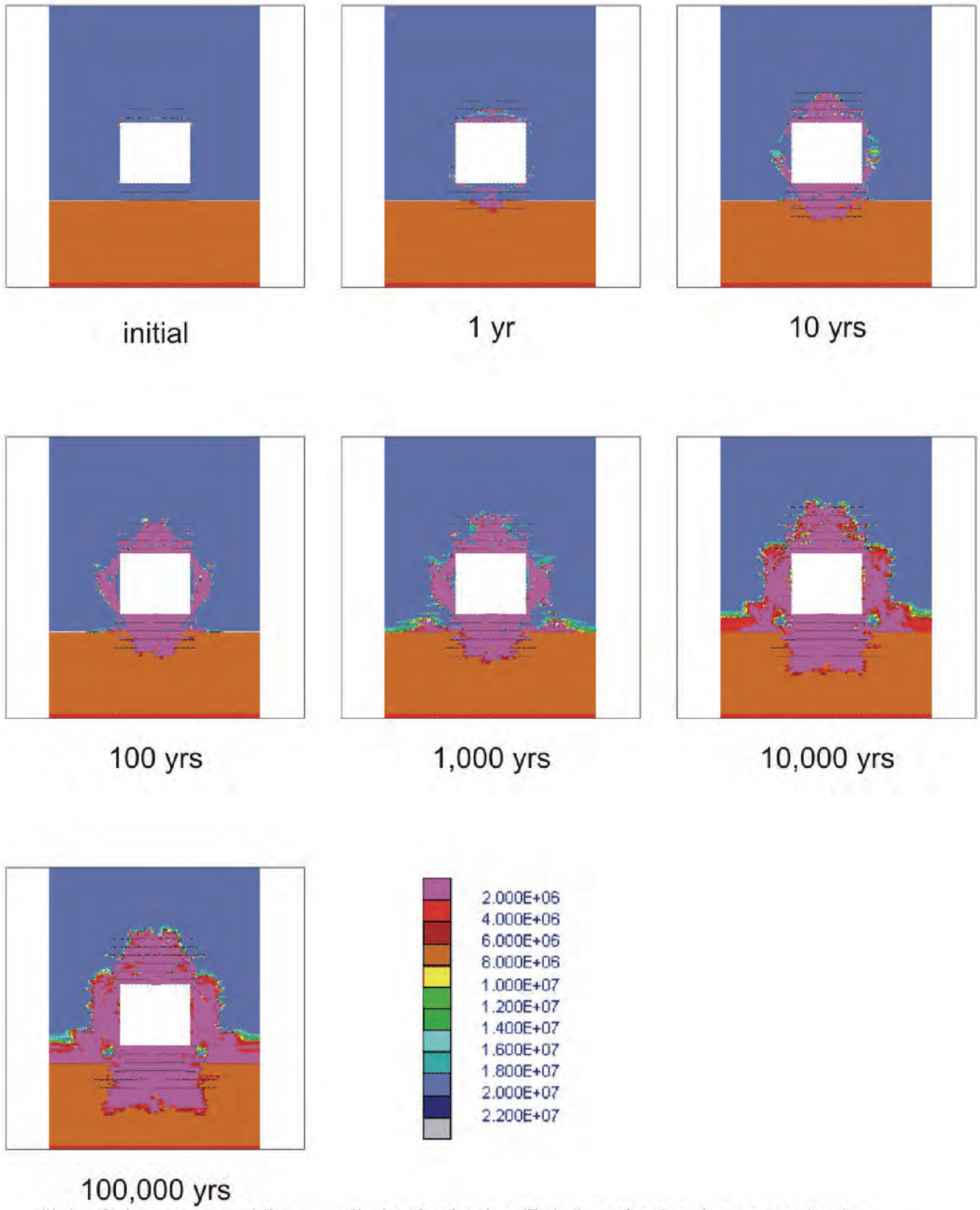
CASE 2 **Effects of Gas Pressure Build-up**

The effect of gas pressure build up on cavern stability has been assessed as corrosion processes in the wastes will likely generate off-gases that can build-up high pressures in the repository that may open fractures in the adjacent rock. In the three scenarios considered in the gas build-up sensitivity analyses, maximum gas pressures ranging between 10 to 15 MPa and occurring between 3,000 and 20,000 years were simulated. A strain-softening Mohr-Coulomb constitutive continuum model is used to represent damage and fracturing of the rock mass.

The gas pressure scenarios, that are additive to time-dependent strength degradation, were analyzed for a period of 100,000 years. The results indicate that gas pressure does not induce opening of bedding planes under the two lower pressure cases. However, as the pressure approaches lithostatic pressure (approximately 17 MPa), fracture propagation could occur preferentially along bedding planes and may reach 16 m. However, gas build-up will not generate vertical features that could result in releases to the biosphere. Figure 4.12 illustrates that the cavern damage is confined to rock surrounding the opening for the most likely 13 MPa maximum pressure build-up in 20,000 years following repository closure.

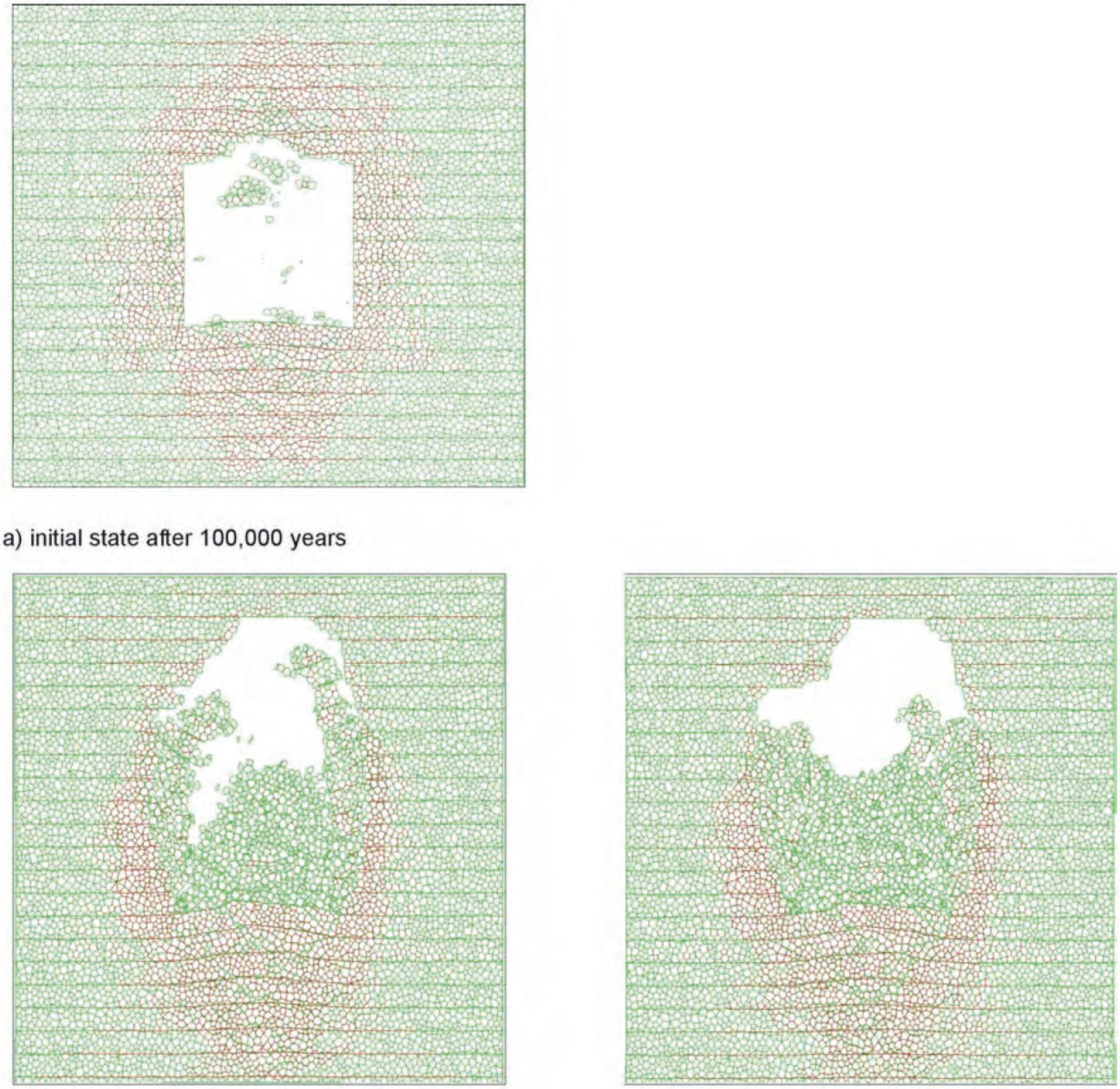
CASE 3 **Effects of Seismic Ground Shaking**

Two seismic events were simulated using the discrete block model to evaluate their impact on cavern stability. A magnitude 5.5 (M5.5) at 15 km distance from the repository and a M7 at a distance of 50 km were selected based on a seismic hazard assessment of the Bruce site (Gartner Lee Limited, 2008b). Both events were assessed with an initial state at (a) immediately upon cavern completion, and (b) after 100,000 years. The former analysis demonstrates that the results of the simulations under both earthquakes are almost identical with no damage to the cavern opening soon after excavation. However, when the seismic shaking is coupled with time-dependent strength degradation there is dislodging of loose rock from the damaged zone of the cavern crown exposing the intact host rock. Figure 4.13a shows the extent of damage around the cavern after 100,000 years prior to seismic shaking. Figure 4.13b & c show the breakout at the crown after the earthquake. The maximum breakout is predicted to be about 5.5 m above the crown. There appears to be no damage to the intact or undisturbed rock mass as a result of the shaking. This analysis is conservative as it does not take into account a bulking factor generated by the emplaced storage waste.



Note: Colors represent the magnitude of cohesion (Pa). As cohesion decreases due to damage, the purple color indicates completely damaged rock. Black lines indicate the locations of fractures along the bedding planes.

Figure 4.12 Time-Dependent Strength Degradation Plus 13 MPa Gas Pressure Build-up Damage around the Cavern Outline (Itasca, 2008)



a) initial state after 100,000 years

b) ground motion M5.5 at 15 km

c) ground motion M7 at 50 km

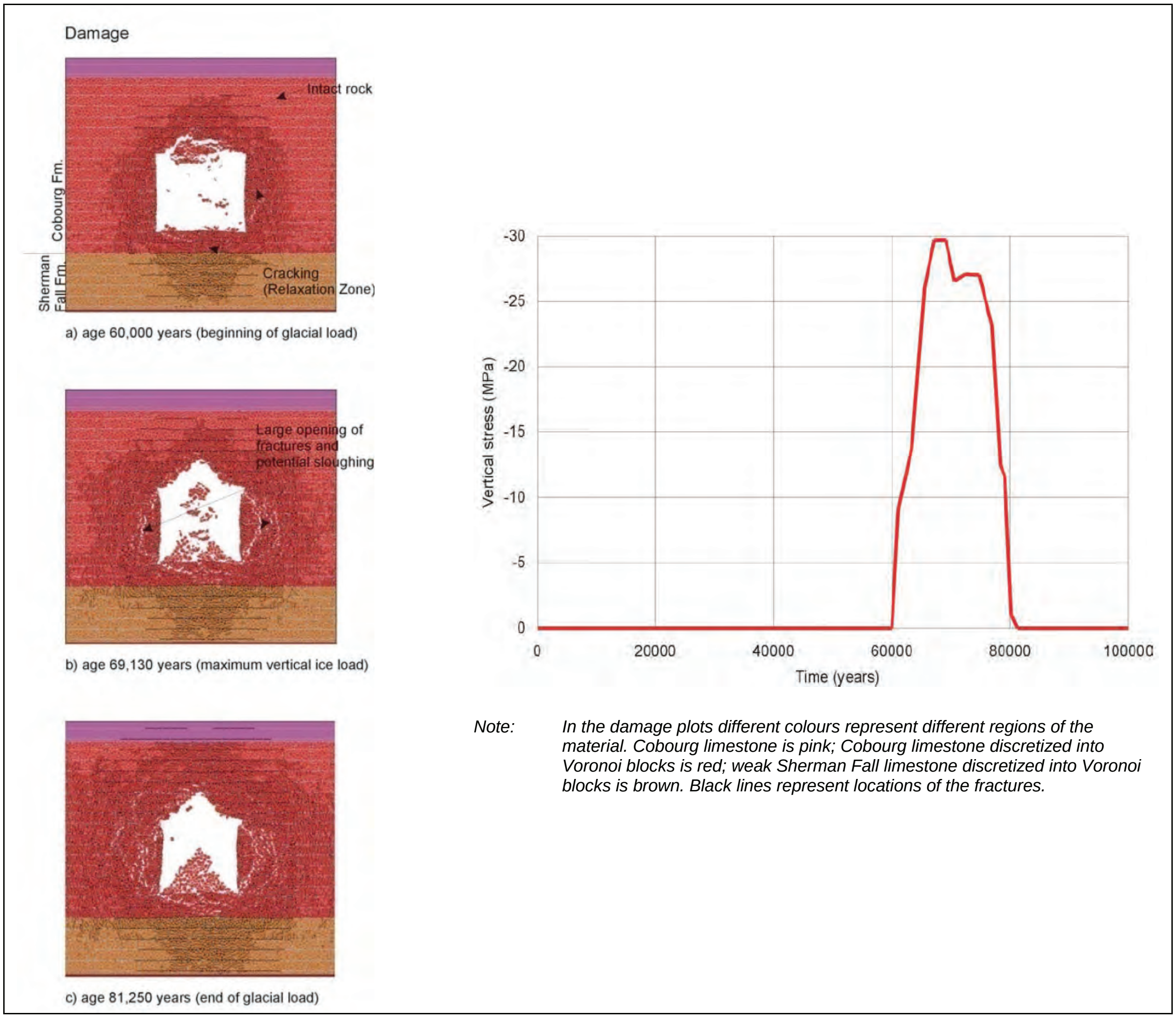
Note: Red lines indicate locations of fractures.

Figure 4.13 Effects of Seismic Ground Motions after 100,000 Years of Time-Dependent Strength Degradation (Itasca, 2008)

CASE 4 <u>Effects of Glacial Loads</u>

The Bruce site is located in a region of North America that has been subjected to numerous glacial episodes over the past million years. Peltier (2008) has estimated that an ice thickness of 2.5 km may be expected at the site generating a vertical stress of almost 30 MPa on the repository. Given the current state of knowledge, Peltier (2008) estimates the onset of the next glacial event at the Bruce site will be in about 60,000 years.

The effects of glacial loading on cavern stability were studied with the combination of the vertical glacial load estimated by Peltier (2008) and the time-dependent strength degradation behaviour of rock. Figure 4.14 shows the results of this analysis. The caverns and pillars between caverns remain stable throughout the glacial cycle.



Note: In the damage plots different colours represent different regions of the material. Cobourg limestone is pink; Cobourg limestone discretized into Voronoi blocks is red; weak Sherman Fall limestone discretized into Voronoi blocks is brown. Black lines represent locations of the fractures.

Figure 4.14 Evolution of Damage around a Cavern during a Glacial Cycle (Itasca, 2008)

4.7 Summary

The study on the regional geomechanical framework and seismological data complied and evaluated available information related to regional joint set system, in-situ stress, seismicity and other geomechanical rock properties for southern Ontario and the US States bordering southern Ontario. Information contained in the study provides an insight on the regional system and the long-term performance of the DGR. The following is a summary of this initial phase study:

a) the joint data collected over the region provide an insight into the general trend of the regional jointing system likely encountered at the proposed repository horizon;

b) interim hydraulic conductivity testing results from borehole DGR-2 reveal extremely low rockmass permeabilities and high total dissolved solids within porewaters. This suggests that the major and minor regional joint systems at depth, if present, are expected to be tight and sealed;

c) the frequencies and orientations of joints at depth, which define the rock mass strength and would control the kinematic stability of the DGR caverns, may vary from those mapped at surface. Two inclined boreholes, DGR -5 and -6, are planned in 2009 to provide further understanding of the joint features at Bruce site;

d) compressive in-situ stresses provide a tight rock environment and may be predictable with depth using regional information. The analysis of the regional in-situ stress data allows an estimate of the approximate range in stress ratios at repository depth at the Bruce site. At the repository horizon σ_H / σ_v will likely vary from 1.7 to 2.5; σ_h / σ_v from 1.0 to 1.2; and σ_H/σ_h from 1.5 to 2.1. The current maximum horizontal in-situ stress in the region is oriented in an ENE direction;

e) the strength and geomechanical properties are favourable for the construction of the DGR in the Ordovician argillaceous limestone of the Cobourg Formation, as uniaxial compressive strength measurements from samples retrieved from DGR-2 reveal much higher strength than results observed from the regional study. The average UCS strength measured from site samples was about 110 MPa compared to 72 MPa based on the regional database;

f) previous underground excavations at Darlington, Wesleyville, Niagara Falls and other locations in southern Ontario were carried out at shallower depth in the Ordovician rock (Queenston, Georgian, Cobourg and Sherman Fall Formations). These cases demonstrate stable and dry openings can be created in Ordovician argillaceous limestones and shales;

g) earthquakes in the region are sparse based on 180 years of historic records of observations and monitoring of seismicity activity. A new microseismic monitoring network installed in August 2007 confirmed such low seismicity rate with only one M1.6 event at 51 km away since the array implementation and nine smaller events within a radius of 150 km since 2000;

h) no seismic events >M5 have been recorded in the past 180 years. All measured events with known focal depths have epicentre depths of several kilometres in the Precambrian basement rock. The average focal depth of these events is 7 km; and

i) as the Bruce site is at the edge of the stable cratonic region of North America, the likelihood of a large seismic event in the region is very low with a seismicity rate comparable to that of the shield region.

j) A preliminary long-term cavern stability analysis was undertaken to provide an overall assessment of the effects of four loading scenarios (long term degradation, gas pressure buildup, seismic events, and glacial loading) in 100,000 year time frame in Itasca (2008). The long term behaviour of the Cobourg limestone showed rock damage extended 6 m or less from the cavern boundaries, with breakouts and rock fall extending at most 2.5 m. The cavern was found to be stable for containment of gas pressures. It was found that both near and far field seismic events do not produce any additional damage to the rock mass. Finally, under glacial loading, the caverns and pillars between caverns remain stable throughout a glacial cycle.

5. REGIONAL HYDROGEOCHEMISTRY

5.1 Introduction

Hydrogeochemical studies seek to understand the nature and timing of physical and chemical processes that have operated to define the chemical characteristics of natural water. The term hydrogeochemistry refers to the chemistry of water as it is affected by a variety of chemical reactions with components of soil, sediment, rocks and minerals and by various physical processes such as pressure-driven advection, evaporation and diffusion. In general, hydrogeochemistry may involve the study of water in the atmosphere, surface water such as rivers and lakes, and groundwater. In most cases these would be considered low-temperature systems (somewhat arbitrarily defined as <100 °C), but there is much interest in hydrogeochemistry of higher temperature systems (>100 °C; commonly referred to as hydrothermal systems) because of their importance in the formation and accumulation of economically important deposits of mineral resources.

In the context of the environmental and safety-assessment requirements for a Deep Geological Repository (DGR), hydrogeochemical studies can provide data that may be used to test the validity of two of the fundamental tenets presented in Section 2.1:

a) Solute Transport is Diffusion Dominated: deep groundwater regime is ancient showing no evidence of cross-formational flow or glacial perturbation; and

b) Multiple Natural Barriers: multiple low permeability bedrock formations enclose and overlie the DGR.

Physical controls on the movement of groundwater and associated solutes, and the timing of such movements, represent the principal theme of these tenets. Groundwater movement and solute transport are commonly the subject of hydrogeochemical studies that focus on exploitation and protection of water resources. These types of investigations generally employ field methods designed to directly or indirectly measure flow rates and solute velocities. Hydrogeochemical studies that focus on water resources are restricted to active flow systems that can be easily exploited for supply water. It is common practice to make direct measurements of flow rate, direction, and solute velocity in active systems. In contrast, investigations of low-permeability geologic systems are limited by very low advection rates and solute velocities, which cannot be detected within the time available for measurements. Consequently, studies of porewater movement and solute transport in low-permeability geologic systems rely, in part, on hydrogeochemistry in order to elucidate the age and origin of the porewater, the processes responsible for observed spatial variations in porewater chemistry, and the mechanisms controlling transport of solutes.

The term “groundwater” is commonly used to represent all water contained in geologic formations below the Earth surface, but in the present context it is useful to distinguish between groundwater that is unconstrained by low permeability media and therefore free to flow under the influence of hydraulic gradients, and groundwater that is contained in the pores of low permeability rocks and therefore effectively immobile. In the remainder of this document we use the term “groundwater” to represent water which can flow under the influence of hydraulic gradients. This includes water within the connected pore space between mineral grains in unconsolidated sediment or in a fractured or porous rock matrix, as well as water in permeable, connected structures in the subsurface. Operationally, groundwater is water which flows into and can be sampled from boreholes, typically over time scales of days to months. We use the term "porewater" to describe water within the connected pore space between mineral grains in low-permeability sediments or rocks in which flow under the influence of hydraulic gradients is inhibited. Operationally, porewater is water which cannot flow into and be sampled from boreholes over time scales of days to months. Laboratory techniques are generally required to extract porewaters from the sediment or rock matrix.

5.2 Objectives

A great deal of hydrogeochemical research has been conducted on the Michigan Basin in Canada and the United States, and the data collected during the course of previous research, in part, provides the basis for the current understanding of the origin and age of the water contained in the sediments of the basin. In addition, site-specific research activities have been ongoing since 2007 at the Bruce site in order to characterize the geoscientific properties of the underlying sedimentary rocks that are relevant to the implementation of a DGR.

The first objective of this section is to summarize existing regional based knowledge of the hydrogeochemistry in the Michigan Basin according to:

a) the hydrogeochemical characteristics of basinal brines and an explanation of the current understanding of their origin and age; and
b) evidence for flow of groundwater or porewater and transport of solutes.

The second objective of this section is to integrate initial data from the first phase of geoscience characterization activities at the Bruce site with data obtained from previous research in and around the Michigan Basin. The purpose of this integration is to begin to develop an understanding of the origin and age of the groundwaters and porewaters and of the mechanisms that cause migration of solutes in Ordovician rocks that underlie the Bruce Site. The interpretation of site-specific data from Phase I site characterization studies presented here is preliminary and will be subject to continued refinement in subsequent work.

5.3 Summary of Existing Hydrogeochemical Knowledge

5.3.1 Michigan Basin: Origin of the brine

The Michigan Basin is an intracratonic crustal depression that contains sediments, dominantly of marine origin, ranging in age from Cambrian to Jurassic (Cambrian to Carboniferous or 543 – 300 Ma, in southwest Ontario). Saline fluids occur at all levels in the basin and although the sediments were deposited in a marine environment, the salinity of the Michigan Basin fluids (TDS commonly > 200 g/L) is generally much higher than sea water (TDS ~ 35 g/L). Numerous processes have been proposed to account for the elevated salinity of brines in sedimentary basins, including: i) evaporation of sea water (Carpenter, 1978; Kharaka et al., 1987; Wilson and Long, 1993a,b); ii) the dissolution of halite or other evaporites (Rittenhouse 1967; Land and Prezbindowski 1981); iii) membrane filtration (Bredehoeft et al., 1963; Berry, 1969; Kharaka and Berry, 1973; Graf, 1982); iv) freezing of water or hydration of silicates (clays) with the resulting concentration of solutes (Hanor, 1988); or v) ingress of concentrated brines from underlying crystalline shield-type rocks. More recently, the origin of the high salinity brines in sedimentary basins has been reviewed by Hanor (1988, 1994, 2001).

Knowledge acquired from sedimentary basins worldwide, as well as research conducted specifically on the Michigan Basin, may be used to evaluate the origin of the groundwater and porewater contained in sediments of the Michigan Basin. Hydrogeochemical data acquired in the course of research conducted at the University of Waterloo over a period of 25 years comprise one of the most complete sources of information on groundwater geochemistry from within the sedimentary sequence underlying southwestern Ontario and these have been combined into a database, hereafter referred to as the UW database. The UW database is described in detail by Hobbs et al. (2008). A map of sampling locations for the UW database is shown in Figure 5.1. The UW database includes groundwater sampled from the formations listed in Table 5.1. Most of these groundwater samples are from oil and gas wells that were in production at the time of sampling and are properly considered brines (Total Dissolved Solids > 100 g/L). A number of the shallow samples have lower salinity, but in all cases the UW database contains data for groundwater – porewater in low permeability formations is not represented. In addition to the UW database, a variety of independent scientific investigations have been conducted over a time span of decades to understand the characteristics of groundwater in sedimentary basins – most commonly brine. These works also utilize data from groundwater sampling and do not represent porewater geochemistry. The results of these works are described and cited below as appropriate.

Table 5.1 Age and Names of Bedrock Formations Sampled for Groundwater in the UW Database

Age	Formations Sampled	Study
Mississippian	Berea	Dollar (1988), Walter (Pers. Comm.)
Devonian	Kettle Point Antrim Shale Hamilton Dundee Detroit River Group Richfield	Cloutier (1994); Walter (Pers. Comm.); Husain (1996) Martini et al. (1998) Cloutier (1994); Weaver (1994); Cloutier (1994) Weaver (1994) Dollar (1988)
Silurian	Salina F-salt Salina A2-salt Salina A1-carbonate Guelph Niagaran Thorold-Grimsby Whirlpool, Guelph/Lockport Goat Island, Gasport Thorold	Dollar (1988) “ “ “ Dollar (1988); Walter (Pers. Comm.) Dollar (1988) Dollar (1988) Hanratty (1996) “
Ordovician	Blue Mountain Cobourg Veralum Bobcaygeon Gull River Shadow Lake Trenton Group Prairie du Chien	Sherwood-Lollar and Frape (1989) “ “ “ “ “ Dollar (1988) “
Cambrian	Cambrian – undifferentiated	Dollar (1988)
Precambrian	Undifferentiated	Sherwood-Lollar and Frape (1989)

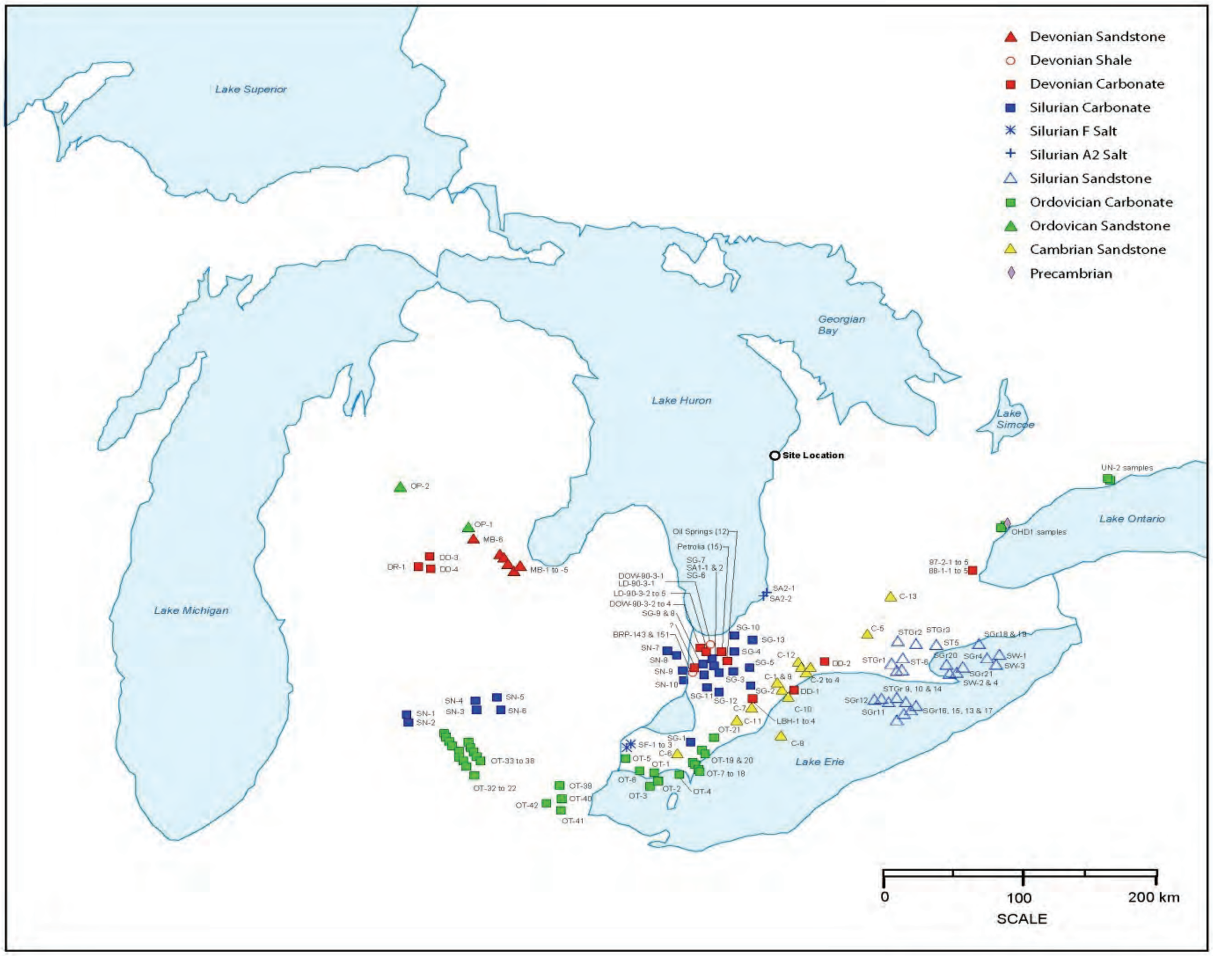


Figure 5.1 Map showing all of the UW database sampling locations for fluids collected from the sedimentary formations in southwestern Ontario and Michigan.

Recognizing that groundwater has greater mobility than porewater, the geochemistry of groundwater may be influenced to a greater extent by processes such as advective mixing among different fluid reservoirs, cross-formational flow and chemical interactions with hydrocarbons. Hobbs et al. (2008) presented two lines of reasoning which suggest that the UW database provides a reasonable starting point for the interpretation of site-specific geochemical data:

a) Good agreement was observed between the chemical composition and salinities of groundwaters sampled from isolated intervals in multilevel wells completed within Ordovician-aged formations at depths of less than 370 m in southeastern Ontario and those sampled within producing hydrocarbon wells. This suggests that groundwaters associated with hydrocarbons can be used as a first estimate of the compositions of groundwaters sampled from the same formations elsewhere in the basin, where hydrocarbons are absent.

b) It is expected that diagenetic processes, such as dolomitization, identified as important influences on groundwater compositions in the sedimentary sequence underlying southwestern Ontario (Hobbs et al., 2008) and elsewhere in the Michigan Basin (Wilson and Long, 1993a,b) will also be dominant influences on the chemical and isotopic compositions of the porewaters and deep groundwaters in the RSA. It is therefore anticipated that the chemical and isotopic information on waters from the regional geochemical database will provide a reasonable basis for comparison with site-specific data generated within the aforementioned geologic RSA.

An initial comparison between the regional hydrogeochemical information within the UW database and interim results from Phase I site characterization activities is presented in Section 5.4.1. Most of the site-specific data are still considered preliminary. In the Ordovician rocks, they represent analyses of leachates extracted from the rock matrix, because the permeability of the Ordovician rocks was too low for groundwaters to be sampled. Below the Silurian, groundwater samples were collected only from the Cambrian formation.

Hanor (2001) states that it is generally agreed that most of the chloride in basinal brines has been derived from the subsurface dissolution of evaporites and/or the entrapment or infiltration of evaporated sea water. This is consistent with the work of Wilson and Long (1993a,b) who present major-ion and water-isotope evidence to support the interpretation that the brines contained in Silurian and Devonian rocks of the Michigan Basin were derived from evaporated sea water in shallow inland seas. During evaporation, the major-ion ratios evolve along characteristic trends that reflect evaporative concentration of the ions, as well as, losses from solution by mineral precipitation (McCaffey et al., 1987). Studies of brines from the Michigan Basin (UW database, Wilson and Long, 1993a,b) show correspondence between trends in Cl:Br ratio in evaporated sea water and the Cl:Br ratios in the basin brines, thereby demonstrating consistency with an evaporative origin of the brine (Figure 5.2).

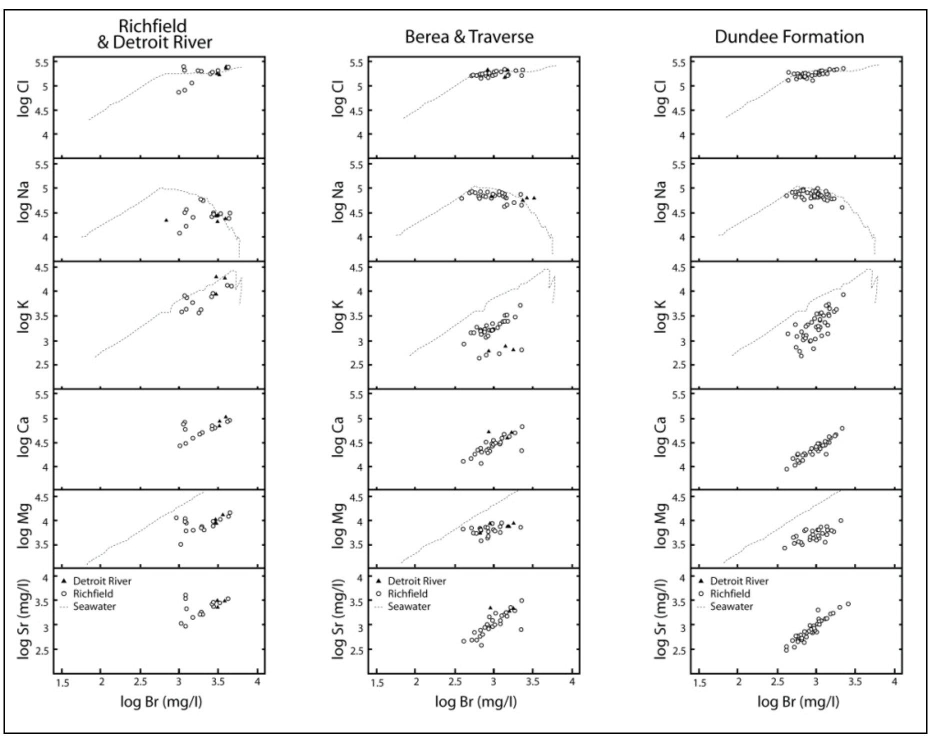


Figure 5.2 Bromide – major ion relationships for Devonian brines from Michigan (from Wilson and Long, 1993a). The line represents the sea water evaporation trend and the sea water evaporation trends for Ca and Sr are not shown because they are off scale at the bottom.

Although Cl:Br ratios presented by Wilson and Long (1993a) (Figure 5.2) suggest an evaporated sea water origin, there is considerable deviation from the sea water evaporation trend in their data for the elemental ratios Na:Br, K:Br, Ca:Br, Mg:Br and Sr:Br. Similar deviations exist in trends displayed by data within the UW database, and in this case, Cl:Br ratios also display deviations above and below the sea water evaporation curve (Figure 5.3). These deviations from the expected evaporation trends can be explained by: i) dilution of brines by lower salinity water; ii) dissolution of halite by meteoric water or sea water at some time in the geologic past, and iii) diagenetic water-rock reaction processes.

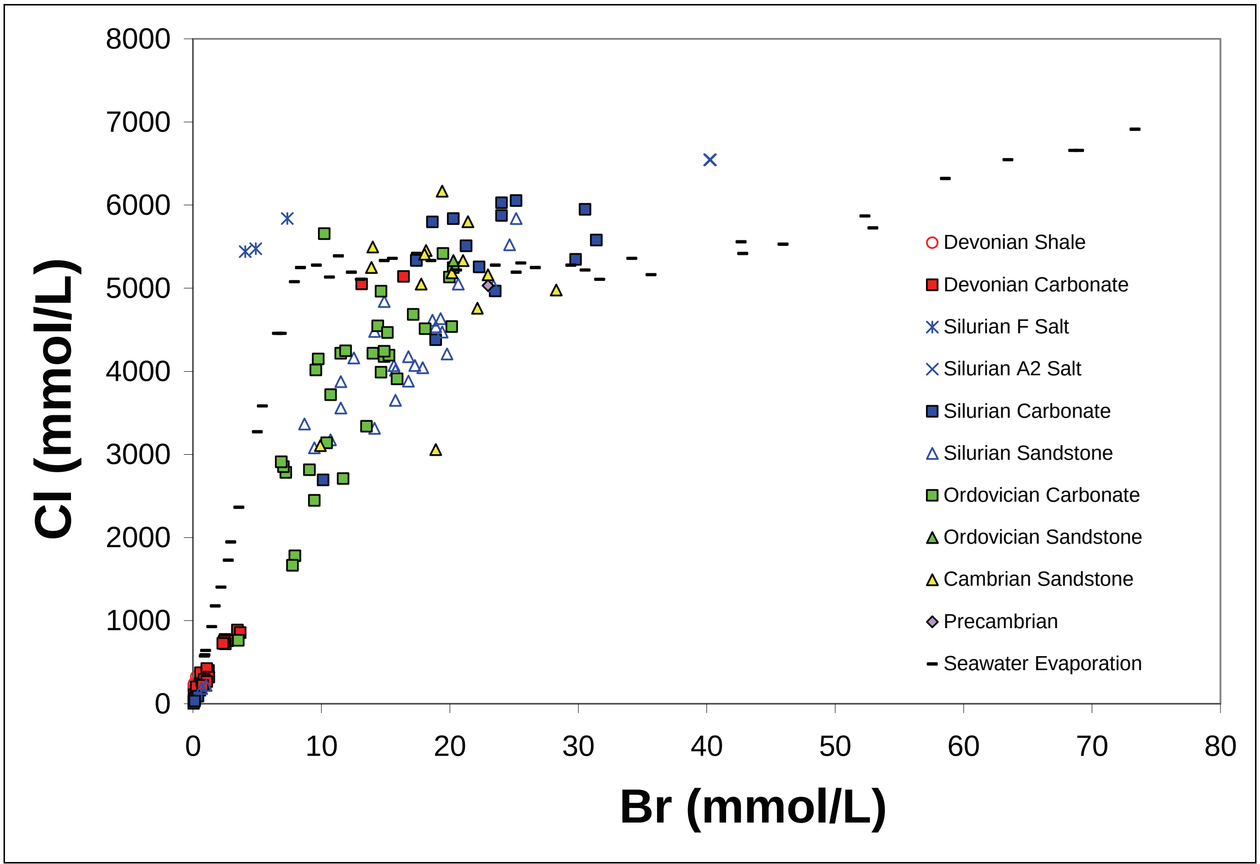


Figure 5.3 Chloride versus bromide concentrations measured for the samples in the UW database. The sea water evaporation trend is shown for reference (McCaffrey et al. 1987).

It is apparent from Figure 5.3 that many of the data points occur below the sea water curve along a linear trend toward the origin. These trends are characteristic of brines that have been affected by dilution with meteoric water or sea water. Groundwaters sampled at depths of up to approximately 200 m below ground surface have isotopic compositions of $\delta^{18}O$ and $\delta^{2}H$ suggesting that they are mixtures of dilute, recent or cold-climate waters and more saline waters. Several groundwaters sampled at depths of greater than 200 m from reservoirs in the Silurian-aged or Cambrian sandstones and Ordovician-aged carbonate formations also have Cl and Br concentrations that suggests dilution by a lower salinity water. However, the majority of the waters in these apparent dilution trends have $\delta^{18}O$ and $\delta^{2}H$ signatures which are clustered together with the concentrated, "end-member" waters from the Ordovician carbonates showing no evidence of dilution and are enriched in $\delta^{18}O$ relative to the Global Meteoric Water Line (Figure 5.4). This suggests that dilution occurred in the geologic past, and their oxygen and hydrogen stable isotopic signatures of these waters have since been altered by water-rock interactions over long groundwater residence times.

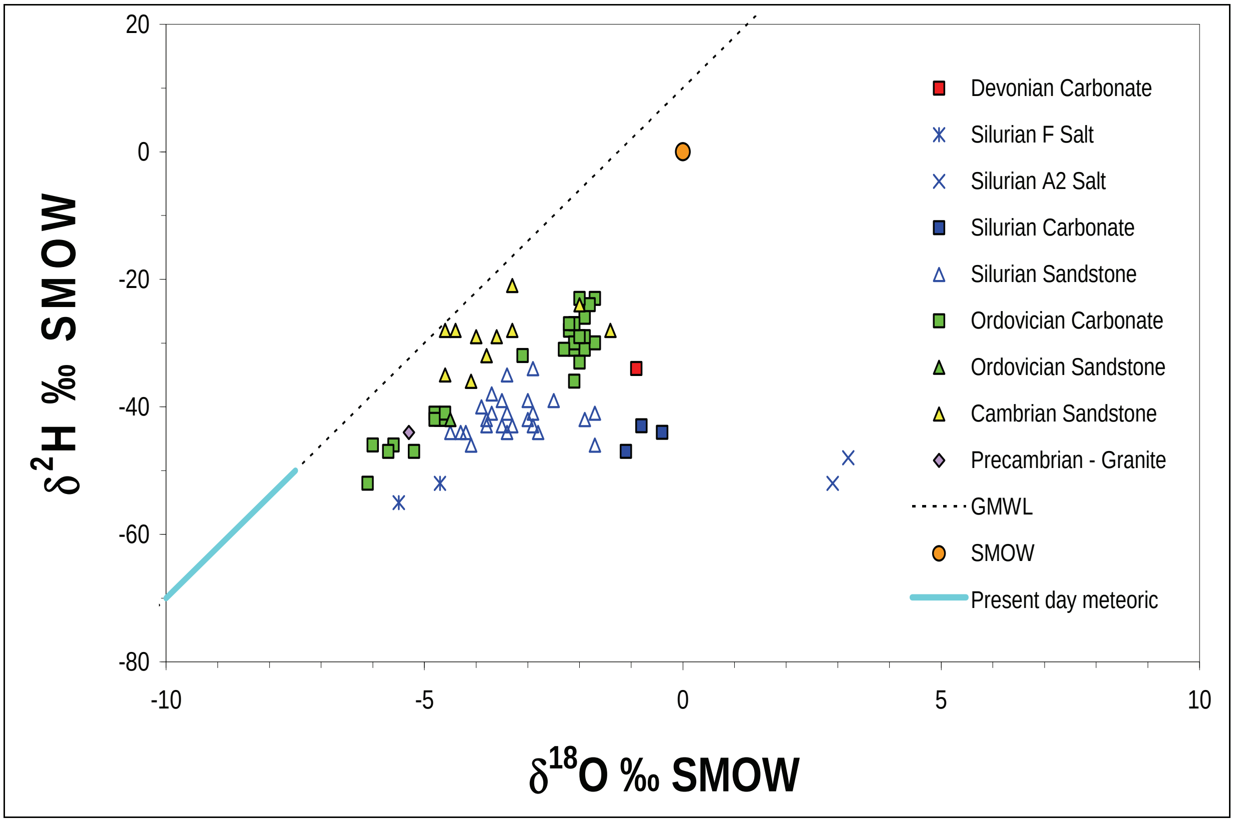


Figure 5.4 Isotopic signatures of hydrogen and oxygen for brines (>100 g/L TDS) from southwestern Ontario. A clustering of the isotopic signatures is observed for the brines; particularly for the Cambrian and Ordovician brines and for Silurian-aged sandstones.

There are a number of samples that plot above the sea water evaporation trend and this type of displacement results from halite dissolution. However, it is not known whether or not regional-scale salt dissolution during the Silurian contributed to the elevated Cl concentrations observed in the waters from the hydrocarbon reservoirs underlying southwestern Ontario. If the sedimentary formations themselves contain (or contained) halite as a primary or secondary mineral phase, dissolution of this halite would comprise a potential source for the excess Cl relative to Br in waters within the UW database, relative to the concentrations expected in evaporated sea water.

Diagenetic water-rock reactions may lead to increases in Ca and Sr concentrations of up to an order of magnitude compared to evaporated sea water, whereas Mg and K concentrations may decrease by as much as an order of magnitude (Hanor, 2001). Water-rock reactions that are commonly invoked to explain deviations in the chemistry of brines from that expected for evaporated sea water include precipitation and dissolution of evaporite minerals, dolomitization, albitization of plagioclase, formation of kaolinite from albite, formation of illite and K-feldspar and carnallite diagenesis (Wilson and Long, 1993a,b; Hanor, 2001; Kharaka and Hanor, 2005). Many of these reactions are described in detail by Milliken (2005) and examples are provided below.

Halite Dissolution – Precipitation

$$NaCl_{(s)} \Leftrightarrow Na^{+} + Cl^{-} \quad [1]$$

- *reversible reaction that may either cause increases or decreases in aqueous Na^+ and Cl^- concentrations.*

Dolomitization

$$2CaCO_{3(s)} + Mg^{2+} \Rightarrow CaMg(CO_3)_{2(s)} + Ca^{2+} \quad [2]$$

- *reaction causes elevated Ca and decreased Mg concentrations in brines.*

Albitization of Plagioclase

$$Na_{0.7}Ca_{0.3}Al_{1.3}Si_{2.7}O_{8(s)} + 0.6Na^{+} + 1.2SiO_{2(s)} \Rightarrow 1.3NaAlSi_3O_{8(s)} + 0.3Ca^{2+} \quad [3]$$

- *reaction causes a decrease in Na concentration and an increase in Ca concentration.*

Kaolinite to Illite Transformation

$$2K^{+} + CaCO_{3(s)} + 3Al_2Si_2O_5(OH)_{4(s)} \Rightarrow 2KAl_2(AlSi_3)O_{10}(OH)_{2(s)} + Ca^{2+} + 4H_2O + CO_2 \quad [4]$$

- *reaction causes increased Ca and decreased K concentrations.*

Smectite to Illite Transformation

$$3[Ca_{0.33}(Mg_{0.33}Al_{1.66})Si_4O_{10}(OH)_2 \cdot nH_2O]_{(s)} + 2K^{+} + Al^{3+} + CaCO_{3(s)} \Rightarrow 2[KAl_2(AlSi_3)O_{10}(OH)_2]_{(s)} + 2Ca^{2+} + Mg^{2+} + CO_2 + 6SiO_{2(s)} + (n+1)H_2O \quad [5]$$

- *reaction causes a decrease in K and increase in Ca and Mg concentration.*

Stable O and H isotope data for Michigan Basin brines are available from studies represented by the UW database and from other unrelated research projects (e.g., Clayton et al., 1966; Wilson and Long, 1993a,b; McIntosh and Walter, 2005, 2006). Isotope data for southwest Ontario brines in the UW database (TDS >100 g/L) are presented in Figure 5.4. The isotopic signatures of these brines are typical of brines in sedimentary basins in that they are enriched in ^{18}O relative to modern meteoric water, plotting to the right of the Global Meteoric Water Line (GMWL). There are several possible causes of this ^{18}O enrichment but it is generally thought to result from extensive water-rock interaction or evaporation of sea water. Interpretation of the shift in ^{18}O and ^{2}H data to the right of the GMWL is necessarily equivocal because of uncertainties such as: i) the sea water isotopic composition during the Paleozoic, ii) the isotope-evolution pathway during evaporation, iii) the isotopic composition of carbonate (and other) minerals that may exchange isotopes with the brine, and iv) the temperature at which isotopic exchange occurred. Wilson and Long (1993a,b) present stable isotope data from groundwater in Silurian and Devonian carbonate formations in northern Michigan, and they provide a detailed interpretation in terms of evolutionary history of the brines. Consistent with the interpretation arising from the major-ion chemistry, they suggest that the isotopic composition of the brines could evolve away from the GMWL as a result of evaporation of sea water and isotopic exchange with carbonate minerals. The trajectory of the evolution path away from the GMWL is shown on Figure 5.5, in which evaporative concentration factors 4×, 10×, and 45× are indicated. The extrapolation of the trajectory to the extreme concentration factor of 45× comes from Knauth and Beeunas (1986). Wilson and Long (1993a) note that trends in the major-ion and isotope data are inconsistent beyond concentration factors of 10× and they state that the observed shift in isotopic compositions to the right of the GMWL can not be explained by evaporative concentration alone.

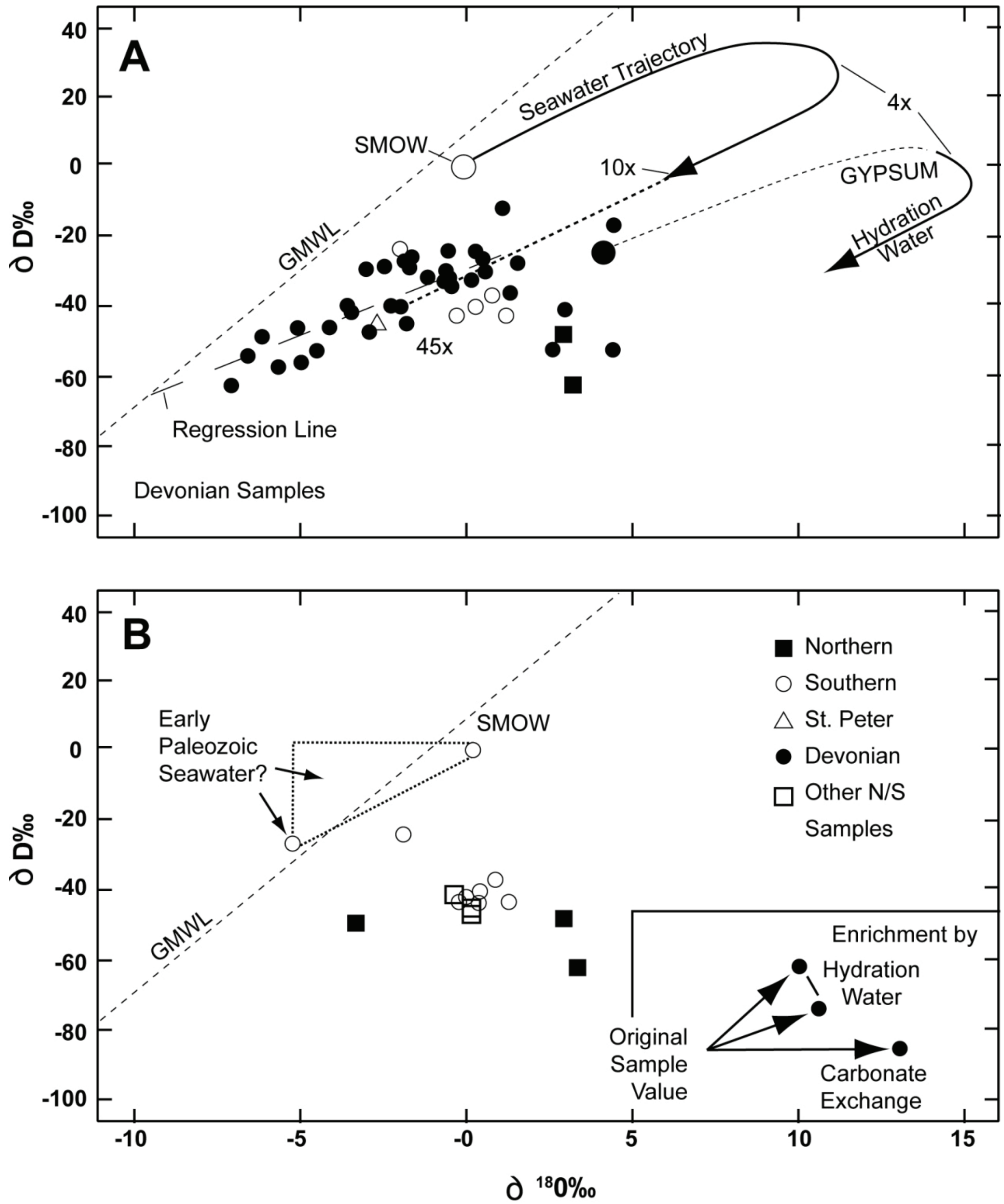


Figure 5.5 (A) δD vs δ^{18}O for the Niagaran and Salina, and (B) δD vs δ^{18}O for the brines from Silurian reefs in southern Michigan (from Wilson and Long, 1993b).

The relative importance of these mechanisms for ^{18}O enrichment of the brines with respect to the GMWL is uncertain. Evaporation of a sea water precursor may be partly responsible but it is generally believed that enrichment occurs as a result of water-mineral interactions wherein relatively heavy isotopes in minerals are exchanged with lighter isotopes in the fluid (Kyser and Kerrich, 1990; Hanor, 1994). The consistently greater enrichment of Silurian carbonates compared to Silurian sandstones (Figure 5.4) suggests that exchange with carbonate minerals may be the principal contributor to the observed enrichment. Isotopic exchange reactions are known to be kinetically inhibited at low temperatures, consequently, isotopic enrichment with respect to the GMWL such as that observed for groundwater in Silurian and Ordovician sediments in southwestern Ontario, is generally understood to reflect a combination of elevated temperature and very long residence time for the fluid in the rocks. Temperature increases are expected during burial and during hydrothermal fluid migration events associated with orogenesis (see Section 5.3.2.1). The occurrence of distinct groupings in the data (Figure 5.4), particularly for Silurian, Ordovician and Cambrian sandstone and carbonate formations, also suggests that the groundwater has been resident in the respective formations for a very long time, with no cross-formational mixing, thereby allowing the water isotopes to evolve to distinct compositions.

Further evidence for modification of sea water-derived brines by diagenetic reactions can be obtained from measurements of Sr isotope variations in brine samples collected from different stratigraphic levels within the basin (McNutt et al. 1987; Stueber et al. 1987). This approach is based on the knowledge that the $^{87}Sr/^{86}Sr$ ratio of sea water is constant globally at any given time (Qing et al., 1998), and that it has oscillated systematically through the range 0.7076 – 0.7092 over the Cambrian to the Mississippian periods (Veizer and MacKenzie 2005; Figure 5.6). The $^{87}Sr/^{86}Sr$ ratio of basin brines formed from evaporated sea water should therefore reflect the isotopic composition of sea water at the time of brine formation. With increased time, the $^{87}Sr/^{86}Sr$ ratio of the brine is expected to change as a result of water-rock reactions – primarily as a result of the dissolution of Sr-containing feldspar minerals, and the *in situ* production of radiogenic ^{87}Sr by decay of ^{87}Rb ($t_{½} = 4.9 \times 10^{10}$ a) contained in clays. Strontium substitutes for Ca in feldspars that may contain relatively high Rb/Sr ratios, and as a result, the $^{87}Sr/^{86}Sr$ ratio in these minerals is elevated by enrichment of ^{87}Sr from ^{87}Rb decay. Leaching of Sr from these minerals during diagenesis, leads to an increase in the $^{87}Sr/^{86}Sr$ ratio in brines. Similarly, Rb that has substituted for K in clay-mineral assemblages decays to produce ^{87}Sr that may leach into solution and cause an increase in the $^{87}Sr/^{86}Sr$ ratio of the brine. McNutt et al. (1987) observe a general enrichment of $^{87}Sr/^{86}Sr$ ratios in Michigan Basin brines compared to the sea water curve (Figure 5.6) and they conclude that the enrichment reflects modification of the initial sea water signature by water-rock reactions. Given the very long half-life for ^{87}Rb, it is likely that the observed increase in the $^{87}Sr/^{86}Sr$ ratios of the brines results primarily from leaching of enriched Sr from feldspar minerals. This inference is supported by the Sr:Br ratios that are well above the sea water evaporation trend (Figure 5.2).

Drawing on the results of research on the origin of brines in sedimentary basins around the world (e.g., Hanor, 1994, 2001), as well as, research focused specifically on the Michigan Basin (e.g., McNutt et al., 1987; Wilson and Long, 1993a,b), the most likely explanation for the high salinity of the formational brines is that they are derived from evaporated sea water which was subsequently modified by diagenetic reactions. Most of the marine sediments in the Michigan Basin are older than 350 million years, suggesting that the brines have been resident in the sediments of the basin for that length of time or longer. The gravitational stability afforded by the accumulation of dense brines in the sediments of the basin is one of the contributing factors to this long residence time. Other factors include low permeability formations overlying the DGR, horizontally bedded laterally predictable stratigraphy, tectonically stable, and insufficient hydraulic gradients (Sykes et al. 2008). The evidence presented for the origin and age of the

Michigan Basin brines is in support of the tenet: *Solute Transport is Diffusion Dominated: deep groundwater regime is ancient showing no evidence of cross-formational flow or glacial perturbation*, but it does not rule out the possibility that formation fluids have been mobile within the basin during Paleozoic tectonic events, as is discussed in Section 5.3.2.

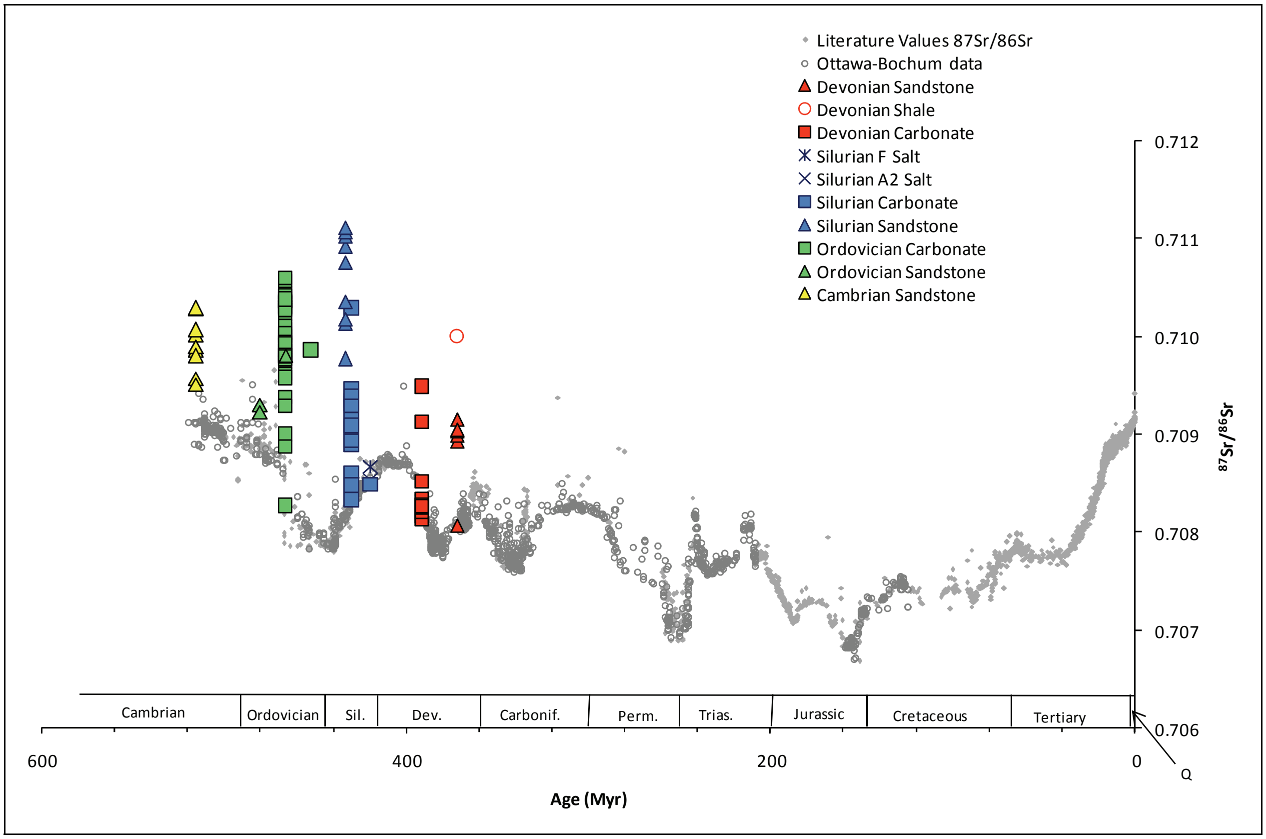


Figure 5.6 **$^{87}Sr/^{86}Sr$ variations for the Phanerozoic sea water based on 4,055 samples of brachiopods, belemnites, and conodonts, normalized to NBS 987 of 0.710240 (after Veizer and MacKenzie, 2005). The data from the UW database, including those reported by McNutt et al. (1987), are superimposed on the sea water curve to illustrate the isotopic enrichment of the groundwater.**

5.3.2 Michigan Basin: Evidence for Fluid Migration

It is important to distinguish between the concepts of flow and solute transport by noting that solute transport results from the combined influence of advection and diffusion. Consequently, solute transport will occur in the absence of advection (flow) provided there is a concentration gradient to drive diffusion.

There is evidence to indicate the occurrence of cross-formational flow within the Michigan Basin in deep Paleozoic formations up to Mesozoic times. There is also evidence of cross formational flow during Pleistocene times due to glacial recharge events to the top of the Salina Formation anhydrite deposits in southern Ontario. The following sub-sections discuss these ancient and more recent events.

5.3.2.1 Ancient Events

As noted in the preceding discussion on the origin of the brines in the Michigan Basin, the presence of hypersaline brines in the sediments should result in a gravitationally stable system, and fluid flow would not be expected without a large perturbation to the system. In a review of fluids in sedimentary basins Kyser and Hiatt (2003) acknowledge this fact, noting that fluids in sedimentary basins normally will not flow without changes to hydraulic gradients and most of these are tectonically induced. The principal tectonic influences on the Michigan Basin occurred during the Paleozoic Era in relation to Appalachian mountain building and were intimately linked to the processes of subsidence and sedimentation that created the Michigan Basin (Howell and van der Pluijm, 1999).

There are numerous studies that provide evidence for tectonically-induced fluid migration in rocks of the Michigan Basin. Ziegler and Longstaffe (2000a,b) studied alteration of the uppermost Precambrian rocks in southwestern Ontario at the Precambrian-Paleozoic boundary, and in the Cambrian and Ordovician sedimentary rocks above the boundary. Based on their measurements of stable O and H isotopes in secondary chlorite, and K-Ar geochronology on secondary K-rich feldspar (Harper et al. 1995), they proposed a conceptual model in which the regional migration of brines responsible for forming the secondary minerals was induced by the Taconic orogenic event to the east, which began in the Late Ordovician. In this model, waters of marine origin trapped within Paleozoic formations within the Appalachian Basin moved westward and were focused along the unconformity between the Precambrian crystalline basement and the overlying Paleozoic sedimentary rocks. Ziegler and Longstaffe (2000a) also reported K-Ar dates and stable O and H isotope data from secondary illite formed at the Precambrian-Cambrian boundary in southwestern Ontario in the early to mid-Carboniferious

Gross et al. (1992) proposed a conceptual model for active fluid circulation during the Acadian orogeny in southern Ontario and western New York to explain the orientation and spatial distribution of an east-northeast-trending systematic calcite vein set in the Lockport dolomite. Fluid inclusion data indicate that these calcites precipitated at approximately 115 °C, which could suggest formation at depths $\geq$ 3 km.

Dolomite in Middle and Late Ordovician strata in Ontario, including the Trenton and Black River Groups, the Blue Mountain Formation, and the Georgian Bay Formation (Manitoulin area) was studied by Coniglio and William-Jones (1992), Middleton et al., (1993), and Coniglio et al. (1994). Two major types of dolomite were identified by Coniglio et al. (1994); a widespread ferroan 'cap' dolomite that overlies the Trenton Group, and dolomite that occurs in proximity to fractures or faults. Coniglio et al. (1994) and Taylor and Sibley (1986) report that the fracture dolomite post-dates the ferroan cap dolomite. Middleton et al. (1994) measured homogenization temperatures ranging between 100 and 220 °C in primary fluid inclusions from the fracture-related dolomite. These temperatures are substantially higher than those likely generated during peak burial of the sedimentary sequence, leading Coniglio et al. (1994) to suggest that the data reflect the influence of hydrothermal fluids but the heat source was not identified. On the basis of carbon and strontium isotope data, Coniglio et al. (2003) suggest that sea water-derived fluids are responsible for regional-scale dolomitization in the Middle Silurian Guelph Formation. Based on examination of primary fluid inclusions, the temperatures ranged between 65 and 130 °C (Coniglio et al., 2003, after Zheng, 1999), indicating that the fluids were hydrothermal in nature as suggested by Coniglio et al. (1994) for dolomite in Ordovician strata in Ontario. It is thought that fracture-related dolomitization and hydrocarbon migration in the Michigan Basin likely occurred during the Late Paleozoic to Early Mesozoic (Prouty, 1988; Hurley and Budros, 1990; Budai and Wilson, 1991). These authors compared fracture-related dolomite in the Michigan Basin with mineral alteration associated with Mississippi Valley-type (MVT) deposits in the central and eastern United States. These fluid-driven processes are considered to be contemporaneous, and were likely the result of the Alleghenian deformation and thrusting events taking place in the east.

Mississippi Valley-type lead-zinc mineralization occurs in the Middle Silurian dolomites in southern Ontario. On the basis of geographic and mineralogical differences sulfide mineralization was distinguished by two groups: i) occurrences in the Bruce District, which is northwest of the Algonquin Arch along the eastern margin of the Michigan Basin, and ii) occurrences in the Niagara District, which is southeast of the Algonquin Arch along the western margin of the Appalachian Basin (Farquhar et al., 1987). Sulfide mineralization is most prevalent in the Niagara District, with only sparse occurrences in the Bruce District (Farquhar et al., 1987). Lead isotope ratios ($^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$) for the Bruce District galena suggest that the Pb was derived from a crustal source distinct from the Pb in galena samples from the Niagara District (Farquhar et al. 1987). Similarly, results of Pb and Sr isotopic analyses of brines from producing oil and gas wells (McKenna et al. 1992), and brines from gas wells and dry wells (Dollar, 1988; and Dollar et al., 1991) indicate that groundwater in Ordovician formations within the Michigan Basin have a different origin than fluids in the Appalachian Basin. McNutt et al. (1987) measured the Sr isotopic composition of oil-field brines from the Michigan Basin and observed that brines obtained near the eastern edge of the basin in Ontario have Sr isotopic compositions that are very similar to samples from deeper within the basin in Michigan. They suggest that this is evidence for intra-basin fluid migration over distances of 100's of kilometres. Although these mineralizing brines have migrated internally within the basins, the Pb and Sr isotope data do not indicate mixing between Michigan and Appalachian Basin fluids.

Hydrocarbons are obvious examples of fluids that have migrated within the sedimentary rocks of the Michigan Basin. Powell et al. (1984) conducted geochemical characterization of hydrocarbons in southwestern Ontario. They demonstrated the occurrence of Cambro-Ordovician oils in two Silurian reservoirs, indicating cross-formational flow between source-rock regions and the reservoirs. Similarly, Barker and Pollock (1984) used chemical and isotopic evidence to demonstrate that Silurian, Ordovician and Cambrian formations hosting gas are not sufficiently mature to have provided a source for the gas. They suggested that the natural gas accumulated by lateral migration into southwestern Ontario from more mature source rocks deeper in the Michigan and Appalachian Basins. Sherwood-Lollar et al. (1994) characterized natural gas from Ordovician and Cambrian strata using isotopic and compositional indicators. They found that the gases have a thermogenic origin consistent with temperatures in excess of 75°C expected at the postulated burial depths of the Cambrian and Ordovician sediments. Samples from wells where the sedimentary rocks are in direct contact with the Precambrian basement strata had anomalously high He concentrations, and based on the elevated He concentrations and $^{3}He/^{4}He$ ratios, Sherwood-Lollar et al. (1994) suggested that the gas originated from a mixing process between gas produced in situ within the Cambrian and Ordovician strata, and a He-enriched end-member that was derived from deep within the Precambrian basement. Based on the structural interpretation of the Chatham Sag, identification of pinch-out structures in oil and gas reservoirs (Sanford et al. 1985; Carter et al. 1996), and data on the temperature of emplacement and maturity of the hydrocarbons, Sherwood-Lollar et al. (1994) also 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. Consequently, results from studies of the hydrocarbon geochemistry are consistent with the Pb and Sr isotopic data in that they indicate intra basin fluid migration for the Appalachian and Michigan basins, but not migration between the basins.

5.3.2.2 Pleistocene and Post-Pleistocene Recharge Events

The widespread occurrence of ancient brines in the basin demonstrates that, under most conditions prevalent since the Paleozoic, it has not been possible for hydraulic heads generated in freshwater aquifers at the top boundary of the basin to drive recharge events capable of displacing the brines. There is one major exception to this statement. Glacial meltwater beneath continental ice sheets can be pressurized to achieve freshwater hydraulic heads far in excess of ambient heads during interglacial periods. It has been demonstrated that these conditions have been effective in causing recharge of glacial meltwater to depths of several hundred metres in Paleozoic aquifers around the periphery of the Illinois and Michigan Basins (see McIntosh and Walter, 2005, 2006; Person et al., 2007 and references therein). Stable O isotope data provide the best evidence for recharge of glacial meltwater which displays strongly depleted δ^{18}O values (between -25 and -11 ‰), and this cold-climate water can be distinguished from: i) hypersaline basinal brines which have δ^{18}O values ranging between -6 and +2 ‰ (Figure 5.4) and ii) modern recharge in southwestern Ontario which has δ^{18}O values ranging between -11 and -9 ‰ (Husain et al., 2004). In addition, ^{14}C analyses suggest the ^{18}O-depleted waters were recharged during the Pleistocene (McIntosh and Walter, 2005, 2006).

Although stable O and H isotopic data demonstrate that fresh glacial meltwater has recharged around the periphery of the Michigan Basin, the composition of the recharged water has been significantly altered by mixing with ancient hypersaline brines and by dissolution of evaporite minerals. Evidence for these changes in water chemistry is reviewed in detail by McIntosh and Walter (2005, 2006) who use major-ion chemistry to interpret the degree of mixing and the nature of mineral-water interactions that have influenced the chemistry of the Pleistocene recharge water. The conceptual model developed by McIntosh and Walter (2006) for Pleistocene recharge around the margins of the Michigan Basin is presented in Figure 5.7. Their research suggests that glacial melt water has penetrated to depths up to 300 m in Silurian-Devonian carbonate aquifers in Michigan.

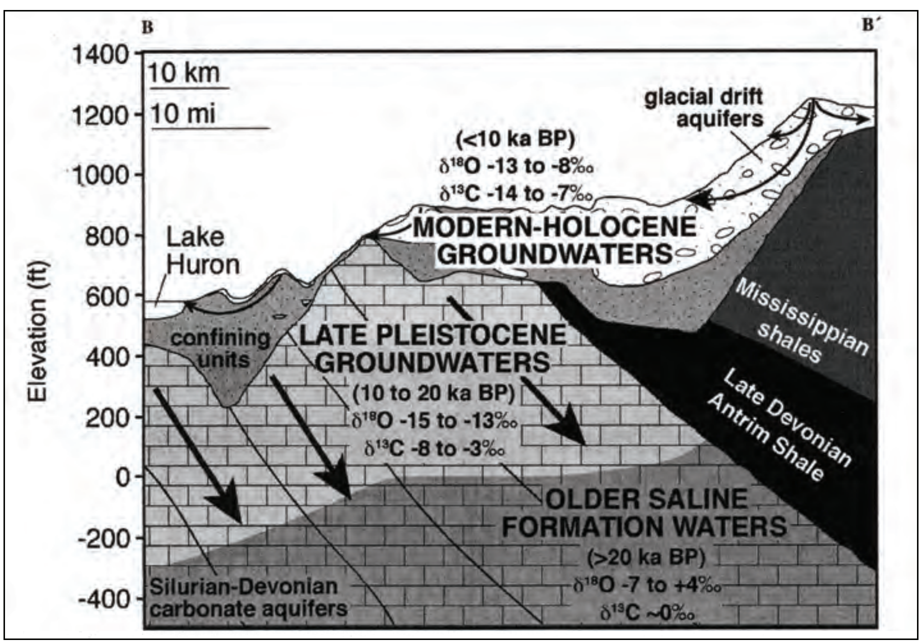


Figure 5.7 Conceptual model developed by McIntosh and Walter (2006) showing ancient brine at depth, cold-climate water recharged during the Pleistocene at mid depths, and modern meteoric water near the surface.

Utilizing the UW database, the concentrations of Cl plotted versus Br (Figure 5.3) display trends that indicate: i) dilution of brines by lower salinity water; and ii) dissolution of halite. It is apparent from Figure 5.3 that many of the samples are likely to have been affected by dilution at some time during their history, causing them to move off the sea water evaporation curve toward the origin. There are a number of samples that plot above the sea water evaporation trend and this type of displacement is expected to result from halite dissolution.

The stable O and H isotopic signatures of groundwater from the Paleozoic rocks of southern Ontario are shown in Figure 5.8. The samples that have the most enriched $\delta^{18}O$ values also have the highest salinity (samples shown in Figure 5.4), and are interpreted to represent ancient brines derived from evaporated sea water. A number of the shallowest samples, from depths of 140 m or less in Devonian and Silurian formations, have more depleted $\delta^{18}O$ values that are typical of present-day meteoric water and plot along the GMWL. In Ontario, glacial waters have been observed in shallow bedrock aquifers at depths of 130 m below ground surface in wells of the Alliston aquifer (Aravena et al., 1995). In Figure 5.8, some data for Silurian sandstones and for one group of groundwaters from Ordovician carbonates, plot between the meteoric water and brine end members consistent with a trend toward depletion of $\delta^{2}H$ and $\delta^{18}O$ that would result from mixing of meteoric water with brine. The trajectory for Cambrian sandstone samples is relatively flat with decreasing $\delta^{18}O$ – possibly a result of mixing with $\delta^{2}H$ enriched brines characteristic of the underlying Precambrian shield (Frape et al. 1984). There are a small number of samples that display highly depleted $\delta^{18}O$ values that plot along the GMWL, which is typically a result of mixing with cold-climate water. These waters were sampled from Devonian- or Silurian-aged formations at depths of less than 100 m.

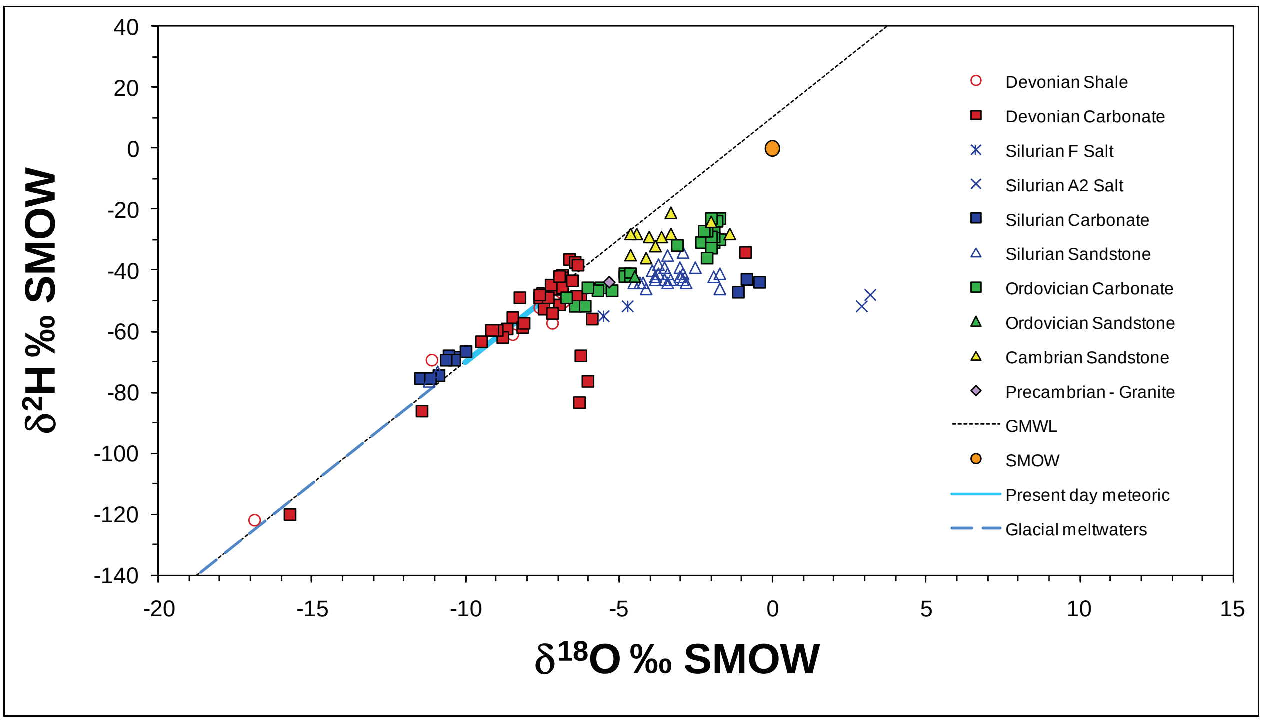


Figure 5.8 Hydrogen versus oxygen isotopic signatures for all fluids within the UW hydrogeochemical database.

Evidence presented by McIntosh and others for recharge of cold-climate water is based on data from groundwater sampling programs, and the data are from aquifers, which by definition are sufficiently permeable to permit groundwater flow. The Paleozoic rocks of southwestern Ontario, particularly rocks of Ordovician age, can not be considered aquifers. Mazurek (2004) compiled hydraulic conductivity data for Paleozoic rocks in southwest Ontario and reports geometric mean values of hydraulic conductivity for Ordovician rocks in all cases lower than 1×10^{-10} m/s, and maximum measured values on the order of 1×10^{-8} m/s. Most recently, straddle packer testing of Silurian and Ordovician formations intersected by drill holes DGR1 and DGR2 at the Bruce site indicates that the horizontal hydraulic conductivity values are very low. The highest recorded value is 1.3×10^{-8} m/s in the Silurian Guelph – Goat Island formation, and with the exception of three intervals, all values are on the order of 10^{-11} m/s or lower (Roberts et al. 2008).

The stable isotope data presented in Figure 5.8 are consistent with the Cl-Br data presented in Figure 5.3 in that they indicate mixing has occurred in the shallow formations between saline brines and more dilute water. Most of the samples from southern Ontario that are affected by dilution display isotopic signatures consistent with recent, rather than cold-climate recharge. Most of the samples that display evidence of mixing with meteoric water are from Devonian and Silurian formations which, in southern Ontario, occur at shallow depths and are commonly overlain by unconsolidated glacial overburden. These formations are therefore directly exposed to waters of Pleistocene and younger age. It is also important to note that in regions where significant petroleum production has occurred, dilution may have resulted from the injection of surface water to enhance petroleum production. Weaver et al. (1995) report the occurrence of detectable ^{3}H in five of ten samples that they analyzed (values between 1.1 and 37.7 TU), strongly suggesting that the formation waters in Devonian petroleum fields of southern Ontario have been influenced by surface water as a result of production activities.

5.4 Hydrogeochemical Data from the Bruce Site

Hydrogeochemical site characterization activities to date focused on the collection of data that could:

a) assist in identifying the age and origin of the porewater and groundwater underlying the Bruce site;
b) provide evidence of meteoric water recharge;
c) allow for estimation of the redox conditions present in the Ordovician shale and limestone formations; and
d) provide constraints on the processes governing solute-transport, particularly in the Ordovician rocks.

The hydrogeochemical characteristics of the porewater and groundwater that underly the Bruce Site are obtained by direct sampling in the case of groundwater (Jackson and Pinder, 2008), and by use of leaching/extraction techniques for porewater in low-permeability rocks (Clark et al., 2008; RWI, 2008). In an attempt to determine the major-ion concentrations in porewater, samples are crushed, dried and leached with distilled water. The leachate analyses are normalized to the water content of the samples (analogous to water-loss porosity) in order to obtain approximate porewater concentrations. The porosity-normalized leach solution concentrations are hereinafter referred to as leachate solutions. There are uncertainties that relate to the accuracy of porosity measurements and the influence of soluble salts, therefore the leachate solutions are not presented as being equivalent to porewater concentrations. Stable water isotope compositions were determined by vacuum distillation techniques (Clark et al., 2008). Potential uncertainties related to incomplete water yields and/or release of structurally bound water (e.g. clay minerals and gypsum) could contribute to experimental results. Subject to on-going independent experimental verification, reported results for major-ion and stable water isotope compositions are considered preliminary

5.4.1 Age and Origin of the Porewater and Groundwater Underlying the Bruce Site

The Cl and Br concentrations in the groundwater and leachate solutions are very low near the ground surface (Figure 5.9). The deepest groundwater sample in the Silurian was collected at approximately 140 m depth, but the concentrations of Cl and Br in the leachate solutions increase steadily with depth to the top of the Ordovician (447.65 mbgs). The concentrations in the leachate solutions remain constant versus depth through the Ordovician shales and the Cobourg Formation limestone (447.65 to 686.5 mbgs), and then decrease slightly in the Ordovician carbonate rocks that underlie the Cobourg Formation. These characteristics of the Cl and Br concentration profiles are representative of trends observed in the leachate solution concentration profiles for the other major ions (Na, Ca, Mg and K). At approximately 850 m depth an increase in formation permeability provided another opportunity to collect a groundwater sample, and there is good correspondence between the geochemical characteristics of the groundwater and the leachate solutions at this depth (Figure 5.9).

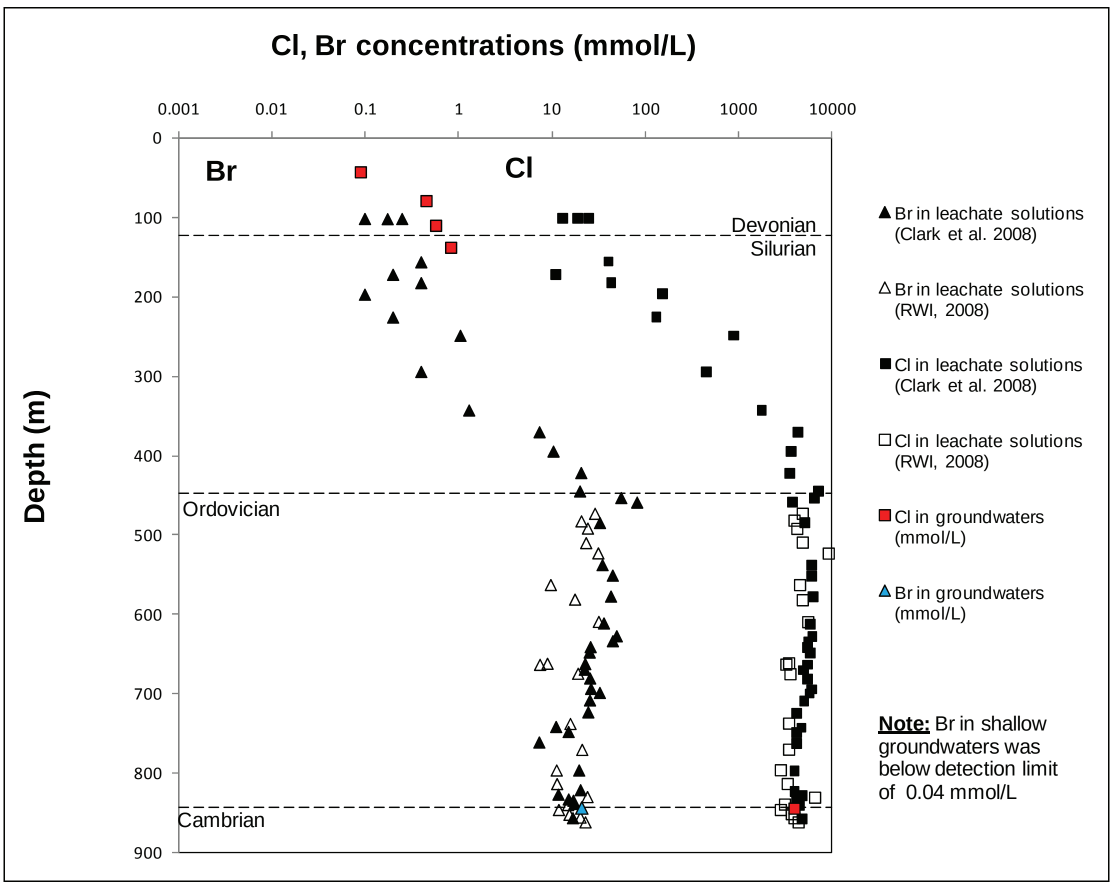


Figure 5.9 Profiles of Cl and Br concentrations in groundwater and in waters extracted from the rock matrix (leachate solutions).

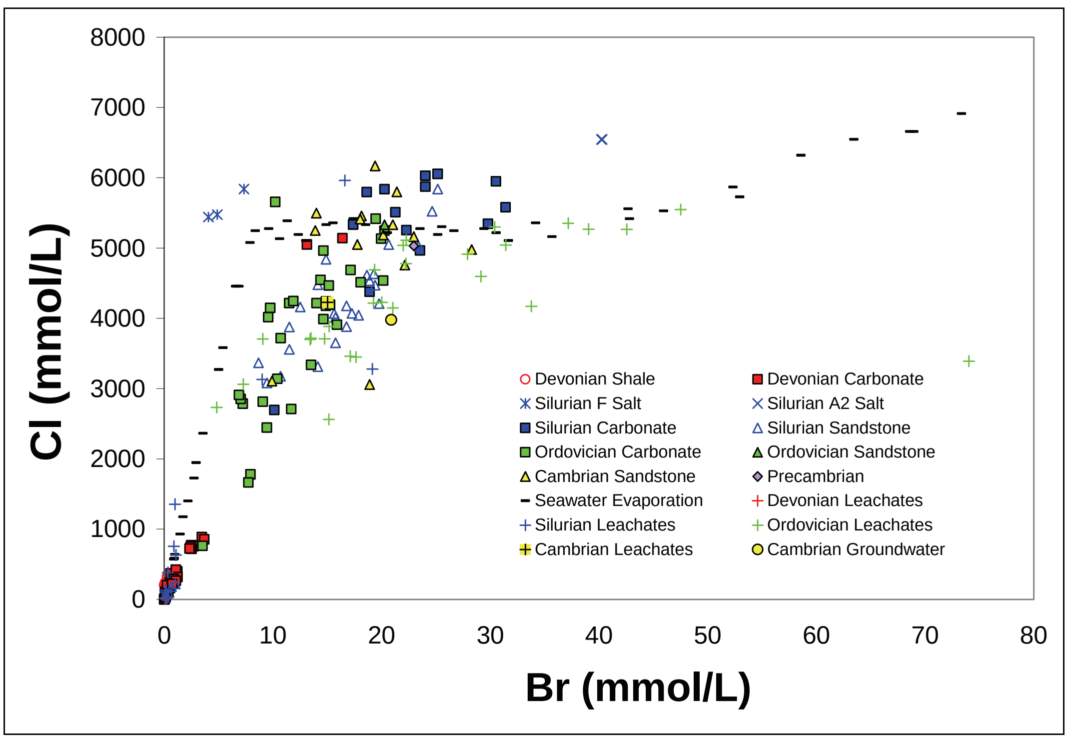
The Cl and Br profiles indicate that high-concentration brines are present at all depths below the top of the Ordovician. The brines that are present in the Ordovician and Cambrian are hypersaline – salinity of 320 g/L was measured for groundwater collected from the Cambrian (Jackson and Pinder, 2008). A strong correlation between Cl and Br concentrations is evident in Figure 5.9, and this is consistent with expectations for an evaporated sea water origin for the brine. The following observations are made when the major-ion data for groundwater and leachate solutions from the Bruce site and the UW database are compared to the respective sea water evaporation data from McCaffrey et al. (1987) in Figure 5.10:

a) Many of the Cl and Br concentrations in leachate solutions appear to be highly evolved with respect to the sea water evaporation curve, particularly in Ordovician samples, but similar to the samples from oil-field brines, there is evidence for dilution by meteoric water or sea water. With the exception of one sample from the Silurian, Cl and Br data plot below the sea-water evaporation curve, suggesting that salt dissolution is not an important control on the concentrations of the leachate solutions.

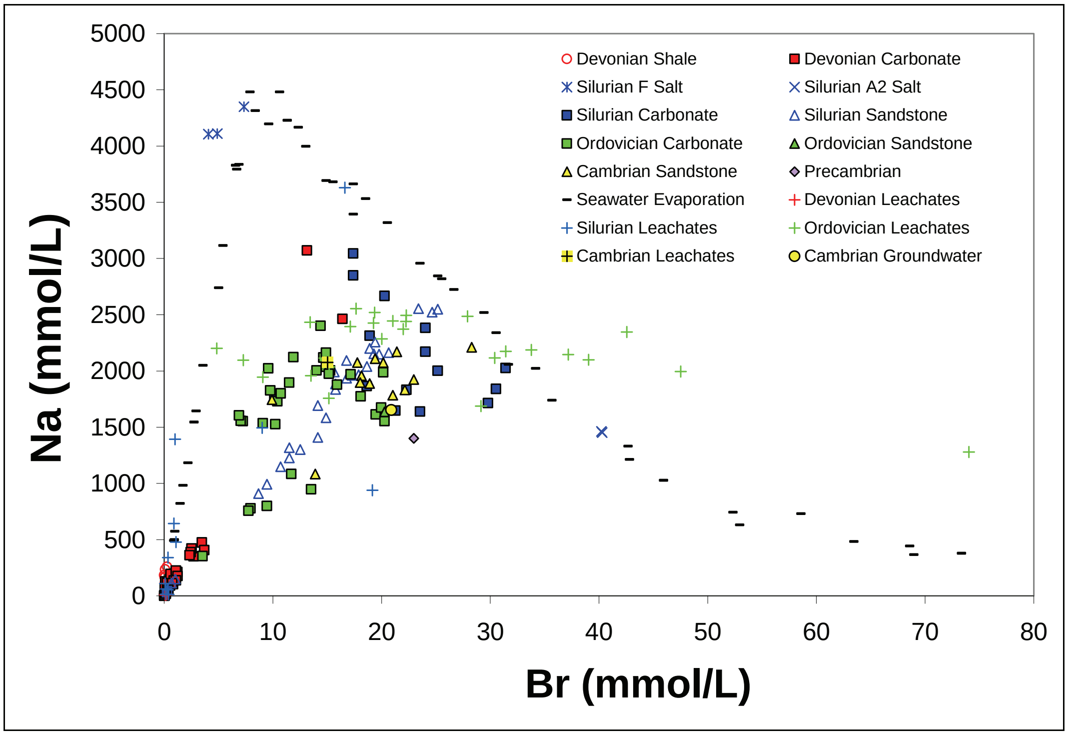
b) In general, fields defined by leachate solutions from the Bruce site for Silurian, Ordovician and Cambrian samples match well with the respective fields from samples in the UW database. Potassium is an exception with concentrations in leachate solutions from Ordovician samples that are approximately two or three times greater than groundwater samples from Ordovician formations in the UW database.

c) Concentrations of major cations in the leachate solutions display deviations from the sea water evaporation curve as would be expected as a result of water-rock interactions.

A)

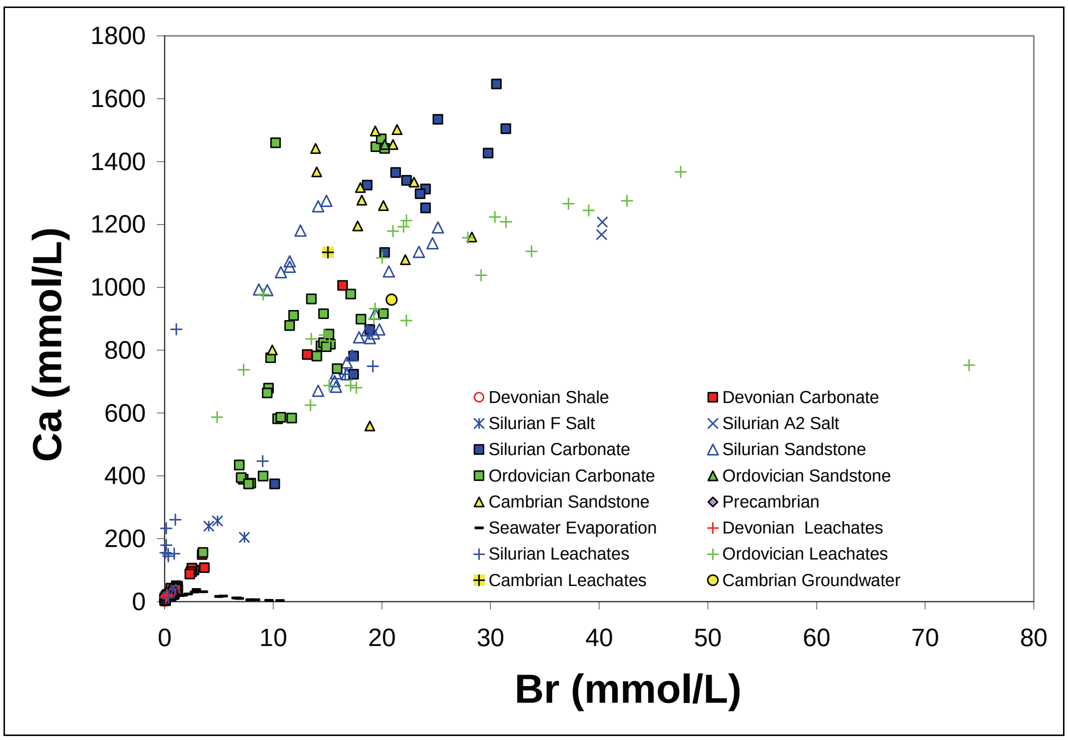


B)



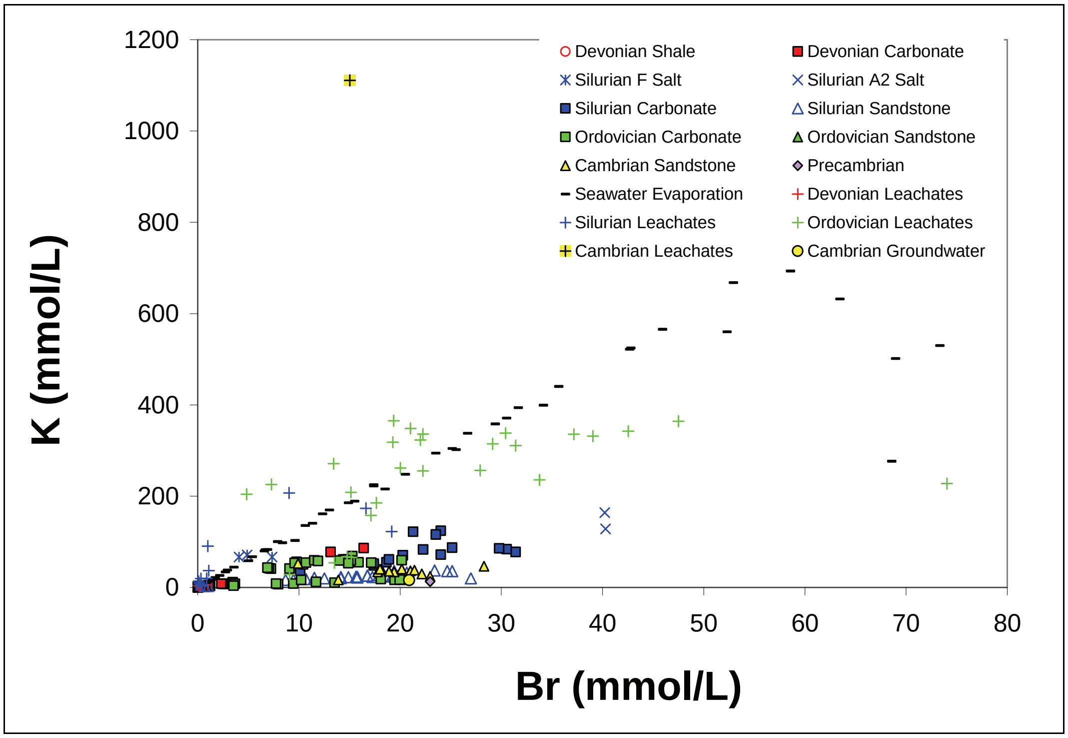
Na (mmol/L)
Br (mmol/L)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
10
20
30
40
50
60
70
80
Devonian Shale
Devonian Carbonate
Silurian F Salt
Silurian A2 Salt
Silurian Carbonate
Silurian Sandstone
Ordovician Carbonate
Ordovician Sandstone
Cambrian Sandstone
Precambrian
Seawater Evaporation
Devonian Leachates
Silurian Leachates
Ordovician Leachates
Cambrian Leachates
Cambrian Groundwater

C)



Ca (mmol/L)
Br (mmol/L)
0
200
400
600
800
1000
1200
1400
1600
1800
0
10
20
30
40
50
60
70
80
Devonian Shale
Devonian Carbonate
Silurian F Salt
Silurian A2 Salt
Silurian Carbonate
Silurian Sandstone
Ordovician Carbonate
Ordovician Sandstone
Cambrian Sandstone
Precambrian
Seawater Evaporation
Devonian Leachates
Silurian Leachates
Ordovician Leachates
Cambrian Leachates
Cambrian Groundwater

D)



E)

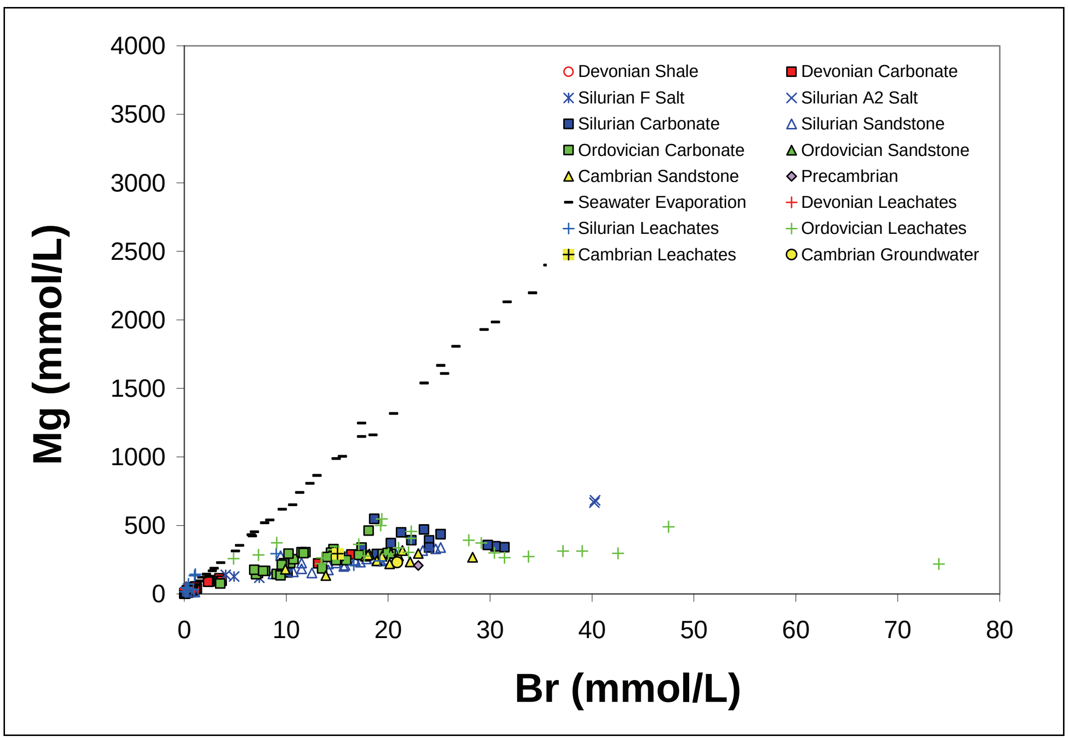


Figure 5.10 Comparison of major ion concentrations versus Br for leachate solutions from drill cores DGR1 and DGR2, with groundwater data from the UW database.

The stable O and H isotopic data from the regional groundwater samples in the UW database and the drill core samples from the Bruce site are compared in Figure 5.11. Similar to the regional groundwater samples, many of the data points from Devonian and Silurian formations at the Bruce site and in the UW database display relatively depleted δ^{18}O and plot close to the GMWL in the ranges of Pleistocene and recent meteoric water. The groundwater data in the UW database from Ordovician limestone formations form two well-defined clusters. Of the two, the cluster closest to the GMWL represents samples from drill holes in which the groundwater is known to have been diluted by drilling fluid (present-day meteoric water) - sampling depths range from 70 to 370 m. The second cluster with more enriched values of δ^{2}H and δ^{18}O are the deep end members. Waters obtained by vacuum distillation from the rock matrix using core from the Bruce site are slightly more scattered, and most of the samples plot to the right of the GMWL, but are not as enriched as the deep groundwater samples from the UW database.

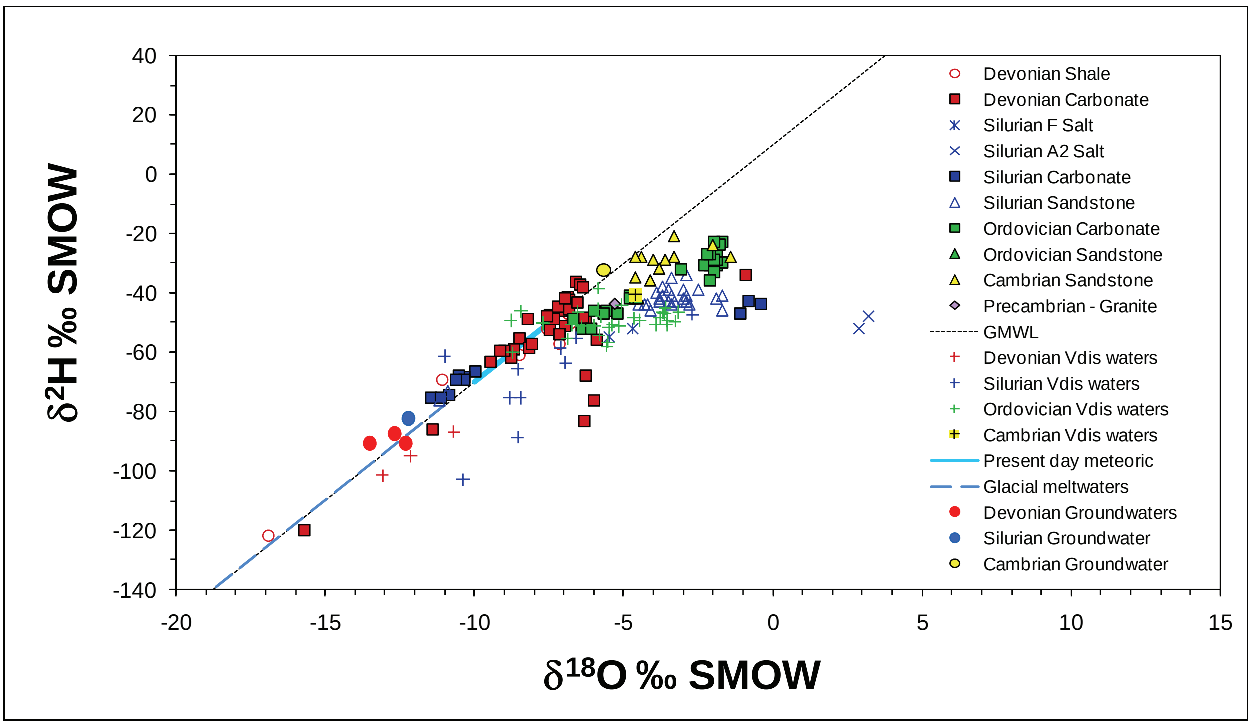


Figure 5.11 Stable O and H isotopic data from regional groundwater sampling in southwestern Ontario (UW database) and from site characterization at the Bruce site (Clark et al. 2008). "Vdis waters" are waters from the rock matrix obtained by vacuum distillation.

The major-ion compositions of the leachate solutions indicate that highly concentrated brines occur through the Ordovician below the Bruce site. In accordance with the discussion in Section 5.3.1, the brine characteristics are consistent with an evaporated sea water origin for the brine – subsequently modified by water-rock interactions, and in many cases, dilution by meteoric water or sea water. In addition, the stable O isotope compositions of the Ordovician porewater display enrichment in δ^{18}O such that the data plot to the right of the GMWL, which is generally considered to reflect water-rock interactions and very long residence time.

5.4.2 Meteoric Water Recharge

The trend toward low major-ion concentrations near the surface, as indicated in Figure 5.9 by low Cl and Br concentrations, likely results from diffusive or advective mixing of surface-derived meteoric water with formational brines within the Silurian formations. This interpretation is supported by $\delta^{18}O$ and $\delta^{2}H$ data for groundwater and waters from the rock matrix obtained by vacuum distillation (Figure 5.12). The $\delta^{18}O$ and $\delta^{2}H$ data for groundwaters and vacuum-distilled waters from the Devonian and upper Silurian formations are relatively depleted with respect to those from the lower Silurian and Ordovician formations. Both groundwaters and vacuum-distilled from Devonian and Silurian formations waters have stable isotopic values in the range expected for meteoric water originating some time between the Pleistocene ($\delta^{18}O$ -25 to -11 ‰; $\delta^{2}H$ -190 to -78 ‰) and the present ($\delta^{18}O$ -11 to -9 ‰; $\delta^{2}H$ -70 to -50 ‰).

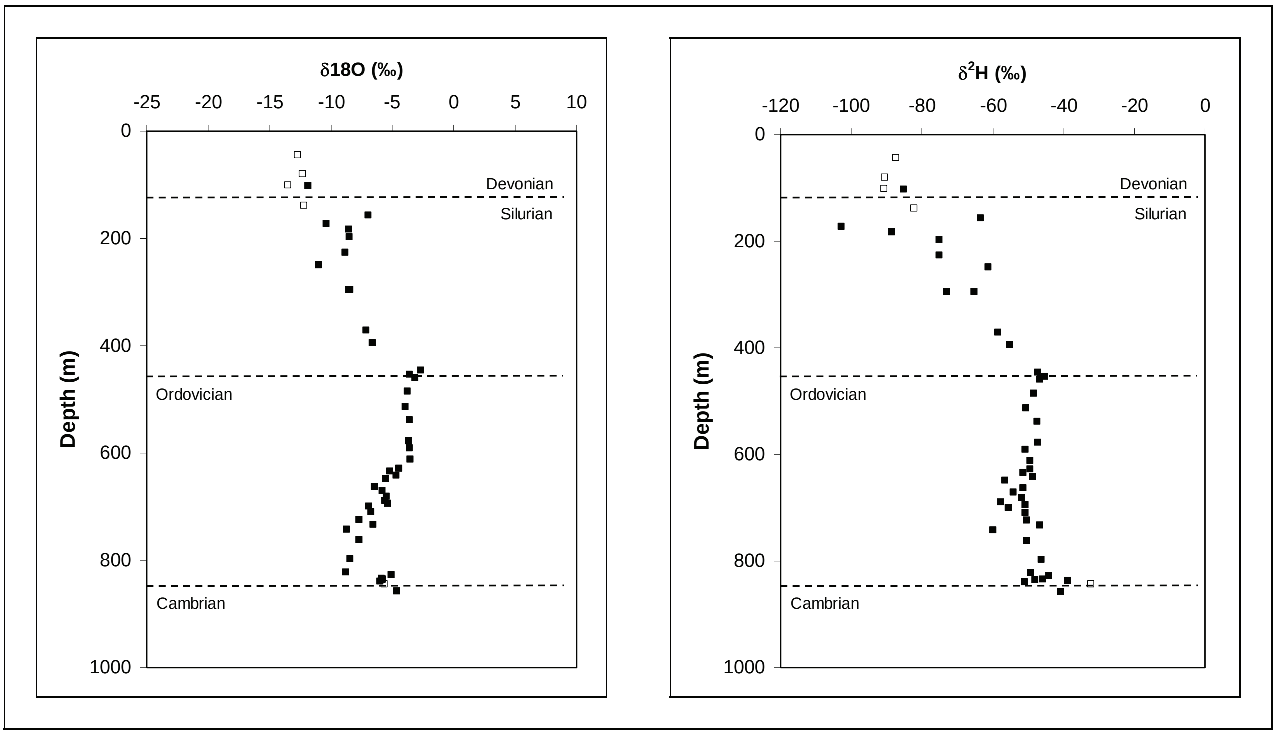


Figure 5.12 Profiles of $\delta^{18}O$ and $\delta^{2}H$ in groundwater (open symbols) and vacuum-distilled water from the rock matrix (closed symbols).

Generation of these profiles over a distance of 300 to 400 m by diffusive transport would require very long time periods, and the possibility that diffusion can explain these profiles will be further investigated in future work. It is also possible that meteoric water has penetrated advectively through permeable units within upper Silurian (Bass Islands) and lower and middle Devonian (Bois Blanc and Detroit River Group) formations. The major-ion and isotope data suggest that meteoric water has influenced the porewater and groundwater compositions to depth in the Silurian, but the exact depth to which advective recharge of meteoric water occurred may be obscured by: i) analytical uncertainties in the porewater isotopic composition, and ii) by diffusive modification of the profiles – particularly if sub-glacial recharge occurred during the Pleistocene.

5.4.3 Redox Conditions in the Ordovician Shales and Limestones

Redox conditions can be defined generally in terms of the principal redox couples that control the oxidation state at a given depth (e.g., Fe^{2+}/Fe^{3+}; S^{2-}/SO_4^{2-}; CO_2/CH_4). It is commonly possible to determine the dominant redox couple by analysis of dissolved gases, stable carbon isotope ratios and the distribution of redox-sensitive minerals. Mineralogical and geochemical evidence (Schandl, 2008; Activation Laboratories, 2008) indicates that sulfide minerals – predominantly pyrite – and organic carbon are common throughout the stratigraphic sequence, particularly below the Silurian. The presence of these materials suggests that redox conditions are likely to range from sulphate reducing to methanogenic.

Analyses of the concentration and stable C isotope ratios for CO_2 and CH_4 were conducted on gases released from core samples during vacuum distillation (Clark et al. 2008). The CH_4 data display elevated concentrations in a zone extending downward from the Georgian Bay shale, through the Blue Mountain shale and into the Cobourg Formation limestone, and a second zone of elevated concentrations in the Gull River Formation. Stable isotopic data indicate that CH_4 in the upper zone is biogenic in origin, while CH_4 in the Gull River formation is likely thermogenic (Clark et al. 2008). The evidence for methanogenesis has been obtained from analyses of pore gas extracted from low permeability shale and limestone samples. Beneath the Bruce site, these formations would not be considered as commercial shale gas resources due to the absence of natural gas shows during the drilling of boreholes DGR1 and DGR2 and the moderate thermal maturity of the Collingwood and Blue Mountain formations. However, the presence of methane at depth below the Georgian Bay Formation demonstrates that the redox conditions have remained strongly reducing.

The CH_4 concentrations are very low in the Queenston Formation shale – a shale unit that is commonly red indicating the presence of fine-grained hematite - suggesting that the redox state of the Queenston Formation is slightly less reducing than the Georgian Bay and Blue Mountain shale. However, detailed petrographic investigations of the Queenston Formation shale (Schandl, 2008) indicates that pyrite is ubiquitous and that the redox state is in the realm of sulphate reduction.

5.4.4 Solute Transport

The low values of hydraulic conductivity reported by Mazurek (2004) and Roberts et al. (2008), particularly at stratigraphic levels within the Silurian and below in the Ordovician, suggest that solute transport is dominated by diffusion. In support of efforts to assess diffusive solute transport, site characterization activities included plans to determine concentrations of species (e.g. $\delta^{18}O$, $\delta^{2}H$, Cl, Br) that could be expected to behave as natural tracers and thereby provide a basis for quantifying rates of solute transport in a manner similar to Rübel et al. (2002) and Gimmi et al. (2007).

In order to provide complimentary data that can be used to evaluate the natural tracer profiles, laboratory-scale diffusion measurements were undertaken to determine porewater diffusion coefficients for selected rock samples from Ordovician shale and limestone formations (Figure 5.13; Al et al. 2008). In future site characterization activities, these measurements will be extended upward into the Silurian rocks in order to gain an understanding of the diffusion properties throughout the stratigraphic profile.

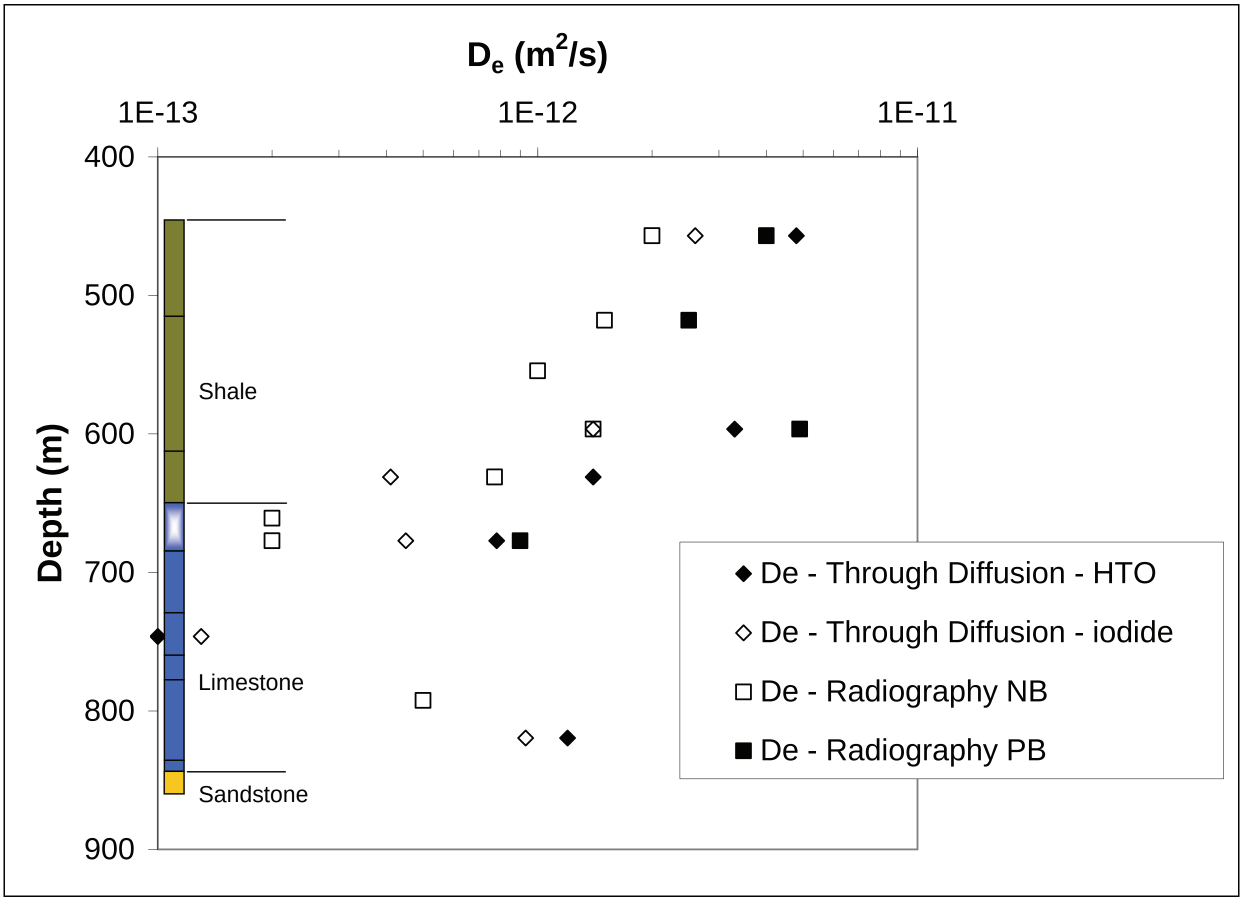


Figure 5.13 Results of laboratory-scale effective diffusion coefficient measurements conducted by Al et al. (2008). All radiography measurements are conducted with iodide tracer (NB = normal to bedding; PB = parallel to bedding).

5.4.4.1 Bromide and Chloride

Bromide ion is conservative in brine systems derived from sea water evaporation, except at very high salinity when K and Mg halide minerals form – Br partitions into these minerals to a slightly greater extent than it does into halite (Hanor, 1994). Consequently, Br should be a good tracer of solute transport in the porewater of the Michigan Basin below the Bruce site. Although the Cl ion may be slightly more susceptible to non-conservative behaviour as a result of precipitation or dissolution of halite, the Br and Cl profiles shown in Figure 5.9 demonstrate close correlation between these ion profiles, suggesting that Br and Cl may be used as conservative tracers in this system. It was noted in Section 5.4.2 that the decrease in Cl and Br concentrations toward the surface likely results from diffusive and/or advective mixing of surface-derived meteoric water with brines within the Silurian Formations. The profiles show very little change versus depth below the top of the Ordovician, suggesting that meteoric water has had no influence on the composition of the ancient brines below the lower Silurian formations.

5.4.4.2 Stable Isotopes

Similar to the Br and Cl profiles, the $\delta^{18}O$ and $\delta^{2}H$ profiles display evidence of diffusive and/or advective mixing between meteoric water at the surface and brines within the Silurian Formations (Section 5.4.2). The $\delta^{2}H$ profile through the Ordovician and into the Cambrian displays very little variation, suggesting there has been no disturbance of the isotopic composition of the brines at depth. However, there is a slight displacement of the $\delta^{18}O$ profile at the boundary between the Cambrian and the Ordovician, and it is unusual that covariance with $\delta^{2}H$ is not observed. In contrast with the observed shift toward relatively depleted $\delta^{18}O$ values in the Ordovician at the boundary, isotopic exchange between the porewater and carbonate minerals would be expected to cause enrichment of $\delta^{18}O$ in the porewater. The cause of this displacement is not understood at the present time and will be investigated further through: i) attempting to replicate these results in drill holes DRG3 and DGR4; and ii) attempting to verify the isotope analyses and observed trends with an independent technique.

5.5 Summary of the Regional Hydrogeochemical Interpretation

The following findings and conclusions were derived from a consideration of the hydrogeochemistry of the Michigan Basin and from an initial comparison of results from Phase I site characterization activities with the regional hydrogeochemistry of southwestern Ontario (UW database):

a) The current understanding regarding the origin of brines from the Michigan Basin indicates that they were formed by evaporation of sea water. At present, the major-ion concentrations (Ca, Mg, Na, K, Cl and Br) deviate from the concentrations that would be expected from evaporation of present day sea water, and these deviations are explained by : i) dilution of brines by lower salinity water; ii) dissolution of halite by meteoric water or sea water, and iii) diagenetic water-rock reaction processes, particularly dolomitization.

b) Brines that occur in association with hydrocarbons in southern Ontario originated from sea water by evaporation and water-rock interactions over time. Stable isotope data from the brines indicate enrichment of $\delta^{18}O$ relative to the GMWL and this enrichment is considered indicative of water-rock interaction and long residence time. Indications of long residence time from the stable isotope data support the interpretation of a marine origin for the brines.

c) Evidence for cross-formational flow exists for ancient events such as dolomitization of Ordovician and Silurian formations, the emplacement of Mississippi-type sulphide deposits in Silurian formations and emplacement of hydrocarbons within structural, stratigraphic or diagenetic (HTD) type traps in formations of Cambrian, Ordovician, Silurian or Devonian age. The presence of Cambrian-Ordovician oils in a limited number of Silurian reservoirs suggests that at least locally, some cross-formational flow of hydrocarbons occurred between reservoirs. Although the timing of these cross-formational flow events is not directly known, the requirement for sufficient driving forces for movement of these fluids suggests that these events occurred in association with tectonic or orogenic events; the most recent event being the Alleghenian Orogeny, which ended approximately 250 Ma BP.

d) Evidence exists in Devonian and Upper Silurian formations (above the F Unit) for ingress of Pleistocene or recent meteoric water, and displacement of ancient brines. In northern Michigan displacement has been documented to depths of 300 m at the margin of the basin. Available data from oil wells in southwestern Ontario indicate the presence of Pleistocene or more recent meteoric water to 140 m depth, but some of these samples may have been contaminated by surface water during petroleum production. In the UW database, the maximum depth at which waters with isotopic signatures indicative of glacial recharge are observed is 100 m below ground surface. In Ontario, glacial waters have been observed in shallow bedrock aquifers at depths of 130 m below ground surface in wells of the Alliston aquifer.

Furthermore, site characterization data from the Bruce site indicate:

a) Concentrated brines occur at all depths below the top of the Ordovician.

b) Similarly to groundwaters in the UW database, the major-ion composition of the Cambrian groundwater and leachate solutions from Silurian, Ordovician and Cambrian formations is consistent with an evaporated sea water origin. There is evidence in groundwaters sampled from Devonian and Upper Silurian formations for dilution by meteoric water (recent or Pleistocene). With the exception of one sample from the Silurian, Cl and Br data plot below the sea water evaporation curve, suggesting that salt dissolution is not an important control on the concentrations of the leachate solutions.

c) Concentrations of Cl and Br increase versus depth from the surface toward the top of the Ordovician, while stable H and O isotope compositions range from relatively depleted meteoric values near surface and increasing to more enriched values through the Silurian to the top of the Ordovician. These trends versus depth may result from diffusive and/or advective mixing between more dilute waters in the Devonian formations with higher salinity waters in the Upper to Middle Silurian formations.

d) The presence of sulphide minerals and organic carbon suggests that redox conditions in the Ordovician and Cambrian formations are strongly reducing, either in the range of sulphate reduction (Queenston Formation) or methanogenesis (Georgian Bay Formation and below).

6. HYDROGEOLOGIC MODELLING

6.1 Introduction

This section provides a summary of the preliminary Phase 1 work completed to investigate the hydrogeologic conditions at regional and site scales as they relate, in part, to the stability and long-term barrier function of the sedimentary sequence underlying the Bruce site. A significant contribution to this work has been the development by the University of Waterloo of a 3-dimensional numerical simulation of the regional groundwater system. As part of model development a conceptual framework or model of a regional scale 18,000 km^2 groundwater domain centered on the Bruce site was created. This conceptual model development significantly benefited from the regional and site-specific geologic and hydrogeochemical studies described in the proceeding sections. This included incorporation of available site characterization data gathered during the Phase 1 deep borehole coring and testing program at the Bruce site undertaken by Intera Engineering.

While interim in nature the numerical simulation presents a reasoned basis to understand the regional and site-specific groundwater system(s) and its evolution. Specific concerns addressed by the modelling include parameter uncertainty, geometric representation of the hydrostratigraphy, parameter anisotropy, appropriate representation of boundary conditions, variable groundwater salinity, and existence of anomalous hydraulic head conditions. The analyses further explore the impact of paleoclimate simulations (i.e., glaciations) to assess the depth of melt water recharge and the resilience of the hosting DGR formations to external perturbations. The section briefly describes development of the conceptual hydrogeologic model, numerical Base Case simulations, sensitivity analyses and the paleohydrogeologic simulations. Specific details are provided in Sykes et al. (2008) and for the long-term climate change simulations Peltier (2008).

6.2 Conceptual Hydrogeologic Model

The sedimentary bedrock stratigraphy of the Michigan Basin and its structure is well understood in southern Ontario as outlined in Gartner Lee Limited, 2008a. In part this understanding has evolved from the knowledge gained through historical oil and gas well drilling in the region. Knowledge of the groundwater system within the sedimentary sequence, particularly that occurring below 200 m depth, is less well understood, as a result of the highly saline nature of the groundwater typically encountered at such depths. Reviews conducted of the hydrogeologic setting in the Paleozoic sediments of southern Ontario as reported by Intera, 1988; Golder, 2003; Mazurek, 2004; Hobbs *et al.,* 2008; and Gartner Lee Limited, 2008c provide insight into formation specific physical and chemical hydrogeologic properties and their spatial distribution that have been integrated to justify and support a conceptualization of the regional groundwater regime. This information has been supplemented by the results of the Phase I geoscientific characterization activities at the Bruce site that have further substantiated the selection of hydrogeologic properties for groundwater system conceptualization.

The regional groundwater model itself occupies an area of approximately 18,000 km^2 roughly centered on the Bruce site. The domain extends from the Niagara Escarpment in the east, to Georgian Bay in the north, 50 km into Lake Huron to the west and about 80 km south of the Bruce site (Figure 6.1). Model surface elevations are constrained by a land based Digital Elevation Model (DEM) and known bathymetry for Lake Huron and Georgian Bay. Model elevations range from approximately 540 m on the Niagara Escarpment to about -1,000 m at the base of the lowermost Cambrian formation below Lake Huron. To ensure internal consistency the 3-dimensional RSA stratigraphic model described in Section 3 was used explicitly to define model layers. This stratigraphic model is comprised of 31 sedimentary bedrock formations as listed in Table 6.1.

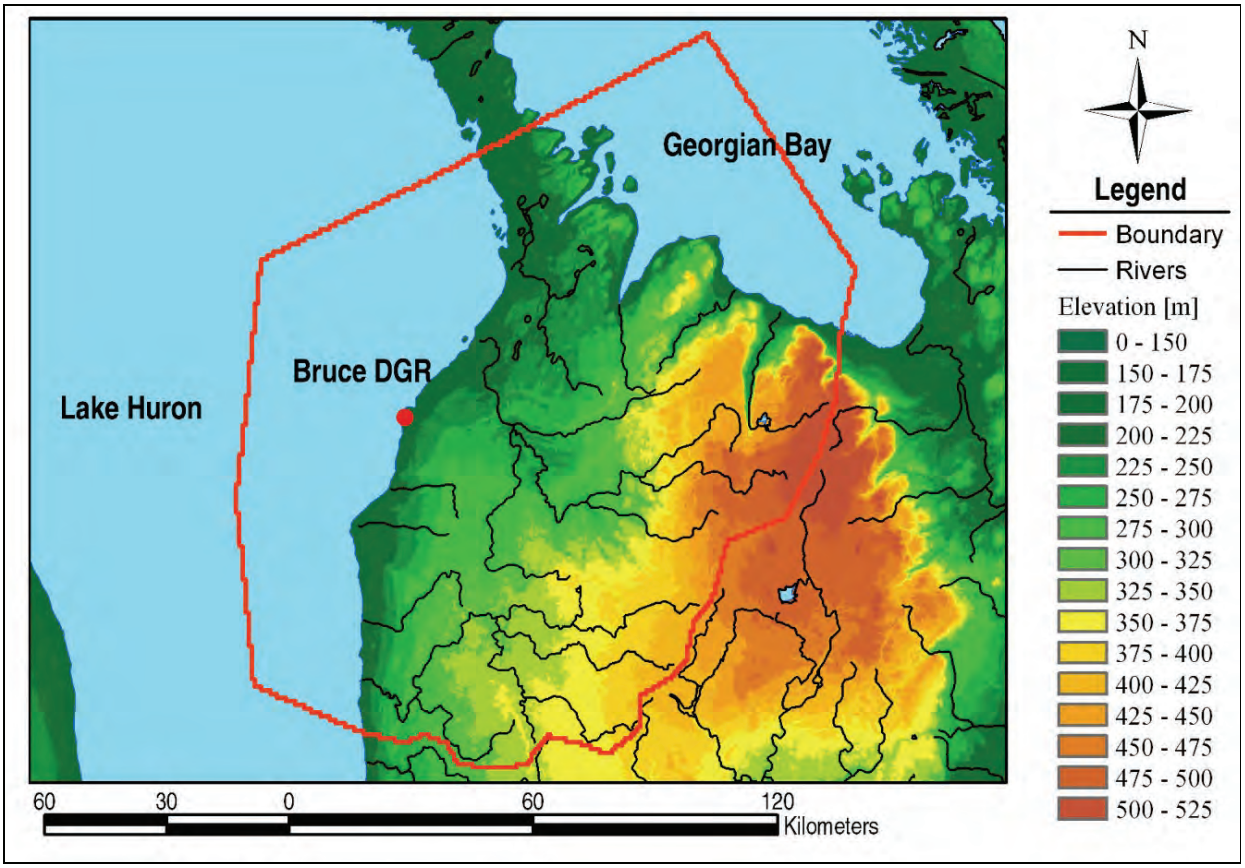


Figure 6.1 Hydrogeologic Regional Model Boundaries (Sykes et al., 2008)

Table 6.1 Material Hydraulic Properties for Base Case Scenario Analysis

Period	Geology	K_H (m/s)	K_V (m/s)	K_V / K_H	Porosity	Specific Stor.	TDS (g/L)
Quaternary	*Drift*	1.0×10^{-7}	2.0×10^{-8}	0.2	0.10	9.9×10^{-5}	0.045
Devonian	*Traverse Group*	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	9.9×10^{-5}	0.045
	Dundee	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	9.9×10^{-5}	3
	Detroit River Group	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}	3
	Bois Blanc	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}	3
Silurian	*Bass Islands*	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}	3
	G-Unit	1.0×10^{-7}	1.0×10^{-8}	0.1	0.08	1.3×10^{-6}	3
	F-Unit	4.0×10^{-12}	4.0×10^{-13}	0.1	0.03	1.2×10^{-4}	300
	F-Salt	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}	300
	E-Unit	4.0×10^{-12}	4.0×10^{-13}	0.1	0.08	1.6×10^{-6}	300
	D-Unit	1.0×10^{-10}	1.0×10^{-11}	0.1	0.03	1.3×10^{-6}	300
	B&C Units	4.0×10^{-12}	4.0×10^{-13}	0.1	0.08	1.2×10^{-4}	300
	B Anhydrite-Salt	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}	300
	A2-Carbonate	1.0×10^{-10}	1.0×10^{-11}	0.1	0.08	1.6×10^{-6}	300
	A2 Anhydrite-Salt	2.0×10^{-13}	2.0×10^{-13}	1.0	0.08	1.6×10^{-6}	300
	A1-Carbonate	1.0×10^{-12}	1.0×10^{-13}	0.1	0.08	1.6×10^{-6}	300

Table 6.1 Material Hydraulic Properties for Base Case Scenario Analysis

Period	Geology	K_H (m/s)	K_V (m/s)	K_V / K_H	Porosity	Specific Stor.	TDS (g/L)
	A-Evaporite	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}	300
	Niagaran	1.0×10^{-7}	1.0×10^{-8}	0.1	0.08	1.6×10^{-6}	300
	Fossil Hill	2.0×10^{-11}	2.0×10^{-12}	0.1	0.08	1.6×10^{-6}	300
	Cabot Head	2.0×10^{-12}	2.0×10^{-13}	0.1	0.03	1.2×10^{-4}	300
	Manitoulin	1.5×10^{-12}	1.5×10^{-13}	0.1	0.01	1.2×10^{-6}	300
Ordovician	*Queenston*	1.3×10^{-11}	1.3×10^{-12}	0.1	0.11	1.2×10^{-4}	300
	Georgian Bay/Blue Mountain	9.1×10^{-12}	9.1×10^{-13}	0.1	0.11	1.2×10^{-4}	300
	Cobourg	9.6×10^{-12}	9.6×10^{-13}	0.1	0.02	1.3×10^{-6}	300
	Sherman Falls	9.0×10^{-12}	9.0×10^{-13}	0.1	0.02	1.3×10^{-6}	300
	Kirkfield	1.4×10^{-11}	1.4×10^{-12}	0.1	0.02	1.3×10^{-6}	300
	Coboconk	5.2×10^{-11}	5.2×10^{-12}	0.1	0.02	1.3×10^{-6}	300
	Gull River	3.6×10^{-11}	3.6×10^{-12}	0.1	0.02	1.3×10^{-6}	300
	Shadow Lake	8.0×10^{-12}	8.0×10^{-13}	0.1	0.01	1.2×10^{-6}	300
Cambrian	*Cambrian*	3.0×10^{-6}	3.0×10^{-7}	0.1	0.01	1.2×10^{-6}	300
Precambrian	*Precambrian*	8.0×10^{-12}	8.0×10^{-13}	0.1	0.01	1.2×10^{-6}	300

Hydraulic conductivity and porosity values for each formation were adopted from Golder (2003) and refined where possible using data from the Bruce site investigations at deep boreholes DGR-1 and DGR-2. Anisotropy at intra- and inter-formation scales within the near horizontally layered bedrock formations is expected to be an important factor influencing fluid and solute migration. As Table 6.1 indicates, Sykes (2008) assumed a vertical anisotropy of 10:1. Regional studies (Golder, 2003, and Mazurek, 2004) indicate that formation properties can be consistent over large distances. Further, the geologic conceptual model of Gartner Lee Limited (2008a) illustrates the remarkable lateral continuity of the bedrock formations at basin scale. Combined, this evidence suggests that as a first approximation the hydrostratigraphy defined in the conceptual model (Table 6.1) provides a reasoned basis to explore and constrain simulations of groundwater and solute migration in the vicinity of the Bruce site.

Salinity plays an important role in groundwater movement. As indicated above, salinity increases significantly with depth in the Michigan Basin from fresh shallow groundwaters to deep saline brines. The increase in salinity (density) at depth influences vertical hydraulic gradients and water viscosity for the Na-Ca-Cl fluids. Assumed groundwater TDS values for the simulations are shown listed in Table 6,1.

Fluid and rock compressibilities are shown in Table 6.2. The transport parameters used in determination of mean life expectancy and mass transport modelling are provided in Table 6.3. The pore water coefficient used for the regional modelling is conservative, about one order of magnitude higher than that obtained by laboratory experiments on Ordovician cores from DGR-2.

Table 6.2 Fluid and Rock Compressibilities (m^2/N)

Compressibility	Value
Fluid	4.4×10^{-10}
Sandstone	1.0×10^{-10}
Limestone	1.0×10^{-10}
Dolomite	1.0×10^{-10}
Shale	1.0×10^{-8}
Precambrian	1.0×10^{-10}

Table 6.3 Groundwater Transport Parameters

Parameter	Value
Tortuosity	1.0
Pore Water Diffusion Coefficient	1.2×10^{-10} m^2/s
Longitudinal Dispersivity	500 m
Transverse Dispersivity / Longitudinal Dispersivity	0.1
Vertical Transverse Dispersivity / Longitudinal Dispersivity	0.01

6.3 Regional Groundwater Model

6.3.1 Model Description

The regional groundwater flow model was developed to provide an understanding of the potential transport pathways from the DGR to the biosphere. FRAC3DVS-OPG (Therrien *et al.,* 2004) was selected for this modelling assignment, as it is capable of simulating three-dimensional, variably saturated density dependent groundwater flow in porous and discretely fractured media. At the regional scale a porous medium is assumed. The model was used to describe the evolution of the system over time, including transient boundary conditions e.g., glacial advances and retreats.

The FRAC3DVS-OPG model is based on solving the governing flow equation to include a porous or discretely fractured media. The model, for this study, is operated under isothermal conditions and the unsaturated flow attribute was not invoked. The physical properties of the groundwater vary considerably with depth. Salinities vary from fresh water in the surficial aquifer to more than 300 g/L in the deep Ordovician sediments, thus density can vary by about 25% and viscosity by an order of magnitude. Such changes in fluid properties can have significant consequence on solute transport. FRAC3DVS-OPG can conduct simulations taking into account variable density and viscosity.

As depicted on Figure 6.1, the regional model covers approximately 18,000 km^2 including both on shore and off shore areas. The aerial discretization contains 200 rows and 200 columns, which represents 27,728 nodes throughout each layer of the 3D domain. Each cell has sides of 760 by 900 m. There are 31 layers in the model that accurately honours the geological model described in Gartner Lee Limited (2008a). Standard modelling approaches were used to deal with such issues as pinch out as the geologic formations approach the Algonquin Arch. As shown in Table 6.1 there is considerable congruency between the properties of adjacent formations (lithofacies) that could be grouped into hydrofacies to enhance computational time. However, the model was kept true to the lithofacies framework so that future more exacting work could be completed once more detailed parametric data becomes available from site investigations.

Calibration of such a large scale regional model is difficult due to lack of information across the domain. Therefore the model was tested to fit behavioural constraints of the hydrogeologic system. For example, the geological configuration is true to the geological model, boundary conditions are appropriate for the current modelling task, and the salinity profile is consistent with known values. The head distribution observed through the site characterization program points towards a transient pressure system, particularly in the Ordovician.

Boundary conditions of the model included no flow boundaries on the sides and bottom. The surface boundary was defined by the digital elevation model for the area and the lake bathymetry. The water table was set at 3 m below surface except in the Georgian Bay and Lake Huron areas where the water table was not allowed to go below the lake level (176 mASL). This is considered an acceptable approach to the surface boundary as recharge and discharge is governed by the surface topography and the permeability of the upper layer. The no flow boundary conditions on the sides of the model are appropriate as flow in the low permeability formations that comprise most of the Paleozoic sequence is expected to be vertical. For the more permeable Niagaran[3] and Cambrian, where it occurs, the boundary conditions are tested during sensitivity analyses (Section 6.3.3) and found to be appropriate at the model scale. The selected boundary conditions are considered appropriate for the scope of this model.

Mean Life Expectancy (MLE) is the performance measure used to assess how the hydrogeologic regime responds to differing stresses imposed on it during steady state regional modelling. MLE is defined as the elapsed time required for a particle at a given point in the model domain to travel though the domain to exit at some discharge point (Sykes, 2008). This concept is used in the following sections to evaluate different modelling scenarios (sensitivity analysis) to assess the transport performance of the Paleozoic rocks, in particular the Cobourg Formation and overlying shales, which host and enclose the proposed DGR.

6.3.2 Base Case Simulation

Input parameters for the base case are presented in Tables 6.1, 6.2 and 6.3. In this particular scenario, the base case does not take into account high heads in the Cambrian and low heads in Ordovician; they are described further in Section 6.4.1.

Output from each modelling run is a series of diagrams (in both block and fence configurations – see Figure 6.2) that describe the domain attributes for different conditions. The following figures (Figures 6.2 to 6.7) taken from Sykes *et al.* (2008) describe the base case results. Figure 6.2 shows the base case piezometric head distribution (equivalent fresh water head) that essentially shows high heads in the topographically high recharge area along the Niagara Escarpment declining with distance down gradient. Figure 6.3 is a portrayal of the base case environmental heads that mimic to a high degree the fresh water heads, but the actual elevations are lower due to density effects. Figure 6.4 shows the total dissolved solids distribution throughout the domain that indicates a shallow fresh water zone, an intermediate transition zone where TDS ranges from fresh to 250 g/L, and a deep zone where the TDS is 300 g/L. Figure 6.5 shows the base case pore water velocities. It can be seen that the active shallow zone has high (>1 m/a) velocities ranging to the deep zone with velocities of 10^{-6} m/a, clearly a diffusive environment. Note on Figure 6.5 the red and orange layers in the intermediate zone. The red layer is the Niagaran Group that has a higher permeability as previously discussed. The orange layers are the Silurian D Unit and A2 Carbonate that exhibit higher permeabilities than their bounding anhydrite layers.

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3. *The Middle Silurian units encountered in the RSA (with the exception of the Fossil Hill Formation) are grouped within the 3D Geological Framework as the "Niagaran", which is simply a convenient term for grouping these units of common geological age/stage of deposition. Beneath the DGR site the Niagaran includes the Lions Head, Gasport, Goat Island and Guelph formations.*

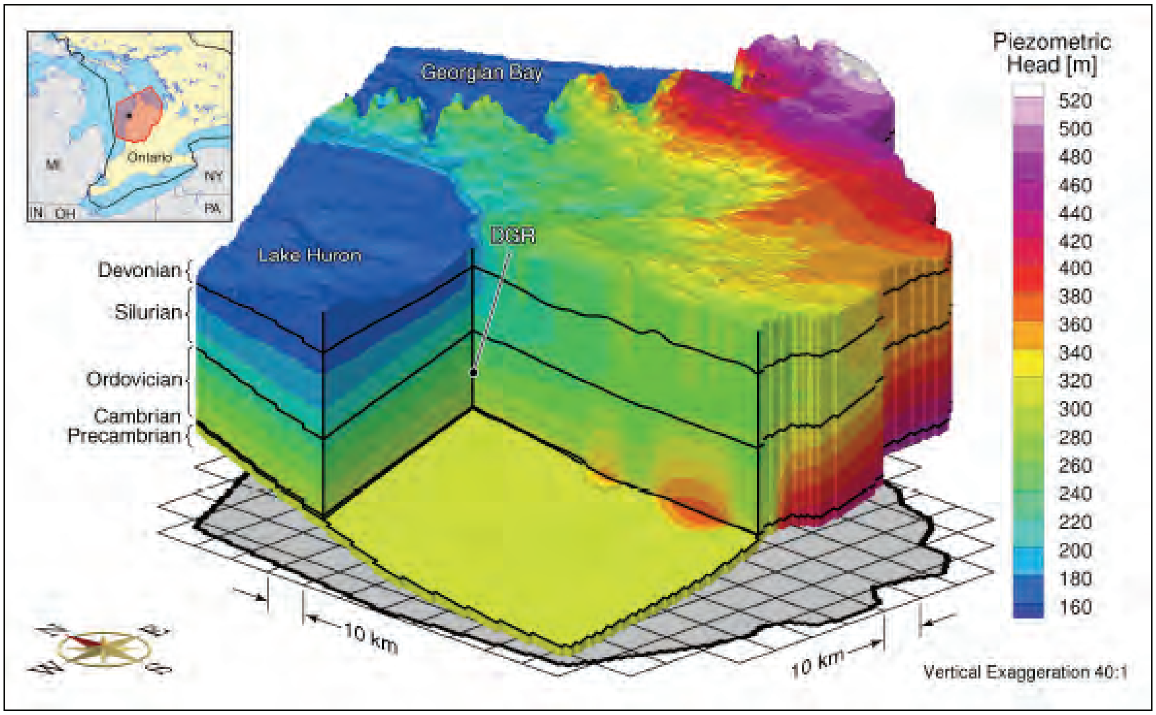


Figure 6.2 Base case equivalent freshwater head (m) distribution.

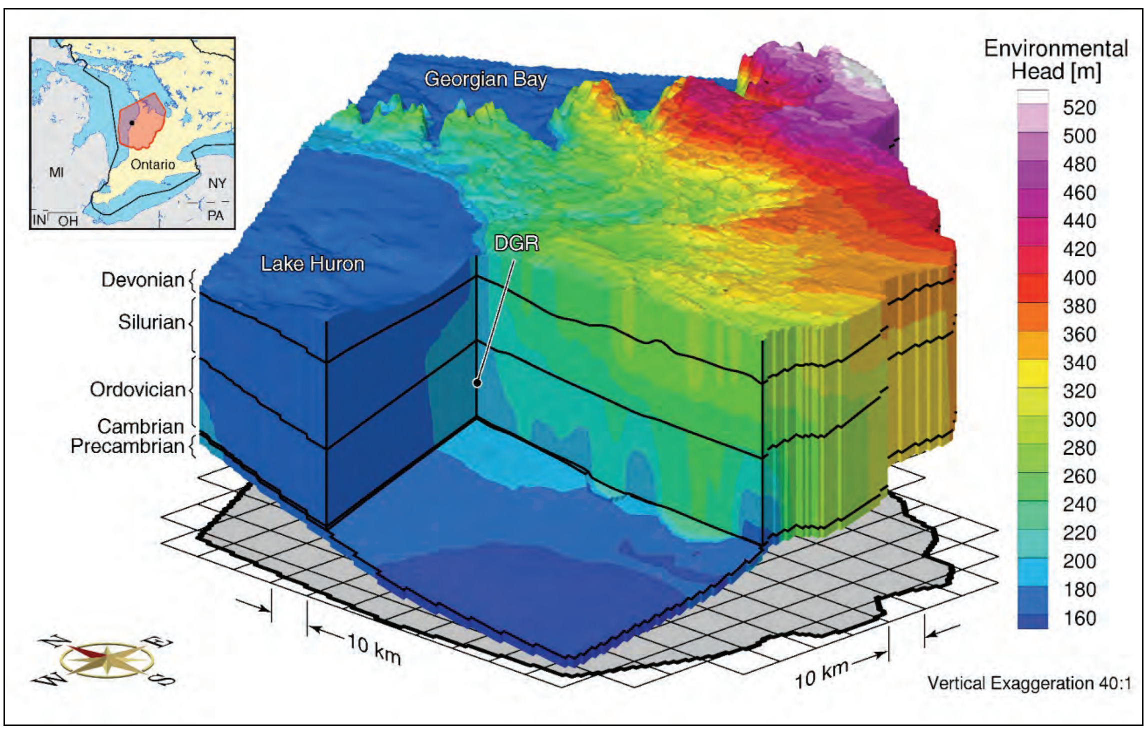


Figure 6.3 Base Case Environmental Head Distribution

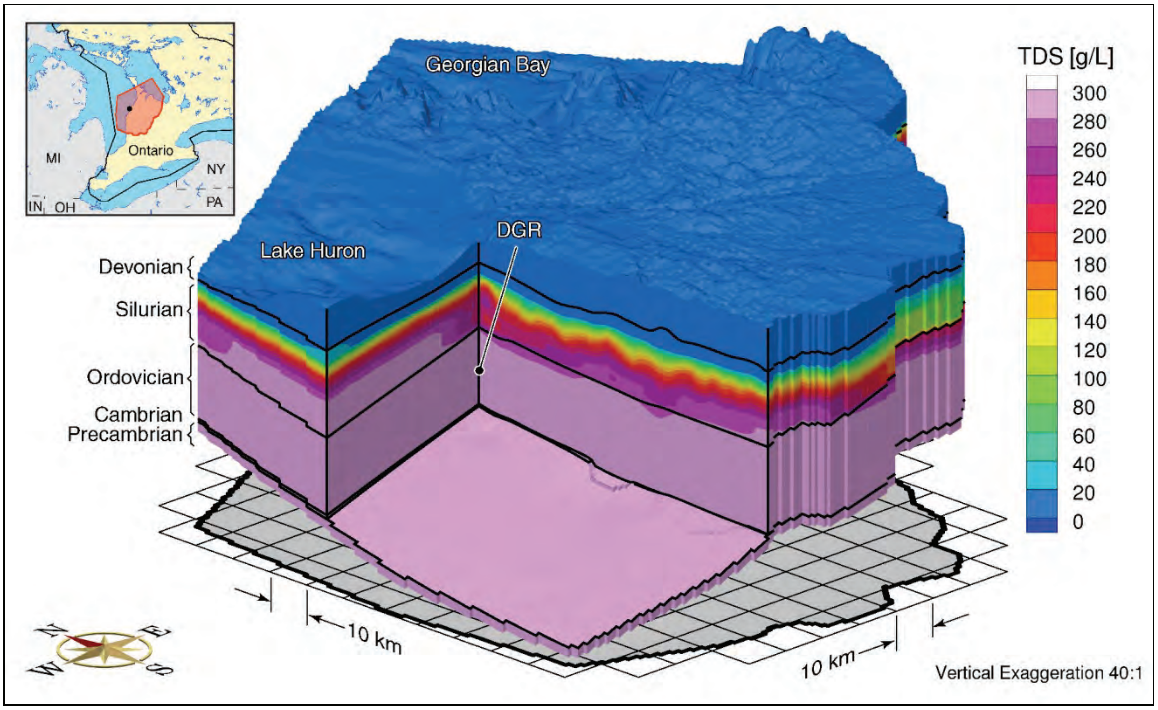


Figure 6.4 Base Case Total Dissolved Solids Distribution

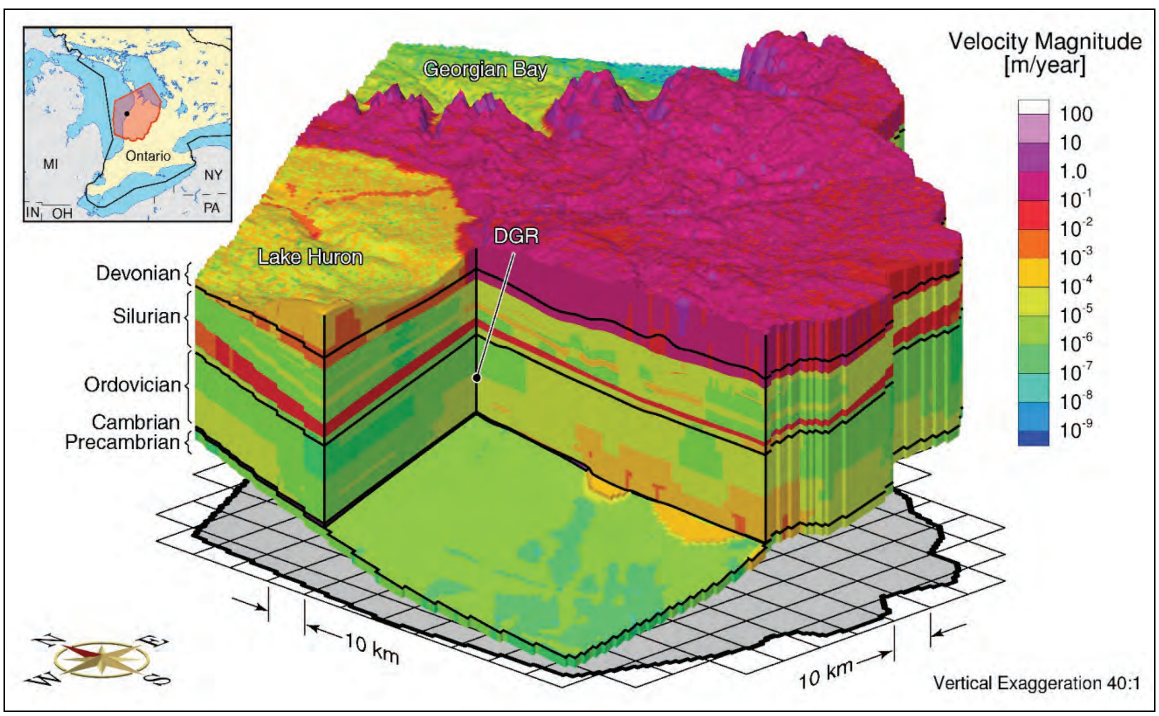


Figure 6.5 Base Case Pore Water Velocity Magnitude Distribution

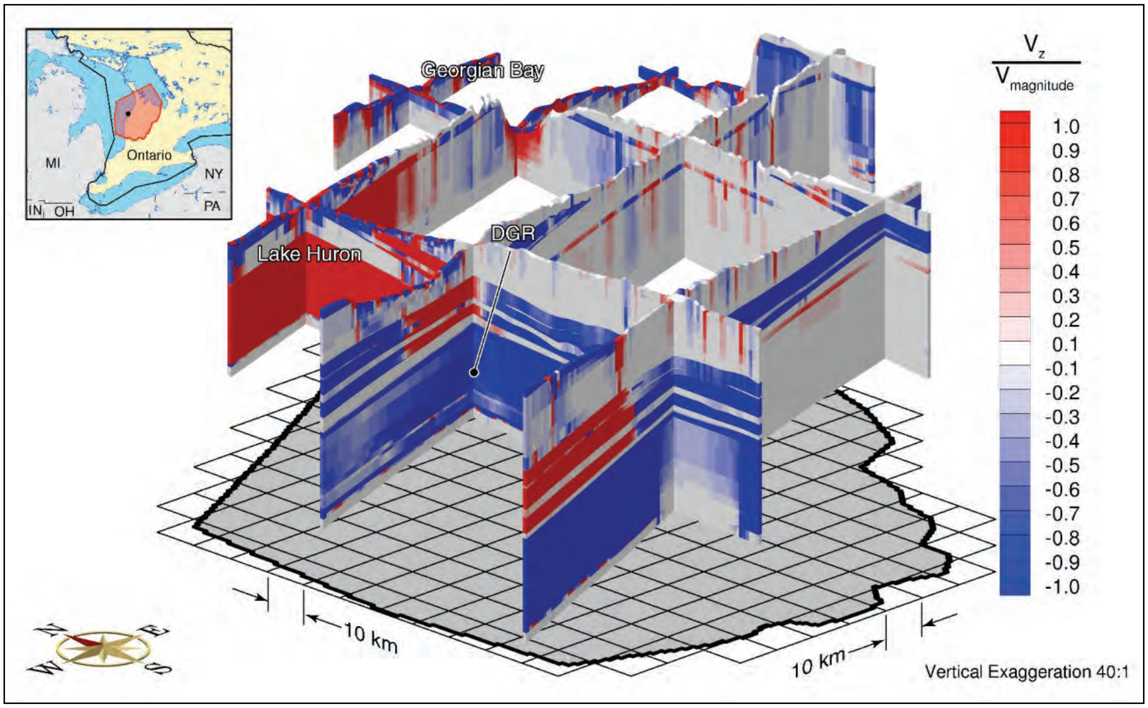


Figure 6.6 Fence Diagram of Base Case Ratio of Vertical Velocity to Velocity Magnitude

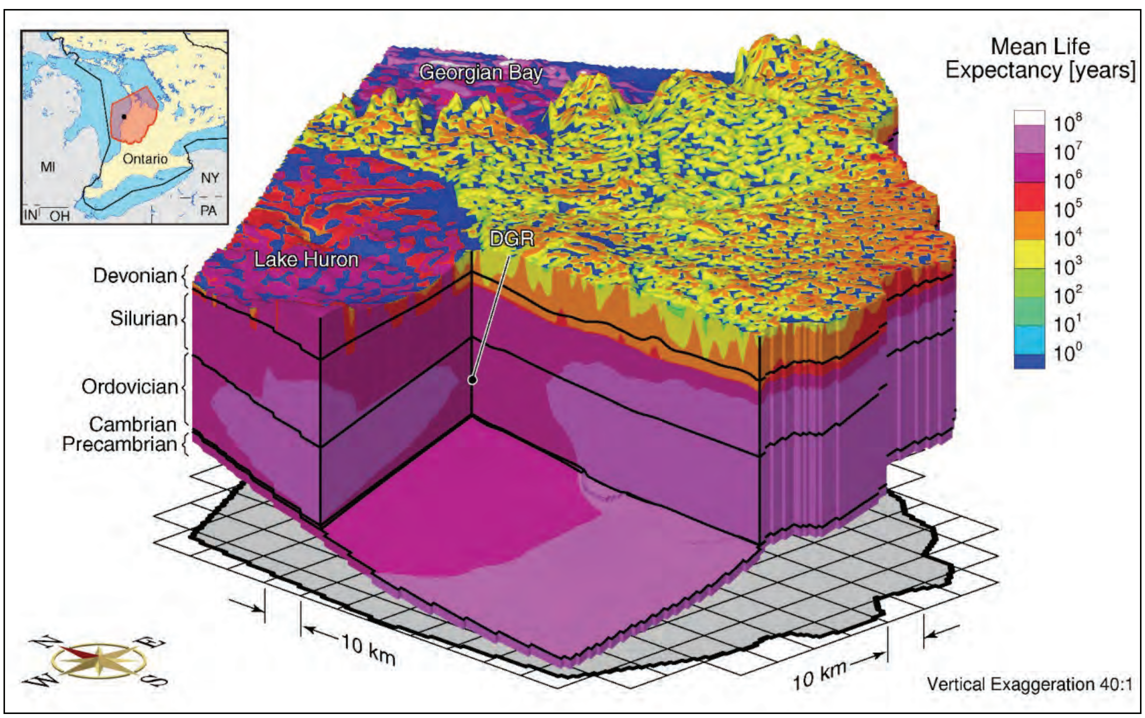


Figure 6.7 Base Case Mean Life Expectancy

Vertical velocity to velocity magnitude ratios are plotted on Figure 6.6. Blue represents vertical downward flow, red vertically upward flow and white horizontal flow. Transition zones are clear between vertically upward and downward flow. Of note is the lateral flow in the higher permeability Niagaran Group and Cambrian formation(s). Lateral flow in the Silurian and Ordovician sediments close to the recharge areas transitioning to vertical flow where the Cambrian is present. Figure 6.7 presents the mean life expectancy output for the base case. The figure clearly shows modern groundwater in the shallow regime and old groundwater in the deep zone at the DGR level. Sykes *et al.* (2008) indicates that mean life expectancy for the base case at the DGR is 8.9 Ma. The base case analyses indicate that transport in the Ordovician sediments is diffusion dominant. This was further explored in a series of sensitivity analyses described in the following section.

6.3.3 Sensitivity Analyses

A series of sensitivity analyses (Sykes *et al.,* 2008) were performed to investigate the attributes that are important to the assessment of the regional groundwater flow system. The following key analyses are discussed below:

a) surface boundary conditions
b) geological model
c) density-independent flow
d) hydraulic conductivity of the Ordovician and Silurian formations
e) lateral boundary conditions
f) Cambrian anisotropy
g) Glaciation Scenario analysis

6.3.3.1 Surface Boundary Conditions

The base case surface boundary conditions assumed a water table at a fixed depth of 3 m to go no lower than the Lake Huron level of 176 mASL and a 20 m thick surface layer of high permeability to reflect a weathered zone. By changing the weathered zone only to reflect the assigned permeabilities of the geological formations the mean life time expectancy remained unchanged from the base case i.e., 8.9 Ma, thus demonstrating the DGR location is insensitive to changes in the shallow flow system.

A second surface boundary condition scenario was explored by forcing recharge into the lower groundwater systems. A new recharge of 0.27 mm/a was used in order that it honour the water table condition. The results of this simulation clearly demonstrate a dampening effect of the low permeability Salina Formation. However, the DGR mean life expectancy is somewhat reduced from the base case to 7 Ma.

6.3.3.2 Stratigraphic Model

Sykes (2007) used a preliminary construction of the geology of southwestern Ontario to develop an understanding of the regional flow regimes in the Bruce region. Gartner Lee Limited (2008a) provides a more in-depth analysis of the regional stratigraphic framework based on a more refined interpretation of the available geologic information. While there were a number of subtle differences between the two models, the main difference was the spatial distribution of the Cambrian formation(s). Early interpretations of the Cambrian indicated that it was more extensive across the model domain; while in Gartner Lee Limited (2008a) there was evidence to suggest that the Cambrian is eroded over the Algonquin arch to the south and pinches out against the Precambrian basement east of the Bruce site. With this spatial geometry for the Cambrian formation a mean life expectancy of 1.6 Ma is predicated. This simulation demonstrates the importance of the analysis demonstrates the importance of the geologic model and that the mean life expectancy is sensitive to the Cambrian distribution due to its relatively high permeability.

6.3.3.3 Density-Independent Flow

The base case analysis was completed using density-dependent flow as the TDS profile recorded at DGR-1 and DGR-2 demonstrate variations from 1 g/L in the shallow system to approximately 300 g/L in the deep system. A scenario was run for density-independent flow by setting the TDS throughout the model to zero. This resulted in a DGR mean life expectancy of 11.2 Ma. For density-independent flow the velocities are essentially vertical in the Silurian and Ordovician and derived peclet numbers are indicative of a diffusion dominated transport regime.

6.3.3.4 Hydraulic Conductivity of the Ordovician and Silurian Formations

A parametric analysis was completed by varying the hydraulic conductivity of important formations to assess the impact on the regional flow domain and the DGR mean life expectancy. Three scenarios were investigated by varying the hydraulic conductivity of the Ordovician sediments and by honouring the rest of the base case assumptions. A horizontal to vertical hydraulic conductivity ratio of 10:1 was used. The results of these simulations are shown in Table 6.4.

Table 6.4 Mean Life Expectancies at the DGR Based on Varying Silurian and Ordovician Hydraulic Conductivities

Scenario	Hydraulic Conductivity (m/s)	MLE (Ma)
Base case	See Table 6.1	8.9
Ordovician	$1x10^{-11}$	14.9
Ordovician	$1x10^{-13}$	38.6
Ordovician	$1x10^{-15}$	44.3
Silurian (B,C,A1)	$1x10^{-8}$	38.6
Silurian (A2)	$1x10^{-13}$	39.1

Two analyses were also completed by varying the hydraulic conductivities of the Silurian carbonate and anhydrite layers. In the first case the hydraulic conductivities were increased and in the second scenario the only change made was to lower the A2 Anhydrite hydraulic conductivity to $1x10^{-13}$ m/s. In addition, in each scenario the Ordovician sequence was assigned a hydraulic conductivity of $1x10^{-13}$ m/s and an anisotropy ratio of 10:1. The results of each analysis yield mean life time expectancies of 38.6 and 39.1 Ma, respectively. These results demonstrate that the MLE is relatively insensitive to changes in hydraulic conductivity in the Silurian as flow exits the system laterally through the Niagaran Group below the impermeable Silurian evaporite sequence.

6.3.3.5 Lateral Boundary Conditions

The regional model domain is a small part of the Michigan Basin and it is therefore important to test the lateral no-flow boundary assumptions made in the model. To do this flow was allowed to enter and exit the model at the boundaries. This was achieved by the placement of a high permeability zone around the entire model from surface to the Precambrian. This allowed flow to enter and exit the system through the more highly permeable Niagaran Group and Cambrian formation(s). This change to the lateral boundaries resulted in a mean life expectancy at the DGR of 6.2 Ma indicating that the integrity of the low permeability Ordovician formations are the primary factor in determining MLE.

6.3.3.6 Cambrian Formation Anisotropy

The base case assumes that the system is steady sate and in equilibrium throughout the domain. However, the results from DGR1&2 have shown that the environmental head distribution is not one that can currently be predicted by the regional model. Freshwater heads in the Cambrian are up to 200 m above ground level, whereas, heads in the Ordovician Georgian Bay Formation are about 150 m below those in the lower Ordovician sediments and the overlying Silurian formations. This is discussed further in Section 6.4.

As indicated previously, the Cambrian distribution may be interrupted by fault blocking (Sanford *et al.,* 1985; Gartner Lee Limited, 2008a) where the permeable Cambrian unit is positioned against lower permeability Ordovician formations. To explore the significance of fault blocking, Sykes *et al.* (2008) assigned high horizontal permeabilities to the Cambrian along the fault strike and lower permeability normal to the fault, the vertical permeability was the same as the base case (i.e. hydraulic conductivity of fault equivalent to juxtaposed low permeability formation). The model was then run with differing orientations to the parallel faults. The results of these simulations yielded MLE of 7.8, 18.4 and 22.7 Ma. The lowest of the MLE coincided with a fault strike of 0^{o}.

6.3.3.7 Paleoclimate Analysis

The previous sensitivity analyses have considered physical changes to the assumptions that built the base case. In this analysis of paleoclimate effects external perturbations to the base case model are evaluated. It is important that long-term climate change is considered as part of the model analysis and in particular glacial events that have occurred in the past and are predicted for the future. This particular analysis considers the Laurentide glacial episode that occurred from about 120 to 10 ka ago that included three major advances and retreats of the ice sheet. Peltier (2008) uses the University of Toronto's Glacial Systems Model (Peltier, 2008) to predict the effect of this recent glacial episode in terms of ice sheet thickness (load), permafrost depth and recharge below the ice sheet (periglacial conditions).

The two most important factors to be considered are permafrost depth and normal stress developed from the ice load. Formulation of these factors into the FRAC3DVS-OPG model are described in Normani *et al.* (2007). Simply put, when permafrost exists it inhibits flow to depth created by the high environmental head imposed by the ice sheet, if the glacier is warm bottomed i.e., no permafrost then enhanced recharge can occur. Normal stress imposed by the height of ice induces over pressures in the underlying formations; it is important to consider both the loading and off loading of the glacier when evaluating present day effects from the past glacial events.

To assess the depth of penetration of glacial waters a tracer is numerically introduced into the model at 120,000 years ago thus tagging the recharge water. The transient model is then allowed to run to the present day. Figure 6.8 show the depth of penetration of the glacial recharge waters. It can be clearly seen that the F Unit at the top of the Silurian sequence retards recharge any deeper into the Paleozoic sequence. This simulation confirms conclusions drawn from the hydrogeochemical evidence using stable isotope analysis that glacial recharge is restricted to the upper 150 m at the Bruce site (Hobbs *et al.*, 2008).

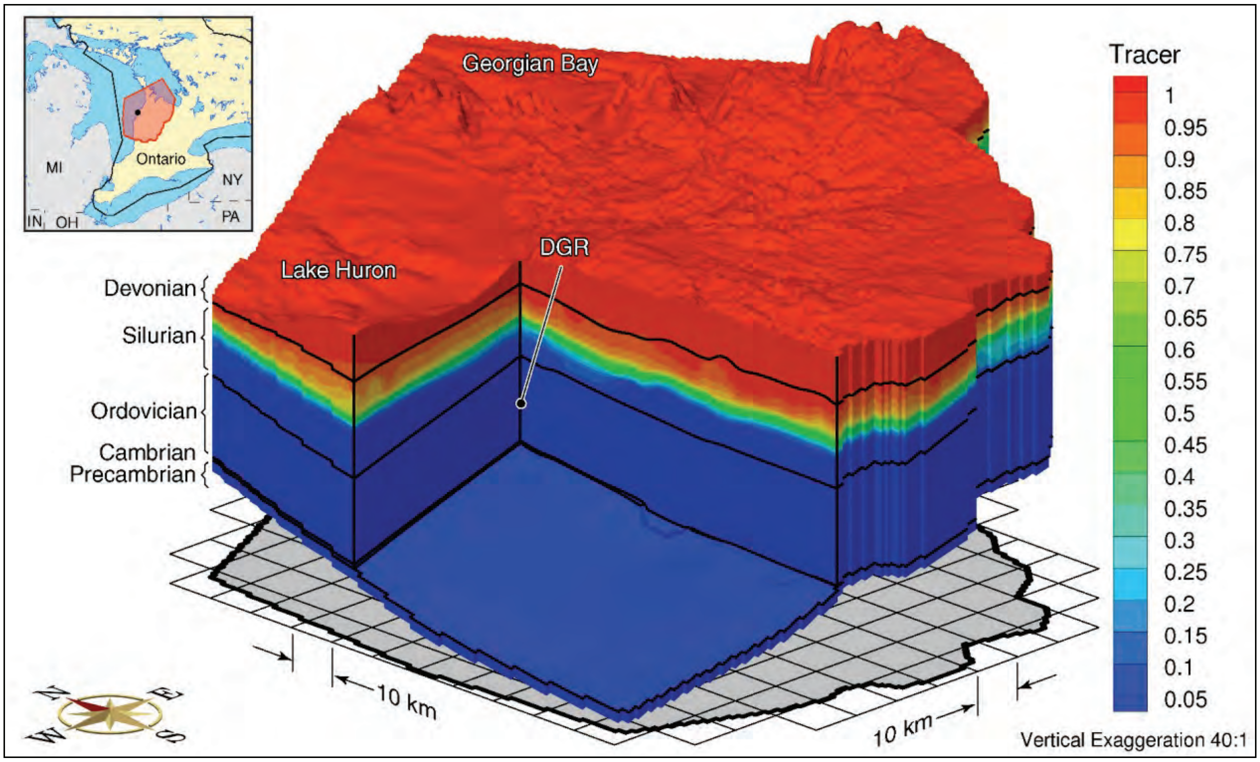


Figure 6.8 Depth of Penetration of Recharging Glacial Waters

The high pressures created by the ice loads in proximity to the recharge areas is transmitted down dip early in the glacial episode. Then over time the more permeable formations transmit the pressures into the adjacent lower permeability strata. This is evident in Figure 6.9 which shows the present day environmental head induced by the Laurentide glacial event; the over pressured Silurian is represented by the white band.

Sykes *et al.* (2008) present a series of simulations that considers formation pressures during glacial advances and retreats using the normal stress information from Peltier (2008). This series of simulations were targeted at understanding the mechanisms that cause the under pressures observed in the Georgian Bay Formation and whether they are caused by dilation of the formation following glacial retreat. Sykes *et al.* (2008) demonstrates that during glaciation the Ordovician rocks are under compression exhibiting over pressures. Over a 20,000 year simulation period the pressures remain unchanged in the Ordovician but are released in the Niagaran and the shallow system. Clearly then it seems that the observed under pressures in the Georgian Bay Formation are the result of some other process or combination of processes.

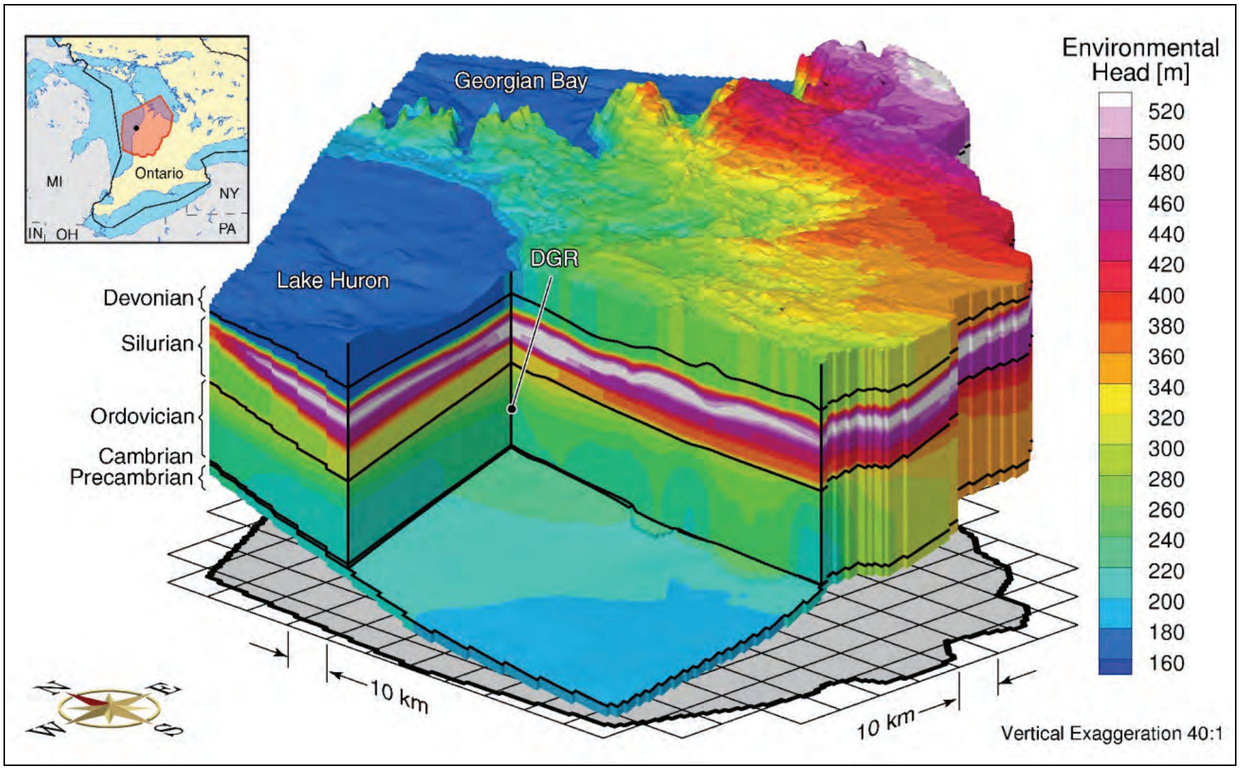


Figure 6.9 Environmental Freshwater Head at the Present Time as a Result of the Laurentide Glacial Episode Loading

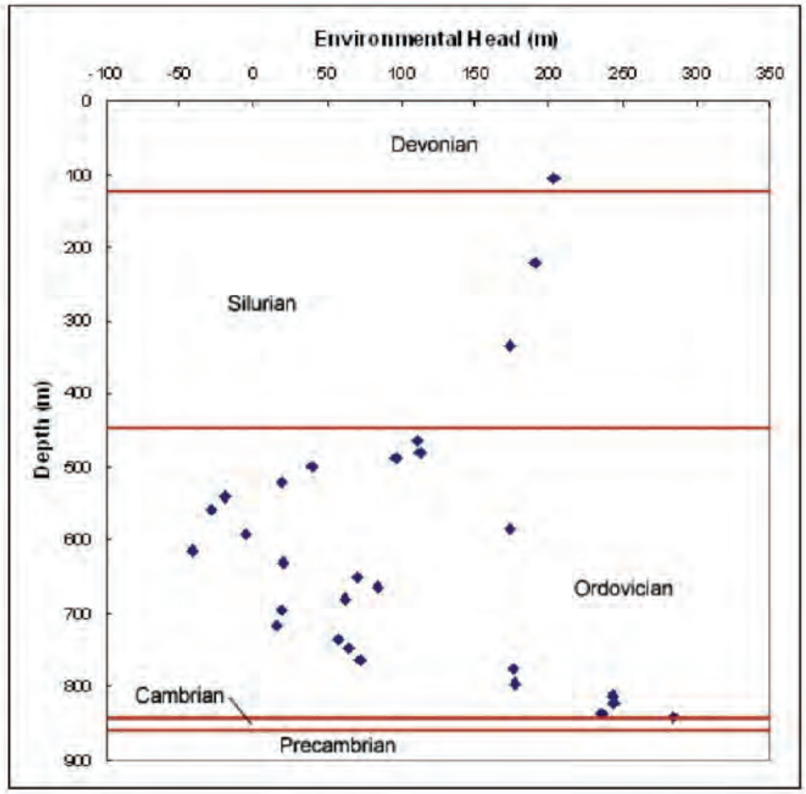
6.4 Bruce Site Groundwater Model

The site model used to assess hydrogeological conditions at the Bruce Site is a refinement of the regional model. A direct embedment approach was used to refine the grid spacing of the FRAC3DVS-OPG model to about 120 x 120 m cell dimensions. The site scale domain is about 19 x 19 km square centered on the DGR. The hydraulic and transport properties used in the regional model are the same for the site scale model. Boundary conditions at the site scale honour the regional boundaries described earlier. The site scale model was used to assess the abnormal hydraulic head condition observed in the Ordovician and Cambrian sediments. Details of this analysis are provided in the following section.

6.4.1 Abnormal Hydraulic Head – Deep Boreholes DGR1/2

Figure 6.10 shows the measured pressures from DGR 1/2 in March 2008. These results are obtained from a Westbay installation that had been in place for about four (4) months. The pressure profile shows an upward gradient from the permeable Cambrian to the under pressured Ordovician Georgian Bay Formation and downward gradients from the Silurian Niagaran Group to the Georgian Bay Formation. Given the gradient information it is therefore predicted that the water deficit in the Georgian Bay Formation will be made up from the underlying Cambrian formation or overlying Niagaran Group.

Figure 6.10 Environmental Heads in DGR2 (March 3, 2008)



Base case parameters were varied only for vertical hydraulic conductivity in the Ordovician rocks. The horizontal hydraulic conductivities assigned were the same values as the base case and the ratio to vertical hydraulic conductivities were set at 0.1, 0.01 and 0.001, which translate to approximately $1x10^{-12}$ m/s, $1x10^{-13}$ m/s and $1x10^{-14}$ m/s. Using these hydraulic conductivity conditions, the pressure profile was investigated by considering four pressure support cases: (a) no support from either the Cambrian or Niagaran, (b) support from the Cambrian only, (c) support from both the Cambrian and Niagaran, (d) support from the Niagara only. The conclusions from this investigation are summarized as follows:

a) With an anisotropy ratio of 0.1 the low pressures in the Georgian Bay Formation cannot be maintained for more that 1 Ma and Cambrian pressures will dissipate, however, downward gradients will persist for 100 ka.

b) With pressure support in the Cambrian and no pressure support in the Niagaran, with anisotropy of 0.1, there is still a downward gradient after 100 ka.

c) With pressure support from both the Cambrian and Niagaran, with anisotropy of 0.1, there is an upward gradient from the Cambrian to the surface after 1 Ma.

d) With only pressure support from the Niagaran, with anisotropy of 0.1, there are still downward gradients after 100 ka.

e) For anisotropy ratios of 0.01 and 0.001 the results indicate delays in dissipation of pressures where there is no support. In addition, under pressures persist in the Georgian Bay Formation for the duration of the transient analysis (1 Ma) and therefore gradients are downwards from the Niagaran Group.

f) The results of this analysis demonstrate that vertical hydraulic conductivities much lower than the base case are required to maintain the under pressurization in the Georgian Bay Formation for more than 1 Ma.

g) The presence of a gas phase in the Ordovician would indicate partial saturation in which case groundwater movement would cease and a stagnant situation would arise, further resulting in maintenance of the high Cambrian heads.

h) To sustain the observed hydraulic over-pressures in the permeable Cambrian sandstone requires that the overlying Ordovician sediments possess an extremely low hydraulic conductivity on the order of 10^{-14} m/s or less.

6.5 Summary

The hydrogeologic characteristics of the Bruce site and surrounding region were explored through the development of a 3-dimensional numerical model of groundwater and solute migration within the Paleozoic sedimentary sequence. This 3-dimensional model provided a structured framework on which to integrate regional and site-specific information governing hydrostratigraphy, hydrogeochemistry and boundary conditions. A total of 24 scenarios were modeled to explore the long-term stability and the barrier function of the far-field at time frames relevant to DGR safety. Specifically, the simulations were used to demonstrate and illustrate;

a) The influence of basin hydrostratigraphy and geometry on ’absence’ of exfiltration zones;

b) The influence of groundwater system anisotropy at inter-/intra-formation scale;

c) The influence of variable density fluid distributions (i.e., variable salinity distributions);

d) The migration of unretarded/non-decaying environmental isotopes within the subsurface;

e) Groundwater system response to external perturbation such as long-term climate change and glaciations; and

f) Estimates of formation scale properties based on observation of anomalously elevated and depressed hydraulic heads in the Cambrian and Ordovician sediments, respectively.

As a performance measure for the simulations, spatially variable rates of groundwater migration and solute residence time were predicted using the time domain probability method, which incorporates transport mechanisms of advection, dispersion and diffusion.

While refinement of the Phase I (2006-2008) numerical simulations presented herein will occur during Phase II (2008-2010) results of the analyses provide a reasoned basis to understand the evolution of the regional and site-specific groundwater systems as they relate to implementation of the DGR concept at the Bruce site. Results from the simulations include the following:

a) The Paleozoic sedimentary sequence groundwater system is comprised of three horizontal stratified zones: i) a shallow zone is defined by the permeable and low TDS groundwater found in the carbonate bedrock formations above the Bass Island Formation; ii) an intermediate groundwater zone comprised of the bedrock between the Salina G-unit and the Manitoulin Formation; and iii) a deep zone comprised of the Ordovician and Cambrian sediments with groundwater TDS values of approximately 300 g L^{-1}.

b) Base case and sensitivity simulations indicated that diffusion was the dominant transport mechanism in the Ordovician sediments. Mean Life Expectancies from the repository horizon were typically greater than 6 Ma.

c) Base case and sensitivity analyses indicate multiple natural bedrock barriers both within the intermediate and deep groundwater zones.

d) Simulation of anomalous vertical hydraulic head distributions within the Ordovician and Cambrian sediments at DGR-1 and DGR-2 indicate that groundwater movement is converging on the Ordovician formations. Depending on the assumed hydraulic conductivity anisotropy (i.e., 10:1 – 1000:1) re-equilibration of these heads to present day boundary conditions may require 1 Ma or longer.

e) The origin of the anomalously low hydraulic heads observed in the Ordovician sediments is unlikely to be due to glacial events as a consequence of the predicted loading-unloading cycle.

f) Extensive low permeability strata overlying the Cambrian Formation are required for the maintenance of the observed hydraulic overpressures. Analyses indicate that to preserve the hydraulic overpressure for 1 Ma vertical hydraulic conductivities of 1×10^{-14} m or less are required.

g) Paleohydrogeologic simulations for a glaciation scenario indicate that basal meltwaters would not penetrate below the Salina Formation. Simulations further indicate that while ice-loading will influence hydraulic head distributions transport processes remain diffusion dominant within the Ordovician sediments.

7. PHASE 1 GEOSYNTHESIS – MAIN FINDINGS AND CONCLUSIONS

Ontario Power Generation (OPG) is proposing the development of a Deep Geologic Repository (DGR) at the Bruce Site, near Tiverton, Ontario for the long-term management of Low and Intermediate Level Radioactive Waste (L&ILW). This proposal envisions the excavation of a repository at a depth of approximately 680 m in a limestone formation overlain by 200 m of low permeability shale. This report describes the Phase 1 Geosynthesis Project completed as part of a stepwise geoscientific characterization program that is supporting an ongoing Environmental Assessment and preparation of a Preliminary Safety Report scheduled for submittal in 2011.

Phase 1 Geosynthesis deals primarily with the undisturbed system as it has evolved to its present day state and to a lesser extent with repository induced disturbances. Information contained in the Geosynthesis through understanding past evolution provides insight on the long-term stability and future evolution of the far-field. This report provides a detailed summary of the regional geoscientific studies conducted to understand the geoscientific attributes related to predictability, stability and geologic isolation provided by the geologic setting at the Bruce site. The studies completed as part of the Phase 1 Geosynthesis Program are:

a) Phase I Regional Geology, Southern Ontario (Gartner Lee Limited, 2008a)
b) Phase I Regional Hydrogeochemistry, Southern Ontario (Hobbs et al., 2008)
c) Phase I Regional Geomechanics, Southern Ontario (Gartner Lee Limited, 2008b)
d) Phase I Hydrogeologic Modelling (Sykes et al*.,* 2008)
e) Phase I Long-Term Climate Change Study (Peltier, 2008)
f) Phase I Long-term Cavern Stability (Itasca, 2008)

The Regional Geological Framework study examined extensive information from numerous sources. A regional geologic model was built based on details from 340 petroleum exploration wells in the 35,000 km^2 regional study area. The Regional Geology study concluded:

a) the Paleozoic geology is predictable over large distances in Southern Ontario and into Michigan beneath Lake Huron;
b) geological formation thicknesses vary based on depositional environment but are predictable over distances of 10s of kilometres;
c) litho-structural properties are understood and homogenous at scales relevant to DGR safety; and
d) the origin and general processes of diagenesis, including dolomitization are understood and widely accepted.

The Regional Geomechanical Framework evaluated existing information related to regional stress and other geomechanical rock properties for southern Ontario and the US States bordering southern Ontario. The database is limited and is mostly confined to large scale energy projects completed by OPG. This work concludes:

a) the structural geology is generally well understood and is predictable at the site;
b) major and minor regional joint sets could exist at depth but if present, they are expected to be less frequently spaced, tight and sealed. Also, their orientations at depth may vary from those at the surface;

c) previous underground excavations within the Ordovician rock demonstrate stable, dry openings;

d) strength and geomechanical properties are favourable for the construction of deep underground facilities in the Ordovician limestone Cobourg Formation;

e) very few earthquakes are observed in the Bruce region. No seismic events >M5 have been recorded in the past 180 years. The events generally have deep epicentres with an average depth of 7 km; and

f) there are no known structural features present in the Bruce area that could trigger an earthquake; the probability of a large seismic event appears very low.

The Regional Hydrogeochemistry study examined groundwater quality information for the Michigan Basin as compiled by the University of Waterloo. This database comprises detailed chemical analyses, including stable naturally occurring isotopes of samples collected predominantly from oil wells in southern Ontario and Michigan. This information yields the following conclusions:

a) the current understanding regarding the origin of brines from the Michigan Basin indicates that they were formed by evaporation of sea water. At present, the major-ion concentrations deviate from the concentrations that would be expected from evaporation of present day sea water, and these deviations are explained by water-rock reaction processes that occur during and following burial;

b) in the Michigan Basin, the last known conditions with marine sediment deposition occurred during the early Carboniferous, approximately 350 million years ago. Thus the brines observed in southern Ontario are likely 100s of millions of years old;

c) stable isotope data from the brines indicate enrichment of $\delta^{18}O$. This enrichment is considered indicative of water-rock interaction and long residence time; indicating that the stable isotope data support the interpretation of a marine origin for the brines;

d) evidence for cross-formational flow exists only for ancient events driven by Paleozoic orogenic or tectonic activity; and

e) there is no evidence in the Bruce area for penetration of glacial or more recent meteoric water below the upper Silurian formations.

The Regional and Site Hydrogeological Modelling study used the geological framework developed in the preceding study together with available hydrogeologic parameters from literature searches and those from the Phase 1 Site Characterization program at the Bruce site. The Regional Hydrogeology study concluded:

a) the regional scale domain can be divided into shallow, intermediate and deep groundwater zones. These groundwater zones are defined based on their hydrogeological properties and hydrochemistry characteristics;

b) there are multiple low permeability formations above the proposed repository horizon, including over 200 m of Ordovician shales and multiple low permeability shale, carbonate and evaporite strata in the Silurian sequence;

c) saline groundwater exists from the Silurian Salina Formation (~180 m below ground) to the Cambrian sandstones at 843 m depth. The saline groundwater has an increased density, which together with the low permeability formations provides a stagnant, diffusion dominated groundwater environment;

d) the performance measure used in the regional hydrogeologic analysis is mean life expectancy. This measure determines the length of time solute at a certain level within the stratigraphic sequence will take to travel to the point of discharge. Calculations show that for the DGR base case simulation the mean life time expectancy is 8.9 million years;

e) the high hydraulic head in the Cambrian and the low hydraulic heads in the Ordovician demonstrate convergent flow towards the repository horizon. These hydraulic head anomalies can only exist if the vertical hydraulic conductivities of the Ordovician rock are extremely low (~$1x10^{-14}$ m/s); and

f) paleoclimate modelling has shown that meteoric recharge does not penetrate below upper Silurian formations.

Long-term climate change could have important implications for the design of a deep repository. In the Phase 1 Geosynthesis, this work was focused on understanding past glacial processes and interpreting them to predict the potential influence of future glacial episodes on the DGR. This work employed the University of Toronto's Glacial Systems Model that performed simulations on a continental scale. This work provided the following conclusions:

a) if a reglaciation of the Canadian land mass should occur it would likely be about 60,000 years into the future. The timing of such an event depends to a large extent on the CO_2 concentration in the atmosphere;

b) future glacial events may have ice thicknesses of up to 3 km over the DGR. Such loadings create significant increases in normal stress;

c) proglacial lakes and glacial melt waters can contribute significantly to recharge of shallow aquifers. Permafrost conditions, if they exist, will limit recharge;

d) predicted permafrost depths in the Bruce area are on the order of a few 10s of metres; and

e) isostatic ground level changes caused by ice load are predicted to range up to 500 m.

Natural and induced perturbations to the repository can impair its structural stability and the integrity of the far-field barriers enclosing the repository in the long-term. A Geomechanical Modelling study was completed to assess such influences on the DGR performance over a 100,000 year timeframe. This work concluded:

a) The maximum time-dependent strength degradation of the repository floor and roof after a period of 100,000 years is 6 m above the cavern and about 4 m in the adjacent pillars. This in turn results in about 2.5 m of rockfall from the cavern crown;

b) Gas pressure build-up from the decay of disposed waste and container packaging was assessed to predict potential hydrofracing of the adjacent formation. The results indicate that fracture propagation will occur preferentially along horizontal bedding planes and may reach 16 m in the maximum gas pressure (15 MPa) case. However, gas build-up in all cases considered will not generate vertical features that could result in releases to the biosphere;

c) Two seismic events of magnitude M5.5 and M7 at distances of 15 and 50 km, respectively from the repository, were modelled and the results demonstrated that in both cases there was no damage to the cavern opening. However, when the seismic shaking is coupled with time-dependent strength degradation there is almost total collapse of the damaged zone of the cavern crown. The predicted breakout extends to about 5.5 m into the roof; and

d) The effects of glacial loading on cavern stability were simulated using normal stresses created by 2.5 km of ice together with time-dependent strength degradation previously determined. Results show that the caverns and pillars between caverns remain stable throughout the glacial cycle. However, the loading causes fracturing throughout the pillar width. There is a need to confirm stability for multiple glacial events that have occurred in the geologic past on a nominal 115 ka frequency.

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