ONTARIO POWER GENERATION'S PROPOSED L&ILW DEEP GEOLOGIC REPOSITORY: GEOSCIENTIFIC ASSESSMENT

Mark Jensen
Nuclear Waste Management Organization
Toronto Ontario, Canada

Ken Raven
Geofirma Engineering Ltd.
Ottawa, Ontario, Canada

Robert Leech
AECOM Canada Ltd.
Markham, Ontario, Canada

ABSTRACT

The Nuclear Waste Management Organization (NWMO) recently completed geoscientific studies on behalf of Ontario Power Generation (OPG) to verify the suitability of the Bruce nuclear site, Municipality of Kincardine, Ontario, to host a Deep Geologic Repository (DGR) for OPG's Low and Intermediate Level Nuclear Waste (L&ILW). The Bruce nuclear site is underlain by a ≈850 m thick Paleozoic sedimentary sequence comprised of near-horizontally layered Cambrian- to Devonian-age sediments occurring on the eastern flank of the Michigan Basin. As envisioned, the proposed DGR would be excavated at a depth of ≈680 m within the upper Ordovician argillaceous limestone Cobourg Formation. Multi-phase geoscientific studies conducted over 4-years indicate that the upper Ordovician formations proposed to host and enclose the DGR comprise a laterally traceable, stable, saline (TDS ≈200-350 g/L) and low permeability ($\leq 10^{-13}$ m/s) groundwater regime in which solute migration has been dominated by diffusive processes. This paper provides an overview of the coordinated site-specific and regional geoscientific studies and how they have provided a basis to understand both the current site conditions and, past and future site evolution as it relates to the assessment of long-term passive DGR safety.

1 INTRODUCTION

The Nuclear Waste Management Organization (NWMO) on behalf of Ontario Power Generation (OPG) has conducted multi-disciplinary geoscientific studies at the Bruce nuclear site to confirm the suitability of the underlying Paleozoic sequence for development of a proposed Deep Geologic Repository (DGR) for Low and Intermediate Level Radioactive Waste (L&ILW) from OPG owned or operated nuclear generating facilities (Figure 1). An Environmental Assessment for the proposed DGR has been completed in accordance with the Canadian Environmental Assessment Act. The Bruce nuclear site, situated 225 km northwest of Toronto on the eastern shore of Lake Huron, is underlain by an ≈850 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 argillaceous limestone of the Cobourg Formation at a depth of ~680 m, which is overlain by 200 m of Ordovician shale.

A key aspect of the DGR Safety Case is the integrity and long-term stability of the sedimentary sequence to contain and isolate L&ILW at timeframes on the order of 1 Ma. 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 [1],[2]. In 2006, site-specific investigations were initiated following the development of a Geoscientific Site Characterization Plan (GSCP) [3],[4].

The GSCP represents a stepwise 4-year, multi-phase program of geoscientific investigations that includes a description of site-specific field and laboratory investigations to further develop and test the existing geoscientific knowledge of sub-surface conditions as they relate to understanding geosphere stability and evolution, engineered repository systems design, and long-term DGR safety.

This paper provides an overview of the DGR project with a focus on geosciences in terms of directed site characterization activities and the completion of a Geosynthesis, which provides an interpretation of past, present and future site conditions as relevant to assessing long-term DGR safety.

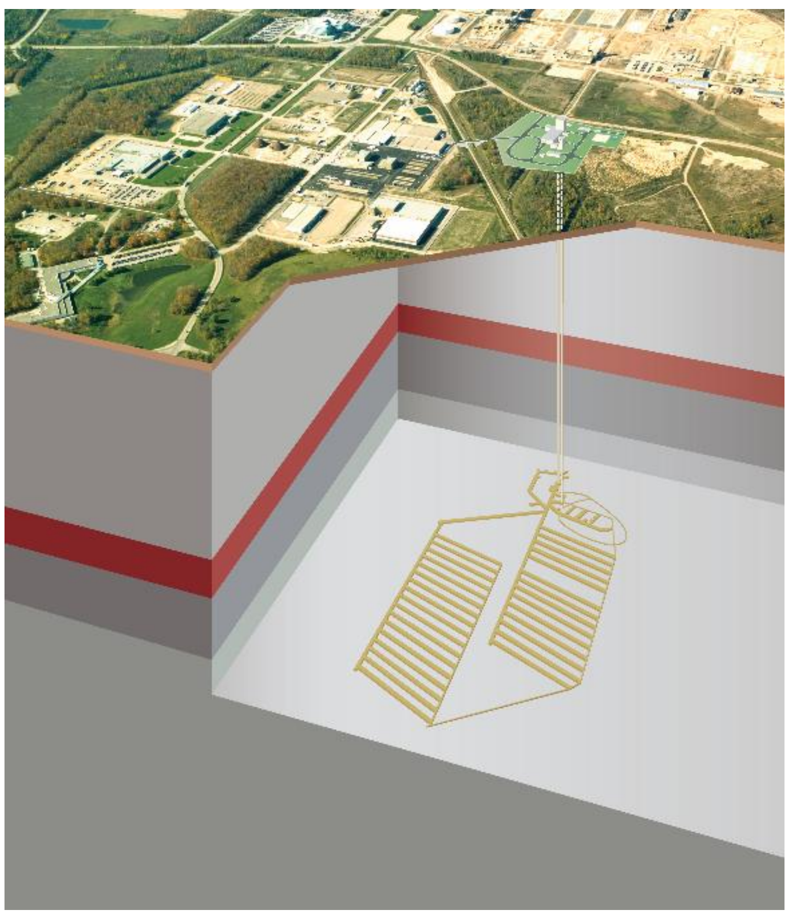

Figure 1. Artist rendering of proposed Ontario Power Generation Deep Geologic Repository at the Bruce nuclear site, near Tiverton, Ontario.

2 BACKGROUND – DGR PROJECT

Ontario Power Generation's Western Waste Management Facility (WWMF) at the Bruce nuclear site has received L&ILW from the Pickering, Bruce and Darlington nuclear stations for over 30 years. The waste is stored in engineered storage structures, both above and below ground, depending on the physical and radiological characteristics of the waste. At present there is approximately 75,000 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 tens of thousands of years.

Since the mid-1980s, OPG has reviewed a wide range of options for the long-term management of L&ILW, including above- and below-ground repository concepts considered by the Municipality of Kincardine and OPG through an Independent Assessment Study completed in March 2004. The outcome of this Independent Assessment Study was that all L&ILW repository concepts were considered technically feasible. Due to margins of safety, the municipality selected the DGR concept in spring 2004, which then became the preferred option for long-term L&ILW management.

In October 2004, the Municipality of Kincardine and OPG signed a Hosting Agreement to site a DGR at the Bruce nuclear site. This agreement explicitly excludes used nuclear fuel from the DGR. The agreement required a formal survey of community support, which was completed in January 2005. Results of the survey indicated a clear majority supporting the DGR project, and the decision to continue with the DGR Hosting Agreement was affirmed by Kincardine Municipal Council on February 16, 2005.

As envisioned, the DGR would involve the excavation of waste emplacement rooms within the Ordovician age argillaceous limestone of the Cobourg Formation at a depth of ≈680 m beneath the Bruce nuclear site (Figure 1). The repository, accessed via two vertical shafts, would require the excavation of nearly 890,000 m^3 of rock to accommodate an emplaced L&ILW volume of 200,000 m^3 (as packaged) within an approximate 30 Ha repository footprint. Support buildings would be located on ground surface, above the underground workings. The current repository concept would consist of a series of emplacement rooms arranged in parallel rows on either side of central access tunnels. A concrete floor will be poured to provide a stable base for stacking of the L&ILW packages, and the low-level waste packages would be segregated from the intermediate-level waste packages in different sections of the repository.

2.1 Planning and Strategy

In July 2005, OPG initiated a process that culminated in the preparation of a Phase I GSCP for the proposed DGR [3]. The GSCP provided a comprehensive and internationally peer-reviewed basis for DGR-related geoscientific studies. The strategy for the development of the GSCP included the following key elements.

- A 4-year, three phase site characterization program designed to allow for iterative development and refinement of a Descriptive Geosphere Site Model (DGSM).

- An assessment of internationally accepted features, events and processes (FEPs) relevant to the understanding and establishment of site suitability.
- Peer review of the GSCP by OPG stakeholders, regulatory agencies, and an independent Geoscience Review Group (GRG).
- Integration of the GSCP with both regional studies in southwestern Ontario and natural geoscience analogue studies to assess the concepts relevant to establishing long-term DGR safety.
- Direct inclusion of international geoscience site characterization experience in investigations of deep sedimentary formations for long-term radioactive waste management purposes.

The activities described in the GSCP supported two key deliverables: 1) a **Descriptive Geosphere Site Model**, which is an integrated, multi-disciplinary, geoscientific description and explanation of the undisturbed subsurface environ as it relates to site-specific geologic, 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 assessing long- term DGR performance and safety.

The structure of the GSCP ensured that the assumed favourable characteristics and features of the site, which form the foundations of the Geosynthesis and the DGR Safety Case, were repeatedly tested. These favourable characteristics, or key hypotheses, are summarized below.

1) **Site Predictability**: near-horizontally layered, undeformed sedimentary shale and limestone formations of large lateral extent;
2) **Multiple Natural Barriers**: multiple low permeability bedrock formations enclose and overlie the DGR;
3) **Contaminant Transport is Diffusion-Dominated**: deep groundwater regime is ancient showing no evidence of glacial perturbation or cross-formational flow;
4) **Seismically Quiet**: comparable to stable Canadian Shield setting;
5) **Geomechanically Stability**: selected DGR limestone formation will provide stable, virtually dry openings;
6) **Natural Resource Potential is Low**: commercially viable oil and gas reserves are not present; and
7) **Shallow Groundwater Resources are Isolated**: near-surface groundwater aquifers are isolated from the deep saline groundwater system.

In this capacity, the GSCP described surface and sub-surface site characterization activities necessary to:

- assess and reaffirm the technical suitability of the proposed DGR concept;
- provide evidence on the geoscientific basis for repository safety at timeframes of 1Ma (i.e., stable rock formations; diffusion dominant transport regime);
- support development of a site-specific engineered repository design;
- provide a geoscientific basis for the post-closure safety assessment; and
- development of an integrated DGR Safety Case describing the expected long-term safety and potential impacts of the DGR.

Upon completion of Phase I investigations in Fall 2008, acquired site knowledge was used to test and revise, as necessary, the GSCP to ensure adequacy for Phase IIa and Phase IIb activities [4]. Phase IIa and IIb activities were successfully completed in June 2010. OPG submitted the Environmental Impact Statement and DGR Site Preparation/Construction license documentation on April 14, 2011. This submittal included the DGR Descriptive Geosphere Site Model [5] and Geosynthesis [6], which are publically available at nwmo.ca/dgr.

2.2 Site Specific Investigations

2.2.1 Overview

Site-specific investigations at the Bruce nuclear site involved a coordinated sequence of field and laboratory studies. Key amongst these has been completion of a 2-D seismic reflection survey and a deep borehole drilling program. In the fall of 2006, a 20 line km 2-D seismic reflection survey was shot along 9 transects. This survey was designed to focus on the imaging of the Ordovician sediments and in so doing provide a basis to assess the lateral continuity of the underlying bedrock formations and the presence of regional or local scale sub-vertical structural discontinuities beneath the 10 km^2 Bruce nuclear site.

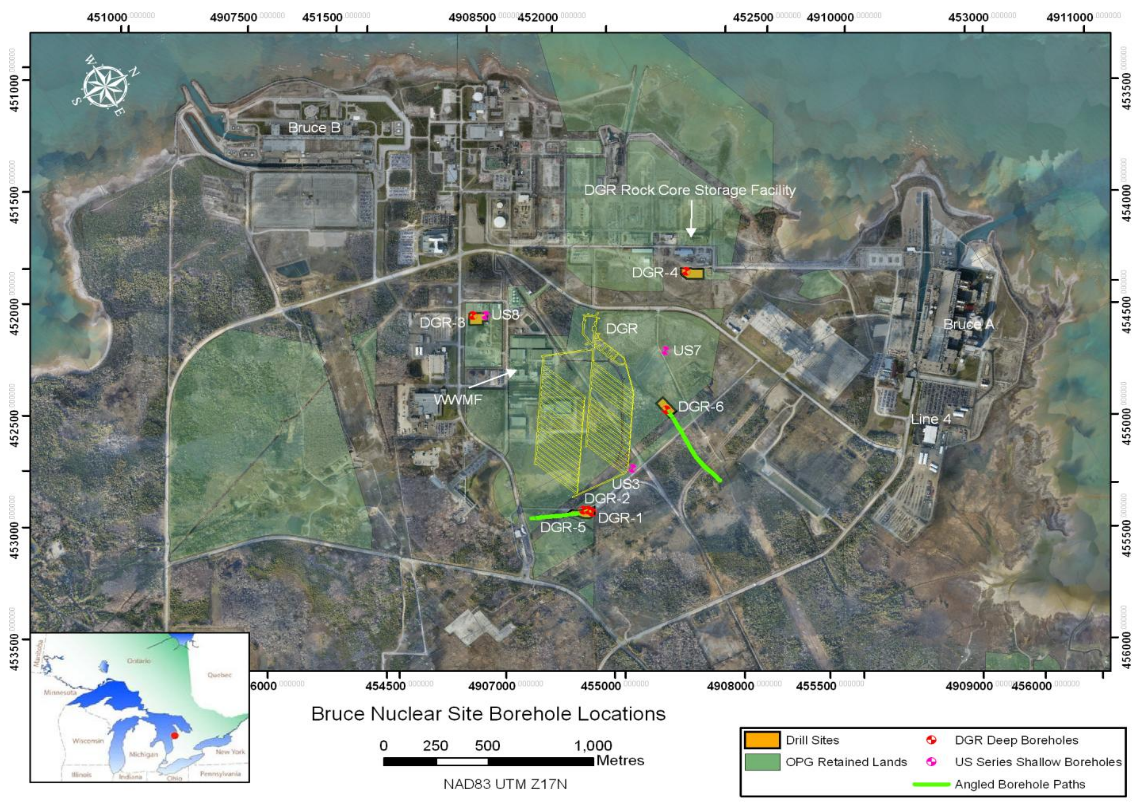

Figure 2. Bruce nuclear site base plan showing location of WWMF, proposed DGR layout, DGR drill sites, DGR(deep) – and US(shallow) – series boreholes, and Core Storage Facility.

The seismic reflection survey is complemented by a deep drilling program that included the drilling, coring and testing of 6 deep boreholes at 4 drill sites, as shown in Figure 2. The first of these deep boreholes (DGR-1 and DGR-2) were completed in the Fall of 2007. These boreholes

(152 mm dia.) intersected the entire sedimentary sequence and were purposely designed to provide isolated access to the Silurian and Ordovician sediments, as shown in Figure 3. In 2008, an additional two deep boreholes DGR-3 and DGR-4 (143 mm dia.) were drilled to establish a triangular pattern enclosing the DGR footprint. The bedrock stratigraphy as determined from rock core logging from these boreholes is depicted in Figure 3. Additional inclined boreholes, DGR-5 and DGR-6 were completed in January 2010.

The drilling program and borehole design were devised to minimize risk of borehole failure during in-situ testing and to provide assurance that intra-borehole flow and head re-distribution did not compromise data integrity. Under the DGR Project Quality Plan specific procedures have been prescribed for the logging, sampling and storage of the rock core. This includes the preservation of core samples necessary for pore fluid/noble gas characterization (University of Ottawa; University of Bern), estimation of effective diffusion coefficients (University of New Brunswick) and geomechanical testing (University of Western Ontario; CANMET). All cores (76 mm Φ) are stored at the Bruce nuclear site core storage facility, which was designed to accept core from the entire work program (≈ 3.8 km).

Upon completion of coring, a program of geophysical logging and hydraulic testing was performed within the open bores to obtain estimates of rock mass permeability. A suite of geophysical logs were completed to assist with formational contact interpretation and initial identification of permeable horizons within the sedimentary sequence. The geophysical logs included conventional and nuclear logs, acoustic televiewer log, borehole video and Fluid Electrical Conductivity logging. Borehole hydraulic testing involved straddle packer drill stem, pulse and slug testing (30 m test interval) dependent of the formation permeability. This latter hydraulic testing program applied in-situ borehole techniques and analysis methods developed at the Waste Isolation Pilot Plant in New Mexico (Sandia National Laboratories). Once in-situ testing was complete retrievable Westbay MP-55 multi-level casing systems were installed into the vertical boreholes to allow long-term pressure head monitoring and, groundwater sampling within permeable intervals. These monitoring data will, in part, allow background physical and chemical hydrogeologic conditions to be established.

For the purposes of this paper, the site-specific data collection programs are summarized in the following subsections, and highlight the magnitude and scope of the geoscientific investigations. In particular, the geomechanical, seismic monitoring, and hydraulic testing programs, provide key information relevant to the suitability and long-term stability of the proposed site for safely isolating waste, as well as providing information necessary for the design and construction of the facility.

2.2.2 Geomechanical Testing Program

Since the implementation of the site characterization program, a field and laboratory program to study the strength and deformation properties of the rock was carried out. Data from DGR-1 through DGR-4 on RQD and natural fractures indicate the Devonian and Upper Silurian dolostones are in poor condition and are moderately to highly fractured. Many of the low RQD values in these formations were attributed to the blocky nature of the rock created by the sub-erosion of salt beds during Late Silurian and Devonian times [1] and to core grinding under difficult drilling conditions. Below these units, the rock encountered in the boreholes is generally in very good condition and sparsely fractured.

The proposed DGR host rock, the Cobourg Formation, is a light to dark brownish-grey, mottled, very fine grained to crystalline, fossiliferous argillaceous limestone. Based on the drilling information, it has a thickness of approximately 28 m and is found below a depth of 650 mBGS. Uniaxial compression tests of 19 laboratory specimens reveal rock strengths (UCS) ranging from 78 and 175 MPa yielding a mean of 126 MPa. These values demonstrate that the proposed host rock is competent and the strength is significantly higher than those of the regional data [6]. This significant increase in strength may be attributed in part to factors such as the rigorous quality control procedure to minimize disturbance during handling of core samples in the laboratory and at the DGR site, the size effect of test samples, the difference in burial depths and lateral mineralogical variations in the depositional environment. The higher strength of the Cobourg limestone is visible in Figure 4 when the UCS is compared with those of sedimentary formations studied internationally in the framework of waste disposal.

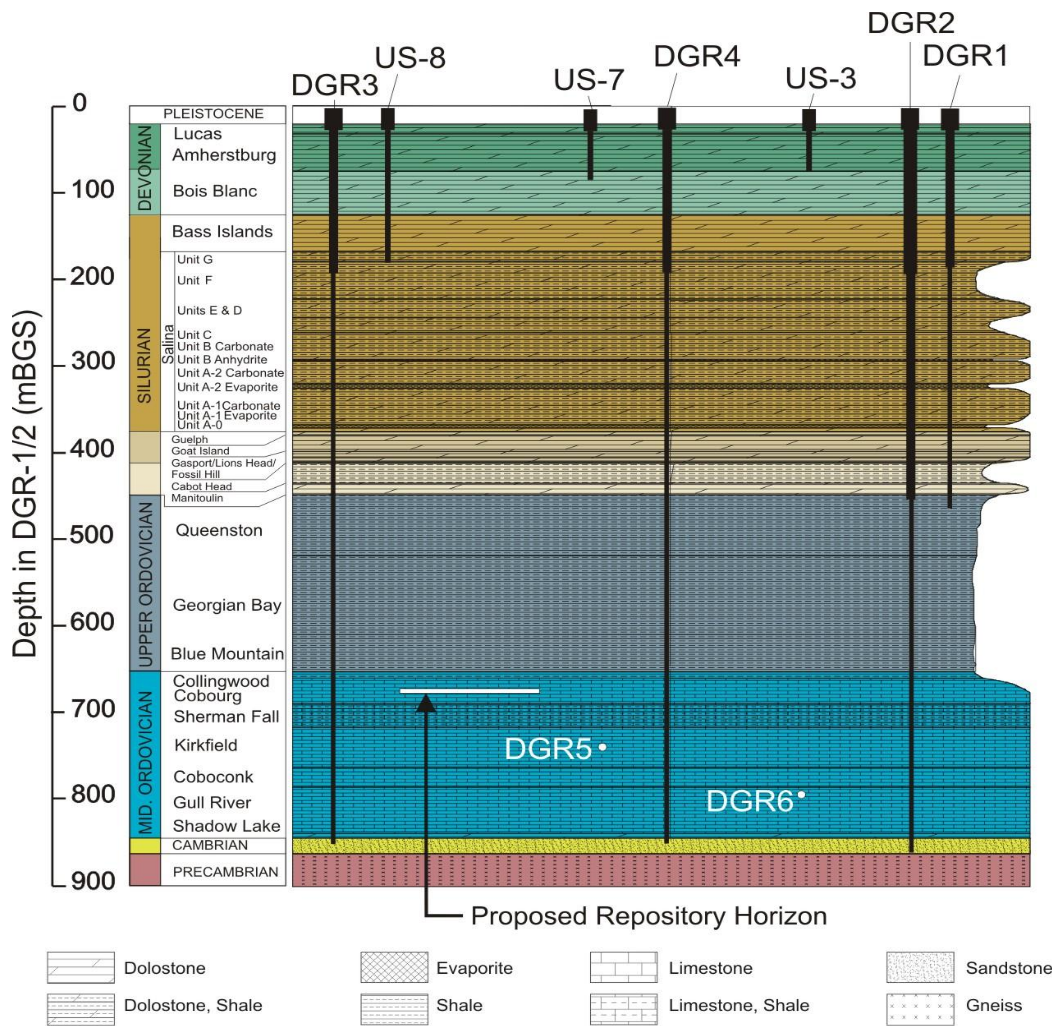

Figure 3. Bruce nuclear site bedrock stratigraphy as determined through core logging of deep boreholes DGR-1 through DGR-6 (plan view shown in Figure 2).

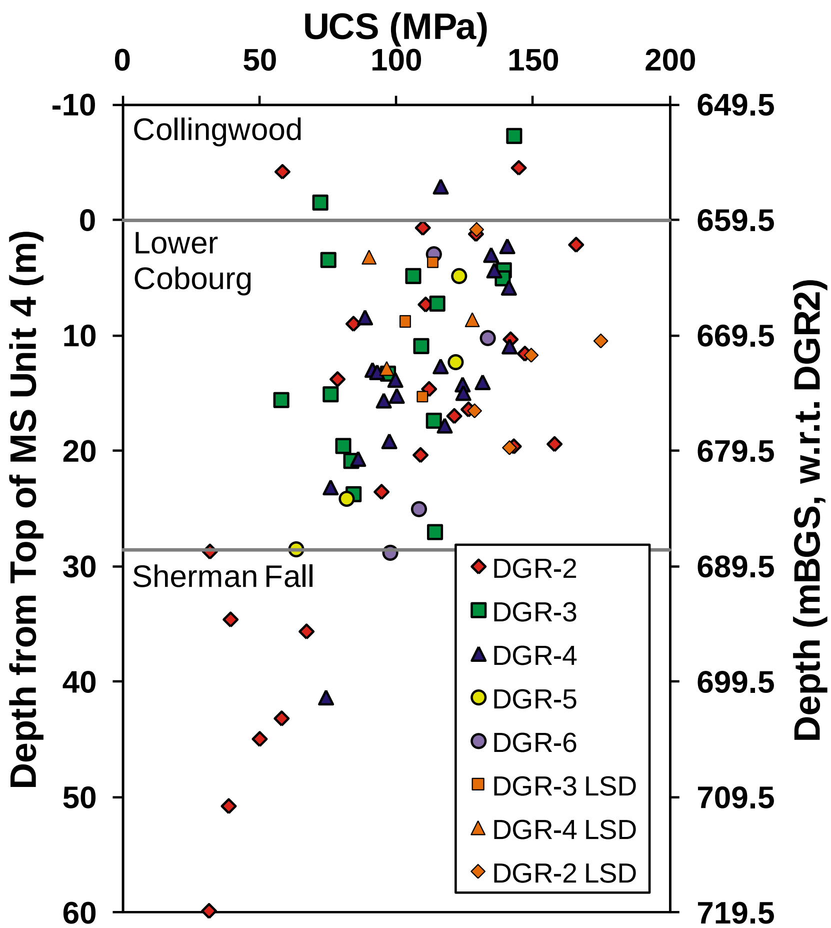

Figure 4. Comparison of uniaxial compressive parameters [6].

2.2.3 Seismic Monitoring

Efforts were taken to improve the ability to monitor low-level seismic activity in the vicinity of Bruce nuclear site during site characterization activities. While located in an area of low seismic hazard [6], an improved understanding of micro-seismicity as it relates to the regional earthquake distributions and interpretation of regional scale faulting is important in assessing DGR performance. To this end, a new borehole seismograph network was installed. The seismographs (3) are positioned in cased bedrock wells 27 to 55 m deep, within 50 km of the Bruce nuclear site. The detection threshold magnitude is $M \geq 1$. The monitoring of the seismograph network, including the processing of data streams from Polaris and Geologic Survey of Canada (GSC) hubs, was, and continues to be, performed by the Canadian Hazard Information Service.

The lack of earthquakes (>1.0M) detected by the new microseismic array around the Bruce nuclear site is consistent with the region's low seismicity rate. Since the stations were installed, there has been only one earthquake larger than 1.0M recorded within 50 km of the site. This was a 1.2 M event located about 34 km off the shore of Lake Huron in 2008. Another 1.9 M event was located at 68 km from the site in December 2007. Figure 5 shows the historical seismicity of the Bruce region, including data up to December 2008.

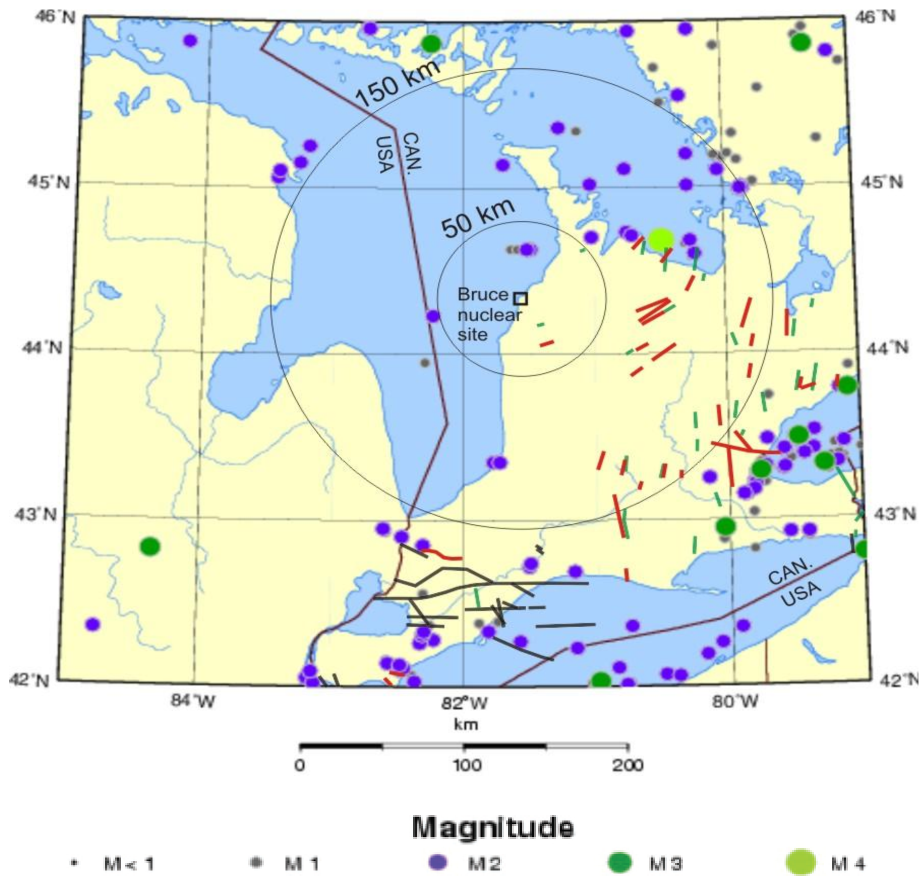

Figure 5. Historical seismicity near the Bruce nuclear site (to December 2008).

2.2.4 Hydraulic Testing Program

Pulse, slug, and drill-stem hydraulic testing using a custom-built straddle packer testing tool was used to quantify horizontal rock mass hydraulic conductivities. The tests were completed in DGR-1 and 2 in 2007, DGR-3 and DGR-4 in 2008, and in DGR-5 and DGR-6 between February and June of 2010. Pulse tests using straddle lengths of 30 m were completed in boreholes DGR-2 to DGR-4 to provide complete coverage of the Ordovician limestones and shales that would host and enclose the proposed repository. Packer testing using 10 m intervals, for the purpose of targeting specific zones within the sedimentary formations, was performed in DGR-6. Straddle packer test results were analysed using the Sandia National Laboratories numerical hydraulic-test simulator – nSIGHTS. Figure 6 shows the measured and average horizontal hydraulic conductivities for all DGR boreholes and the horizontal hydraulic conductivities are typically below 10^{-13} m/s at repository depth and in the immediately surrounding sedimentary formations.

Following the completion of straddle packer testing, three US-series boreholes and boreholes DGR-1 through DGR-4 were equipped with Westbay multiport groundwater monitoring systems. Environmental water heads calculated from formation pressures and the porewater/groundwater fluid density profile range from 140 m above ground surface (325 mASL) for the Cambrian sandstone to less than 265 m below ground surface (-80 mASL) in the Blue Mountain shale. Processes and mechanisms contributing to the observed over- and under-pressures, and to their longevity, are discussed in the Geosynthesis [6] and in the Hydrogeologic

Modelling report [7] and are currently the subject of further investigation. Regardless, the occurrence of significant under-pressures implies low rock mass permeabilities at formation scale.

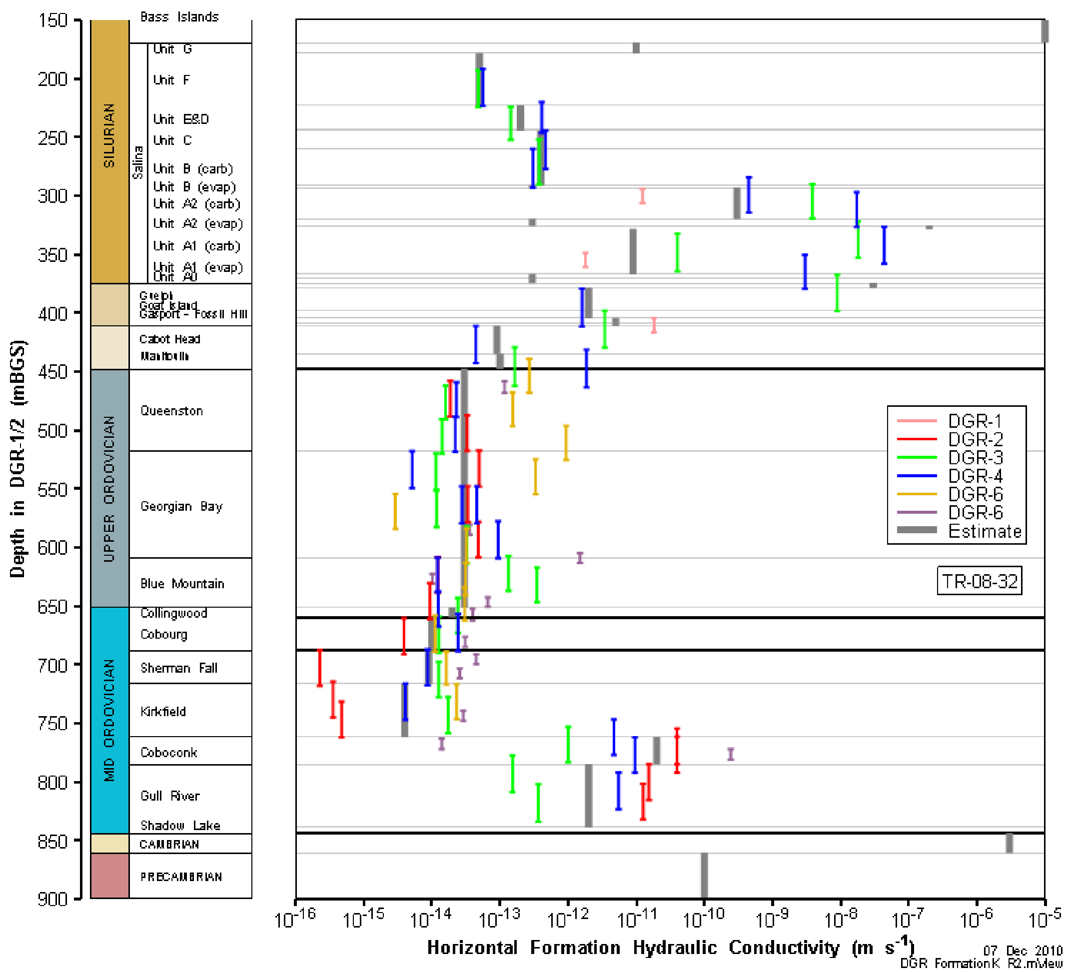

Figure 6: In-situ rock mass hydraulic conductivities and estimated (calculated) formation averages in DGR series boreholes DGR-1 to DGR-6.

These field measurement programs are complemented by an array of laboratory measurements taken from collected samples including petrophysical testing, diffusion testing [8], and porewater characterization [5],[6]. Figure 7 is a plot of groundwater and porewater density, which reflects the presence of significant concentrations of dissolved solids in the waters analyzed from the Ordovician sediments.

2.3 Geosynthesis

2.3.1 Overview

Site characterization activities were part of a focused work program, designed with the intention of testing the aforementioned hypotheses (section 2.1) as they relate to DGR safety and the development of a fully integrated and conservative Safety Case, and to ensure that multiple lines of scientific reasoning from the various geoscience disciplines (geology, hydrogeology, geomechanics, hydrogeochemistry) existed to support each of the hypotheses.

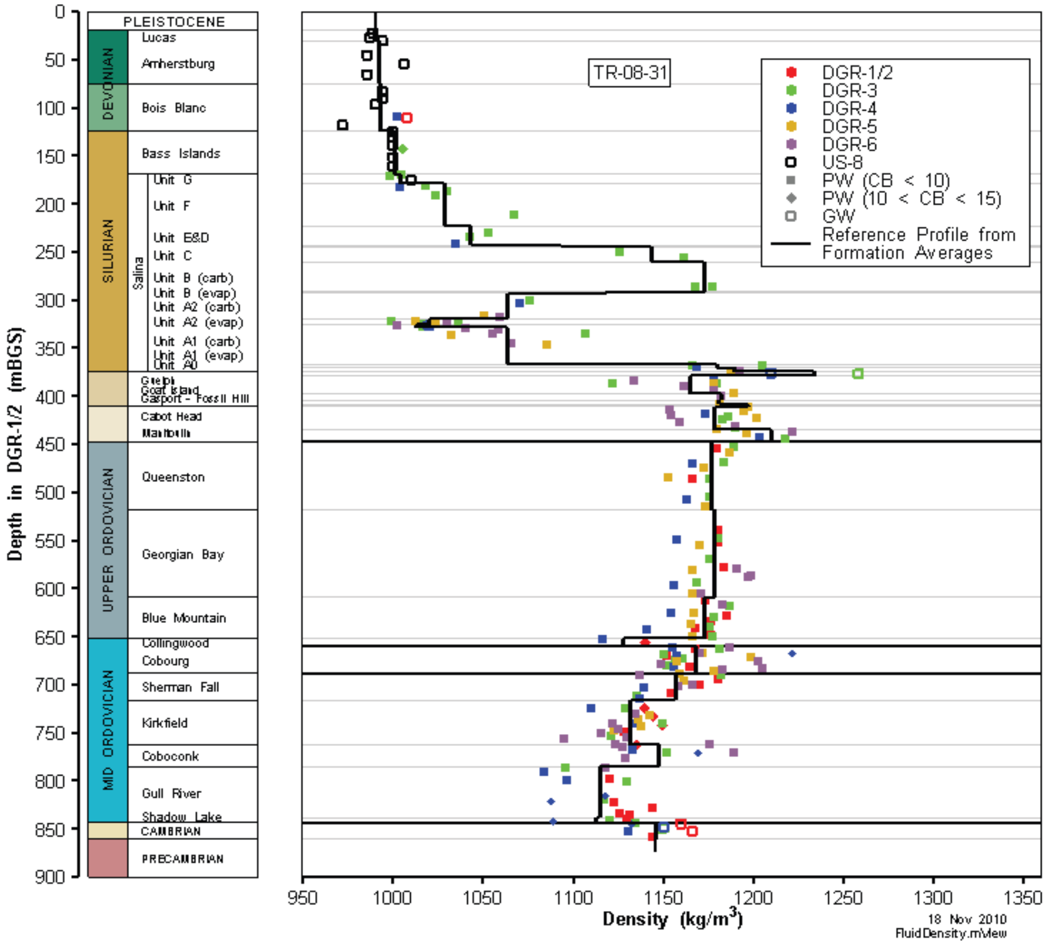

Figure 7. Reference groundwater and porewater density profile for all DGR boreholes.

The Geosynthesis task of the GSCP involved the overall integration of all project data, as well as the development of a Descriptive Geosphere Site Model(s) consistent with the project data, and provided the information necessary for preparation of the DGR Environmental Assessment and regulatory site preparation/construction license application. The Geosynthesis for the GSCP was developed to present the overall geoscientific understanding of the site, the host rock and the geological barrier system, including its present state and future evolution, as well as to provide the geoscientific database for Safety Assessment and Repository Engineering. Geosynthesis is an essential component in the development of a basis to understand the long-term performance of the DGR concept. It is an activity that was conducted throughout the entire site characterization work program and involved the coordinated and collaborative efforts of specialists from all relevant disciplines.

Completion of the Safety Case for the DGR is the result of the integration of results from all scientific and engineering functional groups associated with the design and engineering, environmental assessment, and waste characterization for the proposed DGR. These functional groups, in part, rely on site characteristics/attributes and parameters justified by Geosciences (see Figure 8) that underpin analyses and assessments.

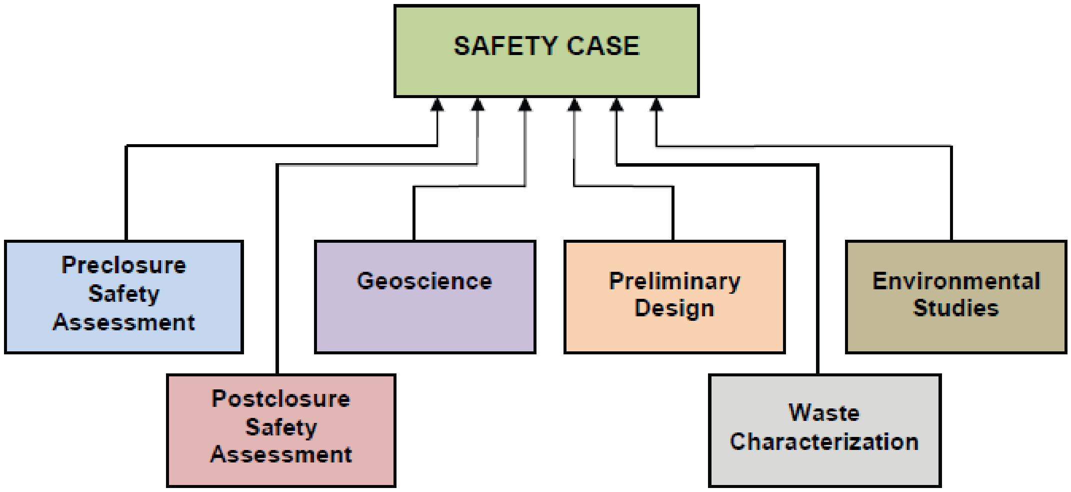

Figure 8. Development of the DGR Safety Case.

As part of Geosynthesis [6] activities, a series of technical reference documents were prepared, in part, to establish a regional context for the DGR program. These technical reports include:

- Regional Geology [9]
- Regional Geomechanics [10]
- Regional Hydrogeochemistry [11]
- Long-Term Climate Change [12]
- Hydrogeologic Modelling [7]
- Glacial Erosion Assessment [13]
- Analogue Study of Shale Cap Rock Barrier Integrity [14]
- Seismic Hazard Assessment [15]
- Long-Term Geomechanical Stability [16]
- Neotectonic Features and Landforms Assessment [17]
- Excavation Damaged Zones Assessment [18]
- Outcrop Fracture Mapping [19]
- Three-Dimensional Geologic Framework Model [20]

These reports are publicly available at www.nwmo.ca/dgr, and the some of the key findings from the site characterization work are summarized below.

2.3.2 Geology

The DGR site is located along the eastern margin of the Michigan Basin. Figure 9 illustrates the general Michigan Basin geology, showing the position of borehole DGR-2, which is immediately adjacent to the proposed DGR site, and also showing the boundary in cross-section of the detailed regional three-dimensional geological framework model (3DGF [20]; see Figure 10).

The 3DGF model covers an area of approximately 35,000 km^2 around the DGR site and was developed to capture and present the current geological understanding of the Paleozoic sedimentary formations and their stratigraphy. This understanding was required to provide context to the geology at the DGR site and was used as the basis to establish the hydrostratigraphy for the regional hydrogeologic modelling.

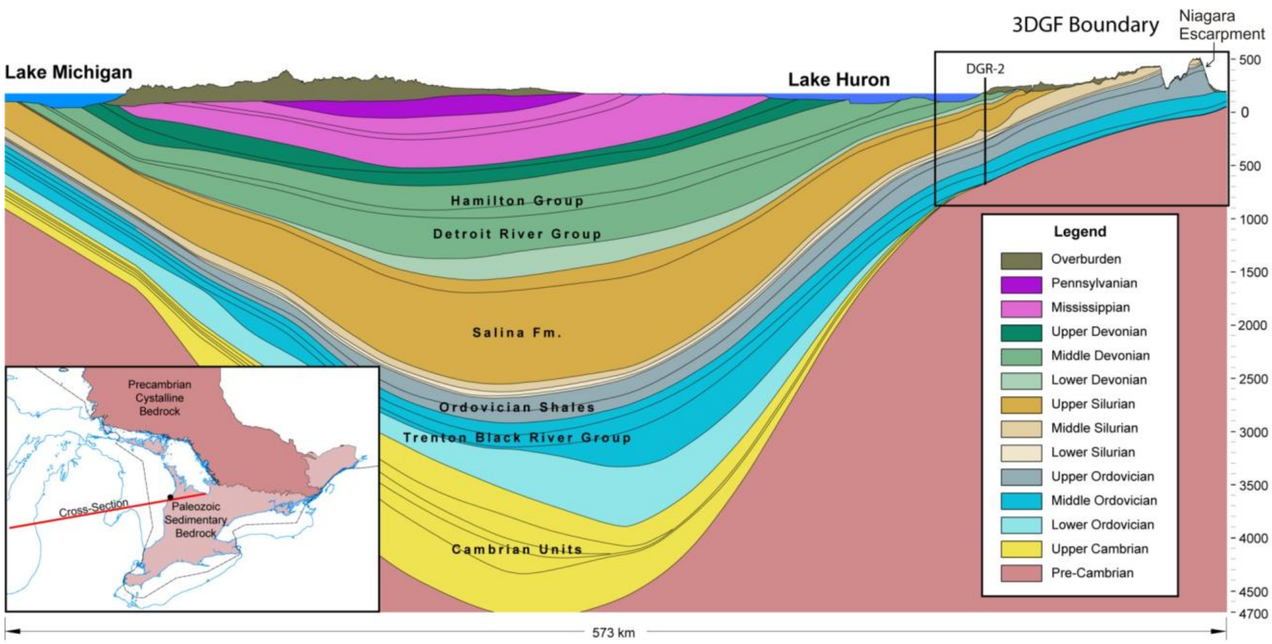

Figure 9. Regional geology of the Michigan Basin. Also shown is the relative location of DGR-2, as well as the 3DGF boundary.

The basal Cambrian sediments were deposited directly over the Precambrian basement, and although these deposits extend from the Appalachian Basin to the Michigan Basin, they have largely been eroded beneath most of southern Ontario. The lithology of the Cambrian units ranges from dolostone, to sandy dolostone, to argillaceous dolostone to quartzose sandstone, and are often described as porous and permeable.

Overlying the Cambrian deposits, or the Precambrian basement, in the subsurface of southern Ontario, are the Middle Ordovician carbonates. These rocks include the Shadow Lake, Gull River, and Coboconk formations of the Black River Group and the Kirkfield, Sherman Fall, and Cobourg formations (DGR host rock) of the Trenton Group. These rocks are generally characterized as limestones to argillaceous limestones and have a uniform and extensive distribution from the Appalachian Basin in New York, into the Michigan Basin of Ontario and Michigan. Capping the Ordovician limestones are the extensive Upper Ordovician shale sequences of the Blue Mountain, Georgian Bay and Queenston formations. These tight shale units are generally composed of non-calcareous to calcareous shales with minor siltstone and carbonate interbeds.

The Lower and Middle Silurian rocks at the DGR site consist of the Manitoulin Formation dolostones, Cabot Head Formation shales and the dolostones of the Fossil Hill, Lions Head, Gasport, Goat Island and Guelph formations. The Upper Silurian Formations are comprised of the Salina Group and the Bass Islands formations.

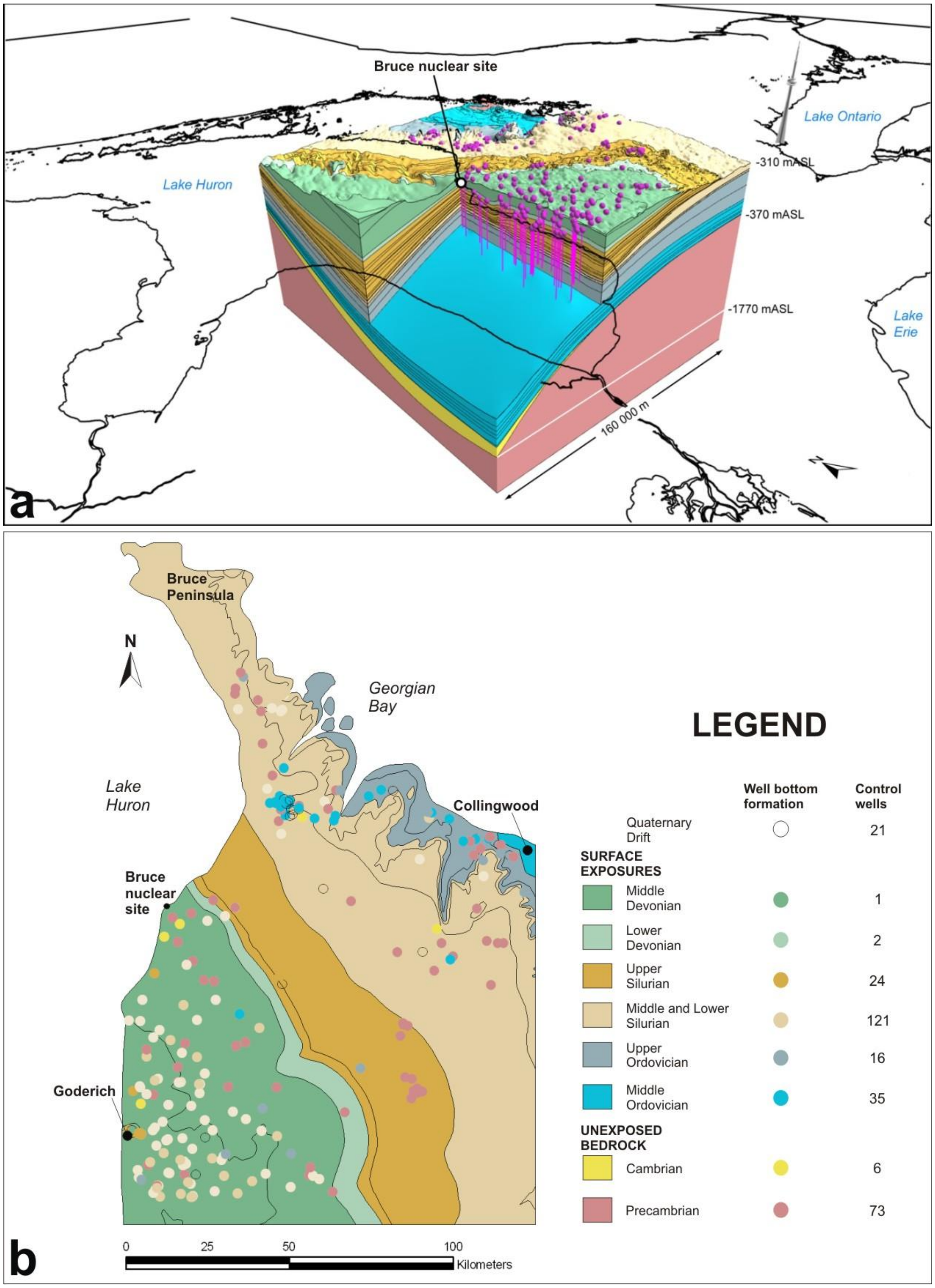

Figure 10. Three-Dimensional Geological Framework (3DGF) Model is shown on the eastern margin of the Michigan Basin.

The youngest rocks in the regional study area include the lower Devonian Bois Blanc Formation dolostones, which are disconformably overlain by Middle Devonian mixed limestones and dolostones of the Detroit River Group (Amherstburg and Lucas formations). The Lucas

Formation subcrops beneath the overburden at the Bruce nuclear site and outcrops along the shoreline.

The geology encountered in site borehole drilling [5] is consistent with the regional geology, as described in the DGR Regional Geology report and presented in the 3DGF model [20]. The Paleozoic bedrock formations below the Bruce nuclear site are highly predictable, including the range of lithologies, depth, thickness, and orientation of the formations over distances of kilometres. The Geosynthesis document [6] further notes that the uniformity of formation depths, as well as thicknesses and orientations at the Bruce nuclear site, provides evidence for the lack of vertical offsetting faults in the vicinity of the proposed DGR.

2.3.3 Hydrogeologic Modelling

A key aspect of the DGR concept is the role of multiple natural geosphere barriers in providing long-term isolation and containment of the L&ILW. Efforts beyond the field and laboratory have involved the integration of field data at local and regional scale into three-dimensional numerical simulations of the regional and site-specific groundwater system [7]. These simulations, performed with the code FRAC3DVS-OPG, have explored uncertainty in bedrock hydrostratigraphy and boundary conditions, the influence of the variable salinity of near-surface fresh compared to deep seated brine waters, and the effect of glacial events on groundwater hydrodynamics and mass transport (Figure 11). Illustrative numerical simulations of the groundwater system predict a sluggish deep seated groundwater system resilient to glacial perturbations, and one in which mass transport is dominantly governed by diffusion. Computed Mean Life Expectancies (time to system discharge), that incorporate advective, dispersive and diffusive transport processes for solute at the repository horizon, are 44 million years or greater.

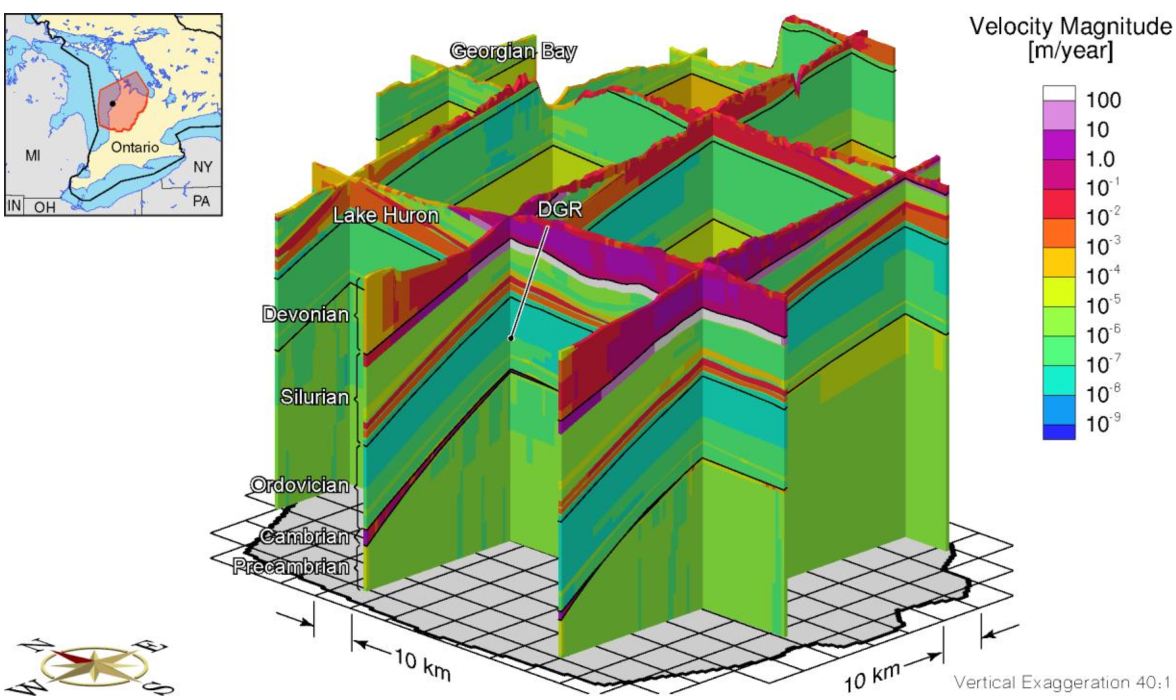

Figure 11. Numerical simulation of regional (18,000 km^2) groundwater system with FRAC3DVS-OPG within Paleozoic sediments in vicinity of the proposed DGR.

The numerical simulations examined long-term field observations of non-hydrostatic or abnormal hydraulic head conditions within the sediments as observed in a multi-level Westbay (MP-55) monitoring system. Particularly of note are the aforementioned depressed environmental heads in the Ordovician sediments that, while still equilibrating after more than two years of monitoring, are currently ca. 265 m below ground surface (Figure 12). These sediments lie unconformably above a thin (17 m), laterally extensive, permeable (K≈10^{-6} m/s) and low storage (S_s≈10^{-6} m^{-1}) Cambrian sandstone aquifer, with an abnormal over-pressure of 140 m above ground surface (Figure 12). The resultant vertical hydraulic gradients sustained across the sediments are high, on the order of 2, and appear convergent on the repository horizon. Model results suggest that vertical formation hydraulic conductivities must be of the order of 10^{-14} m/s or less to preserve the observed hydraulic heads. Studies examining the origin and longevity of the abnormal heads are continuing in order to further the understanding of the Ordovician properties and barrier functions relevant to repository safety, but thus far the results suggest that the abnormal pressures appear to be long-lived phenomena.

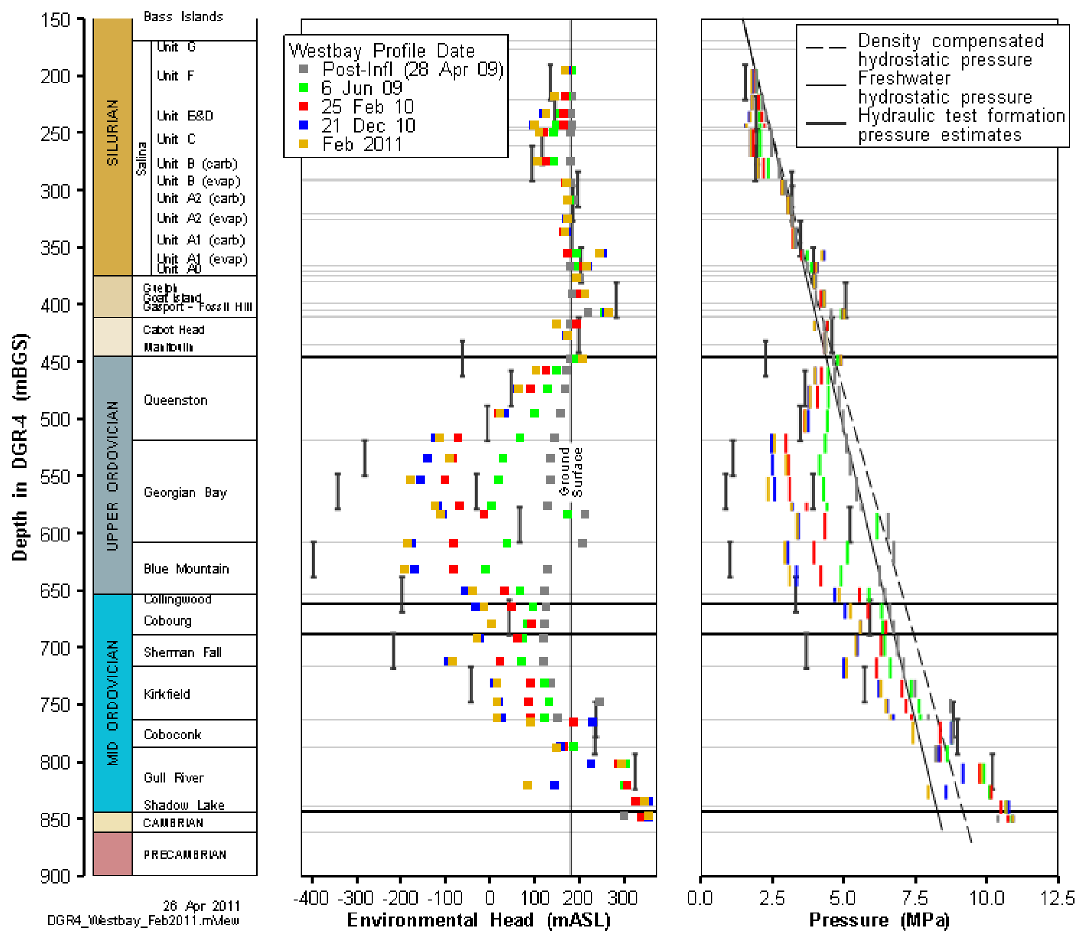

Figure 12. Environmental head and formation pressure profiles in DGR-4 (April 2009 to February 2010).

2.3.4 Hydrogeochemistry

A full suite of site-specific hydrogeochemical data were collected for the groundwaters and porewaters analyzed from boreholes DGR-1 through DGR-6. The geochemical data were collected to test the following geoscience hypotheses with regard to site suitability:

1) **Contaminant Transport is Diffusion-Dominated**: deep groundwater regime is ancient showing no evidence of glacial perturbation or cross-formational flow;
2) **Multiple Natural Barriers**: multiple low permeability bedrock formations enclose and overlie the DGR; and
3) **Shallow Groundwater Resources are Isolated**: near-surface groundwater aquifers are isolated from the deep saline groundwater system.

As part of the work program, a comprehensive geochemical database of elemental and isotopic analyses on groundwater from oil and gas wells within the Paleozoic sediments of southwestern Ontario was assembled at the University of Waterloo [11], and these data were assessed with respect to: i) depth of penetration of glacial waters; ii) cross formational solute transport; iii) inter-formational groundwater mixing; and iv) the spatial variability in formational groundwater composition. The site-specific dataset, including natural tracers ($\delta^{18}O$, $\delta^{2}H$, Cl, Br, $^{87}Sr/^{86}Sr$), major ions (Ca, Mg, Sr, K, Na, SO_4, B), natural and noble gases (CH_4, $\delta^{13}C_{CH4}$, $\delta^{2}H_{CH4}$, CO_2, $\delta^{13}C_{CO2}$, He, $^{3}He/^{4}He$), and radioisotopes (^{14}C, ^{36}Cl, ^{127}I), was used to determine the origin and evolutionary history of the sedimentary brines, and where applicable, was compared with the regional database.

For site characterization activities at the Bruce nuclear site, groundwater samples were collected directly from the producing intervals. Those parameters that could be measured directly in the field (e.g., pH, dissolved oxygen, electrical conductivity) were recorded and samples were then forwarded to various laboratories for further analysis (e.g., major ion concentrations, isotopic analysis). Porewater extraction techniques were necessary for the majority of the analyses performed, particularly for the formations of Ordovician age, due to the extremely low hydraulic conductivities and porosities of the sedimentary formations. The porewaters were analyzed by a variety of methods including crush and leach, vacuum distillation, and isotopic equilibration. Further discussion of these methods is provided in [21].

The geochemical summary presented below highlights the main conclusions of the hydrogeochemical investigations as they relate to the hypotheses tested. A full discussion of the hydrogeochemical investigations, including the analyses and interpretations, can be found in [21].

Key Findings of the Hydrogeochemical Investigations

The brines in the Michigan Basin are considered to be of seawater, or evaporated seawater, origin [22],[23], and deviations from the sea water evaporation curve (Cl versus Br) are interpreted in terms of the processes that may have influenced brine evolution. Dilution is indicated for samples that plot below the seawater evaporation curve on a trend toward the origin, and dissolution of halite is indicated for samples that plot above the seawater evaporation trend. The regional- and site-scale Cl-Br data are consistent (see Figure 13), suggesting an ancient seawater origin for the brines, with subsequent modification by processes such as dilution, halite dissolution, and water-rock interaction [6].

In Figure 14, the $\delta^{18}O$ and $\delta^{2}H$ data collected from the Bruce nuclear site display the same general distribution patterns as the regional data. The shallow formations (including the Bois Blanc, Bass Islands, and some fluids from the Salina Group) have depleted $\delta^{18}O$ and $\delta^{2}H$ signatures ($\delta^{18}O$ = -7.5 to -11‰; $\delta^{2}H$ = -50 to -70‰) relative to modern precipitation and plot on the GMWL, suggesting that they have been influenced by cold-climate waters. The Salina Group samples that plot in the glacial meltwater range are from the A1 Unit carbonate aquifer (see text below). The majority of the deep formation fluids (Ordovician shales, Ordovician carbonates and Cambrian) have enriched $\delta^{18}O$ signatures, plotting to the right of, and below, the GMWL, which is typical of sedimentary basin brines and suggests long time frames for water-rock interaction.

Profiles of TDS, $\delta^{18}O$, and $\delta^{2}H$ for the Bruce nuclear site are shown in Figures 15 and 16. The TDS values measured in the Ordovician formations are highly saline (>200g/L). Of note, is the general consistency in the data distribution between the DGR boreholes in all three natural tracer profiles. The TDS values measured in the Ordovician formations are highly saline (ranging between 200 and 350 g/L), and these salinities are distinct from those of the shallow groundwater system.

Referring to Figure 14 and to Figure 16, the maximum depth of glacial meltwater infiltration at the Bruce nuclear site is approximately 325-328 mBGS in the thin Silurian Salina A1 Unit carbonate aquifer. With the exception of the Salina A1 Unit, the maximum depth of glacial meltwater infiltration that can be observed at the Bruce nuclear site is approximately 190 mBGS, which is consistent with regional trends (~130 mBGS - [11]; 100-300 mBGS – [24]). Between approximately 190 and 325 m depth, there is little to no evidence of glacial meltwater signatures, which is attributed to the confining nature of the units within the Salina Formation (alternating beds of low-permeability carbonate and evaporite) suggesting that the Salina A1 Unit represents an isolated thin interval that has been open to infiltration due to its higher permeability and local outcropping to the east of the Bruce nuclear site along the Niagara Escarpment.

$^{87}Sr/^{86}Sr$ ratios of both water and host rock from the Bruce nuclear site were determined at the University of Ottawa [25],[26]. Consistent with regional results from oilfield groundwaters of the Michigan Basin [27], the $^{87}Sr/^{86}Sr$ ratios from the Ordovician and Cambrian waters at the Bruce nuclear site are more radiogenic than the Paleozoic seawater curve (see Figure 17). The enriched ^{87}Sr values are attributed to the following possible sources: 1) ingrowth of ^{87}Sr from ^{87}Rb decay since the Ordovician; 2) leaching of ^{87}Sr from old shield-derived siliciclastic material in the shales and the argillaceous component of the limestones; and, 3) diffusion of Sr upward from an ^{87}Sr-enriched brine source in the underlying Precambrian shield, all of which are processes that indicate long time periods for water-rock interaction and/or diffusion, and support the hypothesis that the water and solute residence times in these formations are long (i.e., the deep hydrologic system is ancient) and that solute transport is extremely slow.

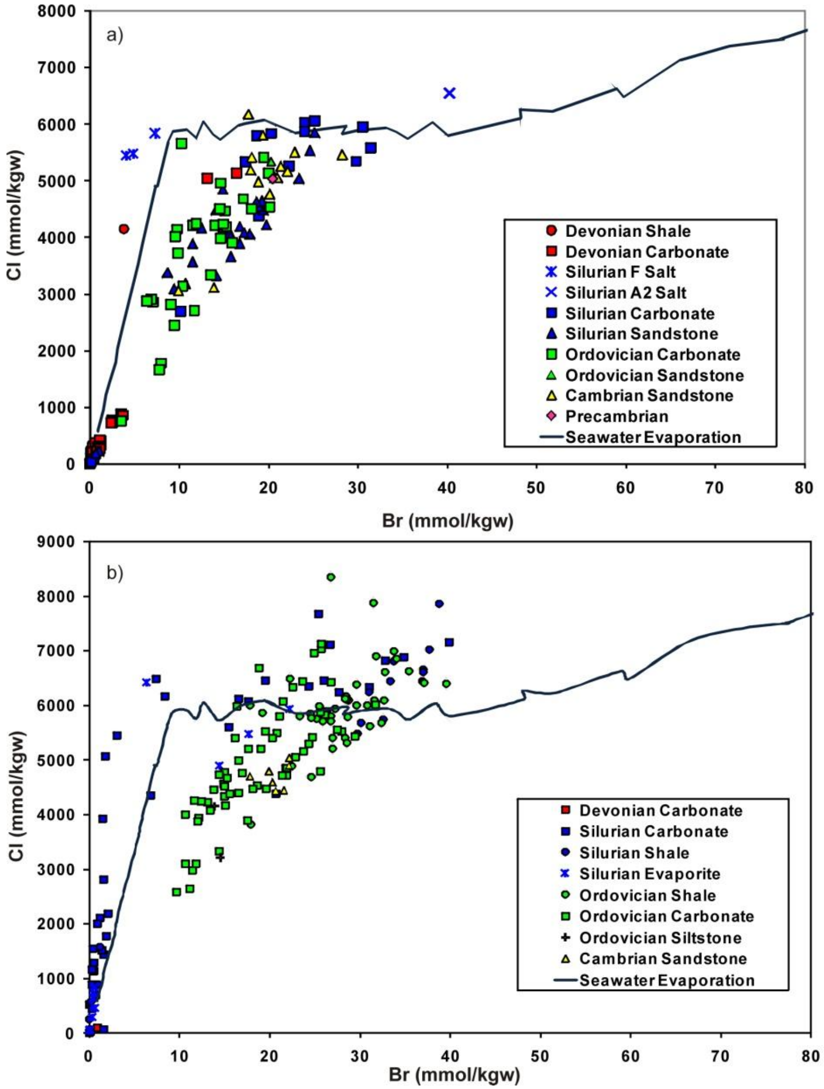

Figure 13. Cl versus Br for groundwaters and porewaters: a) regional dataset and b) Bruce nuclear site.

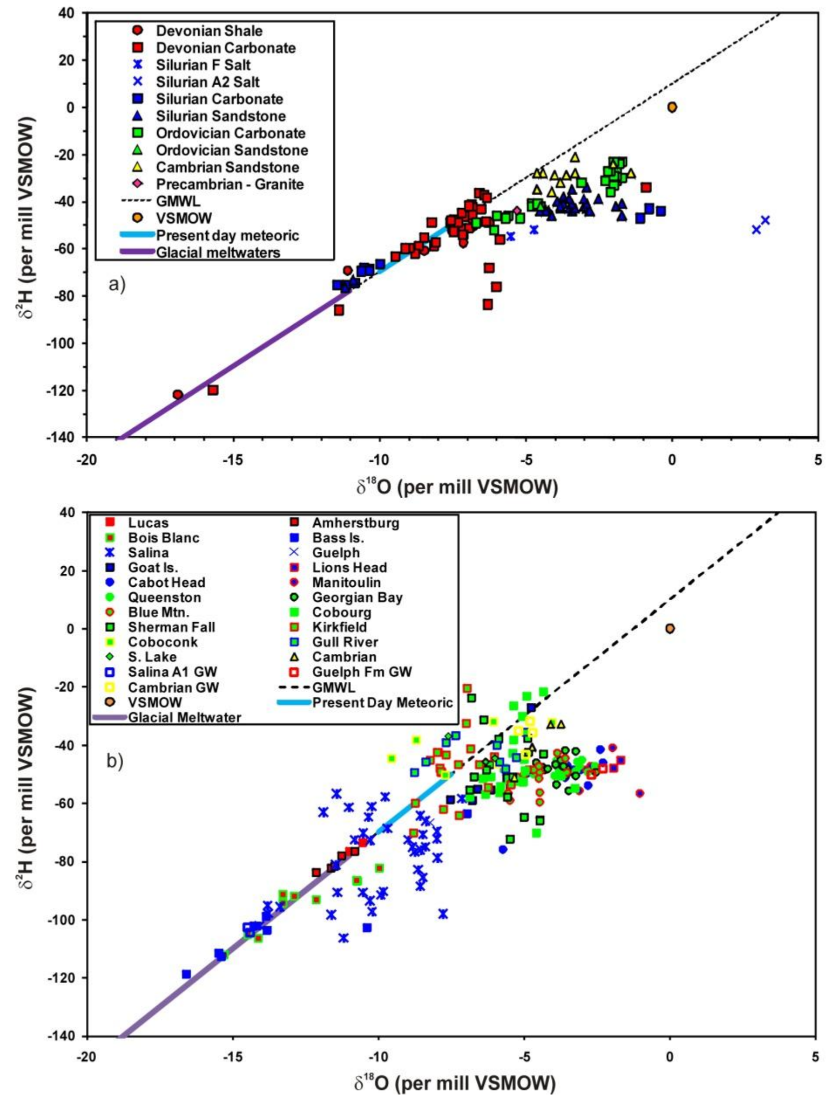

Figure 14. $\delta^{18}O$ versus $\delta^{2}H$ for groundwaters and porewaters: a) regional dataset and b) Bruce nuclear site.

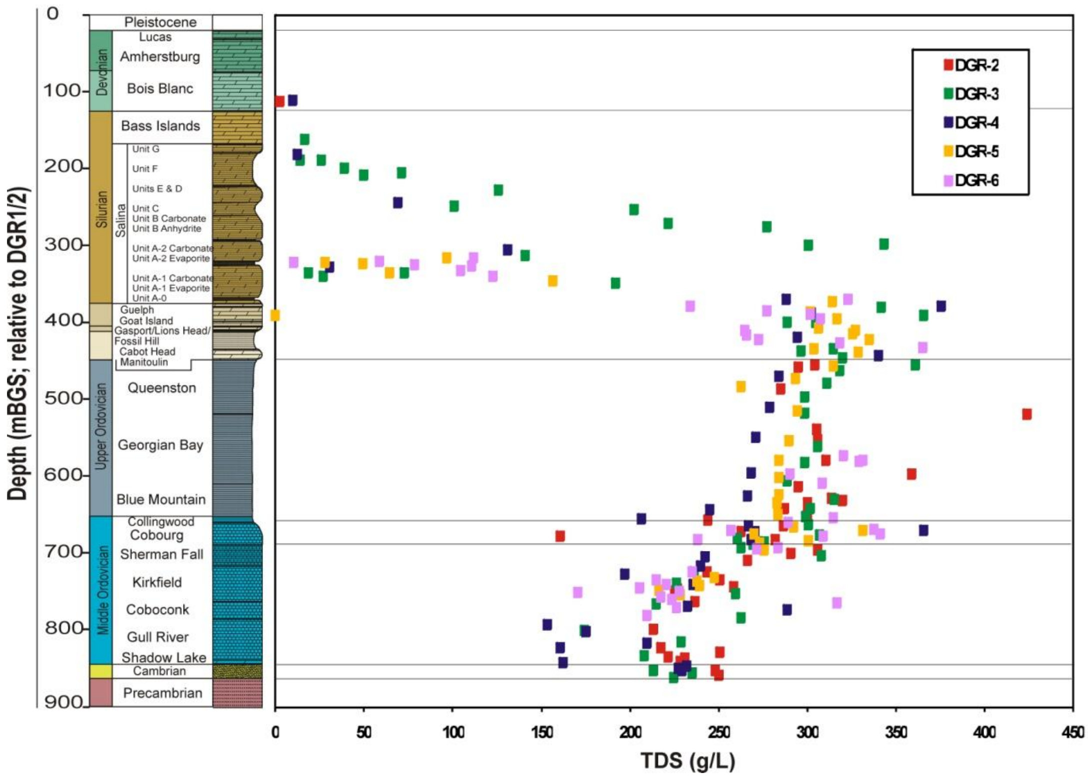

Figure 15. Total Dissolved Solids (TDS) concentrations for groundwaters and porewaters at the Bruce nuclear site.

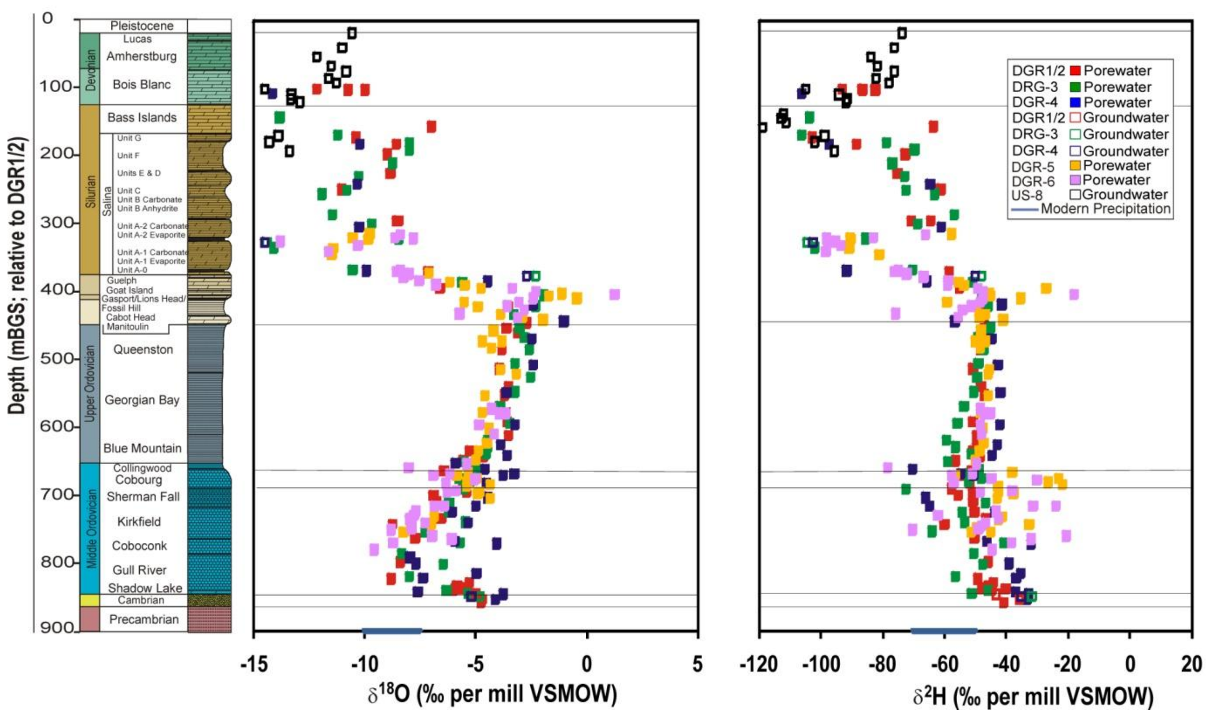

Figure 16. $\delta^{18}O$ versus $\delta^{2}H$ for groundwaters and porewaters from the Bruce nuclear site.

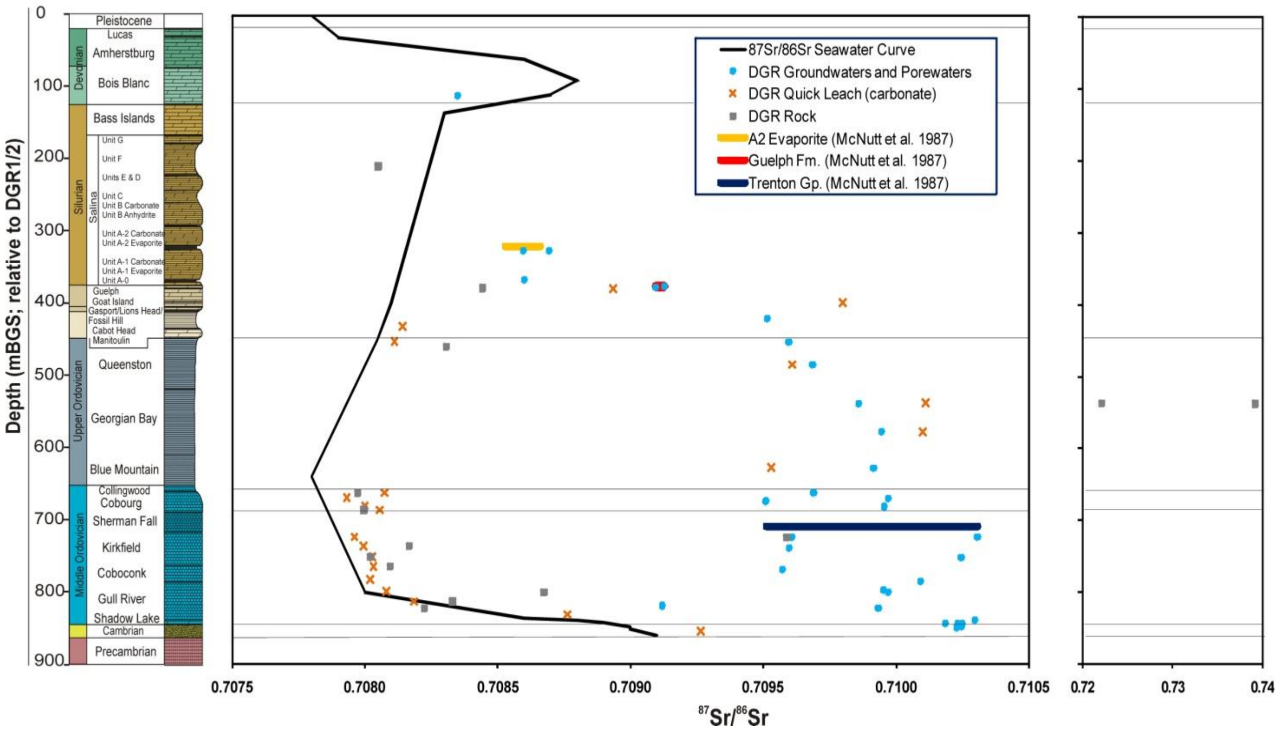

Figure 17. $^{87}Sr/^{86}Sr$ values for the Bruce nuclear site. Shown for comparison are regional ranges from southwestern Ontario [27].

Methane concentrations and isotopic compositions were determined for the entire sedimentary sequence below the base of the Devonian (DGR-1/2 reference depth of 169 mBGS). The concentrations provide insight into the distribution of the methane with depth, whereas the measured isotopic compositions of the methane allow for the determination of origin of the methane. A complete discussion of the full suite of methane data is provided in the Geosynthesis [6], and a comprehensive summary is provided in [21].

A key feature of the methane isotopic data is that the $\delta^{13}C$ and $\delta^{2}H$ data display a clear separation between the Ordovician shales and the Ordovician carbonates (Figure 18). Similar trends are observed in the helium isotopic datal[21]. The stable isotope data from CH_4 define two fields: one field represents CH_4 of biogenic origin in the Ordovician shales and the Cobourg Formation, and a second field represents CH_4 of thermogenic origin in the underlying Ordovician carbonates. The thermogenic nature of the methane in the Ordovician carbonates suggests that the methane is extremely old because the conditions necessary to reach thermogenic methane production within these sediments have not existed at the site since late in the Paleozoic or very early in the Mesozoic (~250 Ma). The observed separation of biogenic gas above, from thermogenic gas below, provides evidence that there has been little or no cross-formational mixing while the gas was resident in the system, and it appears that neither the biogenic nor the thermogenic gas is mobile, at least in the vertical direction. The features of the profile attest to the confining nature of the Ordovician shale and carbonate formations and to the longevity of both porewaters and solutes within the deep hydrologic system.

The Ordovician sediments are characterized as reducing based on the measured Fe and SO_4 concentrations. Mineralogical and geochemical evidence indicates that sulphide minerals (predominantly pyrite) and organic carbon are common throughout the stratigraphic sequence, particularly below the Silurian. The presence of CH_4 suggests that conditions in the Ordovician sediments are strongly reducing and indicate that the formations are most likely in the realm of iron- or sulphate-reduction, and possibly methanogenesis, and support the hypothesis that the deep system is isolated from the shallow oxidizing environment. E_h values were estimated at -150 mV for the whole of the Ordovician sedimentary sequence.

In summary, the hydrogeochemical data at the Bruce nuclear site shows that the deep hydrologic system has not been impacted by surface perturbations (e.g., glaciation), which is consistent with regional observations [11]. Multiple lines of evidence (TDS, $\delta^{18}O$, $\delta^{2}H$, redox conditions) demonstrate that the deep groundwater and porewater system at the Bruce nuclear site is chemically distinct from the shallow potable groundwater system and is isolated from the shallow system by multiple natural geological barriers. The deep fluid chemistry is characterized by extremely high salinities (TDS >200 g/L) and the isotopic and chemical signatures ($\delta^{18}O$, $\delta^{2}H$, $^{87}Sr/^{86}Sr$, isotopes of CH_4) are consistent with long residence times and support the hypothesis that the deep groundwater and porewater system is ancient and that solute transport is diffusion-dominated.

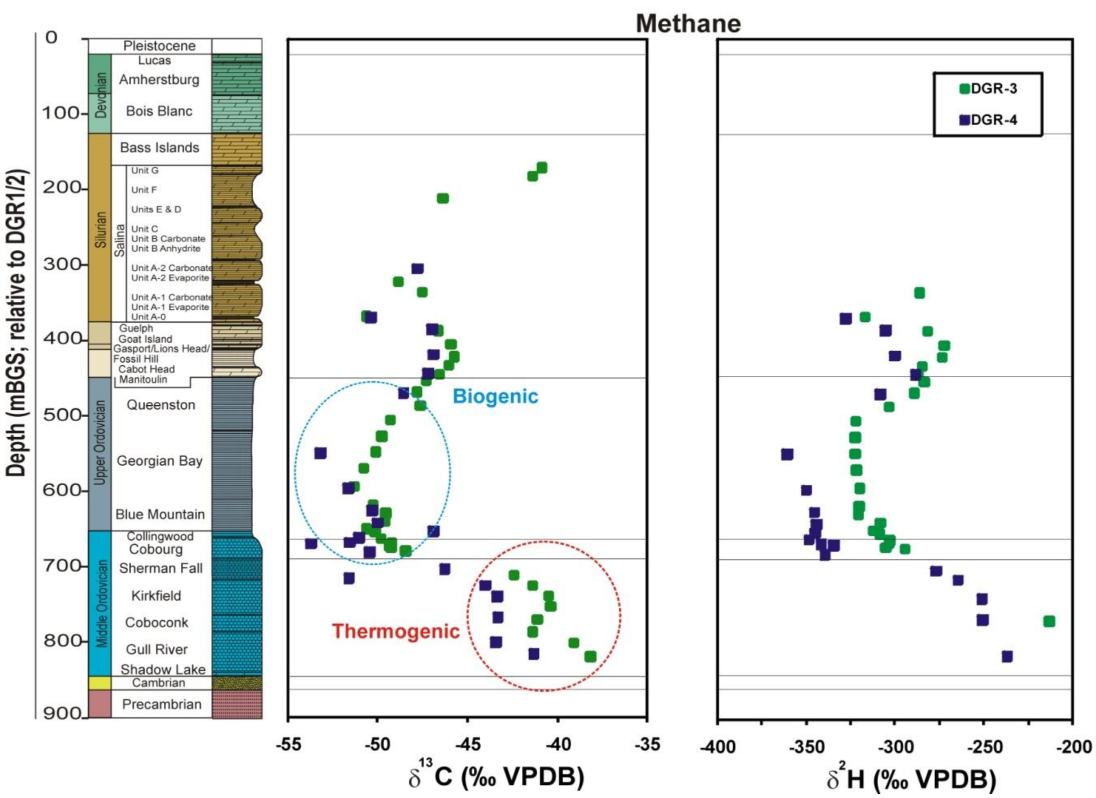

Figure 18. $\delta^{13}C$ and $\delta^{2}H$ for methane in porewaters at the Bruce nuclear site.

2.3.5 Long-term Climate Change

Within northern latitudes, climate change, and, in particular, glaciation events are likely to influence the long-term performance of the DGR. Prolonged and cyclic periods of glacial and peri-glacial conditions have existed in these regions on numerous occasions in recent geologic history. During the latter half of the Pleistocene, long-term climate change has resulted in nine glacial events with a typical 115 ka cycle. Ice-sheet thickness at glacial maximum would have exceeded ≈2.5 km over southern Ontario [12]. Transient temperature, hydraulic and mechanical boundary conditions resulting from glacial conditions may, on a site-specific basis, materially affect groundwater flow system dynamics, fracture network interconnectivity, fracture rejuvenation/propagation, post-glacial lake formation, groundwater redox front migration, and geomechanical stability of repository access tunnels and emplacement rooms. Demonstrating a knowledge and awareness of the time history and magnitude of these effects is an important aspect in the development of a repository Safety Case.

In order to explore the range of surface boundary conditions that could develop at Bruce nuclear site, the University of Toronto Glacial Systems Model was subject to a Bayesian calibration and was employed to construct a suite of equally plausible models of the glaciation-deglaciation processes [12]. These boundary conditions, on normal stress, surface temperature, permafrost depth and meltwater production, are highly time dependent and vary substantially across the suite of models that are able to satisfy the observational constraints. These constraints are taken to be those appropriate to the most recent cycle of glaciation that began following the Eemian interglacial, which was initiated 116,000 years before present and ended approximately 10,000 years ago. A detailed discussion of future glaciations and predicted influence on groundwater system behaviour, mechanical repository stability and bedrock formation barrier integrity is provided in [7] and [16].

3 DOCUMENT QUALITY AND GEOSCIENCE REVIEW

The work included in the geoscientific site characterization activities was performed by various organizations. A number of Canadian universities and consulting firms provided the technical expertise required to complete the site characterization work, and the DGR concept represents a Canadian solution for the management of wastes produced at the various nuclear generation facilities. The geoscience documentation that comprises the Geosynthesis was extensively reviewed by both Canadian and international experts in the respective fields of geoscience (geology, hydrogeology, geomechanics and hydrogeochemistry) and in the area of long-term nuclear waste management. The technical supporting documents referred to above represent the results of a comprehensive and detailed geoscientific assessment, performed in order to gather the information necessary to develop the DGR Safety Case.

As part of the site characterization work program an independent Geoscience Review Group (GRG) was assembled by the NWMO to provide an advisory and oversight role on geoscientific site characterization activities at the Bruce nuclear site. GRG activities focused on guidance and expertise related to the following: i) implementation of field and laboratory measurement techniques/methods; ii) interpretation and synthesis of field and laboratory data given measurement/geosphere uncertainty; iii) international practice for geoscientific investigations in sedimentary sequences for radioactive waste management purposes; iv) review and direction of strategies for Descriptive Geosphere Site Model development; and v) review and direction of strategies for Geosynthesis development.

In this role the GRG was positioned to independently assess the adequacy of all aspects of the Bruce nuclear site investigations, with findings reported directly to NWMO Management. A key benefit of the GRG was the direct involvement and access to international geoscience work programs, in particular, those of ANDRA (France) and NAGRA (Switzerland), which proved to be a significant advantage to the DGR program. Data collected from international work programs for radioactive waste management are compared with site-specific data in Table 1. The table shows how comparable the site-specific data are with international locations being investigated for the long-term management of high-level waste. The physical properties of the geologic and hydrologic system at the Bruce nuclear site are favourable for the management of L&ILW, as supported by the DGSM, Geosynthesis, and the Safety Case.

Table 1. Comparison of international data with results from the Bruce nuclear site.

Property/Parameter	**Callovo-Oxfordian (Bure)**	**Opalinus Clay (Zurcher Weinland)**	**Opalinus Clay (Mont Terri)**	**Ordovician Shale (OPG DGR)**	**Ordovician Lmst. Cobourg (OPG DGR)**
Age (Ma)	158-163	174	174	450	465
Present burial depth (m)	488	596	275	550	680
Maximum burial depth (m)	850	1650	1350	2550	2680
Over-consolidation ratio	1.5-2	1.5-2.5	2.5-3.5	3-4	3-4
Maximum burial temperature (^{0}C)	33-88	85	85	90	90
Thickness (m)	138	113	160	210 m	27 m
Clay minerals (weight %)	25-55	54	66	25-70	0-20
Physical Porosity (-)	0.14-0.18	0.12	0.16	0.066	0.013
Water Loss Porosity (weight % rel. to dry weight)	8.6	4.0	7.03	8.0	2.1
Hydraulic conductivity (parallel to bedding) K (m/s)	$5E^{-13}$-$5E^{-14}$	$2.4E^{-14}$	$4.0E^{-14}$	$2E^{-14}$ – $3E^{-14}$	$1E^{-14}$
Eff. Diffusion Coeff. D_e (HTO), normal to bedding (m^2/s)	$2.6E^{-11}$	$6.1E^{-12}$	$1.5E^{-11}$	$4.8E^{-12}$ - $1.4E^{-12}$	$7.8E^{-13}$
Eff. Diffusion Coeff. D_e (I), normal to bedding (m^2/s)	$1E^{-12}$-$1E^{-11}$	$6.5E^{-13}$	$4.1E^{-12}$	$2.6E^{-12}$ - $4.1E^{-13}$	$4.5E^{-13}$
Uniaxial Compressive Strength (MPa)	21	30	16	50	**120**

4 SUMMARY AND CONCLUSIONS

In summary, geoscientific studies were performed over the course of four years to verify the suitability of the Paleozoic sedimentary sequence beneath the Bruce Nuclear site for implementation of a proposed OPG Deep Geologic Repository for L&ILW. Site-specific studies were performed in 3-phases that upon completion included, among other activities, the drilling, coring, testing and instrumentation of 6 deep boreholes (4 vertical; 2 inclined) within the ≈850 m thick Paleozoic sedimentary sequence underlying the site. Information derived through these site studies coupled with Geosynthesis activities, which examined the evolution of the site both in the past and as influenced by DGR construction, provide a compelling case for the existence of a deep-seated, stable aquitard/aquiclude groundwater system at the proposed repository horizon of ≈680 m. Consistent with international experience, such groundwater regimes provide multiple natural barriers to contaminant transport that would contribute to the passive, safe long-term containment and isolation of the L&ILW.

DGR Geoscientific studies were focused on assessing seven fundamental hypotheses regarding the nature of the geologic, hydrogeologic, hydrogeochemical and geomechanical environment underlying the Bruce nuclear site. Multiple lines of geoscientific evidence were purposefully collected at site-specific and regional scales in order to test and assess each of the hypotheses (favourable characteristics and attributes). Key findings that related directly to assessing the ability of the site to safely host the proposed DGR include:

1) The bedrock stratigraphy is near-horizontally layered (≈10m/km) and undeformed. The large areal extent of the sedimentary formations and the seismically quiet nature of the region make the site and surrounding environment highly predictable, which is an essential part of establishing long-term safety.
2) The shallow hydrologic system is isolated from the deep hydrologic system (i.e., the host and bounding Ordovician formations) by multiple natural geologic barriers, ensuring that the potable shallow groundwater systemwill not be impacted by activities associated with the DGR.
3) Contaminant transport in the deep hydrologic system is diffusion-dominated, as indicated by both the hydraulic and geochemical data. The deep system is ancient, and the hydrogeochemistry data indicate long porewater and solute residence times in the host and bounding formations. Based on hydrogeologic modelling, minimum MLE values for the deep groundwaters and porewaters are > 44 Ma. No hydrological or geochemical evidence was collected that would indicate that the deep system is impacted by surface perturbations (e.g., glaciation).
4) Geomechanical stability of the Ordovician host rock is strongly supported by the collected rock strength data (e.g., uniaxial compressive strength, shear strength), and supports the hypothesis that the Cobourg Formation will provide stable and dry openings to provide for the safe operation of the DGR.

5 ACKNOWLEDGEMENTS

Many individuals and organizations have contributed to the DGR project since it was initiated in 2002. Initial feasibility studies by Golder Associates Ltd. (2002) and Martin Mazurek (University of Bern; 2004) established a geoscientific basis to understand the suitability of the Paleozoic sequence for long-term radioactive waste management purposes. Geofirma Engineering Ltd. (formerly Intera Engineering Ltd.) and AECOM (formerly Gartner Lee) managed the site-specific investigations and Geosynthesis activities, respectively. The Geoscience Review Group comprised of Dr. Andreas Gautschi (NAGRA), Jacques Delay (ANDRA), Dr. F.J. Pearson (Ground-Water Geochemistry Inc.) and Dr. Derek Martin (University of Alberta) has provided valuable access to international experience and expertise throughout the work program. NWMO provided technical oversight to the work program and authored the DGR Geosynthesis.

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