Hydrogeologic modelling in support of a proposed Deep Geologic Repository in Canada for low and intermediate level radioactive waste

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ABSTRACT
A Deep Geologic Repository (DGR) for Low and Intermediate Level (L&IL) Radioactive Waste has been proposed by Ontario Power Generation for the Bruce site. The DGR is to be excavated at a depth of about 680 m below ground surface. The objective of regional-scale groundwater modelling of the Paleozoic sedimentary sequence underlying southwestern Ontario is to provide a basis for the assembly and integration of site-specific geoscientific data and to explain and illustrate the influence of parameter and scenario uncertainty on predicted long-term geosphere barrier performance.

RÉSUMÉ
Ontario Power Generation (OPG) propose de développer un dépôt pour la gestion à long terme des déchets radioactifs de faible et de moyenne activité à une profondeur de 680 m sur le site de Bruce. L'objectif est de développer un modèle hydrogéologique régional de la séquence sédimentaire du Sud-west Ontarien. Le modèle servira comme base pour l'assemblage et l'intégration des données geoscientifiques spécifiques au site. Il sera également utiliser pour illustrer l'influence des incertitudes reliées à divers paramètres et scenarios sur la prédiction de la performance à long terme de la géosphère en tant que barrière naturelle.

1 INTRODUCTION

A Deep Geologic Repository (DGR) for Low and Intermediate Level (L&IL) radioactive waste has been proposed by Ontario Power Generation (OPG) for the Bruce site on the shore of Lake Huron near Tiverton, Ontario (Figure 1). The DGR is to be excavated at a depth of approximately 680 m within the argillaceous limestone of the Ordovician Cobourg Formation (refer to the stratigraphy of the site as listed in Table 1). In order to reasonably assure safety of the radioactive waste at the site and to better understand the geochemistry and hydrogeology of the formations surrounding the proposed DGR, a saturated regional-scale and site-scale numerical modelling study has been completed in Sykes et al. (2008); the regional-scale base-case modelling and analysis of the measured pressure profile in deep boreholes at the DGR site are reported in this paper. This numerical modelling study provides a framework to investigate the groundwater flow system as it relates to and potentially affects the safety and long-term performance of the DGR.

In order to capture and recreate the regional-scale groundwater system, a saturated groundwater flow model is developed, using FRAC3DVS-OPG (developed from FRAC3DVS (Therrien et al., 2004)), for a fully three-dimensional representation of the bedrock stratigraphy within a portion of south-western Ontario centered on the Bruce DGR site. The stratigraphy presented in Table 1 is depicted in the regional-scale three-dimensional fence diagram of Figure 2. From a hydrogeologic perspective, the domain at the Bruce site can be subdivided into three horizons: a shallow zone characterized by the dolomite and limestone units of the Devonian that have higher permeability and groundwater composition with a relatively low total dissolved solids content; an intermediate zone comprised of the low permeability shale, salt and evaporite units of the Upper Silurian, the more permeable Niagaran Group (including the Guelph, Goat Island and Gasport) and the Lower Silurian carbonates and shales; and a deep ground-

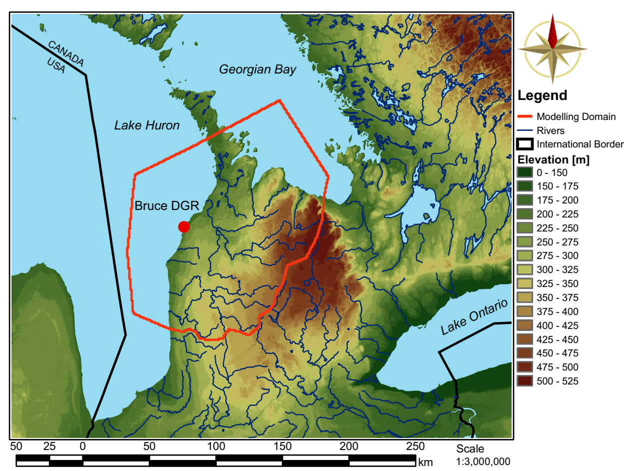

Figure 1. Regional-scale elevations, river courses, and location of DGR site in southwestern Ontario.

Table 1. Material hydraulic properties for regional-scale analysis.

Period	Geology	Thickness [m]	K_H [m/s]	K_V [m/s]	K_V/K_H	Porosity	Specific Stor.
Quaternary	Drift	20.0	1.0×10^{-7}	2.0×10^{-8}	0.2	0.10	9.9×10^{-5}
Devonian	Traverse Group		1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	9.9×10^{-5}
	Dundee	55.0	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	9.9×10^{-5}
	Detroit River Group		1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}
	Bois Blanc	49.0	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}
Silurian	Bass Islands	54.0	1.0×10^{-7}	1.0×10^{-8}	0.1	0.10	1.4×10^{-6}
	G-Unit	5.0	1.0×10^{-7}	1.0×10^{-8}	0.1	0.08	1.3×10^{-6}
	F-Unit	40.0	4.0×10^{-12}	4.0×10^{-13}	0.1	0.03	1.2×10^{-4}
	F-Salt		1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}
	E-Unit	20.0	4.0×10^{-12}	4.0×10^{-13}	0.1	0.08	1.6×10^{-6}
	D-Unit	1.6	1.0×10^{-10}	1.0×10^{-11}	0.1	0.03	1.3×10^{-6}
	B&C Units	46.6	4.0×10^{-12}	4.0×10^{-13}	0.1	0.08	1.2×10^{-4}
	B Anhydrite-Salt	1.9	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}
	A2-Carbonate	26.9	1.0×10^{-10}	1.0×10^{-11}	0.1	0.08	1.6×10^{-6}
	A2 Anhydrite-Salt	8.0	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}
	A1-Carbonate	39.0	2.0×10^{-12}	2.0×10^{-13}	0.1	0.08	1.6×10^{-6}
	A1-Evaporite	3.5	1.0×10^{-13}	1.0×10^{-13}	1.0	0.08	1.6×10^{-6}
	Niagaran	33.8	1.0×10^{-7}	1.0×10^{-8}	0.1	0.08	1.6×10^{-6}
	Fossil Hill	2.7	2.0×10^{-11}	2.0×10^{-12}	0.1	0.08	1.6×10^{-6}
	Cabot Head	20.5	2.0×10^{-12}	2.0×10^{-13}	0.1	0.03	1.2×10^{-4}
	Manitoulin	16.2	1.5×10^{-12}	1.5×10^{-13}	0.1	0.01	1.2×10^{-6}
Ordovician	Queenston	70.4	1.3×10^{-11}	1.3×10^{-12}	0.1	0.11	1.2×10^{-4}
	Georgian Bay/Blue Mtn.	141.5	9.1×10^{-12}	9.1×10^{-13}	0.1	0.11	1.2×10^{-4}
	Cobourg	27.0	9.6×10^{-12}	9.6×10^{-13}	0.1	0.02	1.3×10^{-6}
	Sherman Fall	45.5	9.0×10^{-12}	9.0×10^{-13}	0.1	0.02	1.3×10^{-6}
	Kirkfield	30.0	1.4×10^{-11}	1.4×10^{-12}	0.1	0.02	1.3×10^{-6}
	Coboconk	16.8	5.2×10^{-11}	5.2×10^{-12}	0.1	0.02	1.3×10^{-6}
	Gull River	59.9	3.6×10^{-11}	3.6×10^{-12}	0.1	0.02	1.3×10^{-6}
	Shadow Lake	5.1	8.0×10^{-12}	8.0×10^{-13}	0.1	0.01	1.2×10^{-6}
Cambrian	Cambrian	17.0	3.0×10^{-6}	3.0×10^{-7}	0.1	0.01	1.2×10^{-6}
Precambrian	Precambrian		8.0×10^{-12}	8.0×10^{-13}	0.1	0.01	1.2×10^{-6}

water zone extending to the Precambrian and characterized by the Ordovician shales and carbonate formations and the Cambrian sandstones and dolomites. Pore water in the deeper zone is thought to be stagnant and has high total dissolved solids (TDS) concentrations that can exceed 300 g/L with a corresponding specific gravity of 1.2 for the fluids. In this paper, the term stagnant is used to define groundwater in which solute transport is dominated by molecular diffusion. The presence of a gas phase in the Ordovician and lower Silurian has not been considered in the analyses.

2 GOVERNING EQUATIONS

Equivalent freshwater head is defined as: $h = p/\rho_0 g + z$ where p [L] is the pressure, and ρ_0 [M L^{-3}] is the reference freshwater density at a reference pressure p_0. In terms of equivalent freshwater head, the saturated, density-dependent form of Darcy's Law is given by:

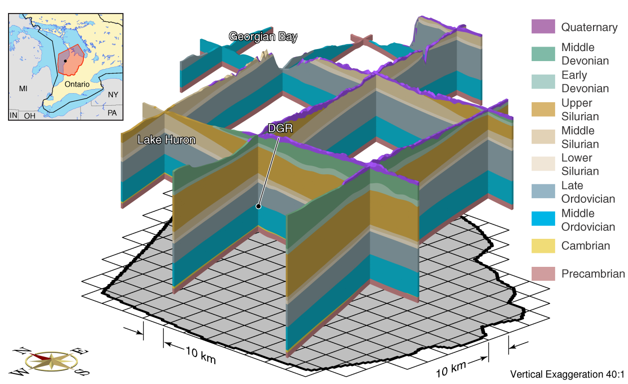

Figure 2. Fence diagram of the regional domain showing all geological units.

$$q_i = -\frac{k_{ij}}{\mu g}\left(\frac{\partial h}{\partial x_j} + \rho_r \eta_j\right) \quad [1]$$

where q_i [L T^{-1}] is the flux in the ith direction, k_{ij} [L^2] is the permeability tensor, μ is the viscosity [M L^{-1} T^{-1}], g is the gravitational constant, ρ_r [dimensionless] is the relative density given by $\rho/\rho_0 - 1$, and η = 1 [L] for the vertical (z) direction, while η = 0 for the horizontal directions (x and y). For elastic fluids, the density of a fluid, ρ [M L^{-3}], becomes a function of the fluid pressure and solute concentration:

$$\rho = \rho_0 \left[1 + c_w (p - p_0) + \gamma C\right] \qquad [2]$$

where , c_w is the compressibility of water, γ is a constant derived from the maximum density of the fluid, ρ_{max} and is defined as $\gamma = (\rho_{max}/\rho_0 - 1)$ and C is the relative concentration.

Under isothermal conditions, the viscosity μ is a function of the concentration of the fluid. For the viscosity, it is assumed that there is a linear relation between the relative concentration so long as the maximum viscosity change is insignificant in isothermal conditions. When the equations for the elasticity of the fluid and the viscosity are included in the Darcy's equation, it becomes:

$$q_i = -\frac{k_{ij}}{\mu_0 g} \cdot \frac{1}{1 + \gamma_\mu C} \left(\frac{\partial h}{\partial x_j} + \left[c_w (p - p_0) + \gamma C\right] \eta_j\right) \qquad [3]$$

The groundwater flow equation can then be derived using Eq. 3 and the continuity of energy principle.

$$\frac{\partial}{\partial x_i}\left[K_{ij}^0 \cdot \frac{1}{1 + \gamma_\mu C} \left(\frac{\partial h}{\partial x_j} + \left[c_w (p - p_0) + \gamma C\right] \eta_j\right)\right] = S_s \frac{\partial h}{\partial t} \qquad [4]$$

where $K_{ij}^0 = k_{ij}/\mu_0 g$ and S_s is the specific storage term.

The solute continuity equation is written in terms of relative concentration as:

$$\frac{\partial}{\partial x_i}\left(\phi D_{ij} \frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(q_i C) = \phi \frac{\partial C}{\partial t} \qquad [5]$$

where the Darcy flux q_i is computed by solving Eq. 4, ϕ is the porosity and D_{ij} is the hydrodynamic dispersion tensor (Bear, 1988):

$$\phi D_{ij} = (\alpha_l - \alpha_t) \frac{q_i q_j}{|q|} + \alpha_t |q| \delta_{ij} + \phi \tau D_w \delta_{ij} \qquad [6]$$

where α_l and α_t are the longitudinal and transverse dispersivities respectively, $|q|$ is the magnitude of the Darcy flux, τ is the tortuosity, D_w is the free solution diffusion coefficient or simply the diffusion coefficient and δ_{ij} is the Kronecker delta.

3 LIFETIME EXPECTANCY AND GROUNDWATER AGE

Groundwater age can be defined as being a relative quantity with respect to a starting location with an assumed age of zero (Cornaton and Perrochet, 2006). For a given spatial position within a domain, the age (denoted as a variable A) of a particle at that position can be determined by the time elapsed since the water particle entered the system at a location where a boundary condition has been applied. Conversely, the lifetime expectancy (denoted as a variable E) of a particle at the same spatial position can be estimated by determining the time required for a particle from that position to reach a potential outflow point. This definition of lifetime expectancy results in outflow points within the model having a mean lifetime expectancy of zero for the water. The variables for both age and lifetime expectancy are random variables and as such their behaviour can be characterized by that of a probability density function describing the distribution of water particles with respect to time (refer to (Cornaton and Perrochet, 2006)). The equation and boundary conditions for the mean age are as follows:

$$-\bigtriangledown \cdot \mathbf{q}\langle A\rangle + \bigtriangledown \cdot \phi \mathbf{D} \bigtriangledown \langle A\rangle - q_O \langle A\rangle + \phi = 0 \quad \text{in } \Omega \qquad [7]$$

$$\langle A\rangle(x) = 0 \quad \text{on } \Gamma_- \qquad [8]$$

$$\mathbf{J}(x) \cdot \mathbf{n} = 0 \quad \text{on } \Gamma_0 \qquad [9]$$

where $\langle A\rangle$ represents mean age. The equation for mean life expectancy, $\langle E\rangle$, can be obtained from the solution of the following equation:

$$\bigtriangledown \cdot \mathbf{q}\langle E\rangle + \bigtriangledown \cdot \phi \mathbf{D} \bigtriangledown \langle E\rangle - q_I \langle E\rangle + \phi = 0 \quad \text{in } \Omega \qquad [10]$$

$$\langle E\rangle(x) = 0 \quad \text{on } \Gamma_- \qquad [11]$$

$$-\mathbf{D} \bigtriangledown \langle E\rangle(x) \cdot \mathbf{n} = 0 \quad \text{on } \Gamma_0 \qquad [12]$$

Using these formulations, mean ages and mean lifetime expectancies will be continuously calculated during groundwater flow. This results because $\phi = \phi(x)$ will act as a source term in equations Eq. 7 and Eq. 10 and implies that the groundwater will be aging an average of one unit per unit time.

4 CONCEPTUAL MODEL DEVELOPMENT

The regional scale domain, shown in Figure 1, occupies an aerial extent of approximately 18,775 km^2. It has vertical elevations that range from −1,000 m at the lowest point in the Precambrian to 539 m at the highest point on the Niagara Escarpment. The domain was discretized into slices with 27,728 nodes each, which were then used to create quadrilateral elements. Based on an areal discretization with 200 rows and 200 columns, these quadrilateral elements have sides of 762.8 m in the East-West direction by 900.9 m in the North-South direction. Each of the 31 units from the geological reconstruction (refer to Table 1) was assigned a model layer so that the numerical model would closely resemble that of the geological framework model. The elevation of the nodes for each slice were determined from the GLL00 geological framework model described in Frizzell et al. (2008).

The site-scale spatial domain has a spatial extent of 19.078 km in the west-to-east direction and 18.918 km in the south-to-north direction centered on the DGR site. The site-scale domain was discretized by using 6 columns (west-to-east sub-gridding) for each regional-scale column and 8 rows (south-to-north sub-gridding) for each regional-scale row. The resulting site-scale domain has 150 columns and 168 rows with each grid block being 127 m in the west-to-east direction and 112.6 m in the south-to-north direction.

4.1 Flow Boundary and Initial Conditions

The boundary conditions of the model were Neumann no-flow boundary conditions for the sides and bottom, and type-one or Dirichlet for the surface of the model. The elevation of the nodes at the top of the model domain are defined by either the DEM or the lake bathymetry. For surface nodes with an elevation greater than 176 m, the assigned prescribed head was set as the elevation minus 3 m but not less than the 176 m Lake Huron water elevation. Areas within the domain that are occupied by either Lake Huron or Georgian Bay have a prescribed equivalent freshwater head for the top slice of the model matching the lake elevation, 176 m. The imposed surface boundary condition permits recharge and discharge to occur as determined by the surface topography and the hydraulic conductivity of the top model layer. The assigned head represents a water table occurring at an assumed depth of 3 m below ground surface. Because of the resolution of the DEM, stream channels are conceptualized to have a depth to water that is 3 m less than defined by the DEM.

4.2 Hydraulic and Transport Parameters

The base-case data set for the conceptual model consists of 31 model layers, with each layer corresponding to a unit in the stratigraphic section. Table 1 shows the layers and their associated hydraulic conductivities, porosities and specific storage coefficients. Table 1 also includes the thickness of the model layers observed at boreholes at the Bruce site developed in the DGR field program. The porosity values were developed from data compiled by Golder Associates Limited (2003) and revised as appropriate by data from the Bruce site field program. The horizontal hydraulic conductivity for the shallow drift layer was assigned a value of 1×10^{-7} m/s.

Following Freeze and Cherry (1979), the specific storage coefficient can be developed as $S_s = \rho g \, (C_r + \phi C_w)$ where C_w is the compressibility of the fluid, and C_r is the rock compressibility. The specific storage coefficients listed in Table 1 were derived using the fluid densities corresponding to a unit's TDS concentration, the unit's porosity and rock dependant compressibility values from literature.

To simulate the impact that a weathered zone will have on shallow flow, the upper 20 metres of the spatial domain was assumed to be characterized by more permeable rock; the horizontal hydraulic conductivity for the zone was assumed to be 1×10^{-7} m/s.

Table 2 gives the parameters assumed for both the migration of total dissolved solids and for the estimation of mean life expectancy. Using a grid Peclet number constraint, the longitudinal dispersivity coefficient was selected as approximately one half of the maximum length of the side of a regional-scale grid block. The diffusion coefficient is listed in the table; temperature effects were not considered.

Table 2. Transport parameters

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

4.3 Total Dissolved Solids

Salinity plays an important role with regard to fluid flow at the proposed DGR. An increase in the concentration of total dissolved solids (TDS) will result in an increase in the fluid density. The increase in density of the deeper fluids will then act as an inhibiter of active flow at depth.

Regional-scale data are not available for either the actual distribution of total dissolved solids in the shallow units or the spatial distribution, particularly, in the deeper units. In the absence of data, a plausible TDS distribution can be generated using the physically-based regional model. For the coupled density-dependent flow and transport system, fresh water can recharge at the surface, reducing the TDS concentration in the shallow zone. However, the time to flush the dissolved solids from a unit is a function of the permeability of the unit and the energy of the displacing fluid as compared to the energy of the fluid being displaced. For low-permeability units with a relatively high total dissolved solids concentration, the time to flush the unit or displace the fluids can be very long (millions of years). Complete flushing may only occur as a result of diffusion because energy gradients and/or low permeabilities may yield low fluid fluxes that may not be sufficient for advective displacement to occur. There is a balance between the accuracy of a solution, the length of time required for the system to reach a pseudo-equilibrium between energy potential, fluid flux and total dissolved solids distributions, and computer simulation time. A suitable balance was established by assuming that pseudo-equilibrium would be obtained 1 million years after the imposed initial conditions.

The spatial distribution of TDS concentration in the units of the Ontario portion of the Michigan Basin have been compiled in studies by Golder Associates Limited (2003) and Hobbs et al. (2008). The initial TDS concentrations are: 0.045 g/L for the drift and Traverse Group, 3 g/L for the Dundee to the G-unit, and 300 g/L for the F-Unit to the

Precambrian. These concentrations were redistributed in a density-dependent flow analysis and in parts of the domain they will be diluted by infiltrating fresh water.

The concentration boundary conditions for the density-dependant flow analysis were: the surface of the model was set as a Type 3 boundary condition with recharge having zero concentration, except areas beneath Lake Huron and Georgian Bay, which had a prescribed relative concentration of zero. Zero-flux Neumann boundary conditions were used for the sides and bottom of the domain. After 1 million years, the model, having been allowed to reach pseudo-equilibrium, produces salinity profiles that are compatible with the geological framework, boundary conditions and hence the flow domain.

5 ANALYSIS OF THE PRESSURE PROFILE AT THE COMPOSITE DGR-1/DGR-2 BOREHOLE

The Phase 1 field activities at the Bruce site are described in the Geoscientific Site Characterization Plan (INTERA Engineering Ltd., 2006). The activities included wireline drilling and core logging of a vertical deep borehole (DGR-1) to the top of the Queenston shale to confirm the stratigraphic sequence and general rock quality of the Silurian and Devonian bedrock sequence. A second adjacent borehole (DGR-2) was developed to the Precambrian bedrock. Rotary drilling with a grout casing was used to the top of the Queenston and wireline drilling with core logging was used for the balance of the borehole. Pressure monitoring and hydraulic testing for both boreholes were enabled by the installation of Westbay MP multi-level casings.

Pressure data from the Westbay MP multi-level casing in the DGR-1 and DGR-2 boreholes have been used to estimate the vertical profile of equivalent freshwater head and the environmental head from the ground surface to the Precambrian at the Bruce site. The estimated environmental head profile in the composite DGR-1 and DGR-2 borehole from pressure data obtained on March 3, 2008 is presented in Figure 3. The first sampling of the pressures in DGR-2 were undertaken on December 11, 2007. Data from subsequent measurement events indicate that the pressures are slowly shifting, particularly for the low permeability units, toward equilibrium values. As such, the pressures used to develop the data shown in Figure 3 are not at their final values. Based on a surface elevation of 185.84 mASL, the environmental head profile in DGR-2 clearly shows that the Cambrian is significantly over-pressured with respect to the ground surface, the Ordovician and Lower Silurian are significantly under-pressured while units in the Niagaran are moderately over-pressured. Groundwater gradients are thus upward from the Cambrian to the Ordovician, and downward from the Niagaran to the Ordovician. The low permeability of the Salina isolates the Niagaran from the more permeable units of the Devonian.

This section evaluates the composite DGR-1 and DGR-2 borehole pressures as they equilibrate to the present day boundary conditions using the site-scale model for the case assuming saturated conditions. An alternate case is the investigation of the pressure profile with a gas phase present

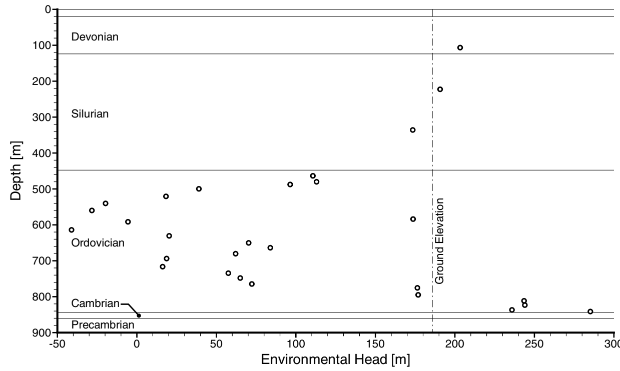

Figure 3. Environmental heads in a composite DGR-1 and DGR-2 borehole based on pressures measured on March 3, 2008.

in the Ordovician and lower Silurian units; this analysis is beyond the scope of this paper. The modelling methodology undertook transient saturated site-scale analyses of coupled flow and brine transport with the measured pressure profile at the composite DGR-1 and DGR-2 borehole as the initial condition. Boundary conditions for the analyses are based on the present day state. The transient analyses assume the base-case parameters (refer to Table 1). In addition to the base-case vertical over horizontal hydraulic conductivity anisotropy ratio of 0.1 for the Ordovician units, anisotropy ratios of 0.01 and 0.001 also were investigated; thus, the horizontal hydraulic conductivities for the Ordovician units were constant for all analyses while the vertical hydraulic conductivities were determined from the horizontal values using the given factors. The initial condition for the site-scale analyses represents the measured pressure profile using equivalent freshwater heads: the Precambrian and Cambrian were assigned an initial freshwater head of 445 mASL; the Shadow Lake to Fossil Hill an initial freshwater head of 125 mASL; while from the Niagaran Group to the surface, the initial freshwater heads were 235 mASL. The initial TDS concentration distribution for the site-scale model was the results from the base-case analysis at a pseudo-equilibrium time of 1 million years. Zero flux Neumann boundary conditions were used for the freshwater heads for the site-scale domain sides and bottom. A Dirichlet boundary condition related to surface topography was used to represent the water table at the top of the domain. For brine transport, a TDS Dirichlet boundary condition of 300 g/L was assigned to the Precambrian while a zero flux Neumann boundary condition was used for the site-scale domain sides.

The more permeable units below the Salina at the site-scale are the Cambrian and the Niagaran Group. It is hypothesized that the water deficit in the Ordovician will be met from either the Cambrian or the Niagaran or from both. It is reasonable to assume that flow in the Niagaran is topographically controlled with this providing pressure support for the unit. The Cambrian at the DGR-2 borehole has a thickness of 17 m while the overlying Ordovician is 396 m thick. Based on the storage coefficient of the Cambrian relative to that of the Ordovician, there is insufficient water per unit area in the Cambrian to meet the deficit in the Ordovician. Limited pressure support for the Cambrian, if any, can come from the underlying Precambrian.

For the case where there is pressure support for both the Cambrian and the Niagaran Group (Figure 4), the pressure and related water deficit in the Ordovician has been met by approximately 10^5 years and as shown at 10^6 years an upward gradient develops from the Cambrian to the surface. In the case where there is no pressure support for the Cambrian and pressure support for the Niagaran Group, the environmental head profiles of Figure 5 indicate that the over-pressurization of the Cambrian has been dissipated by 10^4 years but that the pressures slowly increase as the domain fills from the Niagaran. At 10^6 years water is still moving downward from the Niagaran Group.

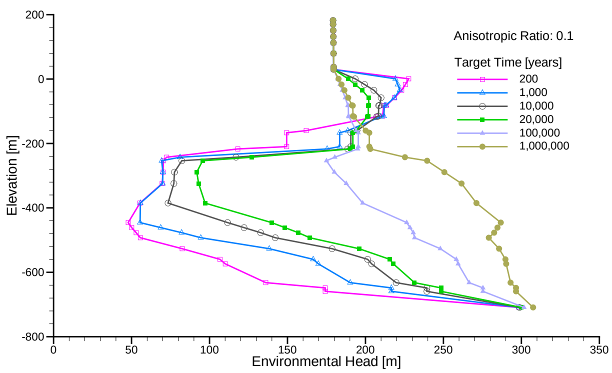

Figure 4. Predicted environmental head profile at DGR-2 for base case parameters; pressure support for both the Niagaran and the Cambrian at various times.

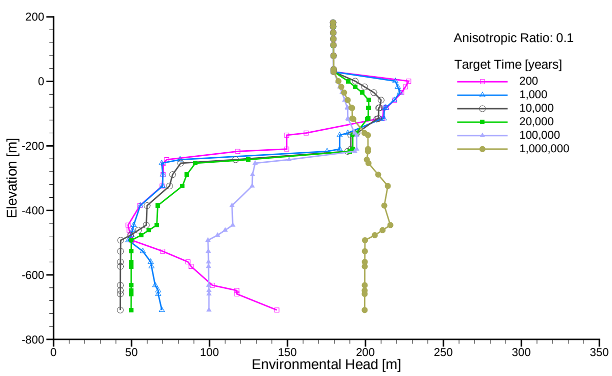

Figure 5. Predicted environmental head profile at DGR-2 for base case parameters; pressure support for the Niagaran and no pressure support for the Cambrian at various times.

The analyses with an anisotropy ratio of 0.1 for the Ordovician units indicate that the low pressures in the Ordovician cannot be maintained for times greater than 10^6 years. Similarly, in the absence of pressure support, the high pressure in the Cambrian cannot be maintained. The analyses with anisotropy ratios of 0.01 and 0.001 investigate the sensitivity of the environmental head profiles to the vertical hydraulic conductivity for the Ordovician units. The impact of lowering the vertical hydraulic conductivity by an order-of-magnitude from that of the analyses described in the preceding paragraph is to delay the dissipation of the pressures in the Cambrian for the cases in which there is no pressure support for the unit or the Niagaran.

The analyses of this section support the conclusion that the vertical hydraulic conductivity required to maintain the elevated pressures in the Cambrian and to prevent the re-pressurization of the Ordovician for a period of time greater than 1 million years are significantly lower than that used for the base-case analysis. The presence of a gas phase in the Ordovician and the impact of a relative hydraulic conductivity that is a function of the water saturation would lower the effective vertical hydraulic conductivity or water mobility. Depending on the saturation of a trapped or residual gas phase, if present, the water mobility effectively could become zero resulting in a stagnant water phase in the Ordovician and an inability of the elevated pressures in the Cambrian to be dissipated.

6 REGIONAL-SCALE ANALYSES

The environmental head distribution, assuming saturated flow, for the base case parameters and boundary conditions after 1 million years (pseudo-equilibrium time) is shown in Figure 6. For density-dependant flow, plots of environmental heads can be used to interpret vertical gradients but not horizontal gradients. The shallow flow regime is the region above the Salina. It is dominated by flow that mimics topography. Beneath the shallow groundwater zone, the heads are not controlled to the same extent by the local elevation of the surface. The main control for the horizontal component of the density-dependent energy gradient at depth is the elevation difference between Lake Huron and the topographic high at the Niagara Escarpment. At a given location, the vertical component of the energy gradient is controlled by the difference in the environmental heads between the more permeable units that are separated by low permeability units. For the regional domain, the higher permeability Cambrian, where present, and Niagaran Group are separated by the low permeability units of the Ordovician and lower Silurian. The Niagaran is confined in the south-western part of the domain by the overlying low permeability units of the Salina. Flow in the Niagaran where it is unconfined is controlled by surface topography.

In addition to the elevation component of the gravitational gradient imposed by the topographic high at the Niagara Escarpment, the density of the brines in the deep groundwater zone will have an impact on the energy gradients. The salinity profile for the base-case at a pseudo-

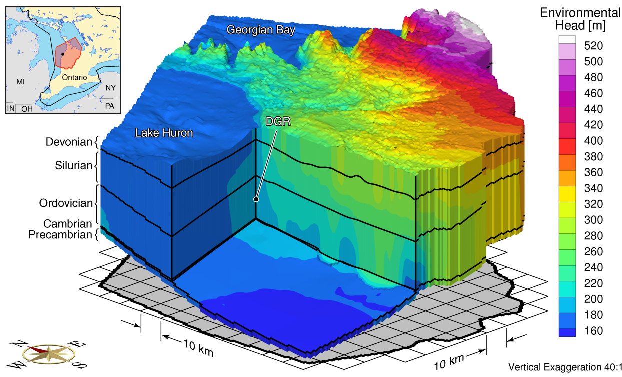

Figure 6. Base-case environmental head (m) distribution.

equilibrium time of 1 million years (Figure 7) consists of relatively fresh groundwater for the shallow groundwater zone and an area with much higher TDS concentrations for the intermediate and deep groundwater zone (below the Salina where present). The shallow groundwater zone will remain devoid of salinity because the continual inflow of meteoric water through recharge to the zone will dilute any salinity that diffuses upward through the Silurian or Ordovician. The brine concentrations in the low permeability Ordovician units at the Niagara Escarpment, where the Silurian is absent, will also experience some flushing as well; however, the higher density groundwater found in the deeper zone that has a higher energy than water with low total dissolved solids will prevent any significant penetration of freshwater. The TDS transition zone occurs across the Salina; variations in the upward flow through this unit in combination with the high longitudinal dispersivity result in the spatial oscillations in the salinity that is apparent in the figure (note the interface between the 200 g/L and the 100 g/L contours).

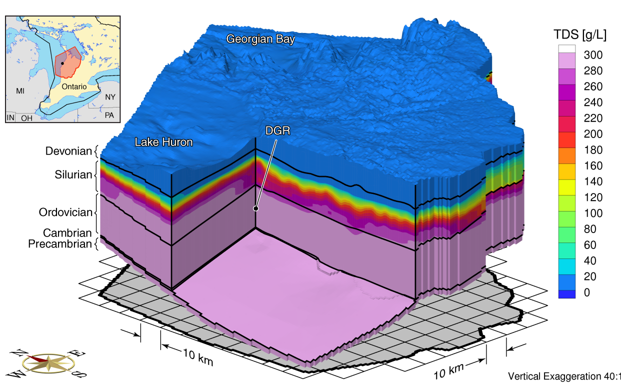

Figure 7. Base-case Total Dissolved Solids distribution.

The base-case pore-water velocity magnitudes are presented in Figure 8. The highest velocities occur in the more permeable shallow groundwater zone. The lower velocities beneath Lake Huron and Georgian Bay are the result of the absence of a horizontal gradient. The reduction of the velocities in the Salina Group is clearly evident in the figure as are the higher velocities of the Niagaran in the Silurian (these velocities appear as the orange/red band above the Ordovician-Silurian interface). Above the Niagaran, higher velocities are also evident in the D-Unit and the A2-Carbonate of the Silurian. In Figure 8, the A2-Carbonate velocities are the orange to yellow band immediately above the Niagaran while the D-Unit velocities are the higher thinner yellow to orange band. Within the Ordovician in the vicinity of the proposed DGR, the groundwater pore velocities are less than 10^{-4} m/year. Higher velocities are predicted for a zone at the bottom of the Ordovician that is upgradient of the eastern extent of the Cambrian. This zone, characterized by the orange at the southern end of the north-south blockcut face in Figure 8, corresponds to the area of higher horizontal gradients. Even within this zone, pore water velocities are estimated to be less than 0.001 m/year. Based on the estimated low velocities and relative to a diffusion coefficient of 1.2×10^{-10} m^2/s, solute transport in the Ordovician will be diffusion dominated.

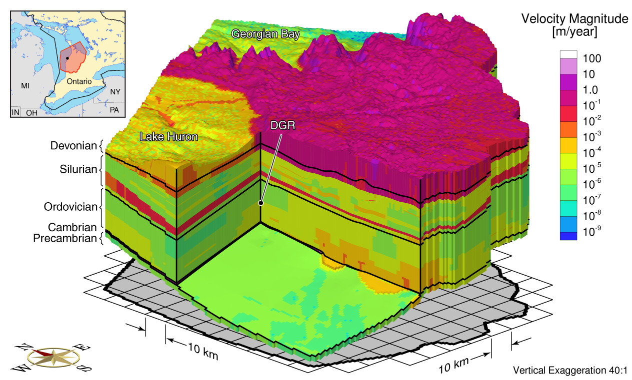

Figure 8. Base-case pore water velocity magnitude (m/a) distribution.

The ratio of vertical velocity to velocity magnitude is plotted in Figure 9 for the regional-scale domain. In the figure, blue corresponds to vertically downward velocities, white to horizontal velocities and red to vertically upward velocities. Transition zones also are evident in the figure. For the base-case parameters and a pseudo-equilibrium time of 1 million years, flow in the shallow groundwater zone is predominantly horizontal as is the flow in the more permeable units such as the Cambrian, Niagaran, A2 Carbonate and D-Unit. These units can be identified by the horizontal white bands in Figure 9. Flow in the Salina is strongly vertical. The direction of flow in the Ordovician and lower Silurian is predominantly horizontal where the Cambrian is absent and vertical where it is present. There is a degree of topographic control on the direction of flow; the trend is for upward flow (red) for the portion of the Ordovician below Lake Huron and downward flow (blue) from the Niagaran to the Cambrian for the land areas with the transition occurring at or near the shoreline.

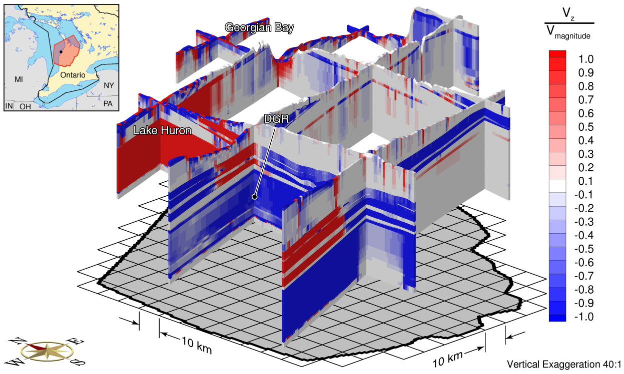

Figure 9. Fence diagram of base-case ratio of vertical velocity to velocity magnitude.

The performance measure selected for the evaluation of the groundwater system is the mean life expectancy (Figure 10). The general trend for the mean life expectancy is similar to that found in the head and velocity distributions. The shallow groundwater zone has significantly shorter life expectancies compared to the deep groundwater zone. The areas of recharge versus discharge can be noted in the figure as the recharge areas have a high MLE while the discharge areas have low MLEs. The groundwater area surrounding the proposed DGR is calculated to have a mean life expectancy of approximately 8.9 million years for the base-case conceptual model.

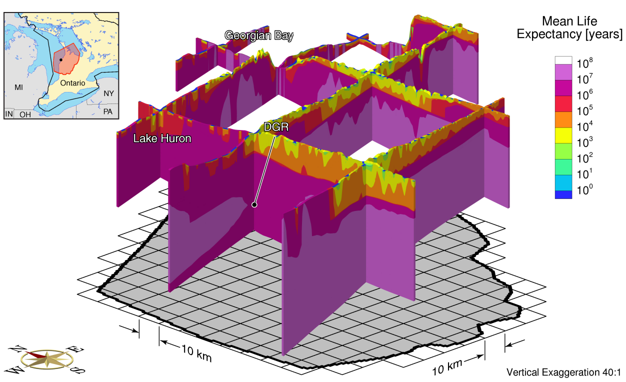

Figure 10. Fence diagram showing base-case mean life expectancy (years).

7 CONCLUSIONS

This paper has developed an analysis of three-dimensional, saturated, density-dependant flow for a region centered on a proposed deep geologic repository for the Bruce site near Tiverton, Ontario. The barriers to solute transport from the horizon of the proposed DGR include the low permeability and thickness of the Ordovician limestone and shales, the low permeability of units in the lower Silurian, the low permeability of the Salina, and the long travel path in the Niagaran. The base-case analysis shows that solute transport in the Ordovician and lower Silurian is diffusion dominant.For the base-case parameters, the estimated mean life expectancy (MLE) for the location of the proposed DGR in the Ordovician is in excess of 8 million years. The possible presence of a gas phase in the rock between the Cambrian and the Niagaran has not been considered in the analyses of this paper; a gas phase would further reduce the estimated MLE for the location of the repository.

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