OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Karst Assessment

March 2011

Prepared by: S.R.H. Worthington

NWMO DGR-TR-2011-22

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AECOM CANADA Ltd.			
Prepared by:	S.R.H. Worthington (Worthington Groundwater)		
Reviewed by:	R. Frizzell		
Approved by:	R.E.J. Leech		
Nuclear Waste Management Organization			
Reviewed by:	A. Parmenter		
Accepted by:	M. Jensen		

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EXECUTIVE SUMMARY

The Paleozoic succession beneath the Bruce nuclear site includes soluble sedimentary rocks such as carbonates and evaporites, which can be eroded by dissolution to create enhanced permeability through the process of karstification. As such, this report presents the findings of a karst assessment completed as part of Geosynthesis activities for Ontario Power Generation's (OPG) proposed Deep Geologic Repository (DGR) project at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The purpose of this report is to document the distribution of karst at and beneath the Bruce nuclear site.

The relevance to OPG's proposed DGR project is that, where present, karstification leads to continuous, large-aperture pathways through a soluble-rock aquifer, which can act as permeable conduits for mass transport. This results in a double-porosity aquifer with most storage in the low-permeability rock matrix and most flow through the high-permeability channels. Groundwater flow velocity through these preferential pathways is enhanced in comparison to an equivalent porous medium or a discretely-fractured porous medium. Consequently, an understanding of karstification is important in assessing site specific hydrogeological data collected as part of the geological characterization activities at the Bruce nuclear site (e.g., INTERA[1] 2011).

Dissolution processes are most active in the shallow subsurface, usually <200 m depth in south-west Ontario, and potentially reaching a maximum of approximately 300 m in the Devonian carbonates in southern Huron County and western Perth County. The proposed DGR would be located approximately 680 metres below ground surface (mBGS) within Middle Ordovician argillaceous limestone of the Cobourg Formation and overlain by more than 200 m of very low permeability Upper Ordovician shale-dominated sedimentary rock.

Multiple lines of evidence support the assertion that the upper approximately 180 m of bedrock beneath the Bruce nuclear site are karstic. Higher-permeability confined intervals at depths of about 326 to 329 mBGS (Salina A1 dolostone) and 375 to 379 mBGS (Guelph Formation) also show evidence of potential karstification. No evidence for karstification in deeper strata at the site was found in the documents reviewed. The deeply buried Ordovician carbonates are unlikely to be affected by modern karstification processes and have extremely low hydraulic conductivities. Furthermore, the presence of significant underpressures or overpressures in the strata between the elevation of the deep repository and the surface suggest that there is an absence of high-permeability karstic pathways between the strata that host and enclose the repository and the surface.

[1] Currently known as Geofirma Engineering Ltd.

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1. INTRODUCTION

The Paleozoic sedimentary succession underlying southern Ontario includes soluble sedimentary rocks such as carbonates and evaporites, which can be eroded by dissolution to create enhanced permeability. This is the process of karstification. This report presents the findings of a karst assessment completed as part of Geosynthesis activities for Ontario Power Generation’s (OPG) proposed Deep Geologic Repository (DGR) project at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The purpose of this report is to document the distribution of karst at and beneath the Bruce nuclear site.

The relevance to OPG’s proposed DGR project is that, where present, karstification leads to continuous, large-aperture pathways through a soluble-rock aquifer, which act as permeable conduits for advective transport. This results in a double-porosity aquifer with most storage in the low-permeability rock matrix and most flow through the high-permeability channels. Groundwater flow velocities through these preferential pathways are enhanced in comparison to an equivalent porous medium or a discretely-fractured porous medium. Consequently, an understanding of karstification is important in assessing site specific hydrogeological data collected as part of the geological characterization activities at the Bruce nuclear site (e.g., INTERA 2011).

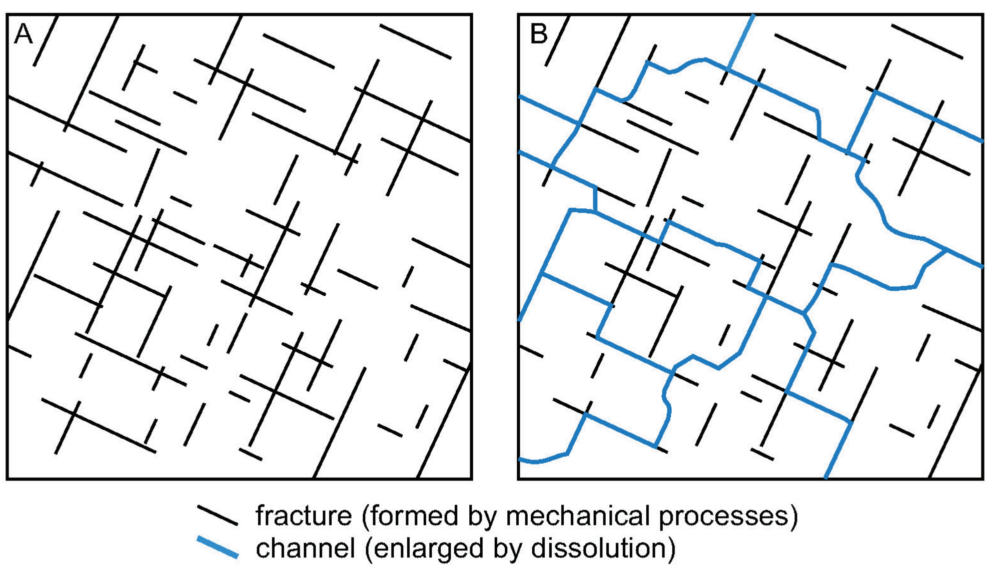
The report first outlines the general process of karstification in soluble rocks, then describes the distribution of karst aquifers in southern Ontario, and finally assesses the degree and influence of karstification within the Paleozoic succession beneath the Bruce nuclear site. This latter section is largely drawn from analysis of data compiled during site investigations at the site (INTERA 2011). Also, the results presented in two additional technical reports (Beauheim 2009 and Heagle 2010) were considered in this assessment.

2. KARSTIFICATION

2.1 Karstification

Soluble rocks such as carbonates and evaporites are deposited by precipitation processes and eroded principally by dissolution processes. At shallow depths below the surface, most of the permeability in these rocks is created by dissolution, or karstification. This process is, broadly speaking, a function of the flux of water through an aquifer and the chemical undersaturation of that water. Consequently, karstification tends to be most pronounced in the upper parts of soluble rock aquifers. There is currently no consensus on the definition of 'karst aquifers', but the broad definition used here is that a karst aquifer is "an aquifer with self-organized, high-permeability channel networks formed by positive feedback between dissolution and flow" (Worthington and Ford 2009). It has been suggested that the hydraulic conductivity divide between karstified carbonate aquifers and non-karstified carbonate strata is approximately 10^{-6} m/s (Freeze and Cherry 1979). However, the contrast between overall hydraulic conductivity and matrix hydraulic conductivity is also a useful criterion; where this value is substantially greater than unity then karstification may have occurred.

Karst aquifers can be considered in terms of two end members, macrokarst and microkarst (Worthington and Ford 2009). Macrokarstic aquifers are those with a wide range of channel apertures, whereas microkarstic aquifers have a narrower range of apertures. A key property of karst aquifers is that the high-permeability channels are interconnected to form a network (Worthington 2009). This constitutes a major difference that distinguishes karst aquifers from fractured-rock aquifers, as shown schematically in Figure 2.1.



Notes: Plan view of a bedding plane intercepted by fractures in (A) a discretely-fractured porous medium and (B) in a karst aquifer, where dissolution has formed a channel network.

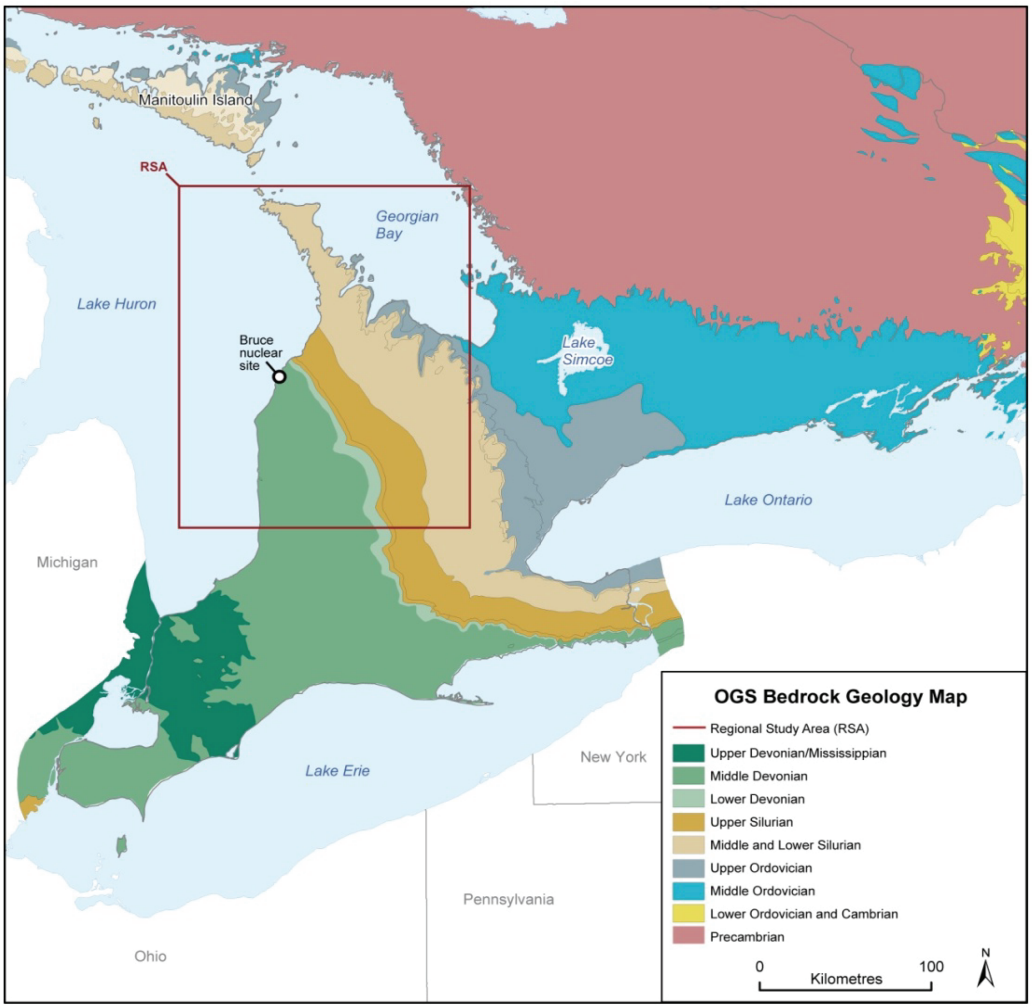
Figure 2.1: Comparison Between Fractured-Rock (A) and Karst (B) Aquifer Networks

The high-permeability fractures in Figure 2.1A were produced by mechanical processes (e.g., joint propagation) and therefore will tend towards having parallel-plate openings; they do not necessarily form an interconnected network. Conversely, the high-permeability channels in Figure 2.1B do form an interconnected network and the solutional enlargement of the fractures is reflected in their shape, which tends to be elliptical rather than constant-aperture. It is apparent from Figure 2.1 that a useful prerequisite for the development of the well-connected channel network shown in Figure 2.1B is the pre-existing fracture population shown in Figure 2.1A.

3. KARSTIFICATION OF CARBONATE AQUIFERS IN SOUTHERN ONTARIO

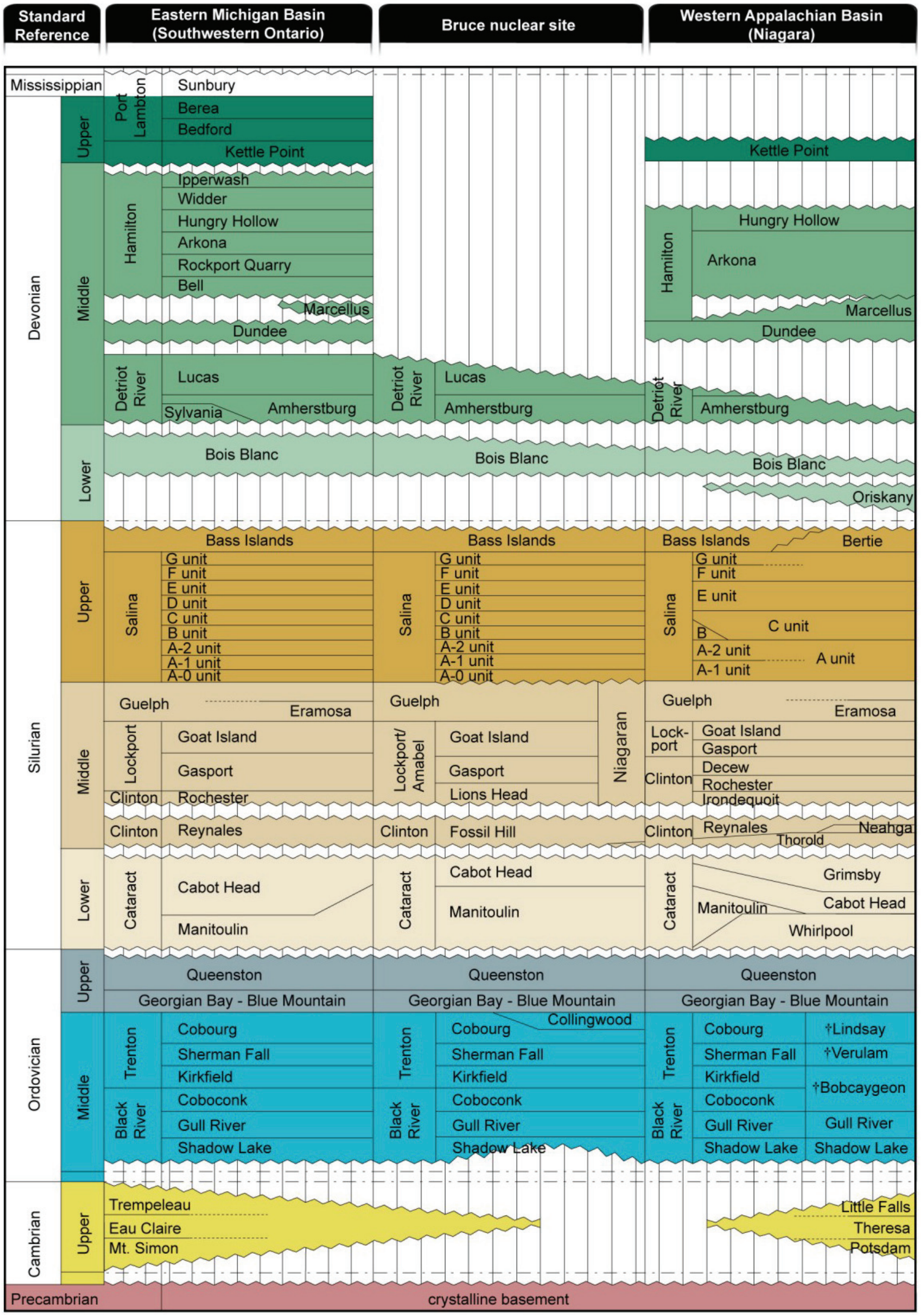
3.1 Regional Distribution of Karst

The distribution of Paleozoic stratigraphy across southern Ontario is shown in Figure 3.1 along with the location of the Regional Study Area (RSA) boundary defined as part of the geoscientific work program at the Bruce nuclear site. Paleozoic stratigraphic nomenclature of the same region is shown in Figure 3.2. Near-surface carbonate rocks of Ordovician, Silurian, and Devonian ages throughout southern Ontario, including the RSA typically are karstified (Figures 3.1 and 3.3).



Note: Modified from Armstrong and Carter (2006).

Figure 3.1: Geologic Map of Southern Ontario

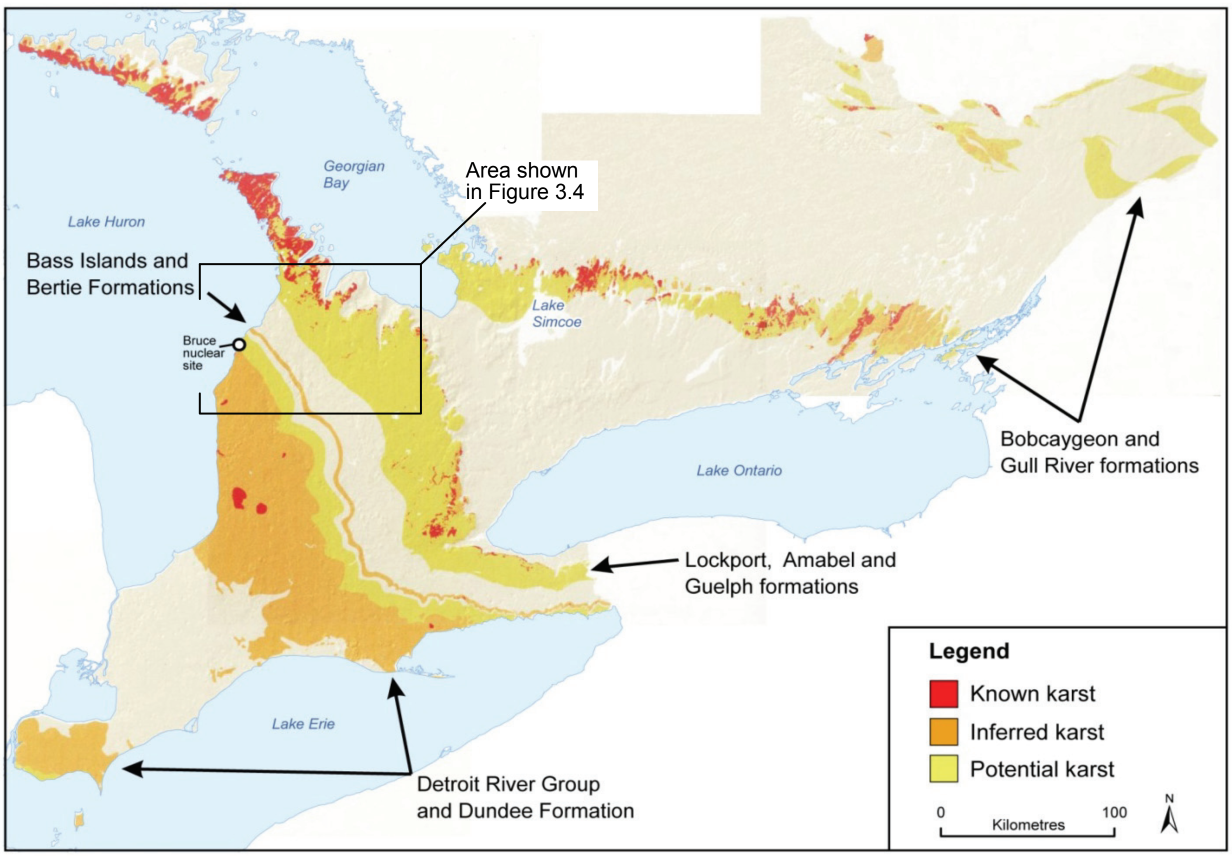


Notes: Includes nomenclature from locations in the Michigan Basin (left), Bruce nuclear site (centre), and Appalachian Basin (modified from Armstrong and Carter 2006). † indicates outcrop nomenclature for southern and eastern Ontario.

Figure 3.2: Paleozoic Stratigraphic Nomenclature of Southwestern Ontario

Areas of mapped karstification based on geomorphological assessment and analysis of cores, as shown in Figure 3.3, include (Brunton and Dodge 2008): the Ordovician carbonates, which crop out to the south of the Canadian Shield and extend into eastern Ontario (e.g., Gull River Formation, Lower Bobcaygeon Formation); Silurian dolostones of the Bass Islands and Bertie formations, especially where exposed along the Niagara escarpment; the aquifer formed by Amabel - Lockport and Guelph formations in some locations such as at Guelph; evaporite units of the Salina formation (Singer et al. 2003); and Devonian carbonates of the Detroit River Group and Dundee Formation in southwestern Ontario, particularly in areas where there is a deep unsaturated zone (>100 m).

Hydrogeological studies of near-surface carbonate aquifers typically find that aquifer-scale hydraulic conductivity is in the range 10^{-6} m/s to 10^{-4} m/s. These high values are very likely to be attributable to karstification. Reactive transport modelling has shown that all near-surface carbonate aquifers are karstified (Dreybrodt 1996). Consistent with this modelling, the author is not aware of any studies of carbonate aquifers in southern Ontario where it has been shown that the uppermost tens of metres of the bedrock aquifer are not karstic.



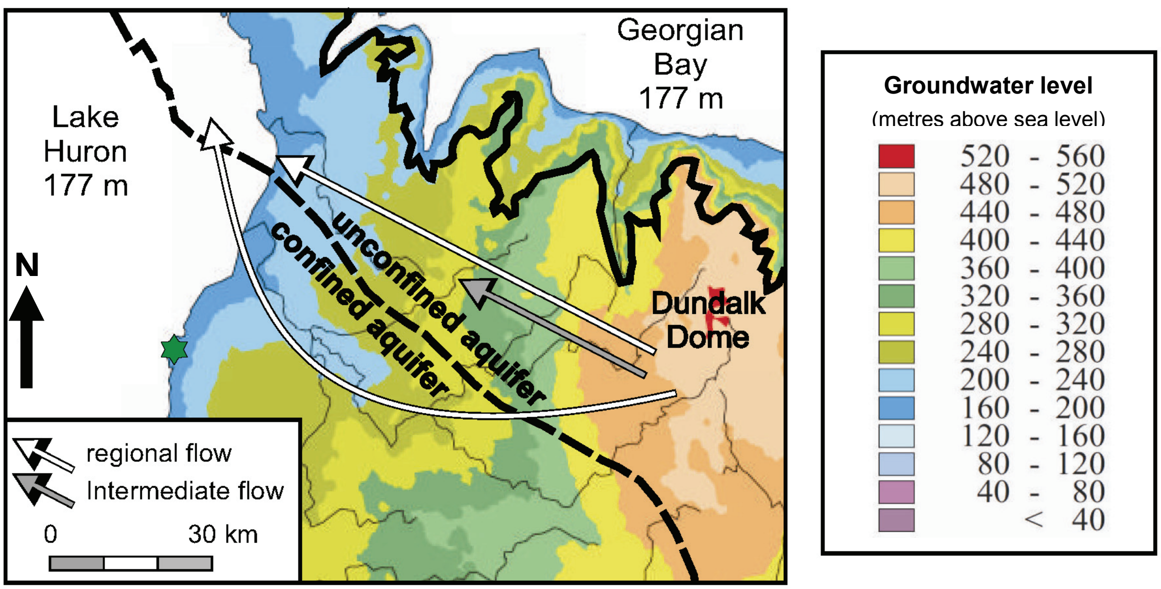
Note: Figure is from Brunton and Dodge (2008).

Figure 3.3: Distribution of Near-surface Karstified Paleozoic Rocks in Southern Ontario

Dissolution processes are most active in the shallow subsurface, usually less than 200 m below ground surface (mBGS) in south-west Ontario, and potentially reaching 300 mBGS in the Devonian carbonates in southern Huron County and western Perth County. Solubilities of gypsum and halite increase with both pressure and temperature, so there will be continued dissolution of these minerals along flow paths that increase with depth. Dissolution can occur wherever there is groundwater flow and the groundwater is undersaturated with respect to any of these minerals. However, it is probable that these effects may be relatively minor below a depth of approximately 300 mBGS in southern Ontario and may not significantly increase permeability.

3.2 Karst Enhanced Regional Flow Paths

In thick, pure sequences of carbonate rocks (i.e., lacking significant shale beds), the depth of karstification has been found to be a function of the dip of the strata and flow path length (Worthington 2001). However, outcrop patterns, aquifer thicknesses, and hydraulic gradients play a predominant role in interbedded, mixed-lithology sequences such as in southern Ontario.

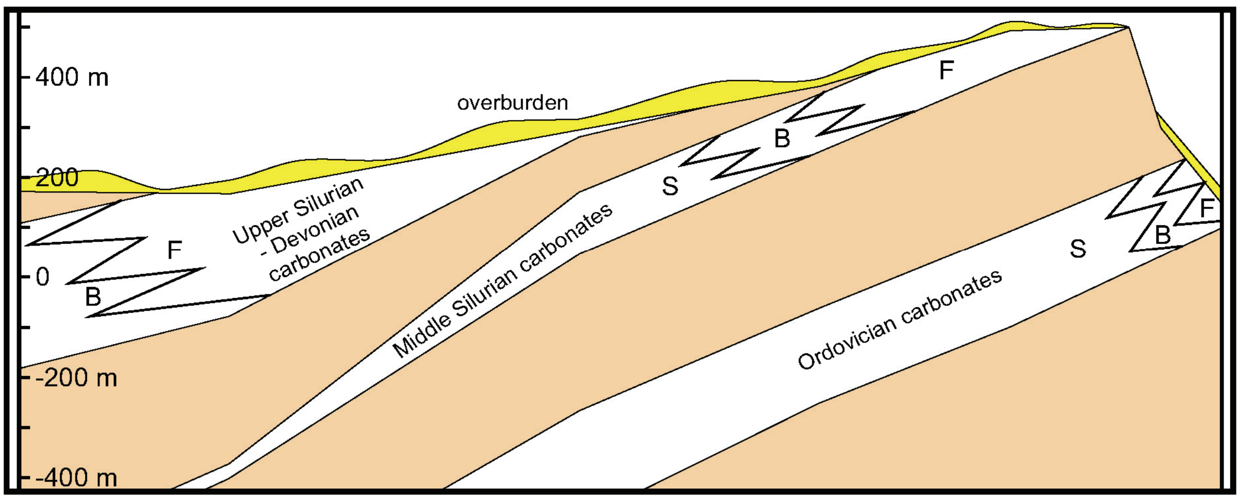


Notes: Green star indicates the location of the Bruce nuclear site. Figure is from Singer et al. (2003).

Figure 3.4: Hypothesized Intermediate and Regional Flow in the Amabel and Guelph Formations

The water table in southern Ontario is highest in the area of the Dundalk dome shown in Figure 3.4 (Singer et al. 2003). Surface runoff from this area flows north to Georgian Bay via the Nottawasaga River, west to Lake Huron via the Saugeen River (Figure 3.4), and south to Lake Erie via the Grand River. The bedrock in the Dundalk Dome area is the Silurian Guelph-Amabel carbonate aquifer as indicated in Figure 3.4. From the Dundalk Dome there is local flow to nearby creeks, and there is likely to also be intermediate flow to rivers such as the Rocky Saugeen and regional groundwater flow in the unconfined aquifer to the northwest to Lake Huron and to the south towards the Guelph - Cambridge area.

A section downdip shows a freshwater zone where the aquifer is unconfined, extending some unknown distance into the confined aquifer (Figure 3.5). Total Dissolved Solids (TDS) increases in the confined aquifer in a brackish zone and saline zone. Modern karstification in the dolostone is likely to occur almost exclusively in the freshwater zone. This increases permeability by several orders of magnitude to typical values of 10^{-6} to 10^{-4} m/s. The distribution of stratigraphy at the Bruce nuclear site, which is discussed in Chapter 4, suggests that the Devonian and upper Silurian carbonates are likely to be karstified. This includes the upper approximately 180 m of carbonate bedrock, which is itself overlain by 7.5 to 20 m of glacial till overburden (INTERA 2011).



Notes: Section indicates the hypothesized relative distribution of freshwater (F), brackish water (B), and saline/brine (S) within each carbonate unit. The stratigraphic contacts are from Armstrong and Carter (2006). Vertical exaggeration is 100x.

Figure 3.5: Schematic Cross-section Showing the Three Principal Carbonate Hydrostratigraphic Units in Southwestern Ontario

3.3 Paleokarst

Paleokarst refers to karst that was formed at an earlier time and subsequently buried and rendered inactive by later deposition of sediments or by changes in groundwater flow conditions. The Paleozoic evaporite and carbonate rocks in southern Ontario were largely deposited in shallow marine conditions with frequent hiatuses in deposition. At such times there may have been flow of freshwater through the sediments, resulting in karstification. Paleokarst is therefore ancient and most likely to have been most extensive at the largest breaks in the sedimentary record such as the Silurian - Devonian unconformable boundary (e.g., Brunton and Dodge 2008) at the top of the Bass Islands Formation (Figure 3.2). Other major breaks include below and above the Reynales/Fossil Hill Formations, below and above the Detroit River Group and within Silurian reefs at the top of the Guelph Formation (Figure 3.2). For instance, Smith et al. (1993) documented eight major episodes of subaerial exposure in bioherms of the Guelph Formation in Lambton and Kent counties, with the formation of paleokarst that formed zones of enhanced porosity and permeability that now host hydrocarbon reservoirs. The lateral extent of these high-permeability zones were a few kilometres at most.

Consequently, this localized karstification is unlikely to contribute significantly to modern regional groundwater flow.

Though karst features are preserved to the present at such paleokarst horizons, subsequent deposition and diagenesis would have occluded much of the karstic function (i.e., enhanced permeability) of such strata.

4. KARSTIFICATION AT THE BRUCE NUCLEAR SITE

There are three major sequences of carbonates at the Bruce nuclear site, of Ordovician, Silurian and Siluro-Devonian ages. The uppermost carbonates (above the Salina Formation) at the site and in the surrounding area are of upper Silurian and Devonian age. The top approximately 180 m (borehole DGR-2 reference depth) of bedrock at the Bruce nuclear site is characteristically fractured (Figure 4.1) with high permeabilities (INTERA 2011). This upper zone, which is overlain by 7.5 to 20 m of glacial till overburden, is recognized as a zone of active karst development. This zone is characterized by higher permeability than is found in the deeper units, and groundwaters that range in TDS from fresh (< 0.5 g/L) to brackish (approximately 5.0 g/L) near the bottom of this groundwater zone as shown in Figure 4.1 (INTERA 2011).

With the exception of two approximately 4 m thick dolostone intervals, which display hydraulic conductivities of approximately 10^{-7} to 10^{-8} m/s (INTERA 2011), the groundwater system below 180 mBGS has very low hydraulic conductivities and is characterized by saline to brine groundwater or pore fluids (Figure 4.1). Despite the relatively higher permeability, the two thin aquifer zones are characterized by Na-Cl saline waters or brines with TDS values in the A1 carbonate (hydrostratigraphic unit 4A) of 29 g/L and the Guelph Formation (hydrostratigraphic unit 4B) of 371 g/L, as shown in Figure 4.1 (INTERA 2011). The Ordovician carbonates are deeply buried and are most unlikely to be affected by modern karstification processes.

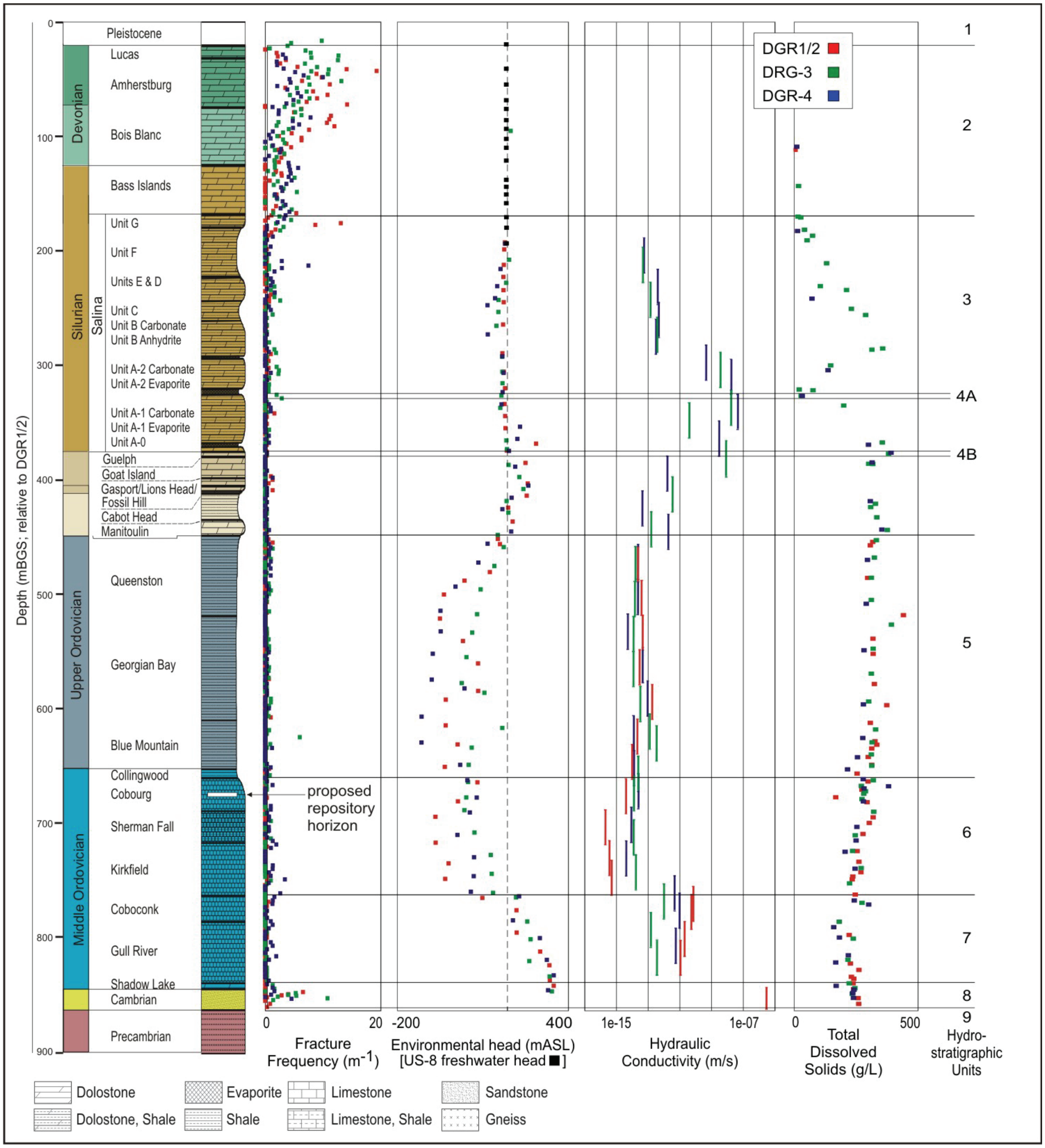
The deep groundwater system in the Ordovician strata at the Bruce nuclear site is characterized by very low hydraulic conductivities, as shown in Figure 4.1 (INTERA 2011).

Sections 4.1 to 4.3 provide a summary of karstification at the site within key units. The discussion is divided into the karstified shallow Upper Silurian and Devonian carbonates (Section 4.1), the Silurian A1 and Guelph formation aquifers (Section 4.2) and the deep Ordovician units (Section 4.3). Reference to the site hydrostratigraphic units as described by INTERA (2011), and shown in Figure 4.1, is also included in the discussion.

4.1 Upper Silurian Bass Islands Formation and Devonian Carbonate Aquifers

The Detroit River Group, Bois Blanc Formation and Bass Islands Formation form the uppermost ~180 m of bedrock at the Bruce nuclear site (INTERA 2011). These aquifers have been grouped at the site as hydrostratigraphic unit 2 (Figure 4.1). These carbonates aquifers thicken to the south of the RSA where the full thickness of the Lucas and Dundee formations are present (Figure 3.1), and the aquifer is highly karstified (Figure 3.3; Brunton and Dodge 2008).

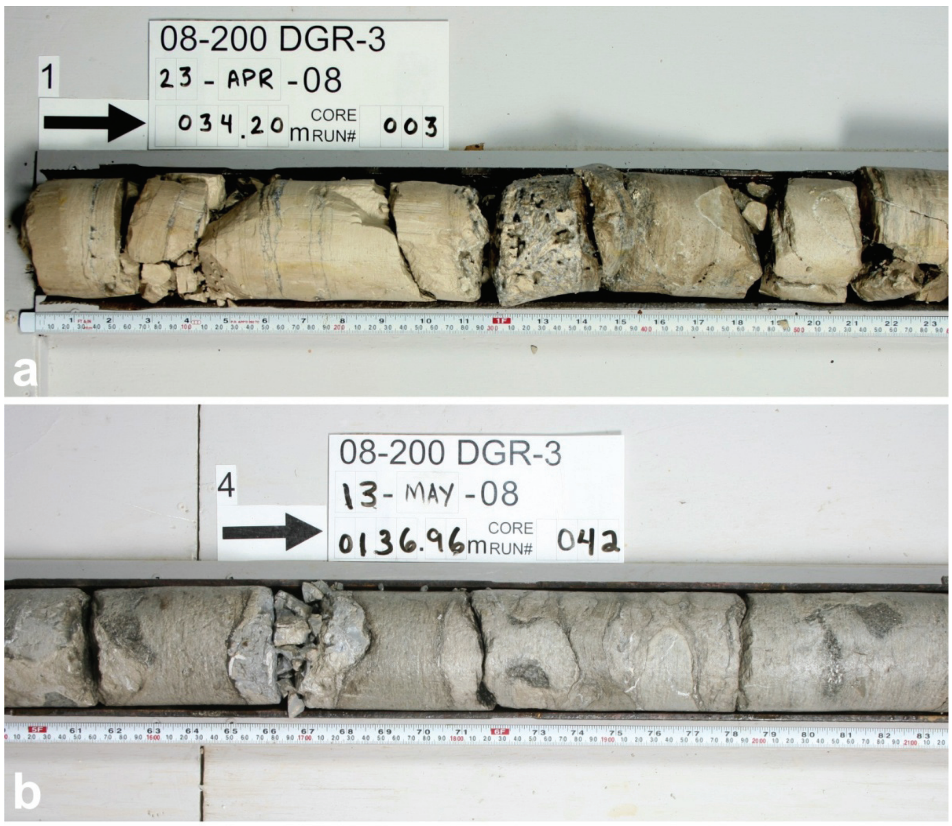
The Bruce nuclear site itself has several metres of glacial till overburden (hydrostratigraphic unit 1). Further away from Lake Huron, the thickness and composition of overburden is highly variable, with thicknesses occasionally exceeding 100 m. However, there are also at least twenty locations on the Walkerton and Chesley-Tiverton map sheets where there is no overburden (Sharpe and Edwards 1979, Sharpe et al. 1979, Kelly and Carter 1993). The composition and permeability of the overburden varies considerably, from high permeability sands and gravels to low permeability tills. The combination of minimal or no overburden in some areas together with high permeability sands and gravels in other areas indicates that there must be substantial recharge to the uppermost bedrock aquifer.



Notes: Compilation plot includes data from vertical boreholes DGR-1, DGR-2, DGR-3, and US-8 only. From left to right: DGR-2 reference stratigraphic column; Fracture frequency; Environmental head; Hydraulic conductivity; Total dissolved solids; and Hydrostratigraphic units. All data is from INTERA (2011).

Figure 4.1: Compilation of Bruce Nuclear Site Data and Hydrostratigraphic Units

The combination of substantial recharge to the Upper Silurian and Devonian carbonates upgradient from the site (to the east and south-east of the site) together with unimpeded discharge from the Lucas Formation to Lake Huron in the vicinity of the site suggests that there is ongoing karstification at the present time in the uppermost ~180 m of bedrock. Figure 4.2a shows core from the shallow Devonian carbonates. This interval is characterized by karst features such as solution-enhanced joints and stained/weathered fractures. There were significant drilling fluid losses in the drilling of all DGR-series and shallow US-8 boreholes in the uppermost 20 m of the Bass Islands Formation, where hydraulic conductivity values as high as of $3x10^{-4}$ m/s were measured (INTERA 2011). The contact between the upper Silurian Bass Islands Formation and the overlying Devonian Bois Blanc Formation probably represents reactivated paleokarstic permeability (Figure 4.2b).



Notes: Arrow points downhole towards stratigraphic bottom in all photographs. (a) Core photo from shallow Devonian Lucas Formation carbonates. This interval is characterized by karst features such as solution-enhanced joints and stained/weathered fractures. (b) Core photo from a section of the Devonian Bois Blanc Formation where present-day groundwater flow may be concentrated along a remnant paleokarst horizon near the top of the Bass Islands Formation. Figure is from NWMO (2011).

Figure 4.2: Potential or Active Karst and Paleokarst Beneath the Bruce Nuclear Site

The Rock Quality Designation (RQD) data (not shown) and fracture frequency with depth (Figure 4.1) also suggest that the aquifer is well karstified. At the site there is a wide variation in RQD values, with average values in the Lucas, Amherstberg, Bois Blanc, and Bass Islands formations being 47%, 47%, 68%, and 33%, respectively (INTERA 2011). Such low values are suggestive of extensive karstification throughout the shallow aquifer units of hydrostratigraphic unit 2, and are consistent with the increased fracture density through this interval, as shown in Figure 4.1 (INTERA 2011).

Karst aquifers such as the Devonian strata at the DGR are characterized by double-porosity behaviour, with the matrix having low permeability and high storage and the fractures and channels forming a low-porosity interconnected network with high permeability (Figure 2.1B).

In karst aquifers, hydraulic conductivity values increase as the volume of the rock being tested increases. This scaling effect has been quantified in many carbonate aquifers (Worthington 2009). Packer tests stress a small volume of the aquifer and the geometric mean values in the Devonian carbonates range from $8x10^{-8}$ m/s in the Amherstberg (below -30 m) to $1x10^{-7}$ m/s in the Bois Blanc to $2x10^{-6}$ m/s in the Lucas and shallow Amherstberg (above -30 m) (INTERA 2011). Slug tests and tunnel dewatering stress a larger volume of the aquifer and so have substantially higher values, with a geometric mean of $1x10^{-5}$ m/s in the combined Amherstberg and Bois Blanc (INTERA 2011). These latter values provide good estimates of the regional-scale hydraulic conductivity of the Devonian carbonates.

This double-porosity behaviour has important implications for transport. First, the relevant porosity for transport (the kinematic porosity) is likely to be in the range 0.01% to 0.1% (Worthington and Ford, 2009). This is about two orders of magnitude lower than the total porosity (Bass Islands 5.5%, Devonian carbonates 7.8% (INTERA 2011)). This implies that calculations based on total porosity could overestimate travel time in these upper carbonates by about two orders of magnitude.

At the site, groundwater environmental heads in the US-series boreholes vary little in the Devonian strata and the uppermost 20 m of the Bass Islands carbonates as shown in Figure 4.1 (INTERA 2011). This suggests that these strata behave as a single aquifer with vertical hydraulic communication. However, there is a substantial increase in major ions in the lower Bois Blanc Formation (INTERA 2011). This suggests that there is low vertical hydraulic conductivity (K_z) at a depth of about 115 mBGS. At a depth of about 155 mBGS (in the middle of the Bass Islands Formation), there is an increase in both heads and in major ions (INTERA 2011), indicating a second low K_z zone at this depth. The implication is that although karst is likely present throughout the entire zone there may be a substantial decrease in vertical connectivity below 115 mBGS.

4.2 Silurian Carbonate Aquifers of the Salina and Guelph Formations

Two aquifers, hydrostratigraphic units 4A and 4B in Figure 4.1, have been identified in the DGR-series wells in the Upper Silurian Salina Formation A-1 Carbonate and the Middle Silurian Guelph Formation (INTERA 2011). The remaining carbonates in the Salina Formation, the Middle Silurian (Goat Island, Gasport, Lions Head, and Fossil Hill formations) and the Lower Silurian (Manitoulin Formation) have low hydraulic conductivities (Figure 4.1). Due to their much lower permeability, it is considered that karstification of these carbonates is absent or much less developed and they are not considered further in this report.

4.2.1 Salina Formation A1 Dolostone

Interpretation of karstification in the Salina Formation at the site is challenging for three reasons. The first is because of the presence of three soluble rocks at the site (gypsum, limestone and dolostone) with greatly contrasting solubilities. This can result not only in normal dissolution of these rocks but also in more complex reactions such as dedolomitization. The second reason is because of the possible former presence of salt horizons, the dissolution of which may have affected the permeability of overlying strata due to collapse. The third reason is the interbedded nature of the strata, which at the site has been divided into nine hydrostratigraphic units. One of these units, hydrostratigraphic unit 4A (INTERA 2011) of the A1 Carbonate has been found to have a much higher permeability than the remainder of the Salina Formation.

Hydrostratigraphic unit 4A is found at a depth of 325.5 to 328.5 mBGS in DGR-1 and includes the upper 3.0 to 3.7 m of the Salina A1 Unit dolostone in the DGR-series boreholes (INTERA 2011). The average horizontal hydraulic conductivity of hydrostratigraphic unit 4A is estimated at $2x10^{-7}$ m/s, from straddle packer testing and observations during targeted groundwater sampling in DGR-3 and DGR-4, as shown in Figure 4.1 (INTERA 2011). This value is about four orders of magnitude larger than hydraulic conductivity measurements on core samples (INTERA 2011), which illustrates the importance of fractures and/or channels.

TDS in opportunistic groundwater samples from this interval is approximately 27 g/L in DGR-3 and 31 g/L in DGR-4 (INTERA 2011). These are the lowest values in the DGR boreholes below a depth of 200 mBGS. At greater depths, TDS values climb sharply to >300 g/L at depths below about 370 mBGS (Figure 4.1).

The occurrence of this isolated relatively low TDS horizon suggests that Unit 4A has been influenced by recharge, during glaciation or more recently during the Holocene, to the east or south-east where the unit sub-crops. A schematic depiction of the flow path is shown in Figure 3.4. Consistent with this conceptual model, regional flow from the Dundalk Dome to Lake Huron occurs principally within the unconfined aquifer, where TDS values are likely to be on the order of 0.2 - 0.4 g/L. There is likely to be some flow in the confined aquifer, given that heads in the Dundalk Dome are much higher than in Lake Huron. Karstification in the confined aquifer will decrease with distance away from the unconfined aquifer because karstification is a positive feedback process. With decreased permeability away from the unconfined aquifer there will also be less flow in the aquifer and consequently less flushing of solutes derived from the dissolution of gypsum and salt.

Hydraulic conductivity and TDS in the unconfined aquifer of the upper Salina A1 dolostone are likely to be about $1x10^{-5}$ m/s and 0.4 g/L, respectively. In the DGR boreholes the respective values are approximately $2x10^{-7}$ m/s and 29 g/L, respectively. The Bruce nuclear site is about 30 km to the south-west from the unconfined Salina A1 aquifer, so gradients in hydraulic conductivity and in TDS are about $-3.3x10^{-7}$ m/s/km and -1.0 g/L/km, respectively, from the unconfined aquifer towards the site. These gradients give a first approximation of the rate of change between the unconfined aquifer and the Salina A1 aquifer at the site.

Groundwater flow direction in the Salina Upper A1 was found to be towards 320°, with a horizontal hydraulic gradient of 0.0086 (INTERA 2011). This flow direction is very similar to the general northwesterly regional flow path shown in Figure 3.4.

4.2.2 Guelph Formation Dolostone

The Guelph Formation aquifer corresponds to hydrostratigraphic unit 4B (Figure 4.1) found at a depth of 374.5 to 378.6 mBGS in DGR-1 (INTERA 2011). Hydrostratigraphic unit 4B encompasses the entire thickness of the Guelph Formation. The average horizontal hydraulic conductivity of this unit is approximately $3x10^{-8}$ m/s, from straddle packer testing and observations during targeted groundwater sampling in DRG-3 and DGR-4 (INTERA 2011). This value is several orders of magnitude larger than hydraulic conductivity measurements on core samples (INTERA 2011), which suggests, as above, that preferential flow through fractures and/or channels is important.

TDS in groundwater samples from this interval, as shown in Figure 4.1, are 365 g/L in DGR-3 and 375 g/L in DGR-4 (INTERA 2011). This is somewhat higher than pore waters in this unit and in both underlying and overlying units (INTERA 2011). The flow direction in the Guelph Formation at the Bruce nuclear site is towards 057° and thus is outward from deeper parts of Michigan basin to the northeast (INTERA 2011). The high TDS in groundwater samples and the flow direction both indicate that the Guelph Formation is not well connected to the regional flow system from Dundalk Dome to Lake Huron.

4.3 Ordovician Carbonates

Ordovician carbonates outcrop to the east of the Niagara escarpment. The closest outcrops are more than 100 km from the Bruce nuclear site and are at elevations that do not greatly exceed the elevation at the site or at Lake Huron. Consequently, horizontal hydraulic gradients are extremely low and the freshwater zone in the aquifer is unlikely to extend very far back from the escarpment. As a result, the occurrence of modern karstification in the Ordovician carbonates at the site is unlikely.

Data from the DGR-series boreholes, as shown in Figure 4.1, indicate that TDS is generally quite high at >200 g/L and average horizontal hydraulic conductivity is extremely low throughout the Ordovician carbonates (INTERA 2011). These results suggest an absence of evidence for modern karstification in the Ordovician carbonates. Furthermore, the presence of significant underpressures or overpressures (INTERA 2011) in the strata between the elevation of the deep repository and the surface, as shown in Figure 4.1, suggest that there is an absence of high-permeability karstic conditions in the Ordovician carbonate sedimentary rocks beneath the Bruce nuclear site.

5. SUMMARY AND CONCLUSIONS

Karstification is, broadly speaking, the product of the flux of water through an aquifer and the chemical undersaturation of that water. Consequently, karstification tends to be most pronounced in freshwater zones in the upper parts of soluble rock aquifers. In accordance with this general observation, karstification is found in near-surface aquifers of Ordovician, Silurian, and Devonian aged sedimentary rocks throughout southern Ontario including the Regional Study Area and the Bruce nuclear site (Figure 3.3; Brunton and Dodge 2008). The process of dissolution, which drives karstification, will be become relatively minor below a depth of 300 mBGS in southern Ontario and may not significantly increase permeability.

Karst processes can result in the creation of connected permeable pathways for mass transport. Such pathways are typical of a double-porosity system comprised of the low-permeability rock matrix and more permeable bounding fractures and interconnected porosity. Groundwater flow velocities estimated through these preferential pathways may be enhanced in comparison to equivalent porous medium or discretely-fractured porous medium approximations. Consequently, an understanding of karstification and its occurrence is important in assessing the suitability of the sedimentary sequence beneath the Bruce nuclear site to host the proposed DGR.

The top approximately 180 m of bedrock at the Bruce nuclear site is fractured (Figure 4.1), with high permeabilities (INTERA 2011). This upper zone, which is overlain by 7.5 to 20 m of glacial till overburden, is recognized as a zone of karst development at the Bruce nuclear site. This zone is characterized by significantly higher permeability than is found in the deeper units, and groundwaters that range in total dissolved solids (TDS) from fresh (< 0.5 g/L) to brackish (approximately 5.0 g/L) near the bottom of this groundwater zone as shown in Figure 4.1 (INTERA 2011).

With the exception of two approximately 5 m thick dolostone intervals, which posses hydraulic conductivities of approximately 10^{-7} to 10^{-8} m/s (INTERA 2011), the carbonate rocks below 180 mBGS have extremely low hydraulic conductivities in the range 10^{-10} to 10^{-15} m/sec) and is characterized by saline to brine groundwater or pore fluid chemistries (Figure 4.1). Karstification has probably been an important process in enhancing permeability in the Silurian A1 and Guelph formation aquifers.

Within the deep Ordovician carbonates, site specific data indicates that TDS is generally > 200 g/L and average horizontal hydraulic conductivities are extremely low (< 10^{-12} m/s). These results suggest an absence of modern karstification in the Ordovician carbonates at the Bruce nuclear site. The presence of a broad zone of anomalous pressures enclosing the deep Ordovician carbonates provides further evidence that there is an absence of high-permeability pathways, characteristic of karst aquifers, and extremely low formation-scale rock mass permeabilities to host and enclose the proposed repository.

6. REFERENCES

Armstrong, D.K. and T.R. Carter. 2006. An Updated Guide to the Subsurface Paleozoic Stratigraphy of Southern Ontario. Ontario Geological Survey, Open File Report 6191.

Beauheim, R.L. 2009. Evaluation of Possible Hydraulic Communication between Boreholes DGR-1 and DGR-2 at the Bruce Site. Intera Engineering Ltd. Report TR-08-07 Rev.0. Sandia National Laboratories, New Mexico, USA.

Brunton, F.R. and J.E.P. Dodge. 2008. Karst of southern Ontario and Manitoulin Island. Ontario Geological Survey, Groundwater Resources Study 5.

Dreybrodt, W. 1996. Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. Water Resources Research 32, 2923-2935.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Heagle, D. 2010. Initial Groundwater Monitoring - US-3, US-7 & US-8. Intera Engineering Ltd. Report TR-08-08 Rev.1. Ottawa, Canada.

INTERA. 2011. Descriptive Geosphere Site Model. Intera Engineering Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-24 R000. Toronto, Canada.

Kelly, R.I. and T.R. Carter. 1993. Drift thickness, Walkerton area, southern Ontario. Ontario Geological Survey, Preliminary Map P.3202.

NWMO. 2011. Geosynthesis. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-11 R000. Toronto, Canada.

Sharpe, D.R. and W.A.D. Edwards. 1979. Quaternary geology of the Chesley-Tiverton area, southern Ontario. Ontario Geological Survey, Preliminary Map P.2314.

Sharpe, D.R., M. Hradsky and L.E. Farrell. 1979. Chesley-Tiverton area, southern Ontario. Ontario Geological Survey, Drift Thickness series, Preliminary Map P.2319.

Singer, S.N., C.K. Cheng and M.G. Scafe. 2003. The Hydrogeology of Southern Ontario, 2nd Edition. Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment. Toronto, Canada.

Smith, L., S. Charbonneau and D.J. Grimes. 1993. Karst Episodes and Permeability Development, Silurian Reef Reservoirs, Southwestern Ontario. Ontario Geological Survey, Open File Report 5850.

Worthington, S.R.H. 2001. Depth of conduit flow in unconfined carbonate aquifers. Geology 29, 335-338.

Worthington, S.R.H. 2009. Diagnostic hydrogeologic characteristics of a karst aquifer (Kentucky, USA). Hydrogeology Journal 17(7), 1665-1678.

Worthington, S.R.H. and D.C. Ford. 2009. Self-organized permeability in carbonate aquifers. Ground Water 47(3), 326-336.