EXPLORABILITY AND PREDICTABILITY OF THE PALEOZOIC SEDIMENTARY SEQUENCE BENEATH THE BRUCE NUCLEAR SITE

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ABSTRACT

Ontario Power Generation (OPG) is proposing to develop a Deep Geologic Repository (DGR) for the long-term management of its Low and Intermediate Level Waste (L&ILW) at the Bruce nuclear site located in the Municipality of Kincardine, Ontario. A 4-year program of geoscientific studies to assess the suitability of the 850 m thick Palaeozoic age sedimentary sequence beneath the site to host the DGR was completed in 2010. The studies provide evidence of a geologic setting in which the DGR concept would be safely implemented at a nominal depth of 680 m within the argillaceous limestone of the Cobourg Formation. This paper describes the geologic framework of the Bruce nuclear site with a focus on illustrating the high degree of stratigraphic continuity and traceability at site-specific and regional scales within the Ordovician sediments proposed to host and enclose the DGR.

As part of the site-specific studies, a program of deep drilling/coring (6 boreholes) and in-situ testing through the sedimentary sequence was completed from 4 drill sites situated beyond the DGR footprint, approximately 1 km apart. Core logging reveals that the stratigraphic sequence comprises34 distinct bedrock formations/members/units consistent with the known regional stratigraphic framework. These layered sedimentary formations dip 0.6^{o} (~10 m/km) to the southwest with highly uniform thicknesses both at the site- and regional-scale, particularly, the Ordovician sediments, which vary on the order of metres. The occurrence of steeply-dipping faults within the sedimentary sequence is not revealed through surface outcrop fracture mapping, micro-seismic ($M \geq 1$) monitoring, inclined borehole coring or intersection of hydrothermal type dolomitized reservoir systems. Potential fault structures, interpreted from a 2-D seismic survey, were targeted by angled boreholes which found no evidence for their existence.

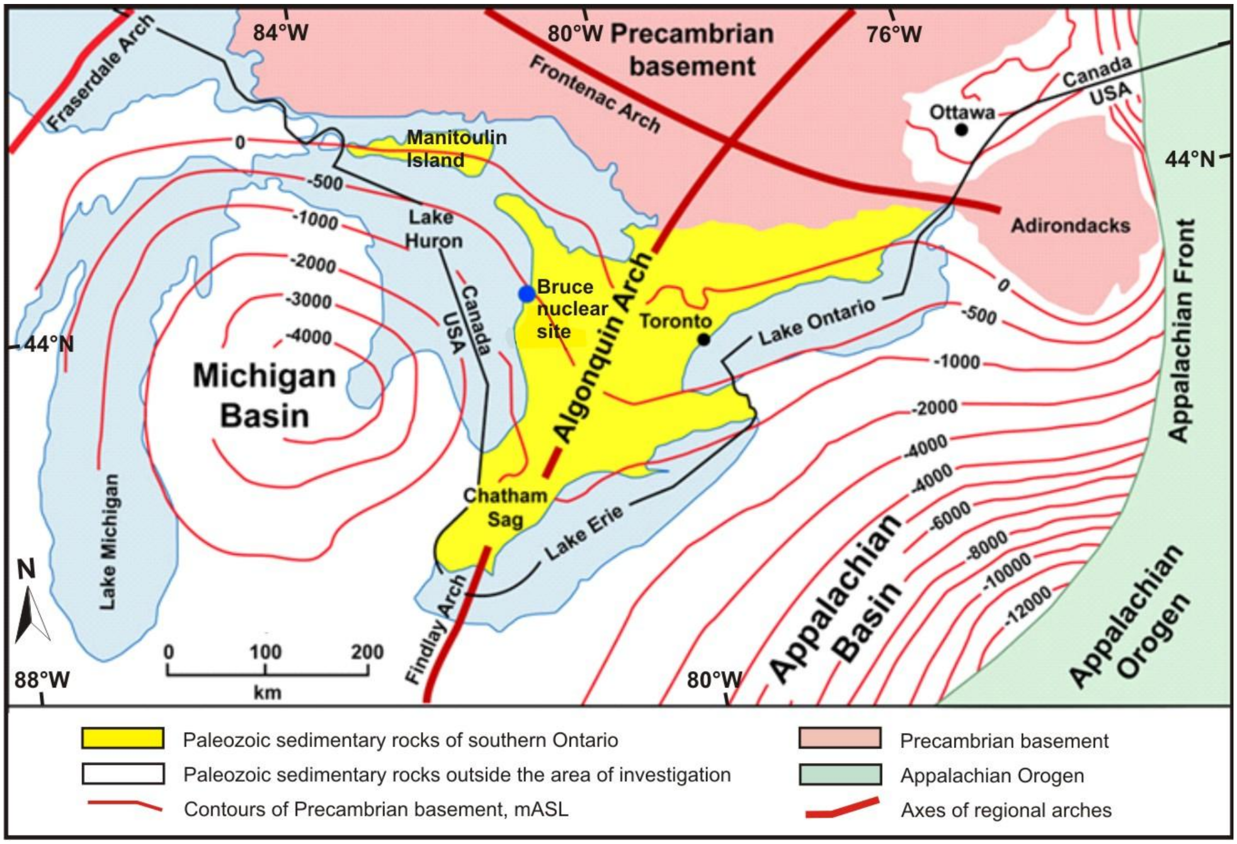
Formation specific continuity is also evidence by the lateral traceability of physical rock properties such as lithofacies and chronostratigraphic marker beds at decimetre scale, whose distribution in turn controls the parameters most important to understanding future system evolution including its extremely low hydraulic conductivities, porosities and diffusion coefficients.

The multi-disciplinary information is compiled and integrated to illustrate the predictability of this particular sedimentary environment. The approach provides an indication of the high degree of explorability in the sedimentary environment, which is beneficial in providing confidence in the DGR safety case.

1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to develop a Deep Geologic Repository (DGR) for the long-term management of Low and Intermediate Level Waste (L&ILW) generated at its owned or operated nuclear facilities. The proposed DGR would be located beneath the Bruce nuclear site in the Municipality of Kincardine, Ontario (Figure 1). A multi-disciplinary program of geoscientific investigation to assess the suitability of the 850 m thick Paleozoic age sedimentary sequence beneath the Bruce nuclear site to host the DGR was initiated in the fall of 2006. The 4-year work program involved 3 phases of investigation each described by a Geoscientific Site Characterization Plan (GSCP) [1]. As envisioned, the shaft-accessed DGR would be excavated at a nominal depth of 680 m within the low permeability Ordovician argillaceous limestone of the Cobourg Formation, which is overlain by more than 200 m of low permeability Ordovician shales. This paper describes the geologic framework of the Bruce nuclear site with a focus on illustrating the high degree of stratigraphic continuity and traceability at site-specific and regional scales within the Ordovician sediments proposed to host and enclose the DGR. The analysis provides insight into two key aspects of the Ordovician sedimentary environment, including 1) its explorability, or certainty with which key geosphere properties affecting the long-term safety of a site can be characterized, and 2) its predictability, in terms of the near-horizontally layered, undeformed nature of the sedimentary shale and limestone formations of large lateral extent which exist beneath the Bruce nuclear site.

Sub-surface investigations at the Bruce nuclear site included a deep drilling and coring program and the completion of a 19.7 km 2-D seismic reflection survey. As part of this program 6 deep boreholes (4-vertical; 2 inclined) were extended through the sedimentary sequence (34 formations) at positions surrounding the 0.3 km^2 DGR footprint (Figure 4). The more than 3.8 km of rock core (77 mm diameter) retrieved has provided, in part, a strong basis to understand bedrock lithology, facies assemblages, structure, and oil and gas hydrocarbon occurrences within the sedimentary sequence underlying the Bruce nuclear site. This information, coupled with in-situ geophysical and hydraulic borehole testing, characterization of groundwater and matrix pore fluids and laboratory based petrophysical analyses, provide a unique opportunity to describe the sub-surface geologic conditions relevant to DGR implementation and safety. Regionally based information on micro-seismicity, neotectonics, hydrothermal dolomitized reservoir diagenesis, structure and geometry, Michigan Basin thermochronology and depositional history, and an understanding of the Upper Ordovician shale cap rock barrier integrity provide additional support for the assessment. An important conclusion that has emerged is that lateral stratigraphic consistency and traceability increases confidence in the prediction of site properties and estimates of long-term performance of the far-field to contain and isolate the L&ILW.



Notes: Figure is modified from [2].

Figure 1. Geological features of southern Ontario.

2. GEOLOGICAL SETTING

The Bruce nuclear site is situated within the tectonically stable interior of North America on the northeastern margin of the Paleozoic Michigan Basin in southern Ontario (Figure 1). The site is located on the northwest flank of the Algonquin Arch, a subsurface topographic high separating the Michigan Basin from the Appalachian Basin to the southeast (Figure 1). The site is underlain by approximately 850 m of sedimentary rocks ranging from Upper Cambrian to Middle Devonian in age (Figures 2 and 3). This Paleozoic succession thickens southwestward reaching a maximum of 4,800 m at the centre of the Michigan Basin where rocks of Jurassic age are preserved. Across the Regional Study Area (RSA; Figure 2), the strata dip uniformly and very gently (0.23 to 1°) to the west or southwest toward the basin centre [3].

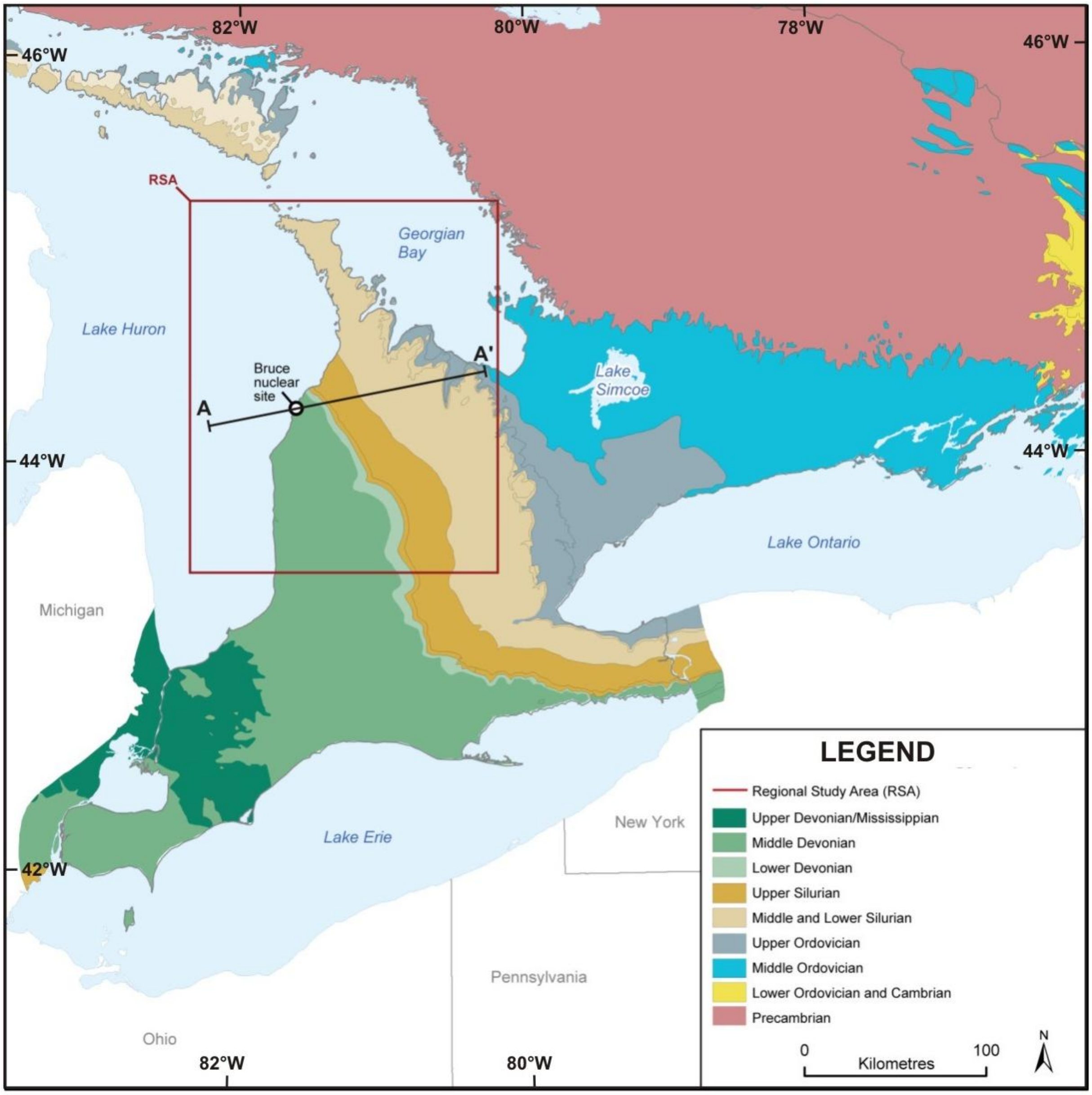


Figure 2. Paleozoic bedrock geology map of southern Ontario.

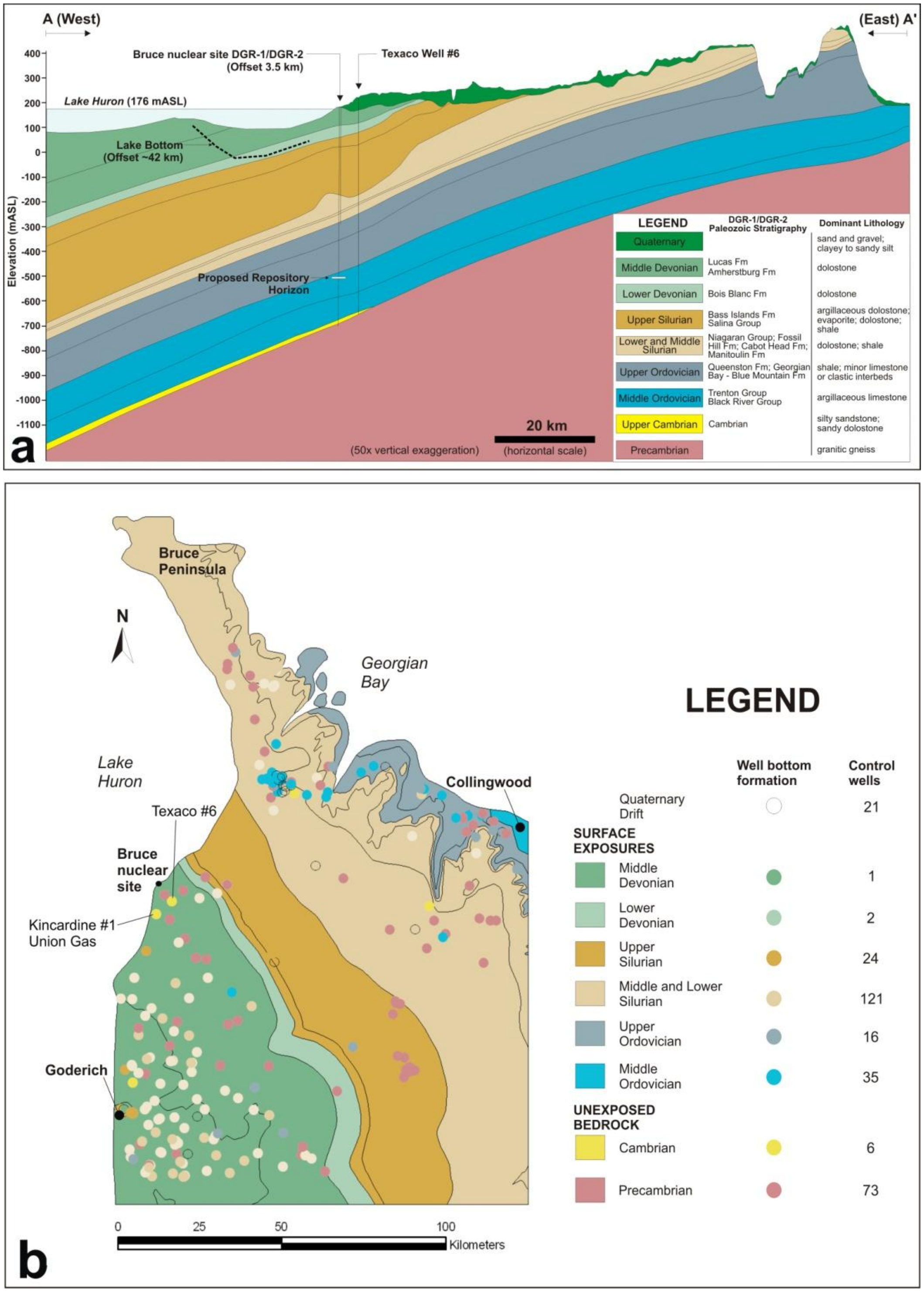
The Paleozoic sediments of southern Ontario rest unconformably upon Precambrian basement (Figure 1), which comprises gneisses and other metamorphic rocks of the ca. 1.0 Ga Grenville Province, and whose ancient tectonic subdivisions can be traced beneath the Paleozoic sedimentary cover across southern Ontario [4]. Older Precambrian rocks occur to the north and west of the Grenville Province and are projected, based on seismic reflection studies, to extend beneath it to the base of the continental crust [5],[6]. Within the RSA, the basement has remained relatively stable since at least the end of the Paleozoic [7],[8],[9]. This interpretation is consistent with the recognition that the Bruce nuclear site is situated within an area of low, diffuse seismicity with no identified active faults [10] or evidence of neotectonic activity [11].

The Ordovician succession was deposited between ca. 460 and 443 Ma ago on a southeast-facing continental margin that transitioned from a broad shelf and passive margin into a subsiding platform during the late Ordovician in response to the evolving Taconic phase of the Appalachian Orogeny. Peak burial conditions occurred during the late Permian, at which time the proposed repository horizon within the Cobourg Formation is estimated to have reached a maximum temperature of ca. 70°C at a burial depth of ca. 1675 m. Erosion subsequently removed approximately 1000 m of sediment from the site, the majority of which occurred prior to deposition of the Jurassic sediments in the centre of the basin [12],[13].

A three-dimensional geological framework (3DGF) model was constructed for the RSA surrounding the Bruce nuclear site [14]. The purpose of the 3DGF model was to better define the stratigraphic and spatial continuity of the Paleozoic succession across this region of southern Ontario. The model is based on observation and re-interpretation of Ontario Ministry of Natural Resources well records. The primary data source for the model construction was the Oil, Gas, and Salt Resources Library (OGSR) Petroleum Wells Subsurface Database [15],[16]. At the time of model development, the regional study area contained a total of 341 wells, from which 299 were determined useful through a data validation process [14]. The 3DGF model accurately reproduced regional stratigraphic relationships using these documented formation contact elevations and thicknesses. The final 3DGF model geometry is consistent with the regional geological framework based on published literature, maps and cross-sections of the region [17],[18].

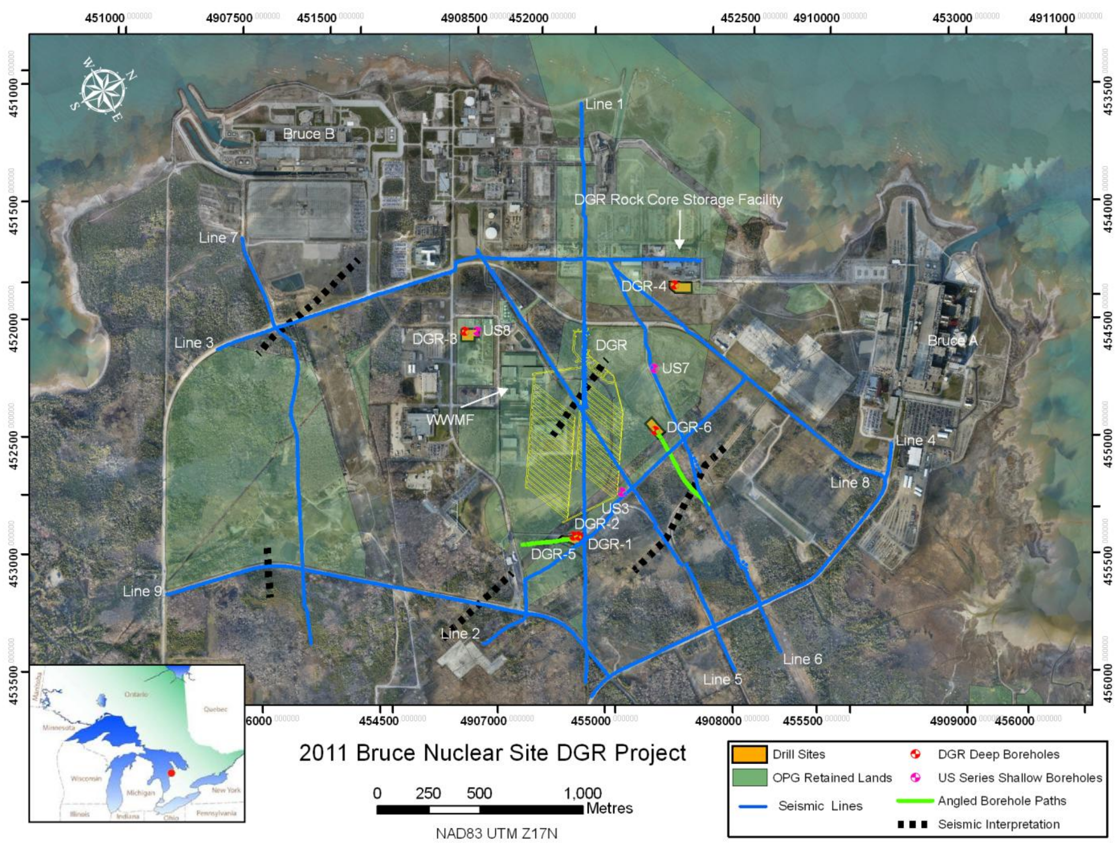
3. BRUCE NUCLEAR SITE GEOLOGY

The GSCP was implemented in three phases (1, 2A, 2B) with a primary focus on subsurface characterization of the geosphere beneath the Bruce nuclear site through borehole drilling, core logging, in-situ and laboratory testing and completion of a 2-D seismic reflection survey [1]. Phases 1 and 2A included the drilling, logging and testing of four deep vertical boreholes, DGR-1 , -2, -3, and -4 (Figures 4 and 5), completed to depths of 462.9, 862.3, 869.2 and 857.0 metres below ground surface (mBGS), respectively. Additional shallow to intermediate depth site characterization work during Phase 1 included the drilling and instrumentation of shallow bedrock borehole US-8 to a depth of 200.4 mBGS and the testing and instrumentation of existing shallow boreholes US-3 and US-7 (Figures 4 and 5) to depths of 74.3 and 90.6 mBGS, respectively. During the third phase (Phase 2B) two deep boreholes, DGR-5 and DGR-6 (Figures 4 and 5), inclined at 60° to 65° from the horizontal, were completed to verify seismic survey interpretations and to investigate for possible vertical/sub-vertical fault structures [1].



Notes: Location of section line A-A’ is shown in Figure 2. In (a), DGR-1/2 and eroded lake bottom feature are both offset to the north of the section line by the distances indicated. In (b), borehole control points are colour-coded to indicate the lowermost stratigraphic unit encountered in each well. Boreholes Kincardine #1 – Union Gas and Texaco #6, proximal to the site, are discussed in the text. Modified from Figure 1.2 of the 3DGF modelling report [14].

Figure 3. Geologic cross-section A-A’ through the Regional Study Area and historic Ontario Ministry of Natural Resources oil and gas well records.



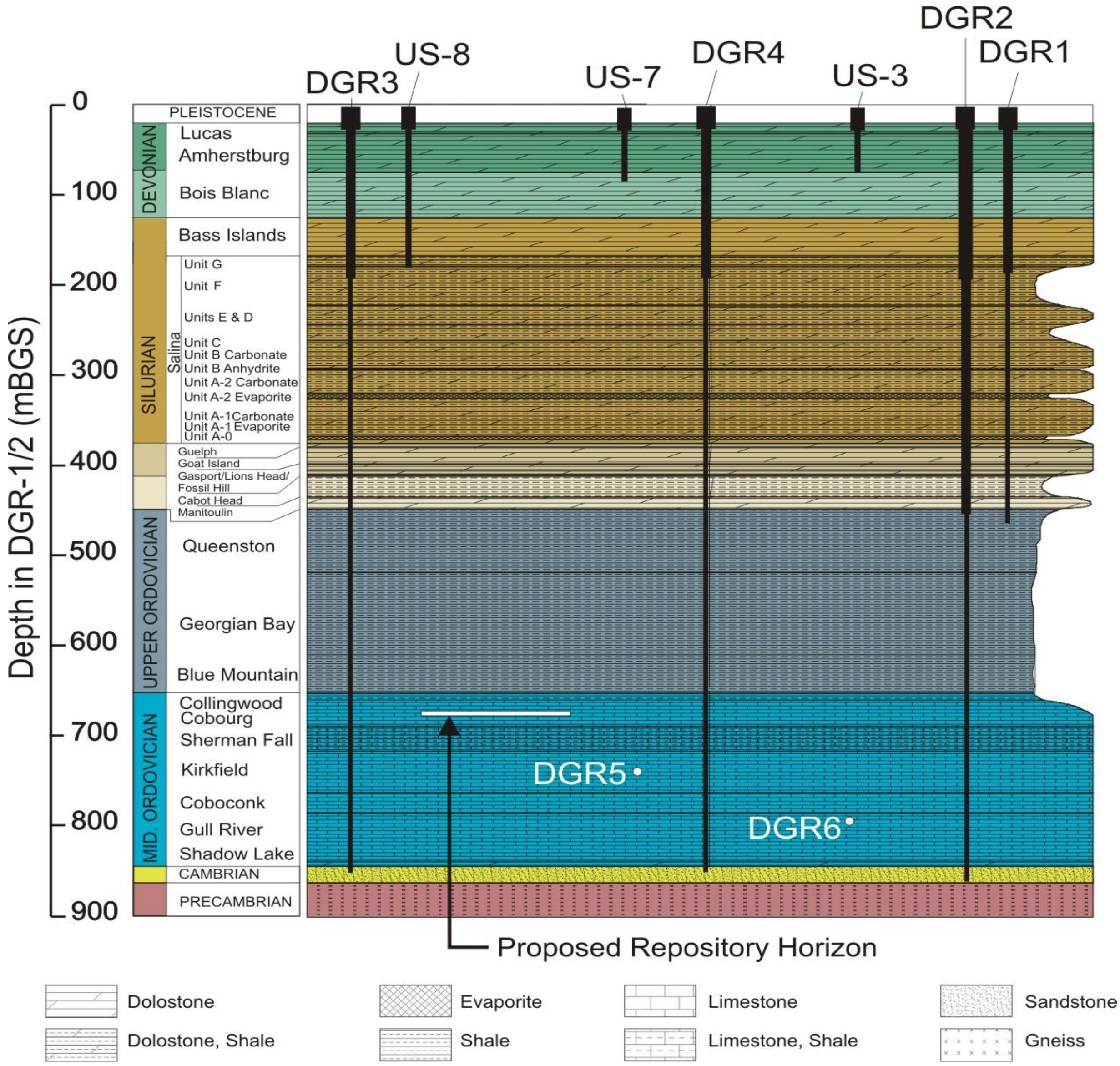
Notes: Figure indicates the position of the proposed DGR footprint, all DGR- and US-series boreholes, the Western Waste Management Facility (WWMF), and the location of the 9 seismic survey lines (19.7 km) (blue lines).

Figure 4. Overview of the Bruce nuclear site.

The deep drilling results confirm that the 34 distinct Paleozoic bedrock formations, members, or units recognized throughout the RSA are also traceable in the subsurface beneath the Bruce nuclear site ([12],[14],[17],[18]). The reference Paleozoic sequence (Figure 5), based on core logging of the DGR-1 and DGR-2 boreholes, comprises 104.0 m of Devonian dolostone, 323.7 m of Silurian dolostone, argillaceous dolostone, shale and evaporite, 211.8 m of Upper Ordovician shale, 179.1 m of Middle Ordovician argillaceous limestone, 5.2 m of Ordovician siltstone and sandstone, and 16.9 m of Cambrian sandstone [1]. The Paleozoic formations beneath the site are overlain by up to 21 m of Pleistocene overburden comprising sand and gravel beach deposits and clayey silt to sandy silt glacial deposits [19].

Understanding the geological framework of the almost 400 m thick Ordovician succession which would host and enclose the proposed DGR is of primary importance in understanding long-term repository safety. To this end, the following sections provide an analysis of the explorability and predictability of the Ordovician sedimentary rocks beneath the Bruce nuclear site in terms of:

- lithological consistency;
- uniformity of formation thickness and attitude; and
- lithofacies and marker bed traceability.



Notes: Vertical borehole penetration depths are indicated by vertical black lines. White dots indicate approximate depth of penetration for angled boreholes DGR-5 and DGR-6. Figure was developed based on information from [1].

Figure 5. Schematic of bedrock stratigraphy beneath the Bruce nuclear site.

3.1 Lithologic Descriptions: Ordovician Sediments

The Ordovician rocks encountered are sparsely fractured and generally of very low permeability and porosity. Visual core logging and natural gamma[1] profiles clearly distinguish the characteristic bimodal lithological distribution comprising a shale dominant Upper Ordovician

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[1] Gamma ray measurements distinguish major lithological differences by detecting the variation in natural radioactivity based on changes in concentration of potassium, thorium, and uranium. Potassium, which is found in sheet silicate minerals, is the most common source of natural gamma radiation in sedimentary rocks. The gamma profile is measured in counts per second (CPS) with higher values indicating higher sheet silicate content.

component and a carbonate dominant Middle Ordovician[2] component (Figures 6 and 7a). The marked similarity between the natural gamma profile of the Ordovician succession from the Texaco #6 borehole (drilled in 1969) and those from the DGR boreholes (see locations on Figure 3), provides an indication of the degree of lateral stratigraphic homogeneity that exists beyond the borehole perimeter.

The Upper Ordovician interval includes the Queenston, Georgian Bay, and Blue Mountain formations. The Queenston Formation is a massively-bedded, red-maroon to locally grey-green calcareous shale with minor limestone interbeds near its base (Figure 6a). The middle of the unit includes an interval of green shale with medium- to coarse-grained, grey fossiliferous, limestone interbeds. The underlying Georgian Bay Formation is dark grey-green shale with grey, fine- to medium-grained, limestone, siltstone, and/or sandstone interbeds whose frequency decreases with depth (Figure 6b). The Blue Mountain Formation is predominantly dark greenish-grey shale with grey siliceous siltstone and sandstone, and fossiliferous limestone, and transitions into dark grey calcareous shale at its base concomitant with an increase in total organic content (TOC, Figure 7d). The Blue Mountain and Georgian Bay formations have a petroliferous odour, especially at the base of the Upper Ordovician sequence, however no oil seeps were observed (Figure 7c). The varying concentration of sheet silicate minerals in samples taken from throughout the Upper Ordovician interval indicates the local abundance of limestone and siltstone hard beds within the upper two-thirds of the Georgian Bay Formation and a portion of the Queenston Formation (Figures 6b and 7a). Halite was found in abundance throughout the Upper Ordovician interval as infill material within hairline to mm-scale fractures (Figure 7e). The total dissolved solids (TDS) profile indicates a highly saline groundwater regime which is disconnected from the shallow groundwater system (Figure 7f). The long-lived barrier integrity of the Upper Ordovician shale cap rock is evidenced by the observation that the deep Ordovician carbonates have not been affected by modern karstification processes [25].

The Middle Ordovician interval includes sparsely fractured low permeability and low porosity argillaceous limestones of the Trenton and underlying Black River Groups (Figure 7). Sheet silicate content is generally low throughout the Middle Ordovician carbonate rocks (Figure 7b). From top to base, the Trenton Group includes the Collingwood Member and the Cobourg[3], Sherman Fall, and Kirkfield formations. The Collingwood Member is interbedded with dark-grey to black calcareous shale and argillaceous limestone. It has a petroliferous odour throughout, shows minor oil hydrocarbon seeps, and yielded the highest TOC of approximately 2.5 wt% in a < 5 m thick zone at its top (Figures 7c and 7d). The underlying Cobourg

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[2] A recently published update of the Paleozoic stratigraphy of southern Ontario [18] includes minor modifications to the relative age nomenclature. The Black River and Trenton groups now comprise the oldest sedimentary rocks of the Upper Ordovician. Acknowledging these recent re-interpretations, this paper follows [17], ascribing these groups to the Middle Ordovician.

[3] In the regional nomenclature the Cobourg Formation is subdivided into an upper Collingwood Member and an underlying Lower Member (Armstrong and Carter 2006, 2010). Herein the Cobourg Formation refers to the Lower Member only and the overlying Collingwood Member is discussed separately.

Formation is a light to dark brownish grey, very fine-grained to crystalline, mottled, fossiliferous and argillaceous limestone (Figure 6c). It also emits a petroliferous odour (Figure 7c). The Sherman Fall Formation is a grey-brown, coarse-grained, argillaceous limestone interbedded with calcareous shale near its base. The Kirkfield Formation is a tan to dark grey, fine-grained, irregular-bedded, fossiliferous and argillaceous limestone with dark grey-green shale interbeds. It emits a petroliferous odour and has minor oil hydrocarbon seeps only near its base (Figure 7c). Halite was recognized locally as a pore-filling material within the Cobourg and Sherman Fall formations (Figure 7d). Although a slight decreasing trend in TDS is observed below the Upper Ordovician shales (Figure 7f), the environment is highly saline (TDS >200 g/L).

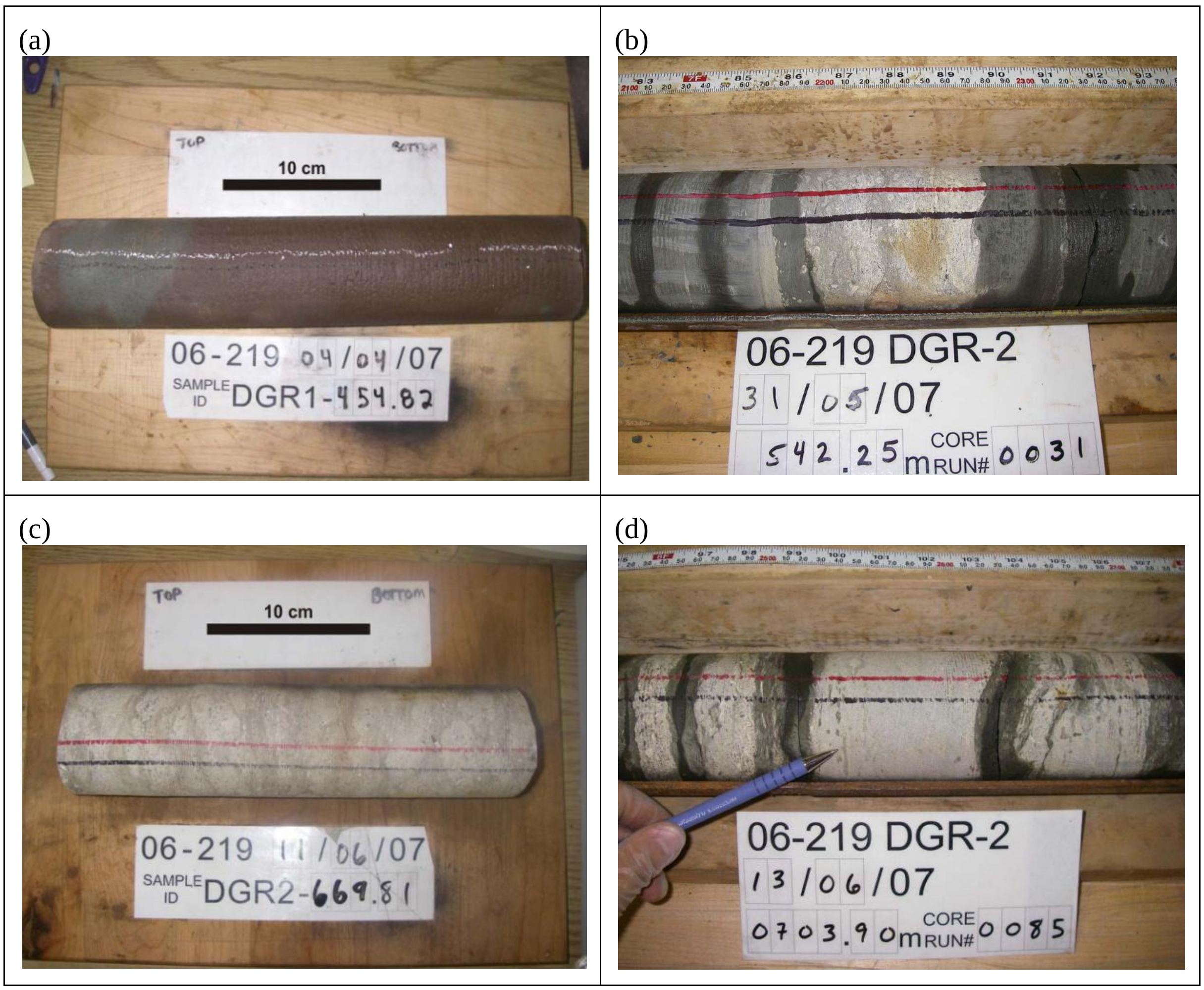
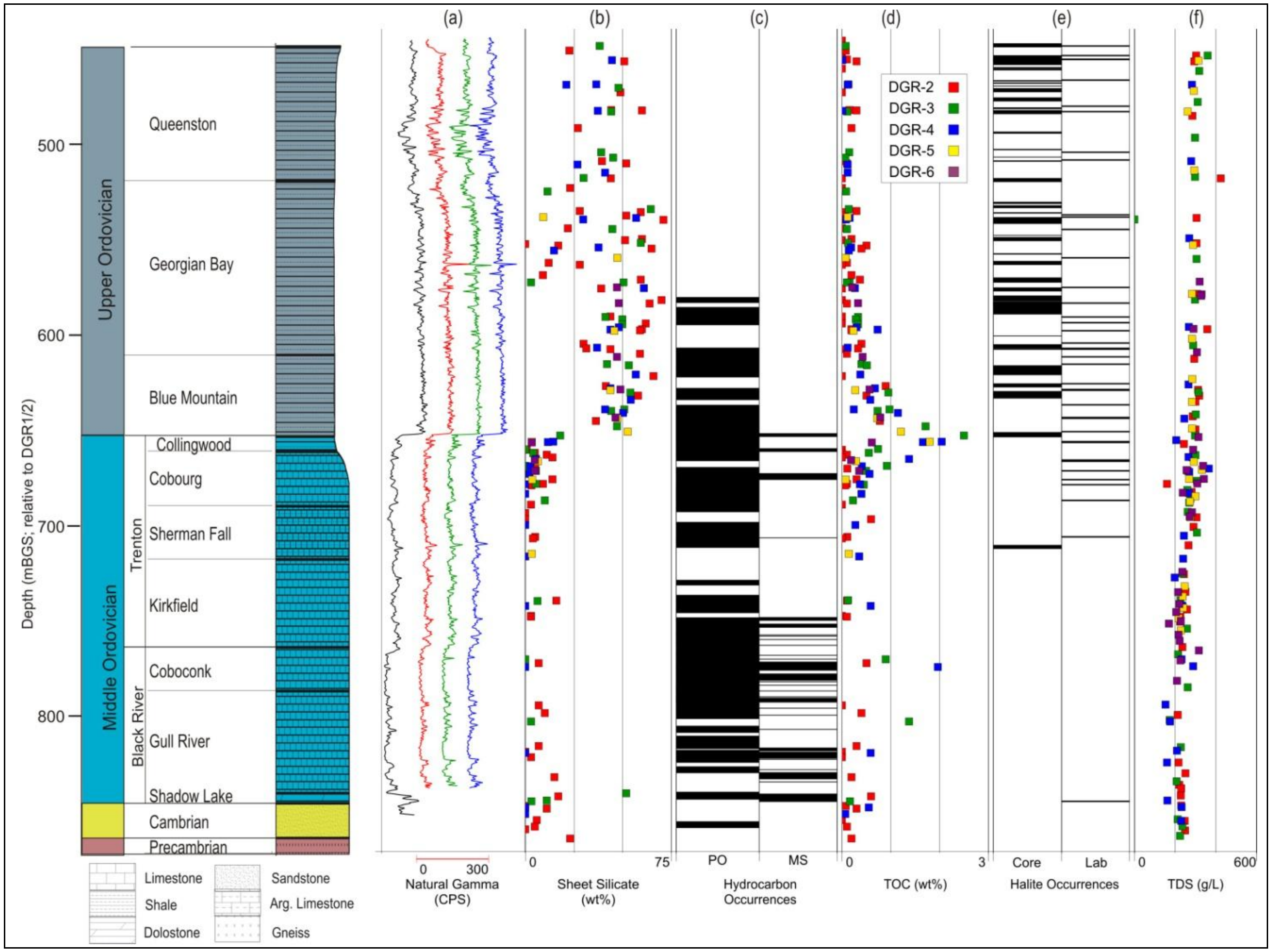


Figure 6. Core samples from the DGR boreholes. (a) Green and red calcareous shale from the Upper Ordovician Queenston Formation, 454.82 mBGS, DGR-1, (b) Interbedded shale and limestone from the Georgian Bay Formation, 542.25 mBGS, DGR-2. (c) Argillaceous limestone from the proposed repository depth, Cobourg Formation, 669.81 mBGS, DGR-2, and (d) Argillaceous limestone and shale interbeds from the Sherman Fall Formation, 703.90 mBGS, DGR-2. Source is [1].



Notes: Key correlative physical parameters of the Ordovician stratigraphic succession. (a) Natural gamma profiles for (from left to right) the Texaco #6 and DGR-2, -3 and -4 boreholes, datum is top of Collingwood Member (see Figures 3b and 4 for borehole locations). Scale in counts per second (CPS) is only shown for DGR-2. (b) Sheet silicate content in weight percent (wt%). (c) Composite of petroliferous odour (PO) and minor seeping oil (MS) hydrocarbon occurrences for all DGR boreholes based on core logging. (d) Total organic content (TOC) in weight percent (wt%) based on laboratory analysis. (e) Composite of halite occurrences based on core logging (left) and laboratory analysis (right). (f) Porewater total dissolved solids (TDS) profile in grams per litre (g/L). See text for further discussion. Source of data set is [1] and references therein. Vertical depth in metres below ground surface (mBGS). Borehole datasets are colour-coded according to inset legend.

Figure 7. Ordovician composite lithological correlation plot.

The Black River Group includes the Coboconk, Gull River, and Shadow Lake formations. In comparison to the overlying Trenton Group, the Black River Group has a lower argillaceous content overall (Figure 7a) and has a prevalent petroliferous odour with minor oil hydrocarbon seeps throughout (Figure 7c). The Coboconk Formation is a light- to medium-grey, very fine-grained, bioturbated limestone with minor dark grey-green shale interbeds and a characteristic mottled texture. An approximately 10 cm thick bentonite bed observed near the upper contact of the Coboconk Formation is interpreted as a volcanic ash layer and is a prominent marker unit traceable across the DGR site [20]. A distinct 50 to 70 cm thick dolostone horizon with petroliferous odour and seeping oil hydrocarbon is observed below the mid-point of the Coboconk Formation. The Gull River Formation is a medium grey, fine- to very fine-grained, fossiliferous limestone with thin dark grey shale interbeds and a distinct m-scale dolostone horizon below its mid-point. The Shadow Lake Formation is a dolomitized silty limestone with sandy mudstone and coarser sandstone layering. The base of this unit marks an unconformity with the underlying Cambrian.

3.2 Thickness and attitude

The intersection of Ordovician stratigraphy by the deep DGR boreholes allows for an assessment of thickness and formation attitude (strike and dip) across the site. Formation top picks and thicknesses were determined through a combination of visual inspection, geophysical log analysis and correlation, and integration with interpretations emerging from three core workshops involving experts from the Ministry of Natural Resources, Ontario Geological Survey and the Geological Survey of Canada. The estimated thickness and orientation of the Ordovician sediments derived from these data reveal a remarkable consistency across the site, as shown in Table 1 [20]. Ordovician formation thicknesses vary by less than 5% and bedding dips by less than 0.1°, averaging 0.60° to the SW. These findings are in accordance with the geometry interpreted from the 2-D seismic analysis [3], to be discussed below in Section 4, for which the Ordovician strata beneath the site dip uniformly at 0.59° +/- 0.08° (~10 m/km) southwestward (see also Figure 10). When combined, this information strongly supports the occurrence of a near horizontally layered, relatively undeformed sedimentary sequence beneath the Bruce nuclear site, with little or no vertical displacement evident.

A comparison between the DGR boreholes and the off-site boreholes Kincardine #1 - Union Gas and Texaco #6 (Figures 3a and 3b) indicates very similar total Ordovician thicknesses of 393.5 and 393.1 metres, respectively. The correlation between units beneath the Bruce nuclear site and the Texaco #6 borehole, which is located 3.5 km to the southeast, is illustrated in Figure 2. This regional-scale traceability is a function of the large lateral extent of the Ordovician paleoenvironment within which these sediments were deposited, and provides further evidence regarding the paucity of major faults on which vertical displacement may have occurred beyond the Bruce nuclear site periphery.

Table 1. Summary of strike, true dip, and thicknesses of Ordovician formations and members encountered in the DGR boreholes.

Ordovician Formation/Member	Strike	Dip	Thickness (m)				
			DGR-2	DGR-3	DGR-4	DGR-5	DGR-6
Queenston	N24ºW	0.41ºSW	70.3	74.4	73.0	70.3	69.3
Georgian Bay	N17ºW	0.61ºSW	90.9	88.7	88.7	88.6	88.2
Blue Mountain	N23ºW	0.51ºSW	42.7	44.1	45.1	45.1	45.0
Collingwood Member	N14ºW	0.56ºSW	7.9	8.7	8.4	8.6	6.5
Cobourg	N14ºW	0.60ºSW	28.6	27.8	27.5	27.1	28.5
Sherman Fall	N17ºW	0.57ºSW	28.0	28.9	28.3	29.3	28.8
Kirkfield	N18ºW	0.63ºSW	45.9	45.8	45.7	-	46.8
Coboconk	N19ºW	0.63ºSW	23.0	23.7	23.8	-	22.4
Gull River	N16ºW	0.66ºSW	53.6	51.7	52.2	-	-
Shadow Lake	N19ºW	0.56ºSW	5.2	4.5	5.1	-	-
Total Ordovician Thickness			396.1	398.3	397.8	-	-

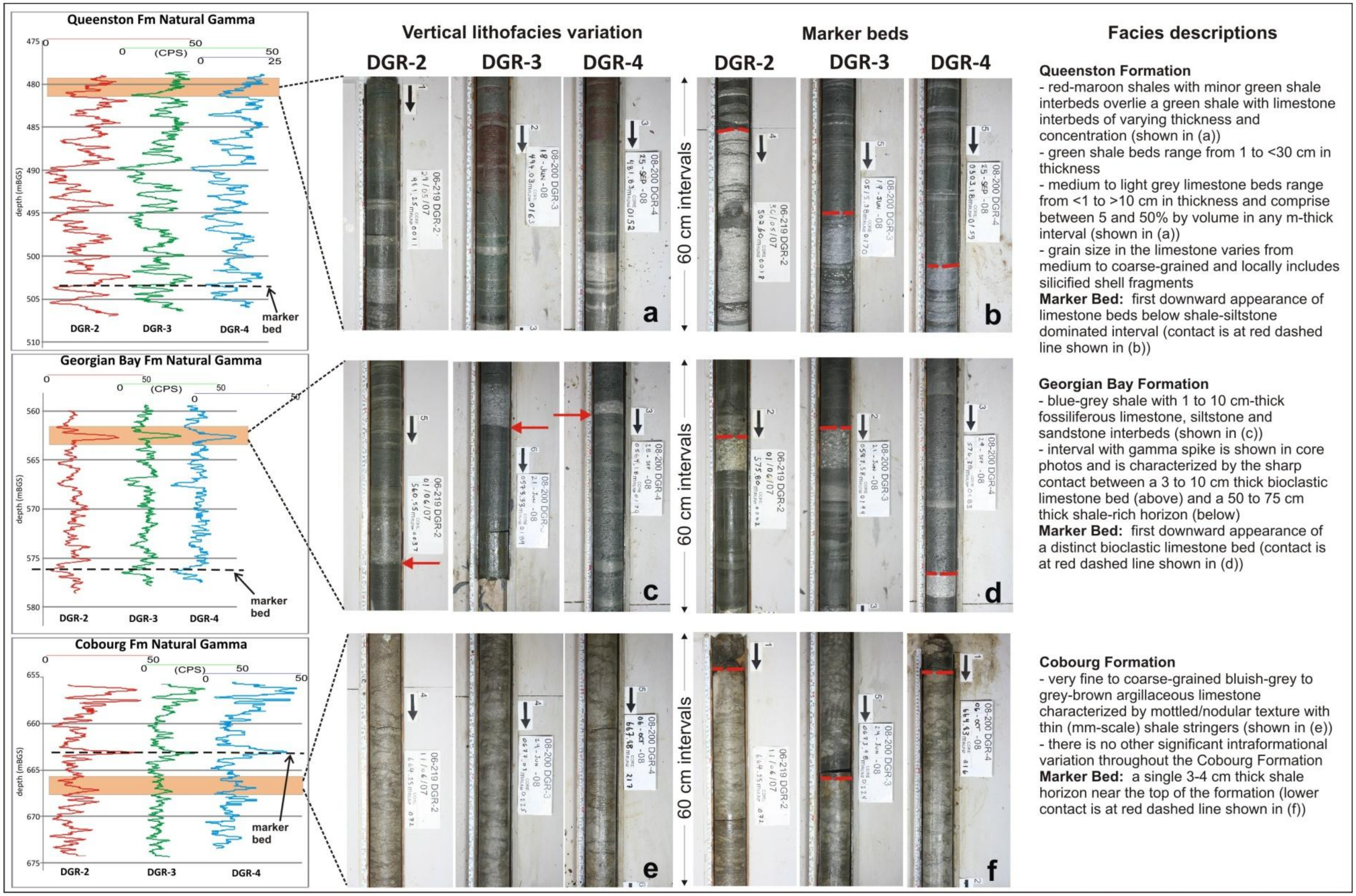
Notes: Strike and dip measurements are based on information from boreholes DGR-2 to DGR-4 only.

3.3 Lithofacies and marker bed analyses

In order to fully assess the degree of predictability of the Ordovician sedimentary succession at the site scale, an evaluation of the lateral (horizontal) homogeneity and vertical variation of lithofacies was conducted using core recovered from within key Ordovician intervals (Figure 8). Lithofacies variation is caused by the changing dynamics of the depositional environment, and can potentially alter the hydrogeological and mechanical properties of the rock mass. However, if sufficient homogeneity exists, then important geophysical, geomechanical, and hydrogeological properties can be associated with specific lithologies. A positive correlation of lithofacies and their variations between the boreholes would, therefore, provide the basis for transferability of the lithofacies-associated properties across the DGR footprint. The specific targets for this analysis were portions of the Queenston, Georgian Bay and Cobourg formations.

3.3.1 Lithofacies comparison of natural gamma ray profiles

The natural gamma ray profiles, including the Ordovician section, from each of DGR-1/2, -3, and -4 are plotted in Figure 7a. Apparent in all three gamma ray profiles is a bimodal distribution of CPS values separating the high count and shale-rich Upper Ordovician from the low count and carbonate-rich Middle Ordovician. Another interesting quality of all three profiles is that the Middle Ordovician carbonate-rich section can be further separated into a relatively sheet silicate-poor Black River Group (Shadow Lake, Gull River and Coboconk formations) overlain by a relatively sheet silicate-rich Trenton Group (Kirkfield, Sherman Fall, and Cobourg formations).



Notes: Intervals chosen for analysis are highlighted in orange in left column of figure. Accompanying photographs of representative facies variations and marker beds are shown in 60 cm intervals. Each of (a) to (f) includes the same approximate stratigraphic interval from DGR-2, DGR-3, and DGR-4 for comparison. Photographs are not stratigraphically aligned.

Figure 8. Intervals chosen for facies analysis from boreholes DGR-2, DGR-3, and DGR-4.

These variations are consistent with an increase in clastic input derived from the east during the evolving Taconic Orogeny and a similar pattern in all three profiles highlights the degree of lateral continuity that is observed. These broad lithological variations are also recognized regionally [17]. The Texaco #6 borehole exhibits a remarkably similar gamma profile (Figures 3 and 7a), indicating the broad lateral traceability of these group-scale lithofacies beyond the site.

An interval from within each of the three Ordovician units was chosen for comparison across all three gamma profiles (Figure 8). The main consideration in deciding which interval (approximately 20 to 30 m) to select was to find a section of the DGR-2 gamma profile that showed variations reflecting lithologic changes, which could then be compared with the other two profiles (Figures 7a and 8). The interval length was selected to be roughly coincident with the hydraulic packer testing intervals used during the in situ hydrogeological investigations.

An example of a facies transition from each interval is shown in Figure 8 to highlight the scale at which the homogeneity occurs. The results indicate that the Ordovician stratigraphy at the Bruce nuclear site is laterally homogeneous and predictable at the decimetre to metre scale, suggesting that interpolation of the borehole correlations across the DGR footprint is valid. The following sections give detailed descriptions of the style and scale of facies variation within the three formations examined.

3.3.1.1 Queenston Formation

The interval chosen for analysis is from the lower middle interval of the Queenston Formation (Figure 8, top left). It is approximately 25 m thick and distinguished by abundant cm to dm scale green shale and siltstone beds interlayered with medium to coarse grained, < 1 to > 10 cm thick, limestone beds commonly containing silicified shell fragments (Figure 8a and b). This interval exhibits an erratic gamma profile with distinct metre scale segments that correspond to variations in thickness and concentration of the limestone beds. Comparison of the three profiles highlights the fact that the observed m-scale variations are traceable between boreholes. In core, the upper part of this facies transition corresponds to the appearance of millimetre to centimetre thick medium to coarse grained limestone beds over a 25 to 35 cm thick horizon within the green shale (Figure 8a). The core photos highlight the fact that facies change is evident in all boreholes at small scales (mm to cm typically) and individual limestone beds are not directly traceable. The consistency is in the decimetre to metre scale transitions from shale and siltstone to more carbonate-rich intervals.

3.3.1.2 Georgian Bay Formation

The upper third of the Georgian Bay Formation is characterized by interbedded shale with fossiliferous limestone. The lower two thirds are characterized predominantly by dark shale, a variation which is seen in the gamma ray profile (Figure 7a). The interval chosen for analysis spans the transition through the lower middle part of the formation (Figure 8, middle left). It is an approximately 20 m-thick interval within which dark grey/green/blue shale is interbedded with up to 10 cm thick light grey fossiliferous limestone, siltstone, and fine-grained sandstone beds (Figure 8c). Of particular interest is the presence of a marked CPS spike in the middle of the gamma profile at the same stratigraphic depth in the Georgian Bay Formation in all boreholes (Figures 7a and 8). Visual core inspection confirmed that this spike is lithologically controlled and defined by the sharp transition from a distinct 3 to 15 cm thick fossiliferous limestone bed into underlying dark shale (Figure 8c, red arrows).

Several other m-scale CPS trends can be confidently traced between all three profiles even though individual spikes are sometimes at too fine a scale to match individually between boreholes. The cm-scale thickness variations reflect the small-scale lithological differences due to locally varying conditions of deposition. However, this sharp lithofacies transition is observed in all boreholes. Therefore this suggests, as with the Queenston above, that the Georgian Bay Formation lithofacies transitions are laterally traceable, exhibiting consistent vertical variations at the dm- to m-scale.

3.3.1.3 Cobourg Formation

The Cobourg Formation is a very fine- to coarse-grained bluish-grey to grey-brown argillaceous limestone unit, locally including thin cm-scale shaley interbeds. Much of the Cobourg Formation at the Bruce nuclear site, including at the proposed repository depth, is characterized by a nodular fabric and bioturbated bedding surfaces with minor intraformational variation (Figure 8e). This minimal amount of facies variation is evident in the consistently low gamma response on the three profiles (Figures 7a and 8). The most distinct marker bed identified in this study in the Cobourg Formation is a single 3 to 4 cm thick shale marker bed in the upper section of the formation (discussed further in the next section; Figure 8f). The lithological and geophysical similarity of the majority of the Cobourg section suggests that this formation is laterally homogeneous and is predictable at the dm- to m-scale across the DGR footprint. Vertically there is a downward increase in gamma response in all boreholes consistent with increasing argillaceous material towards the base of the formation (Figure 8, bottom left).

3.3.2 Marker Beds

Each of the three stratigraphic intervals described above also includes at least one distinct marker bed (Table 2). These marker beds were identified during the detailed core logging and have been used to aid in stratigraphic correlation between the boreholes (Figure 8 herein; [21]), and to confirm the geometry of the succession. They also provide further evidence for the high degree of lateral continuity and traceability beneath the site (see also Section 3.9 in the DGSM [1] for further discussion).

The markers are all < 20 cm thick beds and are lithologically distinct horizons that are laterally continuous and common to all boreholes. The marker for the Queenston Formation is the top of a distinct medium to coarse grained bioclastic limestone horizon (Figure 8b). This marker represents a distinct conformable facies transition recognizable as a low CPS spike on all three gamma profiles (Figure 8, top left). The marker for the Georgian Bay Formation is a single 6 to 10 cm thick coarse grained bioclastic limestone bed within grey shale with minor siltstone interbedded facies (Figure 8d). This marker also represents a distinct conformable facies transition recognizable as a low CPS spike on all three gamma profiles (Figure 8, middle left).

Table 2. Dips calculated from marker beds.

Marker Bed Fm.	Marker	True dip of marker (°)	True dip of formation (°)	Dip Direction (azimuth°)
Queenston	Limestone bed in shale	0.61	0.41	246
Georgian Bay	Fossiliferous limestone bed in shale	0.59	0.61	253
Cobourg	Shale bed in limestone	0.52	0.60	256
Coboconk A	Volcanic ash layer	0.55	0.63	251
Coboconk B	Tan dolostone bed in limestone	0.54	0.63	248

Notes: Marker bed attitudes were determined from boreholes DGR-2, -3 and -4. Includes data from Tables 3.2 and 3.12 of [1].

The marker for the Cobourg Formation is a single 3 to 4 cm thick shale horizon that contrasts sharply with the nodular and bioturbated limestone fabrics that characterize the formation (Figure 8f). The shale bed is characterized by a thin high CPS spike which is observed in all three profiles (Figure 8, lower left). That these isolated marker beds can be readily traced across the site strongly suggests that major lateral changes in depositional environment occurred at a scale larger than that of the Bruce nuclear site and reinforces the notion of site-scale predictability based on the borehole data presented in the Descriptive Geosphere Site Model (DGSM; [1]). As mentioned above, a distinct dolostone marker bed and a volcanic ash layer were also identified from within the Coboconk Formation, well below the proposed repository level [21].

3.4 Lithofacies control of material properties

An important outcome of the site characterization activities is the recognition that lithological variations mapped within the Ordovician sequence represent a primary control on the key material transport properties. The key properties of the Ordovician shale (hardbeds excluded) and repository-horizon Cobourg Formation argillaceous limestone are listed in Table 3 below. These rocks exhibit extremely low hydraulic conductivities and D_e values (Figure 9) characteristic of diffusion-dominated hydrogeological systems suitable for the long-term containment and isolation of waste. The arguments for predictability and explorability discussed above make the relationship between lithofacies and material properties very significant.

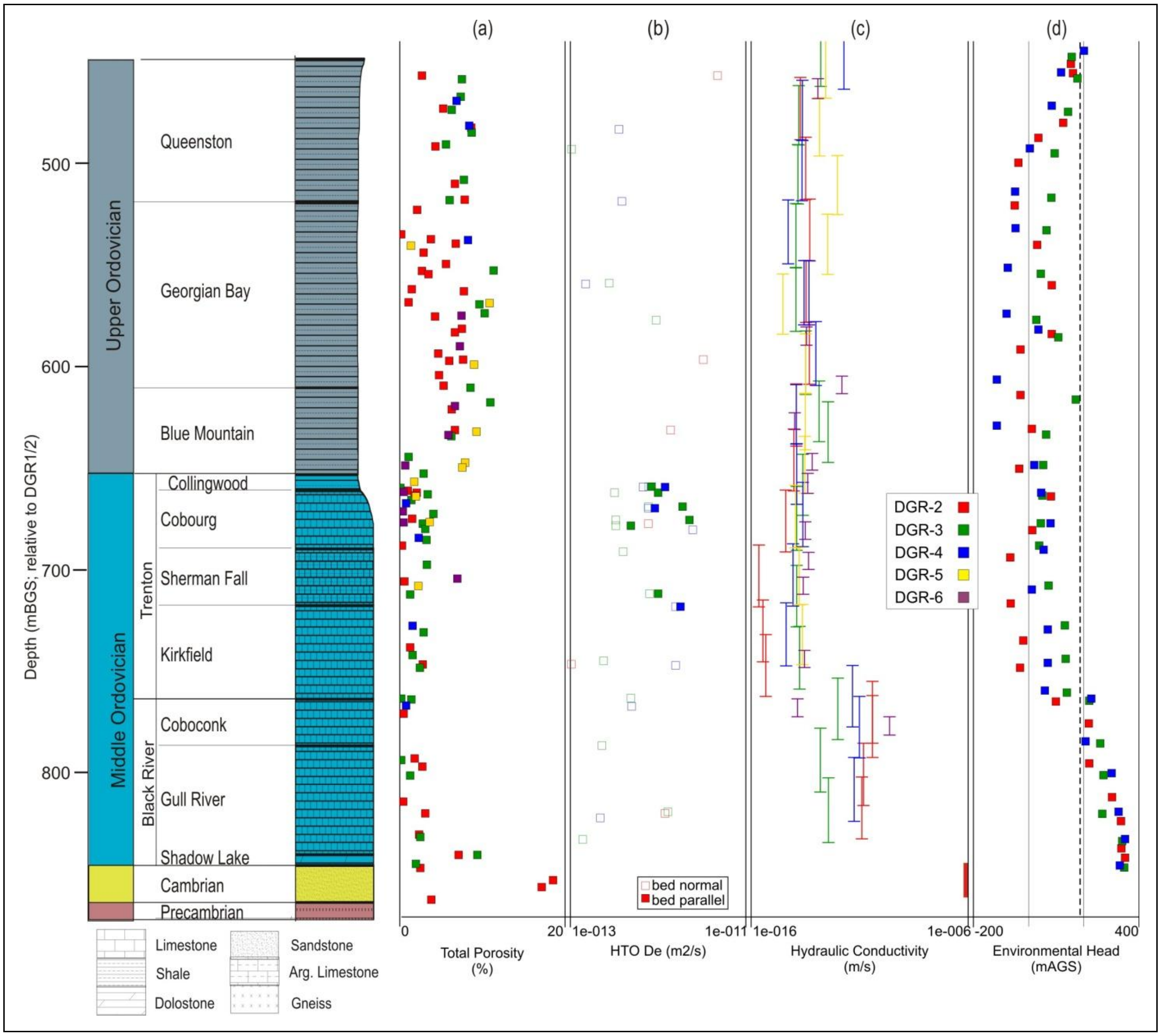
As an example, Figure 9 includes plots of total porosity (%) and tritiated water (HTO) diffusion coefficient (D_e; m^2/s) distributions with depth through the Upper Ordovician shales and into the underlying carbonates. The distribution of porosity within the Upper Ordovician shales is bimodal (Figure 9a), with a well-defined mean of 7.4% through the entire Blue Mountain Formation and upper part of the Queenston Formation, and a broader range in porosity (2.5 to

7.4 %) through the upper Georgian Bay Formation. The similarity between the distribution of this dataset and that of the gamma ray profiles (Figure 7a) and weight percent of sheet silicate components (Figure 7b) indicates that the porosity distribution can be directly linked to this lithological parameter. Detailed core logging and the facies analysis has determined that the zone of broadly ranging porosity is due to the interlayering of siltstone and argillaceous limestone hard beds within the shales. In comparison the Ordovician carbonates have an average total porosity of 1.9% (Figure 9a), consistent with a uniformly low sheet silicate content (Figure 7b). The data trend for D_e (HTO) in Figure 9b shows a similar distribution even though the number of data points is much smaller.

Table 3. Key properties of the Upper Ordovician shales and repository-horizon limestone at Bruce nuclear site.

Property/parameter	Ordovician Shale	Cobourg Fm. Argillaceous Limestone
Age (Ma)	> 443	< 454
Maximum temperature reached during diagenesis (^{o}C)	ca. 65-70	ca. 70
Present burial depth (centre of unit (m))	550	675
Maximum burial depth (centre (m))	ca. 1550	ca. 1675
Thickness (m)	211.9	28.6
Clay minerals (weight %)	40-50	< 10
Clay minerals (in order of decreasing abundance)	Illite & mica, chlorite, illite/smectite	Illite & mica, chlorite, illite/smectite
Total organic carbon (weight %)	0.01-2.5	0.225-1.387
Pore-water type	Na-Cl	Na-Cl
Mineralization/Total dissolved solids (TDS) (g/L)	300	286
Total porosity (%)	7.2	1.9
Eff. diffusion coeff. D_e (HTO) normal to bedding (m^2/s), anisotropy factor	9.3E-14 to 4.8E-12, 1.2 to 4.9	3.2E-13 to 2.3E-12, 1 to 4.2
Hydraulic conductivity, K, parallel to bedding (m/s), anisotropy factor	2.0E-14 to 3.0E-14, 10	1.0E-14, 10
Uniaxial compressive strength, normal to bedding (MPa)	22-48	113

Notes: See Table 7.1 in [13] for data sources.



Notes: (a) Total porosity (%) and (b) Tritiated water (HTO) diffusion coefficient (De, m2/s) show direct correlation with sheet silicate distribution in Figure 7. Along with the uniformly low hydraulic conductivity (m/s) in (c) and anomalously pressured environmental head (metres above ground surface, mAGS), these key properties provide evidence of the natural barrier quality beneath the Bruce nuclear site. Dotted line in (d) represents ground surface elevation for reference. Source is [1].

Figure 9. Key material transport properties and hydrogeologic characteristics beneath the Bruce nuclear site.

3.5 2-D seismic survey results

A 2-D seismic survey, including nine survey lines totalling 19.7 km, as shown in Figure 4, was conducted at the Bruce nuclear site as part of the site characterization activities [3]. The purpose of this survey was to obtain deep bedrock geological, stratigraphic, and structural information for the Bruce nuclear site and to assess the predictability and continuity of the host rock for the DGR (Cobourg Formation) as well as to determine the "potential" location of possible faults and fault zones in the subsurface within the Paleozoic bedrock (e.g., Figure 10).

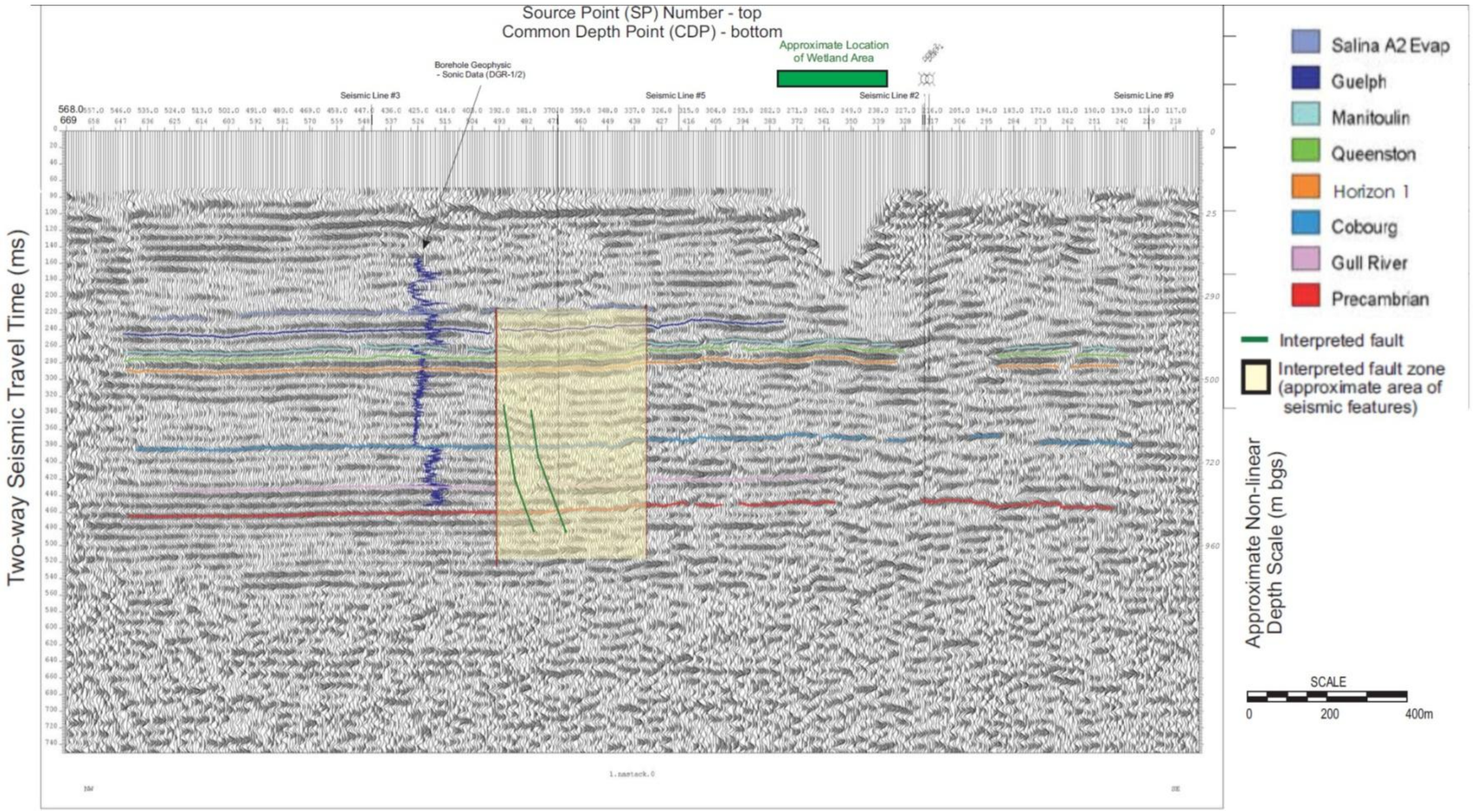
Important results of the seismic analysis include the points listed below.

- In general, the seismic survey imaged horizontal reflections interpreted to represent lateral traceability of the Ordovician stratigraphy across the DGR footprint [3]. The stratigraphy dips uniformly at 0.59° +/- 0.08° (~10 m/km) towards the southwest.
- The seismically interpreted faults within and proximal to the proposed DGR are not consistent with known geometry, size, and seismic profiles of fault-controlled hydrothermal dolomite (HTD) reservoirs [22]. HTD-related structures are localized along km-scale or greater transtensional (strike slip and extensional) fault zones, with characteristic structural depressions (negative flower structures) bounded by steeply-dipping basement-seated faults.
- An interpreted basement high of 10 m on Line 1 (Figure 10) and an equivalent fault offset in the overlying stratigraphy are not supported by the marked consistency in formation thicknesses, strike and dip across the proposed DGR footprint as discussed previously.

The regular and consistently very shallow dip magnitude of all layers through the Ordovician section, and their lateral traceability across the site and beyond (e.g., Texaco #6), significantly reduces the likelihood that basement-rooted normal faults with any significant (10 m-scale or greater) offset exist within or proximal to the DGR footprint. The only fault geometry which could possibly remain undetected is a strike-parallel transcurrent offset; however, no evidence exists either locally or regionally from surface or subsurface data to suggest that faults of this nature are present (e.g., [18], [24]).

Further, direct and indirect evidence supporting the lack of fault structure beneath the site include the following points.

- Petrological, petrophysical and physical hydrogeologic data set from the deep drilling program do not indicate the presence of properties typically attributed to hydrothermal dolomitized (HTD) reservoirs in the Trenton and Black River group carbonates. Such HTD reservoirs are associated with voluminous dolomitization and 'negative flower' fault geometry extending vertically upwards from Precambrian basement-seated faults, neither of which is encountered beneath the site.
- Sub-vertical structural features interpreted from the seismic reflection survey could not be verified by inclined drilling and coring of targeted Ordovician horizons in DGR-5 and DGR-6.
- The interpreted sub-vertical structure did not breach the Upper Ordovician shale cap rock suggesting that the natural barrier or sealing capacity has remained intact since prior to the Silurian Period. This is consistent with analogues studies of Ordovician age shale reservoir cap rock within the Michigan and Appalachian basins [22].
  A surface-based fracture mapping study determined that the majority (600/610) of observed structures within the Devonian-aged outcrop were joints (i.e., no relative offsets) whose genesis could be linked to Paleozoic events, and therefore ancient, basin-scale processes. No shear zones, or faults with greater than 15 cm offset, were identified [24].



Notes: Modified from Figure 16a of the 2D seismic survey report [3].

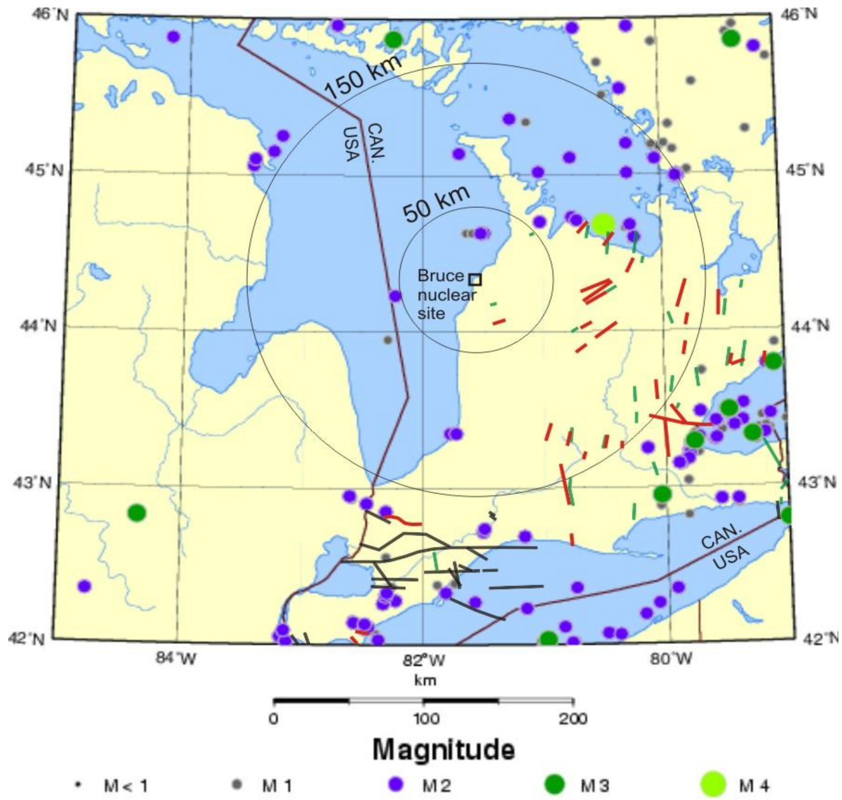
Figure 10. 2-D seismic line #1 with interpreted faults.

- A neotectonics assessment found no evidence of post-glacial seismic activity [11], and this conclusion is also corroborated by the results of the on-going micro-seismic monitoring program (discussed in Section 4 below) which finds no evidence for seismogenic features or active faults of concern at or near to the Bruce nuclear site [10].
- Indirect evidence for a lack of through-going fault structures includes the consistently very low and near uniform rock mass hydraulic conductivities (10^{-12} m/s), anomalous under- and over-pressures (1-3 MPa), and high hydraulic gradients (1-3) observed within the Ordovician sequence (Figures 9c and 9d) which would be unlikely to persist if transmissive high angle features transected these sediments.

4. SEISMICITY

The RSA is within the tectonically stable interior of the North American continent, consistent with the sparse seismic activity near the Bruce nuclear site. Figure 11 shows all known earthquakes in the region between 1985 and 2010 [23] including micro-seismicity from 4 local stations, overlain with the mapped basement-seated faults (black, red and green lines) in southern Ontario (Figure 11). The historical dataset suggests that, in general, the RSA experiences sparse seismic activity and there is no indication for the existence of major seismogenic features or active faults of concern. This conclusion is consistent with the regional seismic activity recorded by the micro-seismic network (e.g. [23]).

Mapped basement-seated faults are shown as coloured line segments in Figure 11. The faults are characterized and grouped by age according to the youngest sedimentary rocks which they offset [18]. The oldest identified faults only offset Cambrian strata and rocks of the immediately overlying Ordovician Shadow Lake Formation. Another group of faults offset rocks as young as the Ordovician Trenton Group limestones. The youngest faults in southern Ontario offset rocks of the Silurian Rochester (Lions Head equivalent) Formation. Within the RSA, where subsurface data are sparse, these features are inferred by subsurface structure contouring and isopach mapping with limited well-control, or through seismic interpretation. The closest fault structure to the Bruce nuclear site is > 20 km away and has experienced no appreciable post-Trenton Group movement. This interpretation is consistent with the results of the site-scale 2-D seismic survey which indicate that no faults have breached the Upper Ordovician shale rock beneath the Bruce nuclear site. It is also consistent with the observed present day tectonic stability of the RSA in general.



Notes: All seismic events plotted in local magnitude (M=Nuttli Magnitude). The circles around the Bruce nuclear site represent 50 km and 150 km radii. Earthquake event data was generated from the database at www.EarthquakesCanada.ca. Modified from Figure 2.14 of [1]. Mapped faults are based on compilation in [18]. Faults are colour-coded by the youngest age of sedimentary offset recognized (black = Silurian, red = Ordovician Trenton Group, green = base of Black River Group/Precambrian). See text for further discussion.

Figure 9. Seismicity in the Bruce region from 1985 to 2010, overlain with mapped faults in southern Ontario

5. SUMMARY AND CONCLUSION

The data presented above details the high degree of stratigraphic continuity and traceability within the Ordovician succession proposed to host and enclose the DGR. The results provide confidence in the interpretation that the Ordovician sedimentary environment encountered within the DGR borehole array beneath the Bruce nuclear site exhibits a high degree of predictability and explorability. The multiple lines of evidence used to support this interpretation include the following points.

- The consistency in formation thicknesses, dips and strikes, which vary by less than 5%, 0.5° and 5.0°, respectively, as derived from distinct formation contacts and chronostratigraphic layers observed in core throughout the stratigraphic section.
- The lateral continuity and low dip of key sub-horizontal bedrock horizons and contacts within the Ordovician sequence (e.g., Figure 10).

- Detailed visual core analysis and complementary borehole geophysical data, which determined a decimetre to metre scale threshold for tracing and lateral correlation of distinct lithofacies at predictable depths between the boreholes.
- The uniformity in terms of depths and thicknesses with regard to the discrete stratigraphic occurrence of marker beds, hydrocarbons, TOC and secondary halite (e.g., Figure 7).
- Lateral correlation of the Ordovician stratigraphic succession in terms of formation thickness and attitude with historical oil and gas wells located several kilometres from site, for example the Texaco #6 well.

Additional evidence for stratigraphic predictability at a regional scale is evident from the consistency between the 3DGF model geometry and independently published frameworks based on published literature, maps and type cross-sections of the region (17, 18).

The data presented above also provides an indication of the structural predictability of the Ordovician sedimentary environment in terms of the lack of faulting within or proximal to the DGR borehole array, the lack of development of a basement-seated fault system typical of a HTD reservoir. This interpretation is consistent with the known regional tectonic history, which suggests that post-Ordovician basement-seated faults are unlikely to occur within the Huron Domain (e.g., Figure 10, [18]). It is also consistent with the results from ongoing micro-seismic monitoring which find no evidence for the existence of major seismogenic features or active faults of concern [23].

Furthermore, we can conclude, based on the predictable and explorable nature of the system, that the direct control that mineralogy and lithofacies have on the distribution of porosity and rock mass diffusion provide a basis for the transferability of these favourable rock mass properties across the proposed DGR footprint. These results provide a high degree of confidence in the assessment of long-term performance of the far-field and its ability to contain and isolate L&ILW.

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