

Project Report

Title: *Descriptive Geosphere Site Model,
Deep Geologic Repository
Bruce Nuclear Site*

Document ID: **PR-08-01**

Authors: **Kenneth Raven, Dougal McCreath, Richard
Jackson, Ian Clark, Dru Heagle, Sean
Sterling, John Avis**

Revision: **1C**

Date: **April 15, 2010**

**DGR Site Characterization Document
Intera Engineering Project 08-200**



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Document ID:	PR-08-01	
Revision Number:	1C	Date: April 15, 2010
Authors:	Kenneth Raven, Richard Jackson, Dougal McCreath, Ian Clark, Dru Heagle, Sean Sterling, John Avis	
Technical Review:	Mark Jensen, Branko Semec, Andy Parmenter, Laura Kennell, Tom Lam (NWMO)	
QA Review:	John Avis	
Approved by:	Kenneth Raven	

Document Revision History		
Revision	Effective Date	Description of Changes
1A	December 31, 2009	Interim draft release
1B	February 28, 2010	2 nd Interim draft release.
1C	April 15, 2010	3 rd interim draft release

EXECUTIVE SUMMARY

The Nuclear Waste Management Organization (NWMO) on behalf of Ontario Power Generation Inc. is managing the development a Deep Geologic Repository (DGR) for low and intermediate level radioactive waste at the Bruce nuclear site, located near Tiverton, Ontario. The DGR will be constructed as an engineered facility comprising a series of underground emplacement rooms at a depth of about 680 m below ground surface within the Paleozoic argillaceous limestone of the Cobourg Formation.

This report describes the Descriptive Geosphere Site Model (DGSM) developed based on the results of Phase 1 and 2A of the Geoscientific Site Characterization Plan (GSCP). The GSCP is a three-phase, multi-year program plan designed for iterative development, testing and refinement of site-specific descriptive geosphere models, that was released in April, 2006 and updated in April, 2008. The DGSM of the Bruce site will be used in preparation of the DGR environmental assessment and site preparation/construction license applications to the Canadian Nuclear Safety Commission. Phase 1 and 2A of GSCP activities were completed in the period August 2006 to November 2009.

The DGSM described in this document summarizes the current understanding of underground geological, hydrogeological and geomechanical conditions of the Bruce nuclear site relevant to DGR repository engineering and safety assessment functions up to November 30, 2009. The geological, hydrogeological and geomechanical site conditions are presented through the development of individual descriptive geological, hydrogeological and geomechanical models of the Bruce nuclear site. The understanding of geological, hydrogeological and geomechanical conditions at the Bruce site will be refined and modified as the results of Phase 2B GSCP data become available. Phase 2B GSCP investigations are focussing on the drilling and testing of two inclined cored boreholes to the lower Gull River Formation.

Descriptive Geological Site Model

The descriptive geological site model defines the occurrence and lithological/structural characteristics of 35 distinct bedrock stratigraphic formations, members or units extending from ground surface to the depths of about 860 metres below ground surface (mBGS) based on drilling, logging and testing of four deep cored boreholes, DGR-1, DGR-2, DGR-3 and DGR-4 and data from several shallow (maximum 200 m depth) US-series boreholes. The geological site model provides the framework for hydrogeological and geomechanical models of the Bruce nuclear site. The reference Bruce site stratigraphy from surface to depth at DGR-1 and DGR-2 comprises: 20 m of recent Pleistocene overburden deposits, 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, 16.9 m of Cambrian sandstone, and Precambrian granitic gneiss.

Logging of boreholes DGR-1 to DGR-4 identified the presence of several important marker beds and 35 distinguishable bedrock formations, members or units at the Bruce DGR site. The thicknesses and orientations of these 35 strata are remarkably uniform over the DGR borehole separation distances of 1047 to 1318 m. The thickness and orientation of formations are somewhat more variable above the Salina B Unit and more uniform below the B Unit. This is most likely due to collapse and minor rotation of the overlying bedrock following paleo dissolution of the Salina B and D Unit salt beds. Below the Salina B Unit, formation thicknesses in DGR boreholes are within 1-2 m of each other in different holes, and the formation strikes are within 5-10° and formation dips are within 0.10° for each formation. The average strike and dip of the deeper Silurian and the Ordovician Formations of N20°W/0.6°SW at the Bruce site is consistent with regional geological mapping of Armstrong and Carter (2006) and with site predictions developed based on the drilling and logging of the Texaco No.

6 oil and gas exploration well located 2.9 km southeast of the Bruce nuclear site.

Detailed core logging and borehole geophysical logging of DGR and US-series boreholes show that that Devonian and Upper Silurian dolostones are moderately to highly fractured and of poor to fair rock quality designation (RQD), whereas the deeper Silurian formations below the Salina G Unit and the Ordovician shales that overly the DGR host formation (Cobourg) and the argillaceous limestones below the host formation are very sparsely fractured to unfractured with excellent RQD. Many of the low core recoveries and RQDs recorded for the Lower Devonian and Upper Silurian dolostones were attributed to difficult drilling conditions created in part by alternating hard and soft beds within these formations. Occasional natural fractures, that were commonly sealed and tight, were also identified within the deeper Silurian and Ordovician formations. Natural fracture frequency also was observed to increase in the Cambrian sandstone. Natural fractures within the Cambrian are open and permeable.

Logging of recovered core and acoustic imaging of the borehole walls of DGR-1, DGR-2, DGR-3 and DGR-4 identified the presence of inclined joints and fractures. Most of the inclined joints and fractures were found within the Devonian and Upper Silurian dolostones. The total number of inclined joints and fractures identified in all DGR boreholes within the Ordovician shales and limestones were limited, ranged from 73 from core logging to 39 from borehole wall imaging. Preliminary analysis of the identified inclined joints and fractures in the Ordovician shales and limestones suggests they preferentially strike in northeast and southeast directions, similar to joint strikes reported for outcrops in adjacent Inverhuron Park and the lower Bruce peninsula.

Core logging and laboratory petrography and X-ray diffraction (XRD) analyses identified the presence of fracture infill, vein and secondary mineralogy in DGR cores. Chert, quartz, calcite, pyrite, anhydrite, gypsum, halite, celestite, illite, chlorite, marcasite and Fe oxide/hydroxide were identified. Several of these minerals (e.g., halite, gypsum, anhydrite and celestite) are soluble and their occurrence is important to interpretation of core porewater analyses and as an indicator of the absence of recent groundwater flow through these discontinuities.

Intact core samples and a limited number of samples of joint/fracture infilling were analysed for mineralogy and geochemistry using laboratory test methods including thin section petrography with electron microscope analyses, whole rock and clay fraction X-ray XRD testing, scanning electron microscope/energy dispersive spectral (SEM/EDS) analyses, trace element ICP analyses, elemental oxide analyses by ICP optical emission spectrometry, carbon and sulphur infrared spectroscopy analyses, and chloride by instrumental neutron activation analyses. These detailed analyses generally confirm the strata mineralogy as defined by Armstrong and Carter (2006).

The laboratory testing of intact cores shows that the Devonian and Upper Silurian carbonate sequences are predominately dolostone with some minor limestone-rich layers and minor occurrence of sheet silicates as illite. Parts of the Cabot Head Formation shale are locally calcareous and dolomitized and the Queenston Formation shale is both calcareous and dolomitized particularly in upper parts of the formation. The Georgian Bay, Blue Mountain and Collingwood shales also show dolomite presence. The deepest Paleozoic strata comprising the Cambrian and overlying Shadow Lake Formation and the lower parts of the Gull River Formation, also show presence of significant amounts of dolomite.

The clay content of the bedrock sequence in the DGR Paleozoic sequence, as reported by total sheet silicates based on XRD analyses, ranges from zero for the Devonian and Upper Silurian dolostones to 15 wt% to 70 wt% within the Silurian Cabot Head Formation and the Ordovician shales of the Queenston, Georgian Bay and Blue Mountain Formations. The clay content of the Ordovician limestones is typically less than 20%. The total sheet silicates within the Precambrian basement are not clays, but are micaceous minerals including biotite and muscovite. The clay minerals identified in the Ordovician shales are predominately illite and mica (>50% of clay minerals), chlorite (20-45%) with

minor interstratified illite/smectite and kaolinite.

The organic geochemistry of the Ordovician shales was characterised by standard source rock evaluation methods ('Rock-Eval' pyrolysis) and by measurement of the total organic carbon (TOC as wt %), presumably present as kerogen. TOC concentrations in the Silurian dolostones are <0.25 %, while in the middle Ordovician limestones they are typically $\leq 0.6\%$. However in the Ordovician shales TOC increases with depth from 0.1% in the oxidised Queenston to $\sim 2\%$ in the lower Blue Mountain and Collingwood shales. The pyrolysis data indicate that this deeper organic matter is a Type II kerogen, typical of marine shales, whereas the TOC in the shallower Queenston and Georgian Bay Formations suggests a more gas-prone Type III kerogen. The mature hydrocarbon identified in the lowermost Blue Mountain and Collingwood shales is associated with methane that originates from biogenic acetate fermentation. Thermal maturity values for this organic carbon indicate high in-situ temperatures during maturation – probably between 70 and 130 °C. The oil that has been observed to bleed from discrete zones within the Coboconk, Gull River and Shadow Lake Formations is associated with thermocatalytic methane.

Core logging, laboratory petrography, SEM/EDS and XRD analyses identified the presence of fracture infill, vein and secondary mineralogy in DGR cores. Evaporite minerals, such as gypsum, anhydrite, celestite and halite, are common and indicate the absence of recent advection. Some Silurian formations are predominately composed of sulphate minerals, e.g., the Salina A1 and A2 Evaporite Units. Anhydrite was frequently found within the Upper Silurian dolostones and appears to be present in trace amounts in the Middle Ordovician limestones. Gypsum was preferentially observed within the Salina G to A2 Units and occasionally within deeper Lower Silurian and Upper Ordovician shales. Halite was frequently detected as fracture-infill and grain-boundary materials in the Ordovician shales (Queenston, Georgian Bay and Blue Mountain Formations). It was also detected by SEM/EDS within the rock matrix of the overlying Silurian formations, such as the Salina E and A1 dolostones, the Salina C and Cabot Head shales, Guelph and Manitoulin dolostones, and Gasport dolomitic limestone and in the underlying Lower Ordovician Cobourg, Sherman Fall and Gull River limestones.

In addition to carbonate and evaporite minerals, oxides and sulphides are detected throughout the Paleozoic sequence in minor amounts with some notable exceptions. For example, the Cambrian contains quartz at up to 85% of the middle and lower sections of this formation. The quartz identified in the carbonate rocks is mainly chert and can comprise 30-40% of some siltstone layers within the Ordovician shales, i.e., the Cabot Head, Queenston and Georgian Bay Formations. Quartz as chert was observed in Devonian and Upper Silurian dolostones. Pyrite is the principal iron mineral and is detected throughout the Paleozoic sequence indicating strongly reducing conditions, although hematite is common in the Queenston and Cabot Head shales yielding their red colour. The most common oxides are the sheet silicates comprising the clay minerals, which are often coloured by iron oxides.

Surface 2-D seismic reflection surveys completed over about 20 km on nine survey lines identified the possible presence of five seismic discontinuities that may represent vertical to sub-vertical faults within the Ordovician formations at the Bruce nuclear site. These possible faults trend north-northwest to northwest. Two of these possible structures are being investigated through inclined drilling in Phase 2B site characterization work. Preliminary results of these drilling investigations did not identify faults at the suspected locations defined by 2-D seismic surveys.

Recommended values of key geological properties of the 35 bedrock layers that comprise the descriptive geological site model are summarized in tabular form together with a qualitative assessment (low, moderate, high) of the confidence in these layer properties.

Descriptive Hydrogeological Site Model

The hydrogeologic site model describes the hydrogeologic properties and 3-D spatial distribution of all important hydrogeologic units and features within the Paleozoic bedrock units at the Bruce nuclear site. The descriptive hydrogeologic model, based on detailed field and laboratory testing, provides the basis for understanding groundwater flow and radionuclide transport properties of the Paleozoic bedrock that will contain and isolate the proposed Bruce DGR. The hydrogeologic site model focuses on description of the physical properties (rock density, porosity, fluid saturations, surface area, permeability, hydraulic head and diffusivity) of the bedrock, and geochemical/isotopic properties of the groundwater and porewater of the Bruce DGR site.

Laboratory testing of DGR cores was undertaken to quantify intact rock physical properties including bulk and grain density, physical and water loss porosity, residual fluid saturations, rock permeability to gas, mercury injection pore-size distribution, gas entry pressure, specific surface area, gas-brine flow properties, effective diffusion coefficients and diffusion accessible porosity. Bulk and grain densities were measured by three different laboratories and showed comparable results that were in accordance with expectations based on formation mineralogy and porosity.

Total and liquid porosities were also measured on DGR cores by four independent laboratories. Total porosity was measured by helium gas expansion and from bulk dry and grain density data. Liquid porosity was measured by vacuum distillation and oven drying. The mean total and liquid porosities ranged from 8.9% and 9.6%, respectively in the Silurian and Devonian strata, to 1.8% and 1.7% respectively, in Ordovician limestones, to 2.7% and 2.3% respectively, for limestone/siltstone hard beds within Ordovician shales, to 7.1% and 8.1% respectively, for Ordovician shales, to 9.5% and 8.1% respectively, in the Shadow Lake siltstone and Cambrian sandstone.

The fluid saturations or fractions of brine, oil and gas within rock pore volumes were determined for DGR cores. No fractional saturations of oil were detected from petrophysical testing of DGR cores. The brine or water saturations range from 70% to 100% and the gas saturations, which are calculated by difference, range from 0% to 30% of the pore space. Although there are some uncertainties in these gas saturations related to sample dehydration, core relaxation and test equipment sensitivity, particularly in the very low porosity Ordovician limestones, analysis of the available data, including calculations of methane supersturation, suggest that a discontinuous gas phase is present within the pore space of the Ordovician shales and limestones.

Vertical and horizontal core permeability were determined on DGR core samples collected from Silurian dolostones, shales and evaporites, Ordovician shales and limestones and from Cambrian sandstone using gas and brine pulse decay methods prior to and following pore fluid extractions. Although these tests were conducted at depth-specific confining stresses intended to simulate in-situ effective stress, the results suggest irrecoverable damage to the cores due to microcrack formation and core dinking, particularly for the Ordovician shales and to lesser degree for the Ordovician limestones. Considering international literature/experience on this issue and the test results, the overestimation of actual in-situ permeability from the lab gas pulse decay testing is likely about a factor of 10 to 100 for Ordovician limestones and 100 to 1000 for Ordovician shales. In-situ permeability of intact Ordovician shale and limestone is therefore estimated to be about 10^{-21} m^2 .

Mercury injection porosimetry data were used to estimate gas entry or displacement pressures for the DGR host formation (Cobourg) and the overlying Ordovician shales and Silurian strata, as well as for the deeper sections of the Gull River Formation and the Cambrian sandstone. The gas entry pressures for the porous deeper parts of the Gull River Formation and Cambrian sandstone are quite low at 40 to 150 kPa, whereas the values for the Cobourg Formation, overlying Ordovician shales, and most of the Middle to Lower Silurian dolostones and shales are typically greater than 10 MPa.

Mercury injection porosimetry data, fluid saturation data and gas pulse permeability data were used to calculate van Genuchten characteristic gas-brine flow parameters. The fitted relative permeability-saturation curves indicate that the measured gas saturations result in reductions of brine permeability by upwards of one order of magnitude.

Diffusion properties of intact DGR cores collected from Silurian and Ordovician formations were measured using conventional laboratory through diffusion methods using iodide, tritium and ^{125}I as tracers to estimate vertical properties, and X-ray radiography using iodide as a tracer to estimate vertical and horizontal properties. The iodide effective diffusion coefficients for the Ordovician shales and limestones were found to be proportional to the porosity of the formations with values of about $1 \times 10^{-12} \text{ m}^2/\text{s}$ for Queenston and Georgian Bay Formation shales and $4 \times 10^{-13} \text{ m}^2/\text{s}$ for the Cobourg Formation limestone. The experimental program also observed iodide diffusion coefficient anisotropy with values parallel to bedding being larger than normal to bedding by factors of 1 to 4. Diffusion coefficients for iodide were less than those for tritium - particularly in shale, and iodide diffusion-accessible porosity was typically 50% of liquid porosity suggesting anion exclusion effects in the iodide diffusion testing of DGR shale cores.

Groundwater and porewater in the Paleozoic bedrock sequence at the Bruce nuclear site were characterized for master variables of pH and Eh, major and trace ions, environmental isotopes, radioisotopes and some gases. Groundwater samples were collected from multi-level monitoring systems established in three US boreholes to maximum 200 m depth and as opportunistic samples collected from permeable packer-isolated intervals during drilling of DGR- boreholes. Groundwater samples were collected during drilling from the Salina Upper A1 Unit, the Guelph Formation and the Cambrian sandstone aquifers. Initial groundwater sampling of the upper 190 m of the bedrock shows that the groundwater transitions from fresh Ca:Mg-HCO_3 water (TDS $\sim 500 \text{ mg/L}$) near the top of the bedrock to brackish Ca-SO_4 water (TDS $\sim 5,000 \text{ mg/L}$) at depth. The depleted ^{18}O and D signature at depth of 100 to 180 m and within the Salina Upper A1 Unit aquifer at reference depth of 325.5 - 328.5 mBGS in DGR-1 suggests presence of a glacial meltwater component. Groundwater collected from the Guelph Formation at reference depths of 374.5 - 378.6 mBGS is the a Na:Cl brine with the highest TDS (375,000 mg/L) of any water samples tested at the Bruce DGR site. Groundwater collected from the Cambrian sandstone at a reference depth of 843.8 – 860.7 is a Na:Ca-Cl brine (TDS $\sim 235,000 \text{ mg/L}$).

Porewaters were extracted from crushed DGR cores at the University of Ottawa by high-temperature vacuum distillation (150°C) for dissolved gases and isotopes followed by deionized water leaching of crushed (2-4 mm grain size) rock samples for major dissolved ions. These porewater analyses, supported by the available shallow and deep groundwater analyses and corroborating porewater analyses for chloride completed by the University of Bern, Switzerland and the University of New Brunswick using crush and leach methods, were used to generate water chemistry profiles for the Paleozoic bedrock at the Bruce nuclear site. The porewater and groundwater data show gradual increasing salinity and major ion concentration profiles from near surface to the depths of about 350 to 400 mBGS where a Na:Cl basin brine occurs (TDS=350,000 mg/L). Below this depth, salinity and major ion profiles decrease gradually through the Ordovician shales and the Ordovician limestones of the Trenton Group (Cobourg, Sherman Fall and Kirkfield Formations), to the top/middle of the Gull River Formation limestone (TDS=200,000 mg/L). Salinity and major ion concentrations in the lower Gull River Formation then increase toward those observed in Cambrian groundwater and porewater (TDS=225,000 mg/L). The environmental isotope data (including deuterium excess) and the major ion data (e.g., Cl, Br, Sr,) suggest the deeper Ordovician limestone porewaters are mixtures of different basin fluids particularly within Gull River Formation. The chemistry profile within the Gull River Formation suggests a freshening of groundwater within the Cambrian sandstone over recent geological time.

Historical hydraulic testing of the upper 100 m of bedrock in combination with the results of pulse, slug and drill-stem hydraulic testing of DGR boreholes using a custom-built straddle-packer testing tool, were used to quantify formation horizontal hydraulic conductivity. Borehole straddle packer tests were analyzed using the Sandia National Laboratories numerical hydraulic-test simulator - nSIGHTS. Measured horizontal hydraulic conductivities ranged from 10^{-15} m/s in the Kirkfield Formation to 3×10^{-6} m/s in the Cambrian sandstone. Considering field and lab permeability testing, core observations and other hydraulic test data, the average estimates of horizontal hydraulic conductivity of the Ordovician shale and Trenton Group limestone formations range from 8×10^{-15} to 5×10^{-14} m/s, with vertical hydraulic conductivity being a factor of 10 less than horizontal hydraulic conductivity. The average estimates of horizontal hydraulic conductivity in the Black River limestones are greater ranging from 7×10^{-13} to 4×10^{-12} m/s, with vertical hydraulic conductivity being a factor of 10 to more than 100 less than horizontal hydraulic conductivity.

Following the completion of borehole geophysical logging and straddle packer testing, boreholes US-3, US-7, US-8, DGR-1, DGR-2, DGR-3 and DGR-4 were equipped with Westbay multiport groundwater monitoring systems. Stable pressure profiles measured in US-3, US-7 and US-8 show slight upward hydraulic gradients in the upper 200 m of dolostone bedrock with lateral flow toward Lake Huron. Monitoring of formation pressures in 42 (DGR-3, DGR-4) to 46 (DGR-1 and DGR-2) packer-isolated intervals in DGR boreholes shows the presence of moderate overpressures in Salina A1 and A0 Units, Goat Island, Gasport and Fossil Hill Formations, significant stable overpressure in the Cambrian sandstone and significant transient underpressures throughout most of the Ordovician shale and limestone. Environmental water heads calculated from formation pressures and the porewater/groundwater fluid density profile range from 165 m above ground surface (350 mASL) for the Cambrian sandstone to less than 300 mBGS (-115 mASL) in the Blue Mountain shale. The exact cause or causes of the observed overpressures and underpressures in DGR boreholes are not evident at this time, although glacial/erosional unloading and presence of a separate gas phase are possible explanations documented in the international literature. Regardless of the exact cause, the occurrence of such significant underpressures implies that the formations in which they are measured must of extremely low permeability in order for them to persist.

Measurements of formation pressures in DGR boreholes were used to determine horizontal groundwater flow directions in the three deep permeable aquifers at the Bruce DGR site. Groundwater flow directions in the Upper A1 Unit aquifer are the same as those in the shallow dolostones, being to the northwest toward Lake Huron. In contrast the calculated groundwater flow directions for the Guelph Formation and the Cambrian sandstone are outward from the middle of the Michigan Basin being toward the northeast (Guelph Formation) and to the east (Cambrian sandstone).

Considering all of the available Phase 1 and 2A hydrogeological site characterization data, the overburden and bedrock formations were categorized and grouped in hydrostratigraphic units that have similar hydrogeologic characteristics. Based on DGR-1 and DGR-2 reference depths, the nine hydrostratigraphic (HS) units include:

- HS Unit 1; Overburden aquitard; 0 to 20 mBGS
- HS Unit 2; Devonian and Upper Silurian Dolostone aquifer, 20 to 169 mBGS
- HS Unit 3; Silurian shale, dolostone & anhydrite aquitards, 169 to 447.7 mBGS, excluding Unit 4
- HS Unit 4; Silurian dolostone aquifers, 325.5 to 328.5 mBGS and 374.5 to 378.6 mBGS
- HS Unit 5; Ordovician shale aquiclude, 447.7 to 659.5 mBGS
- HS Unit 6; Ordovician limestone aquiclude, 659.5 to 762.0 mBGS
- HS Unit 7; Ordovician limestone aquitard, 762.0 to 836.6 mBGS

- HS Unit 8; Cambrian sandstone aquifer, 838.6 to 860.7 mBGS
- HS Unit 9; Precambrian aquitard, >860.7 mBGS.

Estimates of vertical and horizontal hydraulic conductivity, specific storage, liquid porosity, hydraulic gradients, vertical and horizontal effective diffusion coefficient, diffusion porosity and groundwater/porewater properties of these Bruce DGR hydrostratigraphic units are summarized in this report.

Recommended values of key hydrogeological properties of the 39 layers that comprise the descriptive hydrogeological site model are also summarized in tabular form together with a qualitative assessment (low, moderate, high) of the confidence in these layer properties.

Descriptive Geomechanical Site Model

The geomechanical site model describes and summarizes the current understanding of the principal geomechanical properties of the rock materials and rock mass beneath the Bruce DGR site. The geomechanical site model focuses on presentation of quantitative estimated physical properties that will control the geomechanical behaviour of the rock mass beneath the Bruce nuclear site during and after construction of the sub-surface infrastructure required for development of the DGR. Estimated values are based on combining the specific quantitative values of various parameters derived from field and laboratory testing with expert judgement, where appropriate.

Similar to the development of hydrostratigraphic units for the hydrogeological site model, mechano-stratigraphic (MS) units are developed for describing the geomechanical properties of the bedrock formations at the Bruce nuclear site. Considering all of the available Phase 1 and 2A geomechanical site characterization data, five MS units have been defined based on DGR-1 and DGR-2 reference depths:

- MS Unit 1; Devonian and Upper Silurian dolostones, including the Salina G Unit dolostone, 20 to 178.6 mBGS.
- MS Unit 2; Silurian shales, dolostones and anhydrites, 178.6 to 411 mBGS.
- MS Unit 3; Lower Silurian and Upper Ordovician shales (with minor Lower Silurian dolostone and Middle Ordovician shale), 411 to 659.5 mBGS.
- MS Unit 4; Middle Ordovician Cobourg Formation argillaceous limestone (repository horizon), 659.5 to 688.1 mBGS.
- MS Unit 5; all deeper Ordovician, Cambrian and Precambrian units, 688.1 to >860.7 mBGS.

Seismic monitoring at and in the vicinity of the Bruce nuclear site is being undertaken from an expanded seismic monitoring network installed in 2007 to obtain understanding of the contemporary microseismic activity within a 50 kilometres of the Bruce nuclear site. This monitoring will be used to conduct a seismic hazard evaluation for the DGR and to provide information on the contemporary seismicity and microseismicity that can be used in identification of seismogenic features in the region surrounding the Bruce nuclear site. The current and historical monitoring data show that the Bruce nuclear site is located in a seismically quiet area.

The in situ state of stress below the DGR site, and particularly at the repository elevation, is a key geomechanical parameter affecting the design of the repository facilities. Although the vertical stress magnitude and orientation will closely match the gravitational stress caused by the weight of rock above any elevation of interest, the challenge lies in trying to evaluate the magnitudes and orientations of the horizontal stress components at depth. Unfortunately there are no direct measurement

methods for quantifying situ horizontal stresses at the depths of interest from a surface-based exploratory borehole. Based on review of the regional stress measurements and analysis of lack of borehole breakouts in DGR-2 evident over a period of up to 2 years following drilling, the recommended in situ stress levels at the elevation of the DGR (~680 mBGS) are:

- Vertical stress (σ_v) ~ gravity load of super-incumbent materials, ~ 18 MPa
- Maximum horizontal stress (σ_H): $1.5 < \sigma_H / \sigma_v < 2.0$
- Minimum horizontal stress (σ_h): $1.0 < \sigma_h / \sigma_v < 1.2$

The geomechanical site model describes both the rock material geomechanical characteristics and the rock mass geomechanical characteristics for each of the MS units based on Phase 1 and 2A data generated from drilling and testing of DGR-1, DGR-2, DGR-3 and DGR-4. Rock material geomechanical characteristics include, where available, information on short and long-term uniaxial compression strengths, triaxial compression strength, indirect tensile strength, direct shear strength, slake durability, free swell behaviour, abrasiveness, and dynamic properties (elastic and shear moduli, Poisson's ratio) based on the testing of intact cores. Rock mass geomechanical characteristics include, where available, information on rock quality designation (RQD), natural fracture frequency, and bulk properties from borehole geophysical logging (dynamic elastic and shear moduli).

The available data on rock material and rock mass geomechanical characteristics generated from Phase 1 and 2A site characterization work demonstrate that the geomechanical properties of Bruce DGR rocks are in accordance with and better than expectations based on precedent projects and regional data summaries.

Recommended values of key geomechanical properties of the 34 layers that comprise the descriptive geomechanical site model are summarized in tabular form together with a qualitative assessment (low, moderate, high) of the confidence in these layer properties.

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LIST OF KEY ACRONYMS

AEM: Acoustic Emission Monitoring
ANDRA: Agence Nationale pour la Gestion des Déchets Radioactifs
ATV: Acoustic Televiewer
BGS: Below Ground Surface
BP: Before Present
CHIS: Canadian Hazard Information Service
CNSC: Canadian Nuclear Safety Commission
D: Deuterium
 D_e : Effective Diffusion Coefficient
 D_p : Pore Diffusion Coefficient
DGR: Deep Geologic Repository
DGSM: Descriptive Geosphere Site Model
DO: Dissolved Oxygen
DST: Drill Stem Test
EC: Electrical Conductivity
EDZ: Excavation Damage Zone
GMWL: Global Meteoric Water Line
GSCP: Geoscientific Site Characterization Plan
GSI: Geological Strength Index
GW: Groundwater
HS: Hydrostratigraphic Unit
HTO: Tritiated Water
ICP/MS: Inductively Coupled Plasma Mass Spectrometry
K: Hydraulic Conductivity
k: Permeability
kPa: kilo Pascal
mASL: metres above sea level
mBGS: metres below ground surface
MNR: Ontario Ministry of Natural Resources
MS: Mechanostratigraphic Unit
MPa: Mega Pascal
MP: Multi-Port
NWMO : Nuclear Waste Management Organization
OGW: Opportunistic Groundwater
OPG: Ontario Power Generation
 p_{CO_2} : Partial Pressure of CO_2
 ρ : Density
 σ : Compressive stress
 P_c : Capillary Pressure
PLT: Point Load Test
PDP: Pulse Decay Permeability
PQP Project Quality Plan
PR: Project Report
PW: Porewater
QMS Quality Management System
RMR: Rock Mass Rating
RQD: Rock Quality Designation
S: Saturation

SDI: Slake Durability Index
SI: Saturation Index
SEM: Scanning Electron Microscope
SCP: Site Characterization Plan
TDS: Total Dissolved Solids
TP: Test Plan
TR: Technical Report
TU: Tritium Units
UCS: Uniaxial Compressive Strength
V: Linear Groundwater Velocity
VSMOW: Vienna Standard Mean Ocean Water
XRD: X-Ray Diffraction

1 INTRODUCTION

Intera Engineering Ltd., under contract to Nuclear Waste Management Organization (NWMO), is undertaking geoscientific site characterization work at the Bruce nuclear site located at Tiverton, Ontario. The purpose of this site characterization work is to assess the suitability of the Bruce nuclear site to construct a Deep Geologic Repository (DGR) to store low-level and intermediate-level radioactive waste. Ontario Power Generation (OPG) is the sole owner of the DGR, while NWMO is the Project Manager overseeing DGR licensing and development activities. The DGR would be constructed within low permeability limestone at depths of about 680 m and overlain by at least 200 metres of regionally-extensive low permeability shale. The geoscientific site characterization work is being implemented in accordance with a Geoscientific Site Characterization Plans (GSCPs) developed in advance of the work and released in April, 2006 (Phase 1 - Intera Engineering Ltd., 2006) and April, 2008 (Phase 2 - Intera Engineering Ltd., 2008)

This report summarizes the results of the geoscientific site characterization work completed as part of Phase 1 and 2A of the GSCP in the period August, 2006 to November, 2009. This report will be updated as data from Phase 2B investigations become available in 2010. In accordance with the GSCP, geoscientific data collected in Phase 1 and 2 are summarized based on the development of a descriptive geosphere site model (DGSM) of the Bruce DGR. The DGSM for the Bruce nuclear site includes descriptive geological, hydrogeological and geomechanical site models.

This Project Report provides interpretation, analysis and integration of geoscientific data collected as part of a series of investigations which are described in a set of Technical Reports. Technical Reports generally provide limited interpretation and are intended as summaries of collected data. All Technical Reports were completed in accordance with approved Test Plans. Technical Reports, Test Plans and Project Reports were prepared following the requirements of the Intera DGR Project Quality Plan (Intera Engineering Ltd., 2009), which meets the requirements of NWMO's DGR Project Quality Plan.

1.1 Report Organization

This document consists of the following sections:

- Section 1: Introduction – the remaining parts of Section 1 describe organization of this report, the DGR concept, geoscientific site characterization plans, the strategy for development of the DGSM, the existing DGSM and acknowledgements.
- Section 2: Primary Data Sources: - a summary of the Technical Reports, Test Plans and other sources of data used to develop the specific descriptive site models given in Sections 3, 4 and 5.
- Section 3: Descriptive Geological Site Model – a summary of the elements, scope, data sources, detailed description and confidence assessment of the geological site model for the Bruce DGR based on Phase 1 and 2A investigations.
- Section 4: Descriptive Hydrogeological Site Model – a summary of the elements, scope, data sources, detailed description and confidence assessment of the hydrogeological site model for the Bruce DGR based on Phase 1 and 2A investigations.
- Section 5: Descriptive Geomechanical Site Model – a summary of the elements, scope, data sources, detailed description and confidence assessment of the geomechanical site model for the Bruce DGR based on Phase 1 and 2A investigations.
- Section 6: References

1.2 DGR Concept

The DGR is proposed to be constructed at a depth of about 680 m below ground surface within the argillaceous limestone of the Cobourg Formation. Figure 1.1 shows the conceptual layout of the DGR below the Bruce nuclear site. The approximate plan location and extent of the proposed DGR is shown on Figure 1.2. The DGR will require construction of a general access shaft and a ventilation shaft.

The DGR will be designed to receive low and intermediate level wastes currently in interim storage at the Bruce nuclear site and similar wastes produced by OPG-owned nuclear generating stations throughout their lifetime. OPG (2005) provides a detailed description of the DGR project, including the anticipated volumes, types and activities of the wastes to be placed in the DGR.

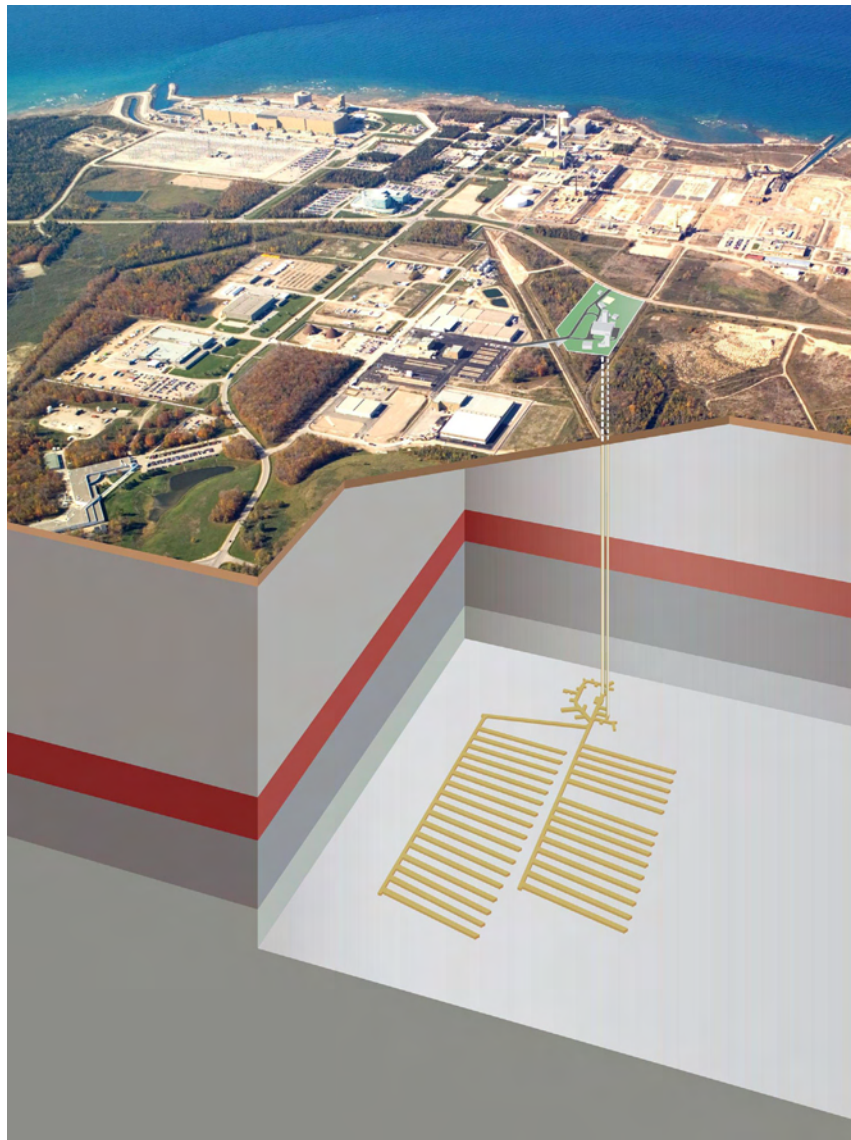


Figure 1.1 Conceptual layout of the DGR below the Bruce nuclear site

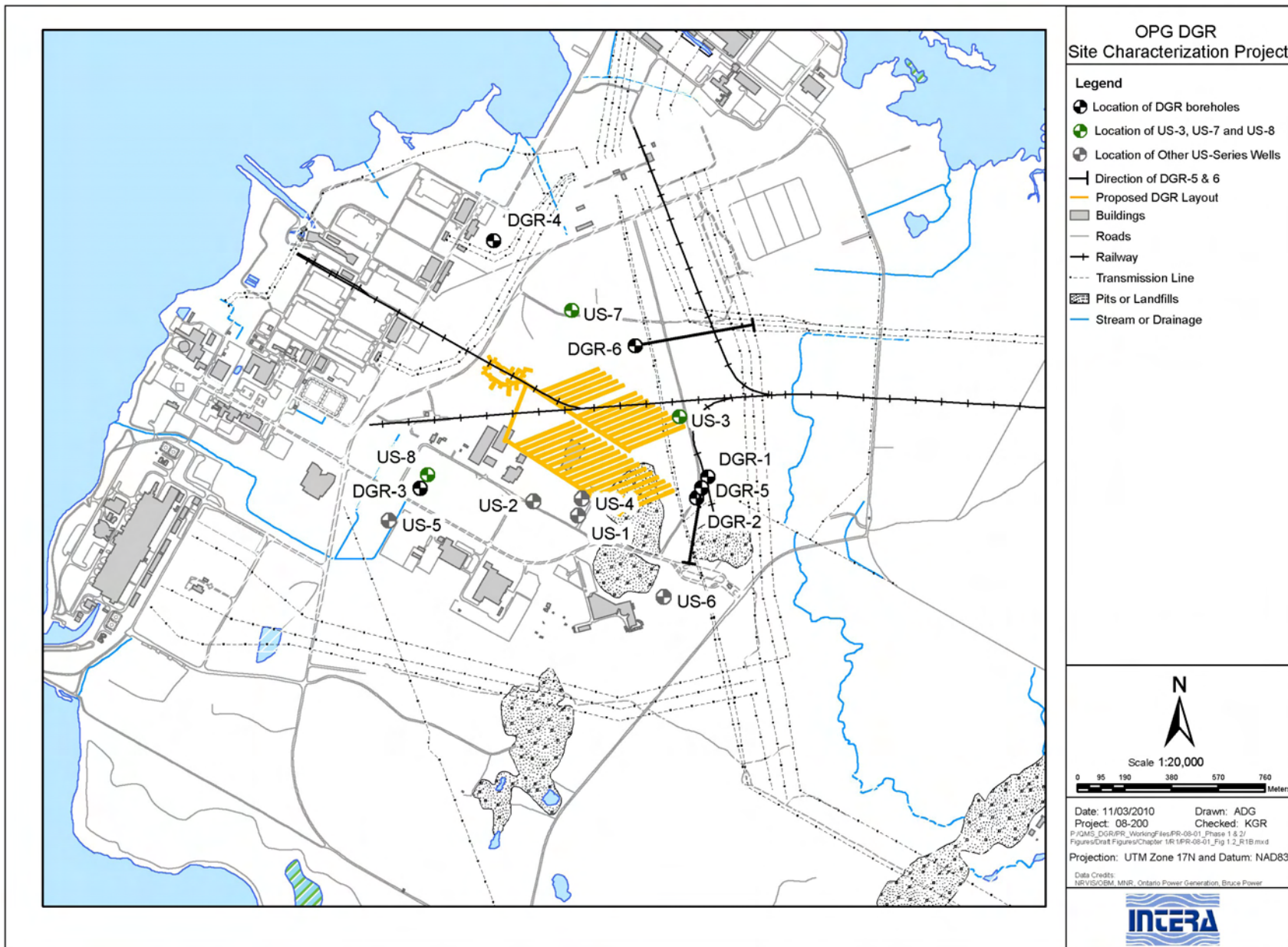


Figure 1.2 DGR boreholes and US boreholes and the proposed DGR layout at the Bruce nuclear site

1.3 Geoscientific Site Characterization Plan

The GSCP provides a technical description of the selection and proposed application of preferred tools and methods for site-specific geoscientific characterization of the deep sedimentary bedrock formations found at the Bruce nuclear site. These tools and methods were identified based on assessment of geoscience data needs and collection methods, review of the results of detailed geoscientific studies completed in the same bedrock formations found off the Bruce nuclear site, within Ontario, and recent international experience in geoscientific characterization of similar sedimentary rocks for radioactive waste storage and disposal purposes. The GSCP also describes recommended off-site or geoscientific studies considered necessary to the development of a comprehensive geosynthesis or geoscientific understanding of the Bruce nuclear site relevant to the DGR safety case.

The GSCP is a multiple year, three phase (1, 2A, 2B) program designed for iterative development, testing and refinement of site-specific descriptive geosphere models, including geologic, hydrogeologic and geomechanical models. The GSCP is structured into three principal work components: a series of initiation activities necessary to start the site characterization work; three investigative phases; and a geosynthesis or analysis and interpretation task.

The primary focus of the GSCP is subsurface characterization through borehole drilling and testing and surface seismic reflection surveys. Furthermore, this subsurface characterization is to be completed through surface-based investigations only and therefore the GSCP does not include underground-based investigations. The overall GSCP and the detailed investigative activities for Phase 1 work are described by Intera Engineering Ltd., (2006).

The Phase 1 GSCP provides a detailed description of initiation requirements; Phase 1 work elements for geologic, hydrogeologic and geomechanical site characterization plans; and of geosynthesis, project quality and data management plans. Phase 2A and Phase 2B GSCP activities are necessarily described in general terms in the Phase 1 GSCP.

The majority of Phase 1 GSCP investigations are based on drilling and testing of two deep boreholes, DGR-1 and DGR-2, completed to depths of 462.87 and 862.25 mBGS into the top of the Queenston Formation shale and the Precambrian basement, respectively. Additional shallow to intermediate depth site characterization work included drilling and testing of borehole US-8 to depth of 200.40 mBGS into the Salina Formation F Unit shale and testing and sampling in existing boreholes US-3 and US-7 completed to depths of 74.31 and 90.56 mBGS, respectively.

The detailed Phase 2 GSCP (Intera Engineering Ltd., 2008a) has been prepared to guide Phase 2 geoscientific site characterization work at the Bruce nuclear site in 2008 to 2010. The Phase 2A site characterization involves core drilling and testing of two deep vertical boreholes, DGR-3 and DGR-4, completed to depths of 869.17 and 856.98 mBGS, respectively, into the Cambrian sandstone, in 2008. Phase 2B site characterization is focussed on completion of two boreholes, DGR-5 and DGR-6, inclined at 60 to 65° from the horizontal, to investigate potential deep sub-vertical structural features in the Silurian and Ordovician formations in 2009 and 2010. Phase 2A and Phase 2B activities were originally described as Phase 2 and Phase 3 activities in the Phase 1 GSCP.

Figure 1.2 shows the location of boreholes DGR-1 to DGR-6, US-3, US-7, US-8, and other US-series boreholes relative to the proposed DGR footprint at the Bruce nuclear site.

1.4 Strategy for Development of the DGSM

The DGSM described in this Project Report is founded on the following strategic considerations:

- A three-phase site characterization program designed for iterative development, testing and refinement of site-specific descriptive geosphere models. This approach allows for adaptive management of the GSCP to respond to acquired geoscientific knowledge and emerging information requirements for development of the DGSM and DGR Safety Case development.
- An assessment of internationally accepted site-specific geoscience attributes relevant to understanding technical site acceptability.
- Peer review of the DGSM by OPG/NWMO stakeholders, regulatory agencies and the independent Geoscience Review Group.
- Integration of the DGSM with on-going regional geologic, hydrogeologic and geomechanical geosynthesis studies in southwestern Ontario relevant to assessing concepts of long-term DGR safety.
- Direct inclusion of international geoscience site characterisation experience in investigating deep sedimentary formations for long-term radioactive waste management purposes.
- Participation in various international forums focused on development of geoscience approaches and methods for demonstrating safety of geological disposal in sedimentary formations.
- Preparation of the DGSM under an appropriate Project Quality Plan.
- Selection and scheduling of geoscience site characterization activities to specifically minimize GSCP and DGR project risk and cost.

1.5 Existing Descriptive Geosphere Site Model

The DGR concept for the Bruce nuclear site is largely premised on an existing descriptive geosphere site model developed based on compilation and review of previous geoscience investigations completed at, near and distant from the Bruce nuclear site (Golder Associates Ltd., 2003, Mazurek, 2004, Gartner Lee Limited, 2008a). This existing site model includes several geoscientific attributes and features judged favourable for the long-term isolation and containment of low and intermediate level radioactive waste. The assumed favourable geoscience attributes and features of the existing geosphere site model for the Bruce nuclear site relevant to demonstrating repository safety include the following.

- The deep horizontally-layered shale and argillaceous limestone sedimentary sequence that will overlie and host the DGR is geologically stable, geometrically simple and predictable, relatively undeformed and of large lateral extent.
- Active faulting and seismicity at and near the site are very limited.
- The deep argillaceous formations that will host the DGR will provide stable and practically dry openings.
- The regional stress regime (horizontally compressive) is favourable with respect to sealing of any vertical fractures and faults.

- The deep shale and argillaceous limestones are thick and of very low permeability, providing a very tight bedrock horizon for the waste management facility, and a very tight 200 m thick barrier to upward migration from the facility.
- Mass transport in the deep shales and limestones is diffusion dominated. The deep groundwater system in the shales and limestones is saline, stagnant, stable and ancient, not showing evidence of either glacial perturbations or cross formational flow or mixing.
- The shallow water supply aquifer in the upper carbonate bedrock is hydrogeologically isolated and protected from the sluggish deep saline groundwater system.
- There is low probability of economic hydrocarbon deposits in the sedimentary formations in the local area of the Bruce nuclear site and the DGR.

1.6 Project Quality Plan

Intera Engineering is an ISO 9001:2008 registered company (BSI Management Systems registration certificate FS 51197) with a specific scope of "provision of environmental consulting services". The company operates under a Quality Management System (QMS) which prescribes procedures and protocols for conducting technical work.

For the Site Characterization project, the QMS has been augmented by a Project Quality Plan (PQP) (Avis, 2009) which describes project specific procedures and documents how the QMS and additional procedures comply with the NWMO PQP (NWMO, 2009). The project specific procedures address unique requirements of the SC project and the NWMO PQP and are intended to insure that: all project deliverables are of uniformly high quality; that all project work is well documented; and that all testing results and interpretations are traceable. A total of seven project specific procedures have been defined, and are briefly described as follows:

- **DGR P1 Organization and QA Program** defines the project organization and project staff and management responsibilities. Describes management of subcontractor quality. Prescribes records retention requirements and provides an overview of other project specific procedures.
- **DGR P2 Document and Activity Record Control** – Describes categories of project documents to be produced and associated review requirements. Activity records are data produced during the execution of a test plan. The procedure prescribes approaches for managing these records.
- **DGR P3 Test Plans** – Plans for all technical activities must be developed before work on the activities commences. Work planning also includes description of verification approaches, where appropriate. This procedure describes the required content for test plans.
- **DGR P4 Sample and Standard Control** – Requirements for the identification of core, surface water, drill water, and groundwater samples acquired from proposed boreholes. Chain-of-custody requirements for sample shipments to laboratories are described.
- **DGR P5 Measurement and Test Equipment Control** – Measurement equipment are used for field analyses of various groundwater and drill-water parameters, for geomechanical tests on core, and for measurement of pressures and flow rates during hydraulic testing. This procedure describes the requirements for equipment calibration and the records to be produced for each calibration event.
- **DGR P6 Scientific Notebooks** - Field and laboratory staff will document daily technical activities

in Scientific Notebooks. The format of notebook entries and content guidelines are described in this procedure. Records requirements specific to scientific notebooks are also addressed.

- **DGR P7 Corrective Action** – Identification and documentation of nonconformances and corrective actions to address nonconformances are described in this procedure.

The PQP also describes an audit regime consisting of bi-annual internal audits and annual external audits.

1.7 Acknowledgments

This document, while authored by Intera Engineering Ltd. and remaining the responsibility of Intera, is based on major geoscience contributions provided by members of the Intera DGR Project Team. The contributions of the following individuals are acknowledged in the preparation of this report.

- Kenneth Raven - Project Manager and Task Leader Geology & Geophysics, Intera Engineering Ltd.
- John Avis - Deputy Project Manager and Task Leader, Quality Plan/Data Management & Modeling/Data Visualization, Intera Engineering Ltd.
- Sean Sterling – Task Leader, Borehole Drilling, Sealing & Monitoring Systems, Intera Engineering Ltd.
- Dr. Richard Jackson – Task Leader, Geochemistry and Laboratory Testing, Intera Engineering Ltd.
- Richard Beauheim – Task Leader, Borehole Hydraulic Testing, Sandia National Laboratories.
- Dr. Dougal McCreath – Task Leader, Geomechanics, Laurentian University.
- Peeter Pehme – Borehole Geophysics, Waterloo Geophysics Inc.
- Randy Roberts – Borehole Hydraulic Testing, HydroResolutions LLC.
- Dr. Ian Clark, Porewater and Isotope Geochemistry, University of Ottawa.
- Dr. Tom Al, Laboratory Diffusion Testing, University of New Brunswick

2 PRIMARY DATA SOURCES

2.1 Technical Reports

The primary sources of data that support the descriptive geosphere site models given in Sections 3, 4 and 5 are a series of Technical Reports. Technical Reports principally present and summarize data collected as part of the Phase 1 and 2 geoscientific investigations of the Bruce nuclear site. In some instances Technical Reports provide some interpretation of collected data, but most interpretations of collected data are presented in this DGSM Report.

Technical Reports are prepared in accordance with approved Test Plans. Test Plans are written plans that describe the purpose and scope, activity process, training and health and safety requirements for all data collection activities within the DGR site characterization program. Test Plan activity processes include description of overall strategy, specific implementation activities, as well as procedures for sample control, data quality control, data identification and test plan verification.

The following Table 2.1 summarizes the Technical Reports that serve as primary data sources in this Project Report. Table 2.1 identifies the Technical Report number, title and report reference. Reference to Technical Reports in this Project Report is by report number. Complete references for Technical Reports as listed in Table 2.1 are provided in Section 6.

Table 2.1 Summary of Bruce nuclear site characterization Technical Reports

Report No.	Report Title	Reference
TR-07-02	Summary of Surrogate Core Analyses	Jackson and Sterling (2008)
TR-07-03	Laboratory Geomechanical Strength Testing of DGR-1 and DGR-2 Core	Gorski et al., (2009a)
TR-07-04	CERCHAR Abrasivity Testing of Argillaceous Limestone of the Cobourg Formation	Maloney (2008)
TR-07-05	Bedrock Formations and Contacts in DGR-1 and DGR-2	Sterling (2009a)
TR-07-06	Drilling, Logging and Sampling of DGR-1 and DGR-2	Sterling (2009b)
TR-07-07	Field Geomechanical Testing of DGR-1 and DGR-2 Core	Gaines and Sterling (2009a)
TR-07-08	Borehole Geophysical Logging in DGR-1 and DGR-2	Pehme and Melaney (2009)
TR-07-09	Drilling Fluid Management and Testing in DGR-1 and DGR-2	Raven and Sterling (2009)
TR-07-10	Westbay MP55 Casing Completions in DGR-1 and DGR-2	Raven and Gaines (2009)
TR-07-11	Opportunistic Groundwater Sampling in DGR-1 and DGR-2	Jackson and Heagle (2009)
TR-07-12	Petrographic and Mineralogic Analyses of DGR-1 and DGR-2 Core	Schandl (2009)
TR-07-14	Fluid Electrical Conductivity Logging in Borehole DGR-1	Beauheim and Pedler (2009)
TR-07-15	2D Surface Seismic Survey of the Bruce Site	Watts et al., (2009)
TR-07-16	Laboratory Swell Testing of DGR-2 Core	Micic and Lo (2008)
TR-07-17	Laboratory Diffusion Testing of DGR-2 Core	Al et al., (2009)
TR-07-18	Laboratory Petrophysical Testing of DGR-2 Core	Whitney and Lee (2009)
TR-07-19	Drilling and Testing of US-8	Briscoe (2009)
TR-07-20	Westbay MP38 Casing Completions in US-3, US-7 and US-8	Raven and Sterling (2008)
TR-07-21	Pore Water And Gas Analyses in DGR-1 and DGR-2 Core	Clark et al., (2008)
TR-07-22	Diffusion of ¹²⁵ I in DGR-2 Core	Van Loon (2009)
TR-08-01	XRD Mineralogical Analysis of DGR-1 and DGR-2 Core	Skowron and Hoffman (2009a)

TR-08-02	Geochemical and SEM/EDS Analysis of DGR-1 and DGR-2 Core	Skowron and Hoffman (2009b)
TR-08-03	Borehole Geophysical Logging of US-3 and US-7	Melaney (2009)
TR-08-06	Borehole DGR-2: Pore-Water Investigations	Koroleva et al. (2009)
TR-08-07	Evaluation of Possible Hydraulic Communication Between DGR-1 and DGR-2 at the Brue Site	Beauheim (2009)
TR-08-08	Initial Groundwater Monitoring, US-3, US-7 and US-8	Heagle (2009)
TR-08-10	Compilation and Consolidation of Field and Laboratory Data for Hydrogeological Properties	Walsh (2010)
TR-08-11	DGR-2 Long-Term Strength Degradation Tests	Gorski et al. (2009b)
TR-08-12	Bedrock Formations in DGR-1 to DGR-4	Wigston and Heagle (2009)
TR-08-13	Drilling, Logging and Sampling of DGR-3 and DGR-4	Briscoe and Wigston (2010)
TR-08-14	Field Geomechanical Testing of DGR-3 and DGR-4 Core	Gaines and Sterling (2009b)
TR-08-15	Borehole Geophysical Logging in DGR-3 and DGR-4	Pehme and Melaney (2010)
TR-08-16	Drilling Fluid Management and Testing in DGR-3 and DGR-4	Pinder (2009)
TR-08-17	Westbay MP55 Casing Completions in DGR-3 and DGR-4	Gaines et al., (2010)
TR-08-18	Opportunistic Groundwater Sampling in DGR-3 and DGR-4	Heagle and Pinder (2009)
TR-08-19	Pore Water and Gas Analyses in DGR-3 and DGR-4 Core	Clark et al., (2010a)
TR-08-20	Petrographic Analysis of DGR-3 Core	Schandl (2010a)
TR-08-21	Petrographic Analysis of DGR-4 Core	Schandl (2010b)
TR-08-22	Mineralogy and Geochemistry of DGR-3 Core	Wigston and Jackson (2010a)
TR-08-23	Mineralogy and Geochemistry of DGR-4 Core	Wigston and Jackson (2010b)
TR-08-24	Laboratory Geomechanical Strength Testing of DGR-3 and DGR-4 Core	Gorski et al., (2009c)
TR-08-25	CERCHAR Abrasivity Testing of Argillaceous Limestone of the Cobourg Formation from DGR-3 and DGR-4	Maloney and Bahrani (2009)
TR-08-26	Laboratory Free Swell Testing of DGR-3 and DGR-4 Core	Micic and Lo (2009)
TR-08-27	Laboratory Diffusion Testing of DGR-3 and DGR-4 Core	Al et al. (2010)
TR-08-28	Laboratory Petrophysical Testing of DGR-3 and DGR-4 Core	Jackson and Wigston (2010)
TR-08-29	Organic Geochemistry and Clay Mineralogy of DGR-3 and DGR-4 Core	Jackson (2009)
TR-08-30	Phase 2 Groundwater Monitoring: US-3, US-7 and US-8	Pinder and Heagle (2010)
TR-08-31	Pressure and Head Monitoring in DGR Boreholes	Sterling and Raven (2010)
TR-08-32	Analysis of Borehole Straddle-Packer Tests in DGR Boreholes	Roberts et al. (2010)
TR-08-33	Two-Phase Flow Parameters from DGR-2, DGR-3 and DGR-4 Petrophysics Data	Calder (2010)
TR-08-34	Assessment of Porosity Data and Gas Phase Presence in DGR Cores	Jackson et al. (2010)
TR-08-35	Analyses of DGR-1, DGR-2, DGR-3 and DGR-4 Borehole Images for Stress Characterization	Valley and Maloney (2010)
TR-08-36	Long-Term Strength Degradation Testing of DGR-3 and DGR-4 Core	Gorski et al. (2009d)
TR-08-37	Vacuum Distillation Experiments on DGR Core	Clark et al. (2010b)
TR-08-38	Radioisotopes in DGR Groundwater and Pore Water	Heagle and Clark (2010)
TR-08-39	Supplementary Uniaxial Compressive Strength Testing of DGR-3 and DGR-4 Core	Gorski et al. (2009e)
TR-08-40	Porewater Characterization – Boreholes DGR-3 and DGR-4	de Haller et al. (2010)

2.2 Other Data Sources

In addition to geoscientific site characterization Technical Reports, other sources of data were used in development of the descriptive geosphere site models. These other sources of data, which are referenced in Section 6 include:

- Compilation of available geological, hydrogeological and geotechnical/geomechanical information for the proposed Bruce DGR as part of a geotechnical feasibility study (Golder Associates Ltd., 2003).
- Geoscientific data compilation, international review and geosynthesis assessment of the Paleozoic sedimentary rock in southern Ontario for radioactive waste disposal (Mazurek, 2004).
- Laboratory and field data collection, review and compilation reports prepared as part of the Ontario Hydro Sedimentary Sequence Study looking at radioactive waste disposal within sedimentary rock formations in Ontario.
- Reports on core drilling, logging and testing of the shallow bedrock (US-series holes) to depths of about 100 m as part of an earlier investigation of the Bruce nuclear site for radioactive waste storage (Lukajic, 1988; Lee et al., 1995).
- Reports on geologic, hydrogeologic and geomechanical conditions of the overburden and shallow bedrock to 60 m depth at the Bruce nuclear site from generating station/intake tunnel construction and operation and monitoring of radioactive waste operations areas and conventional construction landfills (Lukajic et al, 1986; Lukajic and Dupak, 1986; Intera Technologies Ltd., 1988, McKay, 1989).
- Phase 1 Geosynthesis Report (Gartner Lee Limited, 2008a) summarizing the regional geoscientific studies conducted to understand the predictability, stability and geologic isolation provided by the geologic setting at the Bruce nuclear site. Noteworthy supporting studies to this report include Technical Reports on regional geology (Gartner Lee Limited, 2008b), regional geomechanics (Gartner Lee Limited, 2008c), regional and site hydrogeologic modeling (Sykes et al., 2008) and regional hydrogeochemical synthesis (Hobbs et al., 2008).
- Phase 2 Geosynthesis Report (AECOM Canada Ltd., 2010) and supporting Technical Reports.

2.3 DGR Borehole Investigation Program

Most of the geoscientific data presented and discussed in this report were obtained from four deep diamond cored vertical boreholes, DGR-1, DGR-2, DGR-3 and DGR-4. Inclined boreholes DGR-5 and DGR-6 are currently being drilled and tested, and this Project Report will be updated when data from these inclined boreholes become available.

Boreholes DGR-1 and DGR-2, drilled about 40 m apart and were designed to provide two separate boreholes with open bedrock intervals through the relatively shallow dolostone and limestone formations of Silurian and Devonian age (DGR-1) and through the relatively deeper shale and limestone formations of Ordovician age (DGR-2).

DGR-1 was continuously diamond cored, with the upper 182.9 m reamed to accommodate installation of intermediate steel casing. DGR-1 was completed with an open bedrock interval from near the top of the Salina Formation F-Unit shale (182.9 mBGS) to approximately 15 m into the top of the Queenston Formation (462.87 mBGS).

DGR-2 was rotary drilled to depth of 450.7 mBGS to accommodate installation of two intermediate steel casings. DGR-2 was then diamond cored and completed with an open bedrock interval from near the top of the Queenston Formation (450.88 mBGS) to approximately 1 m into the Precambrian basement (862.25 mBGS).

Two separate boreholes for DGR-1 and DGR-2 were designed to minimize vertical cross connection and cross contamination of groundwater between the shallow and deep hydrogeologic environments with suspected distinctly different groundwater chemistry and to minimize risk of borehole loss should caving or other poor drilling conditions be encountered. TR-07-06 describes the rationale and completion of the drilling and casing of boreholes DGR-1 and DGR-2.

Boreholes DGR-3 and DGR-4 were continuously diamond cored from bedrock surface to depths of 869.17 and 856.98 mBGS, respectively, into the Cambrian sandstone. The upper 208.5 m of DGR-3 and the upper 188.7 m of DGR-4 were reamed to accommodate installation of intermediate steel casing. Together, boreholes DGR-1/2, DGR-3 and DGR-4, which are spaced approximately 1047 to 1318 m from each other, triangulate the proposed DGR and allow for assessment of the uniformity of bedrock formation thickness, orientation and properties in the vicinity of the DGR. TR-08-13 describes the drilling and casing installation in boreholes DGR-3 and DGR-4.

A major source of geological, hydrogeological and geomechanical data described in this report is laboratory testing of preserved core samples collected from DGR boreholes. TR-07-06 and TR-08-13 describe the collection and preservation of core samples for laboratory testing from boreholes DGR-1 and DGR-2, and from DGR-3 and DGR-4, respectively. In general core samples were selected to be representative of material for which laboratory testing was to be performed.

3 DESCRIPTIVE GEOLOGICAL SITE MODEL

3.1 Model Elements and Scope

The geologic site model describes the 3-D spatial distribution of all important geologic formations and the occurrence of all important geologic structural features within the Paleozoic (Devonian to Cambrian) and Precambrian bedrock units. The descriptive geologic model provides a basis for geoscientific understanding of the current condition of the Bruce nuclear site, its past evolution and likely future natural evolution over the period of interest for Safety Assessment of the proposed DGR. The descriptive geologic site model also provides the basic framework for the development of descriptive hydrogeological and geomechanical site models that are described in Sections 4 and 5 of this report.

3.2 Data Sources

Primary data sources for the Phase 1 and 2A descriptive geological site model include:

- drilling and core logging of boreholes DGR-1 and DGR-2 (TR-07-05, TR-07-06) and of boreholes DGR-3 and DGR-4 (TR-08-12, TR-08-13);
- borehole geophysical logging of boreholes DGR-1 and DGR-2 (TR-07-08) and of boreholes DGR-3 and DGR-4 (TR-08-15);
- laboratory geochemical, mineralogical and petrographic analyses of DGR-1 and DGR-2 core (TR-07-12, TR-08-01, TR-08-02, TR-08-06) and of DGR-3 and DGR-4 core (TR-08-20, TR-08-21, TR-08-22, TR-08-23, TR-08-29, TR-08-40, TR-08-41);
- drilling and core logging of boreholes US-1 and US-3 to US-7 (Lukajic, 1988);
- drilling, chip sampling and borehole geophysical logging of borehole US-8 (TR-07-19);
- borehole geophysical logging of US-3 and US-7 (TR-08-03);
- 2-D seismic reflection surveys (TR-07-15); and
- regional geological framework developed from related geosynthesis studies (Gartner Lee Limited, 2008b; AECOM Canada Ltd., 2010)

3.3 Reference Stratigraphic Sequence

The reference overburden and bedrock stratigraphic sequence at the Bruce nuclear site, based on the results of DGR-1 to DGR-4 borehole drilling, logging and testing, is schematically illustrated in Figure 3.1. Reference stratigraphy is defined in this report as the stratigraphy present at boreholes DGR-1 and DGR-2 and is required for data presentation purposes due to the slight dip of the bedrock formations at the site (see Section 3.4).

Figure 3.1 and the bedrock formation descriptions that follow in Sections 3.4 and 3.6 are primarily based on the subsurface stratigraphic nomenclature of Armstrong and Carter (2006), lithologic and discontinuity logging of DGR-1 to DGR-4 and US-series boreholes, and the results of geological core workshops attended by senior geologists from the Ministry of Natural Resources, the Ontario Geological Survey, the Geological Survey of Canada and the University of Waterloo (TR-07-05, TR-08-12).

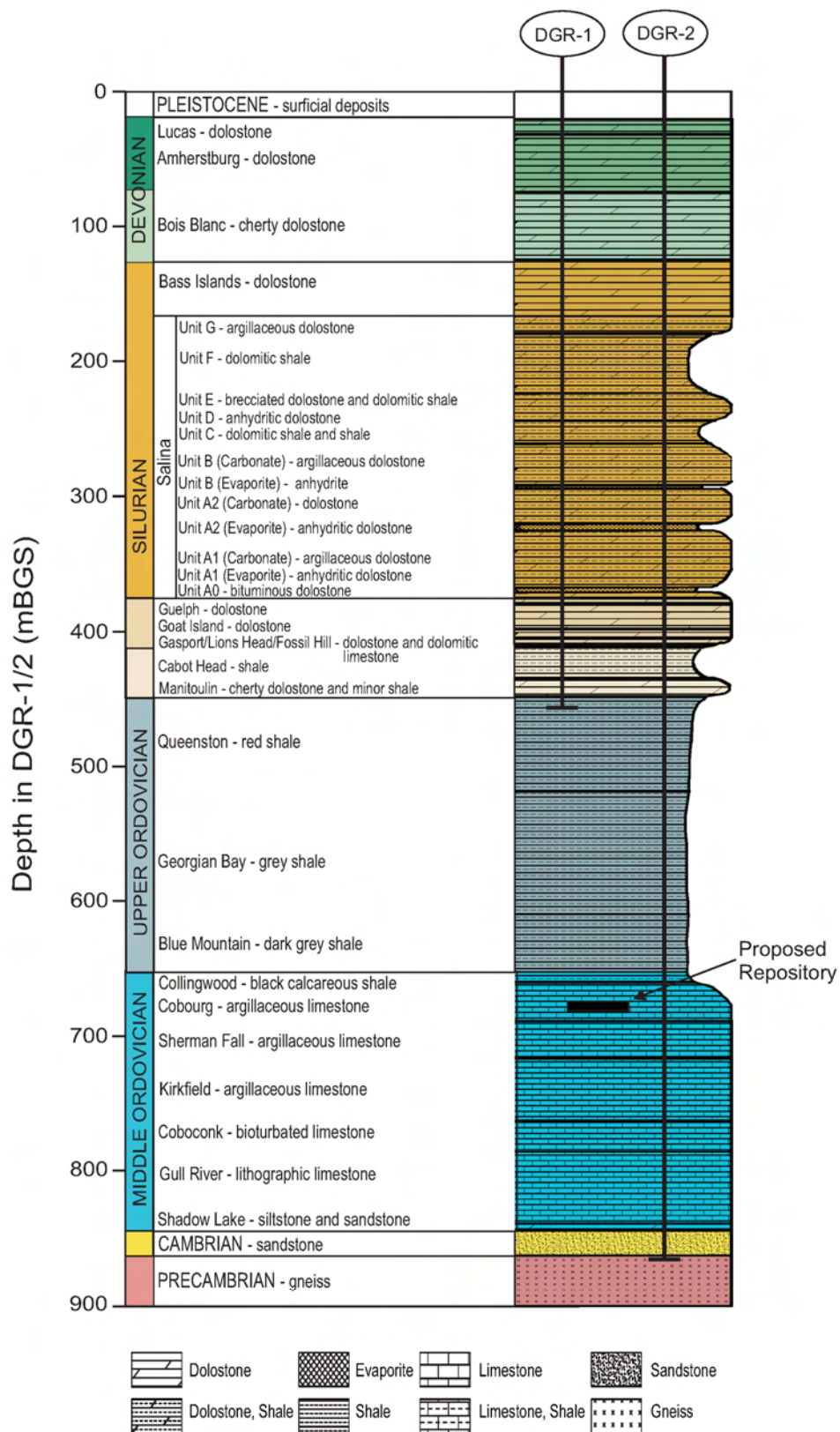


Figure 3.1 Reference stratigraphic column at the Bruce nuclear site based on DGR-1 and DGR-2 borehole data

The geological core workshops were convened to seek expert consensus on the identification and naming of the bedrock formations and members/units present in DGR- and US-series boreholes as well as identification of contacts between formations and units present in these boreholes.

3.4 Formation Depth, Thickness and Orientation

Logging of boreholes DGR-1 to DGR-4 identified the presence of 36 distinguishable bedrock formations, members, units or subunits at the Bruce DGR site (TR-08-12). Table 3.1 summarizes the depth to top and thickness of each bedrock formation, member, unit or subunit in boreholes DGR-1 /DGR-2, DGR-3 and DGR-4. Table 3.1 also lists the strike and dip of the top of each of these bedrock layers based on solution of a simple three-point elevation problem (TR-08-12) assuming all of the boreholes are vertical with zero tilt.

Table 3.1 Summary of top depth, thickness and orientation of DGR bedrock formations, members and units

<i>Formation, Member, Unit</i>	<i>Top Depth (mBGS)</i>			<i>Thickness (m)</i>			<i>Orientation</i>	
	<i>DGR-1/2</i>	<i>DGR-3</i>	<i>DGR-4</i>	<i>DGR-1/2</i>	<i>DGR-3</i>	<i>DGR-4</i>	<i>Strike</i>	<i>Dip</i>
Lucas	20.0	7.9	7.5	10.4	46.6	30.1	-	-
Amherstburg	30.4	54.5	37.6	44.6	39.4	38.6	N16°W	1.15°SW
Bois Blanc	75.0	93.9	76.2	49.0	49.4	49.8	N27°W	0.95°SW
Bass Islands	124.0	143.3	126.0	45.3	44.0	44.1	N25°W	0.95°SW
Salina G Unit	169.3	187.3	170.1	9.3	9.2	7.3	N17°W	0.90°SW
Salina F Unit	178.6	196.5	177.4	44.4	43.1	43.6	N33°W	0.95°SW
Salina E Unit	223.0	239.6	221.0	20.0	23.8	24.5	N35°W	0.90°SW
Salina D Unit	243.0	263.4	245.5	1.6	2.6	1.8	N25°W	1.01°SW
Salina C Unit	244.6	266.0	247.3	15.7	11.9	14.7	N25°W	1.07°SW
Salina B Unit	260.3	277.9	262.0	30.9	25.1	28.8	N24°W	0.86°SW
Salina B Unit-Evap	291.2	303.0	290.8	1.9	1.6	1.7	N24°W	0.55°SW
Salina A2 Unit - Carb	293.1	304.6	292.5	26.6	28.9	28.4	N20°W	0.53°SW
Salina A2 Unit-Evap	319.7	333.5	320.9	5.8	5.1	5.2	N28°W	0.64°SW
Salina A1 Unit - Carb	325.5	338.6	326.1	41.5	41.2	40.7	N21°W	0.60°SW
Salina A1 Unit -Evap	367.0	379.8	366.8	3.5	4.4	5.0	N25°W	0.60°SW
Salina A0 Unit	370.5	384.2	371.8	4.0	2.6	3.8	N19°W	0.63°SW
Guelph	374.5	386.8	375.6	4.1	5.4	4.9	N16°W	0.55°SW
Goat Island	378.6	392.2	380.5	18.8	18.3	18.6	N16°W	0.61°SW
Gasport	397.4	410.5	399.1	6.9	6.5	6.5	N15°W	0.59°SW
Lions Head	404.25	417.0	405.6	4.4	4.5	4.4	N16°W	0.57°SW
Fossil Hill	408.7	421.5	410.0	2.3	1.3	1.5	N17°W	0.57°SW
Cabot Head	411.0	422.8	411.5	23.8	24.7	24.2	N19°W	0.53°SW
Manitoulin	434.8	447.5	435.7	12.9	9.5	10.6	N19°W	0.57°SW
Queenston	447.7	457.0	446.3	70.4	74.4	73.0	N24°W	0.42°SW
Georgian Bay	518.0	531.4	519.3	90.9	88.7	88.7	N17°W	0.63°SW
Blue Mountain	608.9	620.1	608.0	42.7	44.2	45.1	N23°W	0.54°SW
Collingwood Member	651.6	664.3	653.1	7.9	8.7	8.4	N14°W	0.59°SW
Cobourg	659.5	673.0	661.5	28.6	27.8	27.5	N14°W	0.63°SW
Sherman Fall	688.1	700.8	689.0	28.0	29.0	28.3	N17°W	0.60°SW
Kirkfield	716.1	729.8	717.3	45.9	45.9	45.7	N18°W	0.65°SW
Coboconk	762.0	775.6	763.0	23.0	23.7	23.8	N19°W	0.65°SW

Gull River	785.0	799.3	786.8	53.6	51.7	52.2	N16°W	0.68°SW
Shadow Lake	838.6	851.0	839.0	5.2	4.5	5.1	N19°W	0.59°SW
Cambrian	843.8	855.5	844.1	16.9	>13.7	> 12.9	N18°W	0.55°SW
PreCambrian	860.7	-	-	-	-	-	-	-

Table 3.1 shows the formation thicknesses and orientations in DGR boreholes are remarkably uniform over the DGR borehole separation distances of 1047 to 1318 m. The thickness and orientation of formations are somewhat more variable above the Salina B Unit and more uniform below the B Unit. This is most likely due to collapse and minor rotation of the overlying bedrock following paleo dissolution of the Salina B and D Unit salt beds. Below the Salina B Unit, formation thicknesses in DGR boreholes are within 1-2 m of each other in different holes, and the formation strikes are within 5-10° and formation dips are within 0.10° for each formation. The average strike and dip of the deeper Silurian and the Ordovician Formations of N20°W/0.6°SW at the Bruce nuclear site is consistent with results of the regional 3-D geological framework model (Gartner Lee Limited, 2008b). Noteworthy minor excursions of uniformity of thickness and orientation for formations below the Salina B Unit at the Bruce nuclear site include the Queenston Formation whose upper contact is a recognized erosional unconformity.

Additional discussion of formation orientation is given in Section 3.8. This section describes the identification of distinct thin marker beds in the DGR Paleozoic bedrock sequence at the Bruce nuclear site that provide very accurate strike and dip information.

3.5 Core Quality and Natural Fracture Frequency

Table 3.2 lists the rock quality descriptions for core and bedrock formations, including RQD (Rock Quality Designation), used in this report that are determined from core logging data based on International Society for Rock Mechanics (1977) guidance. RQD values determined for the 76 mm diameter core from DGR-1 and DGR-2 were calculated as the sum of lengths of core greater than 15 cm length (i.e., twice the core diameter) excluding drilling-induced breaks, divided by length of hole drilled per core run. Core recovery is defined as the length of core recovered per length of hole drilled per core run. Core runs were typically 3.05 m in length. Natural fracture frequency was calculated as the total number of identified natural fractures divided by the length of recovered core.

Table 3.2 Summary of rock quality descriptions and fracture frequency

<i>RQD (%)</i>	<i>Core Quality Description</i>	<i>Natural Fracture Frequency (/m)</i>	<i>Formation Fracture Description</i>
0-25	Very Poor	>10	Highly Fractured
25-50	Poor	>1.0-10	Moderately Fractured
50-75	Fair	0.5-1.0	Sparsely Fractured
75-90	Good	<0.5	Very Sparsely Fractured
90-100	Excellent	0	Unfractured

Figures 3.2 and 3.3 summarize the RQD and natural fracture frequency data determined from core logging of DGR-1 to DGR-4 as described in TR-07-06 and TR-08-13 with calculated parameter values plotted at the mid depth of each core run in each borehole. Data from boreholes DGR-1 and DGR-2 are combined in these figures to create a combined data set for comparison against DGR-3 and

DGR-4 results.

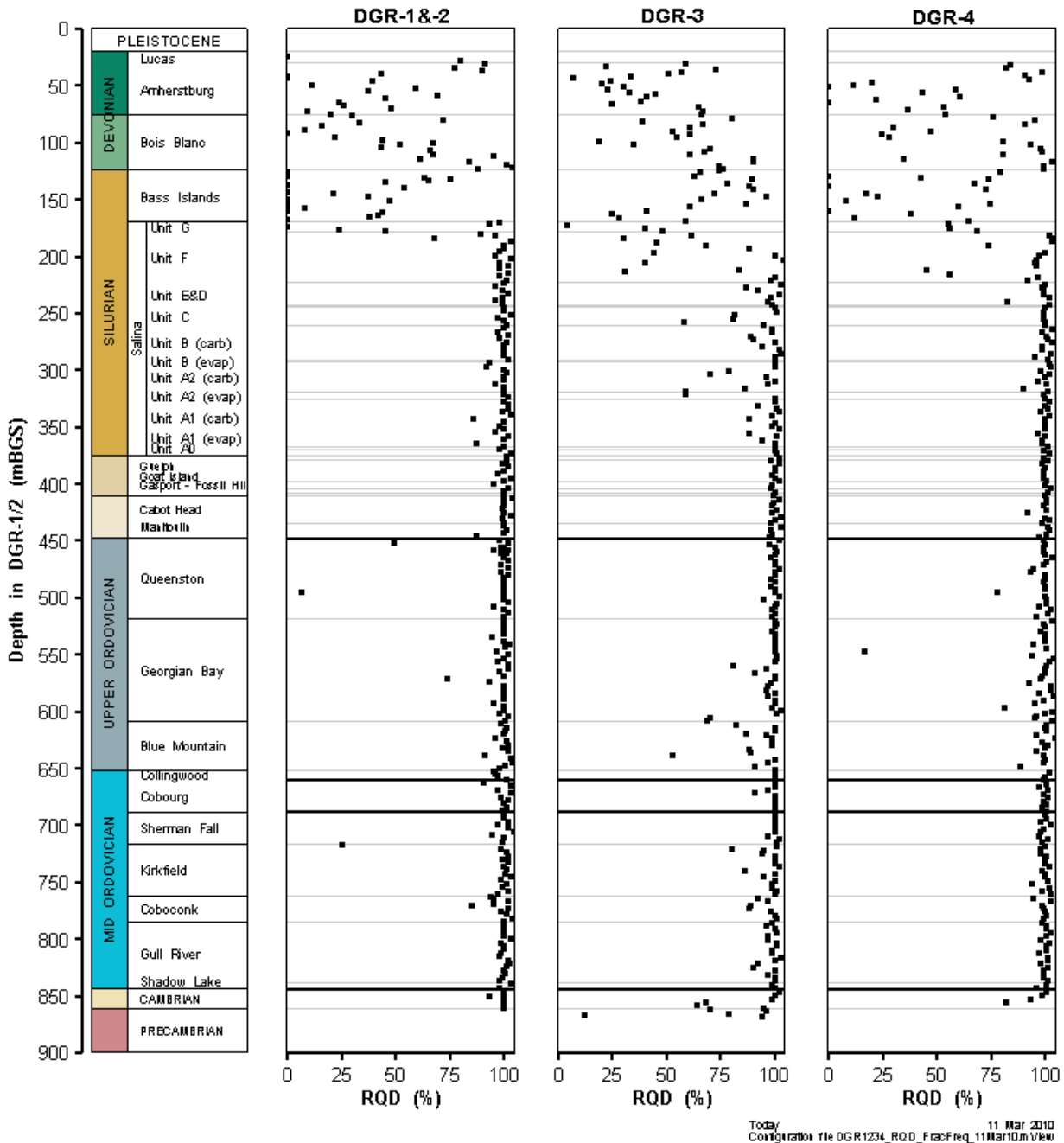


Figure 3.2 Profiles of Core RQD in DGR-1/DGR-2, DGR-3 and DGR-4. Occasional low RQD values in the Ordovician shale and limestones are due core grinding during drilling.

Because core recovery and RQD are calculated from lengths of recovered core and core run lengths, these core parameters may slightly exceed 100% if the length of recovered core exceeds the core run length. Such conditions often occur when a short stub of core is left in the borehole due to breakage of the core at the end of a core run above the bottom depth of drilling. These minor overestimates of core recovery and RQD are balanced by comparable underestimates from adjoining core runs such that on average, accurate core recovery and RQD are obtained during the drilling and core logging process.

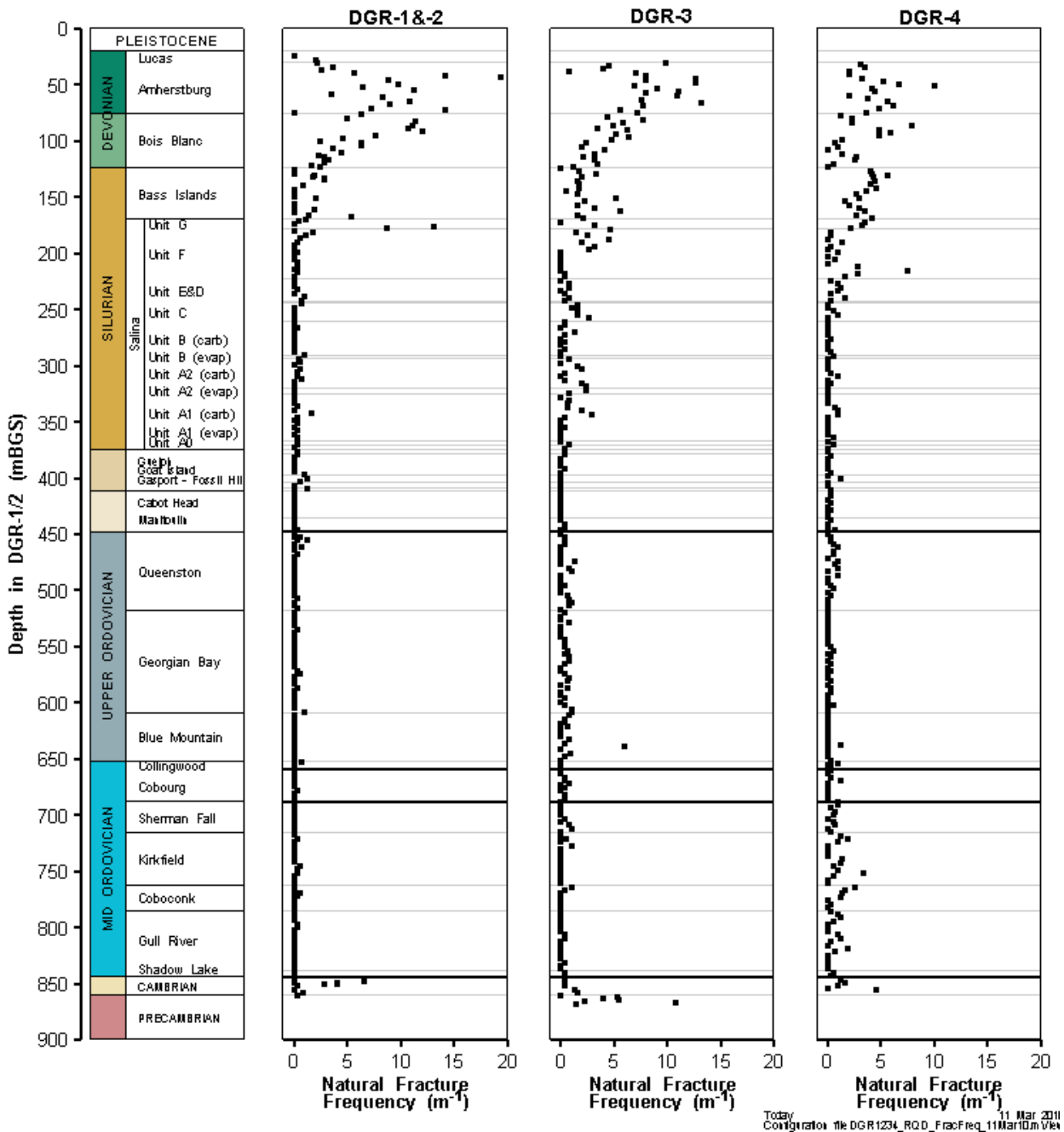


Figure 3.3 Profiles of core natural fracture frequency in DGR-1/DGR-2, DGR-3 and DGR-4

Figures 3.2 and 3.3 show that Devonian and Upper Silurian dolostones are moderately to highly fractured and of poor to fair RQD, whereas the deeper Silurian formations below the Salina G Unit and the Ordovician shales and argillaceous limestones are very sparsely fractured to unfractured with excellent RQD. Many of the low core recoveries and RQDs recorded for the Bois Blanc and Bass Islands Formations were attributed to difficult drilling conditions created in part by alternating hard and soft beds within these formations. Occasional joints/natural fractures were also identified within the deeper Silurian and Ordovician formations from core logging (TR-07-06) and borehole geophysical logging (TR-07-08). These core quality and natural fracture frequency characteristics are very similar in all DGR boreholes. More detailed discussion of these natural fractures is given in Section 3.9.

Figure 3.3 also illustrates that natural fracture frequency increases in the Cambrian sandstone. Results of hydraulic testing of this bedrock sequence (TR-08-32), demonstrate that many of these Cambrian natural fractures are open and permeable.

Table 3.3 provides an overall summary of core recovery, RQD and natural fracture frequency in boreholes DGR-1 to DGR-4 from logging of recovered core given in TR-07-06 and TR-08-13. Table 3.3 lists the minimum, maximum and arithmetic mean values for these parameters grouped by formation and unit from all borehole data.

3.6 Rock Mineralogy and Geochemistry

Samples of core recovered from DGR-1 through DGR-4 were analysed for a full suite of laboratory tests intended to determine intact rock mineralogy and lithogeochemistry, i.e., total rock chemistry including pore waters, as well as to confirm or modify the stratigraphy and lithology of the bedrock sequence as described by Armstrong and Carter (2006).

All core samples are identified in this report by borehole name and mid-sample depth in mBGS. For example, core sample DGR2-606.62 describes a core sample collected from borehole DGR-2 with the middle of the core sample collected from a depth of 606.62 mBGS.

Laboratory testing included thin section petrography with electron microscope analyses to confirm optical identifications, whole rock and clay fraction X-ray diffraction (XRD) testing, scanning electron microscope/energy dispersive spectral (SEM/EDS) analyses, trace element ICP analyses, elemental oxide analyses by ICP optical emission spectrometry, carbon and sulphur infrared spectroscopy analyses, and chloride by instrumental neutron activation analyses.

This work was completed by GeoConsult (TR-07-12) and Activation Laboratories (TR-08-01, TR-08-02) for core samples collected from DGR-1 and DGR-2; and by University of Bern for core samples collected from DGR-2 (TR-08-06, TR-08-40) and DGR-3. For DGR-3 and DGR-4, similar analyses were conducted but clay mineral analysis was only conducted on the Upper Ordovician shales; this study also included the organic geochemical analysis of these shales (TR-08-29). Otherwise, DGR-3 and DGR-4 cores were tested in a similar manner as were DGR-1 and DGR-2 cores, i.e., petrography with electron microprobe analysis by GeoConsult (TR-08-20, TR-08-21) and XRD, SEM/EDS and lithogeochemistry by SGS Laboratories (TR-08-22, TR-08-23) and by University of Bern (TR-08-40).

The similar rock mineralogy and geochemistry analyses performed for core from DGR boreholes by different laboratories allow for corroboration of laboratory test results.

3.6.1 Whole Rock Mineralogy

3.6.1.1 Major Minerals

Figures 3.4 and 3.5 show the individual core measurements and arithmetic formation averages of major minerals identified in DGR-1 to DGR-4 core. Figure 3.4 shows calcite and dolomite (including ankerite or Fe dolomite) in weight percent. Figure 3.5 shows quartz and total sheet silicates or clay mineral contents. Clay minerals also include minor amounts of several dioctahedral micas (i.e., muscovite, hydromuscovite) which are typically not distinguishable from common clay minerals such as illite in XRD analyses. Throughout this report the term illite refers to illite and other related indistinguishable micas. Although not shown on plots in this section, other noteworthy minerals identified in DGR cores include anhydrite, gypsum, pyrite, hematite, halite and feldspar.

Table 3.3 Summary of core recovery, RQD and natural fracture frequency logged in boreholes DGR-1 to DGR-4

Formation	% Recovery			% RQD			Natural Fracture Frequency (m⁻¹)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Lucas + Amherstburg Formations	20%	117%	91%	0%	109%	47%	0.0	19.3	5.4
Bois Blanc Formation	24%	105%	92%	0%	104%	68%	0.0	12.0	3.6
Bass Islands Formation	0%	101%	77%	0%	96%	33%	0.0	5.7	2.7
Salina Formation - G Unit	33%	102%	72%	0%	98%	54%	0.0	13.1	3.8
Salina Formation - F Unit	0%	191%	89%	31%	186%	92%	0.0	7.5	1.1
Salina Formation - E Unit	96%	104%	100%	58%	102%	98%	0.0	2.6	0.6
Salina Formation - D Unit + C Unit	97%	103%	100%	89%	103%	100%	0.0	1.3	0.3
Salina Formation - B Unit	93%	103%	100%	71%	103%	100%	0.0	1.9	0.1
Salina Formation - A2 Unit	90%	103%	100%	59%	103%	99%	0.0	2.4	0.2
Salina Formation - A1 Unit + A0 Unit	94%	141%	100%	88%	141%	100%	0.0	2.9	0.2
Guelph, Goat Island, Gasport, Lions Head, Fossil Hill Formations	97%	103%	100%	95%	103%	100%	0.0	1.3	0.3
Cabot Head Formation	91%	111%	100%	91%	111%	100%	0.0	0.3	0.1
Manitoulin Formation	96%	102%	100%	87%	102%	99%	0.0	0.3	0.1
Queenston Formation	7%	104%	99%	7%	103%	97%	0.0	1.3	0.3
Georgian Bay Formation	16%	124%	98%	16%	124%	97%	0.0	1.0	0.1
Blue Mountain Formation	89%	115%	100%	53%	115%	100%	0.0	6.0	0.1
Cobourg Formation - Collingwood Member	90%	188%	100%	90%	188%	100%	0.0	1.0	0.2
Cobourg Formation - Lower Member	90%	103%	100%	90%	103%	100%	0.0	1.3	0.2
Sherman Fall Formation	80%	133%	100%	80%	133%	100%	0.0	1.0	0.3
Kirkfield Formation	25%	103%	98%	25%	103%	98%	0.0	3.4	0.6
Coboconk Formation	85%	104%	99%	85%	104%	98%	0.0	2.6	0.7
Gull River Formation	97%	103%	100%	90%	103%	100%	0.0	1.9	0.3
Shadow Lake Formation	79%	103%	100%	68%	103%	99%	0.0	1.3	0.3
Cambrian Sandstone	86%	132%	100%	0%	120%	99%	0.0	10.8	1.7
Precambrian	100%	100%	100%	100%	100%	100%	0.3	0.3	0.3

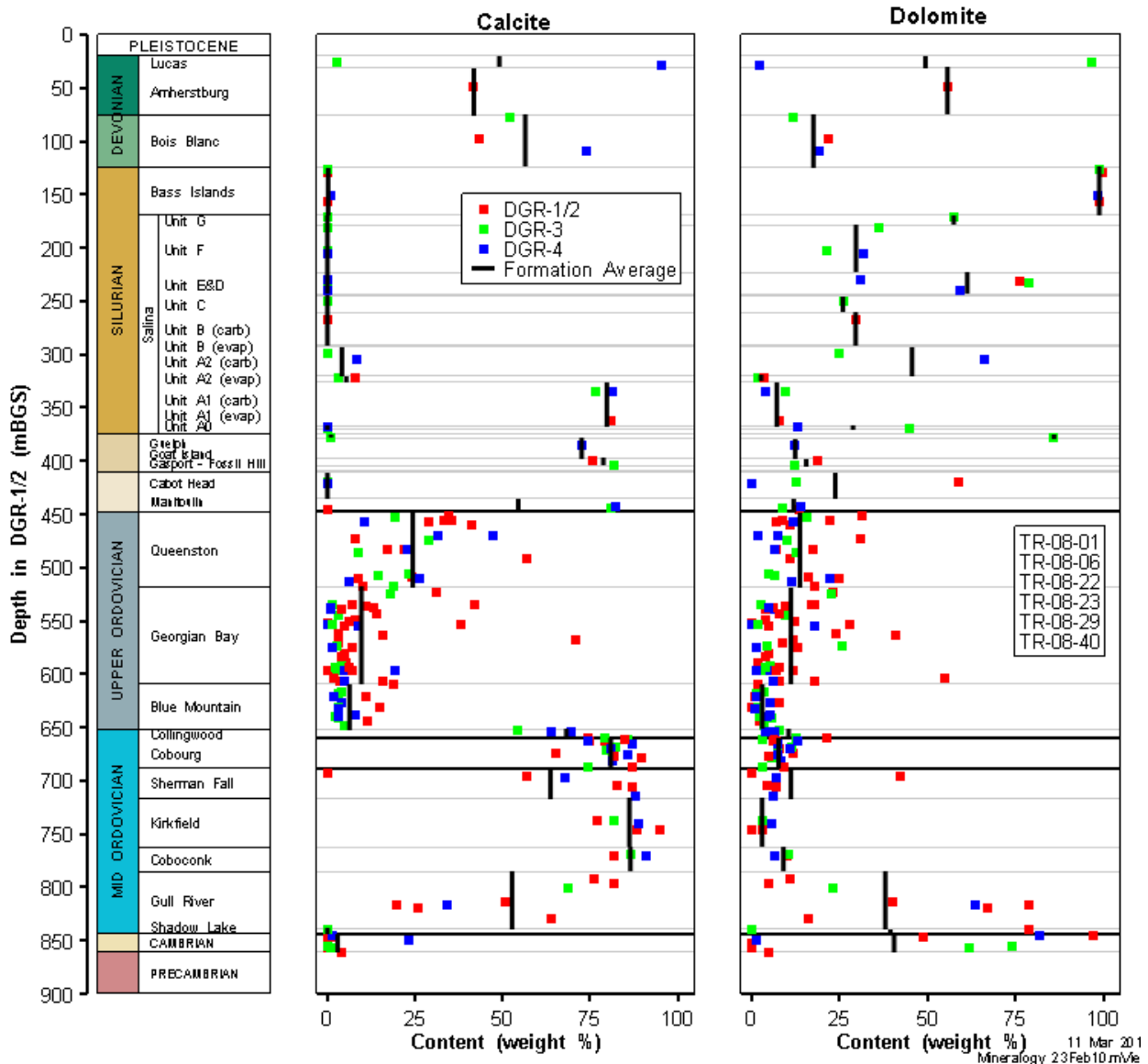


Figure 3.4 Profiles of calcite and dolomite in DGR cores showing point measurements and arithmetic formation averages

As shown on these figures, no significant mineralogical differences are apparent between the Phase 1 cores (DGR-1 and DGR-2) and those from Phase 2A (DGR-3 and DGR-4).

Figures 3.4 and 3.5 show that Devonian and Upper Silurian carbonate sequences are predominately dolostone with some minor limestone-rich layers and minor occurrence of sheet silicates as illite and mica. The quartz identified in these Devonian carbonate rocks is mostly chert. Increasing quartz content is also evident with depth in the Ordovician shales. Quartz content is minimal in the Ordovician limestones with maximum values of about 85% detected in the middle to lower sections of the Cambrian sandstone. Figure 3.4 also shows that parts of the Cabot Head Formation shale are locally calcareous and dolomitized and that the Queenston Formation shale is both calcareous and dolomitized particularly in upper parts of the formation. The Georgian Bay, Blue Mountain and Collingwood shales also show dolomite presence. The deeper Ordovician sequence including the Cambrian and overlying Shadow Lake Formation and the lower parts of the Gull River Formation, also show presence of significant amounts of dolomite, however the Middle Ordovician carbonates are

predominately calcite.

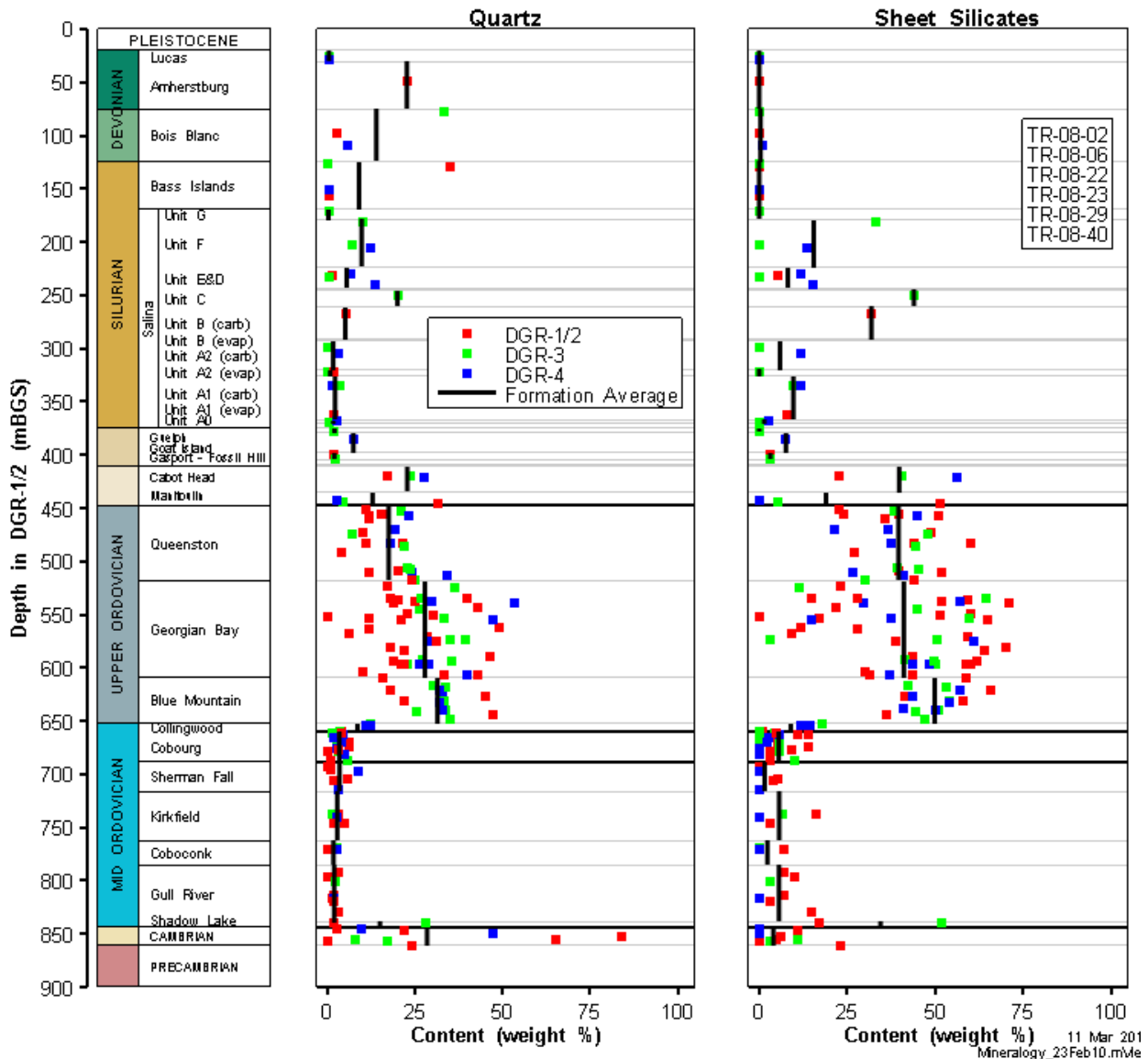


Figure 3.5 Profiles of quartz and total sheet silicates in DGR cores showing point measurements and arithmetic formation averages

The clay content of the Paleozoic sequence as reported by total sheet silicates based on XRD analyses, ranges from zero for the Devonian and Upper Silurian dolostones to 15 to 70% within the Silurian Cabot Head and Ordovician shales of the Queenston, Georgian Bay and Blue Mountain Formations. The clay content of the Ordovician limestones is typically less than 20%. The total sheet silicates within the Precambrian basement are not clays, but are micaceous minerals including biotite and muscovite.

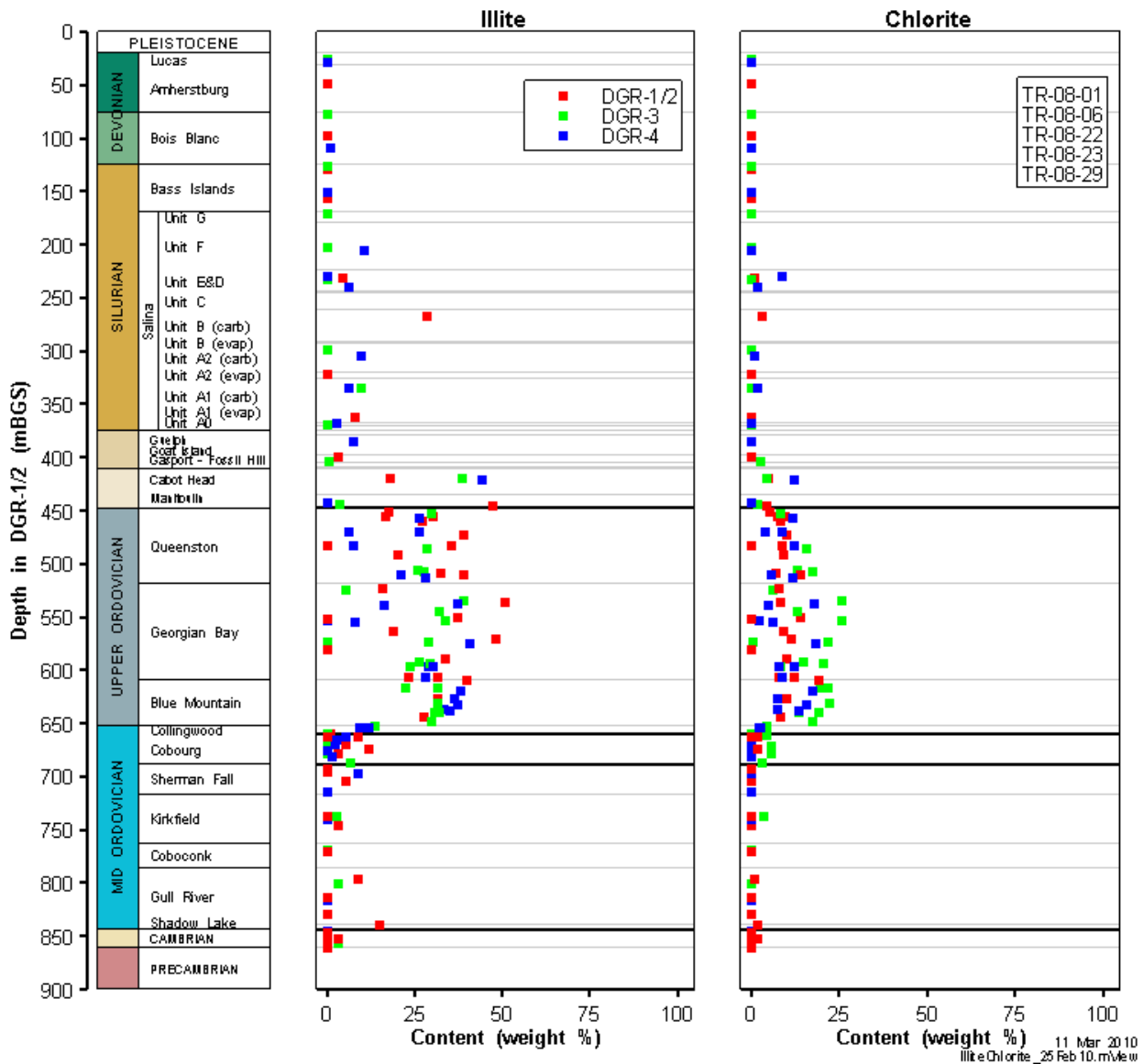


Figure 3.6 Profiles of illite and chlorite clay mineral content in DGR cores

Figure 3.6 shows the composition of the sheet silicates is primarily illite and related indistinguishable micas with lesser amounts of chlorite. Illite is also present within the Salina E Unit dolomitic shale, B Unit argillaceous dolostone and A1 Unit argillaceous dolostone. In the Salina above the B Unit, the illite is frequently associated with a clay-rich matrix that encompasses the brecciated dolostone created by dissolution of the former B Unit salt and collapse of overlying formations. Illite and chlorite dominate the Ordovician shale mineralogy. Only trace levels (2%) of chlorite are evident in the Ordovician limestones and the Shadow Lake Formation. Illite+mica content of the Ordovician limestones appears to decrease with depth from about 12% in the Cobourg Formation to zero in the bottom of the Gull River Formation.

Figure 3.6 also shows that the illite content of the Ordovician shales is variable ranging from about 15 to 50%. The magnitude and range of chlorite contents in the Ordovician shales is less ranging from 5 to 15%. Only trace levels (2%) of chlorite are evident in the Ordovician limestones and the Shadow

Lake Formation. Illite content of the Ordovician limestones appears to decrease with depth from about 12% in the Cobourg Formation to zero in the bottom of the Gull River Formation.

The clay fraction of the DGR-3 and DGR-4 Ordovician shale cores was investigated (TR-08-29) during Phase 2A as part of a larger study involving the organic geochemistry of these shales. The clay minerals identified (Figure 3.7) are predominantly illite and mica – typically > 50% of all clay minerals – chlorite (20-45%) with minor kaolinite and interstratified illite-smectite. The interstratified illite-smectite is predominantly illite, with only 5-10% smectite layers, which therefore comprise only about one percent of all clay minerals. Typically these Ordovician shales contained about 20-30% quartz and highly variable amounts of carbonate minerals. The major iron mineral changes from hematite in the Queenston to pyrite in the Georgian Bay and Blue Mountain, in which iron concentrations reached 4-6 wt%.

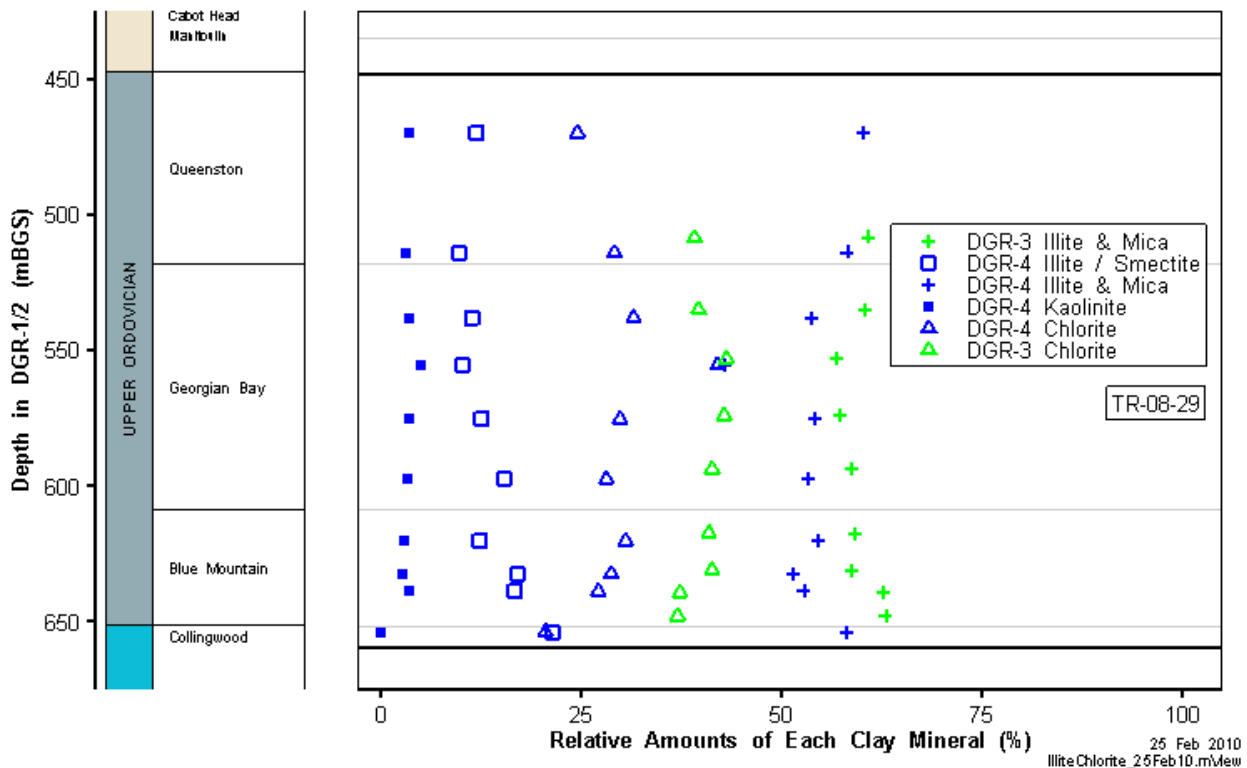


Figure 3.7 Composition of clay fraction present in Ordovician shales of DGR-3 and DGR-4 cores

Comparison of the major mineralogy identified by the different analytical laboratories (i.e., GeoConsult, Activation Laboratories, University of Bern, SGS Laboratories and Core Laboratories) shows comparable results, although the range of results within individual formations and groups of formations is large and suggests that heterogeneity of mineralogy at core scale is significant in these formations.

3.6.1.2 Soluble Minerals

Particular attention has been paid throughout the DGR project to the occurrence of soluble evaporite minerals, such as (1) the sulphate minerals gypsum, anhydrite and celestite, and (2) halite (Table 3.4). These are common in minor or trace concentrations – i.e., <10% – indicating the absence of recent advection through these core sections and presumably through adjacent sections of these formations unless discontinuities indicate otherwise.

Table 3.4 Detection of halite in DGR cores submitted for SEM/EDS analyses

<i>Formation</i>	<i>SEM/EDS detection</i>	<i>XRD detection</i>	<i>Petrographic detection</i>	<i>Nbr of Cores with halite detections</i>	<i>Halite detection in cores</i>
Salina E Unit	✓			2	DGR3-250.98; DGR4-229.77.
Salina C Unit	✓	✓		1	DGR3-270.06
Salina A1 Unit	✓			1	DGR4-335.71.
Guelph	✓			1	DGR3-391.34
Gasport		✓		1	DGR1-399.85
Cabot Head	✓	✓		3	DGR1-419.99; DGR3-432.28; DGR4-422.01.
Manitoulin	✓	✓		2	DGR1-446.25; DGR3-454.24.
Queenston	✓	✓	✓	10	DGR1-456.01; DGR2-482.45; DGR2-535.56; DGR3-462.70; DGR3-496.93; DGR3-518.25; DGR4-456.41; DGR4-469.29; DGR4-482.79; DGR4-510.88.
Georgian Bay	✓	✓		8	DGR2-523.08; DGR2-606.62; DGR2-606.96; DGR3-558.29; DGR3-603.90; DGR4-539.39; DGR4-595.58; DGR4-606.28.
Blue Mountain	✓	✓		3	DGR3-628.54; DGR4-627.38; DGR4-638.49.
Cobourg	✓			2	DGR3-691.32; DGR3-699.62.
Sherman Fall	✓			1	DGR2-704.87.
Gull River	✓			2	DGR2-816.85; DGR2-830.05.
Cambrian	✓			1	DGR3-856.28.

Some Silurian formations are predominately composed of sulphate minerals, e.g., the Salina A1 and A2 anhydrite units. Anhydrite was frequently found within the Upper Silurian dolostones and appears to be present in trace amounts in the Middle Ordovician limestones because of their apparent dissolution during pore-water extraction from Cobourg Formation cores (TR-08-19). Gypsum was preferentially observed within the Salina G to A2 Units and occasionally within deeper Lower Silurian and Upper Ordovician shales.

Halite was specifically targeted for mineral identification because of its solubility in brine (~6000 mmol/kg_w) and its role as an indicator of the absence of recent groundwater flow. Thus the presence of halite recommends the formation as acting as an aquitard. It was frequently detected as fracture-infill and grain-boundary materials in the Ordovician shales (Queenston, Georgian Bay and Blue Mountain Formations). It was also detected by SEM/EDS within the rock matrix of the overlying Silurian formations, such as Salina E and A1 dolostones, Salina C Unit and Cabot Head shales, Guelph dolostone, Gasport dolomitic limestone and Manitoulin dolostone and in the underlying lower Ordovician Cobourg, Sherman Fall and Gull River limestones. Table 3.4 summarizes the cores in which halite was detected, usually by SEM/EDS inspection, but on occasion by XRD or optical microscopy (i.e., petrography).

The two styles of halite occurrence are presented as SEM photographs in Figures 3.8 and 3.9 with the elemental data shown in Table 3.5 for the Queenston sample and 3.6 for the Cambrian. The points identified on the SEM photograph are at the top left-hand corner of the number, which refers to the same number in the tables. In the Queenston core the halite was observed to occur as interstitial veins in a matrix of silicate and carbonate minerals, similar to the photo of orange halite in the Queenston vein shown in Figure 3.43, whereas in the Cambrian sample the halite forms a boundary rim around a silicate mineral in a dolomite matrix.

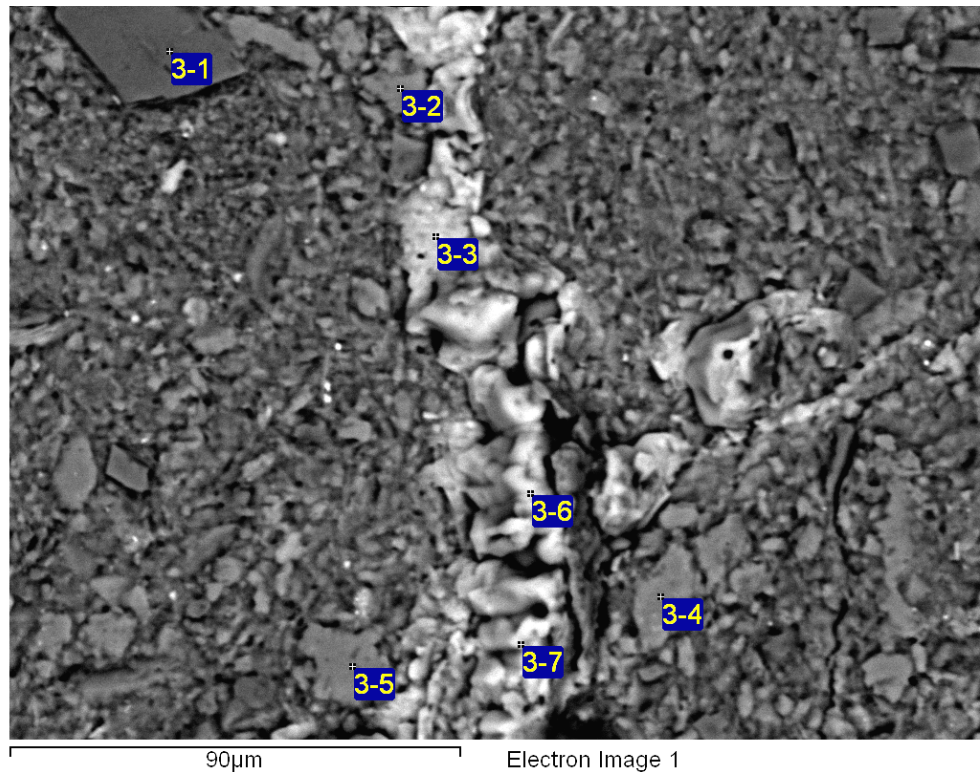


Figure 3.8 Halite in DGR3-518.25 (Queenston Formation)

Table 3.5 Semi-quantitative spot analysis of halite, calcite, dolomite and feldspar in Queenston Formation

<i>Sample: DGR3 – 518.25</i>					<i>Elements (in Wt.%)</i>				
<i>Spots</i>	<i>O</i>	<i>Na</i>	<i>Mg</i>	<i>Al</i>	<i>Si</i>	<i>Cl</i>	<i>K</i>	<i>Ca</i>	<i>Fe</i>
3-1	58.93		6.33	0.72	15.19		0.36	17.16	1.30
3-2	56.62		0.69	0.48	1.12	0.43	0.37	39.81	0.48
3-3	3.60	38.13		1.05	2.74	52.39	0.47	1.11	0.51
3-4	56.50		0.42		0.33	0.25		42.51	
3-5	54.58	0.57	0.67		0.38	0.57		42.65	0.58
3-6	7.17	35.56		0.62	1.01	55.23		0.40	
3-7	14.79	32.11		2.09	3.06	46.32	0.90	0.37	0.35

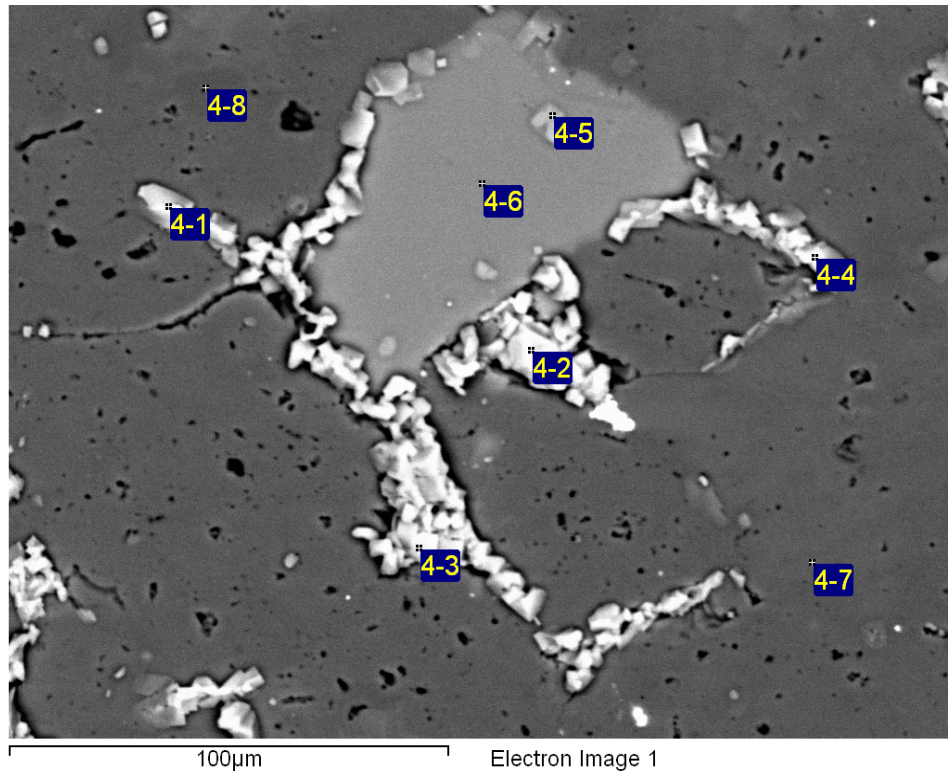


Figure 3.9 Halite in DGR3-856.28 (Cambrian Formation)

Table 3.6 Semi-quantitative spot analysis of halite, dolomite and feldspar in Cambrian Formation

Sample: DGR3 – 856.28				Elements (in Wt.%)						
Spots	O	Na	Mg	Al	Si	S	Cl	K	Ca	Ba
4-1	3.62	37.75	1.91	0.29	0.71	0.46	48.68	0.26	6.31	
4-2		40.31					59.33		0.36	
4-3		34.95		0.28	0.60		63.34	0.27	0.56	
4-4	5.70	33.45	0.54				58.40		1.90	
4-5	21.97	15.25		7.88	26.43		17.18	11.29		
4-6	49.11	0.40		8.91	29.03			11.90		0.65
4-7	59.48		15.34						25.19	
4-8	59.38		15.68						24.94	

Part of the organic geochemistry investigation (TR-08-29) also involved testing Ordovician shale samples at Core Labs for whole-rock and clay-mineral mineralogy by XRD. Halite was detected and quantified in 17 of 19 samples. The DGR-3 samples averaged 0.7 wt % halite, while DGR-4 samples averaged 0.6 wt %. The maximum halite concentrations were in the Blue Mountain shale, in which concentrations ranged from 0.5 to 1.4 wt %.

3.6.2 Lithochemochemistry

Figures 3.10, 3.11 and 3.12 show the results of lithochemical analyses of DGR core samples for major elemental oxides including CaO, MgO, SiO₂, and Al₂O₃, Fe₂O₃ as well as chloride. These compounds and other elemental oxide contents including SO₄, K₂O, MnO₂, Na₂O, P₂O₅ and CO₂ are also reported in TR-08-02, TR-08-22 and TR-08-23. Table 3.7 lists the major elemental geochemistry for DGR-1 and DGR-2 from TR-08-02 that are of use in identification of major rock mineralogy. Review of Figures 3.10 to 3.12 and of Table 3.7 shows that no significant variations were detected between the oxide geochemistry of Phase 1 (DGR-1 and DGR-2) samples and those from Phase 2A (DGR-3 and DGR-4).

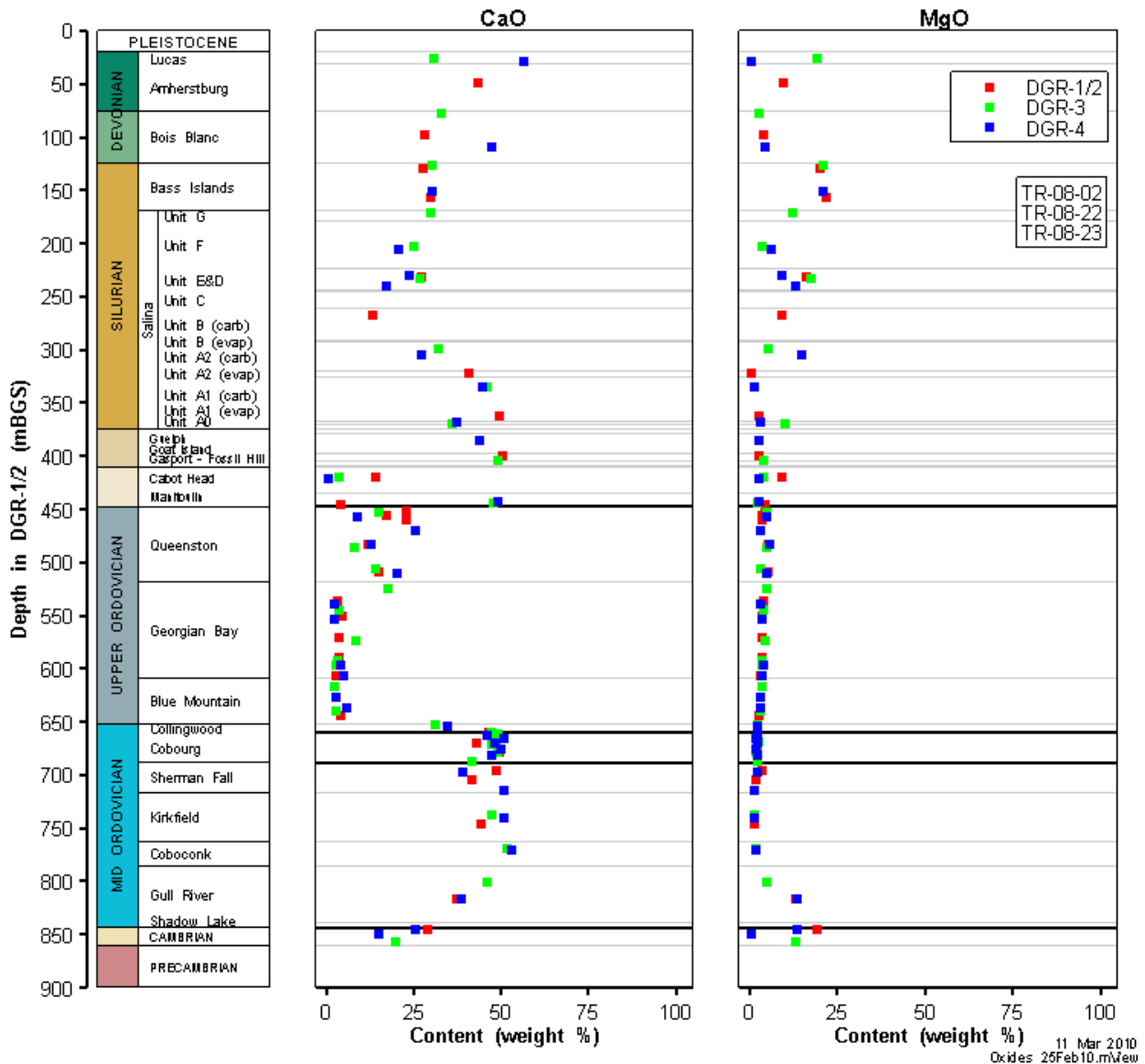


Figure 3.10 Profile of calcium and magnesium oxide content in DGR cores

Table 3.7 Summary of elemental geochemical analyses of DGR-1 and DGR-2 Core (weight %)

<i>Sample</i>	<i>Formation</i>	<i>CaO</i>	<i>MgO</i>	<i>SiO₂</i>	<i>Al₂O₃</i>	<i>SO₄</i>	<i>Fe₂O₃</i>	<i>K₂O</i>	<i>Cl</i>
DGR1-049.16	Amherstburg	43.49	9.48	1.46	0.35	0.4	0.22	0.05	0.05
DGR1-097.08	Bois Blanc	27.99	4.00	39.2	0.83	0.6	0.40	0.33	0.04
DGR1-130.03	Bass Islands	27.73	20.02	5.52	1.16	0.3	0.33	0.66	0.04
DGR1-156.63	Bass Islands	29.97	21.98	0.33	0.08	<0.3	0.07	0.05	0.05
DGR1-231.49	Salina E Unit	27.26	16.12	14.58	3.66	10.6	1.65	0.98	0.13
DGR1-267.78	Salina B Unit	13.38	9.21	36.51	9.20	6.8	3.75	2.37	0.63
DGR1-322.19	Salina A2 Unit-Evap.	40.86	0.36	1.49	0.08	69.8	0.03	<0.01	0.04
DGR1-361.76	Salina A1 Unit	49.64	2.61	4.31	1.45	2.7	0.57	0.47	0.12
DGR1-399.85	Gasport	50.29	2.77	2.07	0.35	<0.3	0.58	0.21	0.10
DGR1-419.99	Cabot Head	14.10	9.13	33.58	9.61	0.5	3.91	3.21	0.61
DGR1-446.25	Manitoulin	4.00	4.28	49.31	15.42	<0.3	8.21	5.05	0.81
DGR1-455.45	Queenston	16.98	3.74	36.44	11.72	<0.3	5.48	3.69	0.63
DGR1-456.01	Queenston	17.02	3.89	35.68	11.36	<0.3	5.24	3.57	1.38
DGR1-460.77	Queenston	22.95	3.64	21.42	9.89	<0.3	3.64	3.09	0.51
DGR2-451.33	Queenston	22.83	4.37	29.96	9.47	<0.3	3.67	3.04	0.45
DGR2-482.45	Queenston	11.77	5.16	42.09	13.26	0.4	5.04	4.27	0.58
DGR2-508.93	Queenston	14.75	5.10	39.74	11.48	<0.3	5.18	3.50	0.57
DGR2-535.56	Georgian Bay	2.97	4.09	51.25	16.31	<0.3	7.09	5.13	0.62
DGR2-550.28	Georgian Bay	4.29	3.60	53.54	15.19	0.4	6.59	4.90	0.56
DGR2-570.73	Georgian Bay	3.48	3.74	51.53	15.61	0.4	7.01	4.92	0.60
DGR2-590.10	Georgian Bay	3.35	3.41	53.94	15.38	0.6	6.77	4.57	0.61
DGR2-606.62	Georgian Bay	2.84	3.34	55.47	15.62	1.8	6.62	4.67	0.57
DGR2-606.96	Georgian Bay	2.76	3.16	55.57	16.28	0.8	6.96	4.94	0.57
DGR2-626.29	Blue Mountain	2.79	3.15	54.83	16.49	0.9	6.95	4.80	0.51
DGR2-644.49	Blue Mountain	4.14	2.87	53.13	15.76	1.4	6.49	4.62	0.45
DGR2-659.31	Collingwood Member	46.60	2.08	8.37	2.32	0.4	0.89	0.92	0.10
DGR2-669.27	Cobourg	42.90	2.19	11.98	3.31	0.5	1.01	1.42	0.14
DGR2-677.93	Cobourg	49.67	2.04	5.03	1.25	0.4	0.68	0.55	0.08
DGR2-695.51	Sherman Fall	48.56	3.34	4.17	1.01	0.4	0.74	0.39	0.08
DGR2-704.87	Sherman Fall	41.48	1.91	14.00	3.86	1.2	1.40	1.64	0.18
DGR2-745.97	Kirkfield	44.30	1.54	11.81	2.83	0.7	0.91	1.19	0.11
DGR2-816.85	Gull River	37.42	12.92	2.46	0.32	<0.3	0.38	0.15	0.24
DGR2-844.95	Cambrian	29.11	19.39	7.04	0.45	<0.3	0.64	0.39	0.26

The major elemental oxide data provide confirmation of the mineralogy presented in Figures 3.5 and 3.6 and discussed in Section 3.7. The CaO and MgO data (Figure 3.10) show that most of the Devonian and Silurian carbonates are dolomitic, that the Queenston shale is calcareous, and that there is dolomitization of the minor carbonate content of the Cabot Head shale and of the Georgian Bay and Blue Mountain shales and of the lower Gull River Formation and upper Cambrian rocks. These data further show that most of the Ordovician limestones are indeed limestone with very minor dolomite present.

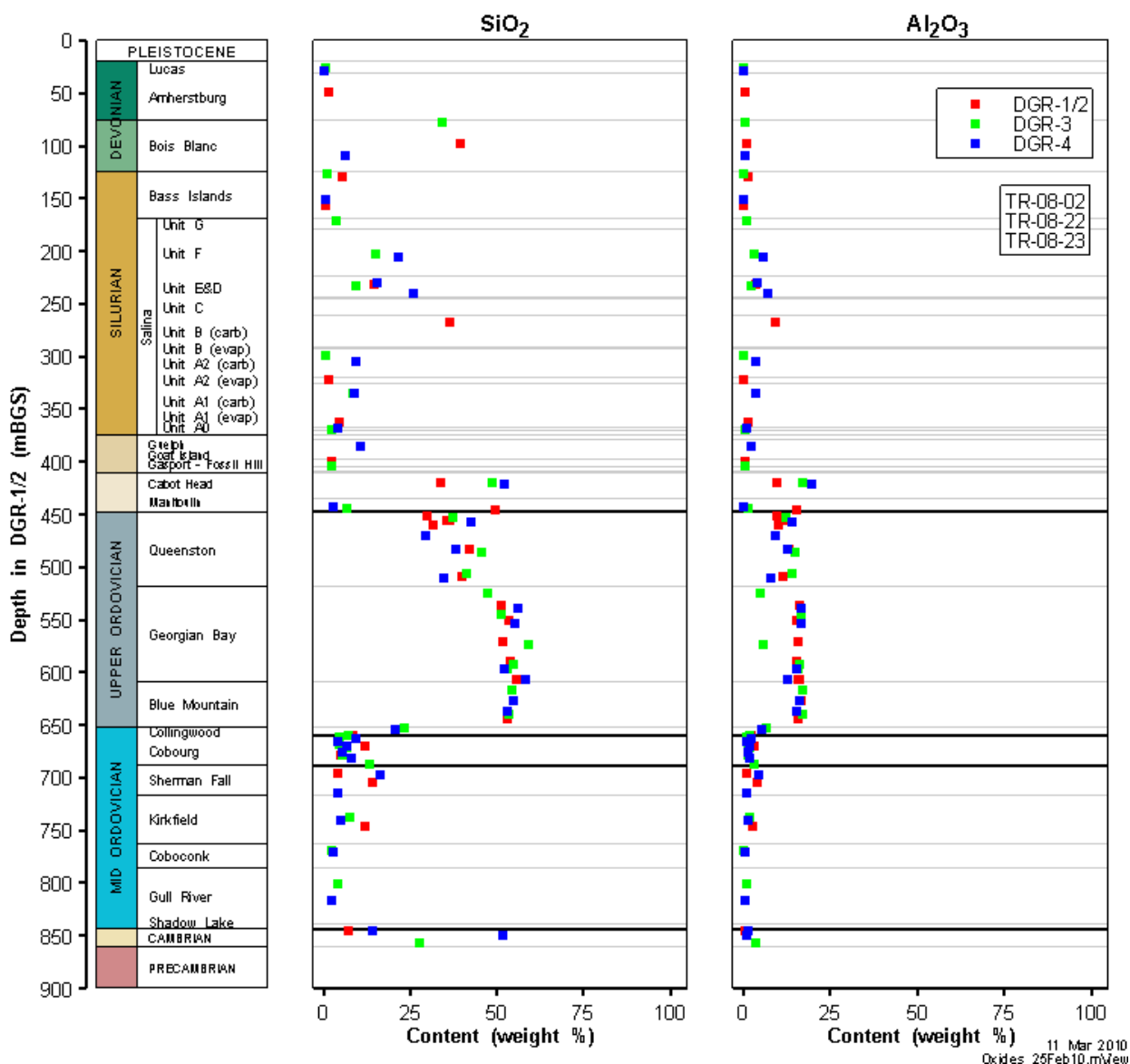


Figure 3.11 Profile of silica and aluminum oxide content in DGR cores

The elevated SiO_2 and Al_2O_3 data (Figure 3.11) confirm the presence of clay minerals as alumina-silicates sporadically in the Silurian formations and throughout the Ordovician shales. The Fe_2O_3 content (Figure 3.12) is generally depleted (<1.5%) in the Devonian and Silurian formations relatively, uniform at about 4 to 8% in the Cabot Head, Queenston, Georgian Bay and Blue Mountain Formation shales, and depleted again in the Ordovician limestones. Most of the detected Fe_2O_3 , especially in the deeper Ordovician formations, is present as a sulphide phase, e.g., pyrite.

Figure 3.12 also illustrates the chloride content of DGR core samples determined by instrumental neutron activation analyses (INAA) in DGR-1 and DGR-2 and wet chemistry and ion chromatography in DGR-3 and DGR-4. Reported total chloride reflects presence of halite or other chloride-bearing minerals, as well as chloride present in porewater in rock porosity. If halite and other chloride-bearing minerals are not present, the chloride content will simply reflect the mass of chloride present in core sample porewater.

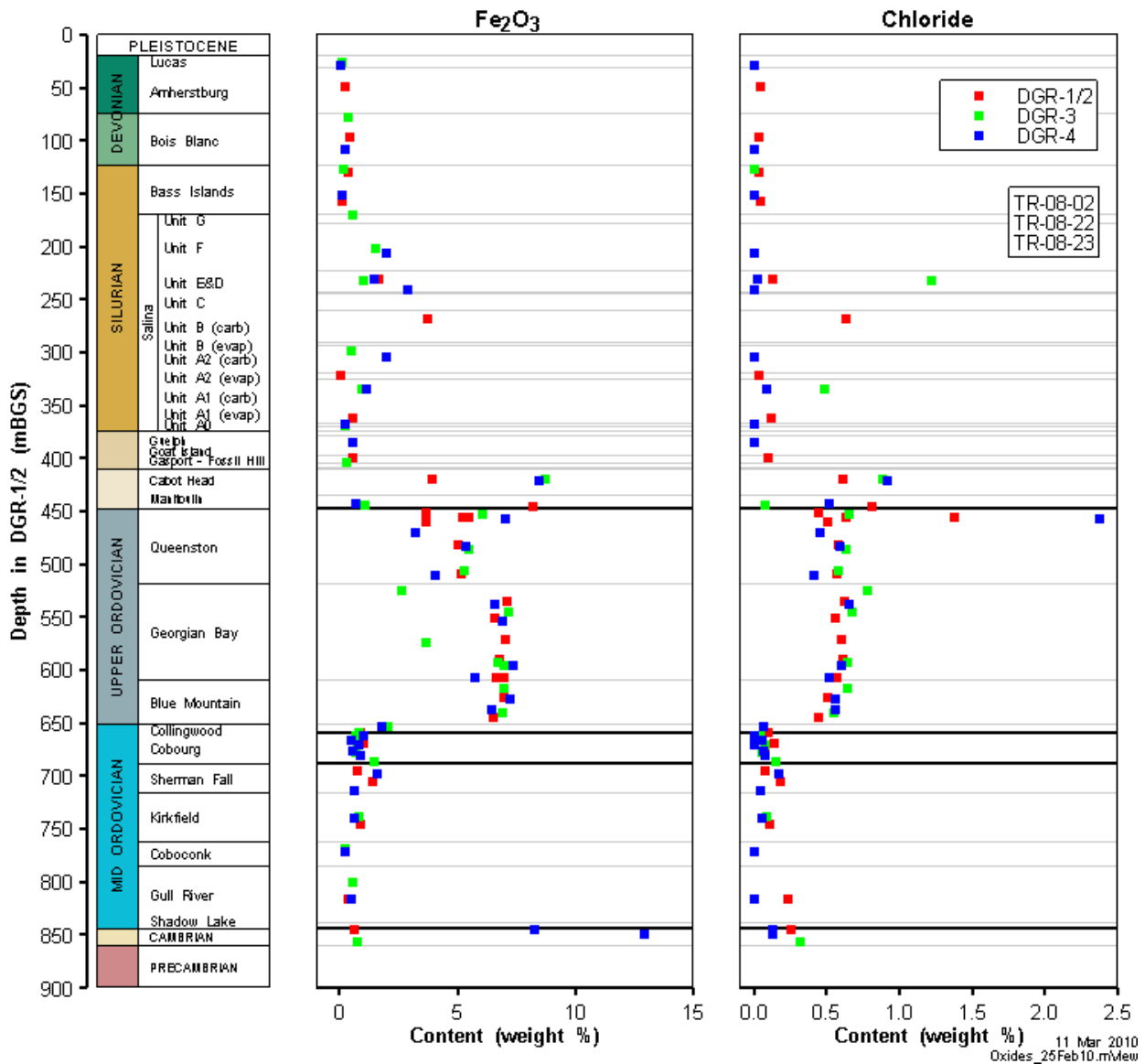


Figure 3.12 Profile of iron oxide and chloride content in DGR cores

Figure 3.12 shows that the chloride content of is typically low (<0.06%) in the Devonian and Upper Silurian dolostones, except in three halite-containing samples from the Salina E, B and A1 units. The chloride content increases to greater than 0.5% in the Cabot Head Formation shale and remains uniform at about 0.5 to 0.6% through the Queenston, Georgian Bay and Blue Mountain Formation shales. The elevated chloride contents of 0.7 to 1.4% were measured at the top of the Queenston and Georgian Bay Formations where halite has been observed in core samples and petrography. Chloride contents in the low porosity Ordovician limestones range from about 0.10 to 0.25% with the higher values associated with the Gull River formation and similar concentrations in the Cambrian formation.

Comparison of elemental oxide and chloride results identified by different analytical laboratories (i.e., Activation Laboratories for DGR-1 and DGR-2, SGS Laboratories for DGR-3 and DGR-4) shows comparable results, which provides confidence in these analytical results.

3.6.3 Dolomitization

Figure 3.13 shows the calculated dolomitization of DGR core. Dolomitization of carbonates detected within core samples is calculated (TR-08-06) as:

$$\text{Dolomitization (\%)} = 100 \times \text{Dolomite (\%)} / [\text{Dolomite (\%)} + \text{Calcite (\%)}] \quad [2.1]$$

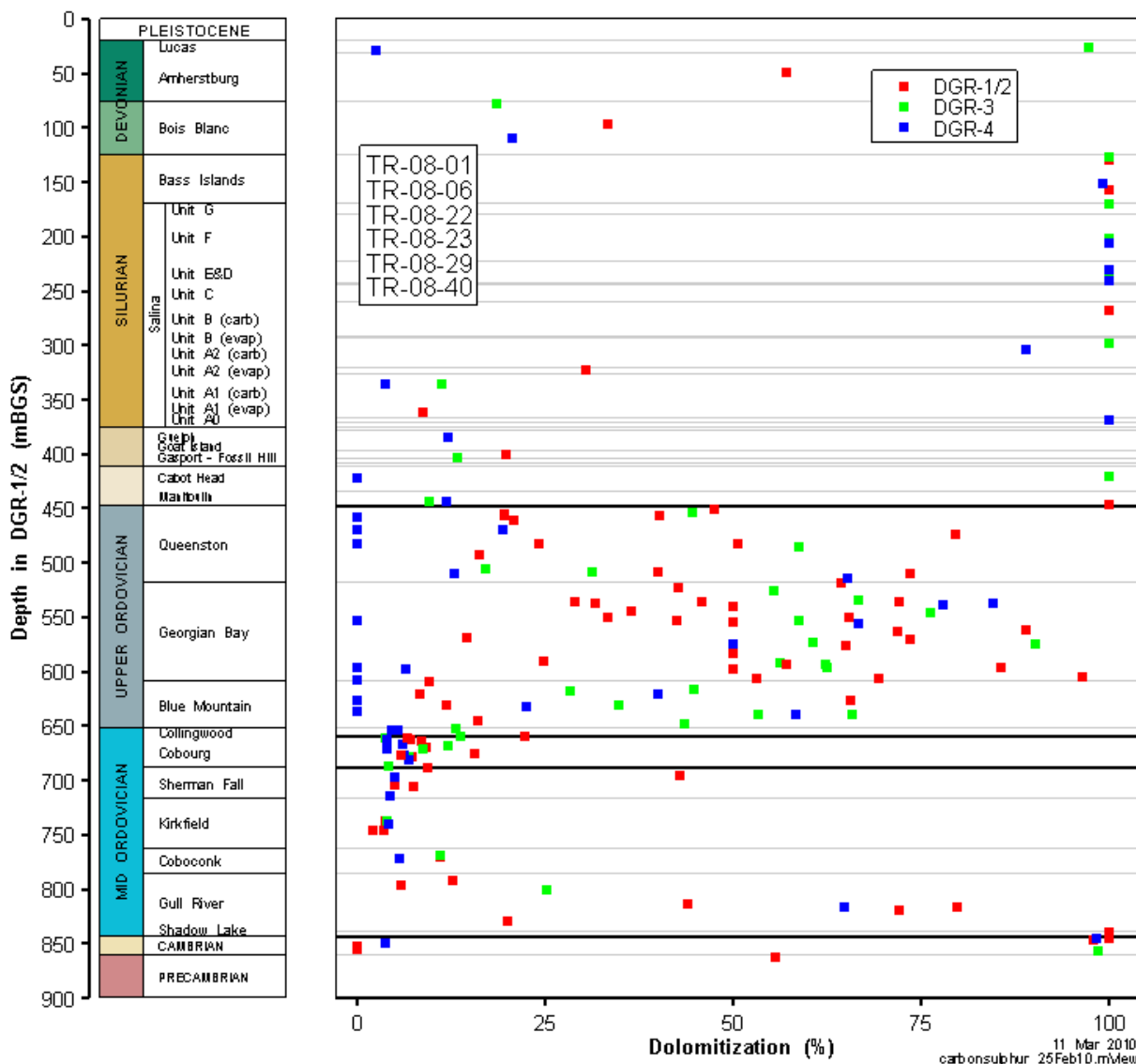


Figure 3.13 Dolomitization in DGR Cores

The significance of the dolomitization plot of Figure 3.13 should be interpreted jointly with the major mineralogy (Figures 3.4 and 3.5) and major elemental oxides (Figures 3.10 and 3.11) plots. For example, although the dolomitization calculated for the Ordovician shales appears large at 25 to 75%, the significance of this result is mitigated by the low carbonate content of these rocks as apparent in Figures 3.4 and 3.10. Conversely, the comparable dolomitization values of 25 to 100% for the Devonian and Silurian formations are more significant due to the much higher carbonate content of these rocks. Figure 3.13 shows that dolomitization of the bottom half of the Gull River Formation and of the Shadow Lake Formation and upper Cambrian is significant at about 50 to 100%.

3.6.4 Organic Carbon and Sulphur

Figure 3.14 illustrates the profile of organic carbon and total sulphur in DGR core. These plots show that many of the formations are quite low in organic carbon (<0.3%). Notable exceptions are middle and lower parts of the Georgian Bay Formation (0.4 to 0.7%), the Blue Mountain Formation and Collingwood Member (0.4 to 2.0%), The organic carbon content of the Ordovician limestones and underlying Shadow Lake and Cambrian rocks are variable (0.1 to 2.0%) likely reflecting the sporadic occurrences of bituminous laminae and oil observed in recovered core.

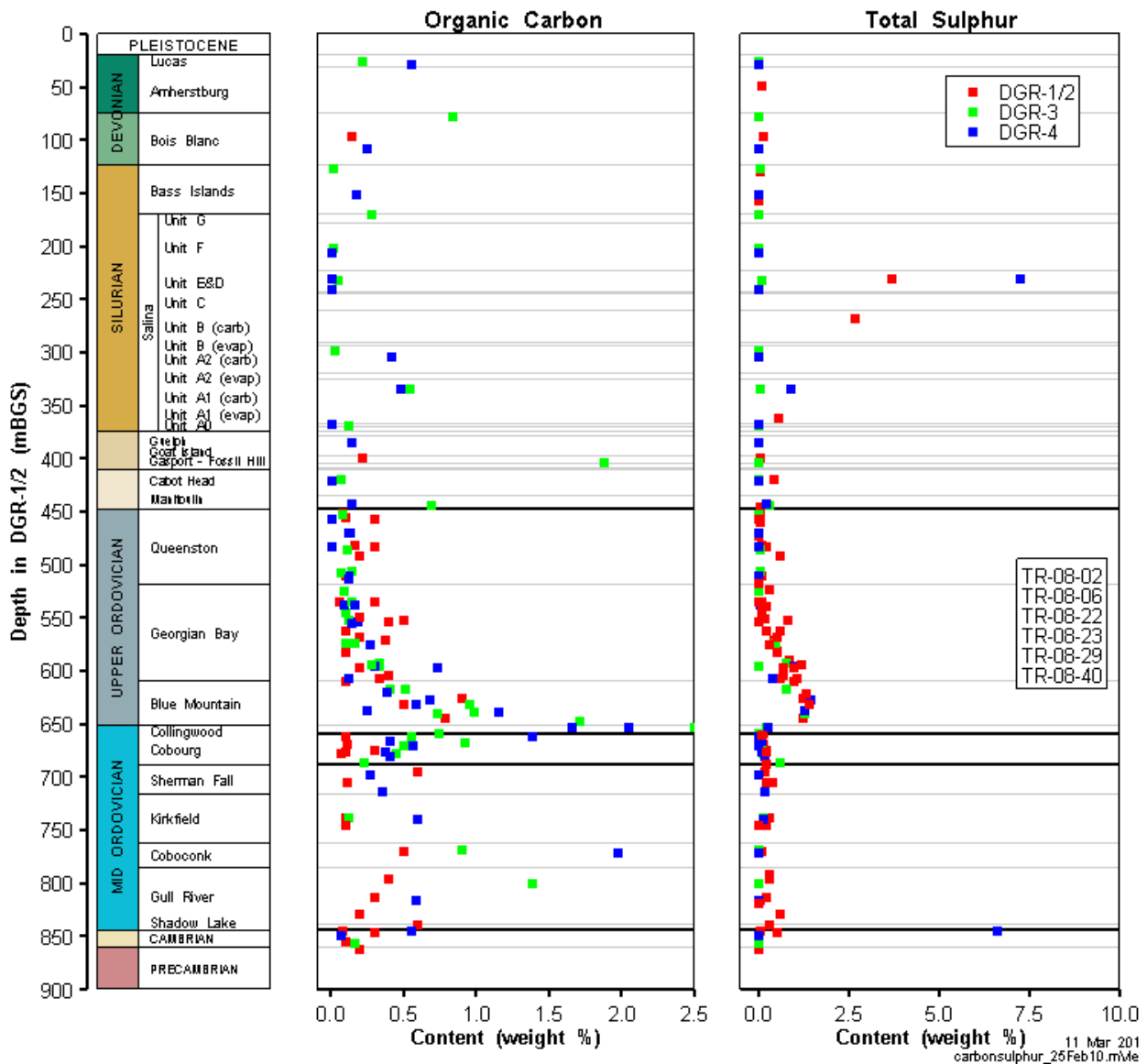


Figure 3.14 Organic carbon and sulphur contents of DGR cores

Total sulphur contents of DGR core reflect the presence of sulphur-bearing minerals including sulphate minerals of gypsum and anhydrite and sulphide minerals of pyrite and to a lesser extent sphalerite, marcasite and chalcopyrite. Not shown on Figure 3.14 due to scale compatibility are the elevated sulphur contents of 23.2% from the Salina A2 Unit anhydritic dolostone and 23.4% from the Salina A2 Unit Evaporite that suggest about 70% sulphate from gypsum and/or anhydrite. The other

detected sulphur contents in the Silurian rocks (0.44 to 7.23%) are reflective of anhydrite and/or gypsum in the Salina and Cabot Head Formations. The detected sulphur contents in the Ordovician shale and limestone (0.1 to 1.4%) likely reflect the presence of sulphide-bearing minerals (pyrite in shales) and traces of anhydrite (limestones).

Figure 3.14 shows that both the total sulphur and organic carbon contents in DGR core peak in the lower part of the Georgian Bay Formation and in the Blue Mountain Formation and then typical decrease with depth in underlying formations. These trends correlate well with occurrences of petroleum and bitumen in the cores that are discussed in the Section 3.6.5.

Although not illustrated, the data in Figure 3.14 shows that comparable organic carbon and total sulphur results are reported for DGR core by the different laboratories (Activation Laboratories, SGS Laboratories, University of Bern, Core Laboratories) that completed these analyses.

3.6.5 Organic Geochemistry

In the part of the Michigan Basin that underlies Ontario, the focus of previous studies of the organic geochemistry of the Paleozoic sequence has been on the properties of hydrocarbons in the producing areas around Chatham (Carter, 2002), approximately 250 km south of the Bruce nuclear site. Obermajer et al. (1996, 1999 and 2002) identified two 'petroleum systems' existing in those Silurian and Ordovician rocks of southwestern Ontario that are present in the DGR. The Ordovician petroleum system is considered to have its origin within the Ordovician rocks themselves such that the petroleum was generated in "thin organic rich shaly Trenton laminae" from which the oil has "migrated to stratigraphically adjacent Cambrian and Silurian reservoirs." The Trenton Group consists of the Cobourg, Sherman Fall and Kirkfield Formations. Secondly, the Middle Silurian formations, such as the Guelph and Salina reef carbonate rocks, are distinctly different "suggesting a carbonate source rock deposited under hypersaline conditions" (Obermajer et al., 2002).

During the drilling of the Phase 1 DGR boreholes, there were observations of hydrocarbons in cores recovered from the Devonian, Silurian and Ordovician formations that are summarized in Table 3.8.

Table 3.8 Observations of hydrocarbon occurrences made in DGR cores

<i>Depth in DGR-1/2 (mBGS)</i>	<i>Formation</i>	<i>Hydrocarbon Occurrence</i>
94-106	Bois Blanc	Dense, bituminous laminations every metre
341-366	Salina A1 Unit Carbonate	Thin lamina of bitumen, hydrocarbon odour throughout, visible oil over 0.4 m vuggy section at bottom of Unit.
384-394	Goat Island	Bituminous laminations throughout
585-591	Georgian Bay	Petroliferous shale with hydrocarbon odour, suspected gas-containing fracture at 585.7 mBGS (see Figure 3.52)
616-653	Blue Mountain & Collingwood Member	Petroliferous shale with hydrocarbon odour
665-677	Cobourg	Bituminous laminations throughout
768-777	Coboconk	Vuggy petroliferous zone with oil weeping from core, strong hydrocarbon odour
814-830	Gull River	Light brown oil seeping from pores and stylolites (see Figure 3.39)
840	Shadow Lake	Oil bubbling from sandstone

There is no evidence in these cores of commercially attractive oil and gas occurrences that might pose a risk of future intrusion into a closed DGR by those seeking to extract oil or gas, nor does there appear to be a risk to repository construction from these observations

The observations of hydrocarbon occurrence made in DGR-1 and DGR-2 , which were corroborated in DGR-3 and DGR-4, identified the need for a Phase 2A program to examine the organic geochemistry of the Ordovician shales (see TR-08-29) that form the cap rock above the proposed repository. This work included studies of clay mineralogy (see Section 3.6.1.1) and the testing of 19 DGR-3 and DGR-4 cores for total organic carbon (TOC) and by Rock-Eval pyrolysis, a standard test method to determine the basic organic geochemical parameters that characterise the thermal maturity of the sedimentary organic carbon or kerogen within the shales.

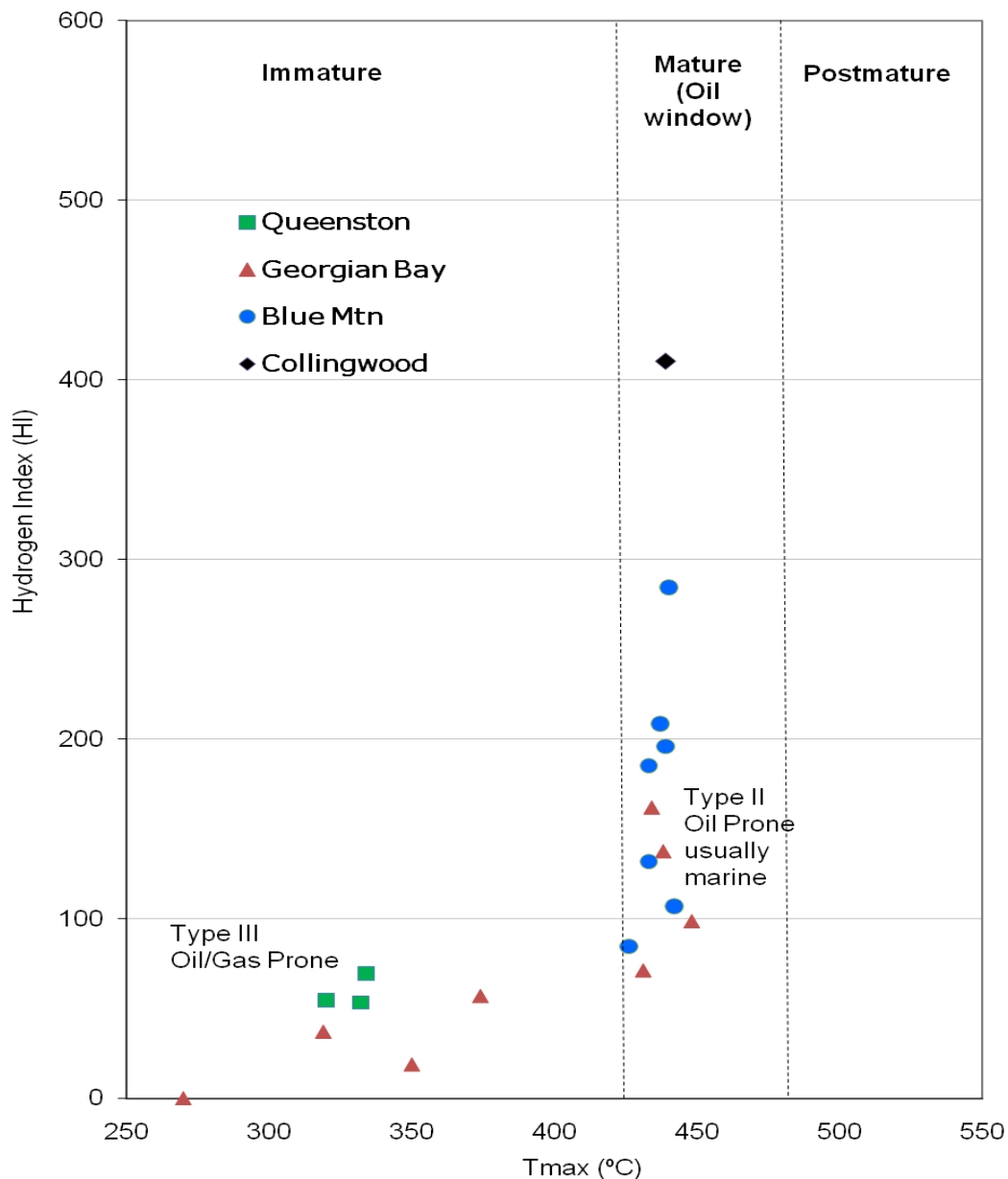


Figure 3.15 Plot of peak pyrolysis temperature, T_{max} , vs. Hydrogen Index indicating kerogen types

The average TOC values for the Ordovician shales increase with depth from 0.11% in the Queenston, to 0.25% in the Georgian Bay to 0.90% in the Blue Mountain. These are shown in Figure 3.14. The degree of thermal maturity of the kerogen correlates with this TOC trend. Figure 3.15 indicates that the peak pyrolysis temperatures at which the kerogen produces hydrocarbon gas – T_{max} – increase with depth through the shales towards the lower Blue Mountain Formation and the Collingwood Member of the Cobourg Formation. The distribution of the Hydrogen Index (HI) – a measure of the amount of kerogen that can still produce oil and gas hydrocarbons normalised to its TOC concentration – versus T_{max} , indicates the ‘oil window’ in which the kerogen of the core samples is presumed ‘mature’.

On this basis the Collingwood sample and all Blue Mountain cores are considered as being thermally mature. Their kerogen is Type II, i.e., that common to marine basins and which tends to form oil rather than gas. Most Georgian Bay and all Queenston cores contain Type III kerogen, which is derived from terrestrial organic matter, e.g., lignin and cellulose, and is more gas prone than Type II kerogen. These conclusions are consistent with what is known about the sedimentary provenance of these shales, i.e., the Queenston is associated with a coastal environment while the Georgian Bay and Blue Mountain are considered to be of marine origin. Thermal maturity values for this kerogen indicate high in-situ temperatures during maturation – i.e., somewhere between 70 and 130 °C. Thus, in terms of petroleum geology, the Ordovician shales that constitute the immediate cap rock to the proposed repository horizon – the lower Blue Mountain and Collingwood members – constitute a ‘self-sourcing’ petroleum system, albeit a non-commercial one, that explains the occasional observation of oil seeping from the DGR cores.

3.7 Formation Stratigraphic Descriptions

3.7.1 Quaternary Deposits

The overburden at the Bruce nuclear site is of variable thickness ranging from a thin veneer in the south-eastern part of the site near Lake Huron to upwards of 25 m in the eastern and north-eastern part of the site near Tie Road and the central guardhouse. The increase in overburden thickness to the east and northeast reflects both a rising ground surface and a deepening bedrock surface.

The overburden stratigraphy typically comprises a surficial fill and sand and gravel unit overlying clayey silt to sandy silt glacial till, which is frequently underlain by a basal gravel deposit at the weathered bedrock surface. The surficial sand and gravels are former beach deposits and the till has been mapped at the Elma-Catfish Creek Till by the Ontario Geological Survey (Sharp and Edwards, 1979). Several reports (Jensen and Heystee, 1987; 1989; Jensen and Sykes, 1993; Intera Engineering Ltd., 2004) provide database listings of the types and thicknesses of overburden deposits in selected areas of the Bruce nuclear site based on historical and recent borehole and test pit investigations.

Table 3.9 summarizes the overburden conditions logged during drilling of DGR-1 to DGR-4 and the US-series boreholes.

Data from US-series boreholes (Lukajic, 1988) and DGR-1 to DGR-4 (TR-07-06, TR-08-13) show the overburden thickness ranges from 7.41 m at US-5 to 22.6 m at US-6, with an average thickness of about 10.4 m at US-7 near the proposed DGR footprint. The overburden stratigraphy at these drilling locations is typically 1.0 to 3.0 m of granular fill overlying 5.0 to 21.0 m of grey sandy silt till, overlying 0 to 2.0 m of basal gravel and weathered bedrock.

Table 3.9 Summary of overburden conditions at DGR- and US-series boreholes

Borehole No.	Ground Surface Elevations (mASL)	Bedrock Surface Elevation (mASL)	Overburden Thickness (m)	Overburden Stratigraphy
US-1	192.12	173.59	18.53	Not logged
US-2	190.92	173.44	17.48	Very dense brown to grey sandy silt till
US-3	184.56	166.27	18.29	Till
US-4	191.18	175.04	16.14	Till
US-5	186.60	179.19	7.41	Not logged
US-6	191.90	169.30	22.60	Not logged
US-7	182.98	172.55	10.43	Not logged
US-8	187.20	178.67	8.53	Gravel fill over grey clay till
DGR-1	185.71	165.71	20.00	Gravel fill over brown/grey sandy silt till with basal gravel
DGR-2	185.84	162.44	20.00	Gravel fill over brown/grey sandy silt till with basal gravel
DGR-3	187.36	179.46	7.90	Gravelly fill over brown/grey sandy silt till
DGR-4	181.60	174.07	7.53	Gravelly fill over brown/grey sandy silt till

3.7.2 Middle and Lower Devonian Formations

Middle and Lower Devonian age bedrock formations identified in DGR- and US-series boreholes include Lucas Formation dolostone, Amherstburg Formation limestone and dolostone and Bois Blanc Formation dolostone.

3.7.2.1 Lucas Formation Dolostone

The Lucas Formation dolostone is the upper bedrock unit over the western half of the Bruce nuclear site including DGR-1 to DGR-4, US-8 and likely US-5 and probably extends north to the vicinity of the Bruce A Generating Station. Regionally, the undifferentiated Lucas Formation is a thin- to medium-bedded, light to grey brown, fine-crystalline, lightly fossiliferous dolostone and limestone with stromatolitic laminations (Armstrong and Carter, 2006).

The Lucas Formation is identified in boreholes DGR-1 to DGR-4 and in US-8 based on the occurrence of predominately grey to light brown dolostone core and chip samples, the inferred maximum thickness of the Lucas Formation of about 99 m at Sarnia (Armstrong and Carter, 2006) and the regional bedrock mapping of the Geological Survey of Canada (1981) that shows the presence of the formation at the Bruce nuclear site. The contact with the underlying Amherstburg Formation is identified as the transition from greyish tan dolostone to brown dolostone.

The erosional surface is found in DGR-1 to DGR-4 at depths of 7.5 to 54.5 mBGS, indicating an eroded formation thickness of 10.4 to 46.6 m. Based on the occurrence in all DGR boreholes, it is likely that the Lucas Formation is also present in all US-series boreholes. However, the upper bedrock in the US-series boreholes was logged (Lukajic, 1988) including the Lucas as part as Amherstburg Formation dolostone.

Petrographic analysis of core collected from DGR-3 and DGR-4 (TR-08-20, TR-08-21) shows the formation to be predominately calcareous mudstone/dolostone and recrystallized wackestone. The cores are very fine grained to microcrystalline with <20% fossil fragments, calcite inclusions in the dolomitic matrix and traces of quartz. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified the major minerals as dolomite, calcite with minor quartz and sphalerite, indicating the rock is a dolostone to limestone. These XRD analyses are confirmed by the lithogeochemical analyses (Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO, MgO and minor SiO₂.

Because of the limited opportunity for coring in DGR holes, RQD and natural fracture frequency data for the Lucas Formation are grouped with Amherstburg Formation in Table 3.3. The available RQD and natural fracture frequency data (Figures 3.2 and 3.3) and US-series boreholes indicate poor to fair core quality and moderately to highly fractured conditions characterize the Lucas Formation. Video logging of this formation in US-8 (TR-07-19) confirms these characteristics with the presence of moderately fractured conditions with several broken zones at depths of 20.1, 28.3, and 49.1 mBGS.

3.7.2.2 Amherstburg Formation Dolostone

Regionally, the Amherstburg Formation is a tan to grey-brown, fine- to coarse-grained, bituminous, bioclastic, fossiliferous limestone and dolostone with vuggy horizons and frequent open weathered fractures and brecciated zones (Armstrong and Carter, 2006). At the Bruce nuclear site the Amherstburg Formation is a dolostone characterized by the presence of abundant rugose and tabulate corals, especially in the bottom 5 to 10 m of the formation. Armstrong and Carter (2006) indicate up to 60 m thickness for the Amherstburg Formation that conformably overlies the cherty fossiliferous dolostones of the Bois Blanc Formation.

In DGR and US boreholes the formation top is found at depths of 30.4 to 54.5 mBGS with thickness of 38.6 m to 44.6 m. The contact with the underlying Bois Blanc Formation dolostone is very difficult to identify in the field, but generally correlates with the dominating presence of chert in the Bois Blanc Formation.

Petrographic analysis of core collected from DGR boreholes (TR-07-12) shows the formation to be predominately fossiliferous carbonates, recrystallized carbonates and void-filling carbonates of various grain sizes. Minor pyrite was noted with the very fine grained ferrous-calcareous mud that is interstitial to the fragmented fossils. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified the major minerals as dolomite, calcite with minor quartz, confirming the field identification of the Amherstburg as predominately dolostone. These XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO, MgO and minor SiO₂.

Based on logged core recovery, RQD and natural fracture frequency recorded in DGR boreholes (Table 3.3 and Figures 3.2 and 3.3), the Amherstburg Formation dolostone is moderately to highly fractured with core of very poor to fair quality. Video inspections of US-8 (TR-07-19) confirm these formation discontinuity characteristics with zones of borehole enlargement and intense fracturing evident.

RQD values for the seven cored US boreholes that intersected the Amherstburg Formation dolostone were higher (0 to 100%, mean 65%) than those recorded in DGR-1, DGR-3 and DGR-4, indicating fair core quality. Tunnelling and other construction and investigation experience associated with the Bruce A and B generating stations (Lucajic et al., 1986; Lucajic and Dupak, 1986) suggest the formation rock quality may be locally poor. Considering the difficulties encountered with coring in the upper parts of DGR boreholes, US-8 data, Bruce tunnelling experience and the broader coverage afforded by US boreholes, the assessment of fair core quality provided by the US boreholes is considered

representative for the Amherstburg Formation dolostone.

3.7.2.3 Bois Blanc Formation Cherty Dolostone

Based on regional data, the Bois Blanc Formation is a greenish grey to brown, thin- to medium-bedded, fine- to medium-grained, fossiliferous, cherty dolostone, with a high natural fracture frequency, local dense bituminous laminations and occasional broken and rubble zones (Armstrong and Carter, 2006). Figure 3.16 shows a core sample of the Bois Blanc Formation collected from DGR-1. The Bois Blanc Formation dolostone at the Bruce nuclear site is characterized by the presence of white to grey to black chert nodules and layers that locally constitute up to 90% of the rock volume. Armstrong and Carter (2006) indicate a 50 m thickness in the area of the Bruce nuclear site for the Bois Blanc Formation that disconformably overlies Silurian strata.

In DGR boreholes and US-8 the formation top is found at depths of 75.0 to 93.9 mBGS with thickness of 49.0 m to 49.8 m. A major discontinuity – the Devonian-Silurian erosional discontinuity occurs at the base of the Bois Blanc Formation.

Petrographic analysis of core collected from DGR boreholes (TR-07-12, TR-08-20, TR-08-21) shows the formation to be predominately a fragmented and silicified fossiliferous carbonate packstone (dolostone) with cherty domains. Part of the rock consists of very fine-grained featureless oxidized and fragmented dark shale intercalated with chert and chalcedony fragments, and the other part consists of fossiliferous packstone with fine-grained dolomite matrix. Petrographically, the core mineralogy is estimated at 65-80% carbonate, trace-30% quartz (chert) with minor accessory minerals of disseminated pyrite, chalcopyrite and hematite. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as calcite, quartz and dolomite with trace of illite. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 , and CaO with minor MgO .



Figure 3.16 Core sample of Bois Blanc Formation cherty dolostone with bituminous laminations, 102.3 mBGS, DGR-1

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Bois Blanc Formation dolostone is moderately to highly fractured with fair core quality. Video inspections of US-8 (TR-07-19) confirm these formation discontinuity characteristics with zones of major borehole enlargement and intense fracturing evident at depths of 113.7, 131.1 and 132.3 mBGS, as well as the frequent occurrence of vertical and horizontal fracturing and minor enlargements.

RQD values for the six US cored boreholes that intersected the upper to middle parts of the formation were higher (64 to 100%, mean 94%) than those recorded in DGR boreholes (0 to 100%, mean 68%) indicating excellent core quality. These higher ratings of core quality are offset by tunnelling and other construction and investigation experience associated with the Bruce A and B generating stations. These tunnelling experiences suggest the formation rock quality may be locally poor. Considering the difficulties encountered with coring in the upper to middle parts of the formation in DGR boreholes, US-8 data, Bruce tunnelling experience and the broader coverage afforded by US boreholes, the assessment of fair core quality provided by the DGR boreholes is considered representative for the Bois Blanc Formation dolostone.

3.7.3 Upper Silurian Formations

The Upper Silurian age formations encountered in DGR boreholes include Bass Islands Formation dolostone and Salina Formation Units G to A0 dolostones, evaporites and shales. Borehole US-8 intersects Upper Silurian Bass Islands Formation and Salina Formation Units G and F.

3.7.3.1 Bass Islands Formation Dolostone

The Bass Islands Formation has not been excavated or previously investigated at the Bruce nuclear site. Regionally, it is a brown to tan-grey, variably laminated, very fine- to fine-grained, argillaceous dolostone, with a high natural fracture frequency and occasional broken and rubble zones, particularly in the upper sections of the formation. Armstrong and Carter (2006) indicate a 10 to 90 m thickness for the combined Bass Islands and Bertie Formations in southern Ontario. The Bass Islands Formation dolostone at the Bruce nuclear site is characterized by the very fine-grained dolostone lacking chert and fossils.

In DGR boreholes and US-8 the formation top is found at depths of 75.0 to 93.9 mBGS with thickness of 49.0 m to 49.8 m. The upper surface of the Bass Islands Formation is a major regional unconformity caused by paleo-erosion between the older Silurian rocks and the younger overlying Devonian rocks. The characteristics of this regional unconformity are discussed in Section 3.10.1 of this Project Report.

Petrographic analysis of core samples collected from DGR boreholes (TR-07-12, TR-08-20, TR-08-21) shows the formation as microcrystalline aphanitic dolostone with minor amounts of gypsum and celestite and trace amounts of quartz (chert), and pyrite. Some samples also show oolitic dolostone, with intergranular pore space at about 0.5 to 1%. Petrographically the core mineralogy is estimated at 85-95% carbonate (principally dolostone) with 8-10% gypsum or celestite. Quantitative XRD analyses of the same core samples (Figure 3.4 and .3.5) identified similar mineralogy with the major mineral as dolomite with trace of quartz (chert) and calcite. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figure 3.10 and 3.11) which show the dominant elemental oxides are CaO and MgO and some SiO₂.

Based on core logging of DGR boreholes (Table 3.3, Figure 3.2 and 3.3), the Bass Islands Formation dolostone is moderately to highly fractured with poor core quality. The low mean core recovery of 77% and low mean RQD of 33% are attributed to difficult drilling conditions and to zones of intense fracturing and weathering due to presence of the regional erosional discontinuity. Similar to better formation discontinuity characteristics are also present in US-8 based on borehole video inspection

(TR-07-19) that showed zones of highly broken rock and intense fracturing at depths of 170.7 mBGS, as well as the frequent occurrence of minor borehole enlargements and fracturing. Based on available DGR-1 and US-8 data, poor to fair core quality is considered representative of the Bass Island Formation dolostone.

3.7.3.2 Salina Formation, G Unit Argillaceous Dolostone

The Salina Formation is a succession of evaporites and evaporite-related carbonate sediments that is subdivided into lettered units A through to G based on subsurface stratigraphic characteristics. All of the Units within the Salina Formation were deposited conformably, although small scale disconformities occur due to post-depositional dissolution of evaporite beds in the Bruce area (e.g., D Unit and B Unit salts) (Armstrong and Carter, 2006).

Regionally the G Unit is a tan to grey, argillaceous dolostone, with shale and anhydrite layers. Armstrong and Carter (2006) indicate a 12 m thickness of the G Unit in the Michigan Basin. The G Unit dolostone at the Bruce nuclear site is identified by the first presence of white, orange and pink anhydrite layers and nodules.

Based on core logging in DGR boreholes, the G Unit is 7.3 to 9.3 m thick and the top of the Unit is found at depths of 169.3 to 187.3 mBGS. It is logged as medium grey argillaceous dolostone with intermittent layers of medium grey fine-grained dolostone and grey dolomitic shale. White, orange and pink anhydrite/gypsum veins and layers are present through the Unit as secondary infilling of healed fractures.

Petrographic analysis of core collected from borehole DGR-3 (TR-08-20) shows the formation to be predominately very fine-grained, fragmented dolostone and coarse-grained gypsum with anhydrite inclusions. The presence of large anhedral grains of gypsum within the dolomite-rich domains and the abundance of fine-grained inclusions of dolostone in the gypsum indicate the dissolution of dolomite and replacement by gypsum. Petrographically, the core mineralogy is estimated at 50% dolomite and 48% gypsum with trace anhydrite with minor accessory minerals of disseminated pyrite and quartz. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as dolomite and gypsum with traces of sanidine (K feldspar) and quartz. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO and MgO with minor SiO₂.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the G Unit dolostone is moderately fractured with fair core quality. These general unit discontinuity characteristics are also present in US-8 based on borehole video inspection that showed good quality borehole wall conditions with occasional horizontal fractures within the G Unit.

3.7.3.3 Salina Formation, F Unit Dolomitic Shale

Based on regional data, the F Unit is a grey/green to grey/blue dolomitic shale with shale and anhydrite. Armstrong and Carter (2006) indicate the F Unit is typically comprised of dark green shales with anhydrite in the upper half and mixed dolostones, shales and anhydrite in the lower half, with an estimated unit thickness of 30 m. The F Unit shale at the Bruce nuclear site is identified by the presence of predominately grey-blue shale and a gamma high on the borehole geophysical logs.



Figure 3.17 Orange anhydrite veins cut by white gypsum veins in Salina F Unit dolomitic shale, 222.6 mBGS in DGR-3.

Based on core logging in DGR boreholes, the Unit is 43.1 to 44.4 m thick and the top of the Unit is found at depths of 177.4 to 196.5 mBGS. The upper part of the Unit is grey to green fine-grained dolomitic shale with white and orange anhydrite/gypsum veins throughout (Figure 3.17). A 0.2 m thick layer of tan massive dolostone found at 182.0 to 200.7 mBGS is a DGR formation marker bed that can be used to accurately estimate formation orientation (TR-08-12). Below this marker bed, the Unit is often stained reddish-brown with increasing content of anhydrite as veins, layers and large nodules that infill and surround brecciated shale and dolostone fragments. The bottom 6.0 m of the F Unit shale is comprised of tan brown brecciated dolostone with abundant veins and layers. The brecciation of the F Unit is likely related to the collapse of the formation caused by paleo dissolution of the underlying the Salina D Unit salt.

Petrographic analysis of core collected from boreholes DGR-3 and DGR-4 (TR-08-20, TR-08-40) shows the formation to be predominately very fine-grained, fragmented dolostone to calcareous shale with coarse- and fine-grained aggregates (veins, interstitial and anhedral grains) of gypsum with anhydrite inclusions. The presence of fragments of dolomitic matrix rock within gypsum veins indicate the gypsum veins post-date the matrix gypsum interstitial to dolomitic shale host rock. Petrographically, the core mineralogy is estimated at 36 to 60% dolomite, up to 33 % sheet silicates and 18-50% gypsum with trace anhydrite and minor accessory minerals of orthoclase, disseminated pyrite and quartz. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as dolomite and gypsum with minor amounts of orthoclase, clays and quartz. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are and CaO and SiO₂ with minor MgO and SiO₂.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the F Unit shale is sparsely to moderately fractured with excellent core quality. These general unit discontinuity characteristics are also present in US-8 based on borehole video inspection that showed good quality borehole wall conditions with occasional horizontal fractures within the F Unit below 194.5 mBGS.

3.7.3.4 Salina Formation, E Unit Brecciated Dolostone and Dolomitic Shale

Regionally, the E Unit is a brown/grey brecciated dolostone and dolomitic shale with anhydrite. Armstrong and Carter (2006) indicate the E Unit is typically 30 m thick. The E Unit shale at the Bruce nuclear site is identified by the presence of a distinctive upper 2 m thick bed of grey-green dolomitic shale as suggested by Armstrong and Carter (2006).

Based on core logging in DGR boreholes, the Unit is 20 to 24.5 m thick and the top of the Unit is found at depths of 221.0 to 239.6 mBGS. In descending order, the E Unit consists of about 2.3 m of grey-green dolomitic shale and brecciated dolostone, 10.9 m of brecciated dolostone with anhydrite, and 6.8 m of tan-grey dolomitic shale with anhydrite and gypsum. The middle horizon contains angular fragments of tan and brown dolostone and grey shale within a grey anhydritic dolomudstone matrix. The anhydrite/gypsum content of the lower horizon as veins, layers and nodules, increases with depth.

Petrographic analysis of core collected from DGR boreholes (TR-07-12, TR-08-20, TR-08-21, TR-08-40) shows the Unit to be predominately fragmented and re-cemented dolomite to dolomitic shale with fibrous gypsum veinlets, pods and aggregates interstitial to the dolomite, and traces of fine-grained anhydrite, quartz and pyrite disseminated through the carbonate-rich matrix. Petrographically, the core mineralogy is estimated at 70-99% carbonate, 1-60% gypsum 0-2% quartz with trace pyrite and anhydrite. Quantitative XRD analyses of the same core sample (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as dolomite and gypsum, with minor illite, chlorite, quartz, orthoclase and sanidine. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO, MgO, SiO₂ and SO₄.

Based on logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the E Unit dolostone and shale is very sparsely to sparsely fractured with excellent core quality.

3.7.3.5 Salina Formation, D Unit Anhydritic Dolostone and C Unit Dolomitic Shale and Shale

The D Unit at the Bruce nuclear site is a thin blue-grey to brown anhydritic dolostone that represents the less soluble or non-salt constituents of the D Unit salt bed that has been dissolved in the geologic past (see Figure 3.18). Armstrong and Carter (2006) indicate the D Unit salt is up to 16 m thick elsewhere in Ontario, where the salt is preserved and that the C Unit is an inter-layered red and green-grey shale with anhydrite veins and nodules that grades into a dolomitic shale or dolomite with depth.

Based on core logging in DGR boreholes, the D Unit is 1.6 to 2.6 m thick and top of the Unit is found at depths of 243.0 to 263.4 mBGS. The C Unit is 11.9 to 15.7 m thick and is found at depths of 244.6 to 266.0 mBGS. The D Unit is a blue-grey to brown fragmented tan to brown dolostone within a white to bluish grey anhydrite/gypsum matrix. The C Unit consists of an upper 6.4 of red and green shale and a lower 7.9 m of dolomitic shale. Anhydrite veins and nodules are common throughout the C Unit. The lower section of the C Unit is broken shale and dolostone infilled and healed with white to blue anhydrite as a secondary mineral.

No core samples of the D Unit anhydritic dolostone were submitted for geochemical, mineralogical or petrographic analyses.

Petrographic analysis of core collected from the C Unit in DGR-3 (TR-08-40) shows the Unit to be predominately red oxidized silty calcareous shale consisting of detrital quartz, feldspar and muscovite (illite) cemented by dolomite. Quantitative XRD analyses of the core sample (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as sheet silicates (44%) and dolomite (26%), quartz (20%), with minor albite, K-feldspar and trace halite.



Figure 3.18 Core sample of Salina D Unit anhydritic dolostone from 243.14 mBGS in DGR-1

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the combined D and C Units are unfractured to very sparsely fractured with excellent core quality.

3.7.3.6 Salina Formation, B Unit Argillaceous Dolostone and Anhydrite

Regionally, the B Unit is a grey-green argillaceous dolostone, a salt horizon and an underlying thin anhydrite and dolostone layer. Armstrong and Carter (2006) indicate the B Unit is up to 90 m thick where it contains salt. The brecciated upper dolostone of the B Unit reflects the dissolution of the former B Unit salt which is the thickest salt bed in Ontario (Armstrong and Carter, 2006). The B Unit anhydrite is the less soluble or non-salt constituents of the B Unit at the Bruce nuclear site that may also contain dolostone and shale.

Based on core logging in DGR boreholes, the B Unit is 26.7 to 32.8 m thick and top of the Unit is found at depths of 260.3 to 277.9 mBGS. Because the salt has been entirely removed this unit is referred to as the B equivalent. In descending order, the B Unit consists of 25.1 to 30.9 m of grey-green brecciated argillaceous dolostone and a basal bed of 1.6 to 1.9 m thick grey anhydrite with brown dolostone layers. The upper brecciated unit consists of angular tan to grey dolomitic mudstone and dolostone clasts within a grey dolomitic shale matrix that is infilled with secondary white to bluish-grey anhydrite/gypsum veins, layers and nodules. The lower anhydrite bed is grey with brown dolostone layers.

Petrographic analysis of cores collected DGR boreholes (TR-07-12, TR-08-40) shows the sample to be very fine-grained, aphanitic calcareous shale to argillaceous dolostone with alternating light and dark domains. Petrographically, the core mineralogy is qualitatively estimated in order of decreasing abundance as illite, carbonate, quartz and traces of anhydrite, pyrite, hematite, zircon and oxyhydroxide. Quantitative XRD analyses of the same core sample (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as dolomite, illite, quartz and gypsum with minor chlorite and trace of halite. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10, 3.11 and 3.12) which show the dominant elemental oxides are

SiO₂, CaO, MgO, Al₂O₃ and SO₄ with minor Fe₂O₃.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the B Unit argillaceous dolostone and anhydrite is unfractured to sparsely fractured with excellent core quality.

3.7.3.7 Salina Formation, A2 Unit Dolostone and Anhydritic Dolostone

The A2 Unit is regionally recognized as a tan-grey argillaceous, laminated to thin-bedded dolostone and an underlying anhydritic dolostone. The A2 Unit is subdivided into the A2 Unit Carbonate and the A2 Unit Evaporite. The A2 Unit Carbonate has been mapped as argillaceous dolostone and the A2 Unit Evaporite as anhydritic dolostone as defined by Armstrong and Carter (2006).

Based on core logging in DGR boreholes, the A2 Unit is 32.4 to 34.0 m thick and the top of the Unit is found at depths of 293.1 to 304.6 mBGS. In descending order, the A2 Unit Carbonate consists of about 13.4 m of grey fine-grained dolomite with black shale layers, 2.0 m of dark grey dolomitic shale, 4.0 m of tan-grey argillaceous dolostone, 2.0 m of anhydritic dolostone and 5.2 m of tan-grey argillaceous dolostone with bituminous laminations. The underlying A2 Unit Evaporite is a 5.1 to 5.8 m thick bed of light grey-blue anhydritic dolostone to dolomitic anhydrite (Figure 3.19).



Figure 3.19 Dolomitic anhydrite of Salina A2 Unit Evaporite, 322.75 mBGS in DGR-4

Petrographic analysis of core collected from the A2 Unit Carbonate in DGR boreholes (TR-08-20, TR-08-21, TR-08-40) shows the Unit to be very fine-grained to fine-grained equigranular dolomite and calcite with minor gypsum. Petrographically, the core mineralogy is estimated at 80-100% carbonate, 0-20% gypsum with trace pyrite, quartz and celestite. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as dolomite and gypsum with minor calcite and illite and trace of quartz, pyrite and orthoclase. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO, MgO and SiO₂ (note SO₄ was not quantified in these samples).

Petrographic analysis of core collected from the A2 Unit Evaporite (TR-07-12, TR-08-40) shows the samples to be massive to fibrous radiating anhydrite, porphyroblasts of gypsum and minor disseminated dolomite. Petrographically, the core mineralogy is estimated at 85-90% anhydrite, 3-10% gypsum and 3-5% carbonate which defines it as mainly anhydrite. Quantitative XRD analyses of the same core sample identified similar mineralogy with the major minerals as anhydrite, with minor calcite, dolomite, gypsum and quartz and trace of feldspar. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SO_4 and CaO .

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the A2 Unit argillaceous dolostone and anhydritic dolostone is unfractured to very sparsely fractured with excellent core quality.

3.7.3.8 Salina Formation, A1 Unit Argillaceous Dolostone and Anhydritic Dolostone, A0 Unit Bituminous Dolostone

Regionally, the A1 Unit is similar to the A2 Unit in that it is divided into an upper A1 Unit Carbonate and a lower A1 Unit Evaporite. The A1 Unit is comprised of a grey-brown, argillaceous, bituminously-laminated dolostone and an underlying anhydritic dolostone. The A0 Unit is a thin bituminous dolostone that is not well mapped in Ontario and historically has been grouped with the underlying Guelph Formation dolostone (Armstrong and Carter, 2006).

Based on core logging in DGR boreholes, the A1 Unit is 44.8 to 45.7 m thick and the top of the Unit is found at depths of 325.5 to 338.6 mBGS. The A1 Unit Carbonate logged in DGR boreholes is a thinly laminated, grey-brown dolostone with black bituminous layers and minor anhydrite layering. The upper 3.2 to 3.7 m of the A1 Unit Carbonate Unit has open vuggy porosity and permeability (Figure 3.20). A thin (0.2 to 0.4 m thick) show of hydrocarbon as crude oil was observed in the bottom of the A1 Unit Carbonate in all DGR boreholes. The underlying A1 Unit Evaporite is a 3.5 to 5.0 m thick bed of light grey-blue anhydritic dolostone.

The A0 Unit dolostone at the DGR site is a 2.6 to 4.0 m thick bed with the top of Unit found at 366.8 to 379.8 mBGS. It is a massive, intact, dark brown-black, thinly-laminated, fine-grained bituminous dolostone. Notably, the bituminous laminations of the A0 Unit in DGR-1 dip at about 5 to 30° increasing with depth in the Unit. The dips of these bituminous laminations are much greater than the expected regional dip of about 1° or less and may be indicative of sedimentation on the flank of a minor local reef that would be in the underlying Guelph Formation, although there is no evidence in the core that the Guelph Formation is reefal. Borehole acoustic televiewer logs of the A0 Unit in DGR boreholes do not have sufficient resolution to allow identification of dip direction of these laminations. Figure 3.21 shows the intact core collected from the A0 Unit dolostone during coring of DGR-1.

Petrographic analysis of core collected from the A1 Unit Carbonate in DGR boreholes (TR-07-12, TR-08-20, TR-08-21, TR-08-40) shows the Unit to be laminated, very fine-grained calcareous shale to dolostone or limestone with alternating light and dark bands. Petrographically, the core mineralogy is estimated in order of decreasing abundance as carbonate, illite, pyrite and trace of quartz and gypsum. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified the major minerals as 76-82% calcite, 7.9-11.6% illite, 4.1-10.7% dolomite and traces of quartz, orthoclase and anhydrite. The XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO , with minor amounts of SiO_2 , SO_4 , Al_2O_3 and MgO .



Figure 3.20 Open vuggy porosity of Upper A1 Unit Carbonate Unit at 326.2 mBGS in DGR-4



Figure 3.21 Intact 3.0 m length core of the Salina A0 Unit Dolostone at 371-374 mBGS in DGR-1

Petrographic analysis of core collected from the A1 Unit Evaporite in DGR boreholes (TR-08-20, TR-08-21, TR-08-40) shows the Unit to be laminated alternating bands of fine-grained dolomite and recrystallized saddle dolomite and anhydrite (Figure 3.22), to fine-grained anhydrite and illite, to massive anhydrite. Petrographically, the core mineralogy is qualitatively estimated in order of decreasing abundance as up to 60% carbonate, 40-66% anhydrite, up to 33% illite and trace of pyrite and quartz. Quantitative XRD analyses of the core samples identified the major minerals as 50-81% anhydrite, 13-45% dolomite, with minor amounts of illite, quartz and sanidine.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the A1 and A0 Units dolostone and anhydritic dolostone are unfractured to sparsely fractured with excellent core quality.

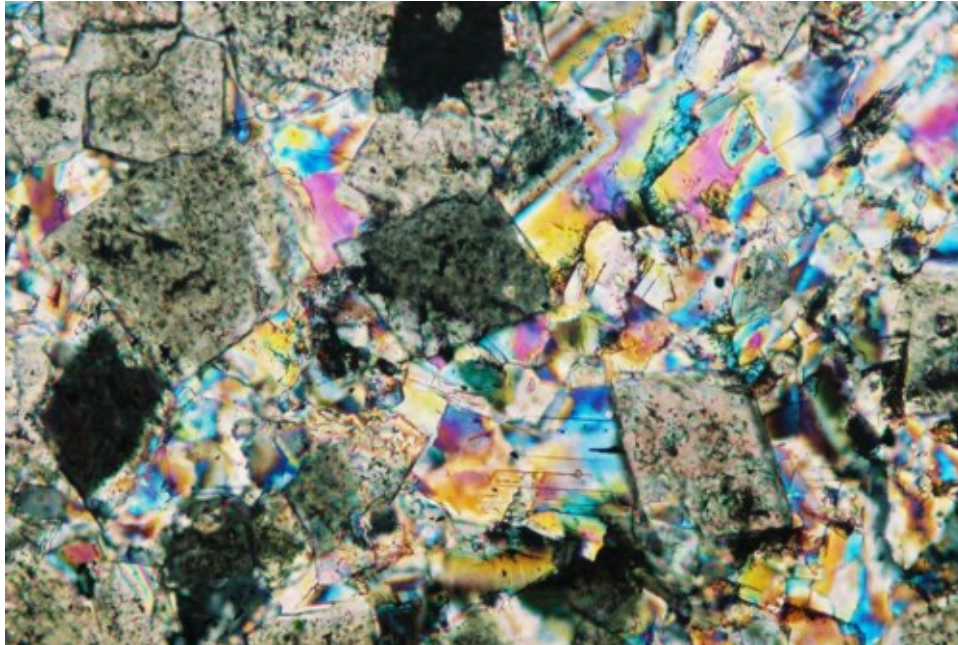


Figure 3.22 Saddle dolomite (tan colour) within anhydrite matrix (multi colour) at 382.29 mBGS in Salina A1 Unit Evaporite in DGR-3, width of photo: 0.45 mm, crossed nicols

3.7.4 Middle and Lower Silurian Formations

The Middle and Lower Silurian age formations encountered in DGR boreholes include the Guelph, Goat Island, Gasport, Lions Head and Fossil Hill Formation dolostones (Middle Silurian), and the Cabot Head Formation shale, and Manitoulin Formation dolostone and shale (Lower Silurian).

3.7.4.1 Guelph, Goat Island, Gasport, Lions Head and Fossil Hill Formations Dolostones

Based on limited thickness and lithologic similarity, the dolostone sequence comprising the Guelph Formation, Goat Island Formation, Gasport Formation, Lions Head Formation and Fossil Hill Formation are grouped together, but individually described here.

The Guelph Formation dolostone in DGR boreholes is a 4.1 to 5.4 m thick bed of brown vuggy sucrosic dolostone with formation top at depths of 374.5 to 386.8 mBGS. It is a thin, porous and permeable formation (Figure 3.23). Although Armstrong and Goodman (1990) and Johnson et al. (1992) have shown the Bruce nuclear site to be located on the edge of the pinnacle reef belt, Carter et al., (1994) and Armstrong and Carter (2006) have interpreted the small thickness of the Guelph, as

evident at the Bruce nuclear site, to be indicative of non-reefal, inter-pinnacle facies on the basin slope. This interpretation is confirmed by the DGR core that shows no evidence of reefal facies.

Petrographic analysis of a core sample collected from DGR 3 (TR-08-40) show the Guelph Formation as veined brown sucrosic dolostone composed dolomite with minor fine-grained disseminated pyrite. The veins are partially infilled with hydrothermal dolomite (ankerite) with minor quartz, and abundant halite. Quantitative XRD analyses of the core sample (Figures 3.4 and 3.5) identified similar mineralogy with 86% dolomite, 10% halite and traces of quartz, calcite and pyrite.



Figure 3.23 Core photograph of Guelph Formation porous dolostone at 376 mBGS in DGR-1

The Goat Island Formation dolostone in DGR boreholes is a 18.3 to 18.8 m thick bed of light to dark brown-grey, very fine-grained, thin to medium bedded, dolostone with formation top found at depths of 378.6 to 392.2 mBGS. Chert and microstylolites are present. It is sparsely to moderately fossiliferous (Armstrong and Carter, 2006). Petrographic analysis of core sample collected from DGR-4 (TR-08-21) shows the Goat Island Formation to be a partly recrystallized fossiliferous packstone with traces of illite and quartz. Quantitative XRD analyses of the core sample (Figures 3.4 and 3.5) identified similar mineralogy with 73% calcite, 11.4% dolomite and ankerite, 7.6% illite and 7.4% quartz. The XRD analyses are confirmed by the lithogeochemical analyses (Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO and SiO₂, and minor amounts of Al₂O₃ and MgO.

The Gasport Formation dolostone at the DGR site is a 6.5 to 6.9 m thick bed of blue-grey to white, fine- to coarse-grained, dolomitic limestone with formation top found at depths of 397.4 to 410.5 mBGS. It has bituminous laminations and microstylolites throughout. Petrographic analysis of cores collected from the Gasport Formation (TR-07-12, TR-08-20) shows the formation to consist of mostly calcareous fossils comprised of mostly calcite with some dolomite within a carbonate rich matrix. Petrographically, the core mineralogy is estimated at 90-99 % carbonate, 0-10% illite with accessory minerals of pyrite, anhydrite and quartz. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified major minerals as calcite and dolomite with minor illite and quartz. The lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) show the dominant elemental oxides are CaO with minor MgO and SiO₂ indicating the tested core sample is a dolomitic limestone.

The Lions Head Formation dolostone in DGR boreholes is a 4.4 to 4.5 m thick bed of light grey to grey-brown, fine- to crystalline-grained, dolostone found with top of formation at depths of 404.25 to 421.5 mBGS. According to Armstrong and Carter (2006) it is sparsely fossiliferous with locally abundant chert nodules. No core samples of the Lions Head Formation dolostone were submitted for geochemical, mineralogical or petrographic analyses.

The Fossil Hill Formation dolostone at the DGR site is a 1.3 to 2.3 m thick bed of light- to medium-brownish grey, coarse-grained, thin- to medium-bedded, fossiliferous dolostone with top of formation found at depths of 408.7 to 421.5 mBGS. According to Armstrong and Carter (2006) it is very fossiliferous, which is consistent with the logging in DGR boreholes. No core samples of the Fossil Hill Formation dolostone were submitted for geochemical, mineralogical or petrographic analyses.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the dolostone sequence comprising the Guelph, Goat Island, Gasport, Lions Head and Fossil Hill Formations are unfractured to very sparsely fractured with excellent core quality.

3.7.4.2 Cabot Head Formation Shale

Regionally the Cabot Head Formation is a grey to green to red-maroon noncalcareous shale with subordinate sandstone and carbonate interbeds (Armstrong and Carter, 2006).

Based on core logging in DGR boreholes, the Cabot Head Formation is 23.8 to 24.7 m thick with formation top found at depths of 411.0 to 422.8 mBGS. In DGR boreholes, the Cabot Head Formation is a green-grey and red massive shale grading to interbedded grey carbonate and black fossiliferous shale at the bottom of the unit. Figure 3.24 shows the upper section of the Cabot Head Formation.



Figure 3.24 Top of Cabot Head Formation shale, 411.02 to 414.07 mBGS in DGR-1

Petrographic analysis of cores collected from the Cabot Head Formation shale (TR-07-12, TR-08-20, TR-08-21) show the samples to be a featureless Fe-stained, very fine-grained oxidized shale. Petrographically, the core mineralogy is estimated as Fe-stained illite (40-80%), Fe-hydroxide (10-

20%), minute angular quartz clasts (10-35%), very fine-grained carbonates (5-10%) and trace of anhydrite (<1%). Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified the major minerals as illite and quartz with minor dolomite, chlorite, orthoclase, goethite and trace halite, gypsum and pyrite. Lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) show the dominant elemental oxides are SiO_2 , Al_2O_3 , Fe_2O_3 and minor MgO and CaO . These laboratory analyses show the cores ranges from non-calcareous to calcareous shale.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Cabot Head Formation shale is unfractured to very sparsely fractured with excellent core quality. Based on review of the borehole acoustic televiewer logs an inclined fracture (50°dip) is evident at a depth of 414.3 mBGS in DGR-1, indicating that top of the Cabot Head Formation is sparsely fractured.

3.7.4.3 Manitoulin Formation Cherty Dolostone and Minor Shale

Based on regional data, the Manitoulin Formation is recognized as a bed of cherty dolostone, argillaceous dolostone and minor grey-green shale. According to Armstrong and Carter (2006), the dolostone is typically grey, thin-to medium-bedded, moderately fossiliferous, fine- to medium-grained and commonly contains chert nodules or lenses and silicified fossils.

Based on core logging in DGR boreholes, the Manitoulin Formation is 9.5 to 12.9 m thick with formation top found at depths of 434.8 to 447.5 mBGS. It is a grey, fine- to medium-grained dolostone with minor grey-green noncalcareous shale. The upper ~9.5 m is cherty dolostone with silicified shell fragments, and the bottom ~3.4 m is fine-grained crystalline dolostone with increasing shale content below 445.0 mBGS in DGR-1.

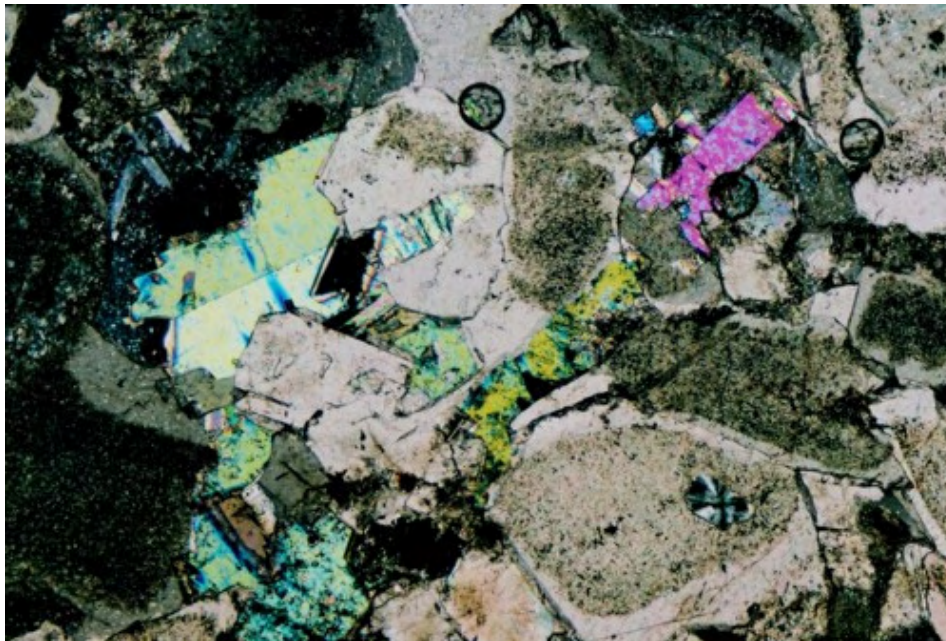


Figure 3.25 Anhydrite grains (multi colour) interstitial to recrystallized calcite at 442.74 mBGS in Manitoulin Formation in DGR-4, width of photo 2.3 mm, crossed nicols

Petrographic analysis of cores collected from the middle to bottom part of the Manitoulin Formation dolostone and shale at the DGR site (TR-07-12, TR-08-20, TR-08-21) shows the samples to be fossiliferous calcareous grainstone to very fine-grained laminated dolomitic shale with alternating bands of fine-grained dolomite and illite. Petrographically, the core mineralogy is estimated as carbonates (39 to 99%), illite (0-60%), anhydrite (2%) (Figure 3.25), traces of quartz (<1%) and pyrite

(1%), and a few minute grains of gypsum. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified the major minerals as calcite (0-82%) illite (5-60%), quartz (0-32%), dolomite and ankerite (8.6-14%) with minor chlorite and hematite and trace of halite and gypsum. The identified higher percentage of quartz in the XRD analyses of one sample is likely attributed to the presence of chert. The petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO and SiO₂, with minor Al₂O₃, MgO and Fe₂O₃.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Manitoulin Formation cherty dolostone and shale is unfractured to very sparsely fractured with excellent core quality.

3.7.5 Upper Ordovician Formations

The Upper Ordovician age formations encountered in DGR boreholes include Queenston Formation shale, Georgian Bay Formation shale and limestone, and the Blue Mountain Formation shale.

Petrography and XRD mineralogical analyses of cores from DGR boreholes are available from independent testing completed by Activation Laboratories Ltd. (TR-08-01), SGS Laboratories (TR-08-22, TR-08-23) and Geoconsult (TR-07-12, TR-08-20, TR-08-21), as well as from Rock Water Interaction, University of Bern (TR-08-06, TR-08-40).

3.7.5.1 Queenston Formation Red Shale

Regionally, the Queenston Formation is a bed of brick red to maroon, noncalcareous to calcareous shale with subordinate amounts of green shale, siltstone, sandstone and limestone (Armstrong and Carter, 2006). Gypsum occurs as locally abundant nodules and thin, subhorizontal fracture infillings. Carbonate content, both of the shale and in terms of abundance and thickness of limestone beds tends to increase regionally to the northwest. On the Bruce peninsula, the middle part of the formation consists of green shale interbedded with fossiliferous limestone (Armstrong and Carter, 2006). The top of the Queenston Formation is an erosional unconformity with the overlying Silurian strata.

Based on core logging of DGR boreholes, the Queenston Formation is 70.3 to 74.4 m thick with top of formation and found at depths of 447.7 to 457.0 mBGS. The upper ~34 m of the formation is massive red-maroon calcareous shale with grey-green calcareous shale layers and pockets. Orange fracture infilling minerals (halite with some bounding calcite) were logged in the upper 10 to 30 m of the formation (Figure 3.26) as well as deeper in the formation. Figures 3.27 and 3.28 show a typical core sample and a thin section for upper part of the Queenston Formation red shale.

The middle ~26 m of the formation is green shale interbedded with medium to light grey, medium- to coarse-grained fossiliferous limestone layers (Figure 3.29). The limestone layers represent about 25 to 50% of the middle part of the Queenston Formation. The bottom 10-11 m of the formation is red-maroon shale interbedded with grey-green shale layers and minor limestone beds.



Figure 3.26 Halite-infilled horizontal fracture at 458.6 m BGS in upper Queenston Formation in DGR-3



Figure 3.27 Core sample of green and red shale, upper Queenston Formation, 454.82 mBGS, DGR-1

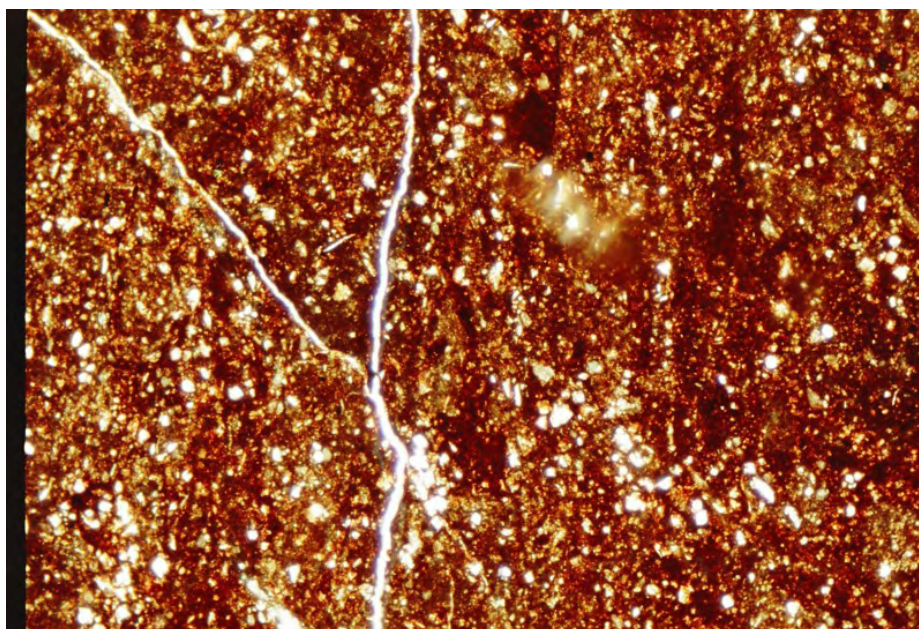


Figure 3.28 Carbonate veinlets in ferruginous shale, upper Queenston Formation, 455.45 mBGS in DGR-1, width of photo: 2.3mm, plane polarized light



Figure 3.29 Interbedded green shale and grey fossiliferous limestone, middle Queenston Formation at 496 mBGS in DGR-3

Core dinking was first observed in DGR boreholes at depths of 511 mBGS within the lower red-maroon shale of the Queenston Formation. Core dinking in this report is the regular breaking of intact core into centimetre-length pieces upon retrieval to ground surface. Although this term is often used in the geotechnical literature as an indicator of high ground stress conditions, its use in this report does

not imply such conditions. It is recognized in argillaceous rocks that core diskings can also be due to other physio-chemical causes as deep core is equilibrated with atmospheric conditions.

A total of 24 core samples from the Queenston Formation in DGR boreholes were subject to geochemical, mineralogical and/or petrographic analyses (TR-07-12, TR-08-01, TR-08-06, TR-08-20, TR-08-21, TR-08-22, TR-08-23, TR-08-29, TR-08-40).

Petrographic analysis of core collected from the upper part of the Queenston Formation shale shows all the samples to be similar as iron-stained, fine-grained calcareous shale with some fossiliferous layers and minor anhydrite-gypsum veins. Petrographically, the mineralogy in these cores is estimated as carbonates (40 to 85%), clays (trace to 50%), calcite fossils (0 to 40%), dolomite (7-10%), halite (0 to 10%), quartz (0 to 12%), gypsum/anhydrite (0 to 2.5%) and traces of pyrite, hematite, goethite, and Fe-oxyhydroxide. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as calcite, illite, dolomite, quartz and chlorite with minor to trace amounts of pyrite, hematite, halite, anhydrite and gypsum. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 , CaO and Al_2O_3 with minor amounts of Fe_2O_3 , K_2O and MgO .

Petrographic analysis of fracture infilling material (vein) collected from the upper part of the Queenston Formation at 456.01 mBGS in DGR-1 shows the sample to be predominately halite with minor amounts of calcite. Quantitative XRD and SEM/EDS analyses of the same vein sample identified similar mineralogy with the halite as predominant, calcite as a medium amount, dolomite and quartz present in small to trace amounts and illite and chlorite present in trace amounts.

Petrographic analysis of core collected from the middle part of the Queenston Formation shale and interbedded limestone shows this formation to be fossiliferous argillaceous limestone and shale. Petrographically, the core mineralogy is estimated as carbonates (25-85%), fossiliferous carbonates (0-25%), quartz (0-40%) and biotite/dark clays (10-35%) with accessory minerals of pyrite, chalcopyrite, anhydrite and celestite. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as illite, quartz, dolomite, calcite and chlorite. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 , Al_2O_3 and CaO with minor MgO , Fe_2O_3 and K_2O .

Petrographic analysis of cores collected from the lower part of the Queenston Formation shale shows this part of the formation to be iron-stained, very fine-grained dolomitized calcareous shale. Petrographically, the core mineralogy is estimated as carbonates (30-53%), Fe-oxide/hydroxides (0-50%), illite (15-20%), quartz (5%) with accessory minerals of pyrite and anhydrite. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified the major minerals as illite, quartz, calcite, dolomite and chlorite. These XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 , CaO and Al_2O_3 with minor Fe_2O_3 , MgO and K_2O .

Based on core logging (Table 3.3, Figures 3.2 and 3.3), the Queenston Formation is unfractured to sparsely fractured with excellent core quality (Figure 3.30 - left). Core logging identified the sporadic occurrence of several smooth natural fractures in the Queenston Formation in DGR boreholes most of which were sealed and infilled with halite, calcite and/or gypsum. Some of these fractures were inclined (i.e., dip greater than 35°). Borehole acoustic televiewer logging identified a similar number and orientation of natural fractures in the Queenston Formation with several of these found in the upper 15 m of the Formation and an equal number of inclined and subhorizontal natural fractures present throughout the formation. Several fracture surfaces showed the occasional presence of discontinuous slickensided surfaces that were most likely formed during consolidation and induration.



Figure 3.30 Intact core runs: left - Queenston Formation, 475.73-478.78 mBGS in DGR-3, right - Blue Mountain Formation, 619.08-622.13 mBGS in DGR-4

3.7.5.2 Georgian Bay Formation Grey Shale

Regional data show that the Georgian Bay Formation is a bed of greenish to bluish grey shale, interbedded with limestone, siltstone and sandstone (Armstrong and Carter, 2006). Generally, the abundance and thickness of non-shale constituents (i.e., limestone, siltstone and sandstone or “hard beds”) and overall carbonate content decreases with depth (Armstrong and Carter, 2006).

Based on core logging, the Georgian Bay Formation at the DGR site is 88.7 to 90.9 m thick and the top of the formation is found at depths of 518.0 to 531.4 mBGS. The upper 60 m of the formation is dark grey-green shale with grey, fine- to medium grained, occasionally fossiliferous limestone, siltstone and sandstone layers (see Figure 3.31). The lower 30 m of the formation is dark grey-green shale with occasional layers and laminations of fossiliferous limestone, siltstone and sandstone. Core diking was prevalent in the Georgian Bay Formation below 10 m of the top of the formation (see Figure 3.32). A suspected gas-bearing and normally-pressured feature was logged in core and by borehole acoustic televiewer at 585.9 mBGS in DGR-2 as a halite-infilled fracture with sulphurous and petroliferous odours. A similar subhorizontal normally-pressured fracture was identified at 594.4 mBGS in the lower Georgian Bay in DGR-4.

A total of 38 core samples from the Georgian Bay Formation in DGR boreholes were subject to geochemical, mineralogical and/or petrographic analyses (TR-07-12, TR-08-01, TR-08-06, TR-08-20, TR-08-21, TR-08-22, TR-08-23, TR-08-29, TR-08-40).



Figure 3.31 Core sample of upper Georgian Bay Formation interbedded shale and limestone, 542.25 mBGS, DGR-2



Figure 3.32 Core diking in upper Georgian Bay Formation shale, 569.90 mBGS, DGR-2

Petrographic analysis of cores collected from the upper part of the Georgian Bay Formation shale shows the samples to be fossiliferous limestone and calcareous shale. Petrographically, the core mineralogy in these cores is estimated as carbonates (20-75%), fossil fragments (10-35%), clays (20 to 40%), quartz (25-40%), anhydrite and halite (0 to 2.0%), and traces of pyrite, biotite, sericite and celestite. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as illite (11 to 35%), quartz (16 to 53%), orthoclase (9 to 23%), dolomite (2 to 23%), chlorite (0.4 to 25%), calcite (1 to 19%) and pyrite (1.4 to 4.5%). These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 and Al_2O_3 with minor Fe_2O_3 , K_2O , MgO and CaO and trace SO_4 .

Petrographic analysis of cores collected from the lower part of the Georgian Bay Formation shale shows the samples to be fossiliferous dolostone/limestone and calcareous shale. Petrographically, the core mineralogy in these cores is estimated as carbonates (5-40%), fossil fragments (0-35%), clays (25 to 55%), quartz (0-10%), anhydrite and halite (0 to 2.0%), and traces of pyrite, sericite and celestite. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as quartz (16 to 43%), illite (23 to 40%), dolomite (1.3 to 55%), chlorite (8 to 19%), orthoclase (5 to 19%), calcite (2.4 to 19%) and pyrite (1.2 to 4.7%). These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 and Al_2O_3 with minor Fe_2O_3 , K_2O , MgO and CaO and trace SO_4 .

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Georgian Bay Formation shale is unfractured to sparsely fractured with excellent core quality.

3.7.5.3 Blue Mountain Formation Dark Grey Shale

Regionally, the Blue Mountain Formation is a bed of dark grey-green to black, soft, non-calcareous shale with decreasing abundance of carbonate content and interbeds of limestone, siltstone and sandstone with depth (Armstrong and Carter, 2006).

Based on core logging in DGR boreholes, the Blue Mountain Formation is 42.7 to 45.1 m thick with top of formation at depths of 608.0 to 620.1 mBGS. It is subdivided into an Upper and Lower Member (TR-08-12), although throughout most of the DGSM, the Blue Mountain Formation is considered a single lithological unit. The Upper Member is a 38.1 to 41.1 m thick sequence of dark greenish-grey shale interbedded with grey siliceous siltstone and sandstone layers and fossiliferous limestone layers. The Lower Member is a 4.0 to 4.6 m thick bed of hard dark grey calcareous shale. Core dinking was prevalent throughout the Blue Mountain Formation, particularly in the Lower Member (see Figure 3.33) although core quality observed immediately after core recovery to ground surface was excellent (Figure 3.30 – right). Sulphurous and petroliferous odours were also present throughout the formation.

Petrographic analysis of cores collected from DGR boreholes from the Upper Member of the Blue Mountain Formation shows the samples to be very fine-grained, weakly laminated calcareous shale and siltstone. Petrographically, the core mineralogy in these cores is estimated as illite and other clays (15 to 83%), carbonate (10-60%), quartz (5-10%), Fe-hydroxide (0-10%) and pyrite (0 and 2%). Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as illite and chlorite, quartz with minor dolomite, calcite, feldspar and pyrite. These petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 and Al_2O_3 with minor Fe_2O_3 , K_2O , MgO and CaO and trace SO_4 .



Figure 3.33 Core diskings of Lower Member, Blue Mountain Formation shale, 652 mBGS, DGR-2

Petrographic analysis of cores collected from DGR boreholes from the Lower Member of the Blue Mountain Formation shows the samples to be very fine-grained, calcareous shale. Petrographically, the core mineralogy in the cores is estimated in order of decreasing abundance as illite and other clays, carbonates, quartz and K-feldspar Fe-hydroxide with traces of hematite and pyrite. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as illite (29-31%), chlorite (13-17%), quartz (215-35%) with minor dolomite (3.6-5.8%), calcite (3.0-4.7%), feldspar (3.2-16.1%) and pyrite (5.5-6.2%) with traces of halite (0.5%). These petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are SiO_2 and Al_2O_3 with minor Fe_2O_3 , K_2O , MgO and CaO and trace SO_4 .

Based on core logging (Table 3.3, Figures 3.2 and 3.3), the Blue Mountain Formation shale with limestone interbeds at the DGR site is unfractured to very sparsely fractured with excellent core quality. However, this formation is subject to rapid and extensive core diskings, upon recovery of core at ground surface.

3.7.6 Middle Ordovician Formations

The Middle Ordovician age formations encountered at the DGR site include Cobourg Formation black shale and argillaceous limestone, Sherman Fall Formation limestone, Kirkfield Formation limestone, Coboconk Formation bioturbated limestone, Gull River Formation lithographic limestone and Shadow Lake Formation siltstone and sandstone. Collectively, the Cobourg, Sherman Fall and Kirkfield Formations are the Trenton Group and the Coboconk, Gull River and Shadow Lake Formations are the Black River Group.

3.7.6.1 Cobourg Formation Black Shale and Argillaceous Limestone

Based on regional data, the Cobourg Formation is a bed of dark grey to black, organic-rich, calcareous shale with very thin fossiliferous limestone interbeds (the Upper or Collingwood Member)

and very-fine- to coarse-grained, fossiliferous, bluish-grey to grey-brown argillaceous limestones (Lower Member) (Armstrong and Carter, 2006). The Lower Member is the proposed host rock for the DGR at the Bruce nuclear site.

Armstrong and Carter (2006) note that Collingwood Member pinches out west of Port Elgin, implying this part of the formation may not be present at the Bruce nuclear site and that in southwestern Ontario the uppermost few metres of the Lower Member are dolomitized. Neither of these geologic conditions are evident in DGR boreholes.

Based on core logging in DGR boreholes, the Cobourg Formation is 35.9 to 36.5 m thick with top of formation at depths of 651.6 to 664.3 mBGS. The Upper Member is a 7.9 to 8.7 m thick sequence of dark-grey to black calcareous shale interbedded with argillaceous limestone layers. Throughout this report the Upper Member of the Cobourg Formation is referred to as the Collingwood Member. The Lower Member is a 27.5 to 28.6 m thick bed of light to dark brownish-grey, hard, mottled, very fine-grained to crystalline, fossiliferous, argillaceous limestone. Core dinking was prevalent and severe throughout the Upper Member, but was absent in the Lower Member. In this report all unqualified references to the Cobourg Formation refer to the Lower Member. The contact between the Blue Mountain Formation and the Collingwood Member of the Cobourg Formation is shown in Figure 3.34. Figure 3.35 shows a typical intact core run of the Lower Member of the Cobourg Formation from the approximate repository depth of 677-680 mBGS in DGR-3

Petrographic analysis of core collected from the Collingwood Member of the Cobourg Formation shows the samples to be fossiliferous limestone with minor mudstone domains. Petrographically, the core mineralogy is estimated as fossil fragments and carbonates (80-99%), and illite clays (0-20%) with accessory minerals of pyrite and quartz disseminated through the rock. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified major minerals as calcite with minor dolomite, illite, chlorite and quartz and trace of pyrite and feldspar. The lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) support the XRD analyses showing the dominant elemental oxides are CaO and occasionally SiO₂, with minor Al₂O₃, MgO and Fe₂O₃. The laboratory petrographic, XRD and lithogeochemical analyses indicate that the tested cores include samples of the thin fossiliferous limestone interbeds, rather than the organic-rich calcareous shales.



Figure 3.34 Contact between dark grey Blue Mountain Formation and brownish-grey Collingwood Member of the Cobourg Formation, 651.6 mBGS in DGR-2

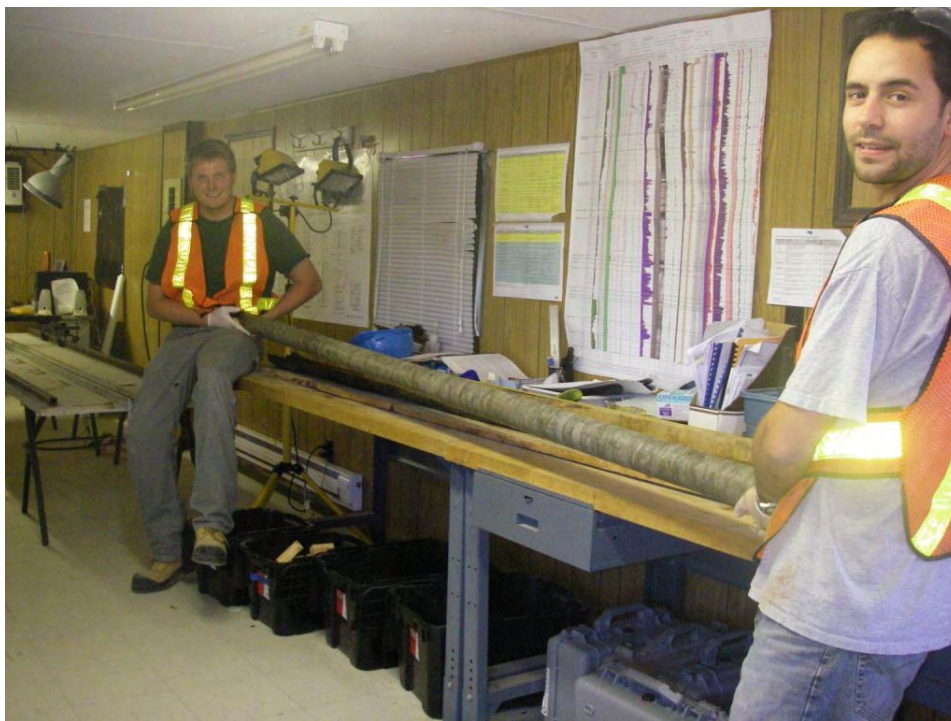


Figure 3.35 Intact core run from approximate repository depth in Lower Member of Cobourg Formation, 677.04 - 680.08 mBGS in DGR-3

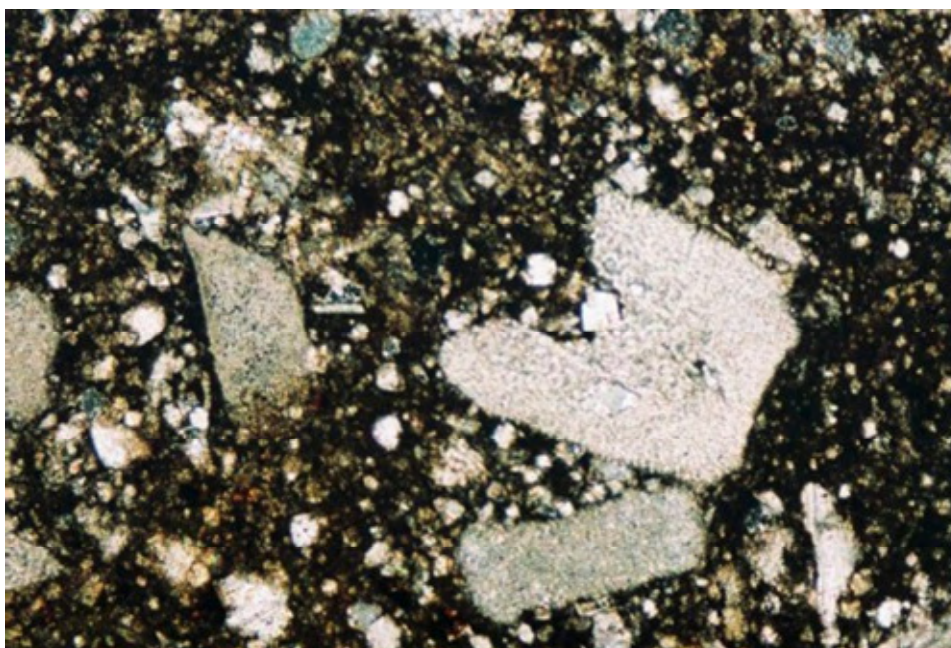


Figure 3.36 Calcareous fossil fragments within illite- and dolomite-rich clay matrix, Lower Member of Cobourg Formation, 664.26 mBGS in DGR-4, width of photo 2.3 mm, crossed nicols

Petrographic analysis of 15 cores collected from the Lower Member of the Cobourg Formation in DGR boreholes (e.g., Figure 3.36) shows the samples to be fossiliferous argillaceous limestone – packstone/wackestone where the abundant recrystallized calcareous fossil fragments are contained in a fine-grained calcareous, Fe-stained clay matrix (micrite). Petrographically, the core mineralogy in these cores are similar, estimated as carbonates (10-50%), calcareous fossil fragments (35-60%), clays (5-20%) and pyrite (0-2%), with accessory minerals of quartz. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as calcite with minor dolomite, quartz and illite with traces of chlorite, pyrite and feldspar. These petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO with minor SiO₂, Al₂O₃, MgO, K₂O and trace Fe₂O₃.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Cobourg Formation shale and argillaceous limestone is unfractured to very sparsely fractured with excellent core quality.

3.7.6.2 Sherman Fall Formation Argillaceous Limestone

Regionally, this formation consists of two members: a thinner Upper Member consisting of coarser-grained bioclastic or fragmental limestone and a thicker Lower Member of argillaceous fossiliferous limestone and shale (Armstrong and Carter, 2006).

At the DGR site, the Sherman Fall Formation is 28.0 to 29.0 m thick with top of formation at depths of 688.1 to 700.8 mBGS. Although the Upper and Lower Members are discussed in TR-07-05, they are not formally distinguished (i.e., see TR-08-12) due to the difficulty in defining the contact between these two Members in both core and borehole geophysical logs. The Upper Member is logged in as a coarse-grained, grey-brown shaley limestone.. The Lower Member is logged as an interbedded grey argillaceous limestone and dark grey calcareous shale (Figure 3.37). Overall the Sherman Fall Formation is logged as an argillaceous limestone.



Figure 3.37 Core sample of Lower Member of Sherman Fall argillaceous limestone, 703.90 mBGS, DGR-2

Petrographic analysis of core collected from the Sherman Fall Formation shows the samples to be similar as fine-grained fossiliferous limestone with varying amounts of fossil fragments, pyrite and Fe-staining of the calcareous clay matrix. Petrographically, the mineralogy in the cores are similar, estimated as carbonates (45 to 70%), calcareous fossil fragments (20 to 30%), clays (10 to 35%) and pyrite (trace to 5%), with accessory minerals of quartz, rutile and chalcedony. Quantitative XRD analyses of these core samples (Figures 3.4 and 3.5) identified similar mineralogy with the major minerals as calcite with minor dolomite, illite and quartz and trace pyrite and anhydrite. The petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO with minor SiO₂, Al₂O₃, MgO, and trace K₂O, SO₄ and Fe₂O₃.

Based on core logging (Table 3.3, Figures 3.2 and 3.3), the Sherman Fall Formation argillaceous limestone is unfractured to very sparsely fractured with excellent core quality.

3.7.6.3 Kirkfield Formation Argillaceous Limestone

Based on regional information, the Kirkfield Formation is thin- to thick-bedded, fossiliferous limestone with shaley partings and locally significant thin shale interbeds (Armstrong and Carter, 2006). It has thickness of 20 m on Manitoulin Island.

Based on core logging in DGR boreholes, the Kirkfield Formation is 45.7 to 45.9 m thick with top of formation at depths of 716.1 to 729.8 mBGS. It is logged as a tan to dark grey, fine-grained, irregular bedded, fossiliferous, argillaceous limestone with dark grey/green shale interbeds. It is distinguished from the overlying Sherman Fall Formation by a minor decrease in natural gamma response on the borehole geophysical logs. Some of the shale interbeds exhibited petroliferous odours.

Petrographic analysis of core collected from the Kirkfield Formation at the DGR site shows the samples to be fossiliferous shale and bioclastic argillaceous limestone comprised of large fossil fragments with carbonate-rich and clay-rich domains. The clay domains contain dolomite grains. Petrographically, the core mineralogy is estimated as carbonates (25-65%), fossil fragments (30-50%), and Fe-stained clays with illite (4-25%) with accessory minerals of pyrite, pyrrhotite, and quartz disseminated through the rock. Veins are noticeably absent in all samples analysed. Quantitative XRD analyses of the same core samples (Figures 3.4 and 3.5) identified similar mineralogical composition from the petrography with the major minerals as calcite with minor dolomite, quartz and illite and trace feldspar and pyrite. The lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) support the XRD analyses showing limited amounts of SiO₂ and Al₂O₃ (i.e., alumina-silicates or clays). The dominant elemental oxides are CaO, with minor SiO₂, Al₂O₃, MgO and K₂O.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Kirkfield Formation argillaceous limestone is unfractured to very sparsely fractured with excellent core quality. Fracturing of the Kirkfield Formation is noticeably higher in DGR-4 than in DGR-2 or DGR-3. The low minimum core recovery and RQD values listed in Table 3.3 are from one core run (DGR-2, CR-90) that experienced difficult drilling conditions resulting in grinding and breaking of the core.

3.7.6.4 Coboconk Formation Bioturbated Limestone

Regionally, the Coboconk Formation consists of light grey-tan to brown-grey, medium- to very thick-bedded, fine- to medium-grained, bioturbated bioclastic limestone (Armstrong and Carter, 2006). It has thickness of 5 m on Manitoulin Island.

The Coboconk Formation at the DGR site is 23.0 to 23.8 m thick with top of formation at depths of 762.0 to 775.6 mBGS. It is logged in DGR boreholes as a light- to medium-grey, very fine-grained, very hard, bioturbated limestone with minor dark grey/green shale interbeds. The bioturbation (stirring

or mixing of sediment by organisms, especially burrowing or boring) results in a characteristic mottled texture with frequent stylolites and nodules. The Coboconk Formation is distinguished from the overlying Kirkfield Formation by a significant decrease in natural gamma response on the borehole geophysical logs reflecting a decrease in shale content.

The lower half of the Coboconk Formation is petroliferous with minor out-gassing and hydrocarbon bubbling from stylolites and some thin vuggy zones. A thin volcanic ash bed, which is a potential DGR formation marker bed that can be used to accurately determine formation strike and dip, was logged in all boreholes in the upper third of the formation (see Figure 3.38). The composition of the ash is not known.

Petrographic analysis of cores collected from the middle sections of the Coboconk Formation shows the samples to be partly dolomitized bioclastic limestone to very fine-grained fossiliferous limestone with traces of Fe-stained clays and pyrite. Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) show major mineralogy as calcite with minor dolomite and clays with trace quartz, pyrite and anhydrite. The petrographic and XRD analyses are supported by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO with minor SiO₂, MgO and Al₂O₃, and trace SO₄ and Fe₂O₃.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Coboconk Formation bioturbated limestone is unfractured to sparsely fractured with excellent core quality. As with the overlying Kirkfield Formation, fracturing within the Coboconk Formation is higher in DGR-4 than in DGR-2 or DGR-3.



Figure 3.38 Volcanic ash bed, Coboconk Formation, 768.6 m BGS, DGR-2

3.7.6.5 Gull River Formation Lithographic Limestone

Based on regional logging, the Gull River Formation, especially the upper part, is characterized by very fine-grained (lithographic), light grey to dark brown limestone, with lesser amounts of dolostone, shale and argillaceous sandstone (Armstrong and Carter, 2006). The abundance of lime mud is noted by Armstrong and Carter (2006) as the distinguishing characteristic of the Gull River Formation as compared to the coarser-grained limestones of the overlying Coboconk Formation. The lower part of the Formation is lithologically variable, consisting of fine-grained dolostones, fossiliferous limestones, sandy dolostones and minor shale (Armstrong and Carter, 2006).

Based on core logging in DGR boreholes, the Gull River Formation is 51.7 to 53.6 m thick with formation top at depths of 785.0 to 799.3 mBGS. It is logged as a medium grey, fine- to very-grained (lithographic), fossiliferous, limestone/mudstone with thin dark grey shale interbeds. It is distinguished from the overlying Coboconk Formation by a minor and spikey increase in natural gamma response on the borehole geophysical logs. Selected thin vuggy and stylolitic sections of the Gull River Formation are slightly petroliferous showing out-gassing and traces of liquid hydrocarbons (see Figure 3.39).

Petrographic analysis of core collected from the Gull River Formation shows the samples to be bioclastic argillaceous limestone with some fine-grained micritic dolomite with Fe-stained clays. Petrographically, the core mineralogy of the samples was estimated as carbonates (75-100%) and Fe-stained clays (0-30%). Quantitative XRD analyses of the core samples (Figures 3.4 and 3.5) identified similar mineralogical composition with the major minerals as calcite and dolomite with minor feldspar, illite and quartz and trace pyrite and anhydrite. These petrographic and XRD analyses are confirmed by the lithogeochemical analyses (Table 3.7, Figures 3.10 and 3.11) which show the dominant elemental oxides are CaO and MgO with minor to trace SiO₂, Fe₂O₃, and Al₂O₃.



Figure 3.39 Trace of hydrocarbon weeping from stylolites, Gull River Formation, 817.0 mBGS in DGR-2

Based on core logging of DGR boreholes (Table 3.3, Figure 3.2 and 3.3), the Gull River Formation lithographic limestone is unfractured to sparsely fractured with excellent core quality. As with the overlying Kirkfield and Coboconk Formations, fracturing within the Gull River Formation is higher in DGR-4 than in DGR-2 or DGR-3.

3.7.6.6 Shadow Lake Formation Siltstone and Sandstone

Regionally, the Shadow Lake Formation is recognized as comprising red and green sandy shales, argillaceous and arkosic sandstones and minor sandy argillaceous dolostones (Armstrong and Carter, 2006). Green glauconitic sandstone is also recognized as a common lithofacies of the Shadow Lake Formation. The Formation has variable thickness due to the irregular paleo-topography of the Precambrian basement, with a maximum reported thickness of 15 m (Armstrong and Carter, 2006).

The Shadow Lake Formation at the DGR site is 4.5 to 5.2 m thick with top of formation at 838.6 to 851.0 mBGS. It is logged in DGR boreholes as a poorly sorted mix of grey-green sandy mudstone, and green-grey siltstone and sandstone. The top of the Shadow Lake Formation is distinguished from the overlying Gull River Formation by the presence of the first grey-green silty sandstone layer. The sandstone layers have increasing grain size with depth and are glauconitic with pyrite and traces of liquid hydrocarbon.

Petrographic analysis of cores collected from the Shadow Lake Formation shows the samples to be partly dolomitized silty limestone with traces of pyrite to silty sandstone comprised of quartz, k-feldspar, clay and pyrite. Quantitative XRD analyses of one of the core samples (Figures 3.4 and 3.5) shows mineralogy as dolomite with minor clays and quartz and trace pyrite. The petrographic and XRD analyses indicate that the tested core sample is representative of a locally dolomitized layer of siltstone with limited shale or sandstone. No samples of the Shadow Lake Formation were submitted for lithogeochemical (i.e., major oxide) analyses.

Based on core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), the Shadow Lake Formation siltstone and sandstone is unfractured to very sparsely fractured with excellent core quality.

3.7.7 Cambrian Sandstone

Regionally, the Cambrian rocks are dominated by the presence of quartzose sandstones. Lithologically the Cambrian succession in southwestern Ontario consists of, in descending order, dolostones, interbedded sandstones and dolostones and quartzose sandstones (Armstrong and Carter, 2006). The Cambrian has highly variable thickness due to the irregular paleo-topography of the Precambrian basement.

Based on core logging in DGR boreholes, the Cambrian sandstone is 16.9 m thick as logged in DGR-2 with formation top found at depths of 844.1 to 855.5 mBGS. It is logged as a tan to orange-grey fine- to medium-grained, very hard, silty sandstone/sandy dolostone with clasts of granitic gneiss and calcite. The upper parts of the formation are tan to grey, sandy siltstone to sandstone interbedded with fine grained sandy dolostone that grades with depth into cream to orange-brown, coarse-grained quartz sandstone. Dolomitization of the upper parts of the unit are significant ranging up to 100% decreasing to about 0% near the bottom of the unit (Figure 3.13). The bottom third of the Cambrian is coarse grained, quartz sandstone that is stained orange-brown with local glauconitic stringers. Figure 3.40 shows the core collected from the middle of the Cambrian sandstone in DGR-2.



Figure 3.40 Light brown Cambrian sandstone, 850.67 mBGS, DGR-2

Petrographic analysis of core collected from the upper and middle parts of the Cambrian shows the samples to be medium-grained, recrystallized dense dolostone and limestone with interstitial detrital quartz and lesser amounts of feldspars and pyrite that grades with depth into quartz sandstone with K-feldspar.

Petrographically, the mineralogy of the upper cores is estimated as carbonates (90-95%), quartz (3-5%), plagioclase (trace-0.5%), pyrite (trace-7%) and traces of K-feldspars, marcasite and Fe-stained quartz. Quantitative XRD analyses of these upper cores (Figures 3.4 and 3.5) identified similar mineralogical composition with the major minerals as dolomite and quartz with minor clays and feldspar and trace pyrite. These petrographic and XRD analyses of the upper parts of the Cambrian are confirmed by the lithogeochemical analyses (Table 3.7, Figure 3.10 and 3.11) which show the dominant elemental oxides are CaO and MgO with minor SiO₂, and trace Fe₂O₃ and Al₂O₃.

The middle parts of the Cambrian show petrology comprised of microcrystalline to medium-grained quartz/chert/ chalcedony (80%) and pyrite (7%) hosted by quartz and carbonate rich sediments. Quantitative XRD analyses of cores collected from the middle section of the Cambrian Formation (Figures 3.4 and 3.5) identified major minerals as quartz, calcite and pyrite with minor illite, feldspars and kaolinite clays and traces of dolomite, gypsum and anhydrite. Lithogeochemical analyses (Table 3.7, Figure 3.9 and 3.10) support these petrographic and mineralogical analyses, showing dominant elemental oxides as SiO₂, CaO and Fe₂O₃ with trace amounts of Al₂O₃ and MgO.

Core logging of DGR boreholes (Table 3.3, Figures 3.2 and 3.3), shows the Cambrian sandstone is moderately fractured with excellent core quality.

3.7.8 Precambrian

The Precambrian in southwestern Ontario is part of the Central Gneiss Belt of the Precambrian Grenville Province. This basement formation consists of a variety of metamorphic rock types ranging from felsic gneisses to mafic metavolcanics to marble (Armstrong and Carter, 2006). The rocks are

typically gneissic with a well-developed mineral foliation parallel to gneissosity. The upper several metres of the Precambrian basement is often comprised of a weathered alteration zone.

Only borehole DGR-2 intersects the Precambrian basement at the DGR site. Based on core logging in DGR-2, the top of Precambrian basement is found at a depth of 860.7 mBGS. The Precambrian basement is logged as a pink to grey, fine- to medium-grained, felsic granitic gneiss. Only 1.55 m of the Precambrian basement was penetrated by borehole DGR-2. The core observations indicate some alteration of the Precambrian with extensive red to green and black staining evident in the upper 1.2 m (see Figure 3.47).

Petrographic analysis of core collected from the upper part of the Precambrian at 861.90 mBGS in DGR-2 shows the sample to be granitic gneiss with quartz, K-feldspar and biotite with minor muscovite alteration and traces of rutile and pyrite. Quantitative XRD analyses of the core sample shows mineralogy as K-feldspar (40%), quartz (24%), clays (23.0%), dolomite (5.0%), calcite (4.0%), albite (4.0%) and pyrite (0.2%).

Based on very limited core logging of DGR-2 (Table 3.3, Figures 3.2 and 3.3), the Precambrian granitic gneiss is very sparsely fractured with excellent core quality.

3.8 Marker Beds

For many of the formations identified in DGR boreholes, the contacts are abrupt and easily discernable from inspection of core and review of borehole geophysical logs. For example, selection of the contacts for the Salina F Unit shale, the Guelph Formation vuggy dolostone, the Cabot Head Formation shale, the Cobourg Formation limestone and the Shadow Lake Formation siltstone and sandstone is unambiguous. However, for many of the other formations, the contacts are gradational and require some judgment.

To assist in assessment of formation orientation, several thin, laterally continuous, diagnostic marker beds were identified in DGR core (TR-08-12). These marker beds are typically 10-20 cm thick beds with visually identifiable lithofacies features and /or borehole geophysical logging signatures that are distinct from the surrounding rocks. Noteworthy marker beds identified to date in boreholes DGR-1 to DGR-4 are listed in Table 3.10. These marker beds confirm the conclusions of Section 3.4 and Table 3.1, that the orientation of the Paleozoic formations below the Salina B Unit at the DGR site are remarkably uniform and consistent with average regional strike/dip estimates of N20°W/0.6°W.

Table 3.10 Summary of marker bed descriptions, depths and orientations in DGR boreholes

Formation	Marker Bed or Horizon	Depth (mBGS)			Orientation	
		DGR-1/2	DGR-3	DGR-4	Strike	Dip
Salina F Unit	brown dolostone bed in grey shale	182.0	200.7	181.5	N32°W	0.98°SW
Queenston	limestone bed in shale	504.3	517.7	505.6	N16°W	0.63°SW
Georgian Bay	fossiliferous limestone bed in grey shale	576.5	589.2	577.9	N17°W	0.59°SW
Coboconk	porous dark grey volcanic ash bed in grey limestone	768.8	781.0	769.0	N20°W	0.58°SW
Coboconk	tan dolostone bed in grey limestone	778.7	790.5	778.3	N22°W	0.57°SW

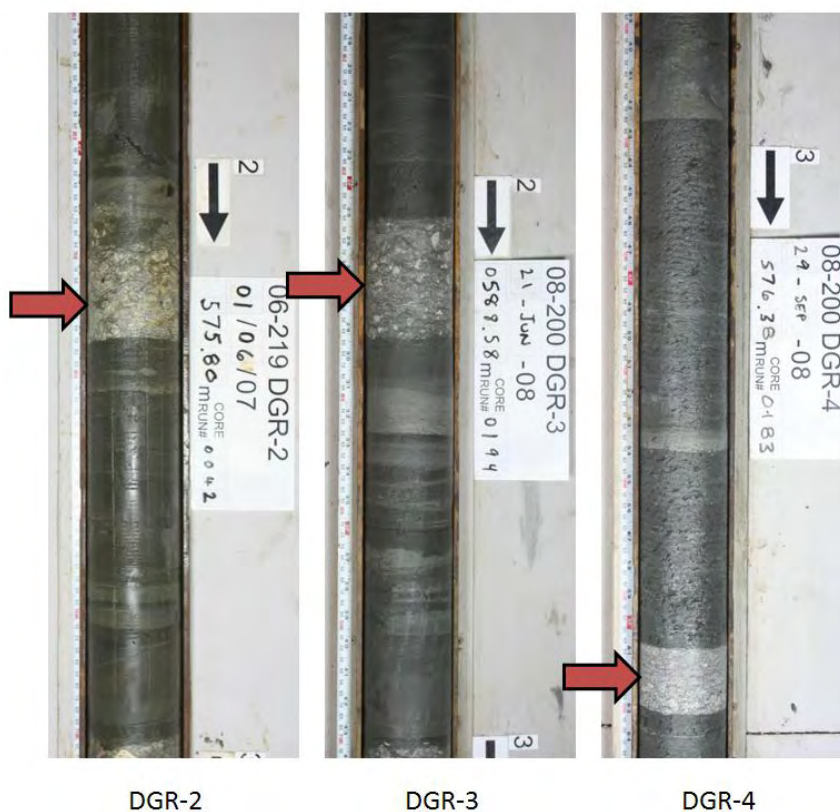


Figure 3.41 Fossiliferous limestone marker bed within Georgian Bay Formation shale in DGR boreholes

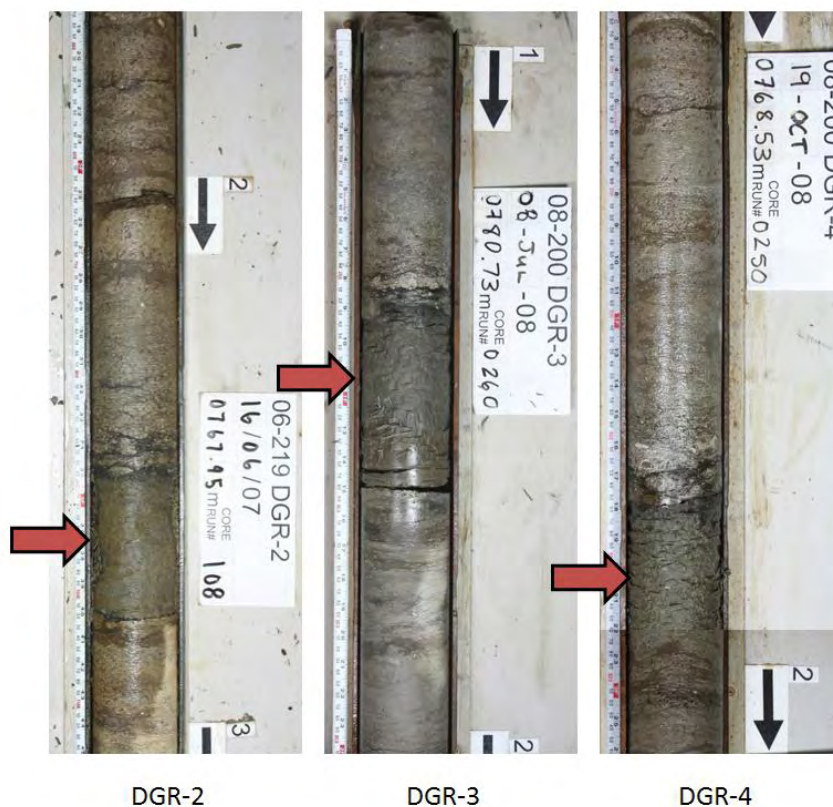


Figure 3.42 Volcanic ash marker bed within Coboconk Formation bioturbated limestone in DGR boreholes

3.9 Fracture Infill, Veins and Other Secondary Mineralogy

Fracture infill, veins and other secondary minerals including nodules were observed during core logging (TR-07-05, TR-08-13), laboratory petrographic analyses (TR-07-12, TR-08-06, TR-08-20, TR-08-21, TR-08-40), and XRD and SEM/EDS mineralogical testing (TR-08-01, TR-08-06, TR-08-22, TR-08-23, TR-08-40) of DGR-1 to DGR-4 core samples.

3.9.1 Core Logging

Logging of recovered core identified a full suite of fracture infill, vein and other secondary mineral features including nodules. This suite included chert, quartz, calcite, pyrite, halite, anhydrite, gypsum, celestite, Fe oxide/hydroxide and clay, were observed in recovered core. Halite was found in core intermittently in the Salina Formation and commonly from the Guelph Formation through the Ordovician shales and occasionally in the Cobourg and Sherman Fall limestones. Anhydrite was frequently observed from the Bass Islands Formation to the Coboconk Formation. Gypsum was observed in the Salina G to A2 Units. Generally, although occasionally ambiguous, differentiation of anhydrite from gypsum was done in the field based on hardness and colour. However, in many samples both anhydrite and gypsum are present (see Figure 3.16). Calcite and pyrite were observed from the Amherstburg Formation to the Shadow Lake Formation.

Soluble fracture infill minerals were commonly observed in the Upper Ordovician shales. Samples of the upper Queenston Formation shale in all DGR boreholes contained prominent halite-filled fractures that were bounded by a carbonate mineral lining along the fracture wall (see Figures 3.26 and 3.43). Other Queenston samples displayed calcite, anhydrite, celestite and gypsum veins. Within the Georgian Bay Formation shales, illite- and calcite-filled veins were observed as were narrow halite-infilled joints or fractures veins. Pyrite and illite veins were observed in the Blue Mountain shale.



Figure 3.43 Orange halite and calcite fracture infill in the Queenston Formation shale at 456.01 mBGS in DGR-1

3.9.2 Petrographic and XRD/SEM Analyses

Petrographic analyses of DGR cores indicated the frequent occurrence of 'vein' minerals. The use of the term 'vein' does not necessarily imply any hydrothermal origin of these infill materials merely that the minerals appear to be secondary infilling features. Some of the identified vein minerals may be the result of simple secondary precipitation reactions that have occurred at ambient temperatures. The vast majority of observed vein minerals as defined here occur as features within the intact rock and therefore represent sealed or healed discontinuities or fractures.

Devonian cherty dolostones often contained quartz and chert veins within shale interbeds. The Silurian core samples frequently displayed both gypsum and anhydrite veins in dark shales and iron-stained illite veins in fossiliferous dolostone.. Many of the vein minerals identified in the brecciated Salina Unit F, E and B Units are related to the healing of these units following collapse and settlement due to underlying salt bed dissolution.

Soluble minerals (e.g., halite, calcite and to a lesser extent gypsum, anhydrite and celestite) were frequently detected as distinct veins and as interstitial material in the Ordovician shales by petrography (Figure 3.44) and XRD/SEM mineralogical analyses. Occasionally, these same soluble minerals were detected within both the underlying Ordovician limestones and the overlying Silurian shales and dolostones (Figure 3.45). Petrographic and XRD/SEM analyses also frequently detected the presence of minor to trace amounts of other secondary minerals including illite, dolomite, feldspars, pyrite, marcasite and sphalerite.

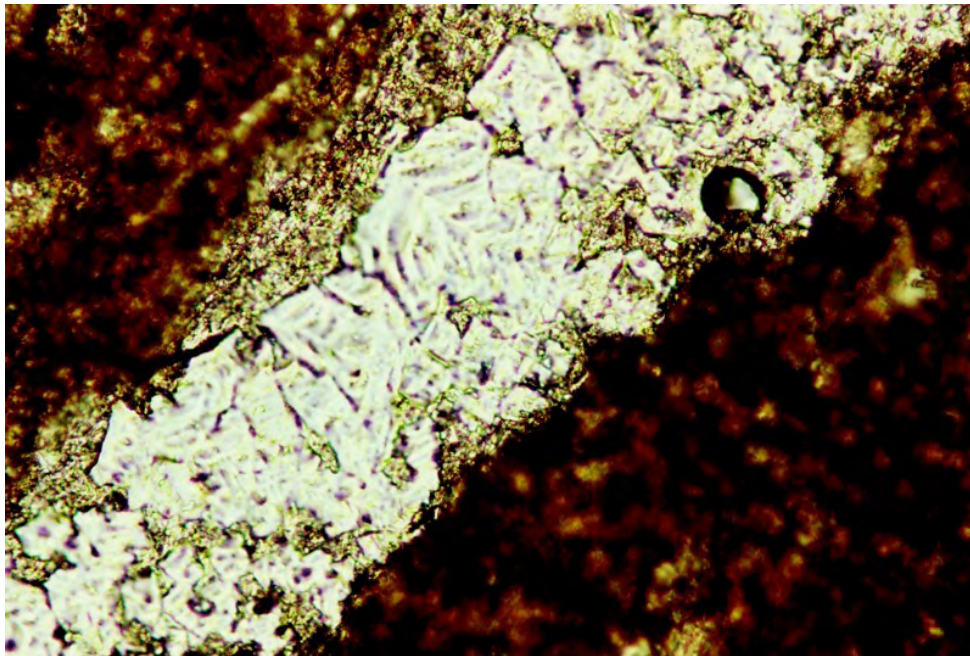


Figure 3.44 Halite vein in Georgian Bay Formation shale at 606.96 mBGS in DGR-2, width of photo: 0.34 mm, plane polarized light

Figure 3.45 shows the SEM/EDS analyses of a sample of Guelph Formation dolostone collected from a depth of 391.34 mBGS in DGR-3 (TR-08-40). Image A shows a vein in dolomitized rock filled by dolomite crystals and paragenetically later halite. Black areas on these photomicrographs correspond

to remaining porosity. The host rock contains traces of disseminated pyrite as white dots. Image B shows EDS analysis of point indicated in image A, corresponding to halite. The small peaks of Ca, Mg and O are due to the matrix effect of the nearby dolomite. Images C to F shows analysis of a small (about 50 µm thick) veinlet filled by dolomite and alter calcite and halite. Black areas on these images are remaining porosity. Image E shows EDS analysis of point shown in image F, corresponding to calcite. The small peaks of Mg, Cl and Na are due the nearby presence of halite and dolomite. All pictures in Figure 3.44 are back-scattered electron views of uncoated thin sections.

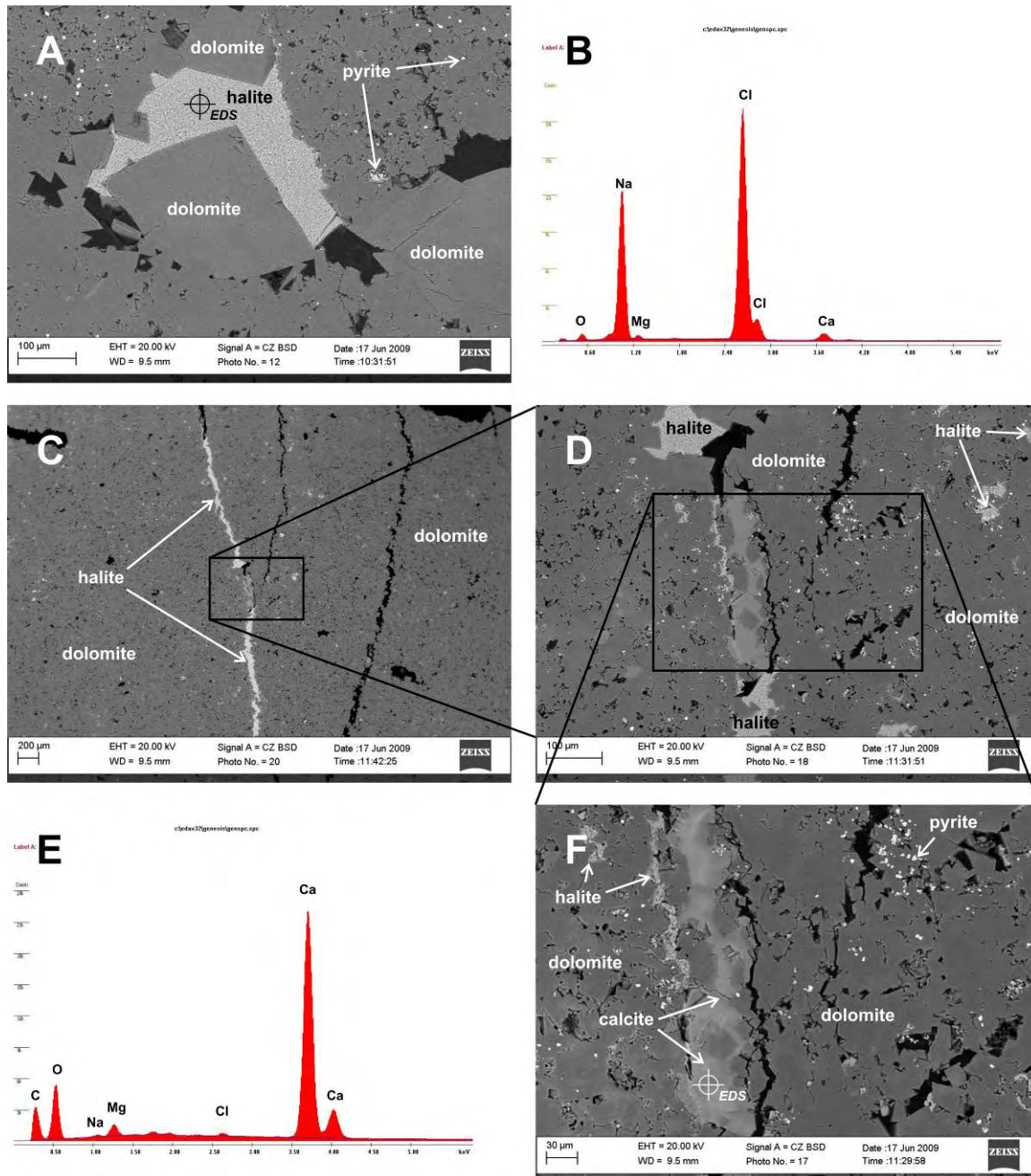


Figure 3.45 SEM/EDS analyses of vein and intact rock mineralogy of Guelph Formation dolostone at 391.34 mBGS in DGR-3. See text for discussion of images.

3.9.3 Summary

Table 3.11 summarizes the observed occurrences of fracture infill, vein and secondary mineralogy in DGR core from core logging and laboratory petrography/XRD/SEM work. There are some minor differences in the listed occurrences of identified minerals in Table 3.11 that are unavoidable and are due in part to differences in the mineralogical detection capabilities of field core logging and laboratory petrography/XRD/SEM work. As noted above differentiation of gypsum and anhydrite is occasionally difficult in the field and identification of individual clay minerals is similarly limited. Furthermore laboratory petrography and XRD/SEM work while generally considered more accurate than field logging, is focussed on smaller scale observations and it is incumbent on the analyst to ensure that the selected sub-sample of the core is representative of mineralogy within the entire core. For many of the formations at the Bruce nuclear site sampling and analysis is representative, but for some of the more heterogeneous units and formations, this remains a challenge.

Table 3.11 Summary of occurrences of fracture infill, vein and other secondary mineralogy in DGR boreholes

Formation	Core Logging	Petrography/XRD/SEM
Lucas + Amherstburg	Calcite, pyrite, Fe staining	Calcite, quartz
Bois Blanc	Calcite, pyrite, chert	Quartz, chert, calcite, pyrite
Bass Islands	Calcite, pyrite, anhydrite, Fe staining	Calcite, gypsum, pyrite, celestite
Salina G+F	Anhydrite, gypsum	Gypsum, anhydrite
Salina E+D	Anhydrite, gypsum	Gypsum, anhydrite, calcite, halite, celestite
Salina C+B	Anhydrite, gypsum	Quartz, chert, halite
Salina A2	Anhydrite, gypsum, clay	Anhydrite, gypsum, calcite
Salina A1+A0	Anhydrite, gypsum, calcite, pyrite	Calcite, pyrite, halite, anhydrite, gypsum
Guelph to Fossil Hill	Calcite, anhydrite, pyrite	Fe-stained illite, halite
Cabot Head + Manitoulin	Chert, quartz, halite, anhydrite	anhydrite, gypsum, quartz, halite, celestite, clays
Queenston	Halite, gypsum, anhydrite, pyrite, Fe staining	Halite, calcite, gypsum, anhydrite, celestite, pyrite
Georgian Bay	Halite, anhydrite, gypsum, pyrite	Illite, calcite, halite, anhydrite, celestite, pyrite, sphalerite, illite
Blue Mountain	Calcite, pyrite, halite, clay	Illite, calcite, pyrite
Cobourg	Anhydrite	Dolomite, Fe-stained illite, pyrite, halite, marcasite, calcite
Sherman Fall	Clay, anhydrite	Calcite, Fe-hydroxide, pyrite, anhydrite, halite, illite
Kirkfield	Calcite	Calcite, pyrite, marcasite
Coboconk	Anhydrite, calcite	Pyrite, calcite
Gull River	Calcite, celestite, aragonite	Fe-staining, pyrite, calcite, dolomite, anhydrite, halite
Shadow Lake	Glaucanite, calcite, pyrite, celestite	Pyrite
Cambrian	Calcite, quartz, pyrite, glauconite, Fe staining	Calcite, quartz, pyrite, marcasite, halite, green chlorite
Precambrian	-	Muscovite, rutile, pyrite

3.10 Major Structural Discontinuities

3.10.1 Silurian-Devonian Discontinuity

The contact between the Bois Blanc Formation and the underlying Bass Islands Formation at depths of 124.0 to 143.3 mBGS at the Bruce DGR site is an erosional unconformity that has resulted in enhanced weathering, dissolution, and permeability in the upper parts of the underlying Bass Islands Formation creating a regional discontinuity. This unconformity is not evident in recovered core in DGR-1 and DGR-3 due to poor core recovery and the presence of rubble zones at the depths of interest in these holes. The Silurian-Devonian unconformity is also not discernable in available video logging of US-8. However the Silurian-Devonian unconformity is evident in recovered core from DGR-4 (Figure 4.46) as the change from grey-brown to tan brown dolostone with attendant moderate fracturing.



Figure 3.46 Devonian-Silurian unconformity (middle of core photo) at the depth of 126.0 mBGS in DGR-4

Observations of drilling fluid loss, core logging, borehole geophysical and video logging and opportunistic groundwater sampling of boreholes that intersect this unconformity (TR-07-06, TR-07-11, TR-07-19, TR-08-13, TR-08-15), show that the upper 15 to 20 m of the Bass Islands Formation is weathered, open and permeable due to the presence of this erosional unconformity. Rock quality in this weathered zone is fair to very poor with moderately to highly fractured intervals. Drilling fluid losses of up to 8 m³/hr were recorded during drilling through this weathered and permeable zone in DGR boreholes and in US-8. These observations indicate that weathered bedrock associated with the Devonian-Silurian unconformity will be a zone of significant groundwater inflow that will require grouting during shaft sinking operations.

Golder Associates Ltd. (2003) provide a regional description of the Silurian-Devonian unconformity based on observations made at the Rockwood Quarry in southeastern Michigan. At this Quarry the contact undulates several metres over distances of hundreds of metres and the upper 2 to 8 m of the Bass Islands Formation is soft, weathered and permeable compared to the deeper more competent Bass Islands dolostones.

3.10.2 Cambrian-Precambrian Unconformity

The erosional unconformity between the Cambrian sandstone and the Precambrian granitic gneiss is found at depth of 860.7 mBGS in DGR-2. The contact as evident in recovered core (see Figure 3.47) is sharp with some evidence of weathering and no evidence of rubble zones.



Figure 3.47 Contact between Cambrian Formation and PreCambrian basement at 860.70 mBGS in DGR-2, NB contact is at start of arrow

3.10.3 Inclined Faults

The possible presence of vertical faults and other steeply inclined major structures at the Bruce nuclear site was assessed through 2-D seismic surveys (TR-07-15) and from detailed mapping of formation contacts and possible offsets in these contacts that may be attributed to faulting (Raven et al, 2009).

Seismic surveys at the Bruce nuclear site included completion of nine survey lines totally 19.7 km over and around the proposed DGR footprint (see Figure 3.48) using oil and gas exploration techniques. TR-07-15 describes the acquisition, processing, interpretation and limitations to the interpretation of the seismic data considering regional geology and southwestern Ontario structural geological models and local site geological information.

The interpretations of the 2D seismic data provide a reasoned assessment of possible geologic features and trend regimes that might be present beneath the Bruce nuclear site. Uncertainty in these interpretations is influenced by variable data quality resulting, in part, from the regionally-experienced poor seismic energy coupling between the low velocity, variably thick and heterogeneous glacial drift and underlying bedrock, and anthropogenic and natural background noise. These uncertainties were however, mitigated through optimization of field data collection techniques and completion of data processing using two independent companies using different data processing procedures.

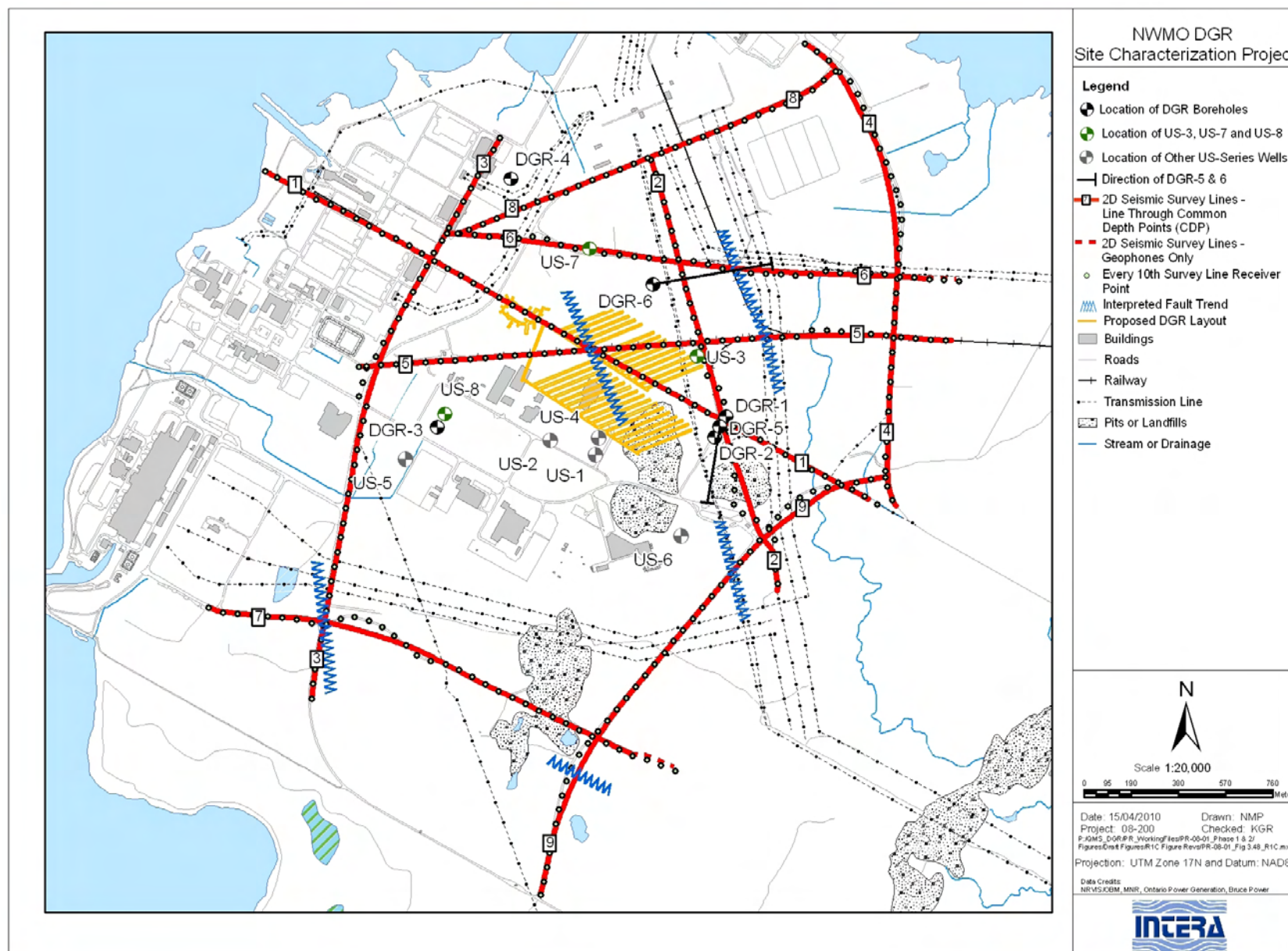


Figure 3.48 2-D seismic survey lines and interpreted occurrence of possible sub-vertical faulting within the Ordovician Formations at the Bruce nuclear site

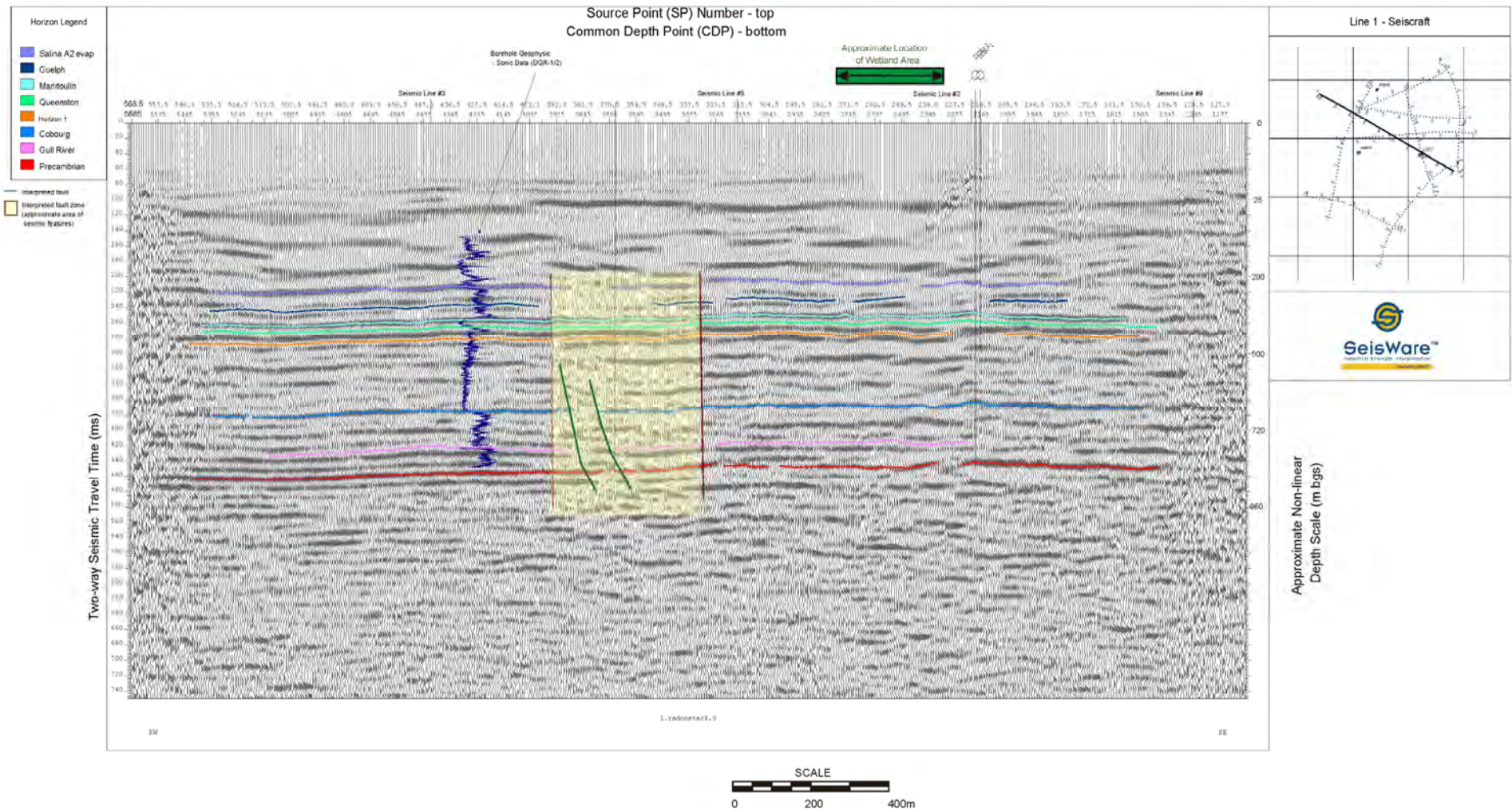


Figure 3.49 Processed and interpreted bedrock stratigraphy and structure of seismic survey line 1

Figure 3.49 illustrates a typical processed and interpreted seismic data set for survey line 1 that extends southeast to northwest through the proposed DGR area. Figure 3.49 shows the interpreted tops of several formations that are good seismic reflectors (i.e., Salina A2 Evaporite, Guelph, Manitoulin, Queenston, Cobourg and Gull River Formations and the Precambrian) as well as the interpreted occurrence of two steeply east dipping faults that propagate upward from the Precambrian to near the top of the Queenston Formation shale. Although these formation seismic reflectors were identified on all survey lines, it is possible that the interpreted faults may be artefacts from the sources of uncertainty listed above.

Upward propagation of faulting from the Precambrian is the most likely mode of fault formation for the Ordovician sedimentary sequence in southern Ontario (Carter et al., 1996), although there is evidence from regional geosynthesis studies (Gartner Lee Limited, 2008b) to suggest there is no major or active basement faulting within the Bruce area.

Figure 3.48 shows the consolidated interpretation of mapped seismic discontinuities that may represent possible vertical to sub-vertical faults at the Bruce nuclear site. These possible faults trend north-northwest to south-southeast. The presence of these possible fault structures will be investigated through inclined drilling of boreholes DGR-5 and DGR-6 as part of Phase 2B site characterization work (Intera Engineering Ltd., 2008a).

Calculations of the depth, thickness and strike and dip of the Paleozoic bedrock formations and marker beds at the Bruce nuclear site (Table 3.1) show remarkably uniformity particularly below the Salina B Unit which is the deepest unit suspected to have experienced settlement due to paleo dissolution of salt. This uniformity in depth and orientation of DGR strata below the Salina B Unit indicates a lack of any significant offsets in formation contacts. The lack of apparent offsets in formation depths between boreholes DGR-1 to DGR-4 and with the off-site Texaco #6 well (see Section 3.12) infers limited evidence for the presence of vertical faults within the Paleozoic bedrock at and near the Bruce DGR site.

Based on the geological data currently available as part of Phase 2A site characterization work, there is no data that confirms the presence of inclined or vertical faults in the area surrounding the proposed DGR defined by boreholes DGR-1 to DGR-4. This conclusion will be updated based on the results of inclined drilling of DGR-5 and DGR-6. Preliminary results from continuous coring of DGR-5 and DGR-6 indicates a lack of vertical faulting associated with the seismic reflection targets shown in Figure 3.48 and hence limited evidence for the presence of vertical faulting in these specific areas and likely within the general area surrounding the proposed DGR.

3.11 Minor Structural Discontinuities

Other minor discontinuities, primarily natural fractures, within the Devonian, Silurian and Ordovician formations, are identified on the core logs for DGR boreholes (TR-07-06, TR-08-13) on borehole geophysical logs (TR-07-08, TR-08-15) as well as in the calculations of natural fracture frequency and RQD that are summarized in Table 3.2 and Figures 3.2 and 3.3. As described in Table 3.2 and Figures 3.2 and 3.3, and the narrative of each formation description given in Section 3.7, there are numerous fractures in the permeable upper dolostones of the Lucas to Bass Islands Formations, but there are few discontinuities clearly evident in the deeper borehole core and geophysical logs, such that the deeper Silurian and Ordovician formations are described as unfractured to sparsely fractured.

There is inherent uncertainty in identification of fractures by core logs, with many identified fractures being potentially mechanical breaks. Correlation of core logs and core photographs with borehole geophysical logs, in particular borehole acoustic televiewer (ATV) image logs, provides confirmation of suspected discontinuities identified in recovered core. However, there is similar uncertainty with identification of discontinuities by ATV, as many of the horizontal features evident on ATV logs that

may be potential discontinuities are actually thin beds of variable lithology from the host rock (e.g., thin siltstone and limestone beds within host shale formation).

3.11.1 Example Discontinuities

Figures 3.50, 3.51, 3.52, 3.53 and 3.54 provide examples of some of the more noteworthy discontinuities identified from review of borehole geophysical logs (ATV borehole wall image and ATV caliper), core logs and core photography. It is beyond the scope of this report to present and discuss all identified discontinuities in DGR boreholes. TR-07-06 and TR-08-13 provide detailed logs of all natural fractures logged in recovered DGR core, and TR-07-08 and TR-08-15 provide detailed identification of all natural fractures identified from ATV images of the DGR borehole walls.

Figure 3.50 shows the occurrence of two horizontal discontinuities at 483.35 and 515.50 mBGS in DGR-2 within the Queenston Formation. The ATV logs show both features created a 5 cm wide zones of borehole enlargement due to drilling activities. The core at 483.35 mBGS however shows the appearance of a mechanical break that was not logged as a natural fracture, while the core at 515.50 mBGS shows the presence of a natural fracture. Fluid temperature and resistivity logs (TR-07-08) show that both of these features create temperature and resistivity anomalies suggestive of an open and relatively permeable feature compared to the surrounding shale bedrock.

Figure 3.51 shows the occurrence of an inclined fracture at 585.7 mBGS and minor borehole breakouts at 616.0 to 616.4 mBGS in DGR-2 within the Georgian Bay Formation. This inclined discontinuity was logged in the core as a closed halite-filled fracture that created a minor zone of borehole enlargement evident on the ATV logs, most likely due to salt washout during drilling. Fluid temperature and resistivity logs show that this is a permeable fracture, while straddle packer hydraulic testing (TR-08-32) and Westbay MP55 pressure profiles (TR-08-31) indicate that this fracture is likely gas producing and over-pressured relative to adjacent rock. The ATV and core photographs show that the minor borehole breakouts are associated with a 5 cm thick hard bed of fossiliferous siltstone and limestone.

Figure 3.52 portrays the ATV logs and core photography images of the contact between the Blue Mountain Formation and the Collingwood Member of the Cobourg Formation at a depth of 651.6 mBGS in DGR-2. Figure 3.52 shows that although the core is broken and a natural fracture was identified just above the contact, the ATV image of the borehole wall shows the faint presence of a closed fracture at this depth. Fluid temperature and resistivity logs confirm the closed nature of this fracture with no evidence of fluid flow.

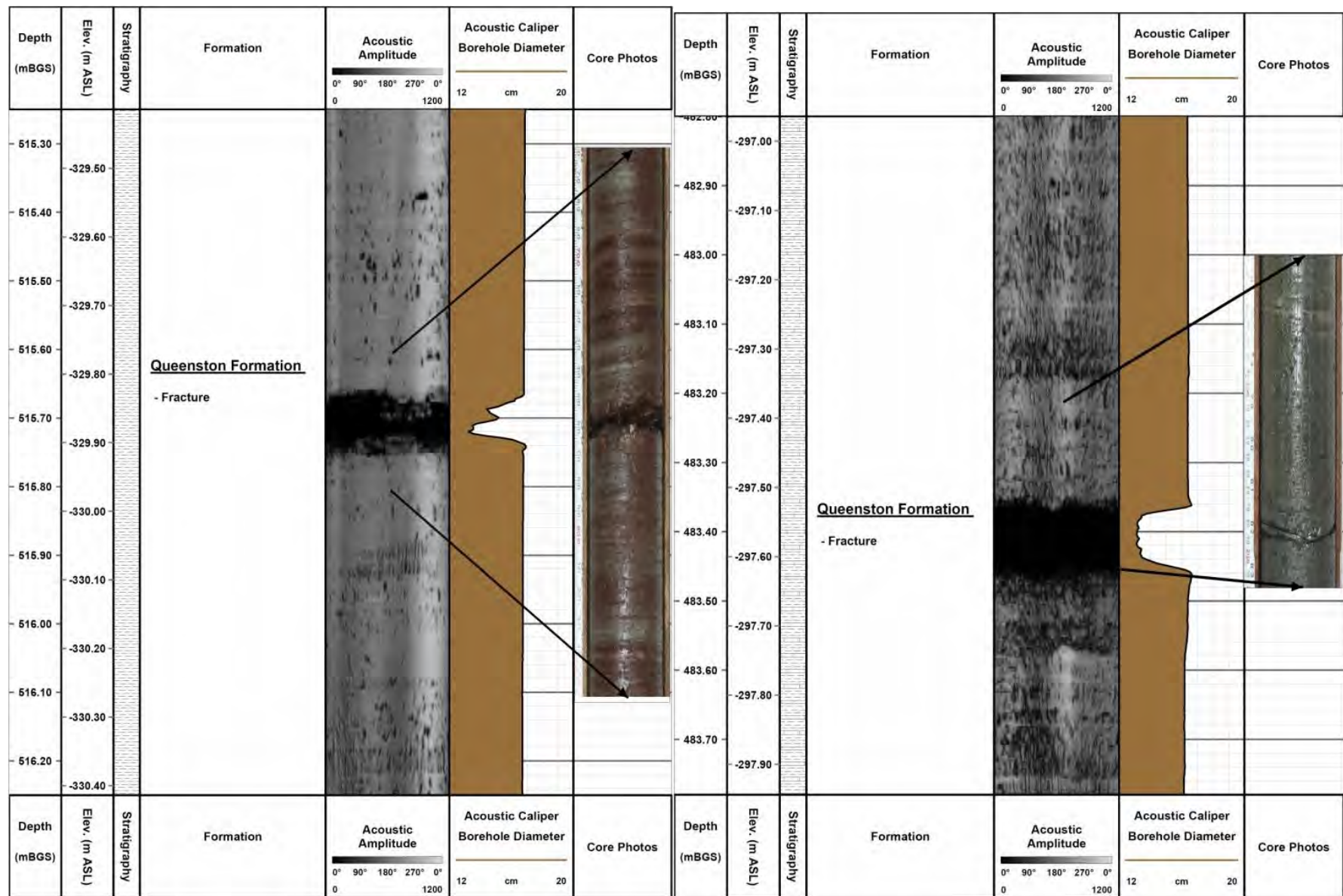


Figure 3.50 ATV logs and core photographs of two subhorizontal fractures in the Queenston Formation, DGR-2

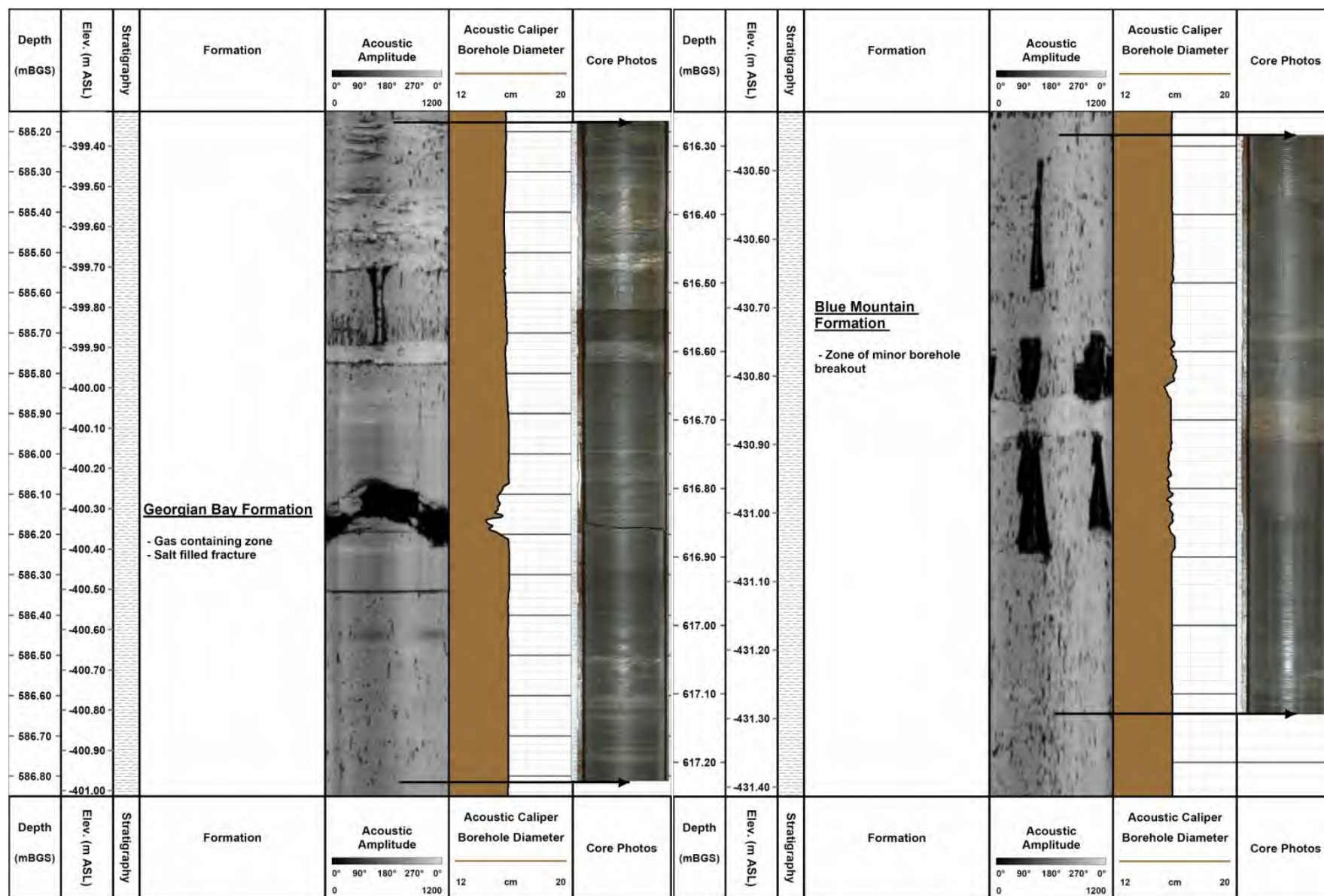


Figure 3.51 ATV logs & core photographs of possible gas containing fracture (left) and zone of minor borehole breakout in Georgian Bay Formation (right) in DGR-2

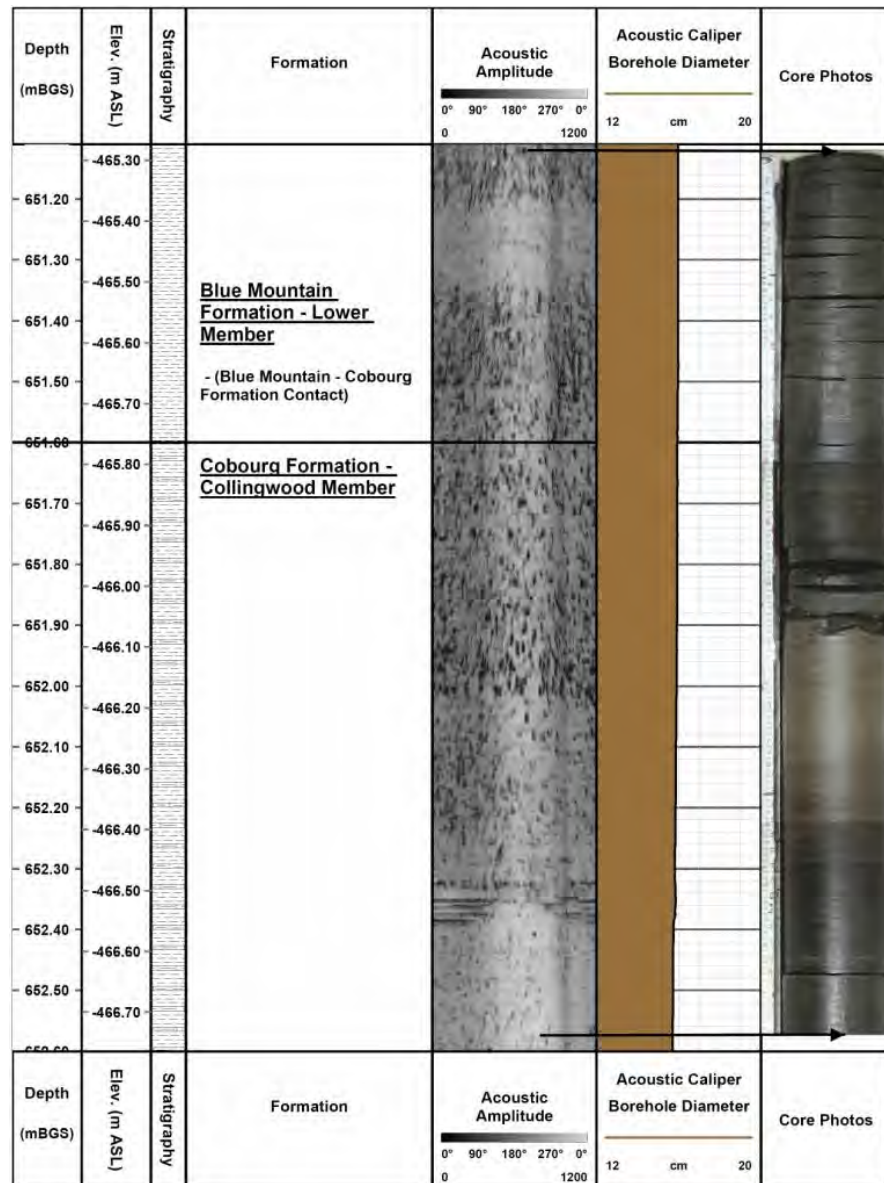


Figure 3.52 ATV logs and core photographs of contact between Blue Mountain Formation and Collingwood Member of Cobourg Formation, DGR-2

Figure 3.53 shows the ATV logs and core photography for the 10 cm-thick volcanic ash bed found at depth of 768.8 to 768.9 mBGS within the Coboconk Formation in DGR-2. This ash bed, which is a DGR formation marker bed, was washed out during drilling resulting in the increase borehole diameter shown on the acoustic caliper log of DGR-2. Although this zone was subject to drilling washout, the borehole fluid temperature variability and resistivity logs (TR-07-08) show that it may not be a zone of fluid flow or enhanced permeability in DGR-2. However fluid temperature logs from DGR-3 and DGR-4 (TR-08-15) clearly show that the volcanic ash bed is a zone of fluid flow and enhanced permeability. Borehole neutron logging of DGR-2, DGR-3 and DGR-4 also shows a neutron low at this location confirming the increased porosity of the ash bed relative to the surrounding low porosity limestone.

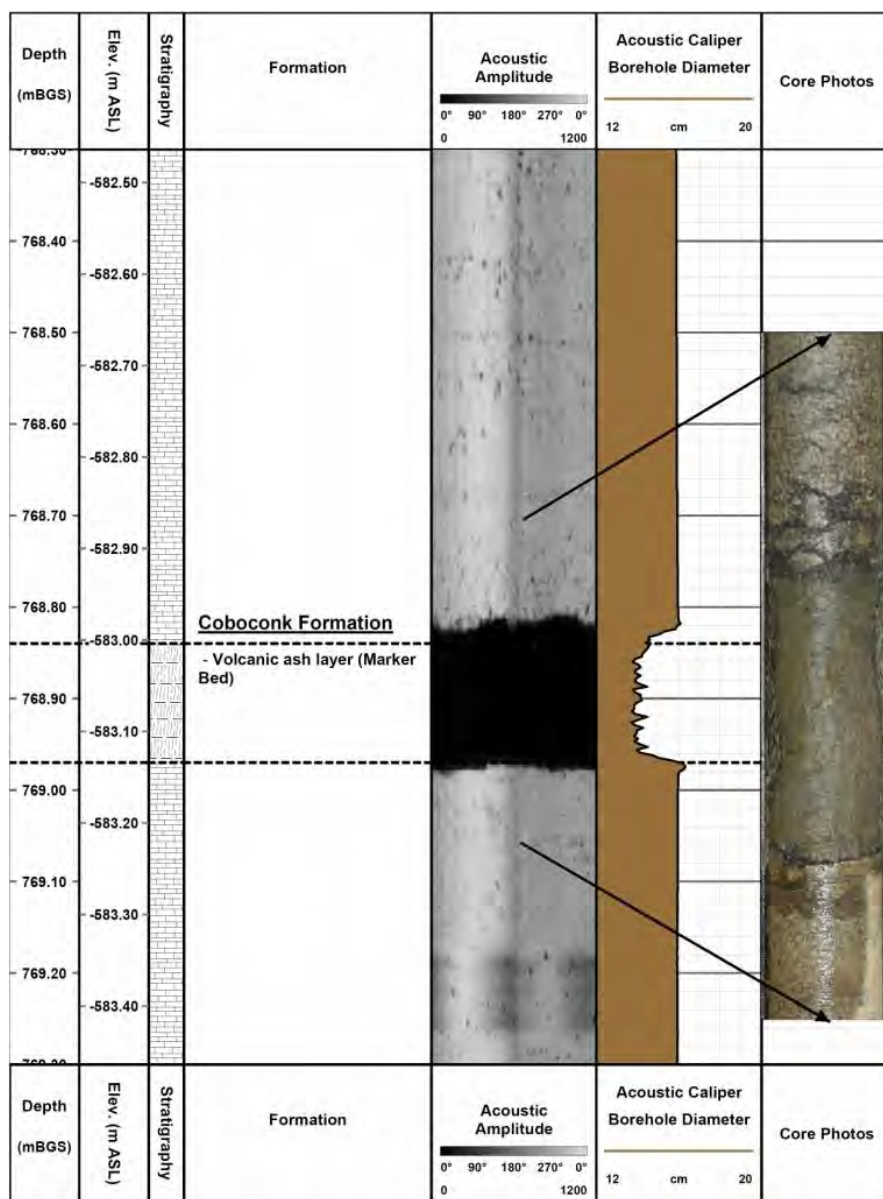


Figure 3.53 ATV logs and core photographs of volcanic ash bed, Coboconk Formation, DGR-2

Figure 3.54 shows occurrence a thin (10 cm-thick) subhorizontal fractured fissile shale layer within core at a depth of 688.6 mBGS in DGR-4 in the bottom of the Cobourg Formation. This feature is evident as a zone of increased borehole diameter on acoustic televiewer and borehole caliper logs indicating washout of the shale during drilling of the borehole. It also shows density and neutron kicks on the borehole geophysical logs indicating a zone of increased porosity or the washout. A minor kick on the temperature variability log is also evident at this depth suggesting potential for increased formation permeability. Similar lithologic and structural features were not detected in the Cobourg Formation in DGR-2 and DGR-3.



Figure 3.54 Fractured fissile shale layer at a depth of 688.6 mBGS in the bottom of the Cobourg Formation, DGR-4

3.11.2 Inclined Fractures

Identification of inclined fractures is an important part of the DGR site characterization program, but such characterization using vertical boreholes is inherently difficult due to limited sampling of such features provided by vertical boreholes. Despite this sampling bias, logging of core and analysis of ATV images of the borehole wall provide some information on the occurrence of inclined fractures in DGR boreholes. More detailed characterization of inclined fractures, including spacing, will be completed as part of the inclined drilling and oriented core logging planned for Phase 2B of the DGR site characterization program.

While logging of core from vertical boreholes DGR boreholes can identify the occurrence and approximate dip of some inclined to sub-vertical structural features, analysis of ATV images provides information on the occurrence and orientation (strike and dip) of such features though analysis of the depths of the tops and bottoms of the elliptical traces made by such features on the borehole wall. For the purposes of this discussion inclined features are defined as those features with dip greater than 35° as measured from the horizontal. Features with dips greater than this threshold can be easily distinguished and separated from more flat-lying features that may be associated with bedding planes and other sedimentological features.

Table 3.12 summarizes the identification of inclined fractures in DGR boreholes based on core logging and from ATV logging. Table 3.12 lists the total number of discontinuities with dip greater than 35° in the Silurian and Ordovician formations and within the Ordovician formations. Silurian and Ordovician formations include all formations from the Salina F Unit down to the Shadow Lake Formation. The Devonian and Silurian dolostones above the Salina F Unit are not included in this overall inclined fracture assessment because the very high fracture frequency in these shallower formations significantly bias the results for the deeper formations (see Figure 3.3), and also because ATV logging and fracture analysis was only performed in boreholes DGR-1, DGR-3 and DGR-4 from within and below the Salina F Unit. ATV-logged inclined fractures includes all minor open and major open

continuous single fractures and broken zones as defined in TR-07-08 and TR-08-15.

Table 3.12 Summary of the number of inclined fractures identified in DGR boreholes

Borehole	Silurian & Ordovician Formations		Ordovician Formations	
	Core Logging	ATV Logging	Core Logging	ATV Logging
DGR-1 and DGR-2	90	21	13	7
DGR-3	245	76	44	11
DGR-4	200	426	16	21
Totals	535	523	73	39

Table 3.12 shows that total numbers of inclined fractures identified by both core logging and by ATV logging. With the exception of DGR-4, more inclined fractures were logged by core inspection than by ATV. This suggests that many of the inclined fractures logged by core inspection are opened by stress relaxation during coring and core retrieval. Table 3.12 also shows that occurrence of inclined fractures is very much reduced within the Ordovician formations compared to the Silurian formations.

The orientation of inclined fractures in the Silurian and Ordovician formations and just within the Ordovician formations determined from ATV logging are illustrated in Figures 3.55 and 3.56, respectively. Figures 3.55 and 3.56 shows contoured polar equal-area plots of inclined joints and fractures generated using Rockscience Inc. DIPS v.5 107 software. These plots are not corrected for Terzaghi sampling bias.

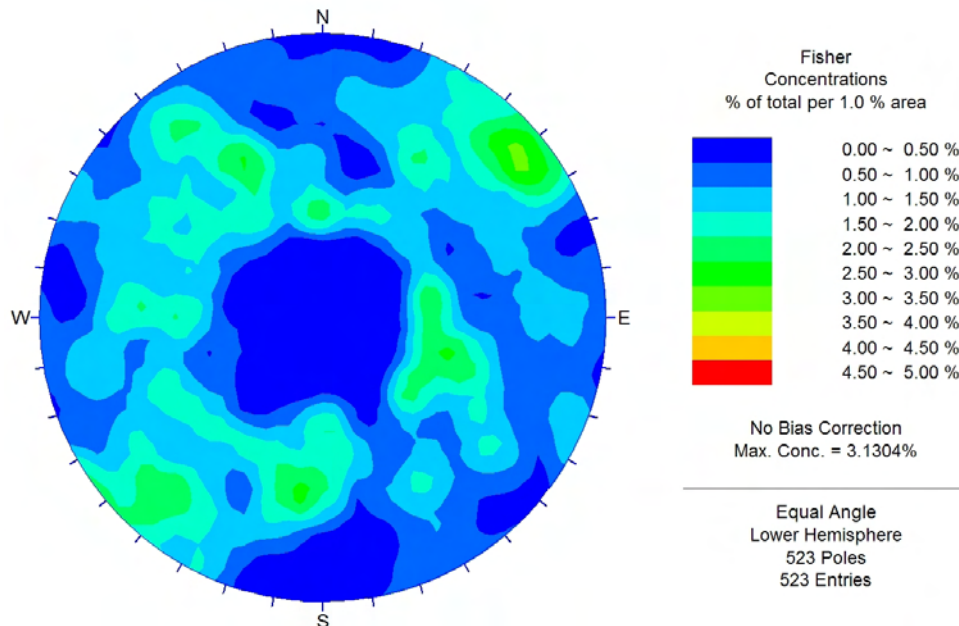


Figure 3.55 Contoured equal-area polar plot of all inclined fractures in Silurian and Ordovician formations from ATV logging in DGR boreholes

Although the data are sparse, Figure 3.55 suggests the presence of SE and NE striking fractures that dip moderately both to the NE and SW, and to the NW and SE, respectively. Figure 3.56 shows similar fracture patterns for the Ordovician formations with exception that the more steeply dipping features that strike approximately SE are absent. These fracture patterns are broadly comparable to those mapped in nearby Inverhuron Park and southern Bruce peninsula (Gartner Lee Limited, 2008c). Local mapping of joints in Inverhuron Park showed strikes of ENE and SSE, whereas mapping of southern Bruce peninsula showed joint strikes of ENE and SE.

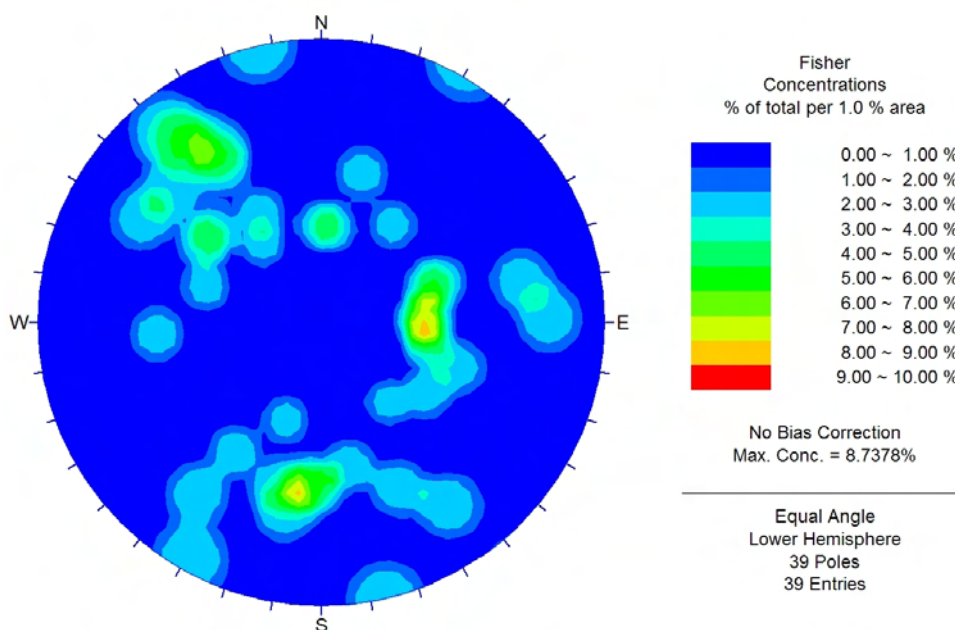


Figure 3.56 Contoured equal-area polar plot of inclined fractures in Ordovician Formations from ATV logging in DGR boreholes

3.12 Formation Lateral Predictability and Cross Section

Prior to the start of DGR drilling, the depth and thickness of bedrock formations at the Bruce nuclear site were estimated (Golder Associates Ltd., 2003) based on the results of chip and geophysical logging of the Texaco #6 oil and gas well (MNR ID: T002636) located approximately 2900 m southeast of boreholes DGR-1 and DGR-2 and identification of the top of the Bois Blanc Formation in US-4. The comparison of estimated and actual formation depths and thicknesses in DGR-1 and DGR-2 are summarized in Table 3.13. The estimated formation depths for DGR-1 and DGR-2 are corrected for the dip of the Bois Blanc Formation as given in Table 3.1 and the distance between US-4 and DGR-1/2. Actual formation depths and thicknesses are for DGR-1 and DGR-2 from TR-08-12.

Table 3.13 Summary of formation predictions and occurrences in DGR-1 and DGR-2

Formation	Predicted Depth to Top (mBGS)	Actual Depth to Top (mBGS)	Difference (m)	Predicted Fm Thickness (m)	Actual Fm Thickness (m)	Difference (m)
Amherstburg	7.8	30.4	+22.6	46.2	44.6	-1.6
Bois Blanc	54.0	75.0	+21.0	38.2	49.0	+10.8
Bass Islands	92.4	124.0	+31.6	42.1	45.3	+3.2
Salina G+F	134.5	169.3	+34.8	46.3	53.7	+7.4
Salina E+D	180.8	223.0	+42.2	32.6	21.6	-11.0
Salina C+B	213.4	244.6	+31.2	47.9	46.6	-1.3
Salina A2	261.3	293.1	+31.8	33.5	31.7	-1.8
Salina A1+A0	294.8	325.5	+30.7	44.2	49.0	+4.8
Guelph - Fossil Hill	339.0	374.5	+35.5	42.1	36.5	-5.6
Cabot Head + Manitoulin	381.1	411.0	+29.9	35.6	36.7	+1.1
Queenston	416.7	447.7	+31.0	79.3	70.4	-8.9
Georgian Bay	496.0	518.0	+22.0	95.1	90.9	-4.2
Blue Mountain	591.1	608.9	+17.8	32.6	42.7	+10.1
Cobourg (Lindsay)	623.7	651.6	+27.9	44.5	36.5	-12.0
Sherman Fall+ Kirkfield+ Coboconk (Verulam+ Bobcaygeon)	659.4	688.1	+28.7	107.9	96.9	-11.0
Gull River	767.3	785.0	+17.7	43.9	53.6	+9.7
Shadow Lake	811.2	838.6	+27.4	4.8	5.2	+0.4
Cambrian	816.0	843.8	+27.8	8.0	16.9	+8.9
Precambrian	824.0	860.7	+36.7	NA	NA	NA

Several simplifications have been made to make the comparison between predicted and actual formation depths and thicknesses meaningful. Most of these simplifications include combining formations that were logged differently by Golder Associates Ltd. and in TR-08-12 due to changes in stratigraphic nomenclature that occurred with release of the updated nomenclature by Armstrong and Carter in 2006 or simply combining formations for ease of presentation. The simplifications and rationale for the simplifications are:

- Combining Salina G+F, E+D, C+B and A1+A0 Units for ease of presentation and because Golder Associates Ltd. assumed the Salina D and A0 Units were not present.
- Combining all of the Middle Silurian dolostone formations because of the complexity of the many thin formations identified in TR-08-12.
- Combining the Cabot Head and Manitoulin Formations for ease of presentation.
- Combining Sherman Fall, Kirkfield and Coboconk Formations as these individual formations were defined and identified differently by Golder Associates Ltd. than in TR-08-12.

Review of Table 3.13 shows that for the vast majority of the formations the actual depths are about 30 m deeper than predicted depths and the cause of the under-prediction of depths appears to be derived from two additive errors. This common under-prediction is likely due to an erroneous identification of the top of the Bois Blanc Formation (~20 m offset) in US-4 and underestimation of the thickness of this formation at the Bruce nuclear site by about 10 m. Correcting for this combined 30 m offset, brings actual formation depths in DGR-1 and DGR-2 remarkably close to predictions based on Texaco #6 stratigraphy.

This last observation implies that almost all of the formation thicknesses were reasonably well predicted. Review of the last column of Table 3.13 shows this to be the case, with most differences in formation thickness being less than 10 m. Those formations with thickness differences greater than this amount are those formations where combining of formations was necessary to offset different formation nomenclature and identification (e.g., Sherman Fall, Kirkfield, Coboconk and Gull River), or formation thickness was uncertain due to natural variability caused by uncertain lower erosional surfaces (e.g., Cambrian sandstone).

Figure 3.57 shows the cross-section constructed between Texaco No. 6 well and boreholes DGR-1, DGR-2 and DGR-3. The contacts for the Ordovician shale and limestone formations in the Texaco No. 6 well log were adjusted to consistent with the formation pick rationale developed in TR-08-12 and applied to DGR boreholes. This adjustment which was made based on borehole geophysical logs (natural gamma) resulted in minor movement of the formation depth contacts for the Queenston, Collingwood, Sherman Fall, Kirkfield and Gull River Formations. Figure 3.57 illustrates the continuity of Paleozoic formation thicknesses and attitudes over distances of 3 to 4 km in the vicinity of the proposed Bruce DGR.

Figure 3.57 shows apparent dips of about 0.8 to 1.0° for the Devonian dolostones and about 0.4° for the Ordovician shales and limestones on the Bruce nuclear site. Lower apparent dips are evident from Texaco #6 to the Bruce nuclear site because that part of the cross section is oriented closer to the strike direction than the dip direction of the formations. These apparent formation dips are consistent with the regional geological compilation (Gartner Lee Limited, 2008b) that concluded regional formation dips in the vicinity of the Bruce nuclear site average 0.5 to 0.6°SW increasing toward the centre of the Michigan Basin.

The descriptive geological site model confirms that a total thickness of 211.9 m of tight shale and argillaceous limestone of Ordovician age overlies the proposed DGR repository host Cobourg Formation. Additional barrier rocks also exist within the overlying 278.4 m thick Silurian formations that contain similar tight shales, evaporites and dolostones.

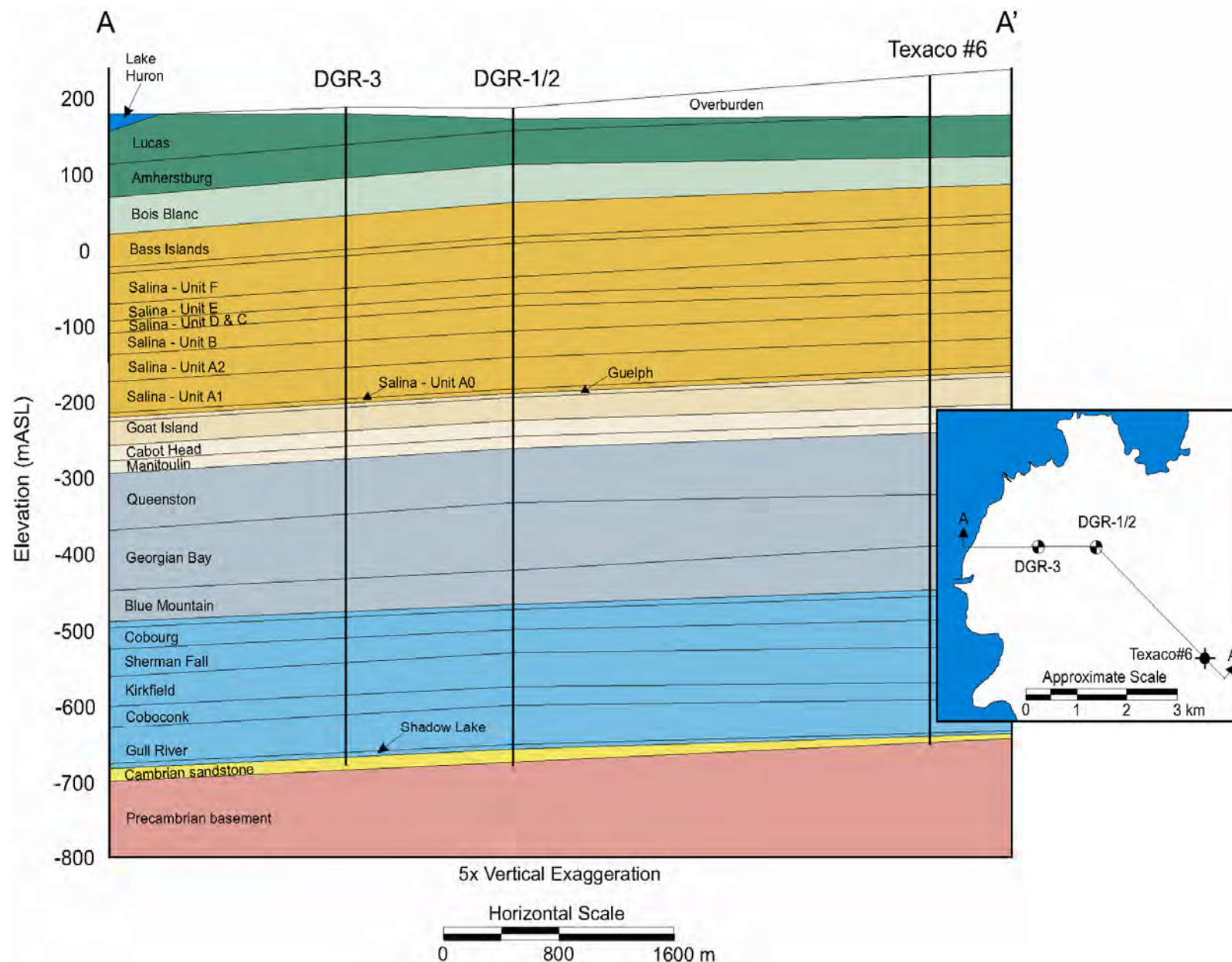


Figure 3.57 Regional stratigraphic cross section - Texaco No. 6 to Bruce nuclear site

3.13 Recommended Estimates of Descriptive Geological Model Properties

Tables 3.14 and 3.15 summarize the recommended estimates of the main structural and mineralogical properties of the 36 layers that comprise descriptive geological model for the Bruce DGR site. Table 3.14 summarizes the estimates of top depth, thickness, strike/dip, Rock Quality Designation (RQD) and natural fracture frequency (NFF) of the 36 layers that comprise the descriptive geological site model. Table 3.15 summarizes the main mineralogical properties, including major primary mineralogy and secondary minor mineralogy of the 36 model layers.

The estimates of the depth of the top and thickness of each model layer are defined based on the reference stratigraphy occurring at DGR-1 and DGR-2, as listed in Figure 3.1 and Table 3.1 (TR-08-12). Strike and dip of the model layers are given in Table 3.14 based on the calculated layer orientations provided in Table 3.1 (TR-08-12) assuming all of the DGR boreholes are vertical with zero tilt. RQD and natural fracture frequency are calculated as arithmetic averages of these measurements made on all 3.04 m core runs completed in within each model layer from boreholes DGR-1, DGR-2, DGR-3 and DGR-4 as summarized in Table 3.1 and presented in Figures 3.2 and 3.3.

Table 3.15 lists the estimates of percent weight composition of major mineralogy for each of the 36 model layers determined principally from semi-quantitative XRD analyses (TR-08-01, TR-08-06, TR-08-22, TR-08-23, TR-08-29 and TR-08-40), supplemented by petrographic analyses. Major minerals include calcite, dolomite, quartz, sheet silicates and others (e.g., gypsum/anhydrite, feldspars, where the weight percentage is estimated to be greater than or equal to 5%). As discussed in Section 3.6.1.1, dolomite includes ankerite or Fe dolomite and sheet silicates include all common clay minerals such as illite, chlorite, montmorillonite, smectite and minor dioctahedral micas (i.e., muscovite, hydromuscovite) which are typically not distinguishable from common clay minerals in XRD analyses. Best estimates of major mineral composition were determined from arithmetic averages for layers presented in Figures 3.4 and 3.5 adjusted considering other major minerals as listed in formation stratigraphic descriptions (Section 3.7) and the need to approximate 95-100% for the weight percentages of listed major minerals present. Where XRD or petrographic analyses were not available for some thin layers (e.g., Salina D Unit anhydritic dolostone, B Unit evaporite, A0 Unit dolostone, Lions Head and Fossil Hill dolostones), mineralogy is estimated from lithologically similar units or formations.

Table 3.15 provides estimates of mineralogy on a unit, member and formation basis, regardless of any major lithofacies changes within such units, members and formations. Thus for the Queenston and Georgian Bay Formations where two sets of lithofacies are evident (massive shale and limestone/siltstone hardbeds) the recommended mineralogy are averages of cores that sample these different lithofacies. Similarly for the Cambrian rocks that are comprised of an upper argillaceous dolostone facies and lower quartzitic sandstone facies, the recommended mineralogy represents an average of these two different lithofacies.

Table 3.15 also lists the reported detections of minor minerals evident from core logging and laboratory XRD, SEM and petrography analyses. Minor minerals are typically minerals that contribute less than 5% weight of a core sample as well as trace soluble minerals that are important to interpretation of porewater chemistries (e.g., halite, gypsum, anhydrite, celestite) and minerals that are useful in interpreting geochemical redox conditions (e.g., pyrite, marcasite, chalcopyrite).

Minor feldspar minerals are listed in Table 3.15 as identified by the laboratory analyst or petrographer. Thus feldspar identifications include both group of minerals (e.g., K feldspar) as well as individual feldspars that comprise such a group (e.g., microcline, orthoclase, sanidine).

Table 3.14 Recommended estimates of structural properties of descriptive geological model layers

<i>Model Layer</i>	<i>Top Depth (mBGS)</i>	<i>Thickness (m)</i>	<i>Orientation</i>		<i>RQD (%)</i>	<i>NFF (m⁻¹)</i>
			<i>Strike</i>	<i>Dip</i>		
Clay till overburden	0	20.0	-	-	-	-
Lucas	20.0	10.4	N16°W	1.15°SW	47	5.4
Amherstburg	30.4	44.6	N27°W	0.95°SW	47	5.4
Bois Blanc	75.0	49.0	N25°W	0.95°SW	68	3.6
Bass Islands	124.0	45.3	N17°W	0.90°SW	33	2.7
Salina G Unit	169.3	9.3	N33°W	0.95°SW	54	3.8
Salina F Unit	178.6	44.4	N35°W	0.90°SW	92	1.1
Salina E Unit	223.0	20.0	N25°W	1.01°SW	98	0.6
Salina D Unit	243.0	1.6	N25°W	1.07°SW	100	0.3
Salina C Unit	244.6	15.7	N24°W	0.86°SW	100	0.3
Salina B Unit dolostone	260.3	30.9	N24°W	0.55°SW	100	0.1
Salina B Unit anhydrite	291.2	1.9	N20°W	0.53°SW	100	0.1
Salina A2 Unit dolostone	293.1	26.6	N28°W	0.64°SW	99	0.2
Salina A2 Unit evaporite	319.7	5.8	N21°W	0.60°SW	99	0.2
Salina A1 Unit dolostone	325.5	41.5	N25°W	0.60°SW	100	0.2
Salina A1 Unit evaporite	367.0	3.5	N19°W	0.63°SW	100	0.2
Salina A0 Unit	370.5	4.0	N16°W	0.55°SW	100	0.2
Guelph	374.5	4.1	N16°W	0.61°SW	100	0.3
Goat Island	378.6	18.8	N15°W	0.59°SW	100	0.3
Gasport	397.4	6.9	N16°W	0.57°SW	100	0.3
Lions Head	404.2	4.4	N17°W	0.57°SW	100	0.3
Fossil Hill	408.7	2.3	N19°W	0.53°SW	100	0.3
Cabot Head	411.0	23.8	N19°W	0.57°SW	100	0.1
Manitoulin	434.8	12.9	N24°W	0.42°SW	99	0.1
Queenston	447.7	70.4	N17°W	0.63°SW	97	0.3
Georgian Bay	518.0	90.9	N23°W	0.54°SW	97	0.1
Blue Mountain	608.9	42.7	N12°W	0.61°SW	100	0.1
Cobourg – Collingwood Member	651.6	7.9	N14°W	0.59°SW	100	0.2
Cobourg – Lower	659.5	28.6	N14°W	0.63°SW	100	0.2
Sherman Fall	688.1	28.0	N17°W	0.60°SW	100	0.3
Kirkfield	716.1	45.9	N18°W	0.65°SW	98	0.6
Coboconk	762.0	23.0	N19°W	0.65°SW	98	0.7
Gull River	785.0	53.6	N16°W	0.68°SW	100	0.3
Shadow Lake	838.6	5.2	N19°W	0.59°SW	99	0.3
Cambrian	843.8	16.9	N18°W	0.55°SW	99	1.7
Upper Precambrian	860.7	-	-	-	100	0.3

Table 3.15 Recommended estimates of mineralogical properties of descriptive geological model layers

Model Layer	Major Mineralogy (%)					Minor Mineralogy
	Calcite	Dolomite	Quartz	Sheet Silicates	Other	
Clay till overburden	-	-	-	-	-	-
Lucas	49	49	0.4	0	0	Sp
Amherstburg	42	56	2	0	0	Py
Bois Blanc	56	18	14	1	0	Ch, Py, He
Bass Islands	1	88	6	0	5-Gy	Ce, Py
Salina G Unit	0	57	1	0	42-Gy/An	An, Py, Sa
Salina F Unit	0	30	10	16	44-Gy/An	An, Py, O
Salina E Unit	0	61	5	16	18-Gy	An, Py, O, Sa
Salina D Unit	0	20	0	0	80-An/Gy	An
Salina C Unit	0	26	20	44	0	An, Sa, Ha
Salina B Unit dolostone	0	30	5	32	15-An/Gy	Ha
Salina B Unit anhydrite	0	10	0	0	90-An/Gy	-
Salina A2 Unit dolostone	8	60	5	10	10-Gy/An	Py, Ce, O
Salina A2 Unit evaporite	5	3	1	0	90-An	Gy
Salina A1 Unit dolostone	79	7	2	10	0	Py, O, Gy, An
Salina A1 Unit evaporite	0	30	2	2	66-An	Py, Sa
Salina A0 Unit	10	75	2	2	0	Py, An
Guelph	1	86	2	0	10-Ha	Py
Goat Island	73	12	7	8	0	-
Gasport	79	15	2	3	0	He
Lions Head	79	15	2	3	0	An, He
Fossil Hill	79	15	2	3	0	An, Py
Cabot Head	0	25	25	40	6-Go/O	Gy, An, Ha, Py, Ce
Manitoulin	54	12	13	19	0	An, Gy, Ha, Py, He
Queenston	24	14	17	40	0	Gy, An, Ha, He, Go
Georgian Bay	10	11	28	41	9-O	Ha, Gy, An, Py, Ce
Blue Mountain	6	3	50	32	7-O/Mi	Ha, Py
Cobourg – Collingwood Member	68	10	9	9	0	M, O, Py
Cobourg - Lower	81	8	3	6	0	Mi, Py, Ha, An
Sherman Fall	75	11	3	2	6-Mi	An, Ha, Py
Kirkfield	86	3	3	2	5-O/Mi	Py, Ma
Coboconk	86	9	2	2	0	An, Py
Gull River	53	38	2	6	0	An, Py
Shadow Lake	0	40	15	35	9-Kf	Gl, Py, Ce
Cambrian	3	42	30	4	12-O/Mi	Py, Ma, Gy, Ha, An
Upper Precambrian	4	5	24	23	40-Kf	Py

An = Anhydrite, Ce = Celestite, Ch = Chalcopyrite, Gy = Gypsum, Go = Goethite, Gl – Glauconite, Ha = Halite, He = Hematite, Kf = K Feldspar, O = Orthoclase, Ma = Marcasite, Mi=Microcline, Py = Pyrite, Sa = Sanidine, Sp= Sphalerite

3.14 Confidence Assessment of Geological Data and Model

Confidence in the descriptive geological site model presented in Section 3 is assessed based on an evaluation of the quality and uncertainty in the key data that comprises the model, consistency of the data sets that comprise the model, and consistency of the geological model with other geoscientific models presented in Section 4 (descriptive hydrogeological site model) and Section 5 (descriptive geomechanical site model).

Data quality is often evaluated based on an assessment of data quality indicators of precision, accuracy, representativeness, comparability and completeness. These so-called PARCC attributes, while developed primarily to assess laboratory environmental quality data (US EPA, 1995), have some relevance and application to geological data quality evaluation.

The following key geological data sets are subject to confidence assessment:

- Depth, thickness and orientation of model layers
- Major mineralogy of model layers
- Occurrence of soluble minerals
- Occurrence of major structural features
- Characterization of minor structural features

3.14.1 Depth, Thickness and Orientation of Model Layers

Confidence in the geometry of the 36 layers that comprise the descriptive geological model is judged to be high. The geometry of the model layers are defined based on identification of formation, member and unit contacts and accuracy in borehole depth and location measurements obtained during drilling and borehole geophysical logging. The collection of continuous core in all DGR boreholes provides a level of confidence in formation identification and depths, not usually obtained in deep sedimentary formation drilling in southern Ontario.

The stratigraphic nomenclature and depth of the top of each formation, member and unit contact in DGR boreholes was defined based on consensus opinion of expert geologists assembled in two core workshops held at the Bruce Core Storage Facility following the completion of drilling and borehole geophysical logging of DGR-1 and DGR-2 (September 5 and 6, 2007) and DGR-3 and DGR-4 (November 25 and 26, 2008). Senior geologists from the Ministry of Natural Resources – Petroleum Resources Centre, Ontario Geological Survey and Geological Survey of Canada, as well as NWMO and Intera geologists attended these core workshops. TR-08-12 describes the methodology and results of these workshops in defining the stratigraphic nomenclature and formation contact depths in each DGR borehole. The stratigraphic nomenclature adopted at these workshops and throughout this report are those of Armstrong and Carter (2006). The resultant stratigraphic descriptions of DGR rocks as given in Section 3.7 are remarkably similar to those of Armstrong and Carter.

Formation contacts are defined in DGR boreholes based on logging of recovered core and borehole geophysical logging. Accuracy of core depths in DGR boreholes is estimated to be in the range of 0.1 to 0.5 m decreasing with depth, although core logging is undertaken to a precision of 0.01 m. Accuracy of borehole geophysical logs is assumed to be similar to that of the core logging as the borehole geophysical logs are adjusted to core log depths to overcome any cable stretch and slippage in the borehole geophysical depth counter.

Formation contacts in DGR boreholes range from abrupt, easily discernable features in core (e.g., top of the Salina F Unit shale, Guelph dolostone, Cabot Head shale, Cobourg limestone and Shadow Lake siltstone and sandstone) to gradational, subjective features requiring judgment and reliance on borehole geophysical logs that provide signals averaged over borehole lengths that are greater than the depth accuracy of core logs. TR-08-12 assesses the relative difficulty of the identification of top of formation in DGR boreholes and notes that top of the Amherstburg dolostone, the Bois Blanc dolostone, Gasport dolostone, Lions Head dolostone, Blue Mountain shale, Sherman Fall limestone and Kirkfield limestone are all difficult picks for both core logging and borehole geophysics. For these gradational contacts the actual contact depths may be out by +/- 1 to 2 m. To improve the depth estimates of DGR formations, thin unambiguous marker beds have been identified in selected formations ranging from the F Unit shale to the Coboconk and Gull River Formations (Section 3.8, Raven et al, 2009, AECOM Canada Ltd., 2010).

As described in Section 3.4, the thickness and orientation of the 36 model layers in DGR boreholes are remarkably uniform over the DGR borehole separation distances of 1047 to 1318 m particularly below the Salina B Unit, considering the potential uncertainty is several formation picks. The variability in formation depths and thicknesses above the Salina B Unit is most likely due to collapse and minor rotation of the overlying bedrock following paleo dissolution of the Salina B and D Unit salt beds. Below the Salina B Unit, formation thicknesses in DGR boreholes are within 1-2 m of each other in different holes, and the formation strikes are within 5-10° and formation dips are within 0.10° for each formation. The average strike and dip of the deeper Silurian and the Ordovician Formations of N20°W/0.6°SW at the Bruce nuclear site are consistent with results of the regional 3-D geological framework model (Gartner Lee Limited, 2008b) and the stratigraphy in the nearby Texaco #6 well (see Figure 3.57) Noteworthy minor excursions of uniformity of thickness and orientation for formations below the Salina B Unit at the Bruce nuclear site include the Queenston Formation whose upper contact is a recognized erosional unconformity. This general consistency in thickness and orientation of formations between DGR boreholes and regional data provides confidence in the depth, thickness and orientation of the model layers in the descriptive geological site model.

Depths, thicknesses and orientations of DGR formations are determined assuming that all of the DGR boreholes are vertical, without any significant tilt. However, borehole geophysical logging of DGR boreholes provides continuous information on the exact azimuth and plunge of the borehole and this information (TR-07-08, TR-08-15) shows that the boreholes are slightly non-vertical with tilts ranging up to maximums of 1.8°, 1.4°, 5.4° and 3.8° from vertical for boreholes DGR-1, DGR-2, DGR-3 and DGR-4, respectively. Integrating the continuous borehole azimuth and tilt angles along the length of each borehole determines the correct depth and lateral position of each formation contact in each borehole. Using these correct contact positions in each DGR borehole, a perturbation analysis was also undertaken to determine the effect of uncertainty in formation contact depth to calculated strike and dip of DGR bedrock formations. Uncertainties in contact depths of +/- 0.1, 0.5 and 1.0 m were considered for two representative formations – the Cabot Head shale and the Coboconk limestone as represented by the volcanic ash marker bed. In the perturbation analysis contacts are raised and lowered by the defined uncertainty level in each well and in combinations of wells (total of 18 combinations for each uncertainty level) such the complete range of strikes and dips are determined. Table 3.15 summarizes the results of the perturbation analyses as strikes and dips, compared against the strike and dip determined assuming borehole verticality as listed in Table 3.1, and the based on the exact borehole positions.

Table 3.16 shows that the error in formation strike and dip associated with the assumption of borehole verticality is insignificantly small and within strike and dip measurement error. For the Cabot Head and Cobourg Formations the strike varies by 0.4 and 0.6° and the dip varies by 0.01 and 0.02°. The perturbation analyses show that uncertainty of +/- 0.1 m in formation contacts results in strike and dip errors of about +/- 1.5° and +/- 0.01° for the Cabot Head Formation; and +/- 0.7° and +/- 0.01° for the

Coboconk Formation. Increasing the uncertainty to ± 0.5 m increases potential errors in strike and dip to about $\pm 5^\circ$ and $\pm 0.05^\circ$ for the Cabot Head Formation; and $\pm 4^\circ$ and $\pm 0.05^\circ$ for the Coboconk Formation. With uncertainty of ± 1 m in formation contacts, the potential errors in strike and dip increase to large values of about $\pm 10^\circ$ and $\pm 0.1^\circ$ for the Cabot Head Formation; and $\pm 8^\circ$ and $\pm 0.1^\circ$ for the Coboconk Formation.

Table 3.16 Summary of effects of borehole and formation contact assumptions on calculated strikes and dips of Cabot Head and Coboconk Formations in DGR boreholes

Formation and Contact Assumption	Strike	Dip
<i>Cabot Head Shale</i>		
Assumed Borehole Verticality	N18.4°W	0.53°SW
True Borehole Positions	N18.0°W	0.51°SW
0.1 m Uncertainty	N16.6°W to N18.5°W	0.49° to 0.51°SW
0.5 m Uncertainty	N12.9°W to N22.5°W	0.44° to 0.55°SW
1.0 m Uncertainty	N6.7°W to N27.7°W	0.39° to 0.60°SW
<i>Coboconk Formation – Ash Marker Bed</i>		
Assumed Borehole Verticality	N19.6°W	0.58°SW
True Borehole Positions	N20.2°W	0.59°SW
0.1 m Uncertainty	N19.4°W to N21.0°W	0.58° to 0.60°SW
0.5 m Uncertainty	N16.2°W to N23.4°W	0.54° to 0.65°SW
1.0 m Uncertainty	N12.4°W to N28.5°W	0.49° to 0.70°SW

Assuming that the strata below the Salina B Unit should have relatively uniform orientation, the ranges of potential errors in strike and dip listed in Table 3.16, when compared to the range of strikes and dips recorded in Table 3.1 suggests that errors in identified formation contacts are likely between 0.1 and 0.5 m, which essentially the potential error in depth determination within DGR boreholes.

3.14.2 Major Mineralogy of Model Layers

Confidence in the reported major mineralogy of the 36 layers that comprise the descriptive geological model is judged to be high. Major mineralogy is determined from a wide range of methods including core logging by field geologists, and laboratory testing using thin section petrography, whole rock and clay fraction XRD, SEM/EDS analyses and elemental oxide analyses undertaken by several different laboratories. Interpretation of these different data sets on a formation or model layer basis, as described in Section 3.7, yields a generally coherent identification of the major mineralogy of the model layers that is consistent with the stratigraphic descriptions provided for these rock by Armstrong and Carter (2006). Consequently, it is reasonable to extrapolate and assume the major mineralogy defined by data at DGR boreholes is representative of mineralogy across the entire DGR site.

Examples of the similar identification of major minerals by different testing laboratories is provided in Figures 3.58 and 3.59. Figure 3.58 shows the percent weight content of calcite and dolomite in whole rock for all DGR boreholes determined from XRD analyses distinguished based on analytical laboratory. Figure 3.58 shows the same information for quartz and total sheet silicate contents. Figures 3.58 and 3.59 are similar to Figures 3.4 and 3.5, except that the data are discriminated based on analytical laboratory rather than based on DGR borehole.

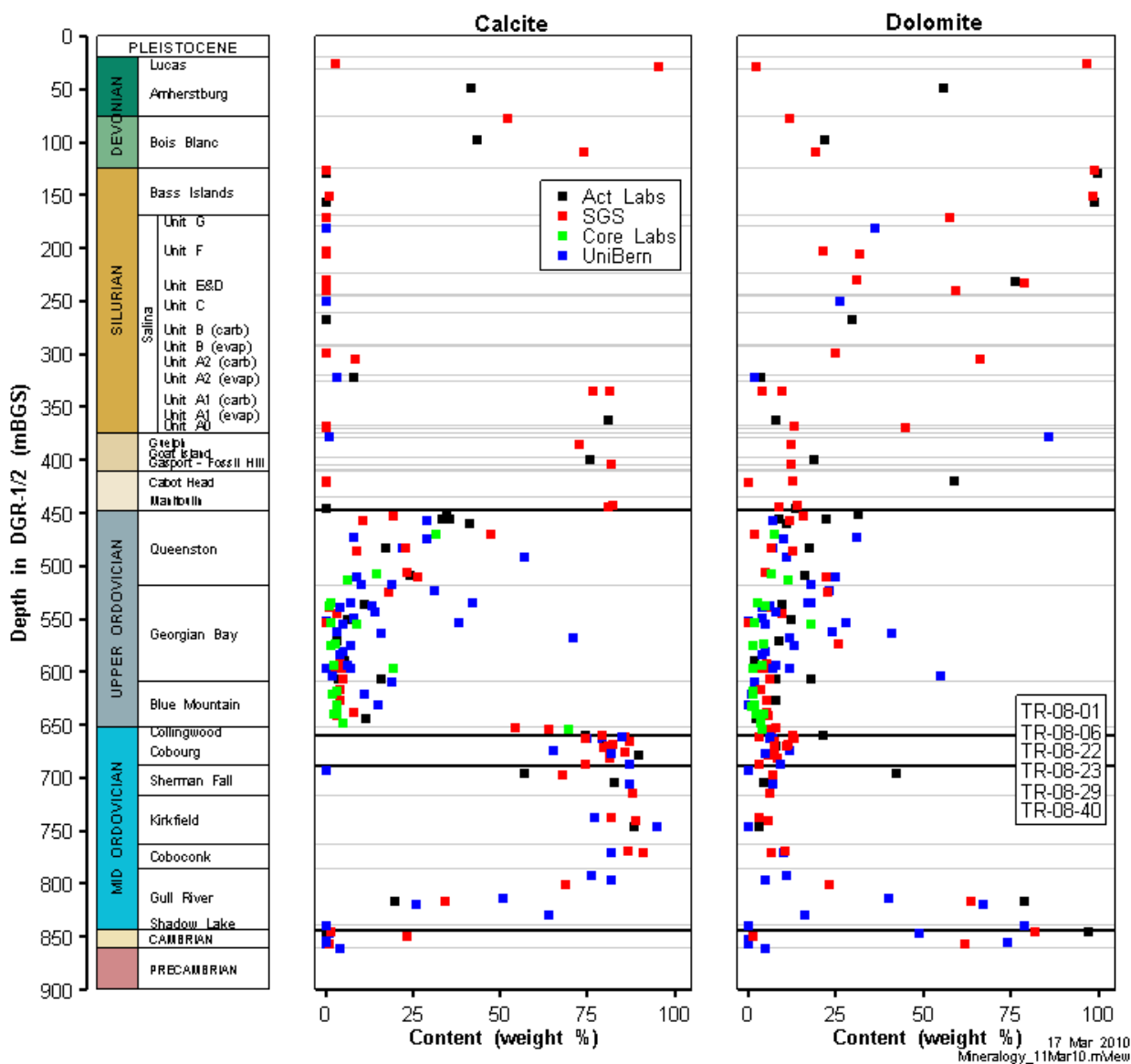


Figure 3.58 Profiles of calcite and dolomite in DGR cores distinguished by analytical laboratory

Figures 3.58 and 3.59 show that the four different laboratories engaged in quantitative to semi-quantitative analyses of major mineralogy by XRD (Activation Laboratories, SGS Laboratories, Core Laboratories and UniBern) generally reported similar contents of calcite, dolomite, quartz and sheet silicates in DGR cores. There is clearly variability in reported major mineral percentages, but this variability is due to mineralogical heterogeneity in the analysed core samples, not to bias or error in laboratory analyses.

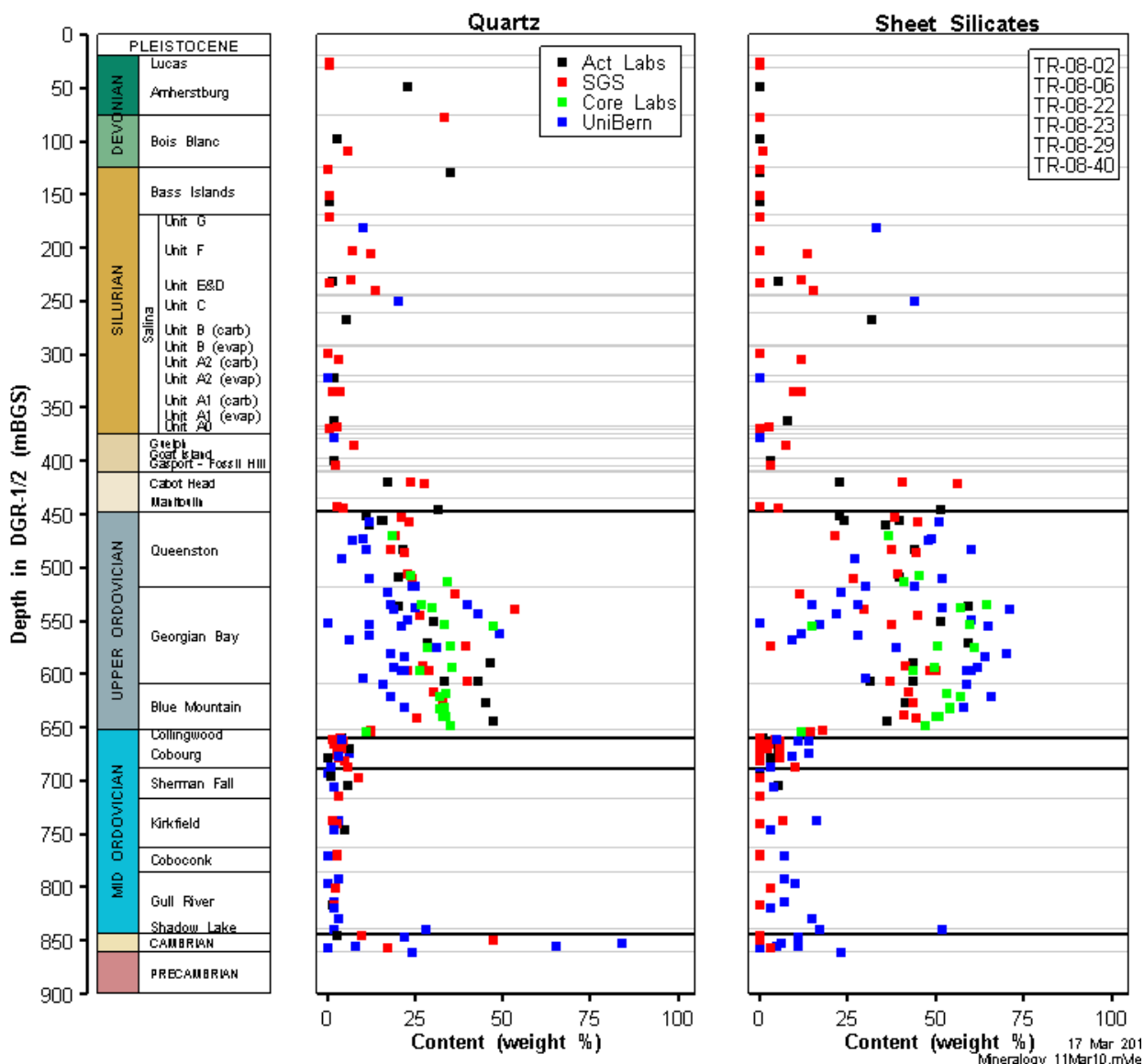


Figure 3.59 Profiles of quartz and total sheet silicates in DGR core distinguished based on analytical laboratory

3.14.3 Occurrence of Soluble Minerals

Confidence in the reported occurrence of soluble minerals in the layers that comprise the descriptive geological model is judged to be moderate to high depending upon the mineral and the model layer considered. For the major evaporite layers (e.g., B Unit anhydrite, A2 Unit evaporite and A1 Unit evaporite) soluble minerals are present in major mineral percentages layers and their detection is not an issue. However, identification of soluble minerals such as gypsum, anhydrite, celestite and halite, when present in minor or trace amounts, is difficult but nonetheless important because their presence or absence is essential to accurate interpretation of pore water chemistries. Dissolution of trace soluble minerals during crush and leach experiments (see Section 4.6) can significantly influence the resultant estimates of Ca, Sr, Na and Cl concentrations in porewater. Furthermore, release of mineralogically bound water from gypsum during heating and vacuum distillation can result in

overestimation of water loss and liquid porosity.

Because soluble minerals are often present in trace amounts, their reliable detection in core and on fracture surfaces during core logging is often difficult and frequently not possible. This is especially true for highly soluble minerals such as halite, which are subject to dissolution by drilling fluids, despite the use of Na-Ca:Cl brine drilling fluids with TDS averaging about 150,000 mg/L for drilling of the Silurian and Ordovician formations. Figure 3.26 is an example of such dissolution of halite as a fracture infilling mineral within the Queenston shale, where the estimated original thickness of halite (~ 1 cm) was sufficiently large that even with dissolution, halite remnants were observed. For thinner halite fracture infillings dissolution would likely remove all visual evidence of halite on the fracture surfaces. For anhydrite, gypsum and celestite, which are moderately soluble, detection in core is practical and has been routinely identified, although distinguishing anhydrite and gypsum is frequently problematic during core logging.

Recognizing these field limitations to identification of soluble minerals, laboratory methods were utilized to provide more reliable identification. Thin section petrography, XRD and SEM/EDS methods were used to directly identify the presence or absence of trace levels of soluble minerals. Anhydrite, gypsum and celestite were routinely detected by thin section petrography, as well as by XRD and SEM/EDS. Lithogeochemical analyses including elemental oxides, as well as sulphate and total sulphur analyses provided support for detection of these soluble sulphate minerals.

However, for halite, detection by thin section petrography was unreliable due to mineral dissolution during thin section preparation despite precautions, including use of oil during cutting and polishing, taken to minimize such effects. XRD and SEM/EDS were much more reliable in detecting halite occurrence as interstitial veins, grain boundary minerals and as mineralogical rims or coatings. Based on frequency of detection, SEM/EDS methods were the most effective at identification of halite in Silurian and Ordovician model layers.

Based on the comparability of soluble minerals identified in different DGR boreholes and by different laboratories and laboratory analytical methods, it is reasonable to assume that occurrence of soluble minerals defined based on DGR borehole data is representative of occurrences across the entire DGR site.

3.14.4 Occurrence of Major Structural Features

Confidence in the ability to recognize the occurrence of major structural features, such as erosional unconformities and faults and other structures other than simple fractures in the descriptive geological model is judged to be high for subhorizontal features and low to moderate for inclined features.

The occurrence of major subhorizontal features are reliably defined based on detections in DGR boreholes. The uniformity and predictability of the bedrock formations at the Bruce nuclear site shows that geological conditions that would identify the presence or absence of subhorizontal structural features can be confidently assessed from DGR borehole data. For example, the presence of subhorizontal structure as erosional unconformities associated with the Devonian-Silurian unconformity and the Cambrian-Precambrian unconformity are reliably identified in DGR boreholes. Similarly, the lack of subhorizontal structure associated with the Silurian-Ordovician unconformity is also evident in all DGR boreholes.

Confidence in the occurrence of major inclined structural features is always low when drilling investigations are based on vertical boreholes, because of the negligible horizontal coverage and potential for intersection of subvertical structure afforded by vertical boreholes. This low confidence in the occurrence of major inclined structures is improved through the completion of 2-D seismic reflection surveys, inclined borehole drilling of identified potential seismic features and the assessment

of vertical offsets in formation contacts that would be indicative of subvertical faults. As discussed in Section 3.10.3, the available data from Phase 2A investigations and preliminary data from Phase 2B drilling indicates absence of major inclined structural features in the vicinity of the DGR site.

Confidence in the assessment of presence or absence of inclined major structural features at the DGR site is in part linked to confidence in the results of the 2-D seismic reflections surveys and the identification of seismic anomalies to be investigated by directional drilling of DGR-5 and DGR-6. There are clearly limitations and uncertainties in the 2-D seismic surveys which are fully described in TR-07-15. These limitations and uncertainties are due to poor seismic energy coupling between the overburden and bedrock, anthropogenic and natural background noise, and constraints on seismic sources and line coverage inherent in completing the surveys in a developed area of a nuclear site. As discussed in Section 3.10.3, these limitations and uncertainties were mitigated by optimization of data collection techniques and additional effort in data processing. The potential 2-D seismic features identified and targeted for drilling are judged to be those with the strongest signatures identified on multiple survey lines and hence most likely to be representative of potential vertical structure at the Bruce nuclear site. If these potential structures with the strongest seismic signatures are shown to be absent based on drilling of DGR-5 and DGR-6, it is unlikely that other sub-vertical structures associated with weaker seismic features would be present at the site.

3.14.5 Characterization of Minor Structural Features

Confidence in the characterization of minor structural features, such as simple fractures (e.g., joints) in the 36 layers that comprise the descriptive geological model is judged to be high for subhorizontal features and low to moderate for inclined and subvertical features based on current borehole data.

As described above, the sampling of subhorizontal fractures is very good with vertical boreholes and the available data on their occurrence and characteristics is given in TR-07-06 and TR-08-13 from core logging and in TR-07-08 and TR-08-15 from borehole geophysical logging, in particular borehole acoustic televiewer logs. As discussed in Section 3.11 there are biases in the identification of fractures from both core logging and from interpretation of borehole geophysical logging. However, judicious comparison of the results of these two data sets considering these biases allows for a reasonable interpretation of the characterization of fractures in the layers that comprise the descriptive geological model of the DGR site.

Fracture occurrence as evident from RQD and natural fracture frequency plots (Figures 3.2 and 3.3) from core logging, is comparable on a formation or model layer basis in all DGR boreholes. This comparability suggests that subhorizontal fracture characterization defined based on DGR borehole data is representative of occurrences across the entire DGR site. For the vertical boreholes of Phase 1 and 2A site characterization, orientation of fractures are only quantifiable from interpretation of borehole acoustic televiewer logs. Core logs of these borehole are not orientated and hence cannot be use to determine strike and dip of logged fractures.

Although inclined to vertical fractures have been logged in DGR boreholes (see Section 3.11.2), the sampling of such fractures in vertical boreholes is very limited and subject to significant bias and underestimation of frequency of occurrence. The limited sampling does indicate that inclined to vertical fractures are present in the DGR strata. More accurate assessment of occurrence, frequency and orientation of these fractures will be determined from oriented core logging and borehole acoustic televiewer logging of inclined boreholes DGR-5 and DGR-6. Because boreholes DGR-5 and DGR-6 are being drilled approximately orthogonal to each other, there should be limited overall sampling bias of inclined to vertical fractures from these holes. Additionally, because fracture orientation will be available from both oriented core logging and borehole acoustic televiewer logging, there will be increased confidence in the resultant data.

4 DESCRIPTIVE HYDROGEOLOGICAL SITE MODEL

4.1 Model Elements and Scope

The hydrogeologic site model describes the hydrogeologic properties and 3-D spatial distribution of all important hydrogeologic units and features within the Paleozoic bedrock units at the Bruce nuclear site. The descriptive hydrogeologic model provides a basis for understanding the groundwater flow and solute transport properties of the Paleozoic bedrock that will contain and isolate the proposed Bruce DGR, based on detailed field and laboratory testing. The hydrogeologic site model focuses on description of the physical properties (rock density, porosity, fluid saturations, surface area, permeability, hydraulic head and diffusivity) of the bedrock, and geochemical/isotopic properties of the groundwater and porewater of the DGR Bruce site.

Therefore this report begins the development of a hydrogeological site model that “will provide the necessary information to define and describe the pathways and migration rates for any radionuclide releases from the DGR” (Intera Engineering Ltd., 2006, p.64). This version of the model is provisional and interim as it is based upon data collected during Phase 1 and 2A of the DGR project. It is based primarily on the results from boreholes DGR-1, DGR-2, DGR-3 and DGR-4, and US-series boreholes. It will be updated as results from Phase 2B investigations (DGR-5 and DGR-6) become available.

4.2 Data Sources

Primary data sources for the Phase 1 and 2A descriptive hydrogeological site model include:

- the descriptive geological site model given in Section 3 of this report;
- observations during drilling of boreholes DGR-1 and DGR-2 (TR-07-05, TR-07-06), DGR-3 and DGR-4 (TR-08-12, TR-08-13) and US-8 (TR-07-19);
- borehole geophysical logging of DGR-1 and DGR-2 (TR-07-08), DGR-3 and DGR-4 (TR-08-15) and US-3, US-7 and US-8 (TR-07-19);
- borehole fluid electrical logging of DGR-1 (TR-07-14) and straddle packer hydraulic testing of DGR boreholes (TR-08-32);
- evaluation of hydraulic communication between DGR-1 and DGR-2 (TR-08-07);
- opportunistic groundwater sampling of DGR-1 and DGR-2 (TR-07-11) and of DGR-3 and DGR-4 (TR-08-18);
- pressure monitoring of DGR boreholes completed with MP55 multi-level monitoring casings (TR-08-31);
- groundwater monitoring of US-3, US-7 and US-8 boreholes completed with MP38 multi-level monitoring casings (TR-08-08, TR-08-30);
- laboratory petrophysical testing of DGR-2 core (TR-07-18, TR-08-06) and DGR-3 and DGR-4 core (TR-08-28, TR-08-40);
- laboratory diffusion testing of DGR-2 core (TR-07-17, TR-07-22) and of DGR-3 and DGR-4 core (TR-08-27);

- laboratory porewater characterization of DGR-1 and DGR-2 Core (TR-07-17, TR-07-21, TR-08-06) and of DGR-3 and DGR-4 core (TR-08-19, TR-08-27, TR-08-37, TR-08-40);
- characterization of groundwater and porewater for radioisotopes (TR-08-38);
- compilation and consolidation of field and laboratory data for hydrogeological properties (TR-08-10);
- a comparative and critical evaluation of porosity and fluid saturation data generated for DGR cores by different testing laboratories (TR-08-24);
- geotechnical investigations and cooling water intake tunnelling experience (Golder Associates Ltd., 2003) and straddle packer hydraulic testing of boreholes US-1 and US-3 to US-7 (Lukajic, 1988); and
- regional hydrogeological modeling (Sykes et al., 2008) and regional hydrogeochemical (Hobbs et al., 2008) geosynthesis studies and Phase 2 geosynthesis updates to these studies (AECOM Canada Ltd., 2010).

4.3 Petrophysical Properties

4.3.1 Rock Density

Wet and dry bulk densities and grain density were measured on DGR core samples by Core Laboratories, University of New Brunswick, and the University of Bern as part of petrophysical, diffusion and porewater characterization programs. These measurements were made on 83 to 283 core samples collected from the Salina F Unit shale to the Precambrian basement for these tests.

Core Laboratories (Core Labs) completed single tests of wet bulk density on “as received” calipered sub-cores and of grain density using Boyle’s Law of gas expansion on “cleaned and dried” sub-cores subject to depth-specific hydrostatic confining stress of 17 kPa/m (for DGR-2 cores) and 34 kPa/m (for DGR-3 and DGR-4 cores) that approximates the effective stress due to the overlying rock mass. Core Labs density measurements were completed on small plugs of core weighing approximately 150 g. Core Labs provided raw lab data which also enabled the dry bulk density of each sample to be determined.

University of New Brunswick (UNB) reported mean grain density for triple to quadruple subsamples subject to oven drying considering the density of the brine porewater. UNB density measurements were completed on small discs of core weighing approximately 140 g. Although UNB did not report bulk densities of DGR cores, dry bulk and “as received” wet bulk densities were calculated in this report using UNB raw lab data.

University of Bern (UniBern) reported mean bulk wet and dry densities using the paraffin displacement method and mean grain density using kerosene-pycnometry based on two replicate measurements from each core subsample. UniBern density measurements were completed on subsamples of core weighing approximately 150-700 g. Mean “as received” wet bulk density values were also calculated using UniBern raw lab data.

The University of Ottawa (UofO) reported, but did not measure, mean grain densities for samples of crushed rock chips used in porewater analyses that weighed approximately 30 g.

In total, approximately 83 measurements of dry bulk density, 190 measurements of “as received” bulk wet density and 265 measurements of grain density were made. Table 4.1 summarizes the mean and standard deviation of the densities grouped by Silurian formations, Ordovician shales, Ordovician limestones and the Cambrian sandstone.

Table 4.1 Summary of wet bulk density, dry bulk density and grain density of DGR cores in g/cm³

<i>Formation</i>	<i>Wet Bulk Density</i>		<i>Dry Bulk Density</i>		<i>Grain Density</i>	
	<i>Mean</i>	<i>Std. Dev.</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Mean</i>	<i>Std. Dev.</i>
Silurian formations	2.62	0.12	2.53	0.23	2.81	0.11
Ordovician shales	2.65	0.03	2.59	0.06	2.76	0.04
Ordovician limestones	2.68	0.04	2.65	0.04	2.72	0.03
Cambrian sandstone	2.55	0.21	2.40	0.33	2.66	0.09

The mean wet bulk density of the Ordovician shales of Table 4.1 is 2.66 g/cm³. This can be compared to a mean of 2.68 g/cm³ for the argillaceous limestones. The difference is a reflection of the porosity distribution and mineralogy of the two rock types. The mean wet bulk density for the Cambrian rocks was 2.55 g/cm³. As expected the dry bulk densities are less than the wet bulk densities due to the loss of porewater. The mean bulk dry densities of the Cambrian sandstone are much lower at 2.40 g/cm³, reflecting its higher porosity of about 15%.

Table 4.1 also presents grain densities of the 283 core samples tested by the three laboratories. Results are similar between laboratories and are in accordance with expectations based on formation mineralogy. The formations with the highest grain densities are the Queenston, Georgian Bay and Gull River Formations, in which certain zones have densities of or approaching 2.8 g/cm³. Such relatively high grain densities appear to be correlated with the presence of relatively heavy iron minerals such as pyrite (5.0 g/cm³) and hematite (5.25 g/cm³). By contrast, limestones, which are composed of calcite (2.71 g/cm³) and dolomite (2.90 g/cm³), or iron-poor shales, in which illite (~2.8 g/cm³) and chlorite (2.6-2.8 g/cm³) are the predominant minerals, yield lower grain densities. The mean grain density of the Ordovician shales is 2.76 g/cm³ that may be compared to a mean of 2.72 g/cm³ for the argillaceous limestones. The mean grain density of the Cambrian sandstone is 2.66 g/cm³ reflecting the dominant presence of quartz and carbonate minerals in the strata..

Figure 4.1 illustrates the wet bulk, dry bulk and grain density data plotted against depth and DGR-1/2 reference formation stratigraphy. Figure 4.1 shows the individual core measurements and the arithmetic formation averages. Replicate analyses from the same core samples were averaged and plotted as single values in Figure 4.1. The Core Labs and UniBern data are “as received” wet bulk densities that reflect the presence of pore water in the samples. The grain densities are from the Boyle’s Law measurements on “cleaned and dried” samples by Core Labs and on oven-dried samples from UNB and UniBern.

Figure 4.1 shows that there is considerable scatter in the Silurian and Cambrian wet bulk and grain densities, but that the densities within the Ordovician shales and limestones are typically more uniform. The scatter in the Silurian samples is likely due to variations in grain density reflecting the porosity variations and the relative abundances of gypsum (2.3 g/cm³) versus heavier minerals such as dolomite (2.9 g/cm³) and anhydrite (2.9 g/cm³). The scatter in the Cambrian data is similarly likely due to porosity and mineralogical variations evident in the dolomitic and quartzose sandstone facies that comprise the Cambrian rocks.

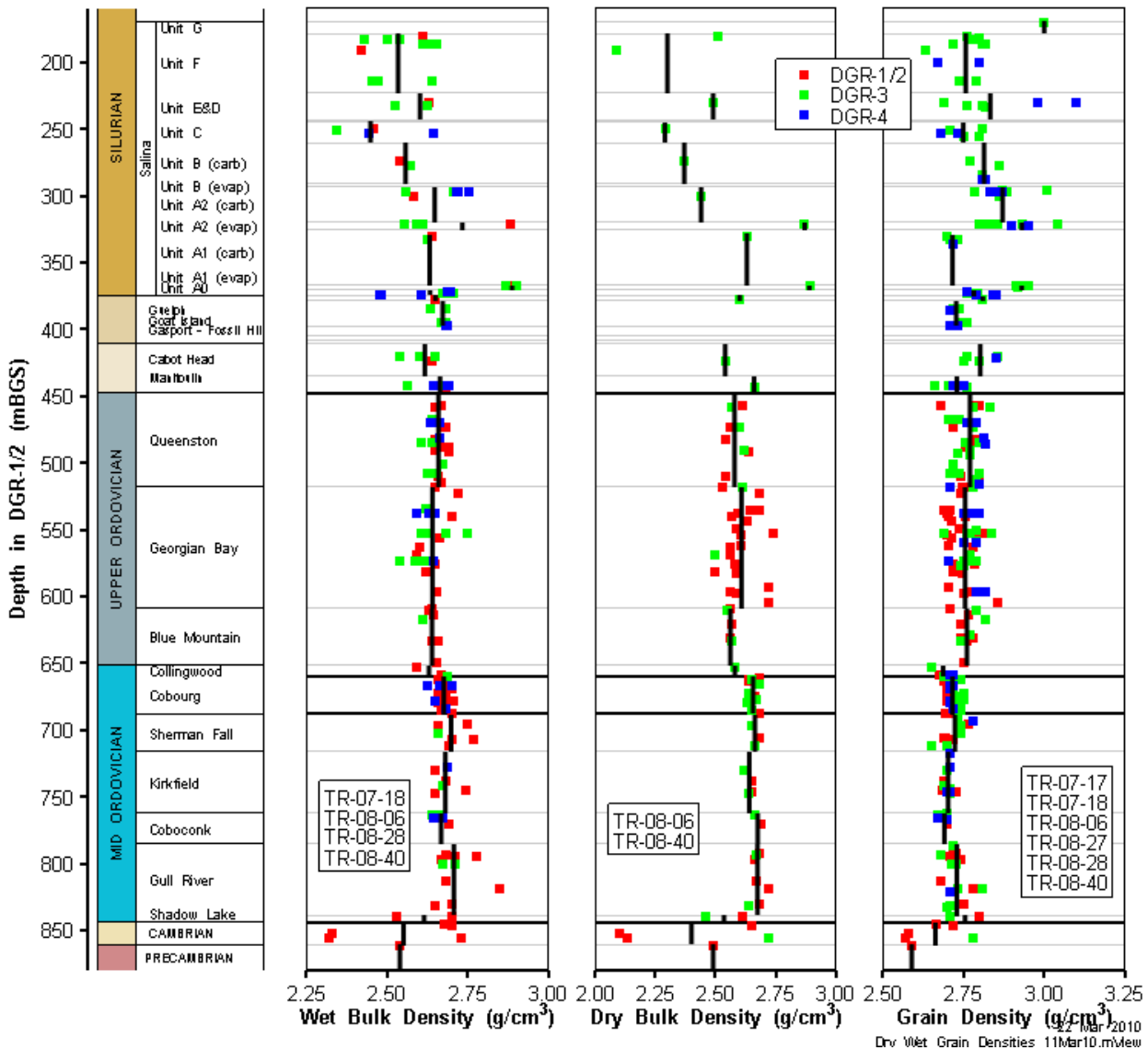


Figure 4.1 Wet bulk density, dry bulk density and grain density data profiles from DGR cores showing point data and arithmetic formation averages

4.3.2 Porosity

4.3.2.1 Definitions and Experimental Methods

Porosity is a general term used to describe the fraction of the volume of voids over the total rock volume. Three types of porosity are defined in this DGSM to differentiate the type of fluid occupying the void space and the measurements made by different testing laboratories - total porosity, liquid porosity and water-loss porosity. Total porosity, also known as physical porosity, is the sample volume not occupied by mineral grains (i.e. total volume of voids) divided by the volume of the sample. Liquid porosity is the volume of the voids occupied by liquid (i.e. pure water plus dissolved solutes and oil) divided by the total volume of the sample. Water-loss porosity is the volume of the voids occupied by pure water divided by the total volume of the sample. Total porosity should equal liquid porosity plus porosity occupied by any gas (e.g., methane).

Total porosity and/or water-loss porosity was measured on DGR rock cores by Core Laboratories, University of Ottawa, University of New Brunswick and University of Bern as part of petrophysical, diffusion and porewater testing programs. Several of these laboratories also reported liquid porosities by correcting the water-loss porosities for an assumed brine density, individually selected by each lab. In order to compare liquid porosity measurements between the different laboratories, a consistent density correction needs to be applied. Therefore, all lab data was reduced to water-loss porosity values and was converted to liquid porosity values by assuming a mass of salts for each sample based on average brine densities and total dissolved solids (TDS) concentrations for each formation. TR-08-34 describes the process of this standardization and conversion of porosity data.

Individual laboratory methods are described and sample measurements reported to date are included in the following technical reports:

- Core Labs - DGR-2 core (27 samples, TR-07-18) and DGR-3 and DGR-4 core (37 samples, TR-08-28);
- University of Ottawa – DGR-2 core (50 samples, TR-07-21) and DGR-3 and DGR-4 core (78 samples, TR-08-19);
- University of New Brunswick – DGR-2 core (14 samples, TR-07-17) and DGR-3 and DGR-4 core (58 samples, TR-08-27); and
- UniBern – DGR-2 core (35 samples, TR-08-02) and DGR-3 core (48 samples, TR-08-40).

Table 4.2 summarizes the various approaches taken by individual laboratories to determine DGR core porosity as well as additional calculations undertaken in this report to provide a common basis for comparison of different porosity data.

Total porosity was typically determined from bulk dry and grain density data on confined and unconfined core samples. Water-loss porosity was typically determined gravimetrically through heating and drying of unconfined core samples.

Core Labs measured total porosity on horizontal and vertical subsamples of core (~150 g plug) by the Boyle's Law gas (He) expansion method on cores that had pore fluids removed (i.e., "cleaned and dried") and were then brought to a depth-specific hydrostatic confining stress (17 kPa/m for DGR-2 cores, 34 kPa/m for DGR-3 and DGR-4 cores). Water-loss porosity values were calculated using lab data from Dean Stark fluid saturation measurements. For DGR-3 and DGR-4 cores, Core Labs also measured total porosity on unconfined cores, such that a direct estimate of the magnitude of porosity increase due to core relaxation could be determined.

UniBern reported total porosity data for cores subsamples (~4-5 g plug) based on the average of two replicate measurements of bulk dry and grain densities for each core subsample. UniBern also analysed larger subsamples (~60-500g) for liquid porosity measurements on DGR-2 core (assuming the density of pore fluid was at halite saturation) and water-loss porosity values on DGR-3 core. All UniBern liquid porosity data were reduced to water-loss porosity values for comparison to similar data from other labs.

University of Ottawa reported volumetric water content for subsamples of crushed cores (~30 g) based on the average of four to five replicate measurements using vacuum distillation methods (150°C) to remove porewater. All University of Ottawa volumetric water content values were converted to water-loss porosity values for comparison to similar data from other labs.

Table 4.2 Summary of porosity measurements for DGR core by different testing laboratories

Test Element	UniBern	UofO	UNB	Core Labs
Reported measurements	83 total porosity 21 liquid porosity	50 water content and 78 liquid porosity	72 liquid porosity	64 total porosity and water saturation
Methods	Bulk dry/grain density calculation using Archimedes Principle (paraffin displacement)	Bulk dry/grain density calculation using Vacuum Distillation	Bulk dry/grain density calculation using Archimedes Principle (brine displacement)	Boyles Law gas expansion on confined & unconfined samples, Dean Stark fluid saturations
Sample size	~4-5 g plug (total) ~60-420 g (water-loss)	~30 g crushed	~40-100 g disc	~150 g plug
Drying temperature	105 °C	150 °C	105 °C	105 °C
Correction for brine density	1.3 g/cc (< 830 mBGS) 1.2 g/cc (> 830 mBGS)	DGR-1/2 (not corrected); DGR-3/4 (sample specific TDS)	variable	1.187 g/cc (TDS=250 g/kg)
Additional Inter calculations	Reduced to water-loss porosity and then converted to liquid porosity based on formation average TDS	Converted water content to water-loss porosity and then to liquid porosity based on formation average TDS	Reduced to water-loss porosity and then converted to liquid porosity based on formation average TDS	Calculated water-loss porosity from S_w and then converted to liquid porosity based on formation average TDS

University of New Brunswick reported liquid porosity values for small discs of core (~40-100 g) based on the average of three or four replicate measurements using oven heating methods and assuming various brine densities based on depth. All University of New Brunswick liquid porosity data were reduced to water-loss porosity values for comparison to similar data from other labs.

4.3.2.2 Porosity Values

Figures 4.2 and 4.3 show the total and liquid porosity data including arithmetic formation averages, respectively, from DGR cores plotted against depth and bedrock formations. Replicate analyses from the same core sample were averaged and plotted as a single value in this figure. Figures 4.2 and 4.3 also show the arithmetic mean values of the porosity data calculated on a formation, member and unit basis. Table 4.3 summarizes the overall mean and standard deviation of all of the porosity data including the standardized water-loss porosity by formation and groups of formations.

To allow for a common basis for comparison with other laboratory test results, only the total porosity values determined from Core Labs for unconfined cores are included in the summary Table 4.3 and Figure 4.3, and in subsequent figures that compare liquid and total porosities. This is because none of the other testing laboratories applied confining stress in the determination of total or liquid porosities. The total porosity values for confined cores determined by Core Labs are used in the calculation of fluid saturations (Section 4.3.3), in the plotting of fluid saturation against total porosity data, and in the assessment of total porosity changes due to core relaxation that occurs from insitu confined conditions to unconfined lab testing conditions.

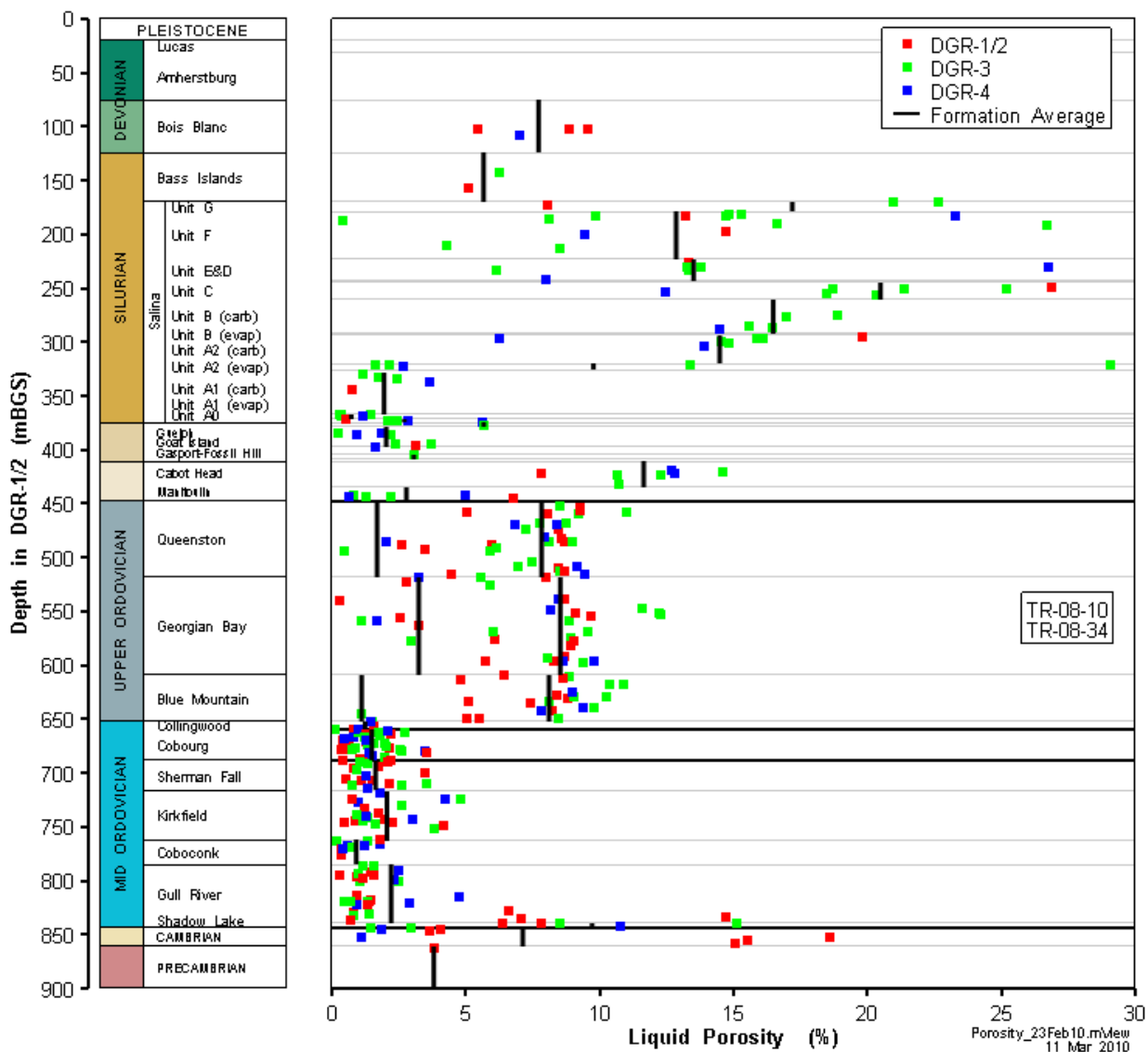


Figure 4.2 Liquid porosity profile for DGR cores showing point data and arithmetic formation averages

Table 4.3 Summary of water-loss, liquid and total porosities of DGR cores in %

Formation	Water-Loss Porosity		Liquid Porosity		Total Porosity	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Silurian and Devonian	9.0	7.2	9.6	7.7	8.9	6.8
Ordovician shales	7.2	1.6	8.1	1.8	7.1	1.7
Ordovician shale hard beds	2.0	1.8	2.3	2.0	2.7	2.0
Ordovician limestones	1.6	1.6	1.7	1.7	1.8	1.1
Shadow Lake and Cambrian	7.4	5.6	8.1	6.0	9.5	7.1

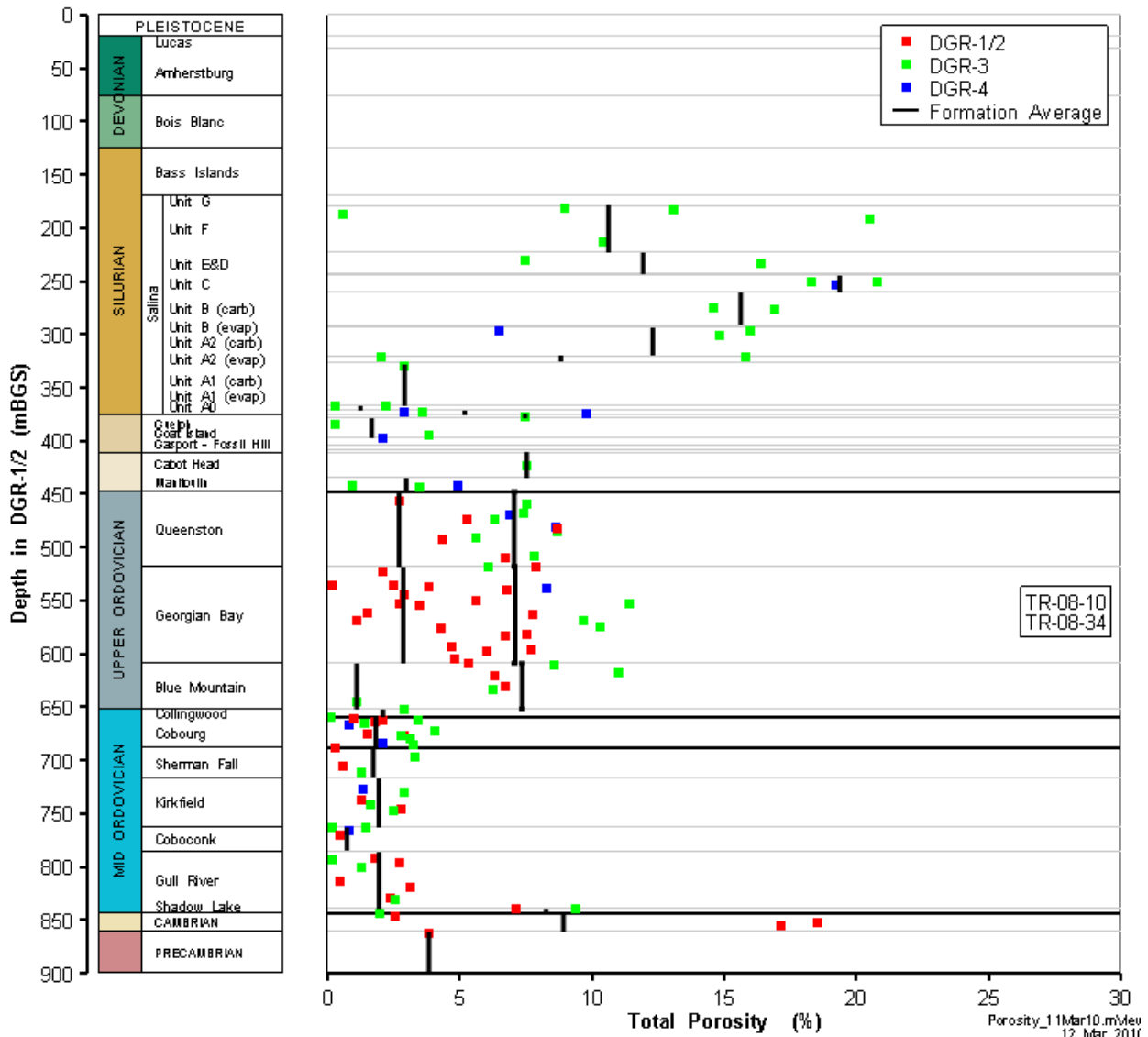


Figure 4.3 Total porosity profile for DGR cores showing point values and arithmetic formation averages

The total and liquid porosity measurements in the uppermost Silurian Salina F through A2 Units, as shown in Figures 4.2 and 4.3, range from 5 to 30% often exceeding 10%. The highest measurements of liquid porosity occur in the Salina C Unit dolomitic shale and a shaly dolostone sample found in the Salina A2 Unit with values of 14-30%. The mean liquid porosities reported for the Devonian and Silurian Units and Formations range from 0.7% for the Salina A1 Unit Evaporite to 20.5% for the Salina C Unit dolostone. Silurian argillaceous dolostone and shale sequences as represented by the Salina G and F Units and Cabot Head Formation show liquid porosities of 17, 13 and 12%, respectively. Other Silurian dolostone sequences including the Bois Blanc, Bass Islands, Goat Island and Manitoulin Formations and Salina A1 Unit show variable liquid porosity ranging from 1.9 to 7.7%. For many of the core samples collected from the Salina Formation where gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) may be present as secondary mineralogy (e.g., G Unit to A2 Unit Carbonate), the liquid porosities are likely overestimations due to release of the hydration water during heating.

The total and liquid porosity profiles display a very pronounced reduction in porosity in the Lower Silurian formations and immediately above the Ordovician shales. This reduction in porosity is generally to below 5% and is consistent with the porosity values observed in the Ordovician limestones and also the limestone/siltstone “hard beds” found in the Ordovician shales.

Figures 4.2 and 4.3 show that the total and liquid porosities for the Ordovician shale formations are clustered by two groupings and that the liquid porosities are slightly larger than the total porosities. The two groupings of porosity data reflect the different mineralogy of samples tested within the Ordovician shale formations. The more massive shale samples show formation mean total porosity of 7.1-7.5% and liquid porosity of 7.8-8.5%. The lower porosity data (mean formation total porosity 1.1-2.9%, mean formation liquid porosity 1.1-3.2%) are for ‘hard beds’ within these shale formations that are primarily limestone and/or siltstone.

The total and liquid porosity data for the Ordovician limestones are very similar with overall mean values of 1.8% and 1.7%, although the University of Ottawa reported high values (6 to 15%) at the base of the Ordovician limestones (i.e., bottom of Gull River Formation). Porosity data for the Shadow Lake and Cambrian sandstone are similar for total porosity (mean 9.5%) and liquid porosity (mean 8.1%).

4.3.2.3 Assessment of Porosity Data

In most hard rocks, total porosity can be similar to or greater than liquid porosity because there are isolated water-filled pores which do not have a physical pathway that allows the water to escape upon heating or solvent extraction. In sedimentary rocks where a separate gas phase may be present, total porosity must also include the gas-filled porosity as well as the liquid porosity.

Figure 4.4 shows the cross plot of liquid porosity and total porosity (unconfined cores) with a 1:1 equivalence or trend line for all data (72 samples) for which total and liquid porosities are measured on the same core sample. Such testing was completed by UniBern and Core Labs. Core Labs total porosity data measured on unconfined core plugs are plotted in Figure 4.4. Figure 4.4 shows the variability in total and liquid porosities discriminated based on major strata groups of Silurian formations, Ordovician shales and Ordovician limestones.

Figure 4.4 shows that 42% of the samples have liquid porosity greater than total porosity and that liquid porosity is more often greater than total porosity for porosities greater than 5%. For total porosities less than 5%, liquid porosity is more comparable to and frequently less than total porosity. Figure 4.4 shows that almost all of the samples with liquid porosity greater than total porosity are Ordovician shales or Silurian formations. The Ordovician limestones plot much closer to the 1:1 trend line and the Cambrian sandstone samples plot very close to the 1:1 trend line. Because many of the units, members or formations with porosity greater than 5% contain clays and gypsum, Figure 4.4 suggests that the exceedences of liquid porosity over total porosity may have a mineralogical explanation.

Therefore the liquid porosity values of the higher porosity shales and most of the Salina units may be inflated by the presence of gypsum that may lose its hydration waters or clays that might lose their bound waters upon heating (see Section 4.6.3 for detailed description and quantification of this effect). This potential mineralogical explanation for elevated liquid porosities is supported by Lucia (1999) who identifies “(1) incomplete removal of all fluids and (2) alteration of rock fabrics that contain minerals with bound water such as gypsum and clay minerals” as two sources of inaccuracies in laboratory porosity measurements of carbonate rocks.

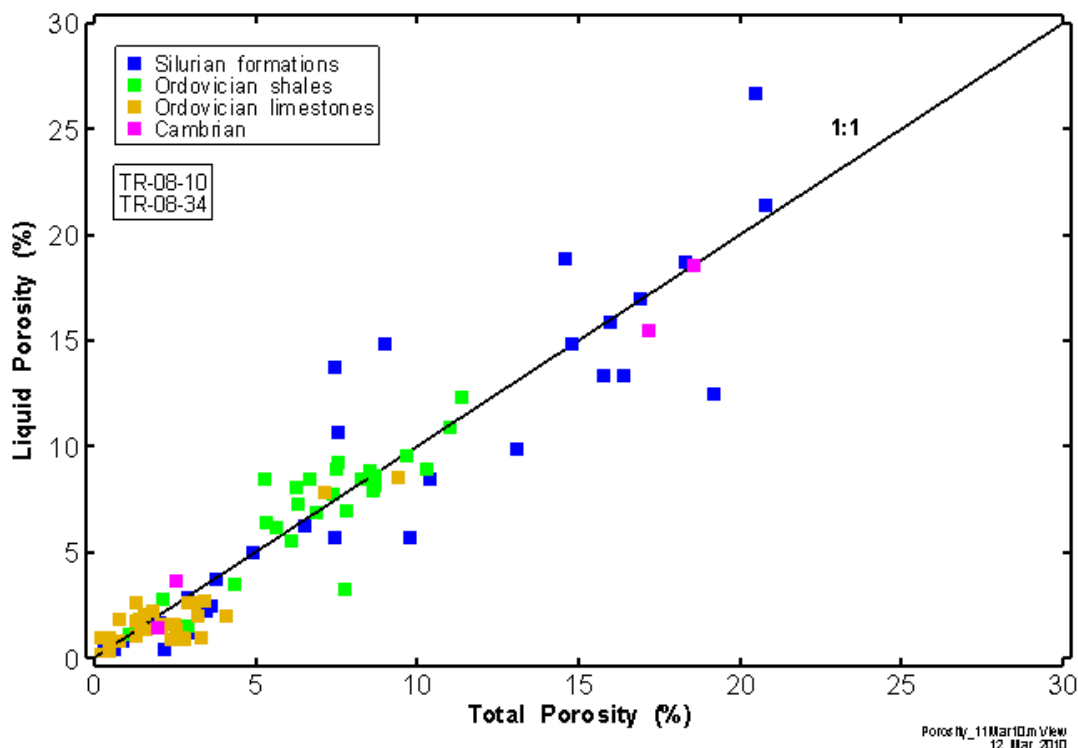


Figure 4.4 Comparison of liquid and total porosities on the same DGR core samples by UniBern and Core Labs, 1:1 trend line is shown

An additional explanation to account for the higher liquid porosity measurements, although not quantifiable, is that total porosity and liquid porosity are measured by some labs using different methods and on different subsamples of core that are subject to different handling and sample preparation. For example, UniBern measures total porosity on a 4-5 g plug of core while measuring liquid porosity on a different 40-500 g subsample of core. The tested volume in the liquid porosity sample is much greater compared to the total porosity sample and given heterogeneity in mineralogy and porosity which is evident in DGR cores at the cm scale and larger, the equivalence of both porosity values is unlikely due to probable sample size effects and sample heterogeneity and possibly anisotropy effects.

Anisotropy in porosity at the cm scale is also evident from comparison of the total porosity measurements (unconfined samples) made by Core Labs on 2-5 cm-length core plugs that were drilled out of adjacent sections of the same 20 cm length core sample but in different directions, i.e., horizontally parallel to the bedding plane or vertically normal to the bedding plane (see Figure 4.5). Figure 4.5 shows the variability of horizontal and vertical total porosities discriminated based on major strata groups of Silurian formations, Ordovician shales and Ordovician limestones. Figure 4.5 shows that there is variability between the total porosity of horizontal and vertical core plugs with horizontal porosity being greater than vertical for the Ordovician limestones and possible the Ordovician shales by factors of less than 2. For the Silurian rocks tested, the anisotropy is less clear with horizontal:vertical total porosity ratios ranging from 0.5 to 2. The Core Lab error in estimating the porosity by Boyle's Law gas expansion is ~0.3%.

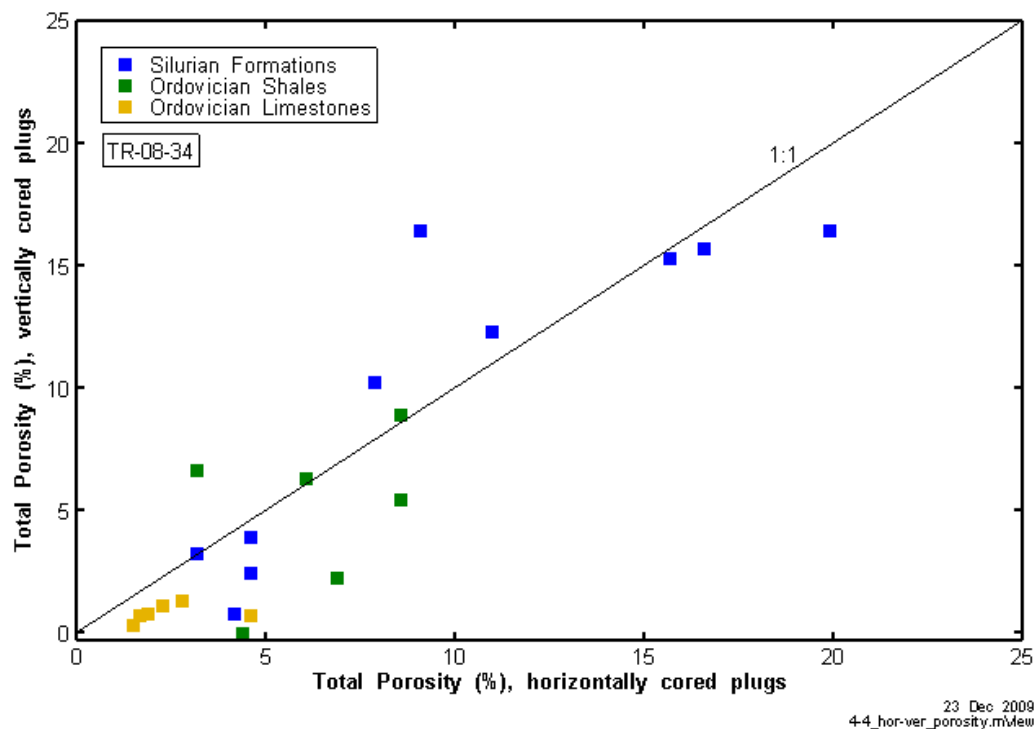


Figure 4.5 Measurements of horizontal and vertical total porosity on core plugs from adjacent sections of the same core sample, 1:1 linear trend is shown

Based on the above discussion it is clear that the most reliable comparison between total and liquid porosity needs to be made based on testing of the same subsample or plug of core. The only lab that completes both measurements on the same plug of core is Core Labs. Figure 4.6 shows the Core Labs total porosity and liquid porosity data generated from sequential testing of the same core plugs under unconfined conditions. Figure 4.6 shows that almost all of the measured total porosities exceed liquid porosities when testing is completed on the same core plug. This suggests that sample size may be factor in understanding the differences in total and liquid porosities reported by some labs.

Some of the observed differences in total porosity between different testing labs may also be due to the effects of imposing a confining stress during the testing of total porosity by Core Labs, which may result in a lower total porosity value due to microcrack closure. The Core Labs testing of total porosity for confined and unconfined DGR-3 and DGR-4 samples allows quantitative assessment of this effect. Figure 4.7 shows that the ratio of unconfined to confined total porosity plotted by major formation groupings against confined total porosity. This figure, which also shows mean ratio values for major groups of formations, indicates that core relaxation results in total porosity increases of about 17%, 31% and 39% for Silurian formations, Ordovician shales and Ordovician limestones, respectively, with the percentage change increasing with decreasing total porosity.

In addition, for the very low porosity Ordovician limestones small errors in measurement procedures may significantly affect calculations of total and liquid porosities (i.e. such that the actual difference between total and liquid porosity may be smaller than the typical measurement error). Measurement error will be different for each analytical method and may include loss or gain of water during handling and testing due to evaporation and condensation, transfer of a droplet of water from a previous sample in the Dean Stark apparatus that could be falsely attributed to the distillate from the current sample being measured, and the sensitivity and accuracy of measurements of water volumes and weights (see Figure 4.13 in Section 4.3.3).

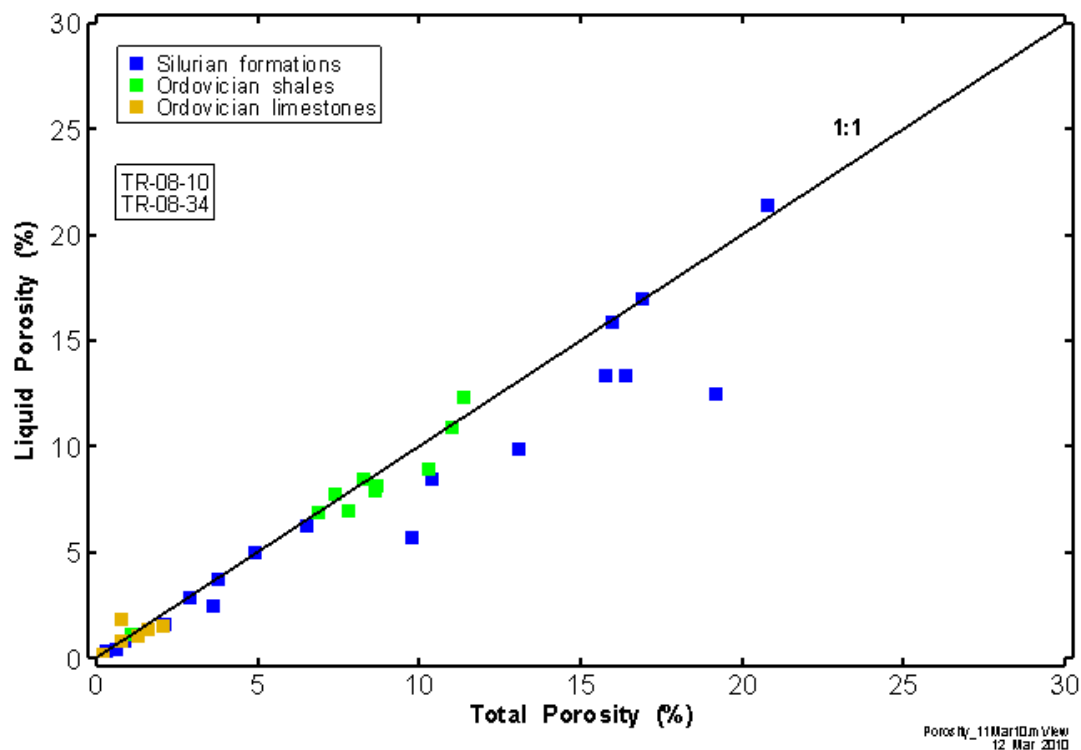


Figure 4.6 Comparison of liquid and total porosity on the same core plugs tested by Core Labs, 1:1 linear trend line is shown.

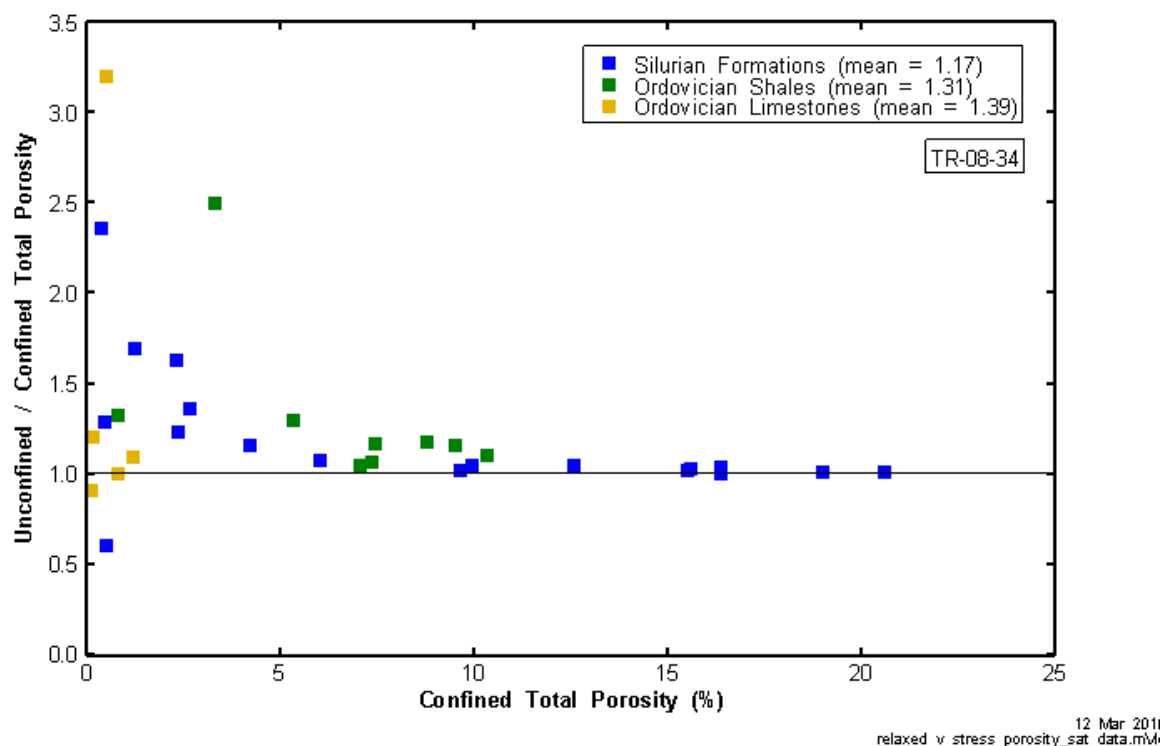


Figure 4.7 Comparison of ratio of unconfined to confined total porosity versus confined total porosity measured by Core Labs on DGR-3 and DGR-4 core plugs. Arithmetic mean ratios for major groups of formations are also shown.

In summary, the available data show that calculated liquid porosities that exceed total porosity measurements can be attributed to a combination of factors including mineralogical effects, sample size effects, sample heterogeneity and anisotropy, application of different testing methods and test measurement errors. Given these differences and complications in interpreting porosity data, the use of total porosity data are recommended for most DGR hydrogeologic assessment purposes.

4.3.3 Residual Fluid Saturations

The fraction (or percentage) of brine, oil and gas in the pore volume of a core plug drilled from the core sample is the 'saturation' or S . This was estimated by Core Laboratories on 64 samples of DGR core by the Dean Stark method and using total porosity measured on confined core plugs.

For these fluid saturation analyses $S_w + S_o + S_g = 1.0$ (or 100%), where the subscripts refer to saline or brine water (w), oil (o) and gas (g). The water content was determined directly by boiling toluene and using the vapour as the solvent to extract the water from the core plugs. After water extraction, the toluene was condensed and used to remove any oil from the core plugs. These two steps determine S_w and S_o . By measuring the total porosity on this "clean and dry" sample by the Boyle's Law method of gas expansion under confining pressure, the residual pore volume not accounted for by water and oil is attributed by difference to the presence of gas, yielding an estimate of the gas saturation, S_g . Thus the estimate of S_g incorporates the errors accumulated in estimating both S_w and S_o . Figure 4.8 presents the measured brine (S_w) and estimated gas (S_g) saturations for the Core Labs core plugs plotted by depth and formation as well as the arithmetic averages of brine and gas saturations for each formation, member or unit.

In these calculations, the oil density is assumed to be similar to other oils in southwestern Ontario and was therefore assigned a value of 0.83 kg/L. The brine salinity was assigned a value in mg/kg equal to the arithmetic average for the formation, member or unit based on porewater and groundwater geochemical characterization (see Section 4.6.5 and TR-08-34). This resulted in the oil saturations being estimated as zero throughout all 64 core plugs. However, there is evidence of oil presence in some core sections – notably a thin section of the Salina A1 Unit carbonate and some of the deeper parts of the Coboconk and Gull River Formation limestones (Table 3.7). Therefore this Core Lab result may be at odds with some core observations. However, inspection of the core plugs subject to Dean Stark testing that were returned to the Core Storage Facility shows that none of the core plugs show visible evidence of oil. Thus, it is likely the case that petroleum is confined to very thin zones that are oil wet and it has not penetrated vertically above or below into adjacent zones that may be water wet and thus inhibit vertical migration of the oil.

Nevertheless, the results provide a measure of fluid saturations that is available by no other method except that of measuring the total liquid saturation ($S_w + S_o$) by Nuclear Magnetic Resonance (NMR) and the gas saturation by the Boyle's Law method using He gas expansion (TR-08-34). The results of a comparison of the traditional Dean Stark method with this NMR/He method are shown in Figure 4.9. For the three cores that were tested under unconfined conditions, the correlation coefficient (r^2) between values (shown as a linear trend in the figure) is 93%. This result was sufficiently encouraging to arrange for DGR-5 and DGR-6 cores to be analysed by both Dean Stark and NMR/He gas methods sequentially on the same core plug.

The range of brine saturations is 60-100%. These values are shown in Figure 4.10 plotted against total porosity measured on confined samples. The Ordovician argillaceous limestone samples have an overall average S_w of 86% (std. deviation = 13%), while the Ordovician shales above the repository horizon have an overall average S_w of 93% (std. deviation = 10%). The Silurian formations tested show similar brine saturations (average S_w of 91%, standard deviation = 13%).

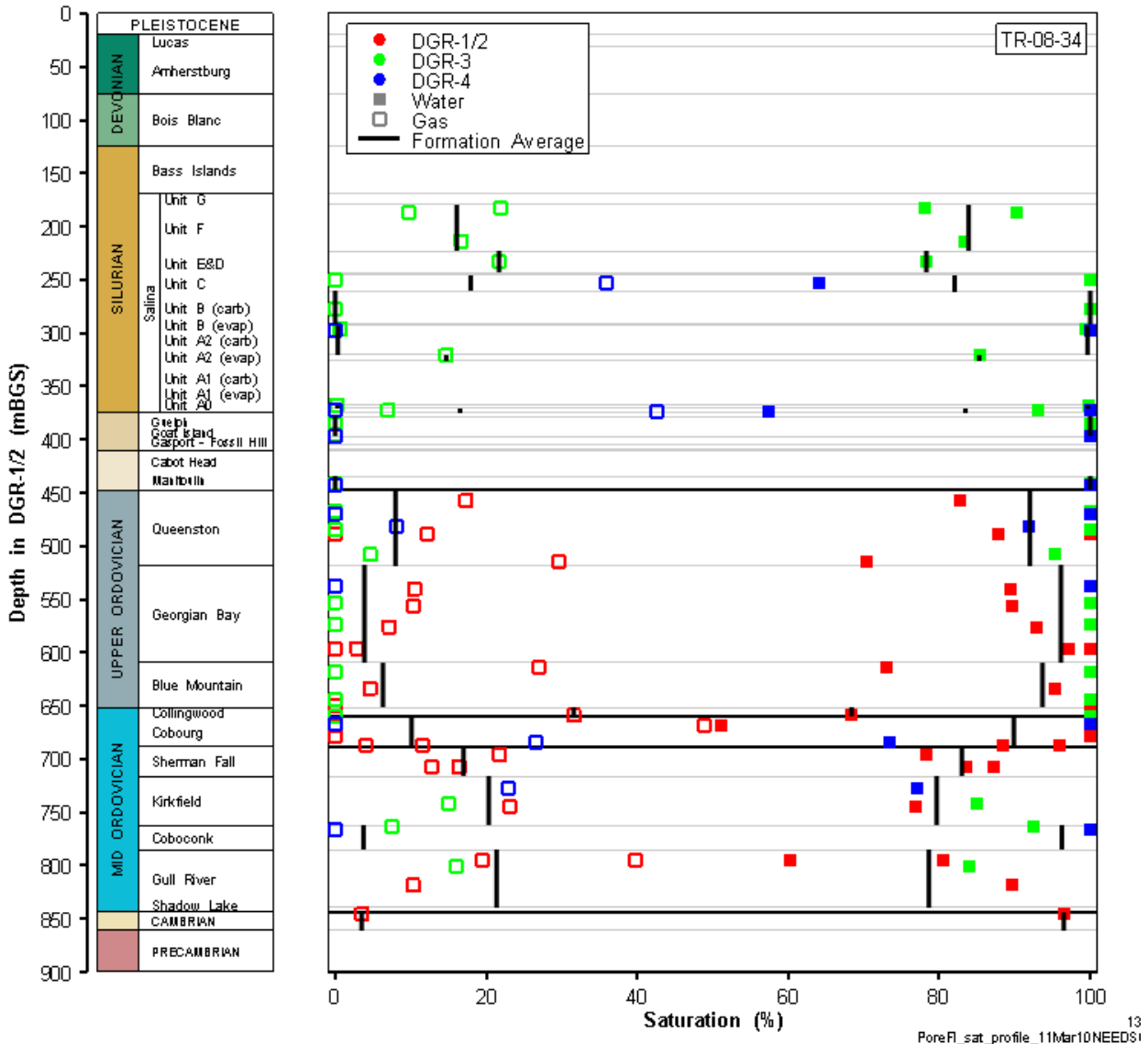


Figure 4.8 Pore fluid saturation profiles in confined DGR cores showing point data and arithmetic formation averages

The gas saturations that have been measured for the 64 cores are shown in Figure 4.10 plotted against total porosity measured on confined cores. The S_g values range from 0% to 46%, which is at the lower end of the range for dense, crystalline carbonate reservoir rocks of low porosity (i.e., <10%) reported by Keelan and Pugh (1975). Their data indicate that such limestones might well have residual gas saturations of over 60%. Consequently, the range of gas saturations for the DGR rocks is well within reported values in the technical literature. These values and the strong likelihood of the reality of this gas phase in the DGR rock column are discussed in TR-08-34. Figure 4.11 shows a histogram of estimated gas saturations for the grouped Silurian, Ordovician shales and Ordovician limestone samples with median values indicated.

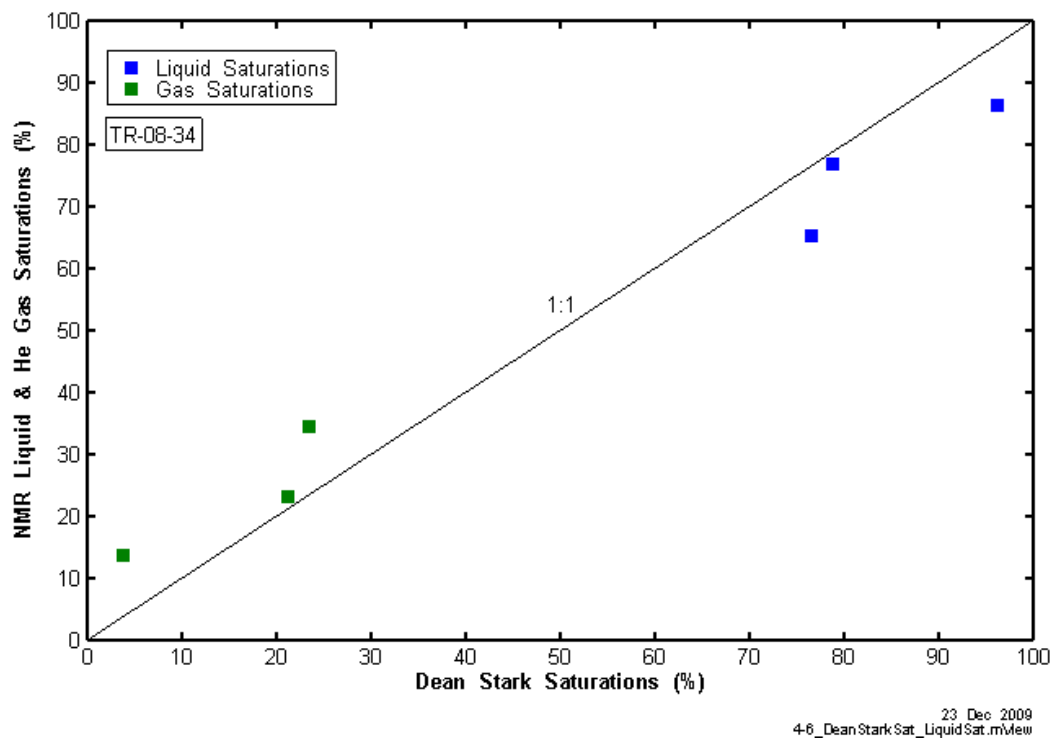


Figure 4.9 Comparison of methods for fluid saturation measurement in unconfined DGR-4 cores

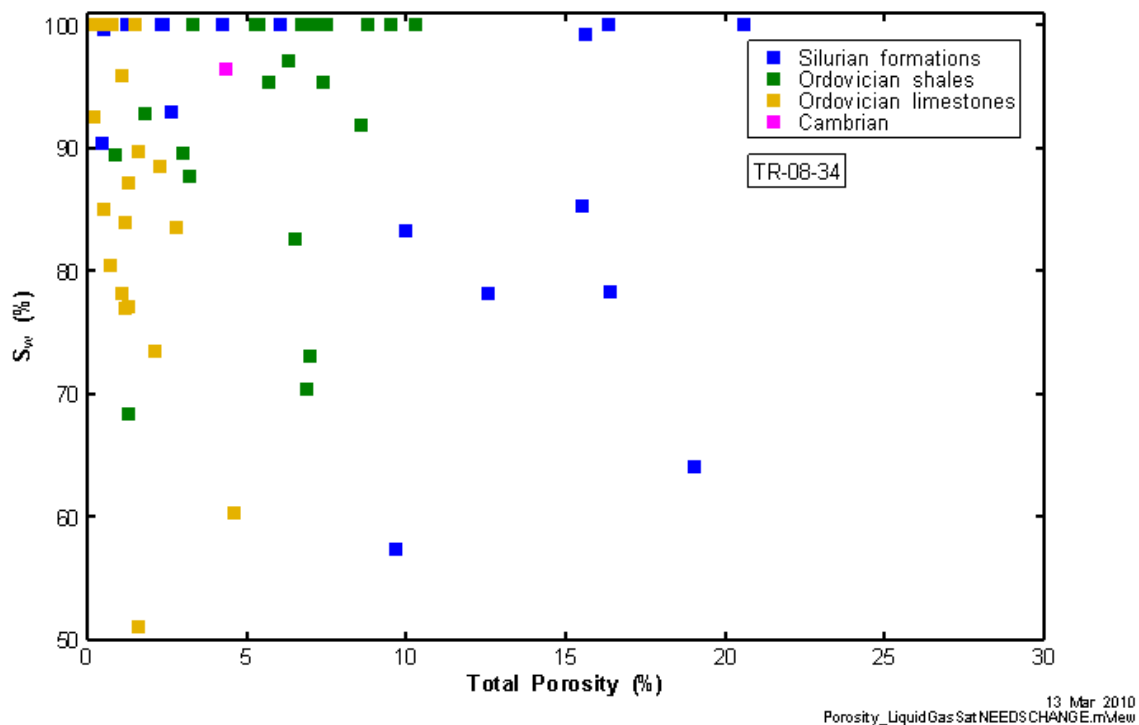


Figure 4.10 Water saturations as a function of total porosity in confined DGR cores

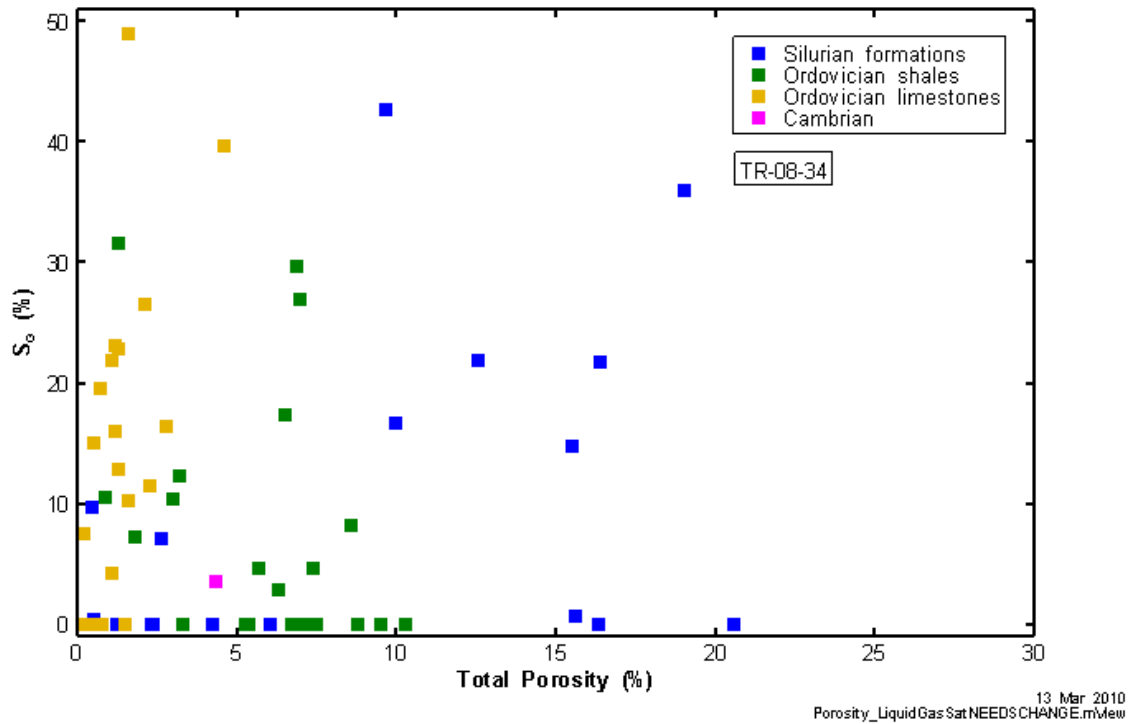


Figure 4.11 Estimated gas saturations as a function of total porosity in confined DGR cores

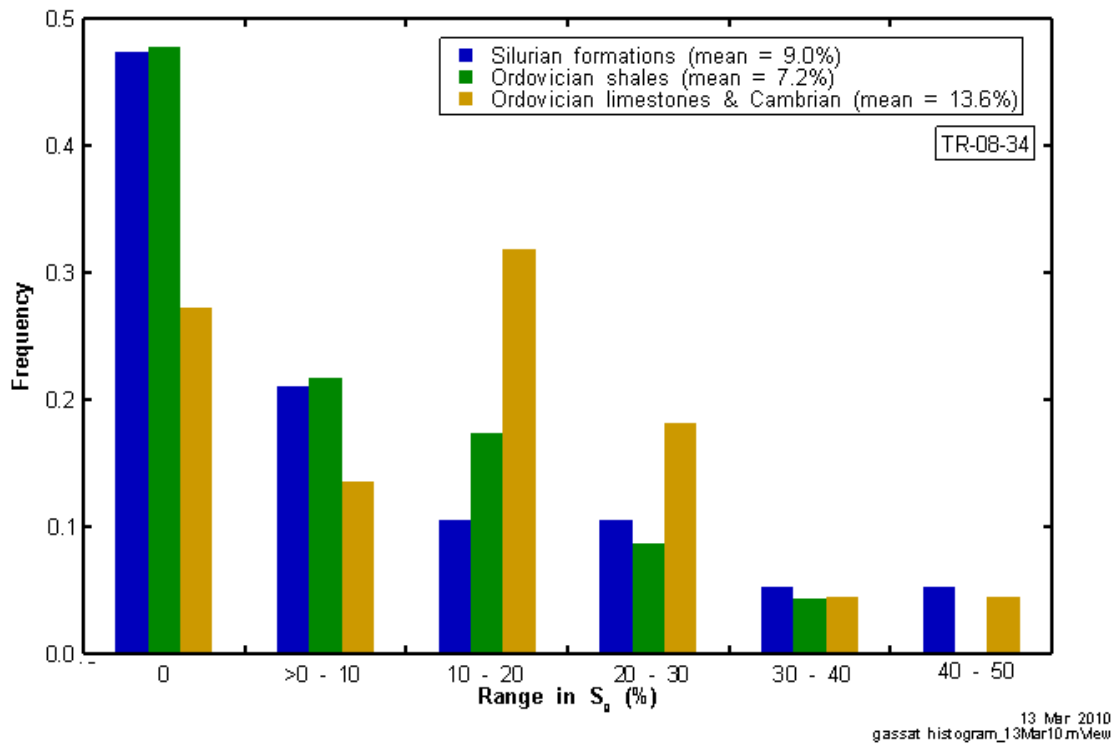


Figure 4.12 Distribution of gas saturations (S_g as % of pore volume) in confined DGR cores inferred from Dean Stark fluid saturation analysis and Boyle's Law (He gas) total porosity measurements. Arithmetic values for major groups of formations are shown in the legend.

In considering sources of error in fluid saturation analysis, two issues are of particular interest: (1) errors due to limitations on the volumetric water contents of cores and (2) errors due to the irrecoverable geomechanical relaxation of the core during in-situ recovery, on-site handling, shipping and laboratory handling and testing.

Figure 4.13 shows the fractional uncertainty in S_w vs. total porosity for DGR core samples based upon error propagation theory:

$$\frac{dS_w}{S_w} = \sqrt{\left(\frac{dV_w}{V_w}\right)^2 + \left(\frac{dV_p}{V_p}\right)^2} \quad [4.1]$$

where V_w is the water yield from the core plug and V_p is the pore volume or total porosity.

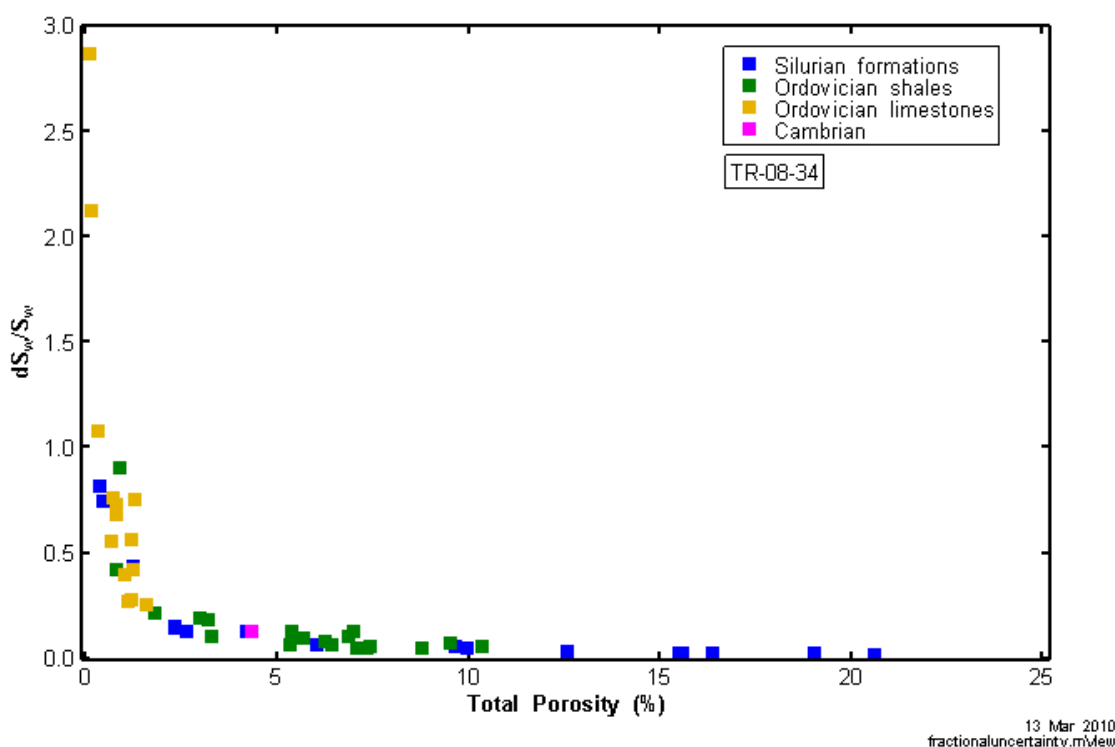


Figure 4.13 Fractional uncertainty in the water (brine) saturation (dS_w/S_w) plotted against total porosity from Dean Stark analysis of confined DGR cores

Figure 4.13 shows that for porosities $< 2\%$, there is a significant error. Because the error in estimating the water yield from the Dean Stark method is $\sim 50 \mu\text{L}$, the low water yields associated with the limestones and shale hardbeds produce large uncertainties. These affect the measured brine saturations and hence the estimated gas saturations. The convergence of data from the Dean Stark and the NMR/He(g) methods indicates that this source of error is limited in its effects.

Another potential source of error in estimating the gas saturation can arise when the in-situ stresses on the core are relaxed (i.e., producing dilational strain) creating new pore space measured by the petrophysical testing in the form of new microcracks that cannot completely close upon sample reloading. Such irrecoverable strains can become filled by a gas phase exsolving from the brine and any oil present in the pore. In addition to cracking due to core relaxation, irrecoverable microcrack-based stains could form due to damage during coring or sample handling and preparation.

Calculations (see Section 4.6.3) indicate that the brine in the Ordovician rocks is at saturation with methane, therefore degassing is a possible effect on the measured values. As indicated in Figure 4.7 the amount of core relaxation is potentially significant resulting in average porosity increases of 15 to 40%.

However, as fluid saturation testing of DGR cores is based on total porosity measured under confined conditions, the amount of porosity increase that may affect gas saturations would be restricted to irrecoverable strains attributed to creation of new microcracks during sample drilling and recovery and laboratory preparation and testing that cannot be completely closed upon sample reloading. Such anelastic porosity increases cannot be reliably quantified from available data including geomechanical stress-strain data from uniaxial and triaxial strength testing (Section 5, TR-07-03, TR-08-24, TR-08-39) because such data measure largely elastic strains during sample loading. The available geomechanical stress strain data can only be used to bracket the possible range of anelastic porosity increases by assuming that a percentage of the calculated elastic relaxation porosity is due to anelastic microcrack behaviour.

Thus to estimate the potential scale of this phenomenon, the microcrack relaxation porosity is estimated by analyzing the volumetric strain curves measured by CANMET during uniaxial and triaxial compression testing as part of the DGR geomechanical strength testing program. Therefore, this analysis, which is presented in TR-08-34, quantifies (a) the total amount of core relaxation that can be attributed to elastic microcrack behaviour, (b) estimates a likely range of anelastic porosity assuming it is a percentage of elastic relaxation porosity, and (c) assesses whether it is likely that the finite gas saturations measured during petrophysical testing of DGR cores are laboratory artefacts and representative of in-situ conditions.

Figure 4.14 shows this analysis for representative samples of the Georgian Bay Formation shale (DGR3-589.61) and Cobourg Formation limestone (DGR3-675.06) that were subject to triaxial compression testing. Data from triaxial compression testing are used in this example analysis as such data likely to provide more representative estimates of volumetric strains than similar data from uniaxial compression testing, which are also given in TR-08-34. It is noteworthy that the microcrack relaxation porosity determined from the geomechanical analyses (e.g. Cobourg - 0.10%) is similar to that determined from petrophysical testing of total porosity of unconfined and confined cores (e.g., Cobourg – unconfined total porosity [1.8% - Table 4.3] – 1.8%/average ratio of unconfined/confined total porosity [1.1 – ignoring one damaged sample – Figure 4.7] = 0.16%).

The calculated theoretical porosity change due to elastic microcrack formation and expansion during core relaxation is shown in Figure 4.14 as 0.18% for Georgian Bay Formation shale and 0.10% for Cobourg Formation limestone. Assuming that the anelastic porosity created by new microcracks that cannot completely close on reloading is 10% of the elastic porosity, the resultant anelastic porosities are 0.018% for the Georgian Bay shale and 0.01% for the Cobourg limestone. These calculated anelastic porosity increases, based on average total porosity of 7.1% and 1.8% for these formations (Figure 4.3), would create equivalent gas saturations of 0.25% (Georgian Bay shale) and 0.5% (Cobourg limestone). Since the calculated gas saturations for the Georgian Bay shale are less than the reported average Dean Stark gas saturations of the Georgian Bay shales of 3.9%, it is unlikely that anelastic pore volume expansion caused by irrecoverable core relaxation can solely explain the occurrence of the reported gas saturations in the Ordovician shales. For the Cobourg limestones, which have average gas saturation of 10.1%, the calculated anelastic gas saturations are also much smaller suggesting that the reported gas saturations are not solely artefacts of irrecoverable core relaxation. However these conclusions for the Cobourg limestones are tempered by the fact that the Cobourg limestone with average porosity of 1.8% has greater fractional uncertainty in fluid saturation estimates (see Figure 4.13).

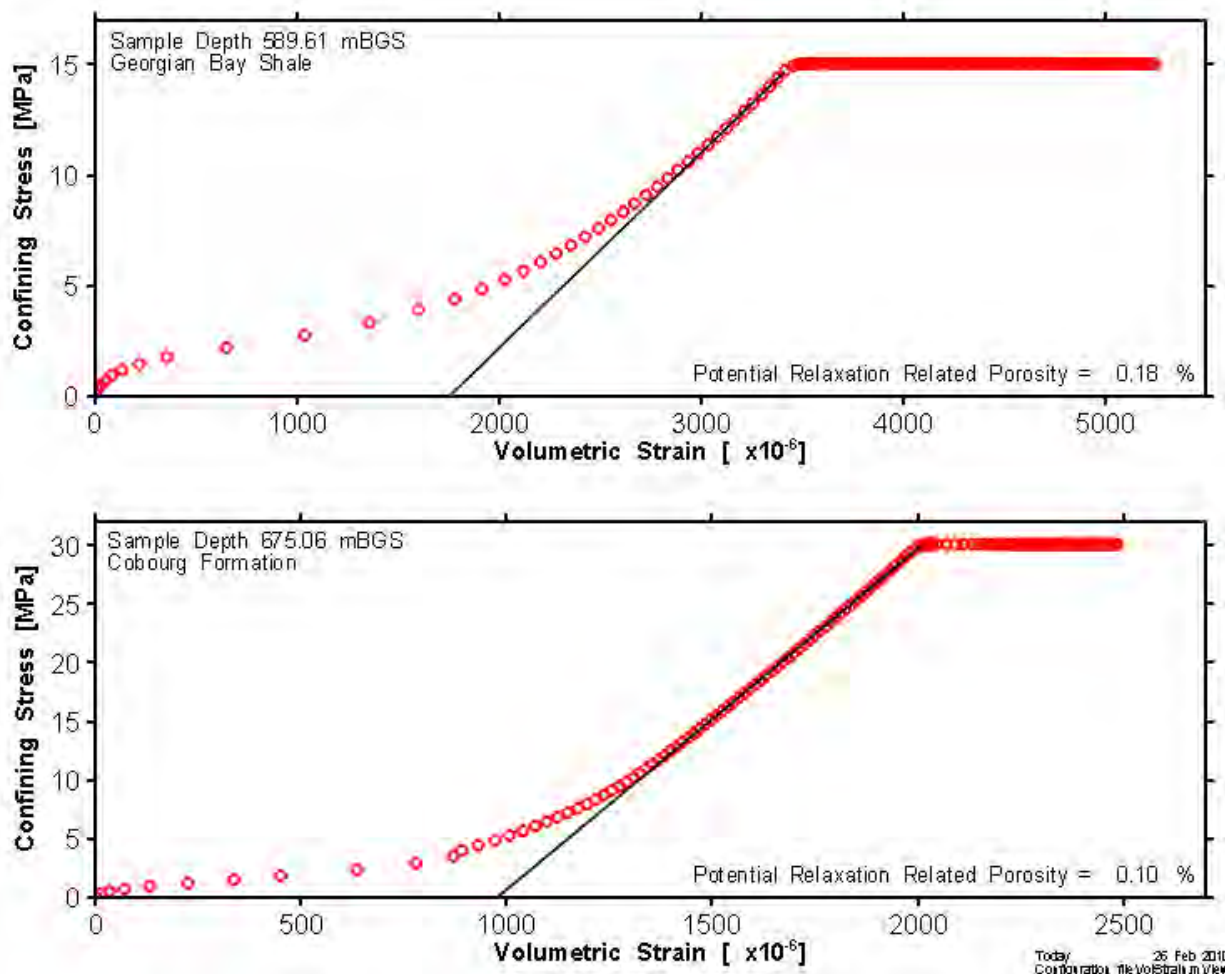


Figure 4.14 Determination of relaxation porosity from volumetric strain data – above Georgian Bay Formation shale (491.32 mBGS), below Cobourg Formation limestone (675.06 mBGS)

4.3.4 Rock Permeability to Gas and Brine

Pulse-decay permeability (PDP) was used to measure the permeability of DGR rock cores to gas and brine. Tests were performed on “as received” core that contains porewater, on “clean and dry” cores that had porewater and salts removed, and on brine-saturated cores (TR-07-18, TR-08-28). The PDP method was originally developed by Brace et al. (1968) for measurement of permeability of intact granites under high pressure and has been adopted for use in rock mechanics (Hart and Wang, 2001), hydrogeology (Finsterle and Persoff, 1997) and petrophysics (Jones, 1997).

The response of a core plug to a gas or brine pulse was measured as a result of a quickly pressurized upstream reservoir discharging through the core plug into a downstream reservoir, while maintaining a very low differential pressure across the entire length of the sample (Jones, 1997). The core plug was hydrostatically loaded to a depth-specific net confining stress (17 kPa/m for DGR-2 cores; 34 kPa/m for DGR-3 and DGR-4 cores), which approximates the effective stress considering the overlying weight and compressive forces of the bedrock. Following this loading, the initial pressure in the core and reservoirs was brought to 7 MPa. The Klinkenberg effect – molecular slippage of the gas in the pore – was only minimized by the use of the high pore pressure and not eliminated by it, which requires multiple runs at different pressures. Jones (1997) indicates that at a mean pore pressure of 7 MPa the measured permeability to gas is 10% higher than the slip-corrected gas permeability. The

range of permeability measurements with Core Labs' test instrument is typically from 10^{-21} m^2 to 10^{-16} m^2 .

Figure 4.15 shows the variation in vertical and horizontal permeability (k) with depth throughout the Silurian, Ordovician and Cambrian sequence of rocks for both "as received" and "clean and dry" tests determined from gas permeability testing. "As received" core plugs contain variable brine contents that are likely to influence the gas permeability measurement because the gas saturations are small compared to the brine saturations. However the PDP testing of 'as received' cores provides a measure of the effective gas permeability of the sample in the presence of brine. After Dean Stark fluid extraction and convection drying, the pore volume is identified as "clean and dry" so that the measured permeability is now that permeability measured in the absence of any other fluid present in the pore space, i.e., the absolute or intrinsic permeability. Consequently, each test produces one point on a relative gas permeability curve. Section 4.3.8 and TR-08-33 discuss the determination of two phase (gas, brine) flow properties from the Core Labs petrophysical data.

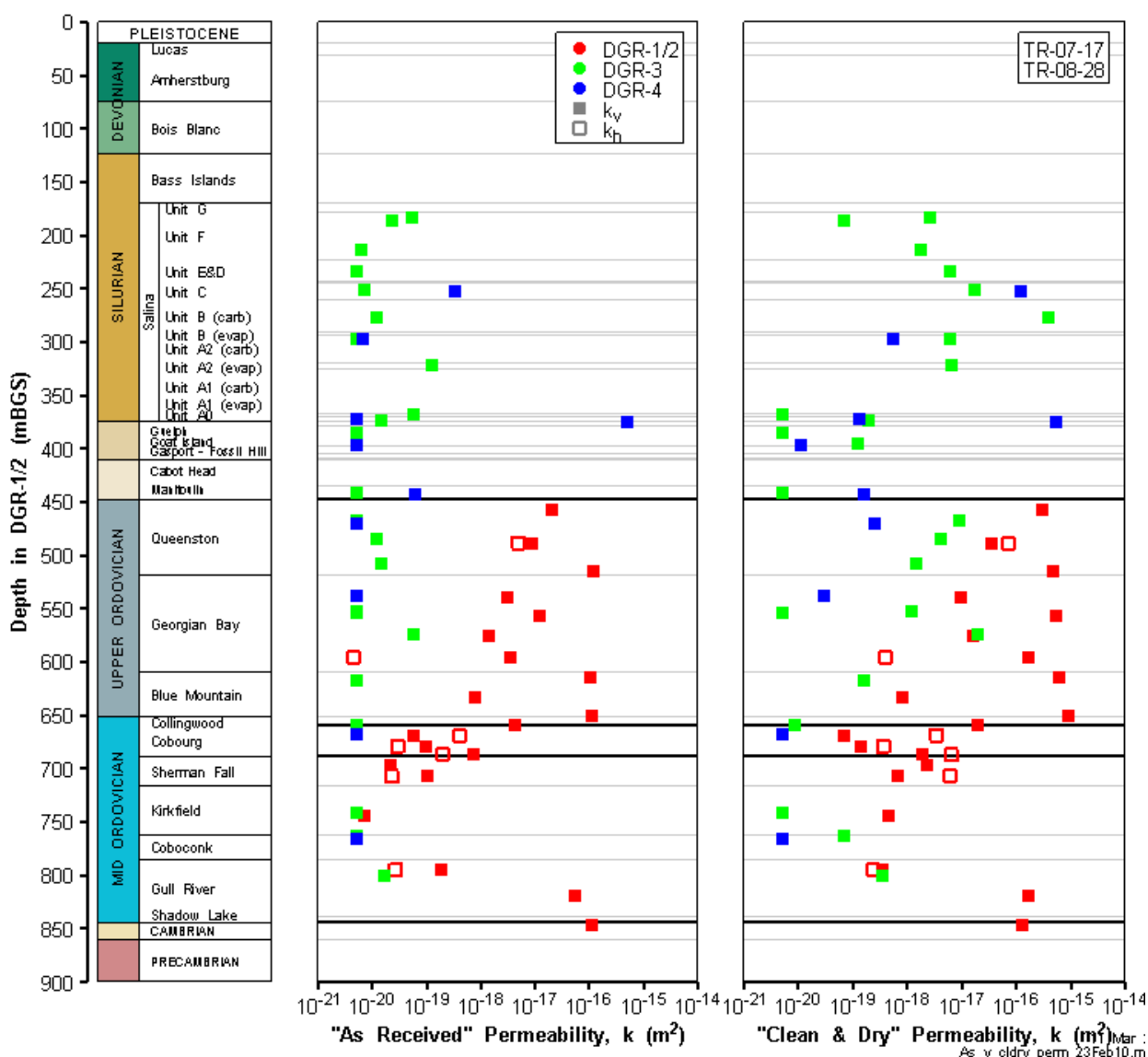


Figure 4.15 Vertical and horizontal permeability profile measured by gas pulse pressure decay testing on DGR cores

The lowest ‘as received’ permeabilities – approximately 10^{-21} to 10^{-20} m^2 – were measured in the Salina F, C, B, A2 and A0 Units, and the Goat Island, Gasport, Manitoulin, Queenston, Georgian Bay and Cobourg, Sherman Fall, Kirkfield and upper Coboconk Formations, although higher values of up to 10^{-16} m^2 were frequently measured in the Ordovician shales. The lowest ‘clean and dry’ or intrinsic permeabilities – again approximately 10^{-21} to 10^{-20} m^2 – were measured in the Salina A1 Unit, and Goat Island, Gasport, Manitoulin, Georgian Bay, Collingwood, Cobourg, Kirkfield and upper Coboconk Formations, although higher values of up to 10^{-15} m^2 were again frequently measured in the Ordovician shales. The cores from the dolomitic upper Cambrian and from the Gull River Formation below 800 mBGS were of similar high vertical intrinsic permeability ($\sim 10^{-16}$ m^2). The clustering of k values at 5×10^{-21} m^2 in Figure 4.15 are for tests with estimated k below the lower testing limit, which are plotted at the lower testing limit of 5×10^{-21} m^2 .

Horizontal k data from gas permeability testing was only completed on a limited number of DGR-2 cores. These limited data show that intrinsic (‘clean and dry’) permeability of horizontal sub-cores are generally greater than that of vertical sub-cores. Additional discussion of core k anisotropy is given below with reference to both air and brine permeability testing.

Figure 4.16 is a cross plot of brine-saturated permeability versus ‘clean and dry’ gas permeability following fluid extraction and convection drying of DGR-3 and DGR-4 cores. Both vertically oriented and horizontally oriented cores are shown in Figure 4.16 without distinction. The data in Figure 4.16 show the calculated gas intrinsic permeabilities are up to four orders of magnitude more permeable than the brine permeabilities for different sub-cores of each sample. These data suggest that the Core Lab processes of cleaning and drying cores results in physical/chemical disturbance and damage of the core and enhancement of core permeability. This disturbance appears to be greater for Silurian formations and the Ordovician shales than for the Ordovician limestones.

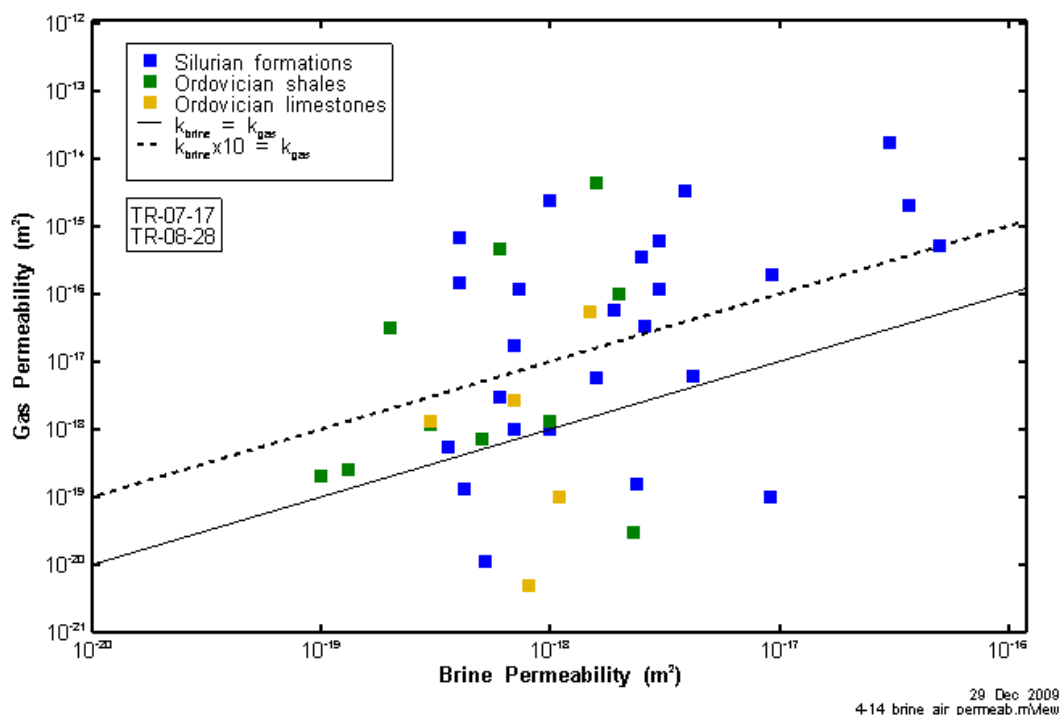


Figure 4.16 Brine-saturated core permeability plotted against gas intrinsic permeability in DGR-3 and DGR-4 cores

In addition to core physical/chemical damage to core during cleaning and drying, core may also be subject to mechanical disturbance and damage (Martin and Stimpson, 1994; Santarelli and Dusseault, 1991). As was shown in the previous section (see Figures 4.7 and 4.14), sample disturbance in tight rocks results in microcrack formation that is likely caused by stress concentration during drilling and by core and pore fluid expansion during sample unloading as core is recovered and brought to surface. Visual inspection of core plugs (Figure 4.17) that had anomalously high measured permeabilities did not show any evidence of damage suggesting that the core damage is occurring at the micro-scale and not at the macro or visible scale of the core samples.



Figure 4.17 Core plugs from DGR2-613.93 (left) and DGR2-650.12 (right) in Blue Mountain Formation had measured vertical permeabilities of $6\text{E-}16$ and $9\text{E-}16 \text{ m}^2$. Hydraulic testing of these intervals yielded in-situ values of $\sim 1\text{E-}21 \text{ m}^2$.

Thus, despite the sophistication of the PDP measurement technique and the application of the confining stress, petrophysical testing is likely to result in much higher measured permeabilities than those measured by in-situ hydraulic testing (see Section 4.9.3 for further discussion of the comparison of field and lab permeability data). The lab k data are considered to be unrealistically high values due to irrecoverable damage of core during drilling, recovery and shipment to the lab for testing and handling and sample preparation in the lab. Based on geomechanical strength considerations and observations of core dinking during core recovery, this mechanical damage is likely to be greater in the weaker Ordovician shales than in the stronger Ordovician limestones.

Quantitative bounds on the amount of permeability overestimation due to mechanical core damage can be inferred from international experience (Martin and Stimpson, 1994; Martin and Lanyon, 2001; Neuzil, 1993). The minimum amount of overestimation is likely to be similar to the 10 fold amount reported by Martin and Stimpson for competent Lac du Bonnet granite at similar depths of 400 to 800 m at the AECL Underground Research Laboratory. This minimum overestimation is likely to be more applicable to the more competent Silurian dolostones and Ordovician limestones than to Silurian and Ordovician shales. The maximum amount can be indirectly inferred assuming that the properties of the relaxed and disturbed cores are similar to the properties of the stress-relieved excavation damaged zone (EDZ) that surrounds deep underground openings. Martin and Lanyon (2001) reported that hydraulic properties of the EDZ in Opalinus Clay at the Mount Terri Rock Laboratory were 100 to 10,000 times higher than undisturbed clay shales with permeability of about 10^{-20} m^2 . These maximum overestimations are likely to be more applicable to the less competent Ordovician shales.

Applying these mechanical and physical/chemical overestimation factors to the Core Labs test results (i.e., “clean and dry” values) for disturbed cores suggests the in-situ vertical permeability of undisturbed Ordovician shales and limestones (excluding the lower Gull River rocks) approximate 10^{-21} m^2 or less. These estimated undisturbed in-situ permeabilities are supported by published data of Neuzil (1994; 1993) who also noted up to 100 fold overestimation by laboratory testing due to sample disturbance.

Neuzil's compilations of porosity and permeability data for argillaceous formations indicates that shale and limestone rocks of similar porosity to those measured in DGR Ordovician formations are likely to have permeability of less than 10^{-20} m^2 . This observation is supported by recent work of Waber et al. (2007) who reported that shallow samples of Cobourg limestone collected from a borehole depth of 62 m at the St. Marys Cement quarry near Bowmanville Ontario had vertical permeability of about 10^{-20} m^2 based on initial flowrates measured during advective displacement testing. Additionally Selvadurai et al. (2010) reported on vertical permeability of triaxial-loaded (5 MPa) cores from a rock block collected at the same quarry determined from pressure pulse decay testing that approximated 10^{-22} m^2 . Vilks and Miller (2007) also reported similar average values of intact rock vertical permeability under triaxial confining pressures of 4-15 MPa of $9.4 \times 10^{-22} \text{ m}^2$ for Cobourg limestone core collected near the St. Mary's Quarry and $4.5 \times 10^{-21} \text{ m}^2$ for Queenston shale core collected at Niagara Falls. Based on the shallow depth of all these sample, core disturbance is likely to be minimal and these samples provide reasonable estimates of intact in-situ permeability of these formations at depth at the DGR site.

The anisotropy in the measured intrinsic permeability data is illustrated in Figure 4.18. The k data presented in Figure 4.18 are based upon gas permeability testing of DGR-2 core and brine permeability testing of DGR-3 and DGR-4 core.

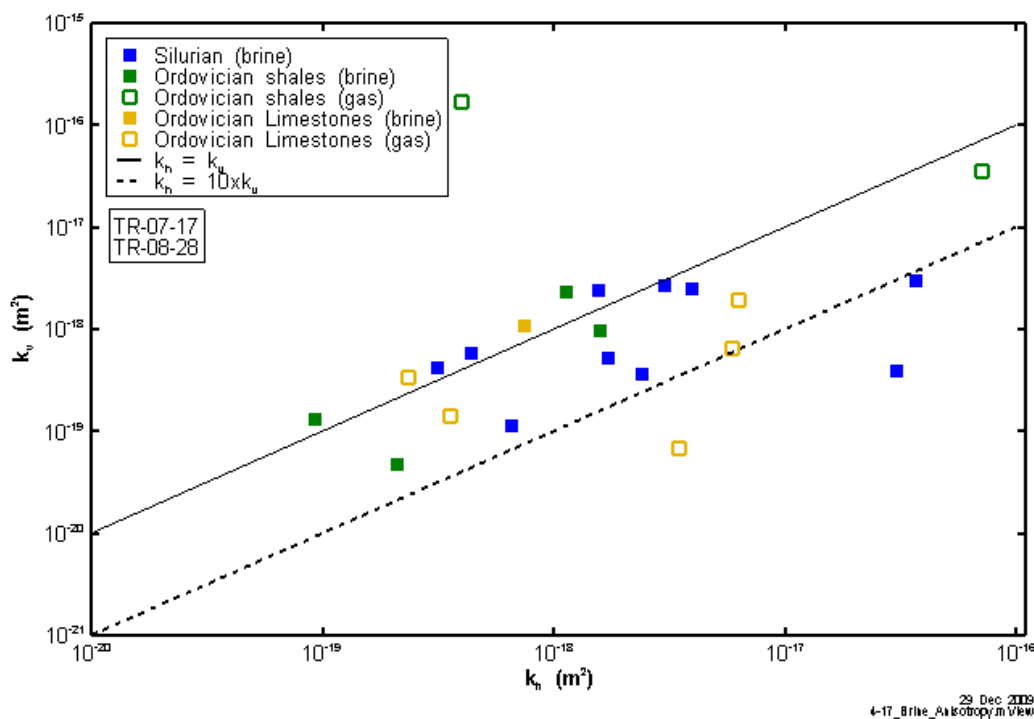


Figure 4.18 Anisotropy in core permeability from gas permeability testing of DGR-2 cores and brine permeability testing of DGR-3 and DGR-4 cores.

Generally, the horizontal permeability exceeds the vertical by a ratio of between 1:1 and 10:1. One limestone core (DGR2-669.10) has an extreme $k_h:k_v$ anisotropy ratio of 50:1 that is reflected in the different total porosities (ϕ) of the two core plugs, i.e., $\phi = 0.007$ for the vertical core plug and $\phi = 0.017$ for the horizontal core plug. One shale sample (DGR2-596.09) that indicates $k_v \gg k_h$, likely fractured during sample handling and testing. The DGR-3 and DGR-4 brine samples show a similar pattern of anisotropy with two outliers, both from the Salina F Unit shale. The small number of DGR-3 and DGR-4 pairs shown in Figure 4.17 was due to a high rate of core plug failure during testing (35%) such that both plugs in only 15 of 25 pairs were tested successfully.

Lucia (1999) developed a series of petrophysical models of carbonate rocks based upon their gas permeability and porosity. The models are based upon the regression analysis of petrophysical data from many carbonate formations in the USA and the Middle East, particularly those from West Texas. Lucia defined three classes of carbonates of which Class 3 is that of mud-dominated fabrics that have a permeability field controlled by the predominance of carbonate grains in the $< 20 \mu\text{m}$ range, i.e., packstone, wackestone and mudstone and fine crystalline, mud-dominated dolostones. This description best fits the petrographic observations of Schandl, who has described the DGR cores, i.e., TR-07-12 (DGR-1 and DGR-2), TR-08-20 (DGR-3) and TR-08-21 (DGR-4).

Figure 4.19 shows the plot of available vertical gas permeability and porosity data for carbonate rocks intersected by DGR boreholes compared against Lucia's Class 3 carbonate model. DGR carbonate rocks included in Figure 4.19 include Silurian dolostones and limestones (carbonates), limestone and siltstone hard beds within the Ordovician shales, Ordovician limestones, and the dolostone-rich upper part of the Cambrian strata.

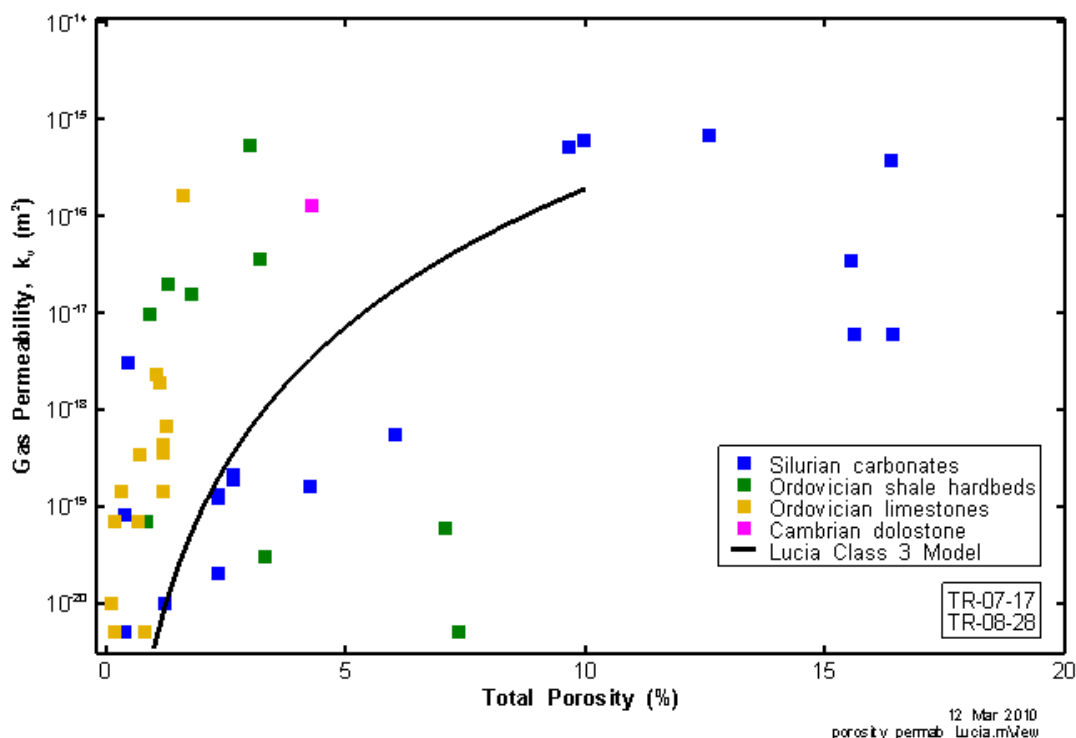


Figure 4.19 Gas permeability plotted against total porosity for DGR cores. Lucia's Class 3 carbonate permeability-porosity model is described by the 'Power' curve fit shown. Points plotting one or more orders-of magnitude above the power curve are suspect due to core disturbance and damage.

Figure 4.19 shows that the vertical gas permeability is roughly correlated with porosity using Lucia's petrophysical model of a Class 3 carbonate model. The plot of gas permeability versus porosity shown in Figure 4.19 reveals that most of the Ordovician limestones (and many of the Ordovician shale hard beds) are two or more orders of magnitude higher in gas permeability than the model predicts. The departure of the data from the Lucia model is very minor at permeability of about 10^{-21} m² suggesting that this may be the representative value of in-situ permeability for the Ordovician limestones. The overestimation of lab permeability for the Ordovician carbonate cores relative to Lucia's model is likely due to core relaxation and damage effects in these gas permeability measurements. A number of samples are very well predicted by the model line; these are Salina A0 Unit and Goat Island Formation dolostones. The good fit by these Lower Silurian formations indicates that these rocks should be considered as the uppermost part of the cap rock overlying the proposed repository formation. The underestimation of lab permeability for the Salina carbonates relative to Lucia's model is likely due to the presence of abundant evaporate minerals (i.e., gypsum, anhydrite) in these formations.

The lower extremity of the permeability-porosity space relationship shown in Figure 4.19 – i.e., $k < 1 \times 10^{-20}$ m² and $\phi < 0.1$ – is referred to by Neuzil (1994) as “a highly lithified, low porosity unit that one would expect to be prone to fracturing”. Given the apparent overestimation of permeability due to sample disturbance, it is likely that all of the Ordovician shale and limestone samples are highly lithified, low porosity rocks that are prone to fracturing during recovery, shipment and sample preparation for testing.

4.3.5 Mercury Injection Pore-Size Distribution

High pressure mercury porosimetry testing was used to determine:

- 1) the capillary-pressure/fluid saturation curve for a non-wetting fluid (i.e., mercury);
- 2) the pore-size distribution of the core sample;
- 3) the entry pressure required for a non-wetting fluid to penetrate the pore space; and
- 4) the Leverett J function for averaging capillary pressure curves.

Figure 4.20 shows example mercury intrusion profiles for four groups of core samples in terms of the injection pressure versus mercury saturation. These are: (a) Silurian formations; (b) Upper Ordovician shales immediately above the proposed repository horizon; (c) the Cobourg Formation; and (d) carbonate formations beneath the Cobourg Formation. In high pressure mercury injection following fluid extraction by the Dean Stark process, mercury is injected into the core plugs under increasing pressure causing air to ‘drain’ from the pores as mercury intrudes. Pittman (1992) reported that full penetration of mercury occurred at a saturation of just 10% (i.e., $S_{Hg} = 0.1$), which he considered as representing a continuous zone of mercury present across the core plug, i.e., in the most permeable set of interconnected pores.

The Silurian formations, shown in the upper left of Figure 4.20, display two styles of capillary behaviour. The flatness of the capillary pressure that occurs after penetration in Goat Island Formation – DGR-3 reflects the homogeneity of the pore-size distribution in this dolostone. This slope indicates that very little incremental injection pressure is needed to significantly increase S_{Hg} , whereas a steep slope indicates a large injection pressure requirement, e.g., Salina A2 Unit – DGR-3 ($k_v = 4.2 \times 10^{-18}$ m²) and Salina A0 Unit – DGR-4, ($k_v > 5.0 \times 10^{-17}$ m²). The deeper formations display a much higher threshold injection pressure (~ 100 MPa) for full penetration by mercury and a somewhat lower brine permeability, e.g., the Goat Island dolostone – DGR-3 ($k_h = 9.7 \times 10^{-19}$ m²), the Cabot Head shale – DGR-3 ($k_v = 2.5 \times 10^{-18}$ m²) and the Manitoulin dolostone - DGR4 ($k_v = 2.4 \times 10^{-18}$ m²). The Lower and Middle Silurian rocks comprising the Manitoulin, Cabot Head, Goat Island Formations (and the

smaller stratigraphic units between them) may be considered the upper extension of the repository caprock formed by the Ordovician shales.

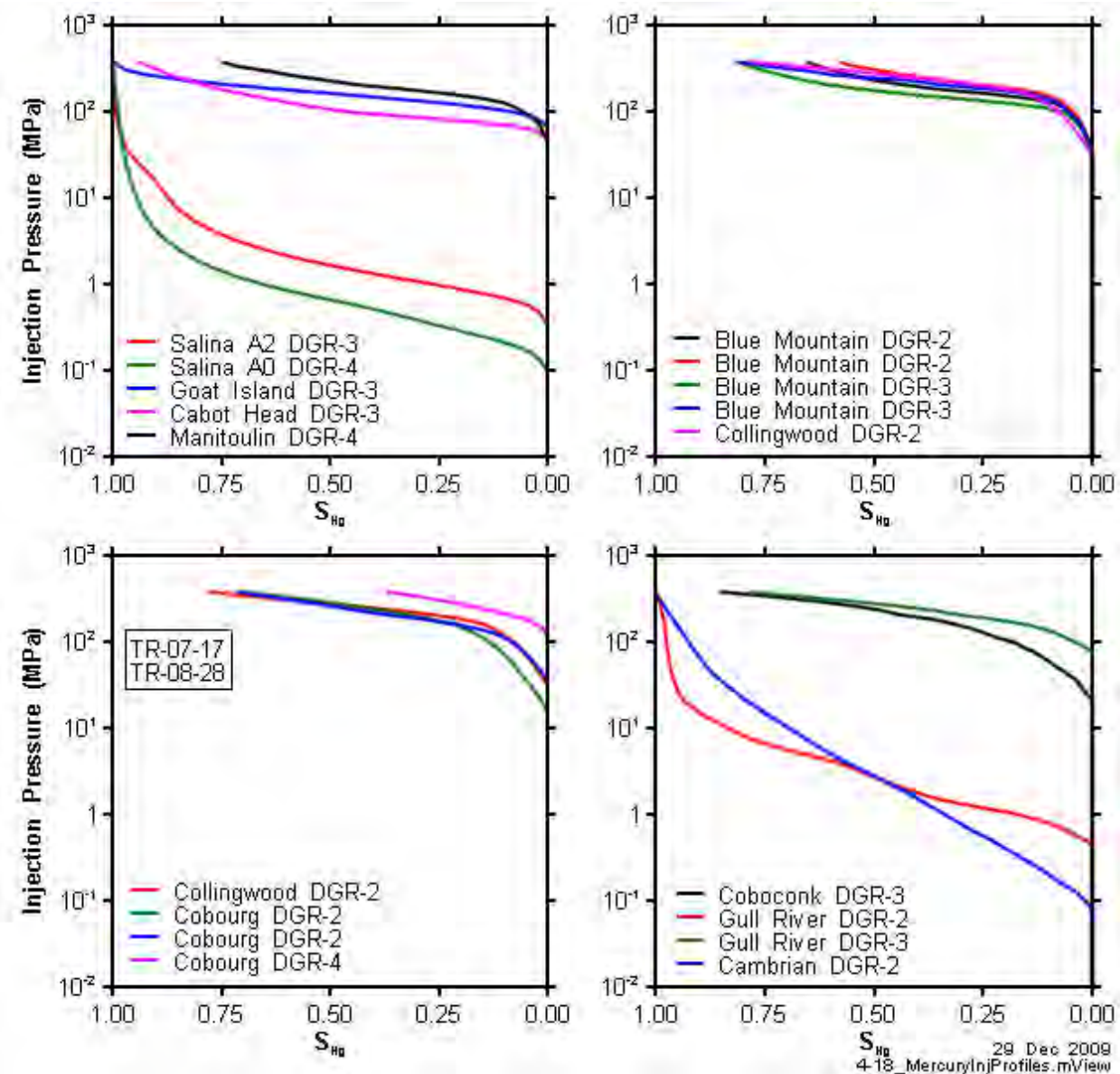


Figure 4.20 Mercury injection profiles (S_{Hg} or mercury saturation vs. injection pressure in MPa) for the Silurian formations (upper left), the Ordovician shales immediately above the repository horizon (upper right), the Cobourgh Formation (lower left) and the Black River limestones and Cambrian sandstone (lower right)

The tight shales that immediately overlie the proposed repository formation, which are shown in Figure 4.20 (upper right), are not fully penetrated by the mercury until the injection pressure exceeds 40 MPa for the Collingwood – DGR-2 sample. The equivalent values for the four Blue Mountain cores (DGR-2, DGR-2, DGR-3, DGR-2) shown exceed 100 MPa indicating an extremely tight cap rock. This very tight zone is associated with biogenic methane that is discussed later.

The lower left of Figure 4.20 shows the capillary pressure curves for the Cobourg Formation. Both the Collingwood Member (DGR-2) and the Cobourg Lower Member (DGR-2, DGR-2, DGR-4) core samples are shown to be of relatively uniform pore size. Although it only reaches 40% mercury saturation, one of the lower Cobourg cores (DGR-4) displays the tightest capillary response of any of the 54 DGR cores tested by high-pressure mercury intrusion, i.e., > 200 MPa for $S_{Hg} = 0.1$.

4.3.6 Gas Entry Pressure

The capillary pressure curves shown for the shales in Figure 4.20 indicate that penetration by gas – a non-wetting fluid like mercury – must overcome significant capillary resistance from the wetting fluid present in the pores. Here it is assumed that brine is the wetting fluid occupying the pore throats, although it may be more reasonable to assume that the carbonate formations are mixed wet, i.e., some pores are oil wet while others are water wet as noted by Lucia (1999). The entry pressure required by gas to penetrate a water-wet pore throat is given by the Washburn equation (Dullien, 1979; Pittman, 1992) which is a form of the Laplace equation for a cylindrical or capillary-tube model of pore structure (Guéguen and Palciauskas, 1994):

$$P_c = \frac{2\sigma \cos \theta}{r} \quad [4.2]$$

where P_c is the capillary pressure (in Pa) required to cause entry of the non-wetting fluid into the water-wet porous medium, σ is the interfacial tension between wetting and non-wetting fluids (in N/m), θ is the contact angle formed by the water with the pore surface and r is the radius of the capillary (in m), i.e., pore throat with a detection limit of ~2 nm (0.002 μ m). Consequently, the Washburn equation can be solved for the pore throat radius, r . In this context, pore throats represent constrictions that control formation permeability.

The capillary pressure (P_c) curves for mercury/air that are shown in Figure 4.20 can be converted to capillary pressure curves for gas/brine by correcting the P_c for mercury/air by the ratio of the $\sigma \cdot \cos \theta$ for methane/brine to that for mercury/air, i.e.,

$$P_{c(Gas / Brine)} = P_{c(Hg / Air)} \cdot \frac{\sigma \cdot \cos \theta_{(Gas / Brine)}}{\sigma \cdot \cos \theta_{(Hg / Air)}} \quad [4.3]$$

Values for the independent variables in this equation are readily available (e.g., Vavra et al., 1992; Guéguen and Palciauskas, 1994) and a capillary curve for methane/brine can be computed. Such curves will be identical in shape to those in Figure 4.19. For methane/brine, the ratio is:

$$P_{c(Gas / Brine)} = P_{c(Hg / Air)} \cdot \frac{72mN / m \cdot \cos 0^\circ_{(Gas / Brine)}}{485mN / m \cdot \cos 140^\circ_{(Hg / Air)}} \quad [4.4]$$

Thus, the P_c value for a gas/brine system is a factor of 0.194 that of the Hg/air capillary pressure profile. The entry pressure for gas into a brine-filled pore volume can thus be computed for a methane/brine system for which the gas entry pressure (P_d) is estimated as the P_c when $S_{Hg} = 0.1$ or 10% of mercury saturation (Pittman, 1992).

Figure 4.21 shows the median pore throat radius (r_{50}) plotted against the calculated gas entry pressure (P_d) into a brine-filled pore throat distinguished by formation. Figure 4.22 shows the depth profiles of both of these parameters. Most samples of limestone and all shales have similar median pore throat radii of 2 – 7 nm. However, the lower Gull River and Cambrian samples have median pore throat radii of ~270 nm. Figures 4.21 and 4.22 show that the calculated gas entry pressures to brine filled pores for the DGR formations range from less than 200 kPa for the Cambrian sandstone (40 kPa), lower Gull River (150 kPa), Salina A2 Unit (130 kPa) and parts of the A0 Unit (40 kPa), to 13 - 21 MPa for the Cobourg Formation, to 10 – 30 MPa for Ordovician shales. The Middle and Lower Silurian formations also have high gas entry pressures (Manitoulin – 20-24 MPa, Cabot Head – 13.5 MPa, Goat Island – 12.5 MPa).

It is noteworthy that for any particular pore throat radius, the gas entry pressure for the shales is higher than that of the limestones. r_{50} is shown varying with depth in Figure 4.22 with an increasing trend in pore-throat size above the proposed repository horizon, i.e., from the Cobourg Formation through the Blue Mountain to the Georgian Bay shales. Figure 4.22 also shows the existence of a gas entry barrier near the contact between the Blue Mountain and Collingwood shales.

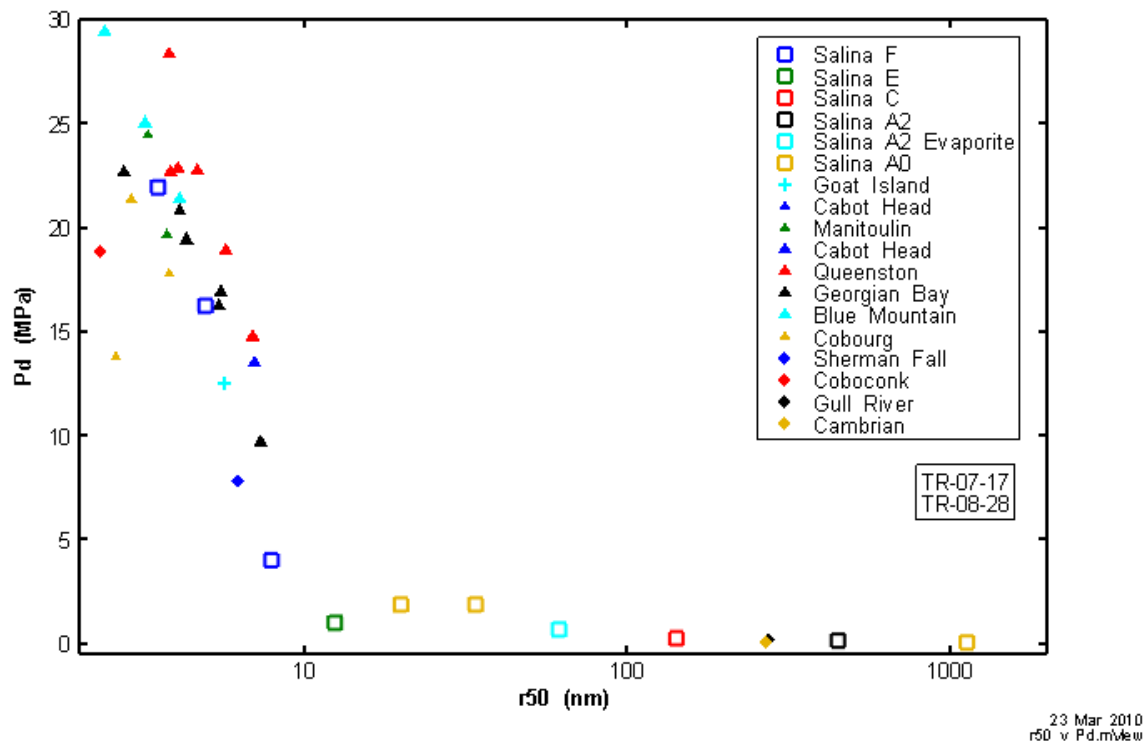


Figure 4.21 Relationship between median pore throat radius, r_{50} in nanometres and gas entry pressure into a brine-filled pore, P_d in MPa for DGR cores

As noted above, the pore throats in the carbonate rocks of the DGR Paleozoic sequence may be preferentially oil wet if the throats themselves are comprised of carbonate minerals, such as calcite and dolomite. Lake (1989) reported that 28% of carbonate petroleum reservoir rocks were determined to be oil wet, 8% were water wet and the rest of an intermediate state (i.e., a contact angle of 75° – 105° as measured through the wetting phase). In the case of an oil-wet pore throat, the mercury would still be the non-wetting phase and would displace the oil as if it were brine; thus the gas entry pressures reported here should also be appropriate for use with an oil-wet system.

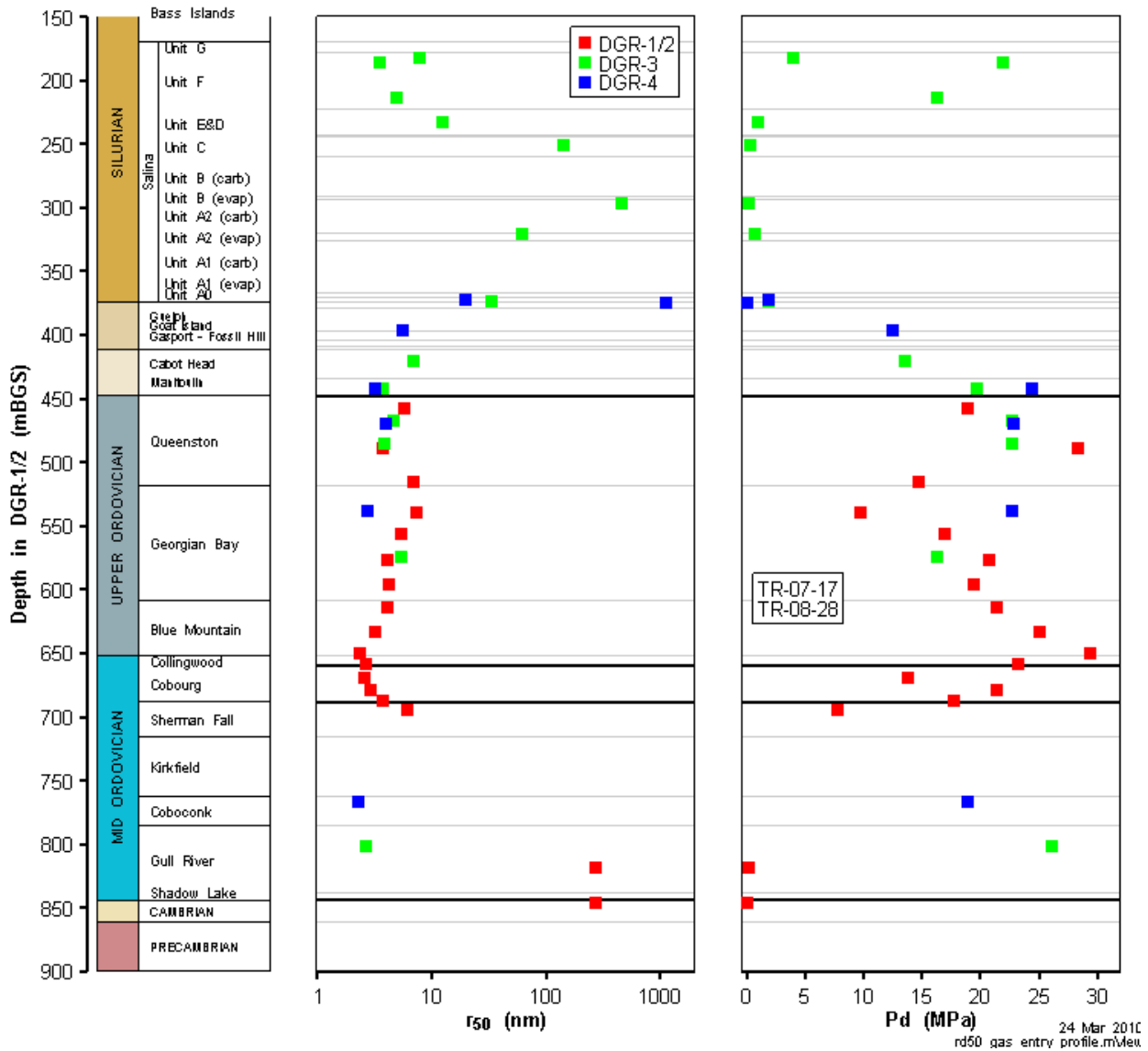


Figure 4.22 Profile of median of pore-throat radii (r_{50}) and gas entry pressure (P_d) of Silurian and Ordovician DGR cores determined from mercury injection porosimetry

Figure 4.23 shows the depth distribution of pore-throat radii and gas entry pressure for the formations that occur in the 280 m of Ordovician shale and Silurian shale and dolostone that form the low permeability barrier above the proposed repository horizon. That is, the figures in this section support the contention that the Middle and Lower Silurian formations – consisting of the Goat Island dolostone, the Cabot Head shale, the Manitoulin dolostone (and the smaller formations between them) – constitute the upper part of the low-permeability barrier overlying the Cobourg Formation. The Upper Ordovician shales constitute the lower part of this cap rock above the Cobourg Formation.

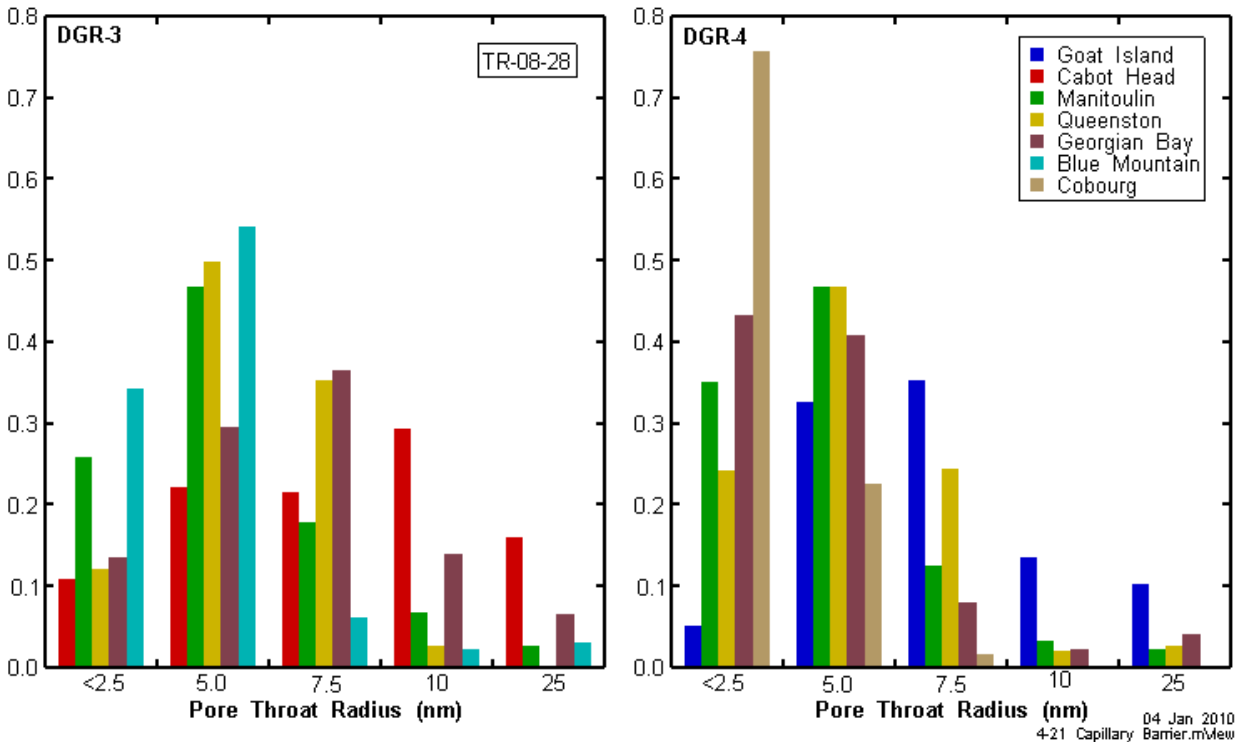


Figure 4.23 Histograms of the distribution of pore-throat radii (r_{50} in nm) for Lower and Middle Silurian shales and dolostones and Ordovician shales and limestones in DGR-3 and DGR-4 cores.

4.3.7 Leverett's J Function

As noted above, there is strong evidence of overestimation in the measured permeabilities of the Ordovician cores that is most likely due to microcracking during coring, shipping and lab testing. However, porosity and mercury intrusion results appear to be correct or at least not subject to the same magnitude of overestimation seen in the permeability data. Leverett's J function is used in reservoir engineering to correlate permeability and porosity characteristics in a single parameter. The J function assumes that the pore geometries of the various core plugs being compared are similar and accounts for changes in permeability, porosity and wettability (Tiab and Donaldson, 2004):

$$J = P_c \frac{\sqrt{k/\phi}}{\sigma \cos \theta} \quad [4.5]$$

where P_c is the capillary pressure (Hg/air), k is the permeability, ϕ is the total porosity, σ is the interfacial tension and θ is the contact angle. Tiab and Donaldson (2004) show how the (dimensionless) J function may be derived by substituting the capillary pressure into the Carman-Kozeny equation. Based upon this reasoning, the J function provides a means of comparing average rock properties in terms of permeability, porosity and wettability (Lucia, 1999).

Figure 4.24 shows the J function plotted against mercury saturation for six DGR cores from the Ordovician shale sequence. Five samples from the three Ordovician shale formations (Queenston, Georgian Bay, Blue Mountain) follow a similar pattern that can be identified as diagnostic of these shales with an abrupt breakthrough prior to 10% mercury saturation and a smooth, flat curve indicating homogeneity in pore geometry before increasing in slope again. However DGR2-650.12, a core from the Blue Mountain Formation, departs from the pattern. Because the J function is computed

using a permeability measurement from a permeameter and not from the mercury porosimeter, the J function plot identifies this particular permeability measurement ($k_v = 9.0 \times 10^{-16} \text{ m}^2$) as an overestimate. Thus, it is possible to identify a more accurate measurement of the permeability of DGR2-650.12 – and of DGR3-661.03 that failed during testing – by comparison with the other shales in the Figure, i.e., $k_v \sim 1 \times 10^{-19} \text{ m}^2$ or $K_v \sim 1 \times 10^{-12} \text{ m/s}$.

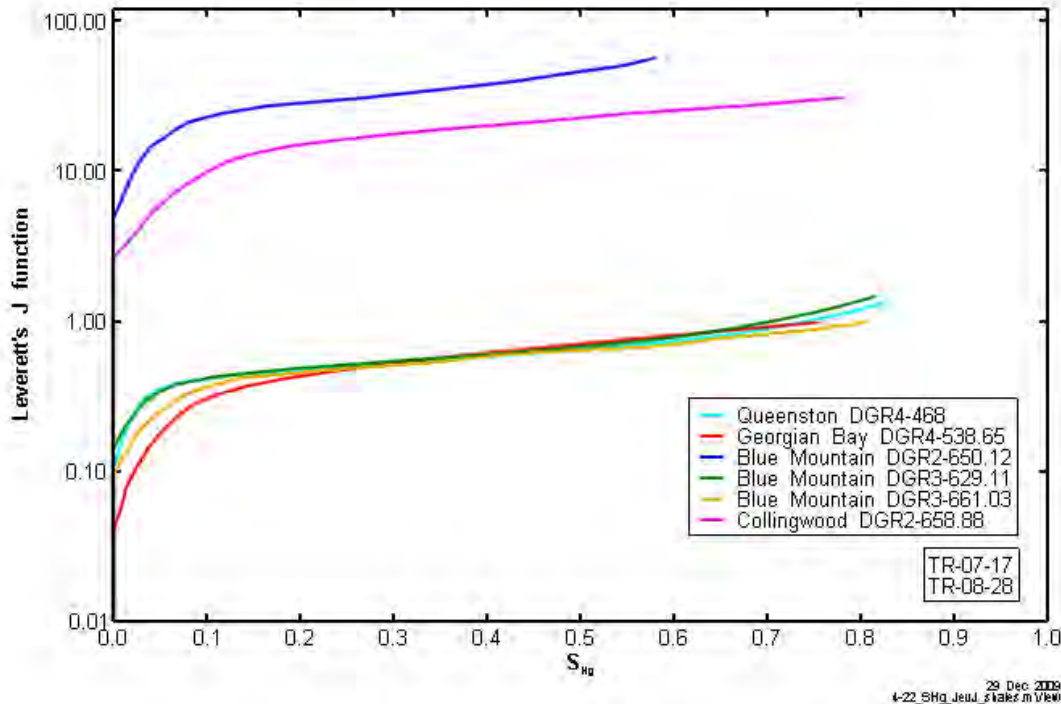


Figure 4.24 Leverett J function curves for DGR Ordovician shale cores

Similarly, Figure 4.25 identifies a diagnostic pattern for the Ordovician limestones shown at the bottom of the figure that exhibits a smoother breakthrough curve. Two limestones cores from the Cobourg Formation – DGR2-669.10 and DGR2-678.63 – also appear to have measured permeabilities that are overestimates, however in this case the measurements are already of the order of $k_v \sim 1 \times 10^{-19} \text{ m}^2$, therefore the true value appears to be $< 1 \times 10^{-20} \text{ m}^2$. But the patterns displayed by these two cores during mercury intrusion otherwise mimic the diagnostic pattern below. A core from the Gull River Formation – DGR2-818.61 – initially follows the diagnostic pattern of the other limestones but then departs from this pattern and appears to be developing microcracks at approximately 1 MPa applied mercury pressure (see Figure 4.20, lower right graph).

Therefore, the Leverett J function plots can be used to identify (1) overestimates in the measurement of permeability – or underestimates in the measurement of total porosity – and (2) diagnostic patterns for permeability-porosity correlation in both the Ordovician shales and limestones.

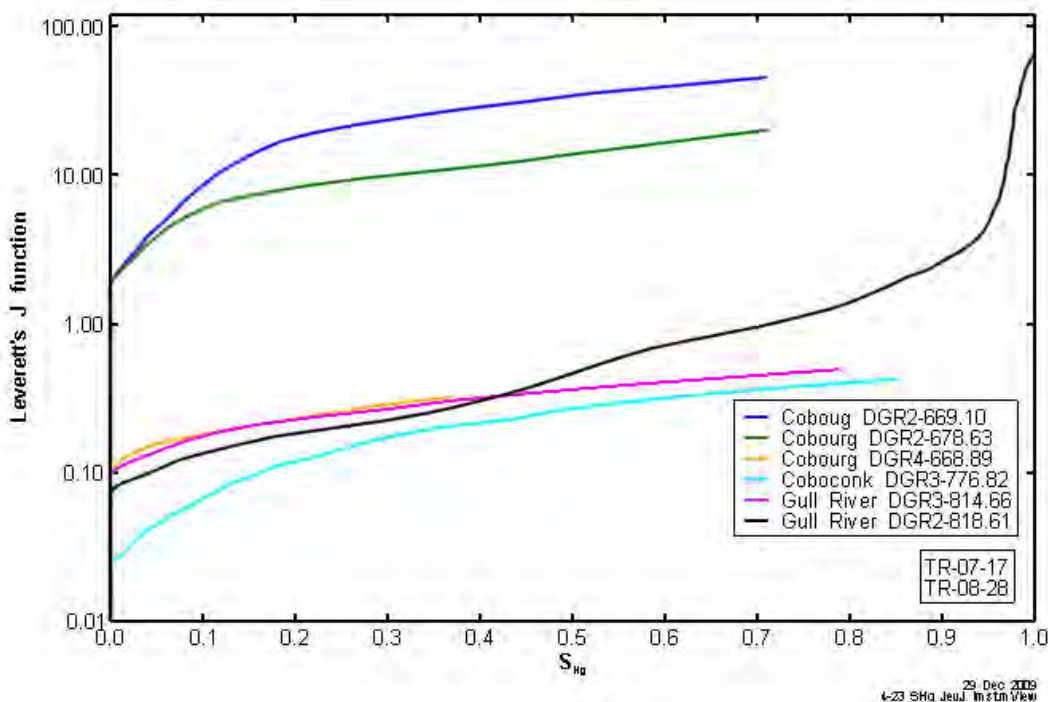


Figure 4.25 Leverett J function curves for DGR Ordovician limestone cores

4.3.8 Surface Area Measurements

The external specific surface areas of DGR-2 core samples were measured by UniBern (TR-08-06, TR-08-40) using the Brunauer, Emmett, Teller (BET) method and are presented in Figures 4.26 and 4.27 as a function of total porosity and total sheet silicate (clay) content, respectively. Specific surface area was quantified as part of characterization of potential sorption properties of DGR cores to aid in reconstruction of porewater chemistries from crush and leach experiments (TR-08-06) and to assist in interpretation of core diffusion experiments (TR-07-17, TR-08-27). In addition, for 11 samples that were selected to cover a wide range of clay contents, the complete N_2 -adsorption isotherms in the P/P_0 pressure range from 0 to 1.0 were obtained (TR-08-06).

Figure 4.26 shows the variation in BET surface area with total porosity. Both the Ordovician shales and limestones show increasing surface area with increasing porosity. While it is possible that a few of the Georgian Bay samples may in fact be carbonate hard beds, there is a clear indication of the very high specific surface area in the Ordovician limestones (e.g., Cobourg Formation). This is consistent with the mercury porosimetry for the Cobourg Formation shown in Figure 4.22 for the DGR-4 cores.

Figure 4.27 shows the BET surface area versus clay mineral content for these same DGR-2 cores. This figure shows that the surface areas are positively correlated with the clay mineral content of the Ordovician shales, but less so for the Ordovician limestones. Figure 4.27 indicates that despite their low porosity, the argillaceous limestones of the Cobourg, Sherman Fall and Kirkfield Formations can have very substantial surface area, often equivalent to that of the shales.

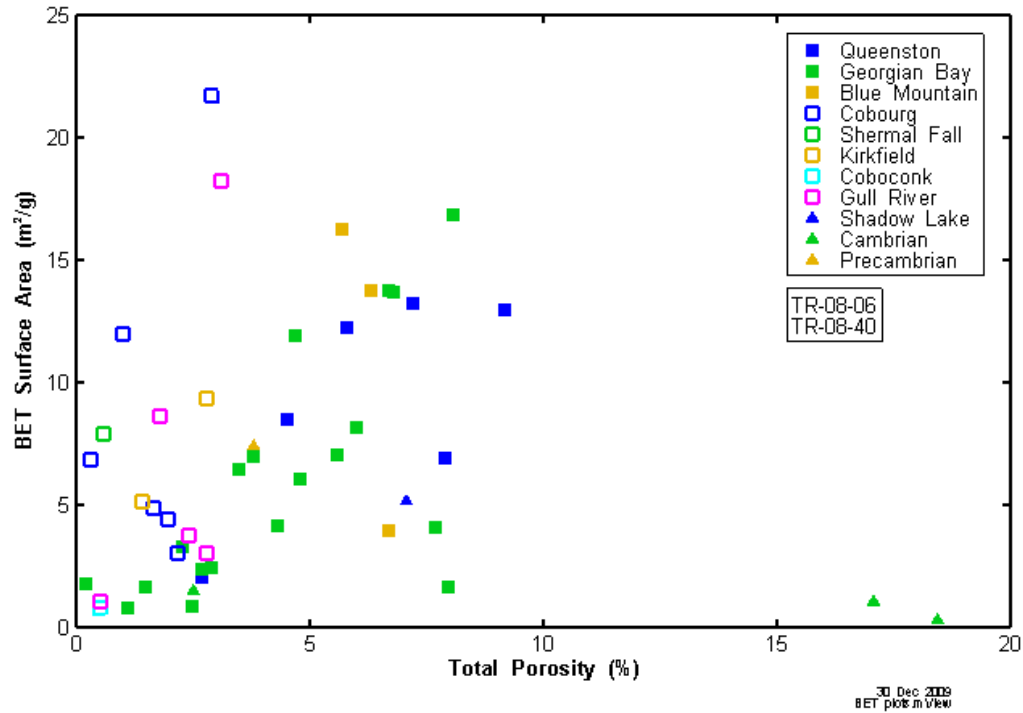


Figure 4.26 Specific surface area as a function of total porosity in DGR-2 cores

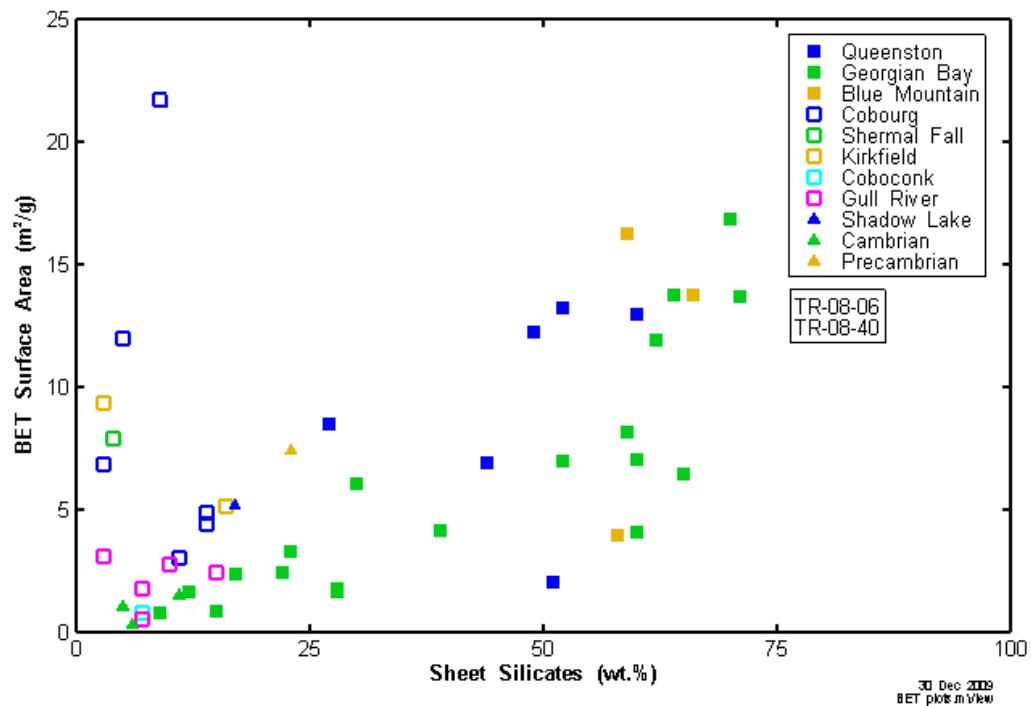


Figure 4.27 Specific surface area as a function of total sheet silicates in DGR-2 cores

Full adsorption isotherms obtained for a subset of all DGR-2 samples are shown in Figure 4.28. All samples have typical S-shaped profiles, which characterises monolayer adsorption at low P/P_0 and multilayer adsorption at intermediate P/P_0 . The BET surface is measured at a sample-specific P/P_0 where the monolayer is saturated, i.e. at the onset of multilayer adsorption.

The break in slope at high P/P_0 corresponds to the onset of capillary condensation, i.e., multi-layer sorption. There is an excellent correlation between clay content and the shape of the adsorption curve. The flattest curve is observed for Cambrian sandstone (DGR2-855.89), whereas clay-rich samples from the Georgian Bay Formation (DGR2-581.32 and DGR2-609.39) indicate a much higher adsorption (and therefore surface area) over the entire pressure range. Capillary condensation starts at lower P/P_0 in clay-rich samples when compared to the almost clay-free Cambrian sandstone, indicative of smaller pore apertures in these rocks (see TR-07-18, Table 4).

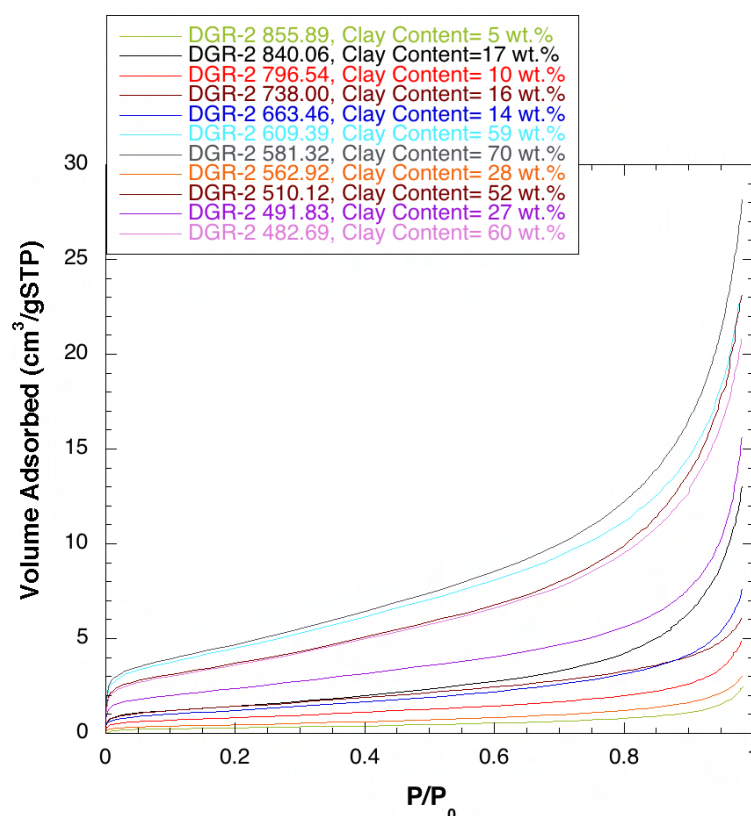


Figure 4.28 Full N₂ adsorption isotherms for DGR-2 cores

4.3.9 Gas-Brine Flow Properties

Mercury injection porosimetry data, fluid saturation data and gas pulse permeability data for “as received” and “clean and dry” core samples were used to calculate van Genuchten characteristic two-phase (gas-brine) flow parameters for DGR cores (TR-08-33) that may be required to simulate multi-phase flow of gas and brine following repository closure. Mercury injection porosimetry data were used to generate van Genuchten fitting parameters for capillary pressure – liquid saturation curves. “As received” permeability data with defined fluid saturations were used with the “clean and dry” permeability data to calculate a relative gas permeability. The relative gas permeability and

associated liquid and gas saturations were used to determine van Genuchten fitting parameters for relative permeability – liquid saturation curves.

Figures 4.29, 4.30, 4.31 and 4.32 show the fitted van Genuchten capillary pressure-saturation curves for gas-brine in DGR cores generated in TR-08-33. Consistent with Figure 4.20, the highest capillary pressures are associated with the Ordovician limestones (Figure 4.32) and the lowest with the Salina Formation Units (Figure 4.29). For the estimated gas saturations of ~10 to 20%, the resultant capillary pressures of 10 to 50 MPa are calculated for the Ordovician shales and limestones.

Each capillary pressure curve is paired with a set of relative permeability-saturation curves shown in Figures 4.33 through 4.36. These figures show that the estimated gas saturations of ~10 to 20% result in reductions of brine permeability by 10-40%. These same gas saturations inhibit gas migration due to this relative permeability effect and the likelihood that pore throats are wetted by brine or even oil. That is, high in-situ gas pressures would be required to cause gas migration. The most likely formations in which this might occur would be in the lower Blue Mountain and Collingwood Formations where the methane solubility limit is exceeded by the largest margin (see Section 4.6.3).

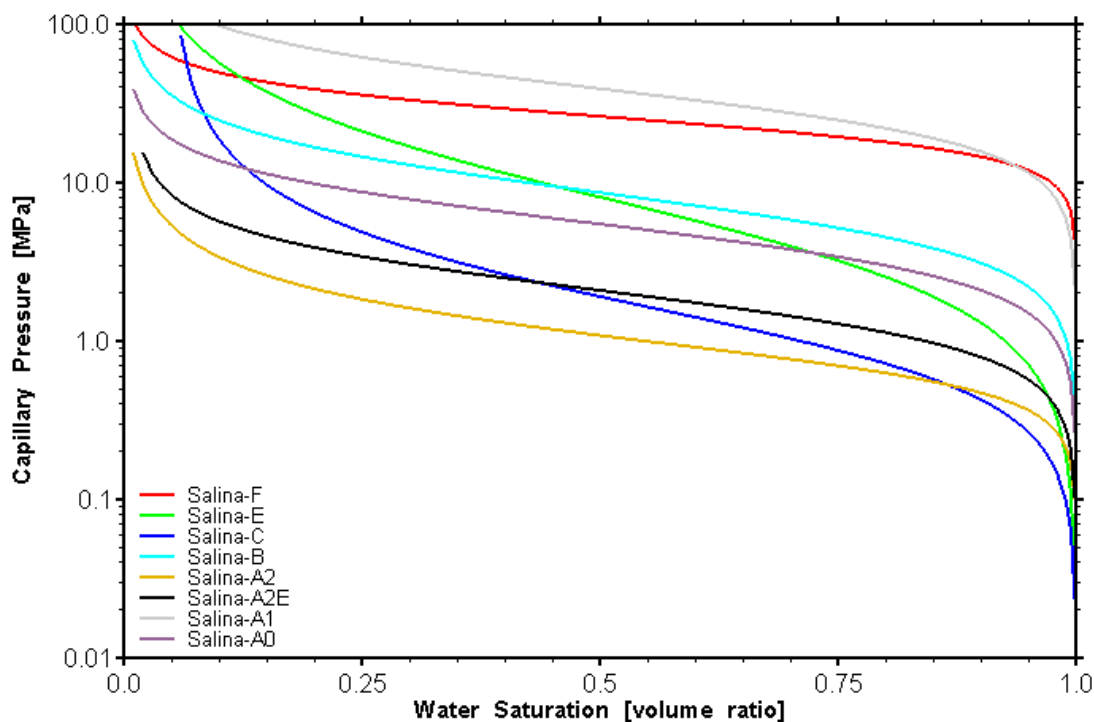


Figure 4.29 Fitted capillary pressure - brine saturation curves for DGR cores from the Salina Formation

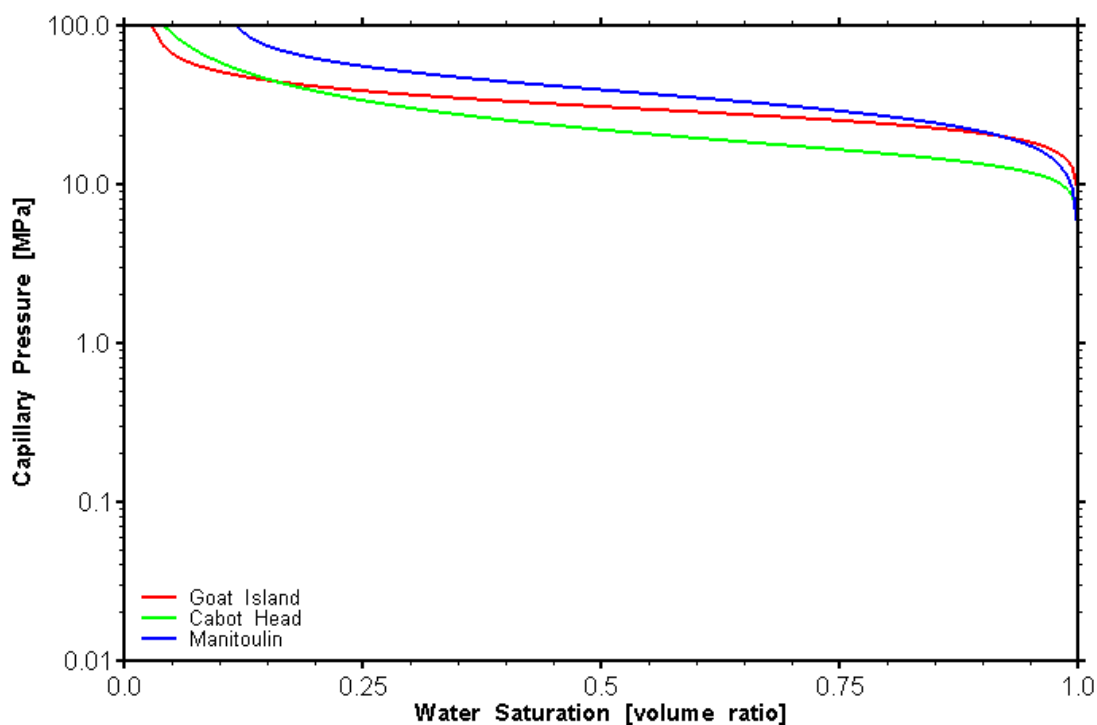


Figure 4.30 Fitted capillary pressure - brine saturation curves for DGR core from Lower Silurian formations

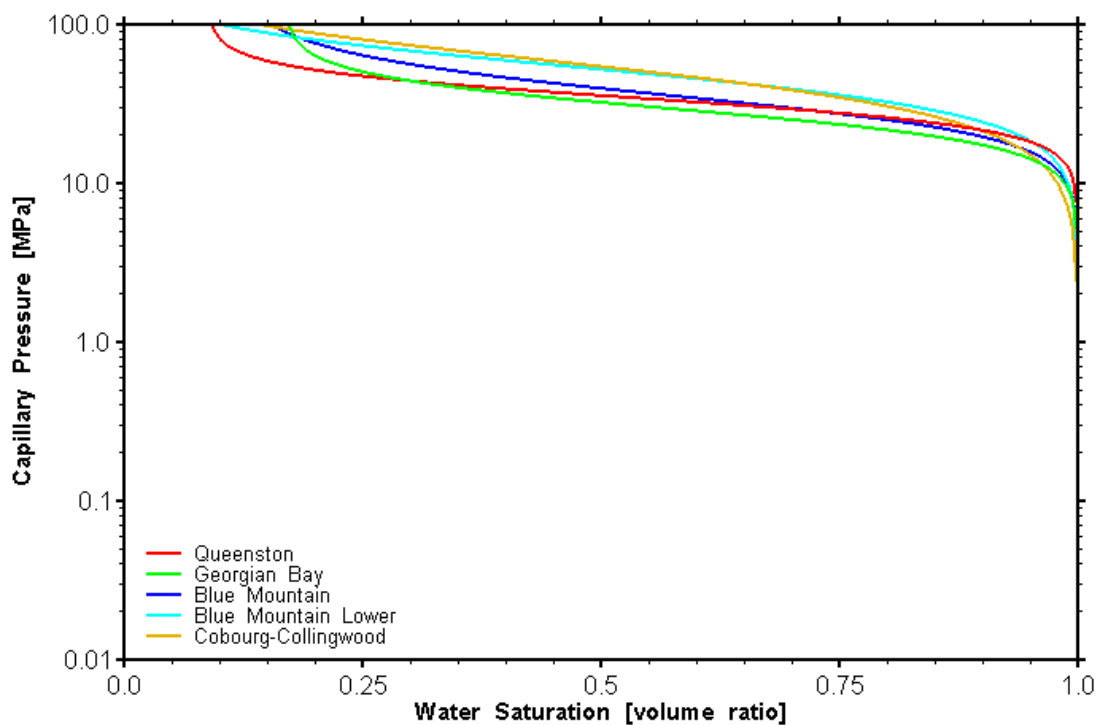


Figure 4.31 Fitted capillary pressure - brine saturation curves for DGR core from Ordovician shale formations

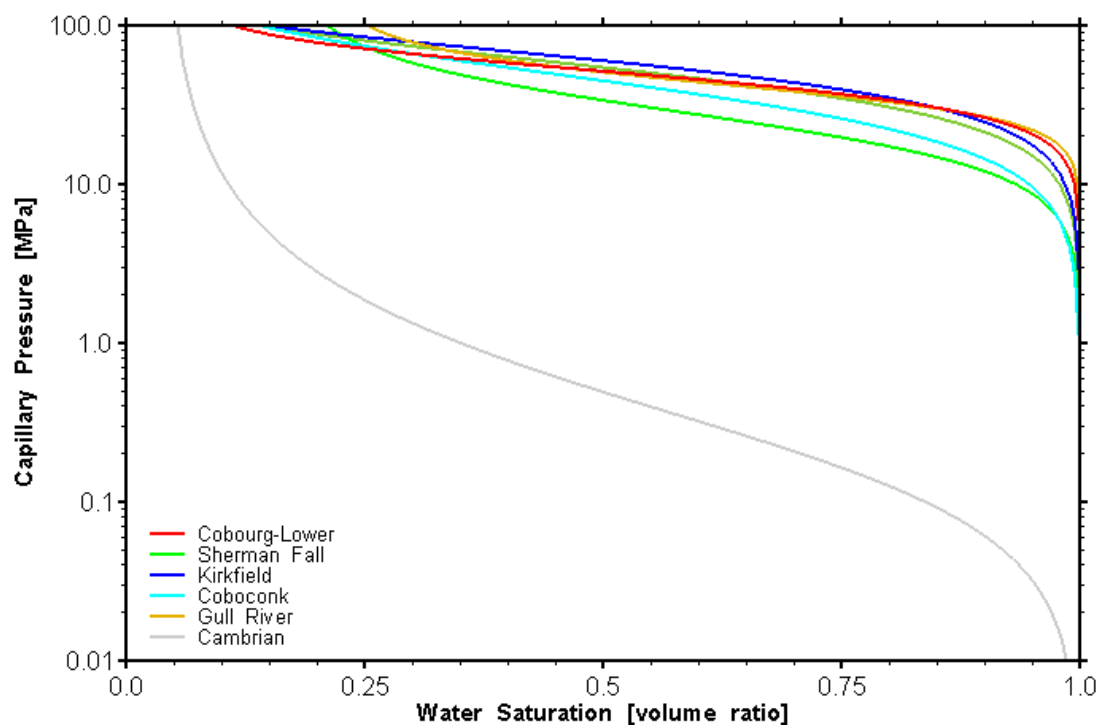


Figure 4.32 Fitted capillary pressure - brine saturation curves for DGR core from Ordovician limestone formations and Cambrian strata

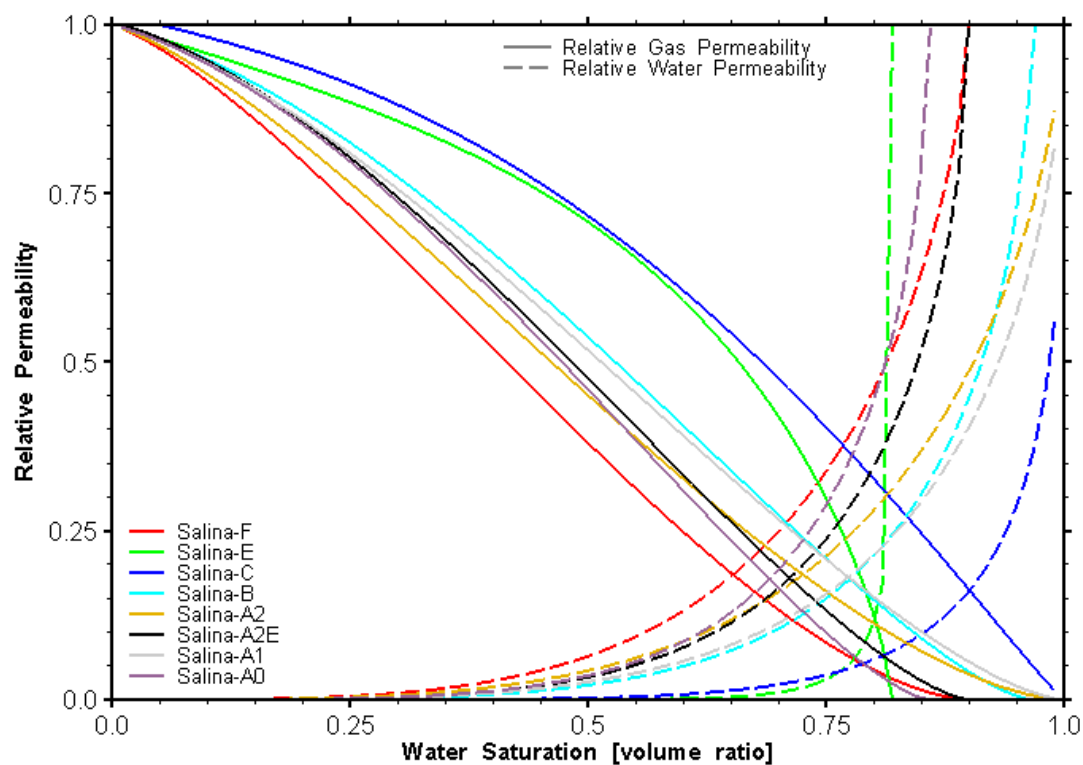


Figure 4.33 Fitted relative permeability - brine saturation curves for DGR cores from the Salina Formation

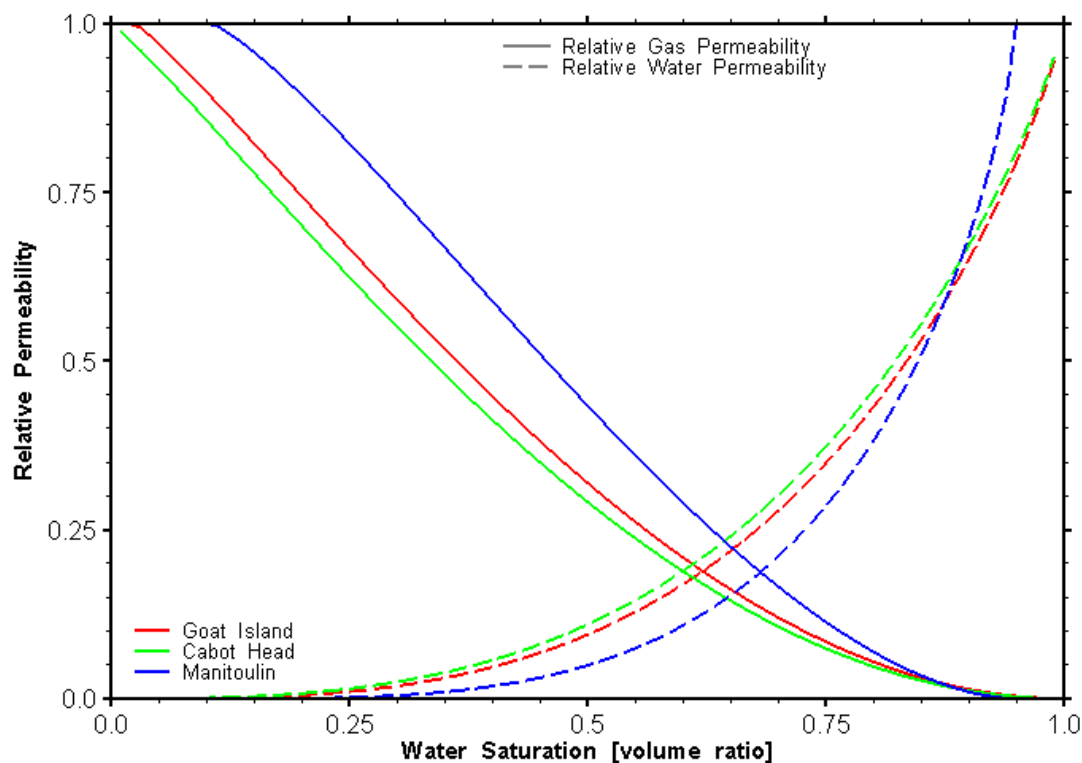


Figure 4.34 Fitted relative permeability – brine saturation curves for DGR cores from Lower Silurian formations

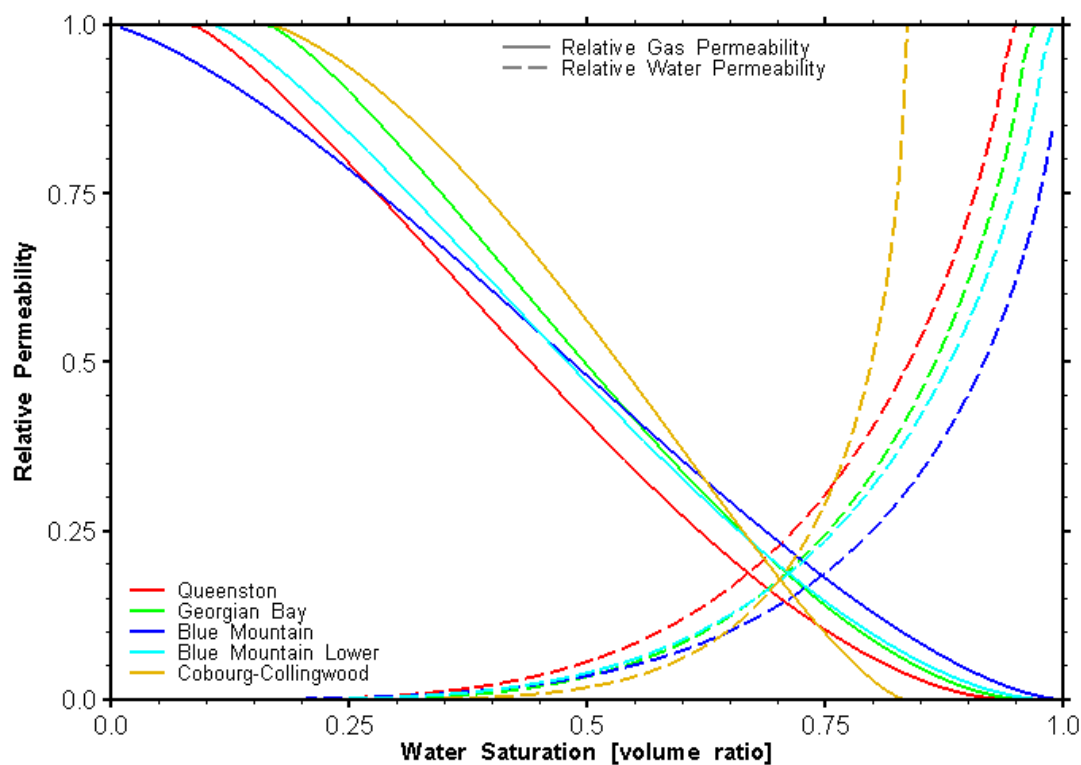


Figure 4.35 Fitted relative permeability – brine saturation curves for DGR cores from Ordovician shale formations

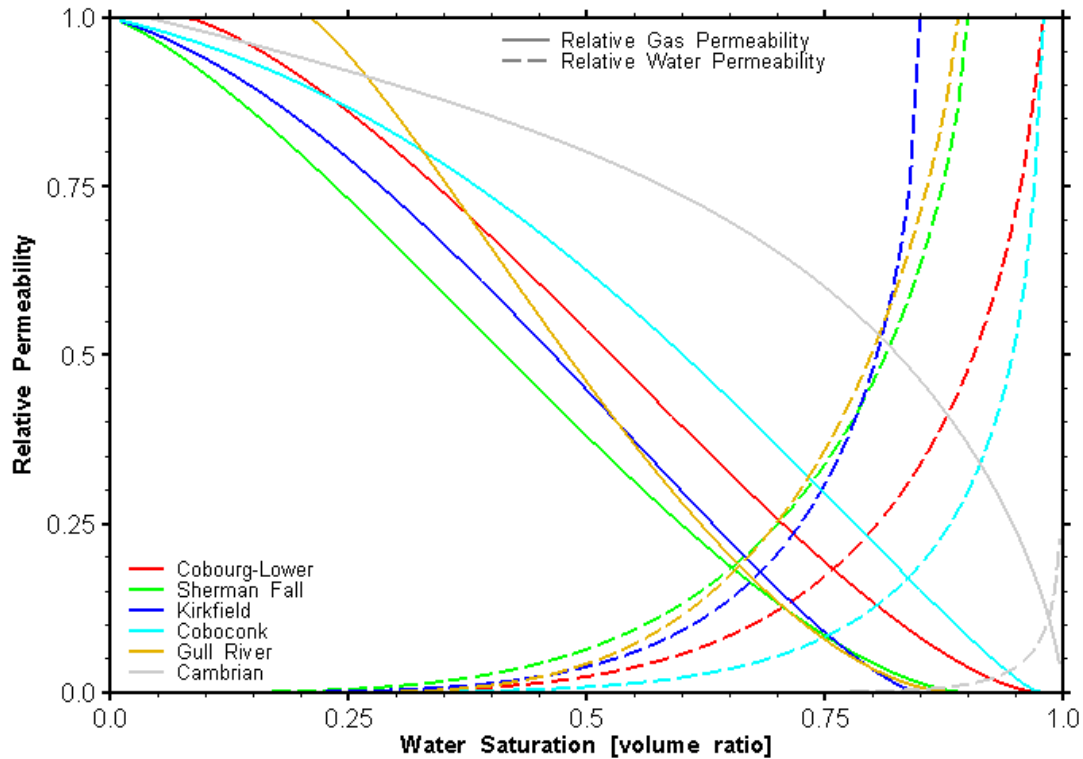


Figure 4.36 Fitted relative permeability – brine saturation curves for DGR cores from Ordovician limestone formations and Cambrian strata

4.4 Diffusion Properties

The very low hydraulic conductivities that are reported above in Section 4.3.4 and later in Section 4.9.2 indicate the likelihood that diffusion will drive solute transport in the Ordovician shales and limestones. Two methods of measurement were employed by the University of New Brunswick (UNB) to determine the effective diffusion coefficient and the diffusion porosity of DGR core samples: an X-ray radiographic technique for measuring normal (vertical) and parallel (horizontal) to bedding and one based upon a conventional through diffusion cell approach for measuring vertical properties (TR-07-17 and TR-08-27). The use of two methods was originally thought necessary in order to check the results of the innovative UNB X-ray radiographic method (Tidwell et al., 2000) against the more widely used through-diffusion method (Boving and Grathwohl, 2001; van Loon et al., 2003). The paper of Cavé et al (2009) provides a benchmark of the two methods.

As it developed, the poor signal-to-noise ratio measured by the radiographic technique in the low-porosity (<0.03) argillaceous limestones required the use of the through-diffusion method for these samples. Irrespective of the method used, the core plugs tested were saturated with a synthetic brine porewater and then the diffusion measurements were made with either a sodium iodide (NaI) tracer solution (radiographic method) or with a tritiated-water (HTO) or NaI tracer solution (diffusion cell). A comparison of the two techniques (TR-07-17, Cavé et al., 2009) indicated that they provide comparable results, differing by no more than a factor of 2.25 for paired sets of samples.

A further comparison of UNB iodide test results was provided through duplicate, normal to bedding, through diffusion testing of DGR-2 core samples of Cobourg Formation argillaceous limestone and Queenston Formation red shale completed by the Paul Scherrer Institute (PSI), Switzerland using ¹²⁵I as a tracer (TR-07-22). Comparative results are presented in Table 4.4 and demonstrate good

agreement between laboratories.

Table 4.4 Inter-laboratory comparison of the effective diffusion coefficients (D_e) and tracer-accessible porosity (ϕ) determined from through-diffusion testing of Queenston shale and Cobourg limestone cores from DGR-2

<i>Diffusion Parameter</i>	<i>PSI DGR2-466.38</i>		<i>UNB DGR2-456.97</i>	<i>PSI DGR2-675.48</i>		<i>UNB DGR2-677.11</i>
	<i>Queenston Sample 1</i>	<i>Queenston Sample 2</i>	<i>Queenston Sample</i>	<i>Cobourg Sample 1</i>	<i>Cobourg Sample 2</i>	<i>Cobourg Sample</i>
D_e (m^2/s)	3.63E-12	3.05E-12	2.60E-12	6.74E-13	6.26E-13	4.50E-13
ϕ (%)	13.4	9.6	9.4	2.4	2.4	1.2

4.4.1 Effective Diffusion Coefficients

The results of all effective diffusion coefficient testing completed by UNB are presented in Figure 4.37 versus DGR-1/2 reference depth and formation, discriminated by borehole, tracer type (NaI or HTO) and testing direction (normal and parallel to bedding). One hundred and thirteen estimates of effective diffusion coefficient (D_e) were measured by UNB using through-diffusion and X-ray radiography testing techniques. Testing was completed on preserved cores collected from Silurian and Ordovician formations in boreholes DGR-2, DGR-3 and DGR-4. For iodide diffusion testing normal to bedding, Figure 4.37 also shows the geometric mean D_e for each formation member or unit. A cursory review of Figure 4.37 shows that there are no discernable differences in D_e values between individual DGR boreholes.

As shown in Figure 4.37, with the exception of a few samples from the Upper Silurian, the D_e values measured from DGR cores all fall in the range of 10^{-12} m^2/s or lower. The few highest values approximating 10^{-11} m^2/s occur in the high porosity (>10%) Salina B, C, E and F Units and the Cabot Head shale as expected based on the known correlation of diffusion coefficients with porosity (Lerman, 1979). The lowest D_e values, on the order of 10^{-14} m^2/s , were measured on gypsum-anhydrite layers of the Salina A2 and A1 Unit evaporites and dolostones, in the carbonate hard beds within the lower Queenston and upper Georgian Bay Formations and on several limestone samples from the lower Gull River Formation. These extremely low values may be the lowest ever measured on sedimentary rocks to date and all of the diffusion data measured as part of the DGR program fall below or near the lower range of reported international data (AECOM Canada Ltd., 2010). The majority of the D_e values are in the range of 10^{-13} to 10^{-11} m^2/s , with the Lower Silurian and Upper Ordovician shale samples representing the higher end of this range due to their relatively high porosity (~10%). Fifteen diffusion measurements have been made on the Lower Member Cobourg Formation samples, which is the proposed DGR host rock; the results indicate consistently low D_e values of 10^{-13} to 10^{-12} m^2/s .

The D_e data display systematic variability as function of the tracer used to make the measurements. As suggested by Figure 4.37, D_e values obtained from through-diffusion testing with HTO tracer are on average 1.9 times greater (range 0.8 to 4.9) than D_e values measured with the iodide tracer. Figure 4.38 provides a cross plot of all of the D_e data measured by through-diffusion for HTO and iodide tracers. This difference is primarily attributed by UNB (TR-08-27) to anion exclusion in lowering the tracer accessible porosity, although 20% of the differences in D_e values are due a 20% larger value of free-water diffusion coefficient for iodide over HTO. Anion exclusion effects in porous media are commonly attributed to charge interactions between ions in solution and the electric double layer

(EDL) present in clay-rich media. Some simple calculations of EDL thickness and comparison to pore throat sizes determined from high pressure mercury injection testing provides insight to this exclusion process.

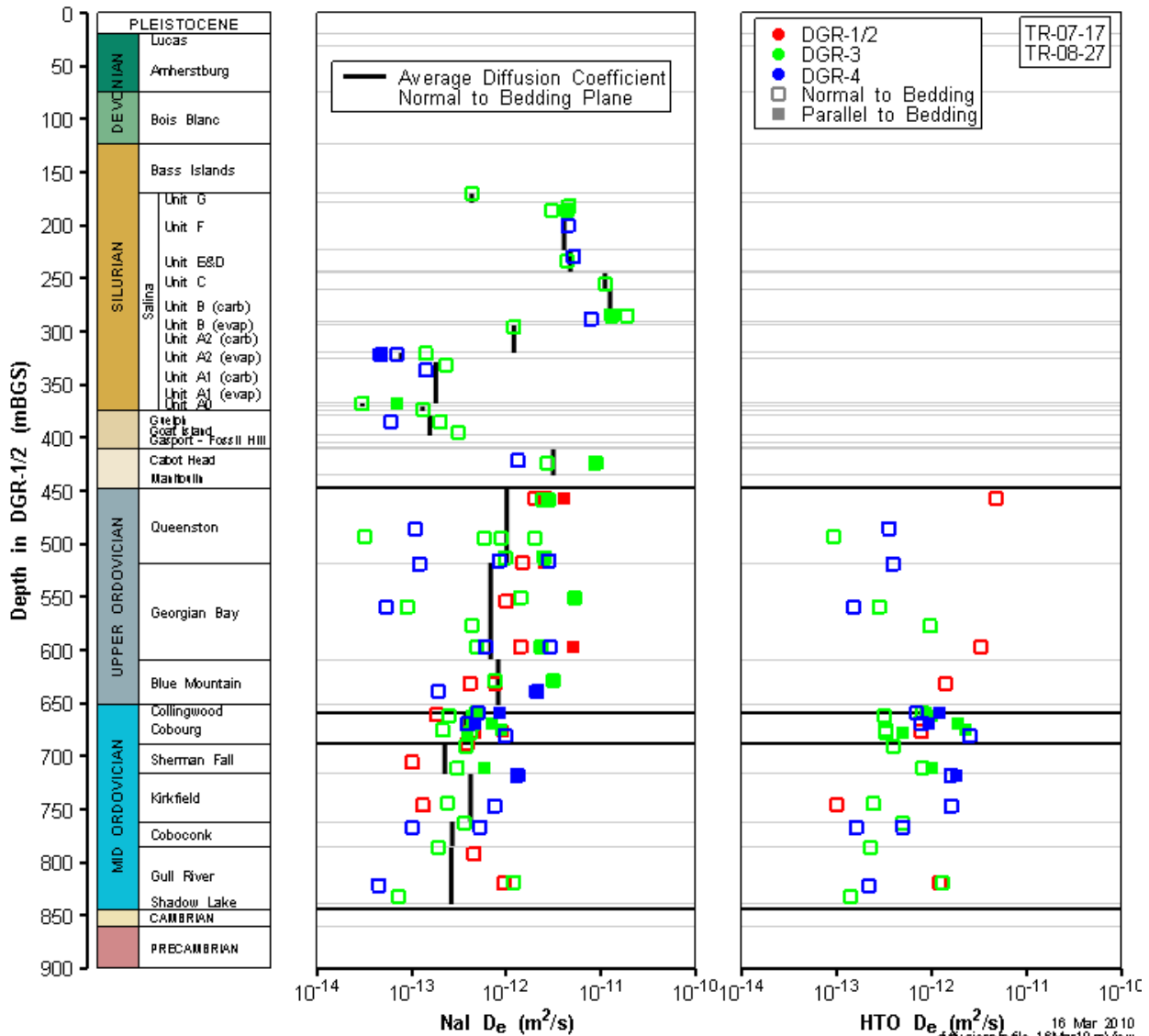


Figure 4.37 Effective diffusion coefficient (D_e) profile as determined by X-ray radiography and through-diffusion testing of DGR cores showing point measurements and formation averages

The thickness of the electrical double layer (EDL) for a 5M NaCl brine is ~ 0.14 nm (Stumm, 1992, p.49) that is an order of magnitude smaller than the smallest of the pore throat radii in Figure 4.21. The EDL associated with a negatively-charged clay colloid such as an illite surface may be estimated by the general equation for the diffuse double layer EDL (Stumm, 1992, pp. 47-49). The inverse of the thickness of the EDL, κ , is given by Stumm as:

$$\kappa = \sqrt{\frac{2F^2 \cdot I \cdot 10^3}{\epsilon \epsilon_0 RT}} \quad [4.6]$$

Where F is the Faraday constant (96490 Coulombs per mol), I is the ionic strength (M) of the solution associated with the charged surface, ϵ is the dielectric constant of water ($\epsilon = 78.5$ at 25°C), ϵ_0 is the permittivity of free space ($8.854\text{E-}12 \text{ C}^2\text{J}^{-1}\text{m}^{-1}$), R is the molar gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$) and T is the absolute temperature ($^\circ\text{K}$). For a brine with a TDS $\sim 300 \text{ g NaCl/L}$, i.e., 5M NaCl , κ^{-1} is $\sim 0.14 \text{ nm}$. By comparison with the method detection limit (MDL) for mercury injection shown in Figure 4.22, the EDL thickness is much smaller than this MDL, which is approximately 2.5 nm . Therefore, pore throats with the median radii shown in Figure 4.22 would exhibit only a limited ability to inhibit anion (and cation) migration because most throats appear $\gg 2\kappa^{-1}$ or 0.3 nm , which is the projection of EDLs by both grain walls into a pore throat. However, experimental evidence presented below, i.e., the marked difference between average tracer-accessible porosity and water-loss porosity, indicates that ion exclusion is likely occurring. Results from porewater chemistry extractions suggest that must be due to ion exclusion occurring in numerous very small pores with pore throat diameters $< 2.5 \text{ nm}$ and that this halite-undersaturated porewater is released during crush and leach extraction.

Thus, anion exclusion does not appear to be the only cause of this difference. Lerman (1979, p.93) indicates that the diffusion of dissolved species in small pore throats of the size shown in Figure 4.22 is also retarded by a combination of geometric and hydrodynamic effects (hindrance of pore walls) through an increased drag force. Because the hydrated iodide ion is larger than the HTO molecule ($\sim 1.4 \text{ nm}$) and the pore throats are of the order of $1\text{-}10 \text{ nm}$, it may be that 'hindrance of pore walls' in addition to anion exclusion is responsible for the differences shown in Figure 4.38. Clastic limestones in Figure 4.38 are the limestone hard beds within the Ordovician shales.

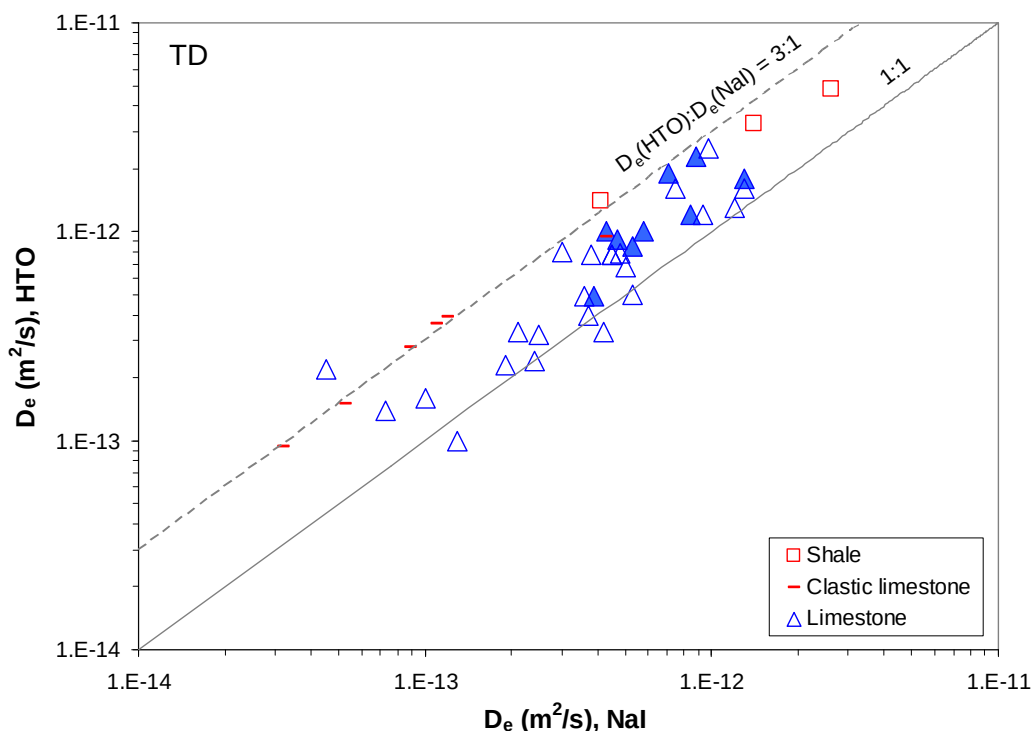


Figure 4.38 Relationship between D_e determined with iodide tracer and D_e determined with HTO tracer on DGR cores measured by through-diffusion. Open symbols are normal to bedding; filled symbols are parallel to bedding.

There is also a systematic difference in the D_e values based on the orientation of the measurements with respect to bedding direction. With only two exceptions (in the Salina B Unit anhydrite and A2

Unit evaporite, Figure 4.37), the D_e values determined from paired samples are greatest for diffusion in the direction parallel to bedding. The anisotropy ratio (D_e parallel/ D_e normal) ranges from 1 to 4 for measurements made with iodide tracer, and from 1 to 7 for measurements made with HTO tracer (TR-08-27). Figure 4.39 shows the relationship between D_e values measured parallel and normal to bedding in all DGR cores tested by X-ray radiography and through diffusion using iodide and HTO tracers.

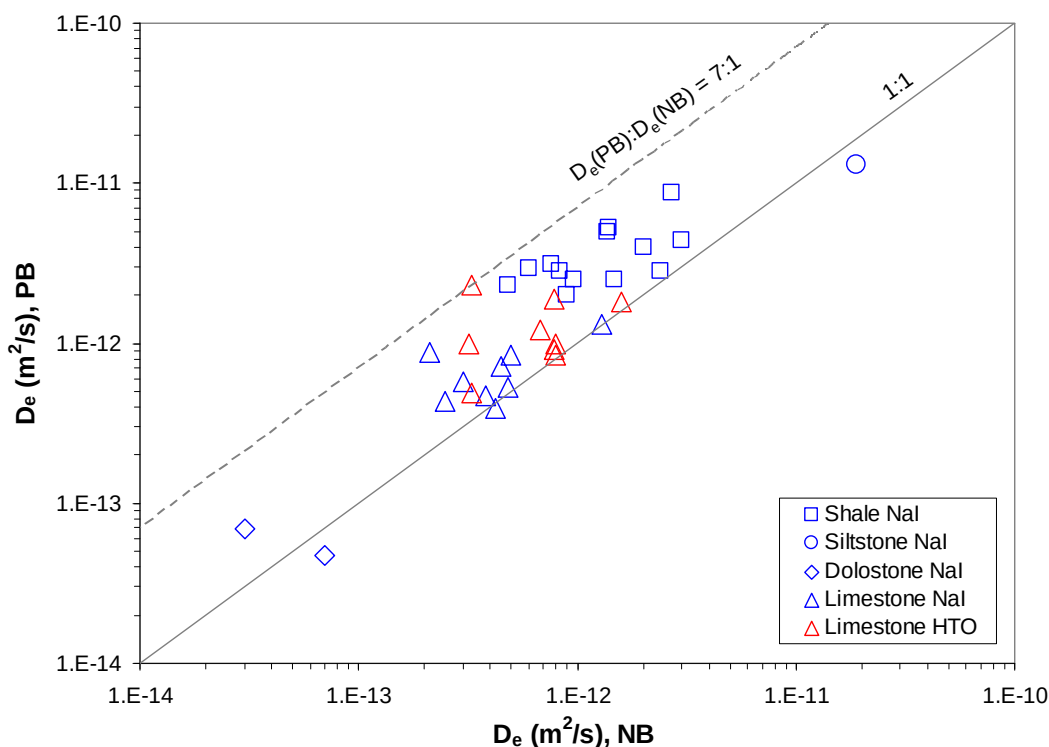


Figure 4.39 Relationship between D_e determined normal to bedding (NB) and parallel to bedding (PB) in DGR cores

4.4.2 Diffusion Porosity

The diffusion (tracer-accessible) porosity values determined from all diffusion testing on DGR core are presented in Figure 4.40 versus DGR-1/2 reference depth and formation, discriminated by testing method (X-ray radiography and through-diffusion [TD]), tracer type (NaI or HTO) and testing direction (normal and parallel to bedding). Liquid porosities determined by UNB for the same DGR samples subject to diffusion testing are also shown on Figure 4.40.

Figure 4.40 shows that liquid porosity values exceed the tracer-accessible porosities by a large margin in some of the Silurian shales (F Unit, C Unit, and Cabot Head) and the Ordovician shales but are similar in the many of the Silurian dolostones and the Ordovician limestones, which is likely the result of the very low water yields that obscure the differences in the measurements. Some of the large differences in the Silurian Formations are also likely due to overestimation of liquid porosity due to incorporation of gypsum-bound water in the liquid porosity estimate. As discussed in Section 4.4.1, the differences in tracer-accessible porosity from diffusion testing and liquid porosity from oven heating are primarily attributed to anion exclusion and hydrodynamic hindrance effects.

Figure 4.41 shows cross plots of tracer-accessible porosity determined by X-ray radiography versus liquid porosity (a – upper plot) and the same plot based on through-diffusion measurements (b – lower

plot). The through-diffusion data indicate that some of the low-porosity Ordovician limestones have higher tracer-accessible porosity than liquid porosity which is physically impossible. This illustrates the uncertainty associated with the porosity values obtained from through-diffusion experiments in the low porosity limestones and for this reason further discussion of tracer-accessible porosity is limited to the results from the radiography testing.

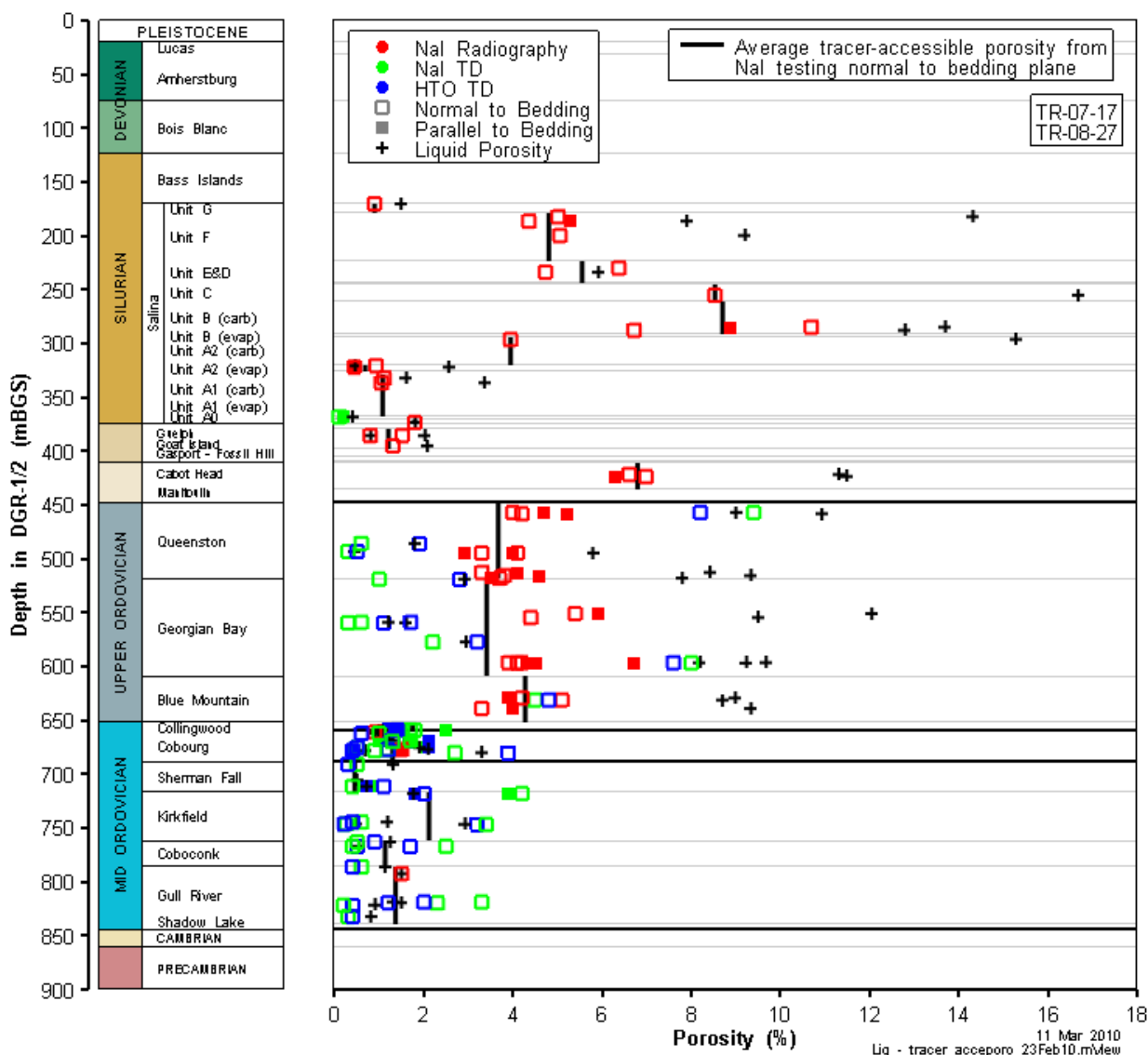


Figure 4.40 Profile of liquid porosity and tracer-accessible porosity determined from diffusion testing of DGR cores. Formation averages of tracer-accessible porosity from Nal testing normal to bedding planes are also shown

Figure 4.41a shows that values of iodide-accessible porosity for the Silurian and Ordovician shales are consistently lower than liquid porosity, on average being 50% of the liquid porosity values consistent with expectations based on anion exclusion theory. For the dolostone and limestone samples, with little to no clay and gypsum tracer-specific difference in porosity is not as evident. The ratio of iodide-accessible to liquid porosity for the limestones and dolostones ranges from 0.5 to 1.0. Outliers shown on Figure 4.41a include Silurian dolostone and limestone samples that likely contain gypsum and samples with low porosity (<1%) which approaches the detection limit for the radiography

method.

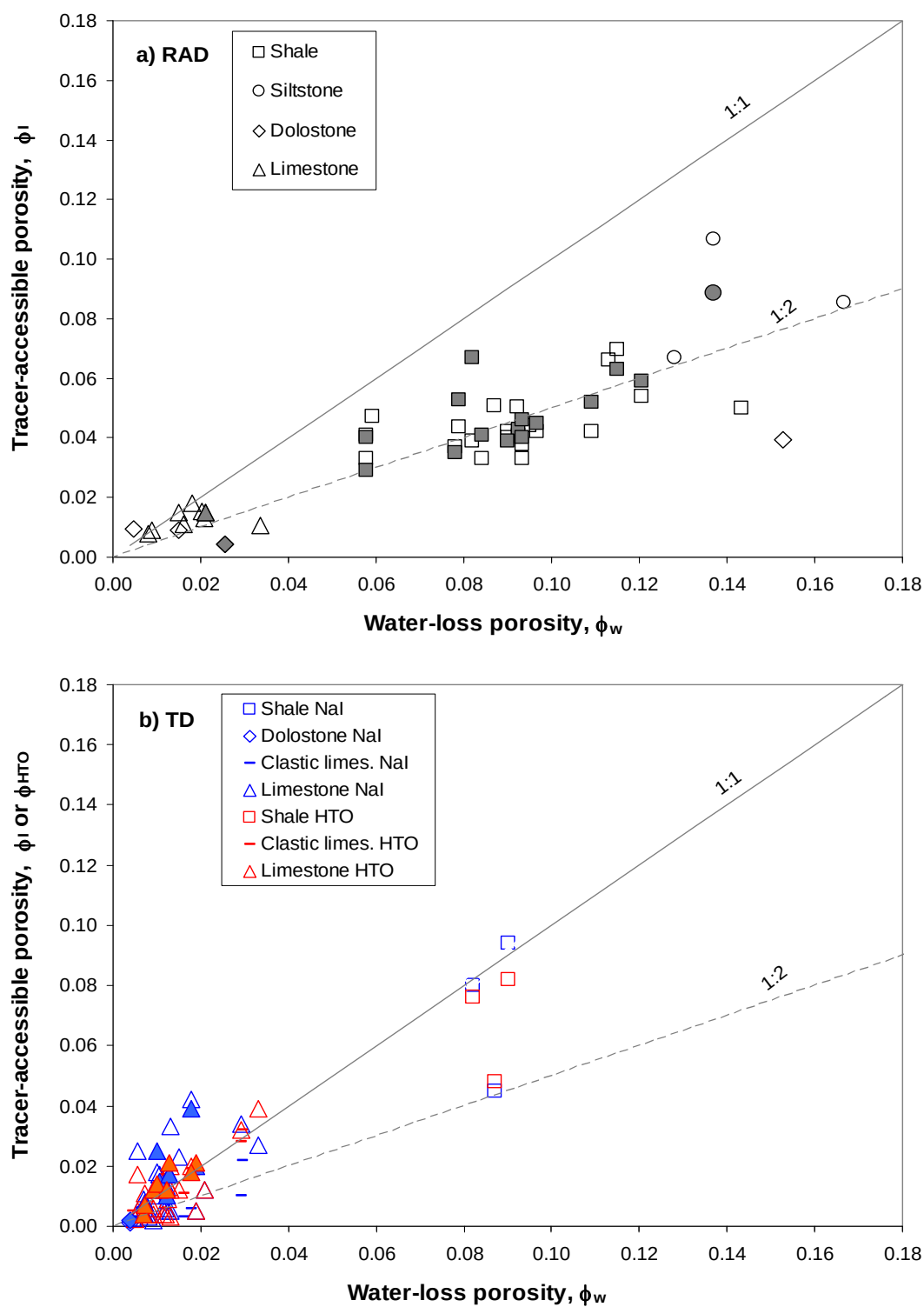


Figure 4.41 Relationship of tracer-accessible porosity to liquid (water-loss) porosity for DGR cores – a) radiography testing and b) through-diffusion testing. Open symbols are normal to bedding; filled symbols are parallel to bedding.

4.4.3 Comparison with International Data

In order to obtain an international perspective, the diffusion coefficient data from the DGR cores can be compared to diffusion coefficient data obtained from argillaceous rocks by researchers involved with radioactive waste programs in other countries. The Claytrac Project is sponsored by the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA) and it included an effort to compile the results of diffusion studies conducted at nine different European sites (Mazurek et al. 2009).

Comparison of the results from diffusion measurements of DGR cores with international data collected from these nine study sites shows that the DGR formations within the Michigan Basin exhibit relatively low D_e and porosity values (Figure 4.42). Figure 4.42 shows the comparison of DGR data and international data for water accessible porosity versus D_e for tritium tracers and anion-accessible porosity versus D_e for chloride and/or iodide tracers.

The international data was critically reviewed and compiled by Mazurek et al. (2009) and represents the most appropriate site specific data from Belgium, France, Switzerland and the United Kingdom available to date. For the UNB data, water-accessible porosity is represented by the measured water-loss porosity and the anion-accessible porosity is represented by the iodide-accessible porosity measured using either radiography or through-diffusion.

Included in Figure 4.42 are curves derived from Archie's Law (Boving and Grathwohl, 2001) which relate D_e to porosity by:

$$D_e = D_0 \phi^m \quad [4.7]$$

where D_0 is the value of the ionic diffusion coefficient in free water, m is an empirical exponent and ϕ is considered to be the total or physical porosity. Lerman (1979, p. 92) indicated the value of m should be about 2.0. Diffusion testing of DGR core by Paul Scherrer Institute (TR-07-22) indicates a m value of 2.3. Figure 4.42 shows that most of the DGR diffusion data is consistent with an m value of 2.0 +/- 0.5.

The diffusion data, both international and from this report, fall within the expected relationships for geologic materials, with the exception of two outliers in the international D_{e-HTO} data, both of which are from un-lithified clay strata, and one outlier in the $D_{e-anion}$ data, a porous limestone sample.

Note that there is very limited international data from limestone formations. The Ordovician limestones, in which the proposed DGR is expected to be hosted, and the Silurian dolostone/limestones represent the lowest measured D_e values by 1 to 2 orders of magnitude. The Ordovician shales of the Michigan Basin fall within and towards the lower end of the range of the international clay and shale D_e values. The four international data points with the highest D_e and porosity values in Figure 4.42 represent unconsolidated clay while the remainder of the data within that group represent shales and claystones. The Silurian shale values are higher than the Ordovician shales, but still fall within the mid-range of the international data, while the Silurian siltstones fall close to the high range of D_e values measured in the international lithified sequences. It is significant to note that in comparison with the data collected from DGR samples, the D_e values obtained from the European site characterization programs are generally higher by a factor of approximately 10.

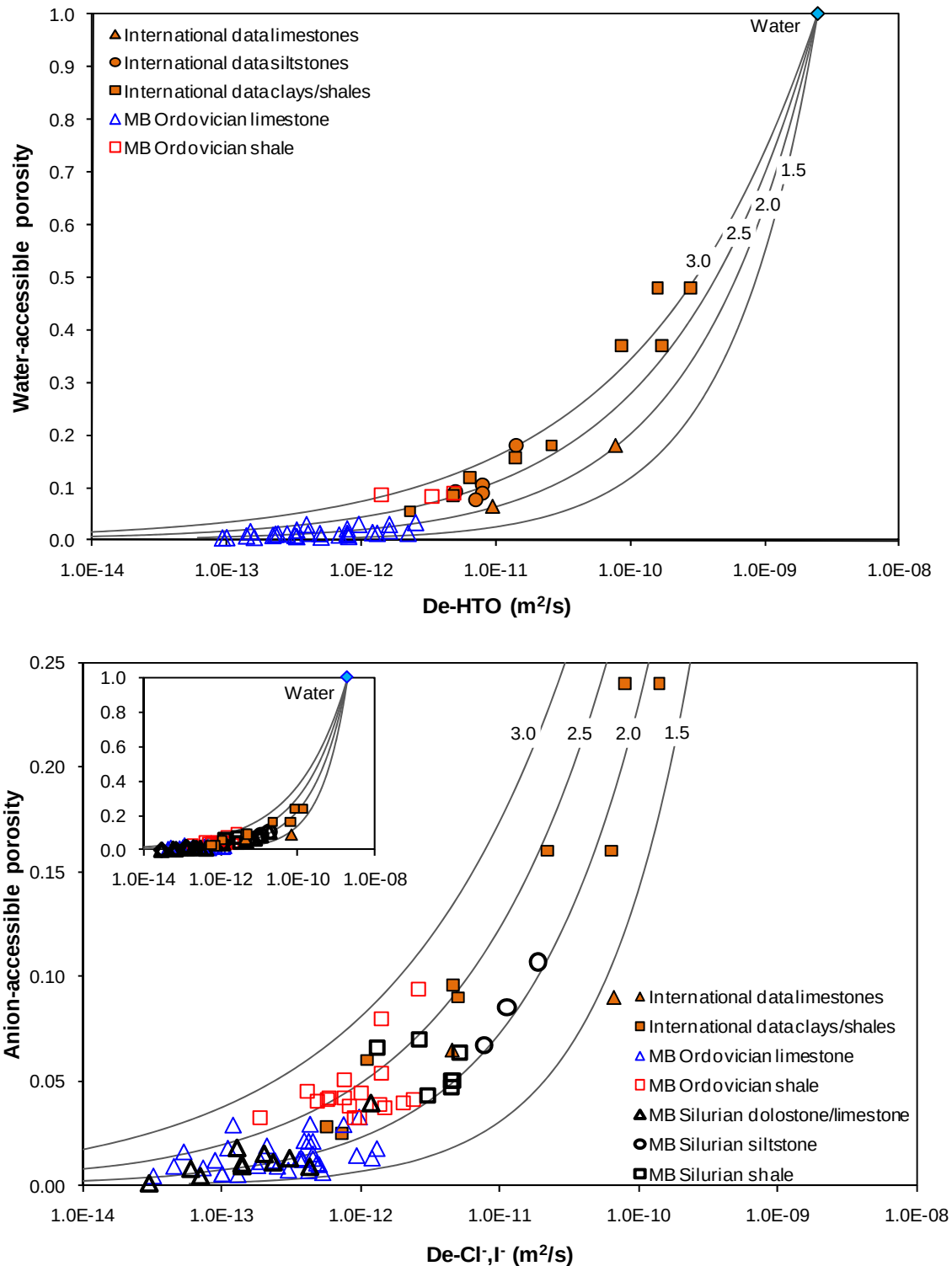


Figure 4.42 DGR diffusion data (Michigan Basin, MB) compared with international data from geologic repository studies. The data represent diffusion coefficients normal to bedding. Plots include D_0 for

tracers in free water. Upper plot – water accessible porosity vs D_e from tritium tracers; lower plot – anion-accessible porosity versus D_e from chloride and/or iodide tracers

4.5 Groundwater Characterization

The water in the fractures and pore spaces at the site is divided into two categories, groundwater and porewater. The term groundwater refers to free flowing groundwater and porewater refers to water from low permeability zones (Gimmi and Waber, 2004). Groundwater samples were collected following completion of shallow boreholes US-3, US-7 and US-8 with MP38 multi-level monitoring casing (TR-08-08, TR-08-30) and during drilling of deep DGR boreholes (TR-07-11, TR-08-18). Porewater was sampled by sub-sampling cores and removing the porewater from the rock in laboratories at the Universities of Ottawa (TR-07-21, TR-08-19), New Brunswick (TR-07-17, TR-08-27) and Bern (TR-08-06, TR-08-40).

4.5.1 Shallow Groundwater Chemistry – US Wells

The three boreholes, US-3, US-7 and US-8 (Figure 1.2), were instrumented with MP38 multi-level casings manufactured by Westbay Instruments Inc. (TR-07-20). These casings allow groundwater pressures to be monitored and groundwater samples to be obtained from packer-isolated intervals. The location of the boreholes was selected to enable three dimensional analysis of groundwater flow direction as well as to determine the spatial variability of shallow (<200 mBGS) bedrock groundwater chemistry.

US-3 and US-7 were completed in the upper 90 m of bedrock, which includes the Amherstburg Formation (dolostone) that overlies the Bois Blanc Formation (cherty dolostone). US-8 was completed into the top of the Salina F Unit (dolomitic shale), at a depth of approximately 200 mBGS as described in TR-7-19.

Groundwater samples were obtained in the spring and fall of 2008 and 2009 from all three boreholes. However, the only sampling event that all of the intervals were sampled was spring 2008. The subsequent sampling dates only obtained groundwater samples from approximately one third of the sample intervals in the boreholes. Therefore, the results presented in the figures are for the 2008 spring sampling event that occurred from the end of May to the beginning of June.

Sampling was performed following interval purging and was completed using the Westbay MOSDAX system, which involved lowering stainless steel sample containers to the desired port to retrieve groundwater samples. The sample water was returned to surface where field parameters (EC, pH, Eh, and DO) were measured in a closed flow cell. After the measurements were conducted, sample water was conveyed into bottles for major ion, tritium, as well as deuterium and ^{18}O in water analyses.

4.5.1.1 Field Parameters and Major Ions

Colourimetric and potentiometric measurement of DO showed concentrations were below 2 mg/L, except for one measurement of 6.3 mg/L. The measured DO concentrations were similar to the concentrations measured by Lee et al. (1995). These low oxygen levels indicate dissolved oxygen is limited in the shallow groundwater. However, iron staining in the Amherstburg and Bois Blanc Formations was likely due to ferric iron, or oxidized iron (Fe^{3+}), which is commonly associated with relatively oxidizing conditions. The presence of ferric iron suggests oxidizing conditions were present in isolated zones of the upper two hundred metres.

Ferrous iron, or reduced iron (Fe^{2+}), concentrations in US-series samples were between 0 and 1.3 mg/L. Where there was dissolved ferrous iron in the groundwater, the reduction-oxidation state may be classified as iron reducing. This classification is supported by the core logging, which noted pyrite in the DGR-1 core near the base of the Amherstburg Formation and inconsistently observed through

the Bois Blanc and Bass Islands Formation in DGR boreholes (TR-07-06, TR-08-13). Although pyrite was identified in the core, sulphide was not detected in the groundwater samples.

The observed low oxygen and ferrous iron concentrations in the groundwater, combined with the iron and pyrite evidence in the cores, suggests oxygen is almost absent in the shallow groundwater, and the redox conditions are in a transition from near-anaerobic to iron reducing. The Eh results in US-3 and US-7 support a low-oxygen, or iron reducing environment, which is also indicated by low dissolved oxygen readings (TR-08-08). The Eh results in US-8 suggest oxidizing conditions are present, which is supported by dissolved oxygen readings in water samples (TR-08-08).

The concentration of total dissolved solids (TDS) in solution may be used to classify the salinity of water into four categories (pg. 84 in Freeze and Cherry, 1979) as shown in Table 4.5.

Table 4.5 Classification of groundwater salinity

<i>Water Category</i>	<i>Total Dissolved Solids (mg/L)</i>
Fresh Water	0 – 1,000
Brackish Water	1,000 – 10,000
Saline Water	10,000 – 100,000
Brine Water	>100,000

The TDS of the groundwater samples from the US series wells indicated groundwater in the Lucas and Amherstburg Formations was fresh to brackish water, and groundwater from the Bois Blanc to the top of the Salina G Unit was brackish (up to 5,700 mg/L TDS). These TDS concentrations were relatively low compared to the deeper groundwater and porewater at the site (Sections 4.5 and 4.6).

Groundwater concentrations were converted to units of molarity (mol/L). Molar concentrations of the major ions were used to calculate molar ratios. In turn, the molar ratios were used to determine the dominant ions in the groundwater and classify groundwaters.

Groundwater in the overburden aquifer was classified as a Ca:Na-HCO₃ type water (Intera Engineering Ltd., 2007). The groundwater in the bedrock above 178 mBGS is described as a transition from Ca:Mg-HCO₃ water near the top of the bedrock to brackish Ca-SO₄ water near 178 mBGS. Sodium was the dominant cation at depths of about 150 mBGS. The concentration of each of the major ions is presented with depth for US-8 in Figure 4.43.

Only US-8 data is shown in these figures because it is the deepest of the three US-series boreholes, and to avoid presenting duplicate results. Concentrations are reported as molality (mmol/kg water) to remain consistent with the presentation of major ion concentration for the deeper groundwater and pore water (see Section 4.6). Generally, groundwater concentrations in US-3 were greater than US-7 and US-8, but the molar ratios were similar in each borehole and groundwater concentrations increased with depth in each borehole (TR-08-08, TR-08-30).

Groundwater alkalinity ranged from approximately 1 to 3 mmol/kgw as CaCO₃. The pH of the samples was commonly near 7.5, but was between 6.7 and 8.5. The distribution of carbonate species with pH indicates alkalinity was dominantly in the form of HCO₃ (pg. 51 in Drever, 1988); assuming all of the

alkalinity in the samples was derived from carbonate species, i.e. alkalinity from silicate, boron, and organic carbon compounds was negligible.

The major ion concentrations and pH were input to PHREEQC (Parkhurst and Appelo, 1999) to calculate the mineral saturation indices. Calcite was saturated in all of the groundwater samples except for one sample at depth of 93 mBGS in US-8. Calcite was also observed in core samples analyzed by XRD (TR-08-01, TR-08-22, TR-08-23). Gypsum and celestite were near saturation below 135 mBGS, consistent with the observation of the occasional presence of gypsum, anhydrite and celestite in the Bass Islands Formation by visual inspection and/or XRD analyses of the recovered core (Table 3.11).

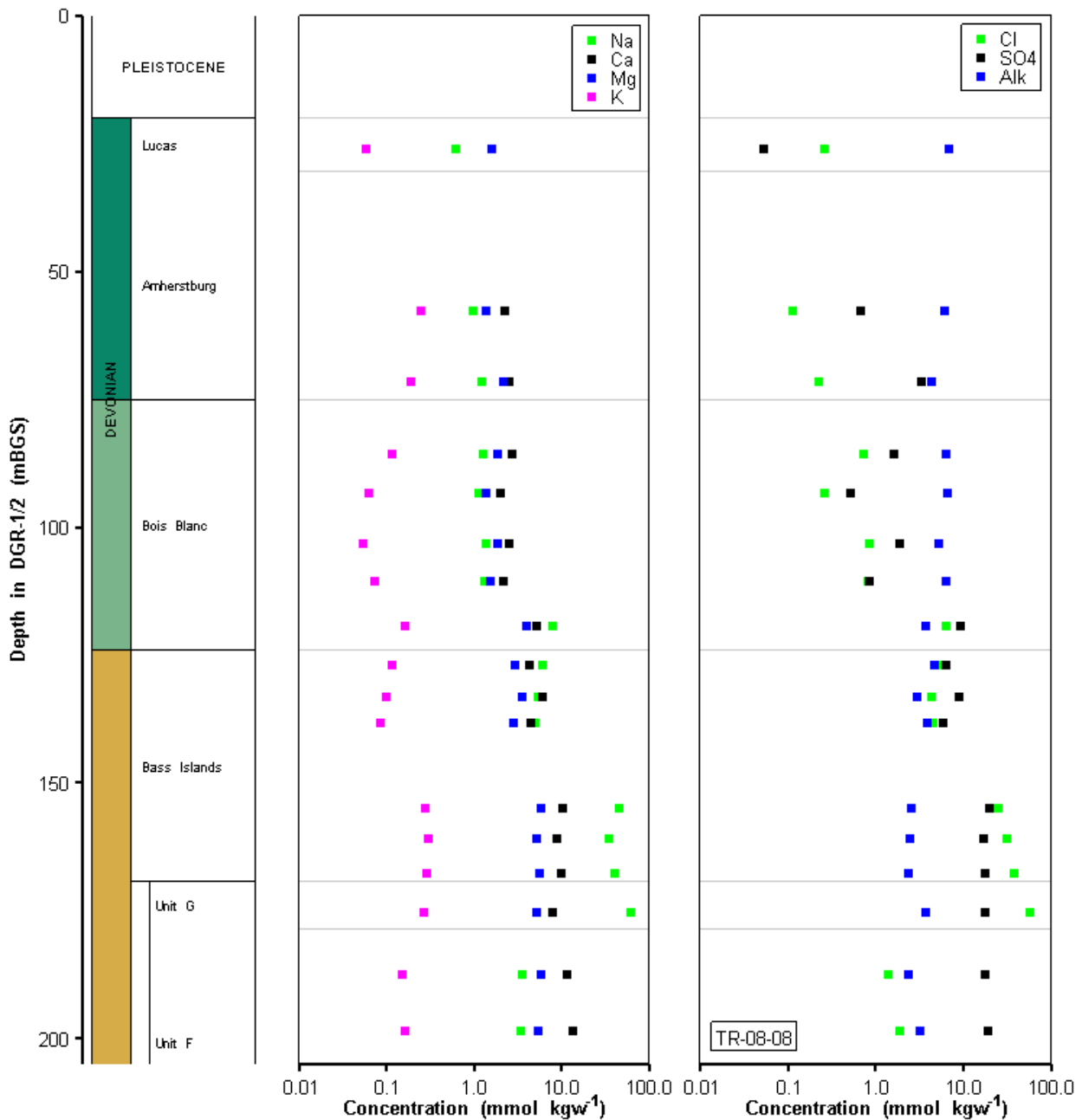


Figure 4.43 Major ion chemistry profile of shallow bedrock groundwater: left cations, right anions - US-8

4.5.1.2 Environmental Isotopes

The water isotope data, $\delta^{18}\text{O}$ and $\delta^2\text{H}$, for shallow bedrock groundwaters collected from US-3, US-7, US-8 and DGR-2, as well as drill waters and Westbay casing installation waters are plotted in Figure 4.44 and compared to the Global Meteoric Water Line (GMWL). Figure 4.44 shows the shallow bedrock groundwaters grouped by Middle-Lower Devonian dolostones (Lucas, Amherstburg and Bois Blanc Formations) and Upper Silurian dolostones (Bass Islands and Salina G Unit). For comparison purposes the groundwater samples collected from the Cambrian sandstone in DGR-2 are also shown.

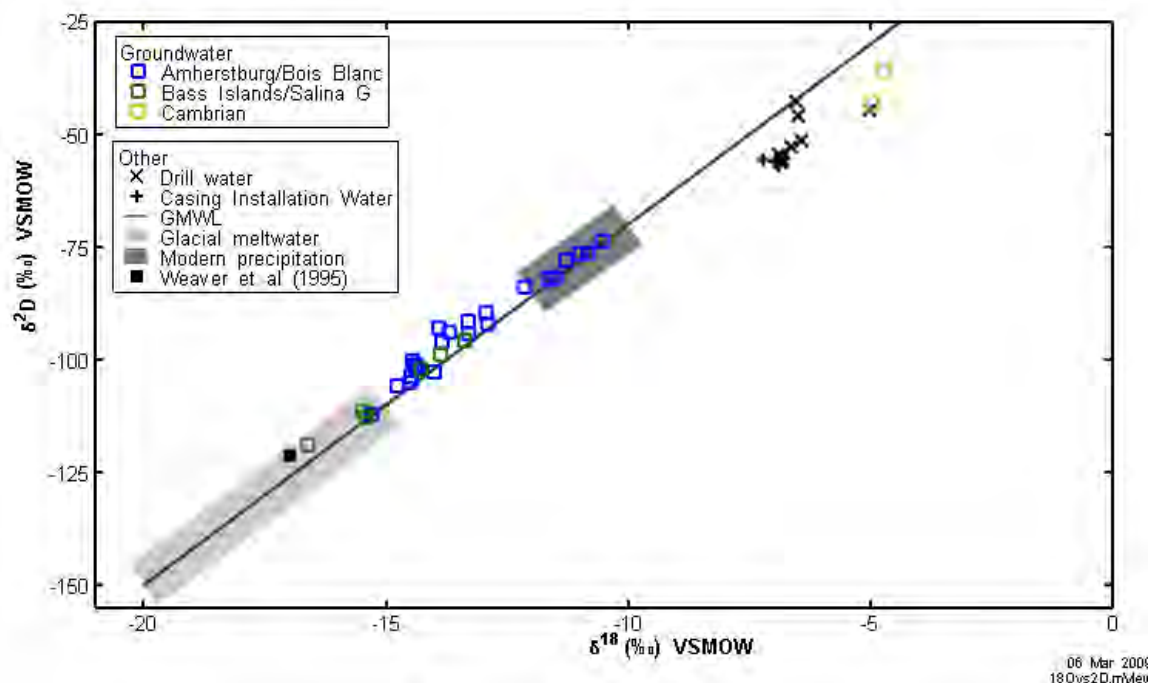


Figure 4.44 Cross plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ for drill waters and groundwater samples from US-3, US-7, US-8, DGR-1 and DGR-2. Also shown is the range of modern precipitation (Fritz et al., 1987) and the range (Aravena et al., 1995) and best estimate (Weaver et al., 1995) of glacial meltwater for southern Ontario

Figure 4.44 shows that the Lake Huron water used for drilling and installing MP38 and MP55 casings has a characteristic evaporative enrichment signature and that the Cambrian groundwater is significantly enriched but plotting close to the GMWL. Both of these waters plot remotely from the Devonian and Upper Silurian dolostone groundwaters suggesting that the shallow bedrock groundwaters are not influenced by drill water, casing installation water or Cambrian sandstone water.

Figure 4.44 shows that the deeper Upper Silurian dolostone groundwaters are depleted relative to the Middle – Lower Devonian dolostone groundwaters, suggestive of glacial meltwater presence in the deeper dolostone units (see Sections 4.5.2.3 and 4.6.6.1 for further discussion of this topic considering deeper opportunistic groundwater sample and porewater data, respectively).

4.5.1.3 Tritium

Groundwater from the US-series wells had < 35 tritium units (TU), but 14 out of 29 samples had tritium

counts below the detection limit for direct counting analysis (6 TU). Tritium in precipitation at the Bruce nuclear site is elevated and averaged 1700 TU during 2005-2006 (Bruce Power, 2007). The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ ratios indicate the groundwater is from atmospheric origin (Figure 4.44). The low tritium counts in the groundwater samples suggest the groundwater does not contain recent atmospheric water that is affected by activities at the Bruce nuclear site. The Bruce nuclear site has been active since the late 1960's, which indicates the groundwater collected from US-3, US-7 and US-8 pre-dates the operation of the Bruce nuclear facility, or the groundwater recharged in an area not affected by the tritium emitted from the Bruce nuclear site.

4.5.2 Deep Groundwater Chemistry - DGR Boreholes

Drilling of DGR-1, DGR-2, DGR-3 and DGR-4 provided opportunities to sample groundwater that flowed into the borehole at permeable intervals. These samples are referred to as opportunistic groundwater samples (OGW), although in DGR-3 and DGR-4 the sampled zones were targeted based on results of hydraulic testing of DGR-1 and DGR-2. This section characterizes the OGW samples from the four boreholes.

A total of seven OGW samples were obtained in the course of drilling DGR-1 and DGR-2, as part of Phase 1. Permeable horizons were observed in the bedrock in the top 150 mBGS (Devonian and Silurian) and below 840 mBGS (Cambrian sandstone). Westbay installations in the US-Series boreholes (TR-07-20) provide excellent coverage for the top 150 mBGS; therefore, the zones above 150 mBGS were not targeted for OGW sampling in Phase 2.

Two additional permeable horizons were also identified by hydraulic testing DGR-1 and DGR-2 that were not sampled in Phase 1. These horizons were 1) the top of Salina A1 Unit dolostone; and 2) the Guelph Formation dolostone. The permeable horizon in the Salina Units is referred to as the Salina Upper A1 Unit permeable zone. These two horizons as well as the Cambrian were sampled in both DGR-3 and DGR-4. There were a total of 13 OGW samples obtained in Phase 1 and Phase 2A. Opportunistic samples were collected and given identifiers as OGW-1 through to OGW-13 (Table 4.6).

Table 4.6 Opportunistic groundwater (OGW) samples used for geochemical interpretation

OGW #	OGW-3	OGW-6	OGW-7	OGW-8	OGW-9	OGW-10	OGW-11	OGW-12	OGW-13
Borehole & Sample No.	DGR1-111.22	DGR2-844.73	DGR2-852.70	DGR3-339.66	DGR3-389.99	DGR3-860.53	DGR4-327.08	DGR4-377.42	DGR4-848.50
Sampling Interval (mBGS)	107.81-114.63	841.96-847.50	843.70-860.70	337.80-341.51	386.61-393.36	851.89-869.17	324.83-329.33	373.66-381.18	840.01-856.98
Bedrock Formation	Bois Blanc	Cam-brian	Cam-brian	Salina Upper A1 Unit	Guelph	Cam-brian	Salina Upper A1 Unit	Guelph	Cam-brian

Once each permeable horizon was reached, drilling fluid was circulated in the hole and the drilling fluid was sampled when it returned to the surface. This sample is called the drill water return. The drill water return is a representative sample of the chemistry of the drilling fluid used to drill the sample horizon.

After the drill fluid was circulated, an inflatable packer was set above the top of the horizon to hydraulically isolate the permeable horizon. The drilling fluid and groundwater were then purged from

the isolated permeable horizon. Field analyses of Na-Fluorescein (NaFl) tracer concentration and EC of the purge water was used to estimate when the NaFl concentration was <3% of the drill water concentration and EC measurements were similar to the electrical conductivity of the previous swab samples. Once these criteria were met the permeable horizon was sampled.

In addition to NaFl concentrations, field measurements of pH, dissolved oxygen (DO), redox conditions (Eh) and electrical conductivity (EC) were also made in flow cells as the OGW samples were obtained (Figure 4.45, Table 4.7).



Figure 4.45 Serially-connected flow cells with electrodes connected to digital voltmeters

Table 4.7 Field geochemical measurements for OGW samples

<i>Parameter</i>	<i>OGW-3</i>	<i>OGW-6</i>	<i>OGW-7</i>	<i>OGW-8</i>	<i>OGW-9</i>	<i>OGW-10</i>	<i>OGW-11</i>	<i>OGW-12</i>	<i>OGW-13</i>
Depth Interval (mBGS)	107.81-114.63	841.96-847.50	843.70-860.70	337.80-341.51	386.61-393.36	851.89-869.17	324.83-329.33	373.66-381.18	840.01-856.98
% Drill Water Contamination	6%	<1%	<1%	3.1%	24%	0.2%	0.9%	0.3%	0%
pH	7.6	6.6	6.5	7.3	7.1	7.3	7.0	6.5	6.6
Eh (mV)	-48	165	166	-13	-165	-159	-98	-141.9	-123.4
DO (mg/L)	0.22	1.24	1.24	0.3	0.04	0.08	0.45	0.23	0
Ferrous or Total Iron (mg/L)	1	>10	>10	>10	>10	>10	1	>10	>10
Sulphide (mg/L)	0	0	0	5	<1	<1	4	<0	0
Electrical Conductance (mS/cm)	1.76	200.4	130	52	236	197	51	228	226

Although NaFI and EC were used as the field indicators for drill fluid contamination, tritium is considered to be the final parameter for calculating the percent drill fluid contamination. Tritium is assumed not to be present in the formation waters, therefore, any tritium detected in the OGW sample is due to drill water contamination. The final percent drill water contamination was calculated by dividing the OGW sample tritium result (which is listed in Table 4.8) by the tritium in the first return water sample, and converting the result to a percentage.

The Phase 1 OGW samples were OGW-1 through OGW-7. High pH measurements for OGW-1 and OGW-2 (9.8 and 8.8 pH units respectively) indicated the sample water was affected by the casing cementing, and the geochemical results were not fit for interpretation. OGW-4 contained approximately 18% drill water and OGW-5 was almost 100% drill water, therefore, OGW-4 and OGW-5 were not fit for interpretation. The tritium results confirm the field calculated drill water contamination results and indicate all of the six samples, except for OGW-9 (DGR-3, Guelph Formation sample), contained minimal drill water contamination.

The tritium calculations show OGW-9 had 24% drill water contamination, which is significantly higher than the 0.2% drill water contamination shown using the NaFI concentrations. Despite the significant drill water contamination in OGW-9, corrections for drill water contamination applied to the OGW-9 sample data produced comparable results to the OGW-12 results (DGR-4 Guelph Formation sample), except for Na and Cl. The OGW-9 results should be interpreted with caution.

4.5.2.1 Field Parameters, Major Ions and Trace Elements

Dissolved iron in the filtered samples (Table 4.7) suggests ferrous iron was present, since ferric iron has a low solubility at near neutral pH ($K = 10^{-38.3}$, pg. 253 Appelo and Postma, 1996). The presence of reduced iron is considered to be a more appropriate indicator of redox conditions considering values obtained from Eh electrodes reflect mixed potentials (Stumm & Morgan, 1981, pp. 490-493). Pyrite was detected, both visually and through lithogeochemical analyses (Section 3.6.2) at numerous depths throughout the Paleozoic formations. Pyrite provides mineralogical support for the ferrous iron observed in the OGW samples.

Electrical conductivity (EC) is a function of the total dissolved solids in water. The EC results from OGW-3 (1.8 mS/cm) suggest the water was relatively fresh, whereas groundwater from the other permeable horizons was relatively saline. The EC in the Guelph Formation samples (OGW-9 and OGW-12) was the highest measured at the site, which is consistent with the calculated total dissolved solid concentration in the Guelph Formation water samples (Table 4.8).

The Bois Blanc (OGW-3) sample water was characterized by Ca-SO₄ water, the Salina Upper A1 Unit (OGW-8 and OGW-11) sample water was a Na-Cl type water, the Guelph (OGW-9 and OGW-12) samples were a Na-Cl type water, and the Cambrian groundwater (OGW-6, OGW-7, OGW-10 and OGW-13) was Na:Ca-Cl water.

The pH values for the OGW samples were measured in the flow cells to be 7.6, 6.6 and 6.5 for OGW-3, OGW-6 and OGW-7, respectively. This range of pH values suggests the carbonate content of the groundwater samples were carbonic acid (H₂CO₃) and bicarbonate (HCO₃⁻). Assuming all of the alkalinity in the samples was derived from carbonate species, i.e. alkalinity from silicate, boron, and organic carbon compounds was negligible, the alkalinity in the groundwater samples was due to HCO₃⁻.

The major ion concentrations for the two Salina Upper A1 Unit OGW samples (OGW-8 and OGW-11) are within 8% of each other, except for calcium and chloride, which are approximately 13 and 16%

different, respectively. The water isotopes showed small differences between OGW-8 and OGW-11.

Table 4.8 Major ion and environmental isotope chemistry results for OGW samples

Borehole	DRG-1	DGR-2		DGR-3			DGR-4		
Parameter	OGW-3	OGW-6	OGW-7	OGW-8	OGW-9	OGW-10	OGW-11	OGW-12	OGW-13
Depth (mBGS)	107.81 -114.63	841.96- 847.50	843.70- 860.70	337.83- 341.51	386.6- 393.36	851.89- 869.17	324.83- 329.33	373.66- 381.18	840.01- 856.98
General Parameters									
Calculated TDS (mg/L)	2156	238000	247800	26760	365604	224518	30455	375468	227001
Fluid Density (kg/m ³)	1008	1160	1170	1019	1258	1150	1017	1210	1150
Environmental Isotopes									
Tritium (TU)	8.1	4.3	2.5	9.4	133.1	1.6	2.3	5.2	<1
δD (‰)	-92.9	-43.3	-35.8	-104.3	-48.1	-31.7	-102.7	-50.0	-35.2
δ ¹⁸ O (‰)	-13.91	-4.97	-4.71	-14.4	-2.3	-4.8	-14.5	-2.7	-5.2
Major Anions (mmol/kgw)									
Cl	0.58	4589	4790	388	7115	4453	462	7761	4584
Br	0.04	19.0	19.9	0.4	26.8	21.7	0.37	25.7	20.3
SO ₄	15.7	5.6	4.1	37.5	0.0	3.9	39.9	2.6	4.5
Alkalinity as CaCO ₃	2.2	0.35	0.36	3.6	1.8	0.90	4.8	0.71	0.82
Major Cations (mmol/kgw)									
Na	2.0	1817	1648	344	4482	1523	374	5168	1494
Ca	10.5	1080	1112	25.3	946	977	29.1	945	970
Mg	4.3	295	280	24.1	376	262	25.8	390	255
K	0.13	24.2	21.3	3.2	112	25.4	3.2	112	26.0
Sr	0.12	7.6	10.4	0.20	6.8	10.0	0.20	5.6	8.5

The concentrations differences between the Guelph Formation samples (OGW-9 and OGW-12) were less than 7% for the major ions, except for Na and Cl. The calculated groundwater sulphate concentration was zero for the OGW-9 sample, which is not likely true. The calculated sulphate concentration was likely affected by the drill water contamination (24%) and errors associated with analyzing the low sulphate concentration.

The difference between the δ¹⁸O results in the OGW-9 sample was near 0.5‰ and the δD values were offset by less than 2‰. The similarity between the major ions (except for sulphate) and the water

isotopes between OGW-9 and OGW-12 suggests the correction factor to account for the high drill water contamination in OGW-9 was appropriate.

Small differences were calculated between the Cambrian samples (OGW-10 and OGW-13) with the differences between the majority of solutes being below 4%. The $\delta^{18}\text{O}$ results were offset by 0.4‰ and the δD by 3.4‰. The only OGW samples that were obtained from similar stratigraphic zones between the four boreholes from Phase 1 and Phase 2A were the Cambrian samples. A comparison of OGW-6 (DGR-2, TR-07-11) and OGW-13 (DGR-4, TR-0818) shows between 0 and 18% difference between major ions. The chloride concentrations had a 0% difference, calcium was 10% greater in OGW-6 and sodium was 18% greater in OGW-6. Also, the difference in $\delta^{18}\text{O}$ was only 0.2‰ and the difference in δD was also small, 8.1‰.

The small differences between the isotopes values from each borehole suggests the correction factors applied to the OGW samples were appropriate. Assuming the correction factors were appropriate, the water isotopes are similar between OGW samples at equivalent horizons in each borehole.

The data shown in Table 4.8 was input into PHREEQC (Parkhurst and Appelo, 1999) to calculate log mineral saturation indexes (Table 4.9). Concentrations reported as "less than" (i.e., <) were entered as the less than value, e.g. sulphate concentration for OGW-6 was input as 500 mg/L. The effect of analytical errors on the calculated SI values was examined by increasing the groundwater concentrations and decreasing the concentrations by 20% for each of the OGW samples and recalculating the saturation indexes in PHREEQC. Changing all concentrations by 20% altered the charge balance for each of the samples, but the objective of this arbitrary concentration change was to examine the potential effect of 20% error in laboratory analyses on the interpretation of mineral saturation.

The effect on the SI values are shown in the brackets in Table 4.9, first the 20% increase, second the 20% decrease. The 20% changes were attempted for the Guelph OGW samples, however, the geochemical model was not able to converge both the 20% increase and the 20% decrease. Percent changes of 5, 10 and 15% were also attempted, but the geochemical model could not converge. This is assumed to be due to the very high solute concentrations in the Guelph OGW samples. Therefore, the effect of analytical error could not be examined on the Guelph samples.

Table 4.9 Calculated log saturation index results for OGW samples

OGW	pH	Calcite	Dolomite	Gypsum	Celestite	Halite
3	7.6	0.5 (0.6, 0.3)	0.8 (1.1, 0.6)	-0.2 (-0.1, -0.3)	0.0 (0.04, -0.16)	-7.7 (-7.5, -7.8)
6	6.6	0.4 (0.8, 0.1)	0.8 (1.6, 0.1)	0.4 (0.7, 0.1)	0.4 (0.8, 0.1)	-0.4 (0.1 -0.7)
7	6.5	0.4 (0.9, 0.1)	0.8 (1.7, 0.1)	0.3 (0.7, 0.03)	0.5 (0.9, 0.2)	-0.3 (0.1, -0.7)
8	7.3	0.4 (0.6,0.3)	1.1 (1.4, 0.8)	-0.1 (0.1, -0.1)	-0.1 (	-2.8 (-2.6, -3.0)
9	7.1	1.8 (-,-)	3.9 (-,-)	-1.8 (-,-)	-1.4 (-,-)	0.9 (-,-)
10	7.3	1.8 (1.9, 1.6)	3.5 (3.8, 3.1)	0.5 (0.2, -0.1)	0.4 (0.7, 0.1)	-0.6 (-0.2, -0.9)
11	7.0	0.3 (0.4, 0.1)	0.8 (1.1, 0.5)	-0.1 (0, -0.2)	-0.1 (0, -0.2)	-2.7 (-2.6, -2.9)
12	6.5	1.6 (-,-)	3.4 (-,-)	0.6 (-,-)	0.9 (-,-)	1.0 (-,-)
13	6.6	1.6 (1.9, 1.4)	3.2 (3.7, 2.6)	0.2 (0.6, 0.0)	0.4 (0.8, 0.1)	-0.5 (-0.1, -0.9)

The calculated SI values showed calcite and dolomite were saturated in all of the samples. Gypsum was saturated in the Guelph (OGW-9 and OGW-11) and Cambrian (OGW-6, OGW-7, OGW-10 and OGW-13) samples. XRD results showed calcite and dolomite were in almost all rock samples (TR-08-01, TR-0822, TR-08-23 and Table 3.4) Celestite was calculated to be at equilibrium or near

equilibrium (Table 4.9) in accordance with the mineralogical analyses showing celestite was occasionally observed throughout the Paleozoic bedrock sequence at the Bruce DGR site (Table 3.11). Halite was calculated to be supersaturated in the Guelph samples consistent with Table 3.11 and Figure 3.45 observations.

The relatively large range of concentrations ($\pm 20\%$) that was applied to the sample results to examine the potential impact of analytical error on geochemical interpretation showed large potential analytical errors had a small impact on the interpretation of the OGW results. For example, calcite and dolomite were consistently calculated to be supersaturated. The high supersaturation for the carbonate minerals may be due to erroneously high pH values due to CO_2 degassing while sampling. The saturation index calculations for gypsum and celestite were not possible for OGW-9 because the calculated sulphate concentration was zero (see above).

Some calculations, for example gypsum, showed calculated super-saturation using the OGW results, but showed slight under-saturation when the concentrations were lowered by 20%. Overall, the results indicate analytical error likely has a minimal impact on geochemical interpretation, however, consideration should be made for errors when interpreting geochemical results (analytical and model results) from saline environments.

The calculation results for the Guelph OGW samples both showed halite super-saturation.

4.5.2.2 Evaporated Sea Water and OGW Chemistries

The potential for deep groundwater at the Bruce nuclear site to develop from sea water evaporation was investigated using the DGR-4 OGW results (OGW-11, OGW-12 and OGW-13). The DGR-4 samples were selected because of the negligible amount of drill water contamination in the samples (Table 4.7 and TR-08-18). Selecting samples with minimal drill water contamination minimizes the amount of uncertainty in the interpretation of the results of this analysis due to drill water contamination corrections.

The investigation was carried out using the geochemical modeling software PHREEQC (Parkhurst and Appelo, 1999). The objective of this modeling exercise was to use sea water evaporation, and dilution for OGW-11, as a diagnostic tool to examine the likelihood that deep groundwater at the Bruce nuclear site could be from sea water evaporation/dilution.

This modeling exercise is not meant to be a comprehensive examination of all of the potential reactions that occurred over that long-time period. This exercise is meant to qualitatively determine if sea water evaporation/dilution alone can explain the present day deep groundwater chemistry. The long time period from the deposition of the rock formations at the Bruce nuclear site to the present leaves an opportunity for many geochemical reactions to occur. Time constraints were not used in this model, this simple model is only intended to see if sea water evaporation (or dilution) and mineral precipitation can create the observed OGW chemistries. Also, this analysis does not account for ion transport or groundwater mixing and temperature was assumed to be 25 °C.

The sea water composition for the OGW samples in the Silurian formations (OGW-11 and OGW-12) was obtained from Lowenstein and Timofeef (2008). The sea water composition for the Late Silurian was estimated from fluid inclusions extracted from Silurian sediments from the Michigan, Illinois, and Appalachian basins. Lowenstein et al (2001) and Petrychenko et al (2005) suggest the major ion ratios were generally similar in the Cambrian compared to the Ordovician and the Silurian, particularly for the purposes of this modeling exercise. Therefore, the Silurian seawater chemistry was also used to examine the role of sea water evaporation on the evolution of the groundwater in the Cambrian.

The Pitzer database was used for the geochemical modeling due to the high ionic strengths of the

water. The strategy for the modeling was to evaporate sea water in PHREEQC by removing water through the Reaction command until the calculated sea water chloride concentration was equal to the OGW chloride concentration. When the calculated gypsum saturation index reached the saturation index listed in Table 4.9, gypsum was set to the saturation index values listed in Table 4.9. Similarly, when the calculated halite saturation index reached the value listed in Table 4.9 for OGW-12, the halite saturation index was set to 1.0. Ion substitutions were not accounted for in this exercise, for example, strontium was not allowed to precipitate into gypsum.

The Salina Upper A1 Unit sample (OGW-11) had lower concentrations than sea water. Freshwater was added to the sea water until the chloride concentration of the calculated sea water was the same as OGW-11 (Table 4.10). The percent differences were calculated as the difference between the OGW concentration and the evaporated sea water concentration multiplied by 100 and divided by the OGW concentration. Positive percent difference values indicate the OGW concentration is greater than the calculated sea water concentration. For this analysis concentration differences within 100% difference are considered to be similar given the time-scale for sea water evaporation and the number of geochemical and transport processes that may have affected the current OGW concentration.

Table 4.10 Comparison of OGW samples to calculated evaporated sea water results (mol/kgw)

Water Source		Na	K	Ca	Mg	Cl	SO₄
Sea Water		420	11	33	45	565	10
Salina Upper A1	OGW-11	344	3.0	25.4	23.6	442.2	35.9
	Calculated	328	8	25	35	442	7.8
	% Diff.	5	-186	-1	-49	0	78
Guelph	OGW-12	5107	111	933	334	7671	2.6
	Calculated	1502	429	982	1907	7648	7.4
	% Diff.	71	-286	-5	-470	0	-185
Cambrian	OGW-13	1494	26.0	970	254	4584	4.5
	Calculated	3407	89	204	365	4583	17.5
	% Diff.	-128	-242	79	-43	0	-288

Sea water was diluted by approximately 30% to lower the calculated sea water chloride concentration to the OGW-11 chloride concentration. The major ion results of the diluted sea water were similar to the OGW-11 results. This similarity suggests seawater dilution likely played a significant role in the evolution of the groundwater chemistry in the Salina Upper A1 Unit permeable zone. However, this does not preclude the role of other geochemical processes (e.g. dolomitization) on the geochemical evolution of the groundwater.

The calculated sea water was concentrated 12 times in order to match the chloride concentrations in the Guelph permeable horizon (OGW-12). Gypsum and halite were allowed to precipitate from the calculated seawater. The calculated K, Mg, and SO₄ results were greater than 100% different from the OGW-12 results. These large differences suggest other geochemical processes play a significant role in the evolution of the groundwater geochemistry at the site. However, the high concentrations in the groundwater suggest evaporation or dissolution of soluble minerals played a significant role in the evolution of the groundwater chemistry.

Note the error associated with modeling the high concentrations in the Guelph Formation may be significant. Multiple ion interactions at high concentrations likely lead to moderate errors in the ion activities, which effect the precipitation of ions in the model. The calculated sea water was

concentrated 8.6 times in order to match the chloride concentration to the chloride concentration of the Cambrian groundwater (OGW-13). Only gypsum was allowed to precipitate. The large percent differences between the calculated seawater and the OGW-13 concentrations for all of the ions except for Ca suggest other processes besides seawater evaporation played a significant role in the evolution of the groundwater chemistry.

4.5.2.3 Environmental Isotopes

The $\delta^{18}\text{O}$ and δD data for the opportunistic groundwater samples and the US well samples are shown on a cross plot of $\delta^{18}\text{O}$ vs δD (see Figure 4.46). Also shown for comparison purposes are the selected data for US and DGR well drill water obtained from Lake Huron that show a conventional evaporation signature.

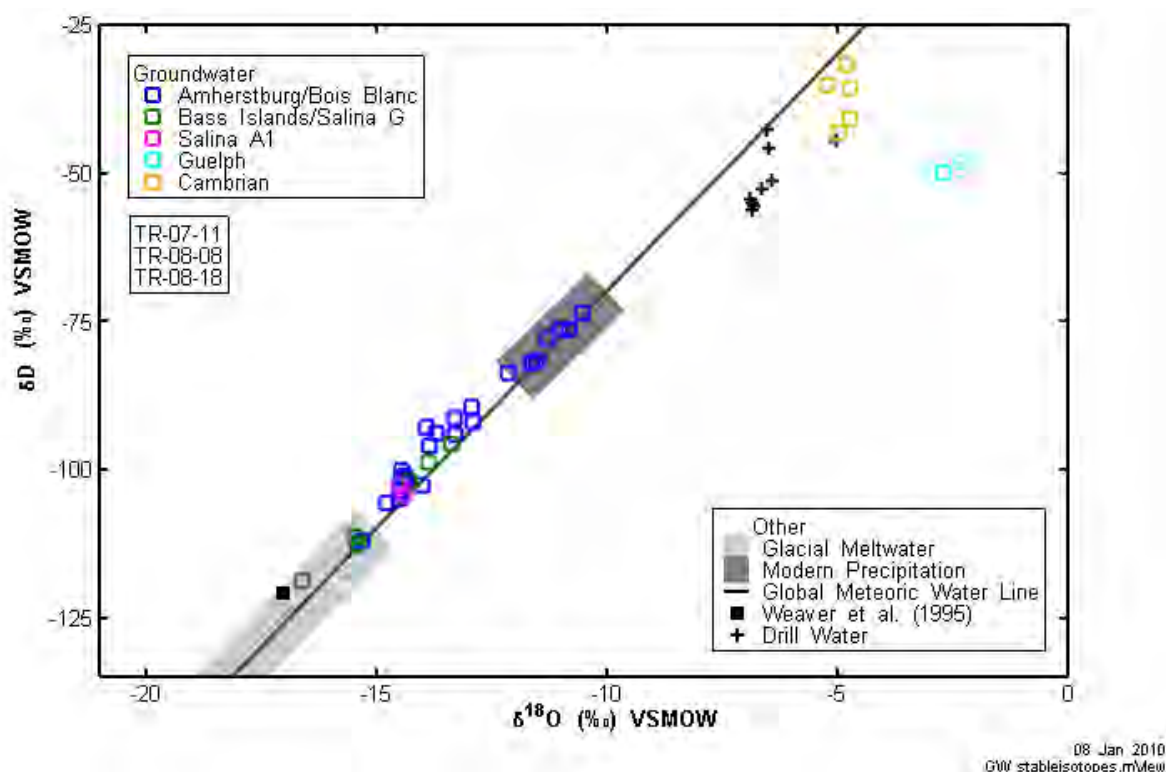


Figure 4.46 Cross plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ for groundwater from US-series wells and all OGW samples from DGR boreholes

The majority of the groundwater data plot very closely to a regional meteoric water line (Fritz et al., 1987) derived from precipitation data in the 1980s. The OGW samples from the permeable Guelph horizon show the greatest influence from evaporation, which is consistent with the high major ion concentrations discussed above.

The spread of the environmental isotopes data from the Phase 1 and 2A investigations exceeds the range of modern waters shown in Figure 4.45. The groundwater values in the Devonian and Silurian aquifers plot between modern precipitation (mean ~ -12 ‰ for $\delta^{18}\text{O}$) and glacial meltwater (i.e. -20 to -15 ‰ for $\delta^{18}\text{O}$; Aravena et al., 1995; Hobbs et al., 2008) indicating that these groundwaters are mixtures of glacial meltwater and modern precipitation. Further, the range of values for the Devonian Amherstburg and Bois Blanc Formation groundwaters from values close to the mean of modern precipitation to more depleted values indicates varying degrees of mixing between modern groundwaters and glacial meltwater.

A strictly modern or sub-modern groundwater would have a well-mixed mean-annual isotope composition rather than the observed range of values. The depleted values attributed here to glacial recharge are within the range suggested by Aravena et al. (1995) for southern Ontario, and are more depleted than the groundwaters observed in the Alliston aquifer of Southern Ontario, to which Aravena et al. attribute a glacial meltwater component.

On their own the OGW provide data for adequate interpretation of the flowing groundwater at each depth. However, more in depth interpretation of the groundwater chemistry at the site is augmented by examining the OGW and porewater chemistry together, which is performed in the following Section 4.6.

4.6 Porewater Characterization

4.6.1 Overview

Porewater characterization studies were undertaken by the University of Ottawa (TR-07-21, TR-08-19, TR-08-37, TR-08-38), the University of Bern (TR-08-06, TR-08-40) and the University of New Brunswick (TR-07-17, TR-08-27). The presentation and discussion of porewater characterization given in this section, unless otherwise noted, focuses on University of Ottawa and University of New Brunswick data, as these data are the most complete and available set of data at the time of preparation of this DGSM report.

Porewaters were extracted from crushed DGR cores at the University of Ottawa by high-temperature vacuum distillation (150°C) for water isotopes. This was followed by deionized water leaching of crushed (2-4 mm grain size) rock samples to recover dissolvable salts (TR-07-21, DGR-1 and DGR-2; TR-08-19, DGR-3 and DGR-4). The mass of salts in the leachate solutions were divided by the mass of water collected during the heating. The resulting values (mass per kg H₂O) are taken to be the porewater concentrations. The porewater data from the Universities of New Brunswick and Bern were determined from crush and deionized water leach experiments with four solid:liquid weight ratios of 0.1, 0.25, 0.5 and 1.0.

Some of the measured geochemical parameters, such as Cl and Br, and the stable isotopes of water ($\delta^{18}\text{O}$ and δD), are 'natural tracers' that may be used to constrain the hydrogeological and geochemical properties of the geological materials from which they are extracted (e.g., Desaulniers et al., 1981; Remenda et al., 1996; Hendry et al., 2000 and 2005; Boisson et al., 2001, Rübel et al., 2002, Gimmi et al, 2007). When plotted versus depth, the solutes, gases and isotopes provide information concerning paleo-hydrological and geochemical conditions within the rock column and allow inferences to be made concerning the validity of the basic tenets of the Geoscientific Site Characterization Plan (Intera Engineering 2006, 2008).

Estimations of major ion concentrations in the porewater using leaching techniques are susceptible to artefacts from the dissolution of naturally occurring soluble salts such as halite, anhydrite, gypsum and possibly carbonate minerals. Measured cation exchange capacities were between 2 and 40 meq/kg rock (TR-08-06), which is relatively low compared to the porewater concentrations (see Section 4.6.5). Cation exchange may effect relatively low porewater concentrations, <500 meq/kg.

The first task was to correct the major ion analyses for these contributions from evaporite mineral dissolution during the crush and leach procedures. This is addressed in section 4.6.2 by conditioning the raw porewater extraction data using the USGS computer programme PHREEQC (Parkhurst and Appelo, 1999) to correct for mineral dissolution.

Porewater chloride is of particular concern because it is generally very mobile, although can be precipitated as halite (NaCl) salt. The presence of halite within a formation or group of formations is a strong indicator that there has been no flow of fresh water through that rock sequence since the halite was precipitated. In their Regional Hydrogeochemical Synthesis, Hobbs et al. (2008) concluded that the Ordovician geochemistry indicated that the porewaters had evolved from seawater by evaporation leading to halite saturation; therefore it appears that these porewaters have remained halite saturated over geologic time. Halite is commonly observed in the Ordovician shales and several other formations in the DGR Paleozoic sequence by both SEM/EDS and XRD methods of identification (see section 3.5), therefore the second task, described in section 4.6.3, was to resolve why the extracted pore waters were undersaturated with respect to halite when halite was present in rock cores (see Table 3.4).

The body of hydrogeochemical data follows presenting the results from the Universities of Ottawa and New Brunswick of their analysis of environmental isotopes, major ions and gases:

- Section 4.6.5: the major-ion analytes from high-temperature vacuum distillation and crush leach testing;
- Section 4.6.6: the environmental isotopes of water ($\delta^{18}\text{O}$ and δD) and of strontium;
- Section 4.6.7: the major dissolved gases – i.e., CO_2 and CH_4 ;
- Section 4.6.8: the estimation of porewater pH and the redox potential; and
- Section 4.6.9: the distribution of helium gas – He(g) – and helium isotopes.

4.6.2 Correction of Major Ion Concentrations for Potential Mineral Dissolution During Analyses

The porewater extraction results for the major ions were interpreted using PHREEQC to calculate mineral saturation indexes for the principle evaporite minerals, i.e., gypsum, anhydrite, celestite and halite. Mineral saturation calculations showed that all of the porewater samples are saturated with respect to anhydrite and celestite (SrSO_4). Super saturation was likely a result of dissolution of sulphate minerals during the crush and leach extraction (TR-07-21 and TR-08-19). Also, the pore water was assumed to be saturated with respect to calcite due to the high carbonate content of the bedrock at the Bruce nuclear site.

To correct for mineral dissolution during pore-water extraction, the pore-water concentrations from each sample were adjusted to equilibrium with anhydrite and calcite using the Equilibrium Phases command within PHREEQC. The anhydrite and calcite equilibrium correction decreased the calcium and sulphate concentrations from the initial pore water results. Forcing calcite to equilibrium requires estimating alkalinity concentrations, which were calculated by satisfying the pore-water charge balance and which are not considered to be representative of the true pore-water alkalinities.

Celestite was not forced to equilibrium due to the relatively low concentrations of strontium compared to other ions. Small analytical errors may account for the positive celestite saturation indices. Further discussion of pore-water concentrations in subsequent sections refers to these anhydrite/calcite “corrected pore-water concentrations”.

4.6.3 Apparent Porewater Halite Undersaturation in Halite-Containing Shales

The observation of anhydrite and celestite in rock core samples was also apparent in the calculated

saturation indexes for pore water concentrations. Halite was also observed in small amounts in rock core samples in the Ordovician shales in DGR boreholes by SEM/EDS and XRD analytical techniques (Section 3.6.1.2, Table 3.4). However, the calculated porewater halite saturation indices in the Ordovician shales were below saturation.

A porewater extraction experiment was designed to examine the apparent halite undersaturation in the Ordovician shale porewaters. Rock core samples from adjacent carbonate (limestone) interbed and shale beds within the Georgian Bay Formation in DGR-4 were analyzed to examine the differences between water isotope results in the carbonate and shale beds in the Ordovician shales that were noted when interpreting data from Phase 1 site characterization work (TR-08-37). Porewater Na and Cl concentrations were also analyzed as part of this experiment which is described in TR-08-37.

The adjacent rock core samples consisted of three samples from the shale beds from DGR-4-550.32, DGR-4-550.75 and DGR-4-550.95, as well as one sample from a limestone interbed at DGR-4-550.54. The results (blue and orange circles in Figure 4.47) show the porewater concentrations in the shale samples were less than the concentrations in the carbonate interbed. The small difference in depth between these samples (<1 m depth) suggests diffusion should have created similar concentrations over time.

The Na and Cl concentrations were interpreted using PHREEQC with the Pitzer database to determine if the porewaters were saturated with respect to halite. The pore water in the carbonate bed was saturated with respect to halite while the shale pore waters were below halite saturation. The PHREEQC calculations showed an increase in the Na and Cl concentrations in the shale samples by 15% (green and red data points in Figure 4.47) resulted in halite-saturated porewater in the shales and a more uniform chloride concentration. This 15% difference raises the question, why are pore water Na and Cl concentration results from the Ordovician shales 15% lower than halite saturation compared to adjacent carbonate bed/unit Na and Cl concentrations?

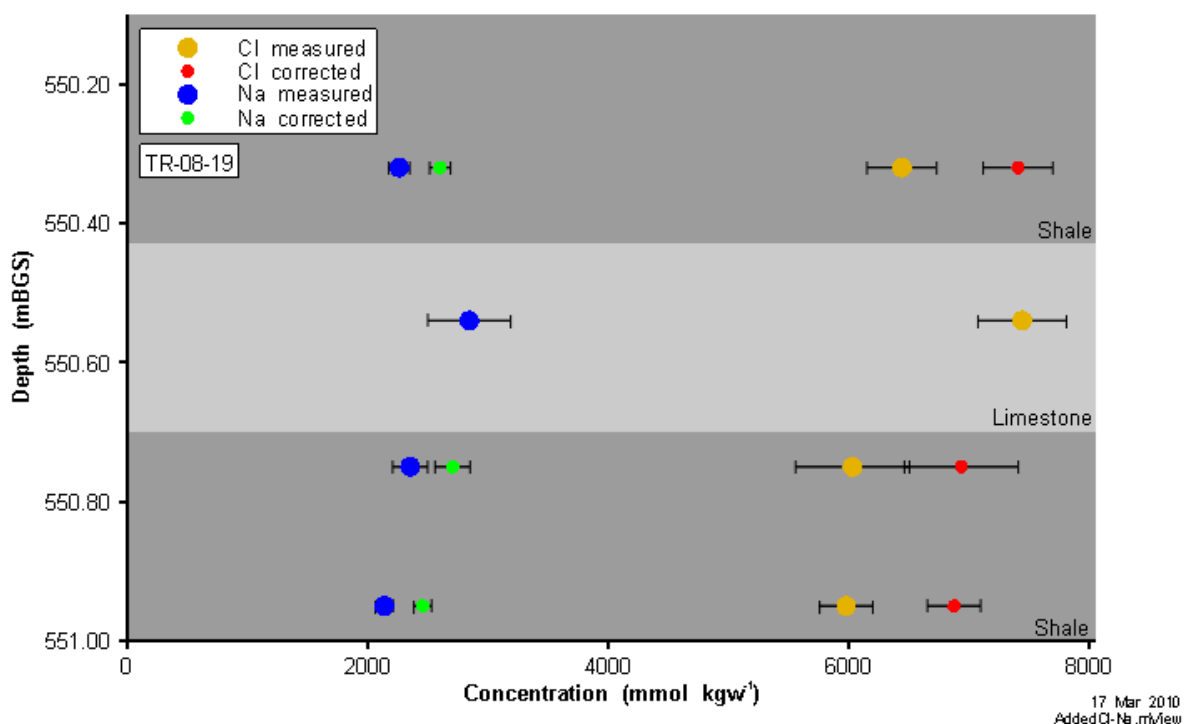


Figure 4.47 Chloride and sodium concentrations in adjacent shale and limestone beds in the Georgian Bay Formation in DGR-4

Visual inspection of the saturation indexes from the anhydrite/calcite correction for all porewater samples from DGR-2, DGR-3 and DGR-4 show all porewater results are undersaturated with respect to halite, except for DGR3-539.46 and the one carbonate bed sample from the Georgian Bay Formation that was discussed above (DGR-4-550.54). However, halite was observed in core samples from the Ordovician shales in DGR boreholes by SEM/EDS and XRD analytical techniques (Section 3.6.1.2, Table 3.4). An example of halite saturation in the Blue Mountain formation is shown in Figure 4.48. Assuming the halite is in contact with the porewater, the porewater sodium and chloride concentrations are below what is expected for porewater in equilibrium with halite for the Ordovician shales.

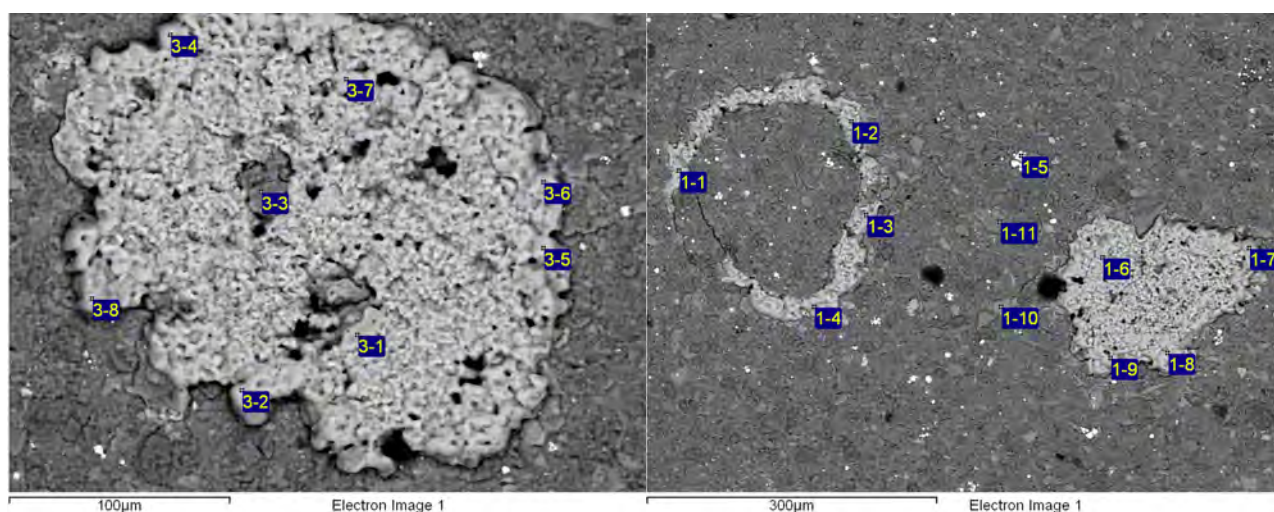


Figure 4.48 SEM photomicrograph of DGR3-628.54 core – Blue Mountain Formation showing halite presence as rimming of minerals and interstitial to the matrix. The light grey areas are halite and black areas are pores. All spot analyses, excepting 1-6, 1-11 and 3.3 indicate halite

Porewater concentrations were increased in PHREEQC using the Reaction command by which water was “evaporated” from each porewater result from the shales until halite reached saturation (log saturation index for halite = 0.0 ± 0.01). This process increased all of the porewater concentrations while keeping anhydrite and calcite at saturation indexes of 0.0.

The difference between the “evaporated” porewater concentrations and the original concentrations is an indication of the amount of Na and Cl that would have to be added to the porewater (on a molal basis) in order to reach halite saturation (Figure 4.49). Also shown in Figure 4.49 is the percent increase in Na and Cl concentrations, which provides a relative comparison of the solute addition.

The results show Ordovician shale porewaters in DGR-2 and DGR-3 required between an additional 8 to 38%, with an average of 17%, increase in Na and Cl to reach halite saturation. The DGR-4 samples required between 23 and 48% more Na and Cl (average of 33%) to reach halite saturation. The average increase in Na+Cl concentration from all of the boreholes was 20%, which is similar to the 15% concentration increase required to maintain a uniform porewater concentration between shales and a carbonate bed in the Georgian Bay Formation as shown above.

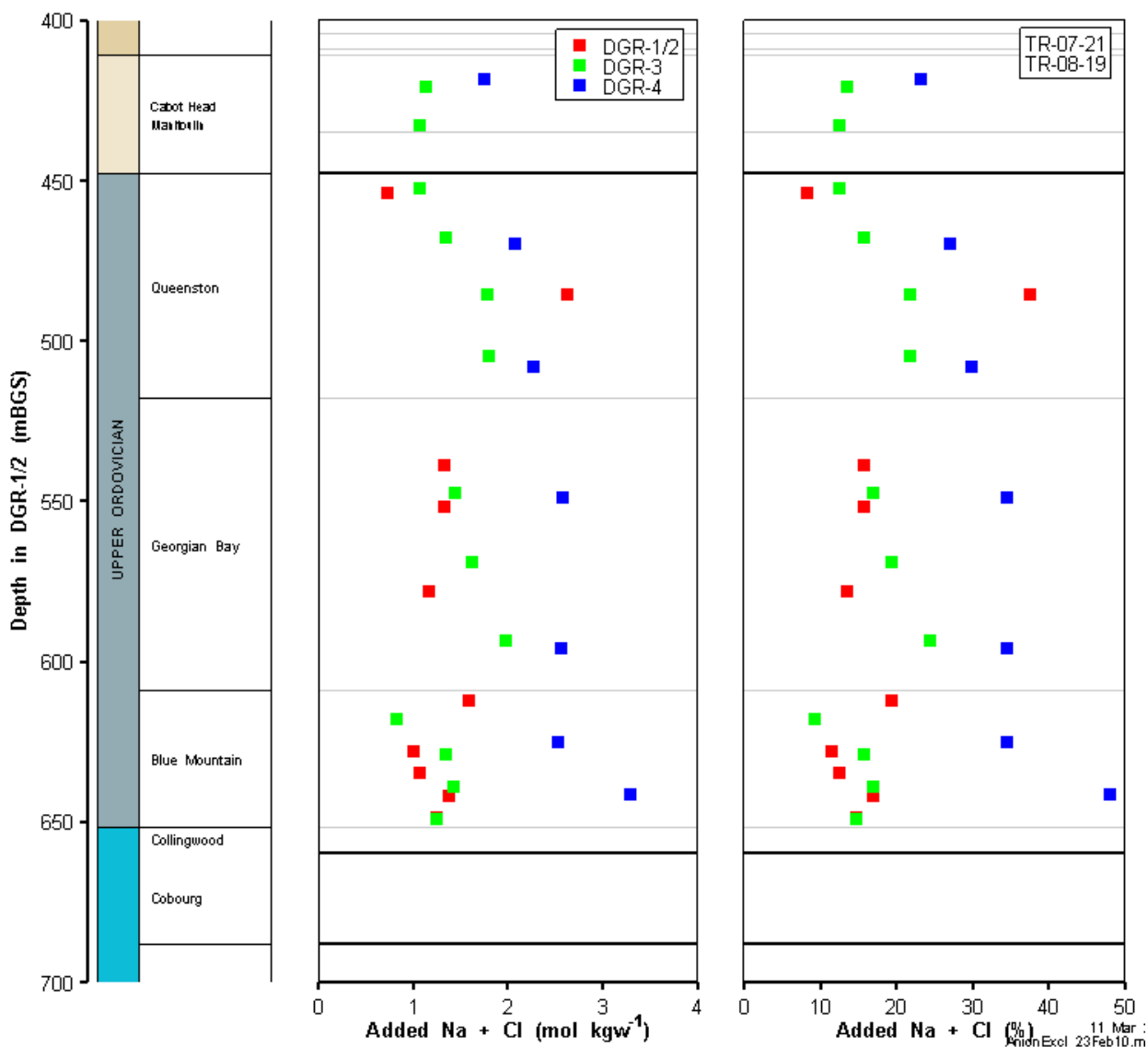


Figure 4.49 Na and Cl added to porewater to obtain halite saturation

Lower pore water concentrations may be caused by underestimating the amount of solute in the rock core samples, over estimating the amount of water in the samples, or both. Each of the laboratories examined solute leaching in the course of completing the crush and leach process to determine pore water concentrations (TR-07-21, TR-08-06, TR-08-19). The amount of water used in the leach processes was significantly more than the amount of pore water in each rock core sample. Separate water/rock ratios were used to examine the potential for mineral dissolution and incomplete solute extraction. Additionally, solute leaching conducted by the University of Ottawa for carried out over 60-days, suggesting there was sufficient time to leach solute from the rock core samples.

The leach process likely dissolves some soluble and sparingly soluble minerals in the rock core samples, potentially leading to an overestimation of solute concentrations. For example, mineral saturation index calculations and the rock core petrography indicate high Ca, Sr, and SO₄ concentrations are due to dissolution of sulphate minerals. Even trace amounts of halite observed in the rock core samples (Table 3.4) should slightly overestimate the amount of Na and Cl in the

porewater. Therefore, low porewater concentrations are not likely the result of underestimating the porewater solute mass in the rock core samples.

Lower pore water concentrations may also be due to extracting water from the rock that is not in contact with the pore water. Water in the pores is assumed to be free water or bound water. Free water is able to move between pores under a pressure or chemical gradient. Bound water includes water strongly adsorbed to negatively charged clay mineral surfaces and the hydration water associated with cations adsorbed to the clay surface. The surfaces of clay minerals commonly have a negative charge. Water is "bound" to the negative charge through hydrogen bonding. Water may also be bound to the edges of clay minerals where charge imbalances may exist. The volume of clay-bound water is proportional to the surface area of the clay. Clay bound water is immovable by mechanical means although it can be removed by evaporation (Dacy and Martin, 2006).

The clays in the Ordovician shales are primarily illites and chlorites (TR07-12, TR-08-20, TR-08-21). Swelling clays with interlayers of water, e.g. smectites, were not identified in significant amount. Therefore, the water associated with clays is not interlayer water, but is clay-bound water. The bound water does not associate with the free water in the pore. However, heating the rock core samples for determining water content in the rock core may release the bound water, which overestimates that amount of free water in the pores. Dacy and Martin (2006) showed clay bound water was approximately 20% of the total porosity in shaley sandstones with illite and chlorite clays. These results suggest underestimating porewater concentrations by 15-20% may be a result of releasing clay bound water during the heating phase of the porewater analysis.

The amount of bound water required to underestimate the pore water concentrations by 15-20% was examined through the following calculation. The average dry bulk density for the Ordovician shales is $2,590 \text{ kg/m}^3$ (Table 4.1). Figures 3.5 and 3.6 show illites and chlorites account for approximately 50% of the shale mass, which equates to 1300 kg of clay in 1 m^3 of shale.

The average liquid porosity for the Ordovician shales was approximately 7% (Table 4.3), or 70 L of water in 1 m^3 of shale. If water adsorbed to the clays accounts for a 15% decrease in the shales then there is approximately 10 L of water ($70 \text{ L} \times 15\%$) adsorbed to 1300 kg of illite and chlorite in the Ordovician shales. If the water density is 1000 kg/m^3 then the adsorbed water has a mass of 10 kg, and 10 kg of adsorbed water is 0.8% of the clay mass by weight. By weight percentage, only a small amount of adsorbed water is required to dilute the porewater concentrations by 15% in 1 m^3 of rock because of the high clay content and low porosity of the shales.

Therefore, the underestimated solute concentrations in the Ordovician shales are assumed to be due to the release of clay-bound water during the heating to estimate the water content of rock core samples. Clay bound water does not have a significant effect on the porewater concentrations for the carbonate hard beds in the Ordovician shales or the Ordovician limestone units because the carbonate rocks have a significantly lower clay content (<20%) compared to the Ordovician shales (near 50%)

4.6.4 Anion Exclusion

Anion exclusion is a process where anion transport through pores is inhibited or prevented due to the negative charge of a mineral surface across small pore throats. Anions are unable to overcome the negative charge repulsion and cannot move through the small pore throats. The high clay content and relatively small porosities of the Ordovician shales provide a suitable environment for solute transport to be affected by anion exclusion.

Through-diffusion analyses for determination of iodide accessible pore space and effective diffusion coefficients showed iodide could only access approximately half of the pore spaces that were accessible to tritium in the Ordovician shales (TR-07-17). This disparity of iodide accessibility compared to water accessibility was considered to be due to anion exclusion (Cave et al., 2009).

The pore-throat distributions measured in DGR-3 and DGR-4 Ordovician shale core samples by mercury porosimetry are shown in Figure 4.50. The small pore spaces may be an intrinsic property of the shale, and may be due to mineral precipitation (halite, gypsum or other minerals) in the pores.

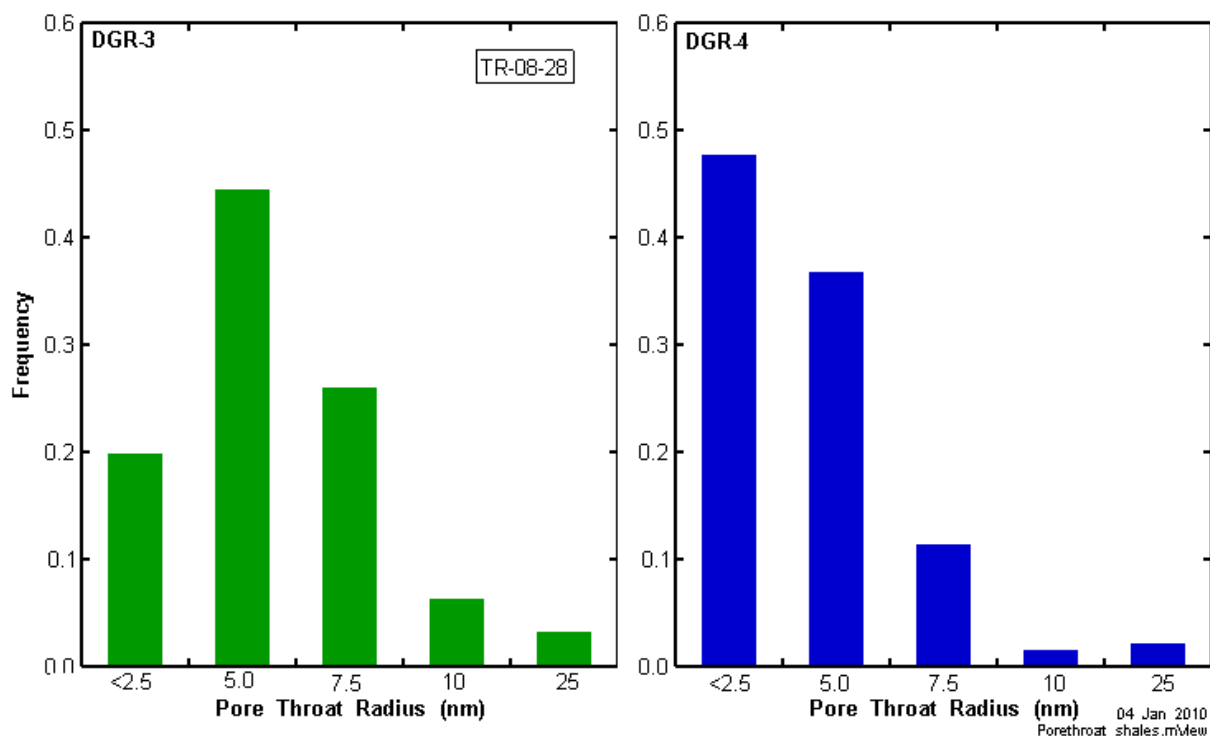


Figure 4.50 Pore throat radii for mercury injection porosimetry testing of DGR-3 and DGR-4 shales

Pusch (2008) categorized discontinuities such as fractures, joints and smaller openings in crystalline rocks including both granites and clay shales into seven classes. The smallest class of openings is called crystalline pore spaces (Figure 4.51). Crystal junctions might produce spherical pores while intercrystalline edges produce very small pores. The pore throat radii shown in Figure 4.49 are relatively small compared with the illustration in Figure 4.51. However, crystal junctions and mineral in-growth is a possible mechanism for creating small pore spaces in the Ordovician shales because evaporite minerals are common in the shales.

The presence of clay minerals in small pores can also cause anion exclusion. The negatively charged sites on the clay surface attract a layer of cations to the surface, which in turn attracts anions to the cation layer. Together, these two layers are referred to as the electric double layer (EDL). In the middle of the pore is the free pore-water solution, which is the water that is outside of the influence of the EDL. The EDL may prevent anions from moving through pore throats, if the EDL occupies the pore throat.

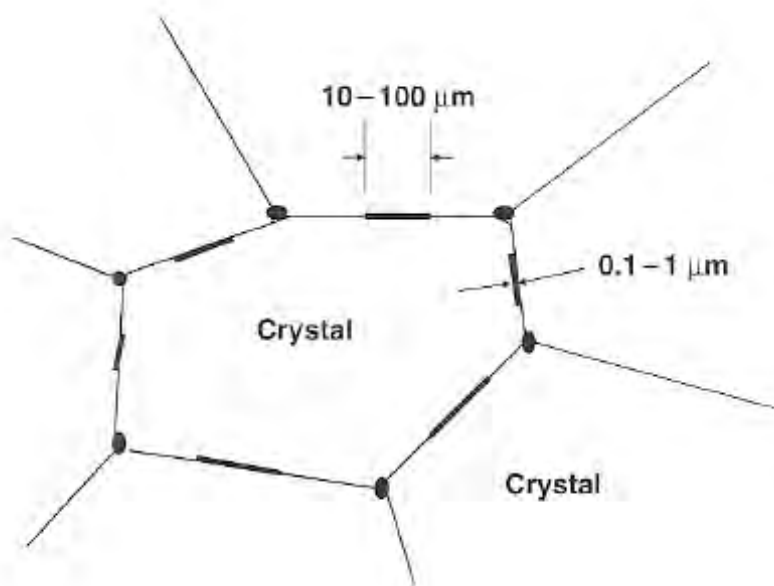


Figure 4.51 Schematic of inter-crystalline pore spaces (after Pusch, 2008)

The thickness of the EDL was determined in Section 4.4.1 as approximately 0.14 nm in brine with TDS ~ 300 g NaCl/L. Because the equation used to calculate the EDL thickness was developed for freshwater and brackish systems, not the high ionic strength porewater in the Ordovician shales, the accuracy of this EDL thickness prediction is unknown. However, the results are used to illustrate the potential for anion exclusion to occur.

If a pore is lined with clay, the cross section of the pore should have two EDLs, one on each pore wall. Therefore, the calculated EDL shown above was doubled (= 0.3 nm) to account for clay on both sides of a pore cross section. Since hydrated radii of many ions including I, Cl are near 0.3 nm (Nightingale, 1959), pores less than approximately 0.6 nm are required for anion exclusion to occur. Even considering the uncertainty of the EDL calculation at high ionic strengths, these results suggest anion exclusion would only occur in very small pore throats.

Mercury porosimetry data presented in Section 4.3.5 has a method detection limit of 2.5 nm. Approximately 20% of the pores in DGR-3 were smaller than 2.5 nm and 35% of the pores in DGR-4 were smaller than 2.5 nm (Figure 4.50). The relatively high proportion of pore throats <2.5 nm suggests there may be a significant fraction of very small pore throats (<0.6 nm) capable of anion exclusion.

The net effect of anion exclusion may be twofold. Firstly, the anions are made less mobile because they are restricted from moving through certain fine pore throats in which the EDLs prevent ready access. Secondly, when pore throats are extremely small, as in the case of the DGR Ordovician sequence, the aqueous concentration of ions in the outer layer of the EDL may be different from that in centre of the pore beyond the influence of the EDL. This may create a case where the centre of spherical pores may have porewater at halite saturation, while along the edges of the sphere there is a chloride deficiency due to anion repulsion by the negatively charged crystalline surface. This second effect may also be a factor in the underestimation of shale porewater concentrations that was discussed in Section 4.6.3.

4.6.5 Major Ions

The discussion above suggests porewater concentrations from the crush and leach method underestimate porewater concentrations in the Ordovician shales. The magnitude of the underestimated porewater concentrations is likely different for each rock core sample. Therefore, it is difficult to accurately correct the underestimated porewater concentrations. The major ion results presented here are based on analyses performed by University of Ottawa and University of New Brunswick with some selected data (Cl, Br and Na) determined by the University of Bern. These presented data do not account for the potential underestimation (approximately 15%, Figure 4.47) of ion concentrations in the Ordovician shales. The major ion results presented in this section account for mineral dissolution during porewater extraction, including anhydrite and calcite (see Section 4.6.2).

The ions considered discussed in some detail below with a rationale for their evaluation are the following:

- a) Na^+ and Cl^- : the source of these ions in brines is halite, which is a clear indicator of largely immobile brine porewater;
- b) Ca^{2+} and Mg^{2+} : these ions are associated with the dolomitization of the Paleozoic rock sequence (Hobbs et al., 2008);
- c) K^+ : low potassium concentrations are associated with Shield brines, and can be associated with transformation of smectite to illite;
- d) B is a conservative tracer that also has a diagnostic signature in Shield brines; and
- e) Br^- is a conservative tracer that is used to form Cl/Br ratios that are useful as tracers of seawater and brines.

Figure 4.52 presents the depth profiles of Cl, Na and TDS determined from porewater analyses of DGR cores and from analyses of groundwater samples collected from US-8 and DGR boreholes. The groundwater results from US-8 and the OGW results shown in the concentration-depth profiles and were converted from measured concentration units (mg/L solution) to units of molality (mmol/kgw).

The shallow groundwater and porewater Cl concentrations are low from the Lucas Formation to the top of the Salina units (Figure 4.52), which is consistent with the permeable Devonian freshwater system. The porewater Cl concentrations generally increase from the Salina G Unit to the Salina B Evaporite Unit. Below the Salina B Evaporite Unit, the Cl concentration decreases from the top of the Salina A1 Unit. Below the top of the Salina A1 Unit the concentrations increase down to the Guelph Formation. Possible porewater dilution complicates the interpretation of chloride concentrations in the Ordovician shales and the Cabot Head shale, however, below the Guelph Formation concentrations generally decrease to the top of the Gull River Formation. The Cl concentrations increase from the bottom of the Gull River Formation to the Cambrian sandstone. The porewater and groundwater Cl concentrations were similar for the Salina A1, Guelph and Cambrian permeable horizons, which provides the confidence in the porewater results.

The groundwater and porewater total dissolved solids (TDS) concentrations are also presented as g/L in Figure 4.52. Note the pattern of TDS is similar to the pattern of Cl due to the significant role chloride plays in the groundwater and porewater TDS. The similarity between the groundwater TDS and the porewater TDS suggests all of the major ions are accounted for in the porewater analyses.

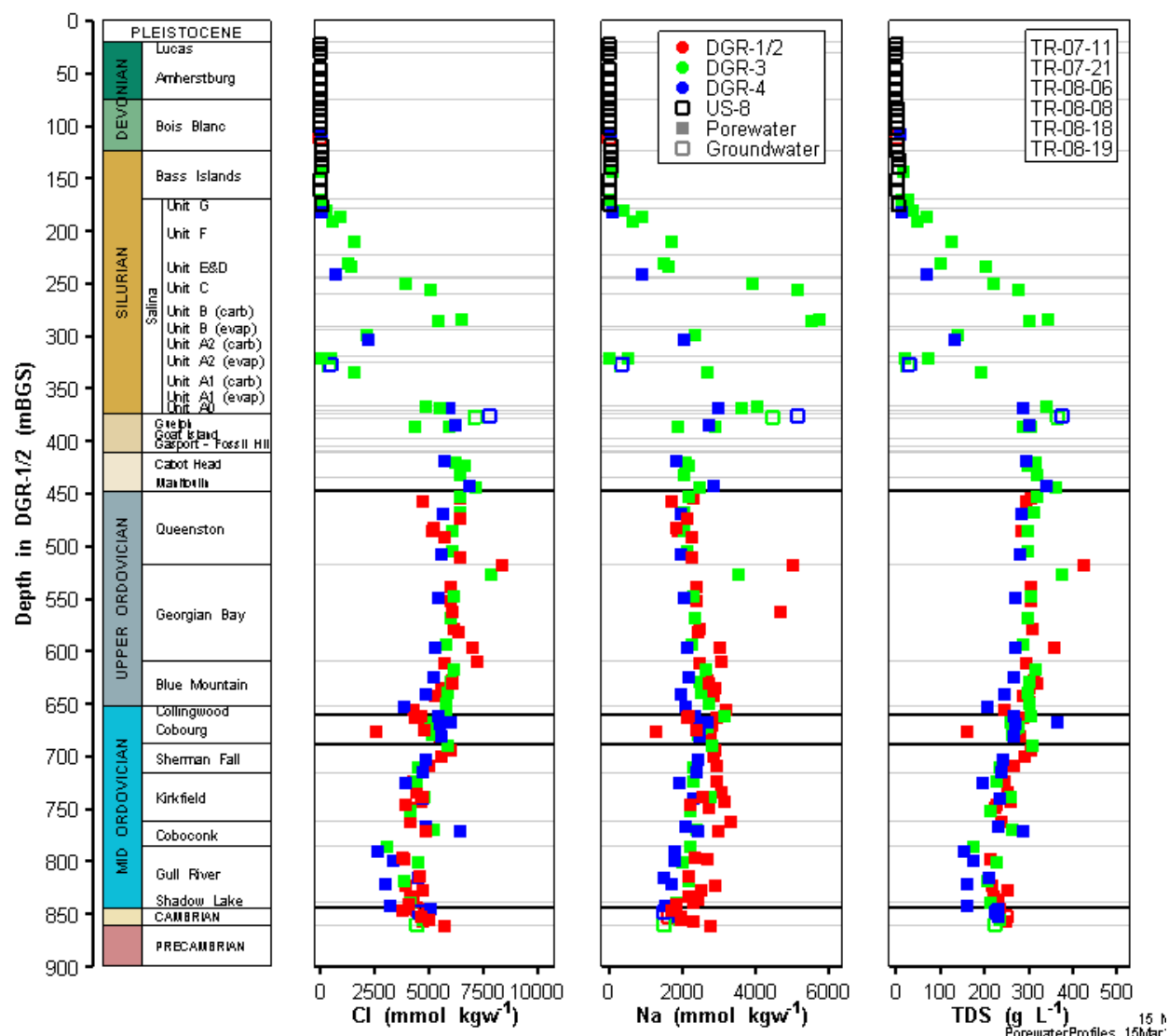


Figure 4.52 Profiles of chloride, sodium and TDS concentrations in porewater and groundwater from US-8 and DGR boreholes

The patterns observed in the Cl concentration depth profile described above were also observed in the concentration depth profiles of Na, K, and Br (Figures 4.53 and 4.54). However, Br concentrations from the University of Ottawa for DGR-1 and DGR-2 (TR-07-21) were not shown due to analytical uncertainties in the Br data. The analytical uncertainties were addressed for Phase 2A, and the results are shown for DGR-3 and DGR-4. The DGR-2 porewater Br concentrations shown are from the University of Bern and the University of New Brunswick. Br was not measured on dilute groundwater samples collected from the US-series boreholes.

The Na, K and Br profiles show the highest porewater concentrations near the bottom of the Silurian formations and these ions shown minimum concentrations in the Coboconk or Gull River Formations.

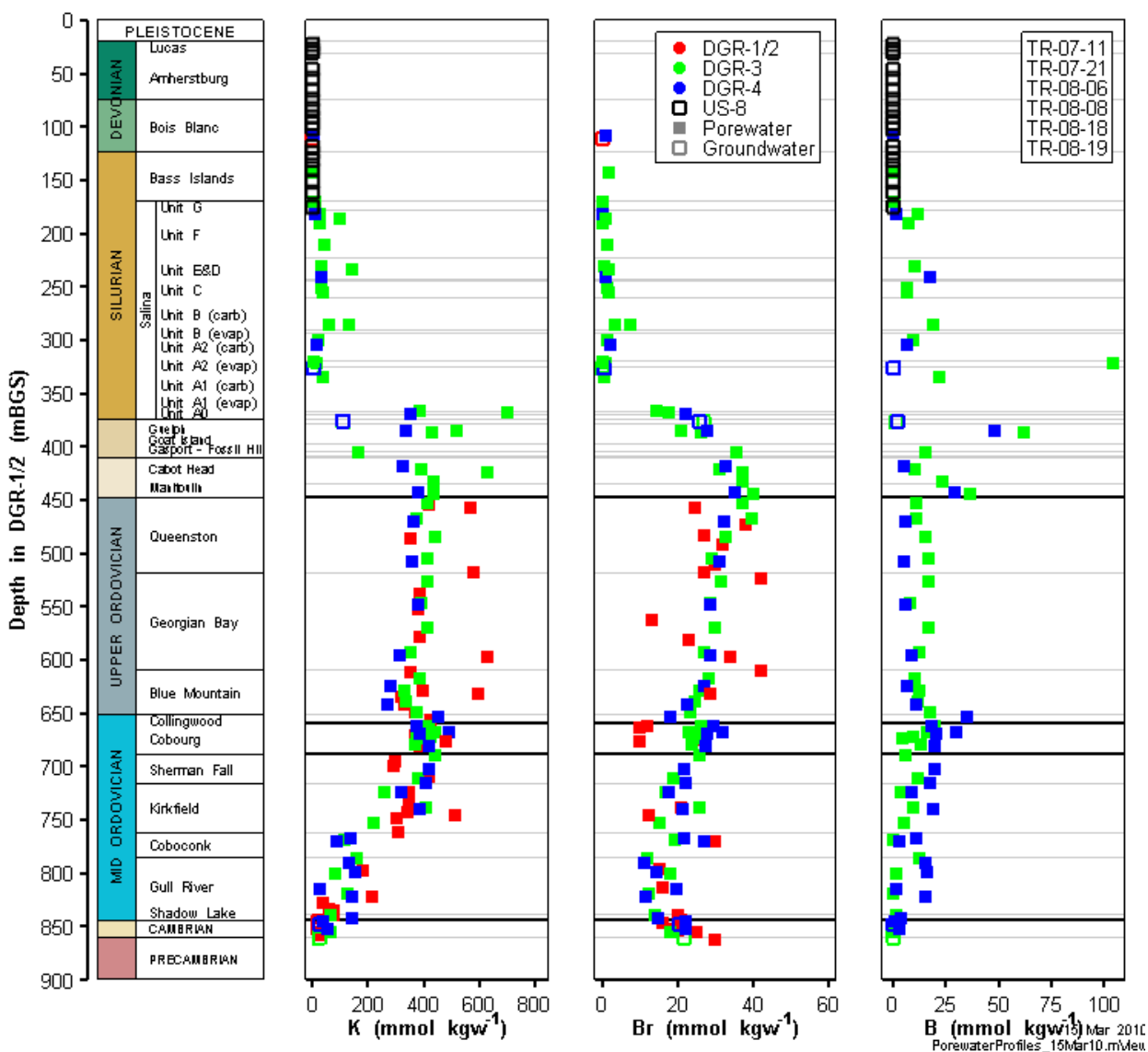


Figure 4.53 Profiles of potassium, bromide, and boron concentrations in porewater and groundwater from US-8 and DGR boreholes

One difference between the Cl and K profiles is the K concentration does not increase in the Cambrian, compared to the overlying Shadow Lake and Gull River Formations. The porewater and groundwater Na, K, and Br concentrations were similar for the Salina Upper A1, Guelph and Cambrian permeable horizons, which improves the confidence in the porewater results.

Although it is not a major ion, B has a similar depth profile to Na, K and Br, however the magnitude of the changes in concentration in the Ordovician limestones are smaller. One difference is a slight increase in porewater concentration near the top of the Gull River Formation, which was not observed in the Cl profile.

Figures 4.55 and 4.56 present the groundwater and porewater chemistry profiles for Ca and Mg, and for Sr and SO₄, respectively.

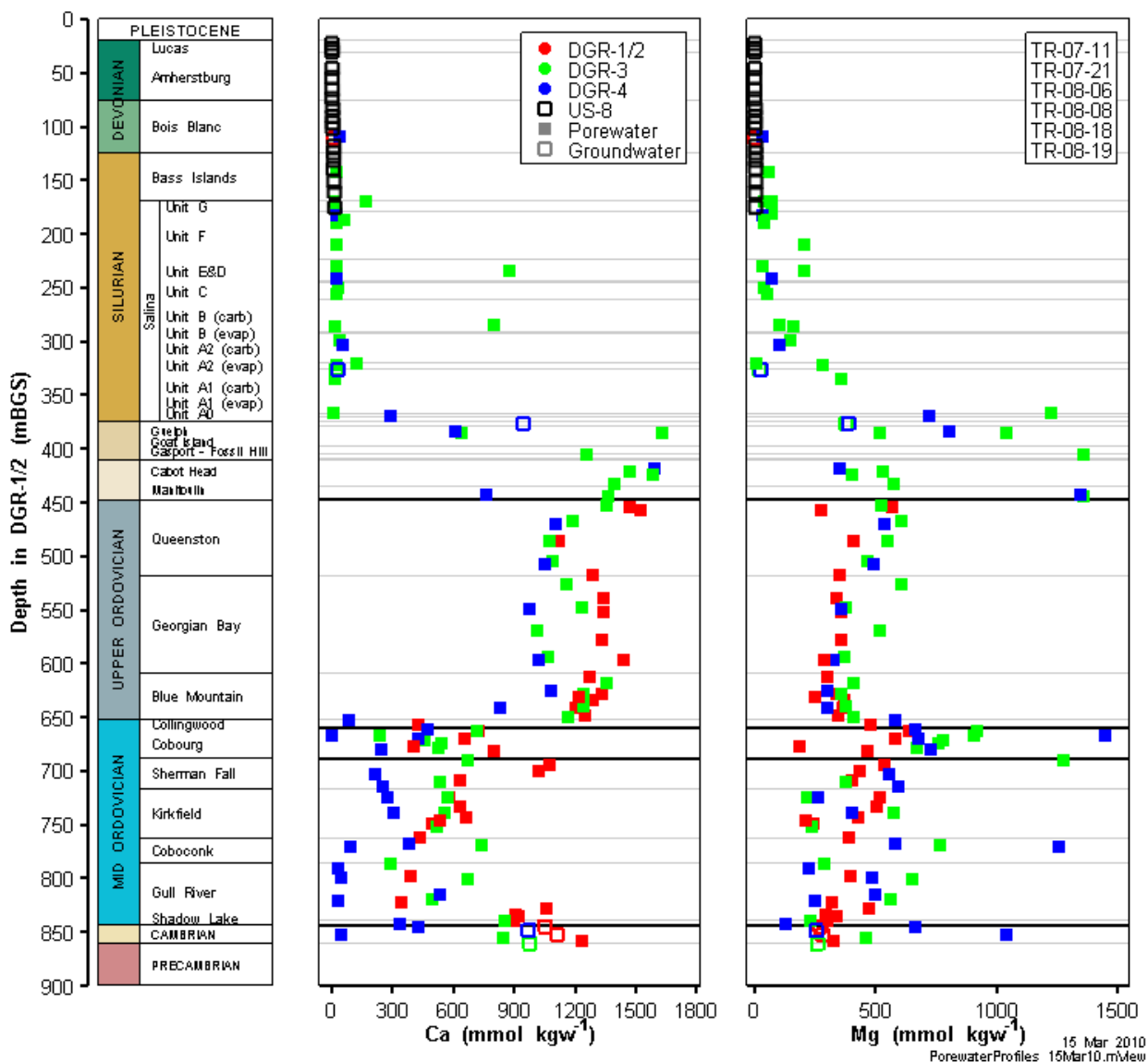


Figure 4.54 Profiles of calcium and magnesium concentrations in porewater and groundwater from US-8 and DGR boreholes

The major ions, Ca, Mg, SO₄ as well as minor ions including Sr and B do not follow the same general concentration trends as Cl. Corrections for anhydrite saturation significantly affect the Ca and SO₄ results, making these results difficult to interpret at this stage of the site characterisation. In particular the Ca porewater concentrations within the Ordovician limestones in DGR-4 are significantly reduced relative to DGR-2 and DGR-4, due to the elevated concentrations of SO₄ in DGR-4 core porewater. The differences in Ca, Mg, Sr and SO₄ between adjacent porewater and groundwater samples for the Salina Upper A1 and Cambrian permeable horizons are relatively minor suggesting the porewater concentrations are reasonable and reliable in these aquifers. However the differences in these ion concentrations in porewater and groundwater for the Guelph aquifer are greater. These larger differences are likely due to dissolution of minerals during the crush and leach procedure and calculated corrections for mineral dissolution. Consequently, Ca, Mg, Sr and SO₄ concentrations in porewater in the Lower Silurian rocks should be interpreted with caution.

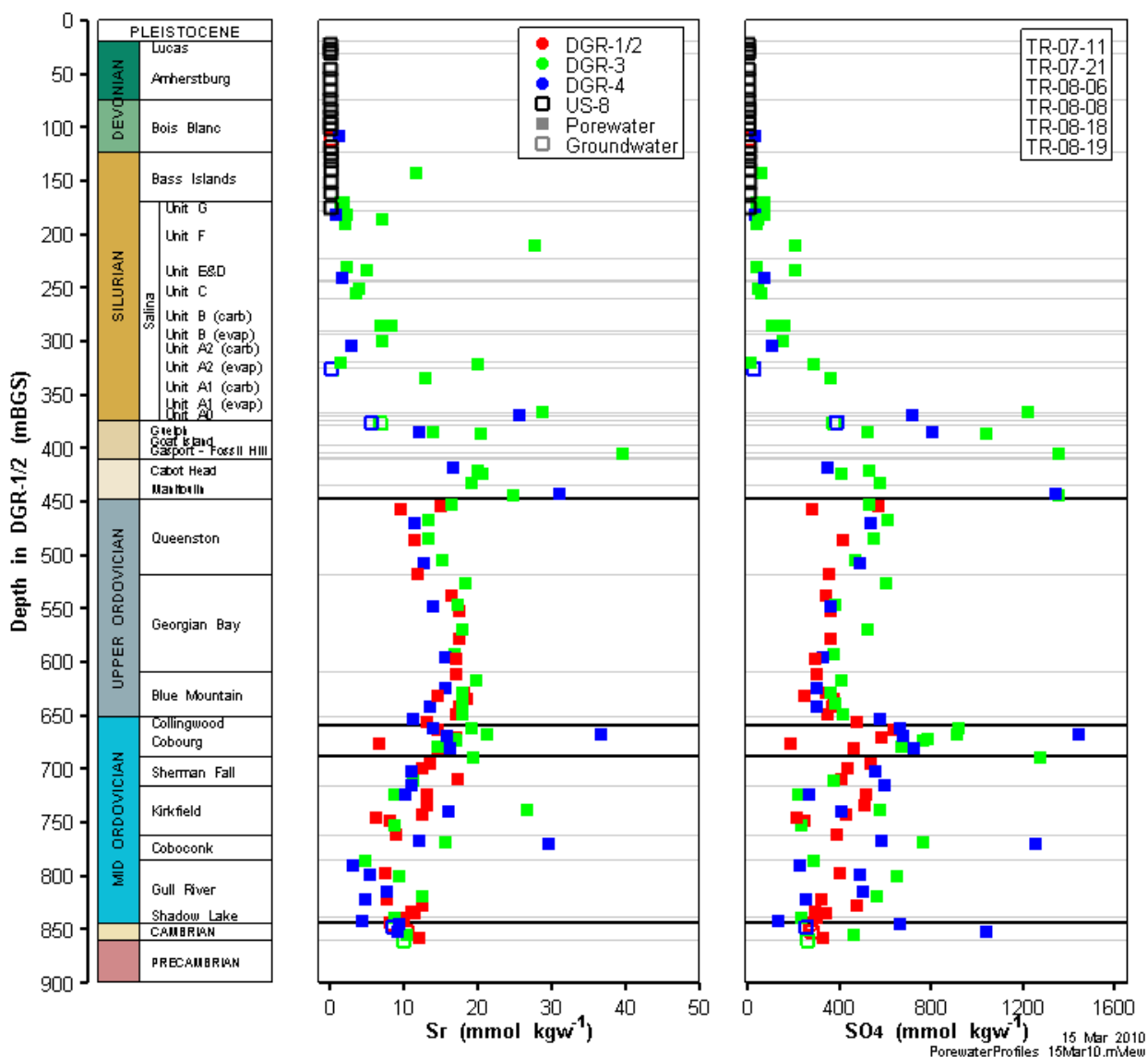


Figure 4.55 Profiles of strontium and sulphate concentrations in porewater and groundwater from US-8 and DGR boreholes

Similarly, the porewater Mg results are likely affected by assumptions of the porewater in equilibrium with calcite (CaCO₃) rather than Mg-calcites or dolomite. Finally, Sr concentrations may be affected by dissolution of celestite that was occasionally observed in the Silurian formations and the Ordovician shales (see Section 3.9.3, Table 3.11) during the mineralogical analyses. Therefore, the concentration profiles of Ca, Mg, SO₄ and Sr should only be used for limited interpretations.

The trends in groundwater and porewater major ion depth-profiles are also illustrated by considering the ion molal ratios shown in Figure 4.57. Figure 4.57 shows the ion molal ratios of Cl/Na, Cl/Br and B/K in groundwater and porewater. An ion ratio of 1 for Cl/Na is expected if halite dissolution is the primary process controlling the Na and Cl concentrations. Stability in Cl/Br ratios are expected if halite dissolution is not a important process controlling Cl concentrations, elevated B/K ratios can be indicative of dissolution of evaporite minerals and sedimentary basin brines.

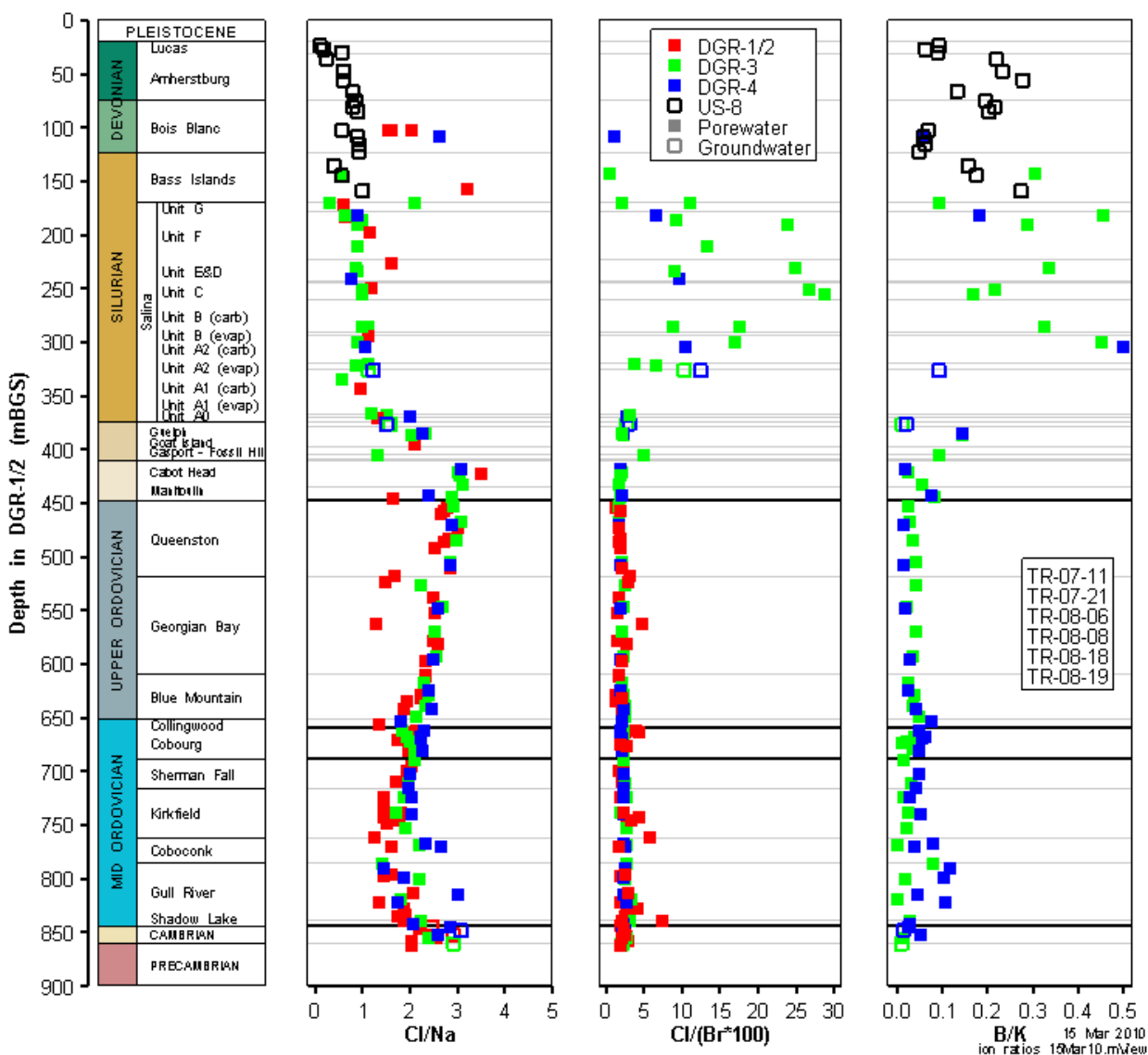


Figure 4.56 Profiles of ion molal ratios of porewater and groundwater from US-8 and DGR boreholes

Although there is some scatter of porewater Cl/Na in the Devonian, the Cl/Na ratios of groundwater in the Devonian and of porewater and groundwater in the Silurian uniformly increase from 1.0 in the Amherstburg Formation to about 1.5 in the Guelph Formation. Below the Guelph the Cl/Na ratio increases to about 3.0 in the Cabot Head Formation and then uniformly decreases to about 1.25 at the top of Gull River Formation. The ratio increases again from the top of the Gull River Formation to the Cambrian with Cl/Na ratio of about 3.0. The Cl/Na data indicate most of the salinity in the Devonian and Silurian rocks are derived from halite dissolution and the porewater and groundwater below the Guelph to the Cambrian did not evolve from the same Devonian/Silurian composition and/or the waters have been affected by processes that add Cl or remove Na over time.

The Cl/Br ratio is highest in the Salina units and is relatively constant in the Ordovician. There are small increases in the Cl/Br ratio in the Kirkfield, Gull River and Shadow Lake Formations. These increased ratios may be due to halite dissolution increasing the Cl concentrations, however, there may be other processes affecting the Cl or Br concentrations in these formations such as solute transport.

Assuming Br is not contained within halite minerals, the relatively constant Cl/Br ratio in the Ordovician and Cambrian rocks suggests halite dissolution is not a significant factor affecting the Cl concentration in these rocks

The B/K ratio (Figure 4.56) shows a relative enrichment in B associated with the evaporite Salina units, and a relative depletion of B in the Ordovician formations including the Cambrian sandstone. However, there is also a small trend of increasing ratio from the Cambrian up to the Coboconk Formation.

4.6.6 Environmental and Sr Isotopes

4.6.6.1 Oxygen and Deuterium Isotopes

The combined $\delta^{18}\text{O}$ and δD plot for all DGR porewaters and groundwaters is shown in Figure 4.57. The range of $\delta^{18}\text{O}$ and δD for modern precipitation in southern Ontario as $\delta^{18}\text{O}$: -12‰ to -10‰ and as δD : -85‰ to -70‰ is also given on this plot. Figure 4.58 also presents the same data for the many porewater samples and the Guelph and Cambrian groundwater samples that crowd the relatively enriched zone at the top right hand corner of Figure 4.57 in expanded scale.

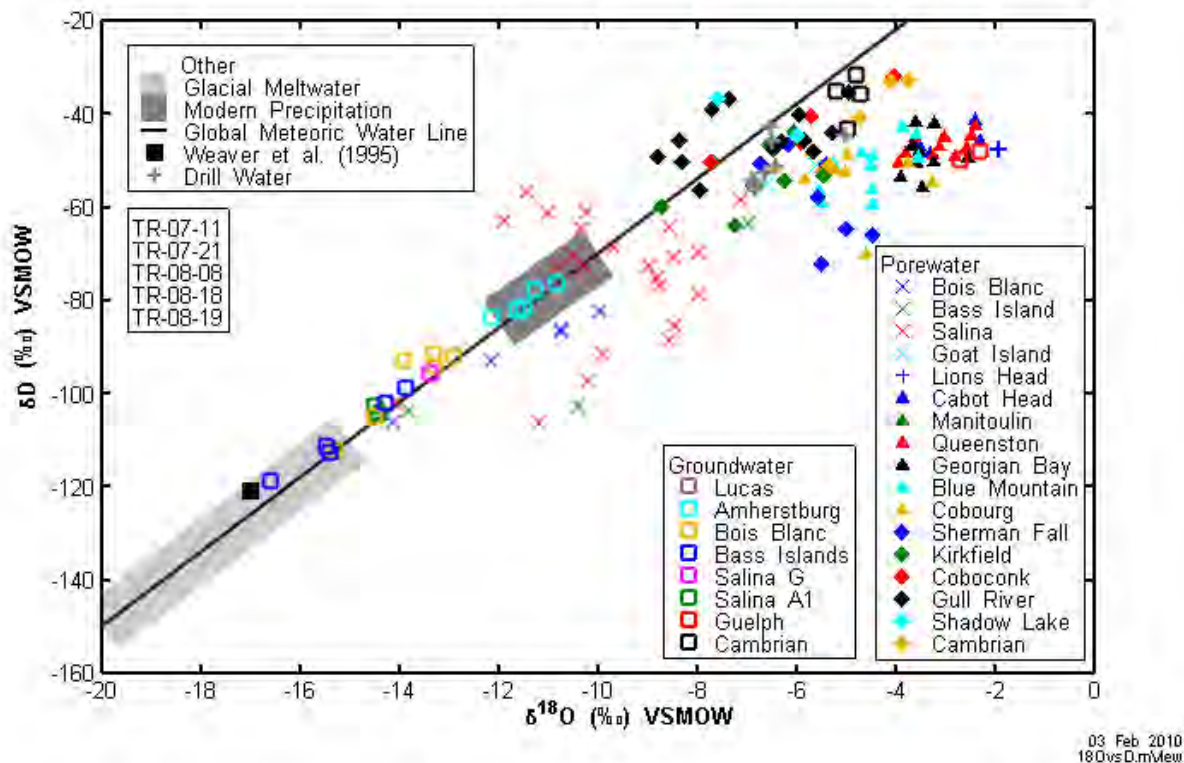


Figure 4.57 Cross plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ for all groundwater and porewater samples from US wells and DGR boreholes.

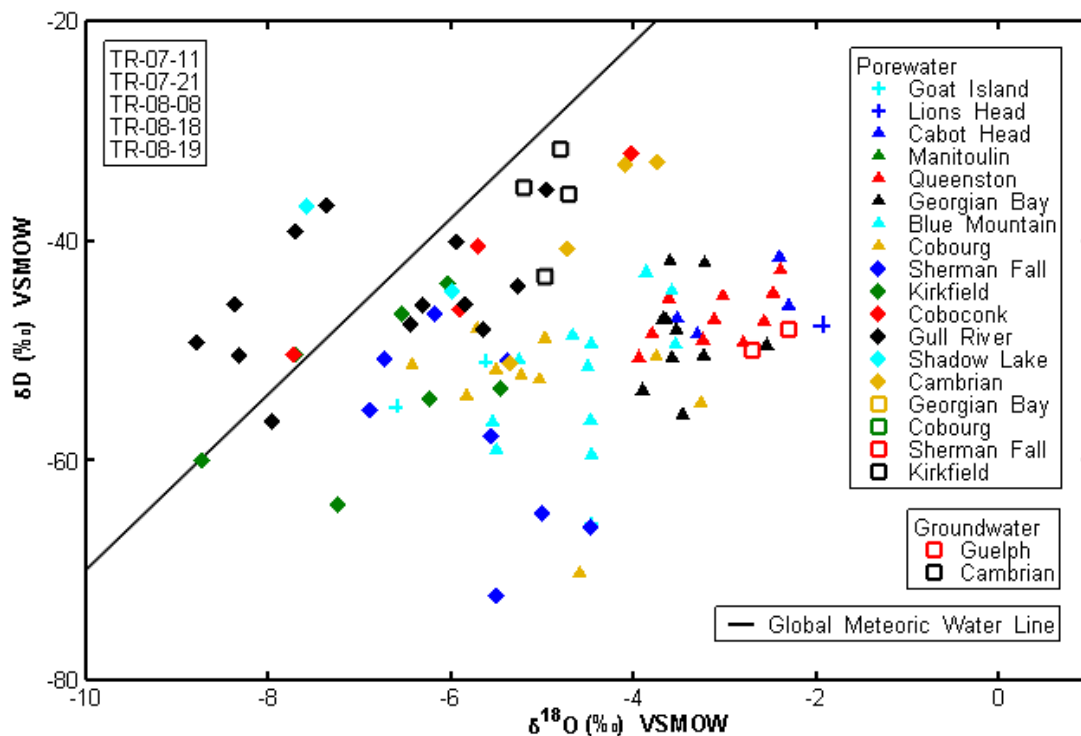


Figure 4.58 Expanded scale for porewater samples and Guelph and Cambrian groundwaters from Figure 4.56

As is typically the case, $\delta^{18}\text{O}$ and δD are shown as cross plots that permit evaluation of data trends and the results with respect to the Global Meteoric Water Line or GMWL (i.e., $\delta\text{D} = 8.13 \cdot \delta^{18}\text{O} + 10.8$) that defines the relationship between $\delta^{18}\text{O}$ and δD in worldwide fresh surface waters, including modern precipitation and glacial meltwater which are shown on Figure 4.58. Evaporation causes a water to plot beneath the GMWL as is shown by most samples in Figure 4.58 and 4.59 although some samples from Black River Group (Coboconk, Gull River and Shadow Lake limestones) indicate a deuterium excess and plot above the GMWL.

Review of Figure 4.58 shows a clear clustering and evolution of $\delta^{18}\text{O}$ and δD values from the Guelph and other Middle and Lower Silurian Formations including the Queenston Formation with depth through the deeper Ordovician shales and limestones to the Cambrian. The evolutionary path with depth is primarily one of $\delta^{18}\text{O}$ depletion to the GMWL with a reversal above the GMWL followed by $\delta^{18}\text{O}$ and δD enrichment to the Cambrian groundwater and porewater values. The major reversals of evolutionary path evident on this $\delta^{18}\text{O}$ - δD cross plot indicates that cross-formational mixing and exchange has occurred in the Black River and Cambrian rocks in DGR boreholes.

Figures 4.59 and 4.60 shows the $\delta^{18}\text{O}$ and δD groundwater data for US-8 multilevel well and OGW samples collected in the DGR boreholes together with similar data from core porewater plotted against the DGR-1/2 reference depth. Figure 4.59 shows there is some apparent $\delta^{18}\text{O}$ enrichment in porewaters relative to groundwaters for the Devonian and Upper Silurian dolostones, although the Salina Upper A1 Unit and Cambrian groundwater and porewater results are very similar, therefore it is believed that the differences in the dolostone samples are due to groundwater flow through the dolostone fractures and solution channels that has not equilibrated with the porewaters in the less permeable rock matrix.

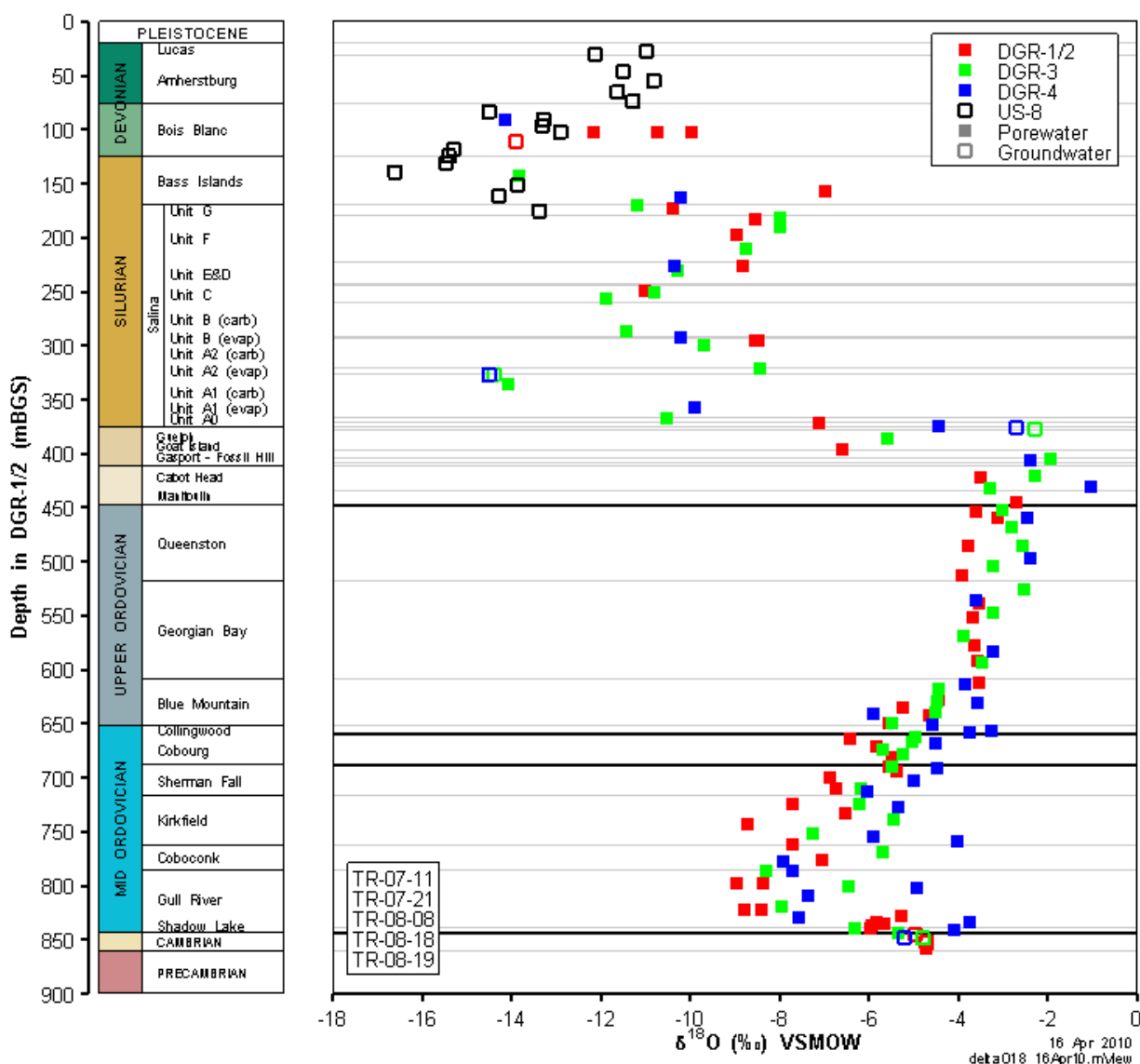


Figure 4.59 Profile of $\delta^{18}\text{O}$ of porewaters and groundwaters from US-8 and DGR boreholes

The DGR porewaters in the Devonian and Upper Silurian sequence show an $\delta^{18}\text{O}$ enrichment trend with depth, although some isotope values for gypsiferous samples from the upper Salina Formation likely have up to 3‰ $\delta^{18}\text{O}$ enrichment as an artefact of hydration waters released during extraction. Porewaters and groundwaters in the shallow Bois Blanc Formation have values that are close to the local groundwaters (−12‰) with excursions to lower values that likely represent mixtures of modern meteoric water and glacial meltwater (−15 to −20‰; Aravena et al., 1995 and references therein). Deeper porewaters in the Silurian formations trend towards the more enriched values observed in the Guelph Formation and Upper Ordovician shales ($\delta^{18}\text{O}$ ~ −3.5‰) which are similar to Michigan Basin brines (Clayton et al., 1966). This trend suggests a gradual flushing of basin fluids in these Devonian and Upper Silurian formations with meteoric waters over time. This trend is observed in porewater salinity as well (see Section 4.6.5). The depth of penetration of this recharge is approximately 350 m, i.e., into the Salina Upper A1 Unit aquifer, which shows evidence of deep meltwater recharge, i.e., OGW-8: $\delta^{18}\text{O}$ = −14.4 and δD : ‰ −104‰.

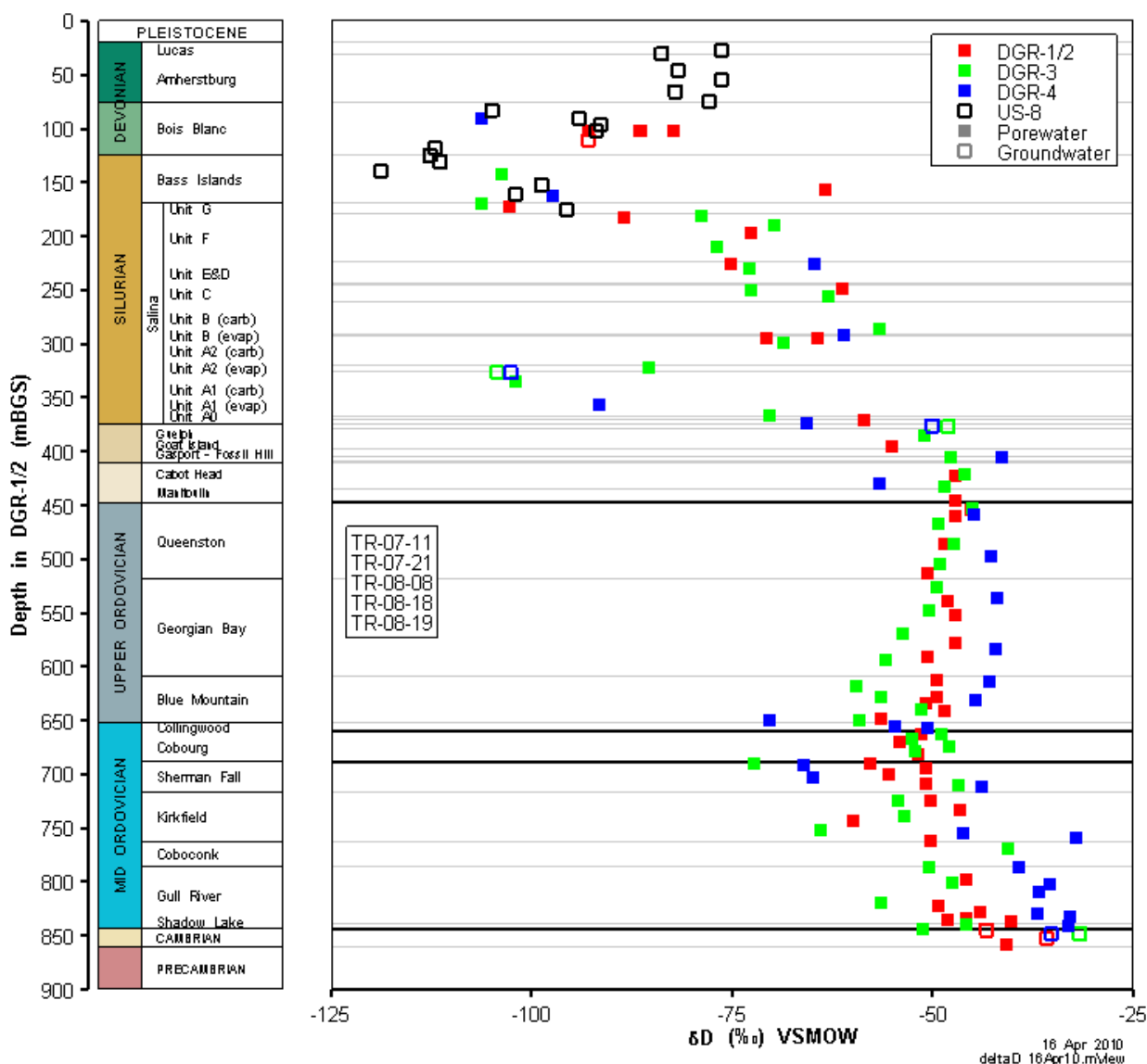


Figure 4.60 Profile of δD of porewaters and groundwaters from US-8 and DGR boreholes

Deuterium concentrations were similarly depleted in the shallow Devonian groundwaters from the US-series multi-level wells, i.e., -75 to -120‰ for δD (see Figure 4.60), as those identified by Aravena et al. (1995) for the Alliston aquifer (δD : -101 to -95‰). The deuterium values increase throughout the upper Silurian formations to approximately -75‰ and, with the significant exception of the Salina Upper A1 Unit aquifer, continue this enriched trend reaching -50 to -40‰ in the formations in proximity to the Ordovician shales, i.e., the Cabot Head shale and the Manitoulin dolostone. The deuterium value of -104‰ in the Salina Upper A1 Unit aquifer is mid-way between the isotopic values for modern meteoric water and glacial meltwater (see Figure 5, TR-08-19) and is therefore a strong indicator of the deep penetration of Quaternary waters in that unit.

By contrast with the Devonian-Upper Silurian profile, the Middle and Lower Silurian - Ordovician porewaters show a minor reverse trend with depth. Both $\delta^{18}O$ and δD values show minor decreases from the Guelph Formation ($\delta^{18}O \sim -2.5$ ‰ and $\delta D \sim -48$ ‰) downward through the Ordovician shales.

The $\delta^{18}\text{O}$ profile within the Ordovician limestones continues to show depletion with depth reaching a minimum value of about -9‰ in the top of the Gull River Formation before increasing to the Cambrian groundwater value of about -5‰ . The δD profile within the Ordovician limestones is more scattered than the $\delta^{18}\text{O}$ profile, but shows decreasing or stable values to the bottom of the Kirkfield Formation with minimum values of about -50 to -60‰ , before increasing to the Cambrian groundwater and porewater values of about -35‰ .

As is shown in the depth profiles of Figures 4.59 ($\delta^{18}\text{O}$), and 4.60 (δD) several core samples in the Gull River and Coboconk Formations have the same isotopic composition as the Cambrian values. AECOM Canada Ltd. (2010, Figure 4.26) indicates that these samples also showed enriched values for Cl and Br as well as $\delta^{18}\text{O}$. These Cambrian-like Cl, Br, $\delta^{18}\text{O}$ and δD signatures within the overlying Black River limestones may reflect localized upward transport along increased porosity and permeability pathways within the Black River limestones.

Figure 4.61 presents the cross plot of $\delta^{18}\text{O}$ versus the deuterium excess, d , determined as the enrichment of D relative to ^{18}O where (Dansgaard, 1964):

$$d = \delta\text{D} - (8 \times \delta^{18}\text{O}) \quad [4.9]$$

Deuterium excess is a useful parameter with insights into meteoric and non-meteoric processes responsible for partitioning D differently than ^{18}O and expresses the deviation of D from the Global Meteoric Water Line (GMWL) relationship. Figure 4.61 shows the cross plot of $\delta^{18}\text{O}$ versus the deuterium excess for all of the porewater and groundwater data available from the Guelph Formation downward to the Cambrian sandstone.

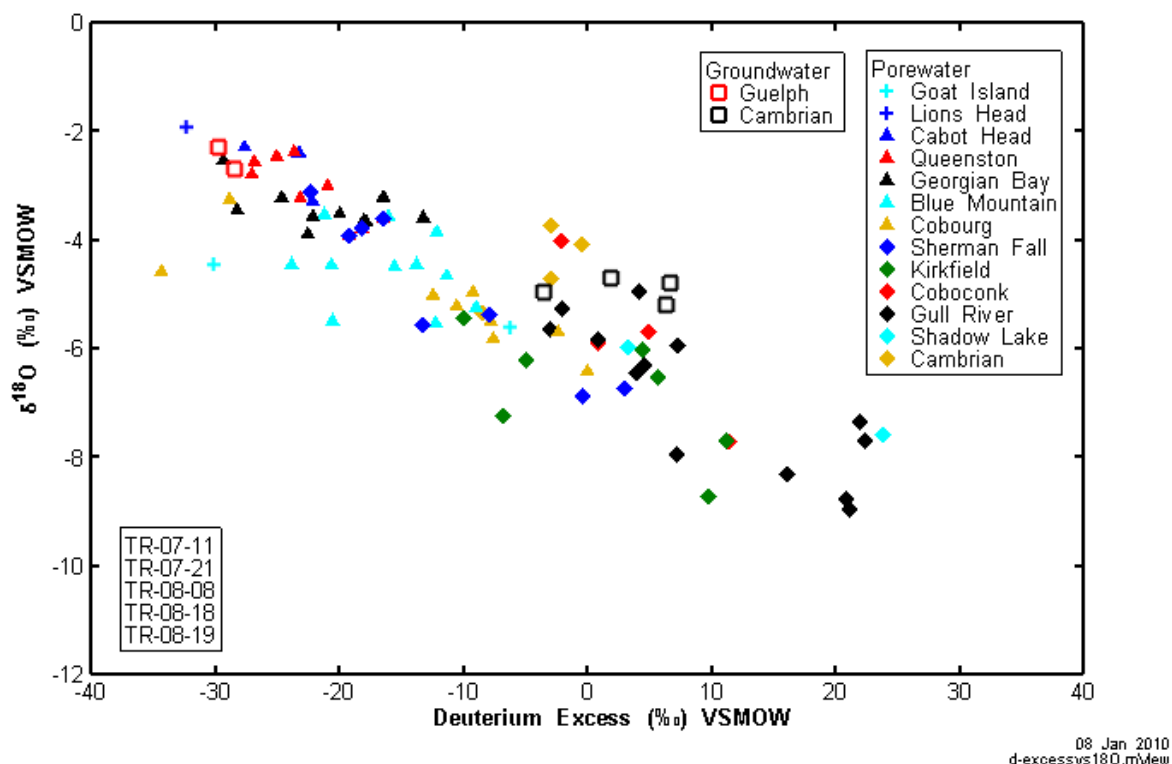


Figure 4.61 Deuterium excess as a function of $\delta^{18}\text{O}$ for DGR porewaters and groundwaters from the Guelph Formation to the Cambrian sandstone

Figure 4.61 shows matched trends in depletion of $\delta^{18}\text{O}$ and enrichment of d with depth from the Guelph Formation down through the stratigraphic column to the upper Gull River Formation. The Cambrian porewaters and groundwaters and the lower Gull River and Shadow Lake Formation porewaters are separated from the overlying Ordovician porewaters on this plot showing an $\delta^{18}\text{O}$ enrichment and deuterium excess depletion with depth in these deepest strata. Therefore this $\delta^{18}\text{O}$ versus d plot also indicates that cross-formational mixing and exchange has occurred in the Gull River, Shadow Lake and Cambrian rocks in DGR boreholes.

Figure 4.62 shows the variation of d with depth that indicates a common d value of +11‰ in the permeable Devonian and Upper A1 Unit aquifers, with systematic shift from a stable deuterium excess of about -30‰ in the Guelph and Lower Silurian formations down through the Ordovician shales and limestones towards a very enriched value of about +20‰ in the Gull River limestone. The values for d then decrease to the base of the profile to match those measured in the Cambrian at about 0‰.

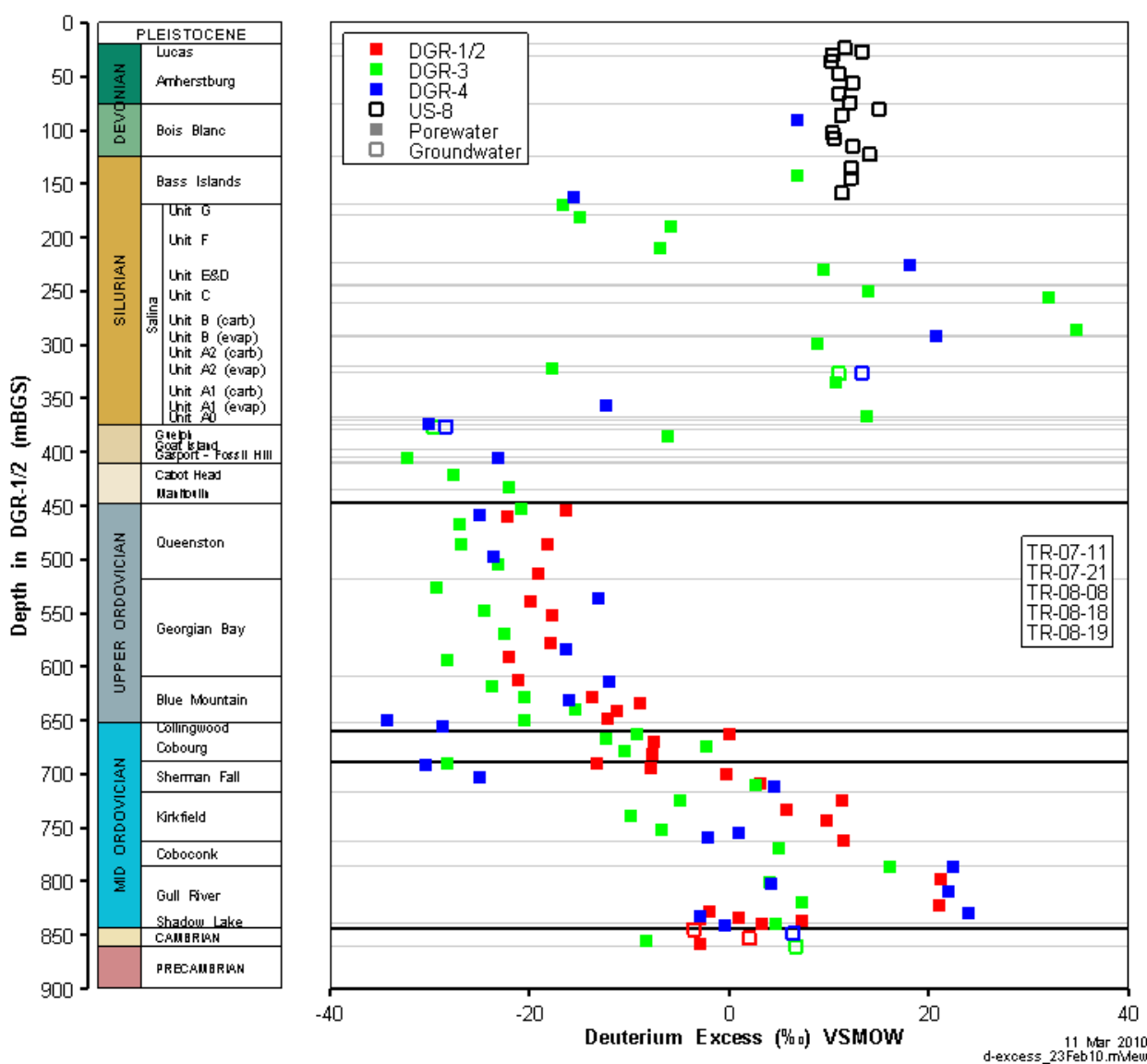


Figure 4.62 Profile of deuterium excess as a function of depth in US-8 and DGR boreholes

The observed ^{18}O and D depth trend also applies to Cl, Br, and TDS (see Section 4.6.5), as well as Sr (see below) where dilution trends are found in the sections with ^{18}O depletion trends. Na^+ , by contrast, shows the reverse trend of does not show the major ion dilution - ^{18}O depletion trend. This suggests that the isotopically-depleted and lower salinity water which likely occupied the Cambrian sandstone in the past and penetrated the deeper Black River limestones carried a stronger Na-Cl facies and was replaced by a higher salinity brine with a stronger Ca-Na-Cl facies and may reflect brine inputs from the crystalline basement.

4.6.6.2 Strontium Isotopes

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is a reflection of the source of Sr in the rock and water. The present $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in seawater is a relatively constant value of 0.709, although this has varied over the Phanerozoic. The Ordovician to Devonian strontium isotope curve varies between about 0.7077 and 0.7087. Increases in this value represent greater contributions of Sr from weathering of the continental crust, which displays enrichments in radiogenic ^{87}Sr from the decay of ^{87}Rb .

Strontium isotopes were measured in groundwaters, porewaters and core samples. For the core samples, paired leaches were analyzed, including a rapid (single pass) leach of crushed rock to minimize mineral dissolution yet maximize uptake of porewater solutes, and an extensive leach in deionized water (using the leach water from the vacuum distillation experiments after 60 days contact with the rock fragments). This was undertaken to test the potential that strontium may be leached from the carbonate minerals in addition to the porewater solutes. Following leaching, the rock samples were rinsed extensively with deionized water and dried. These samples were then crushed to powder and leached with a mild acetic acid. Sr was then removed from these solutions on ion exchange columns and re-eluted for preparation of filaments for analysis by thermal ionization mass spectrometry (TIMS) on a Triton instrument at Carleton University.

Figure 4.63 shows the new DGR-3 and DGR-4 analyses plotted together with the results of the DGR-2 analyses. Duplicate $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the DGR-3 porewaters are the results from the rapid leach and the 60 day leaching for porewater solutes. The good reproducibility demonstrates that there is little to no influence of the carbonate matrix on the measured porewater strontium isotopes.

As observed for the DGR-2 data, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in DGR-3 porewater from the Ordovician formations is more radiogenic than the host carbonate rocks. The DGR-2 samples through the Ordovician shales show a slight trend towards equilibrium with the host rock. The DGR-3 samples in the Silurian section show that this trend continues up section to full equilibrium with the marine $^{87}\text{Sr}/^{86}\text{Sr}$ values. Both Silurian groundwater samples from the Upper A1 Unit and the Guelph Formation plot close to or on this porewater trend. The trend observed in the Ordovician shales continues downward through the Ordovician limestones, although with a greater variability. The Cambrian porewater samples fall very close to the two Cambrian groundwater samples, with an enriched $^{87}\text{Sr}/^{86}\text{Sr}$ signature.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for acetic acid leachates of the host shales and limestones in Figure 4.63 fall close to the marine strontium curve (Veizer, 1989). Also shown are rock measurements from Brand (2004) from eastern Ontario. These measurements show that the porewaters throughout the Ordovician shales and limestones are anomalously enriched in radiogenic ^{87}Sr . Two sources can be proposed, including authigenic inputs from decay of ^{87}Rb present within the clays, or migration of ^{87}Sr from the crystalline basement. However, the acid leachates would not have extracted ^{87}Sr from the clastic materials. Clastic materials in these rocks are primarily clays or sheet silicates. The Ordovician carbonates are composed of calcite and dolomite (Figure 3.4), with only a small amount (formation averages near 10%) of sheet silicates (Figure 3.5). The Sr content of the sheet silicates is not expected to have a significant impact on the Sr results shown in Figure 4.63, but whole rock analyses will be carried out to determine the total $^{87}\text{Sr}/^{86}\text{Sr}$ content of the rocks, including the clastic materials

Stratigraphic Column (Left):

- PLEISTOCENE**
 - Lucas
 - Amherstburg
- DEVONIAN**
 - Bois Blanc
- SILURIAN**
 - Bass Islands
 - Unit G
 - Unit F
 - Unit E&D
 - Unit C
 - Unit B (carb)
 - Unit B (evap)
 - Unit A2 (carb)
 - Unit A2 (evap)
 - Unit A1 (carb)
 - Unit A1 (evap)
 - Unit A0
- Carboniferous**
 - Grebe Island
 - Cabot Head
 - Manitowish
- UPPER ORDOVICIAN**
 - Queenston
 - Georgian Bay
 - Blue Mountain
- MID ORDOVICIAN**
 - Collingwood
 - Cobourg
 - Sherman Fall
 - Kirkfield
 - Coboconk
 - Gull River
 - Shadow Lake
- CAMBRIAN**
- PRECAMBRIAN**

87Sr/86Sr vs. Depth Plot (Right):

- Y-axis:** Depth in DGR-1/2 (mBGS) from 0 to 900.
- X-axis:** $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.707 to 0.712.
- Legend:**
 - DGR-1/2 (Red circle)
 - DGR-3 (Green circle)
 - DGR-4 (Blue circle)
 - Porewater (Grey square)
 - Groundwater (White square)
 - Eastern Ontario (Yellow circle)
 - Ingrowth from rock Rb (+)
 - Rock (Black triangle)
 - Seawater (Orange line)
 - Precambrian (Black diamond)
- Key Features:**
 - Seawater Curve:** Orange line showing a general decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ with depth, with a notable step down around 650 mBGS.
 - TR-07-21 and TR-08-19:** Horizontal lines at approximately 650 mBGS.
 - Data Points:** Various symbols representing different sample types are plotted, showing a general trend of increasing $^{87}\text{Sr}/^{86}\text{Sr}$ with depth, with some scatter in the upper Ordovician and Silurian units.

In-growth calculations based on Rb and Sr concentrations in both the Ordovician shales and limestones were made assuming a partially open system for release of ingrown ^{87}Sr to the pore fluid. Results are shown for sample depths on Figure 4.64 (+ symbols). These calculations show that the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the shale porewaters can be achieved using a 30% release factor to the pore brine of ^{87}Sr accumulating from ^{87}Rb decay over a 260 My period (termination of the Alleghanian orogeny). No evidence for such Phanerozoic ^{87}Sr accumulation is observed in the carbonate fraction of these shales, as analyzed by acetic acid leach made in the Queenston, or in the Brand (2004) data. Nonetheless, contributions of ^{87}Sr from decay of ^{87}Rb since the Paleozoic have likely contributed to the radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured in the shales.



materials (sheet silicates) in the limestones was not accounted for as described above. The $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio of whole rock samples, including the clastic (sheet silicates), will be used to evaluate the porewater $^{87}\text{Sr}/^{86}\text{Sr}$ signature. Once this is completed, the porewater $^{87}\text{Sr}/^{86}\text{Sr}$ signature may be more thoroughly evaluated.

4.6.7 CH_4 and CO_2 Gases

4.6.7.1 Methane

Methane concentrations in DGR-2 core were obtained from rock core samples from the Queenston Formation down to the Cambrian (Figure 4.64) as well as from some groundwater samples. The amount of gas extracted from each rock core sample was normalized to water content to calculate a gas concentration. The normalization assumes all of the gas is dissolved by the porewater, which may not be the case. Therefore, these concentrations are considered to be apparent concentrations.

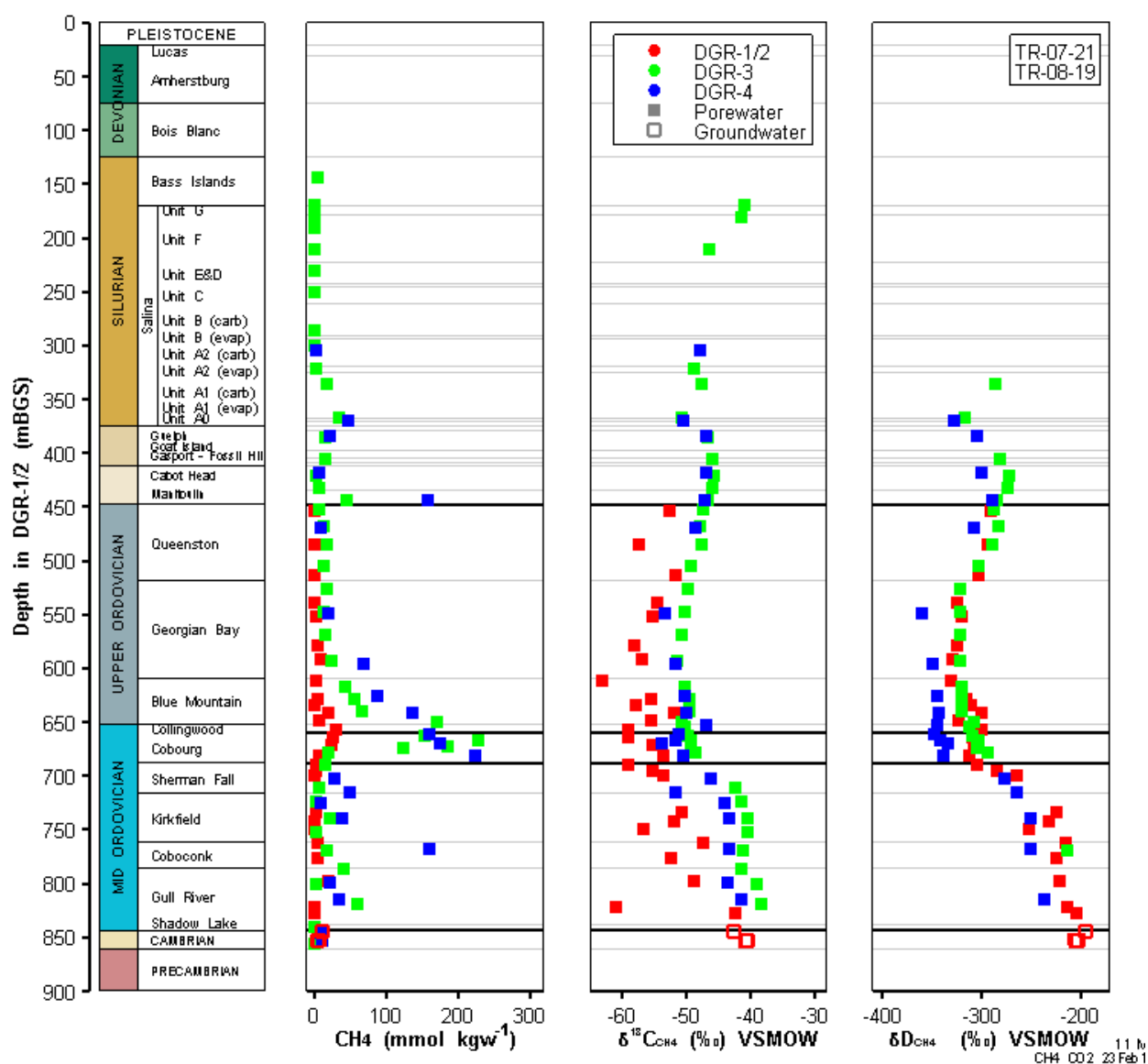


Figure 4.64 Profiles of CH_4 apparent porewater and groundwater concentrations and $\delta^{13}\text{C}$ and D in CH_4 in DGR boreholes

The DGR-2 results showed apparent methane concentrations increased from the Queenston Formation to the bottom of the Collingwood Member. The maximum methane concentration was measured in the Cobourg Formation.

Methane concentrations in DGR-3 and DGR-4 were analyzed from the Devonian carbonate formations down to the Cambrian. Apparent methane concentrations in DGR-3 and DGR-4 increased from near the Cabot Head Formation to the maximum in the Cobourg Formation. Relatively high apparent concentrations were also observed in the Coboconk and Gull River Formations. Not shown on Figure 4.64 in order to maintain trend resolution are two very high values of CH₄ (1210 and 460 mmol/kgw in the Collingwood and Cobourg, respectively). Although the magnitude of methane concentrations was different between DGR-2 and DGR-3/DGR-4, the patterns were similar.

Isotope ratios are perhaps better indicators of methane production and movement at the DGR site since they do not rely on assumptions of gas saturation. $\delta^{13}\text{C}$ and D isotope analyses of methane were carried out on the same samples as the concentrations were obtained from (Figure 4.64). The $\delta^{13}\text{C}$ and D depth profiles from DGR-2 show depletion in the isotope signatures from the Cabot Head Formation to the top of the Blue Mountain Formation. Below the Cobourg Formation the isotope signatures generally become more enriched with depth. The same general pattern is observed in DGR-3 and DGR-4.

A cross plot of $\delta^{13}\text{C}$ and D in methane for all of the DGR cores (Figure 4.65) shows methane at the Bruce nuclear site was derived biogenically by acetate fermentation and thermogenically by cracking hydrocarbons to produce methane. The data show a trend from biogenic methane in the Silurian and upper Ordovician to thermogenic methane in the lower Ordovician limestones and Cambrian. The high methane concentrations in the lower Blue Mountain Formation and the Collingwood Member are derived from biogenic processes.

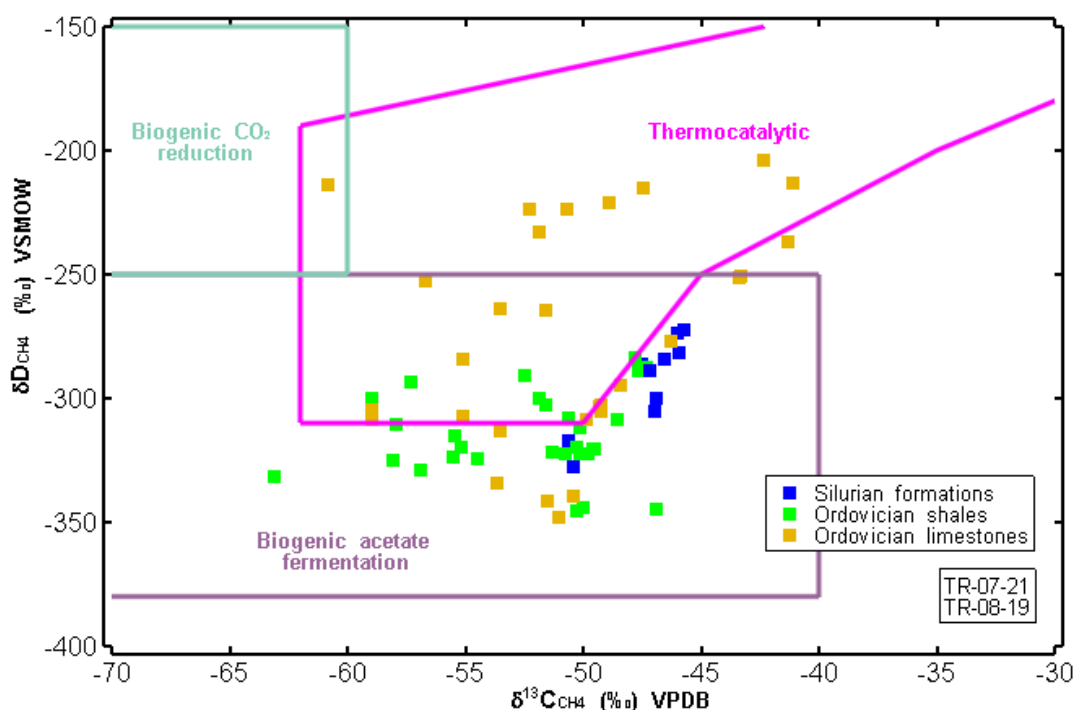


Figure 4.65 Cross plot of δD vs $\delta^{13}\text{C}$ of methane from DGR porewaters

The isotope signatures (Figure 4.64) have a steep gradient near 700 mBGS between the biogenic and thermogenic isotope signatures. This steep gradient is observed below the high methane concentrations observed in the Collingwood Member and upper Cobourg Formation. The steep gradient in isotope ratios (both $\delta^{13}\text{C}$ and D) is an indication of very slow methane transport in the Cobourg, Sherman Fall and Kirkfield Formations.

The $\delta^{13}\text{C}$ and D isotopes cannot be used to determine the age of the methane. Steep concentration gradients, including gradients of isotope ratios, should dissipate over time despite the presence of a transport barrier. The strong isotope ratio gradient near 700 mBGS suggests methane formation is either on-going, or ended relatively recently in geologic time.

4.6.7.2 Carbon Dioxide

Carbon dioxide concentrations and $\delta^{13}\text{C}$ values were measured on DGR core porewater and groundwater samples. The carbon dioxide concentrations from DGR cores were also normalized to porewater mass. As with the methane, this assumes that all of the carbon dioxide is dissolved in the porewater, therefore, the carbon dioxide concentrations are apparent concentrations. Although there is scatter in the carbon dioxide concentration and $\delta^{13}\text{C}$ isotope data, the results from DGR-2, DGR-3 and DGR-4 show the same general patterns (Figure 4.66).

The porewater $\delta^{13}\text{C}$ results show values close to the measured groundwater DIC $\delta^{13}\text{C}$ values at the same depth (Figure 4.66). The $\delta^{13}\text{C}$ in carbon dioxide is enriched in the lower Georgian Bay Formation to the Collingwood Member, which suggests biological activity is enriching the $\delta^{13}\text{C}$ signature since inorganic exchange or reaction is not likely to impart a significant enrichment. Further, this zone of $\delta^{13}\text{C}$ enrichment occurs just above a zone of higher CO_2 and CH_4 concentrations, which suggests the $\delta^{13}\text{C}$ in CO_2 enrichment may be a result of methanogenesis.

4.6.7.3 Calculated Gas Saturations

The methane and carbon dioxide concentrations measured in the porewater were calculated by dividing the mass of methane released from a rock sample by the amount of water released from the same sample (TR-07-21, TR-08-19). Although this calculation assumes that all of the gas is dissolved in the porewater, this methodology allows a convenient comparison of the apparent porewater methane and carbon dioxide concentrations to the gas solubility. Apparent methane and carbon dioxide concentrations that exceed the solubility limits suggest a separate gas phase is present.

The thermodynamic-based model developed by Duan and Mao (2006) calculates the solubility of methane and carbon dioxide at a range of solute concentrations, water temperatures and water pressures. Due to the complexity of ion-ion interactions at high solute concentrations, the Duan and Mao (2006) model assumes a binary solution, in this case NaCl.

Methane and carbon dioxide solubility curves were calculated using the Duan and Mao (2006) model at a constant temperature of 25 °C and three pressures – 2, 6 and 11 MPa. These pressures were measured in the Ordovician shales, the Cobourg Formation and the Cambrian, through hydraulic testing and groundwater monitoring using the Westbay systems at the Bruce nuclear site (Section 4.11.2).

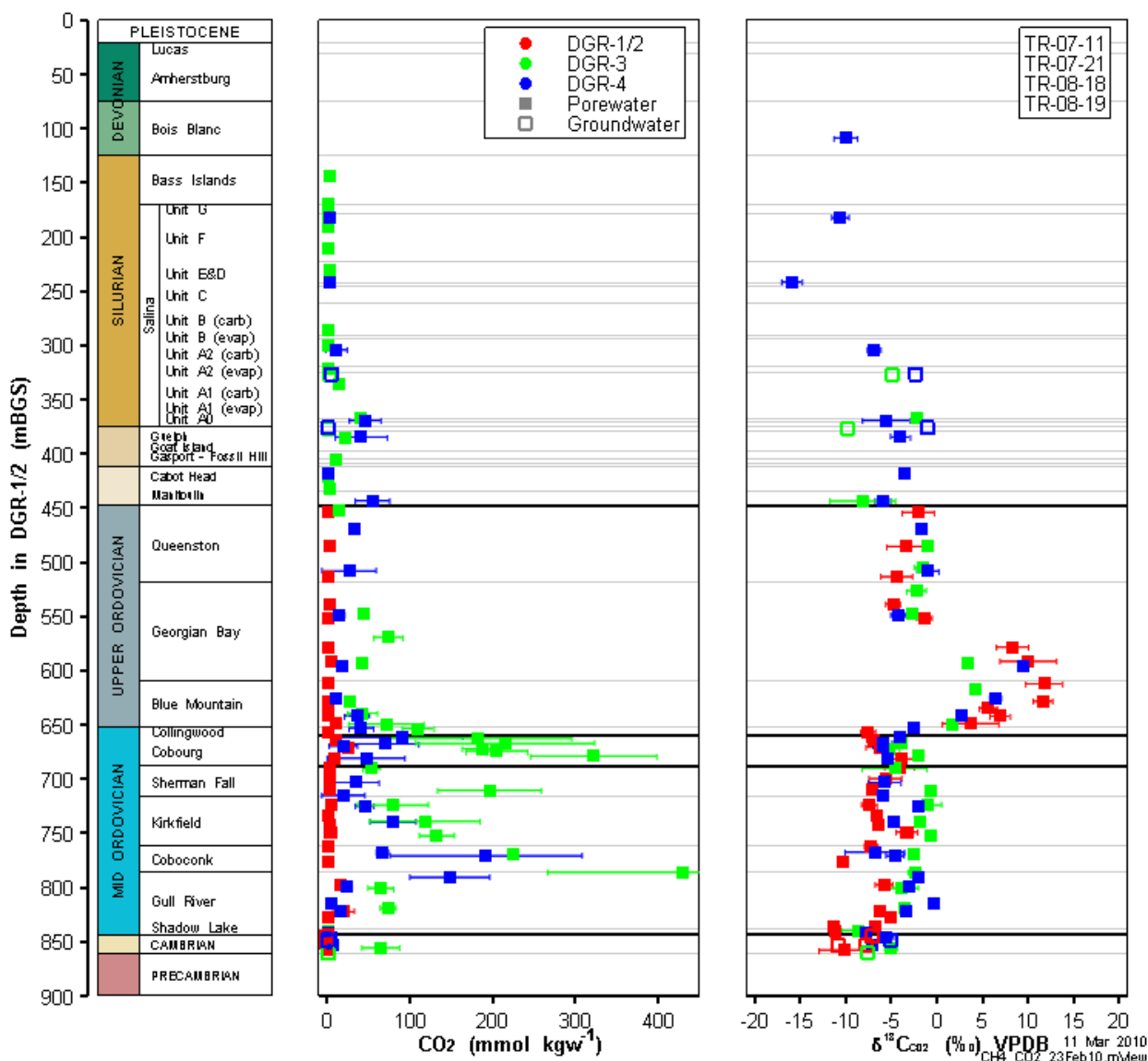


Figure 4.66 Profiles of CO₂ apparent porewater and groundwater concentrations and $\delta^{13}\text{C}$ in CO₂ in DGR boreholes

The Duan and Mao (2006) model requires solute concentrations for binary salts (i.e. NaCl). Since the porewaters at the Bruce nuclear site contain more than just Na and Cl, an equivalent NaCl concentration was calculated by two methods. The first method summed together all of the cations and anions and divided the result by two. This method assumes all of the ions in solution have the same ion-gas interaction as Na and Cl have with methane. The type of anion, for example chloride and sulphate, has a small effect on the solubility of methane in water, however, methane is more soluble with divalent cations than monovalent cations (Byrne and Stoessell, 1982). This method assumes all cations are Na ions, which likely underestimates the solubility of methane since divalent calcium and magnesium are assumed to have the same interaction with methane as monovalent sodium.

The second method used to estimate the equivalent NaCl concentration summed together the porewater Na and Cl concentrations were summed together and divided by two. This method significantly underestimates the actual porewater solute concentrations, whereas the first method listed above overestimated the equivalent NaCl concentration. A comparison of the results of the

calculated gas saturations using the equivalent NaCl concentrations calculated by both methods was presented in TR-08-34. The comparison showed the method used to estimate the NaCl concentration had little effect on the assessment of gas saturation. Subsequent discussions refer to Figures 4.66 to 4.69, which present the first method for calculating the equivalent NaCl concentration.

The methane solubility curves for NaCl concentrations were calculated for concentrations from 0 to 6 m NaCl for pressures of 2, and 11 MPa (Figures 4.67 and 4.68). The Duan and Mao (2006) model was only applicable to a NaCl concentration of 6 m for methane solubility. The dashed lines presented in Figures 4.67 and 4.68 are extrapolations of the calculated methane solubilities at each pressure. The solubility curves may not be applicable at these high molal concentrations due to ion-ion and ion-gas interactions.

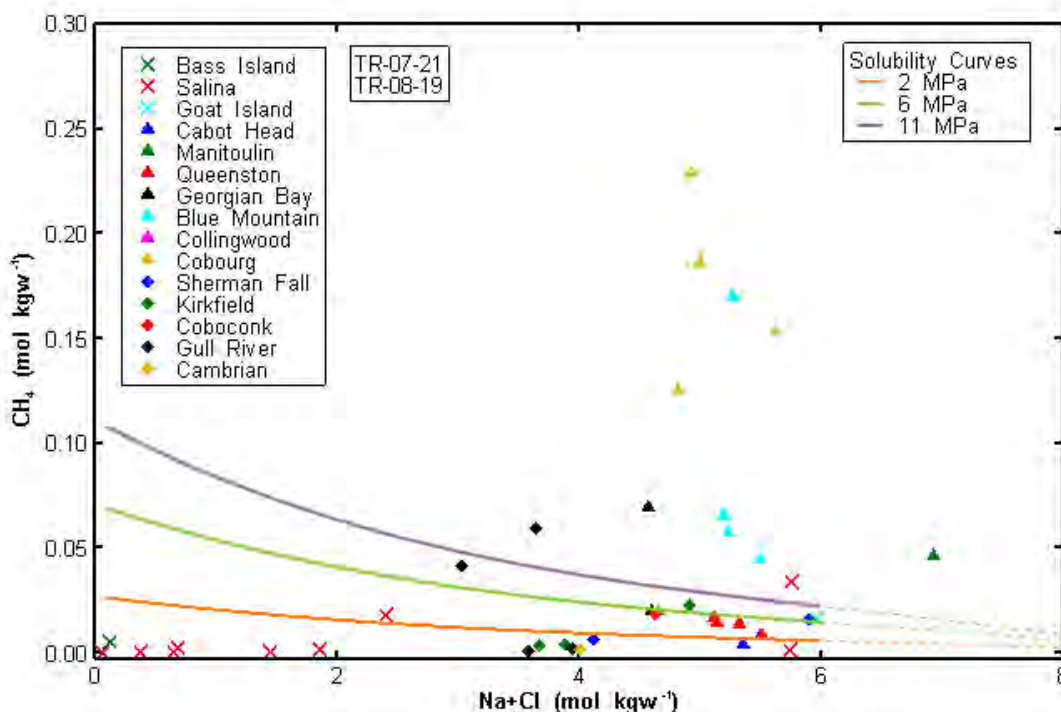


Figure 4.67 Cross plot of apparent CH_4 and $\text{Na}+\text{Cl}$ porewater concentrations compared to calculated CH_4 solubility in DGR-3

Considering the errors in analysis and solubility calculations it is difficult to confidently identify samples with methane concentrations below the 11 MPa solubility curve as super-saturated for this initial analysis. Small errors in the thermodynamic model or laboratory analyses could move the samples located near the 6 MPa line below the 2 MPa line. Even with this consideration there are several samples that plot above the methane solubility line. Methane concentrations above the 11 MPa solubility curve are primarily from the Collingwood/Cobourg and Blue Mountain formations with one to two samples from each of the Salina A1 Unit, Manitoulin, Georgian Bay, Kirkfield and Gull River Formations.

These results suggest methane could be present in the Salina A1 Unit, the Manitoulin, the Georgian Bay, Blue Mountain, Collingwood, Cobourg, Coboconk, Sherman Fall and Kirkfield units/formations. This analysis does not account for methane adsorbed to organic carbon in the formations. Methane adsorption to organic carbon may be significant where high Total Organic Carbon (TOC) is present. However, methane is still likely present as a gas phase in the Collingwood member and possibly the Cobourg and Blue Mountain Formations. Additionally, a decrease in pore pressure may cause

dissolved methane to exolve from the porewater.

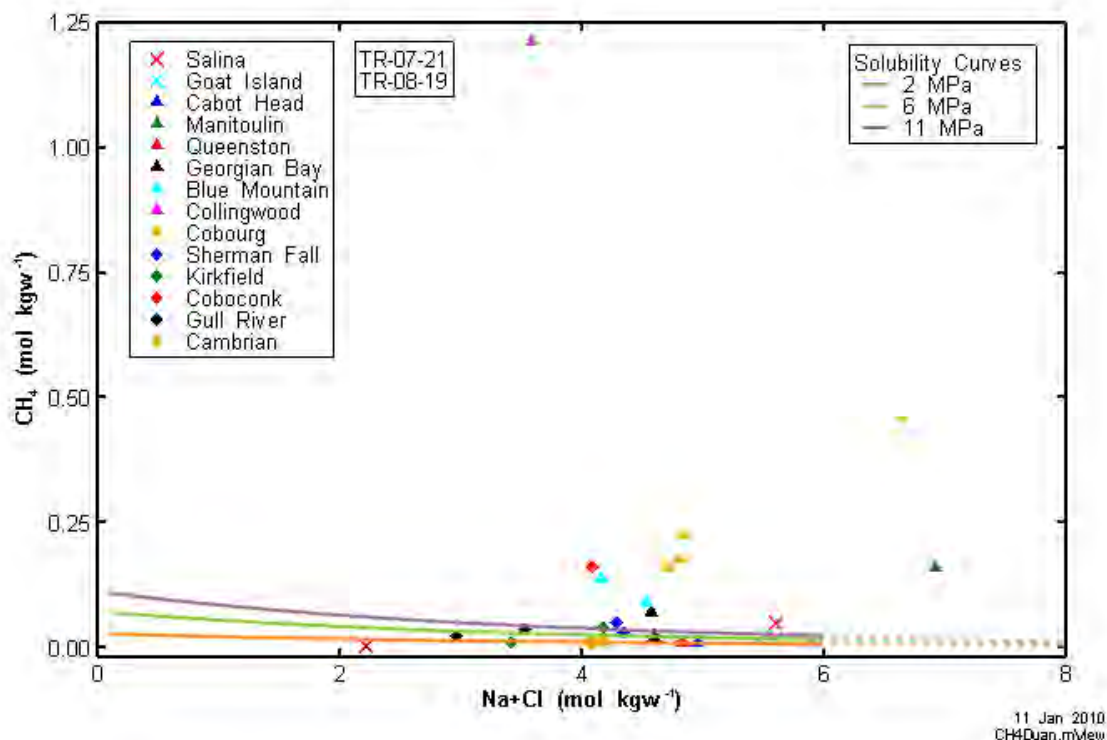


Figure 4.68 Cross plot of apparent CH_4 and Na+Cl porewater concentrations compared to calculated CH_4 solubility in DGR-4

Carbon dioxide solubility curves were calculated using the Duan and Mao (2006) model at a constant temperature of 25 C and three pressures – 2, 6 and 11 MPa (Figures 4.69 and 4.70). The equivalent NaCl concentrations used for this model were calculated using the first method described above, which summed together all of the anions and cations and divided the total by two.

The Duan and Mao (2006) carbon dioxide model was only presented for NaCl concentrations from 0 to 4.5 m. The dashed lines in Figure 4.69 and 4.70 represent the extrapolation of the thermodynamic model up to 6 m NaCl. Molal NaCl concentrations were calculated as the summation of all of the anions and cations as described above.

Comparison of the carbon dioxide concentrations to the solubility limits show carbon dioxide has not exceeded the solubility limits. Therefore, a separate carbon dioxide gas phase is not likely present. However, a decrease in the pore pressure may result in the creation of a separate carbon dioxide phase.

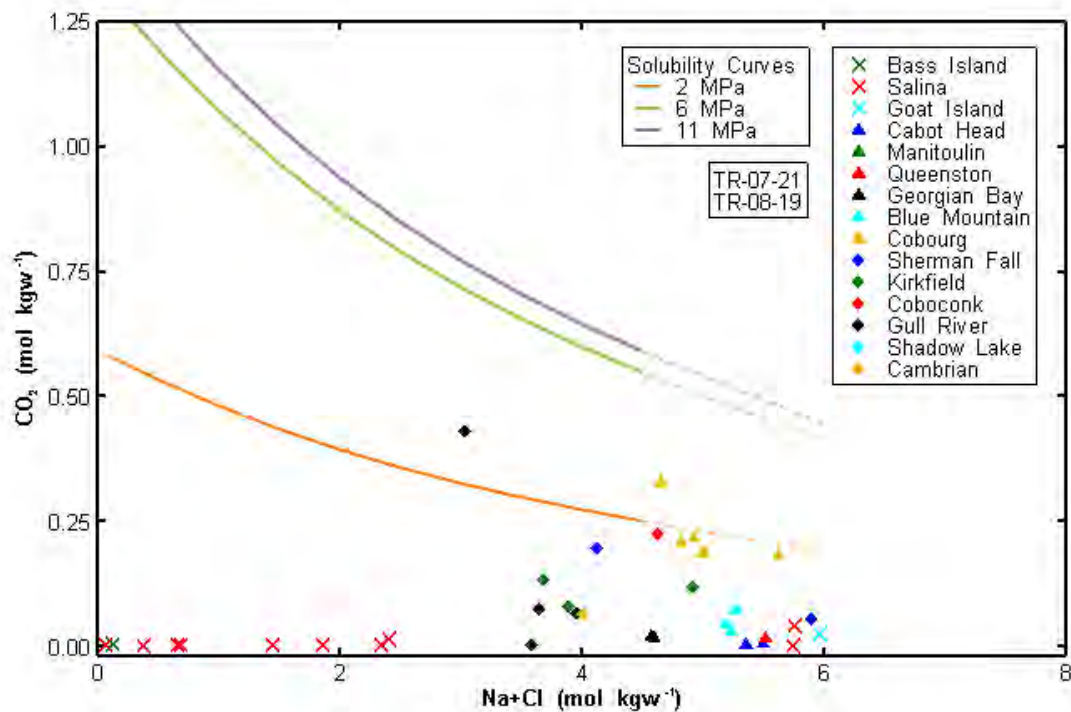


Figure 4.69 Cross plot of apparent CO_2 and Na+Cl porewater concentrations compared to calculated CO_2 solubility in DGR-3

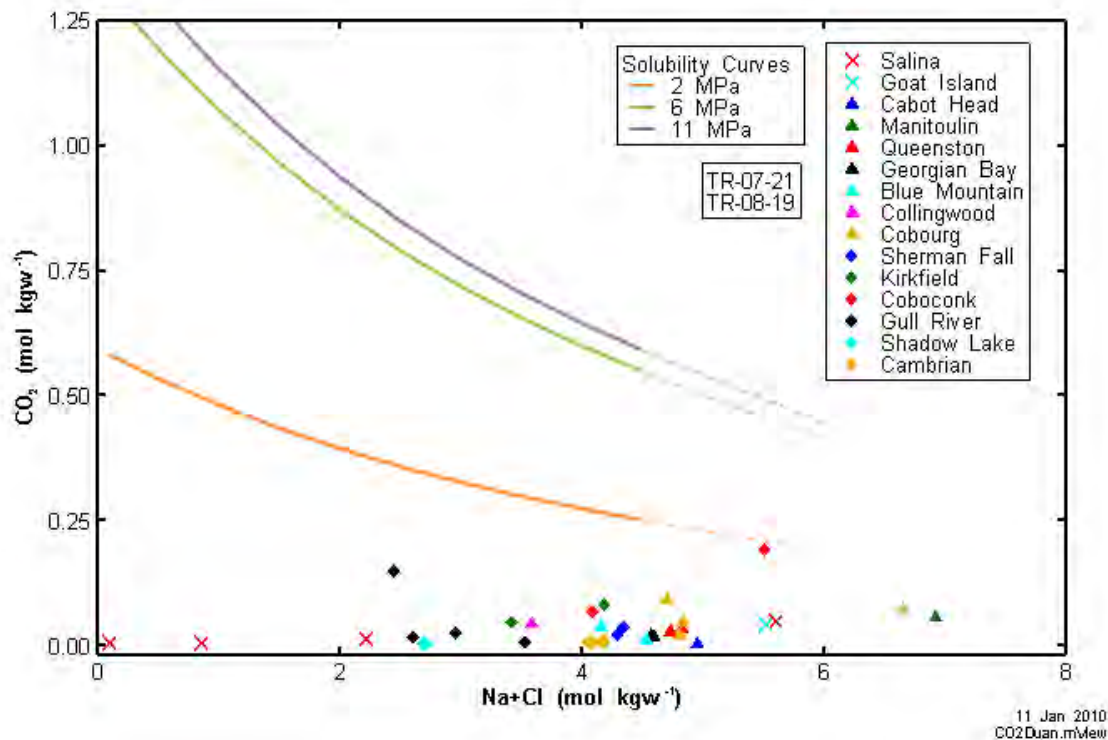


Figure 4.70 Cross plot of apparent CO_2 and Na+Cl porewater concentrations compared to calculated CO_2 solubility in DGR-4

4.6.8 Estimated Porewater pH and Redox Conditions

Porewaters were extracted at high temperature and under conditions that allow oxidation. Therefore, it is necessary to determine the pH and redox potential of these waters by indirect estimation. PHREEQC calculations were used to estimate values of pH. The CO₂ obtained from the rock core samples was added to the PHREEQC calculations and forcing calcite to have a saturation index of 0.0.

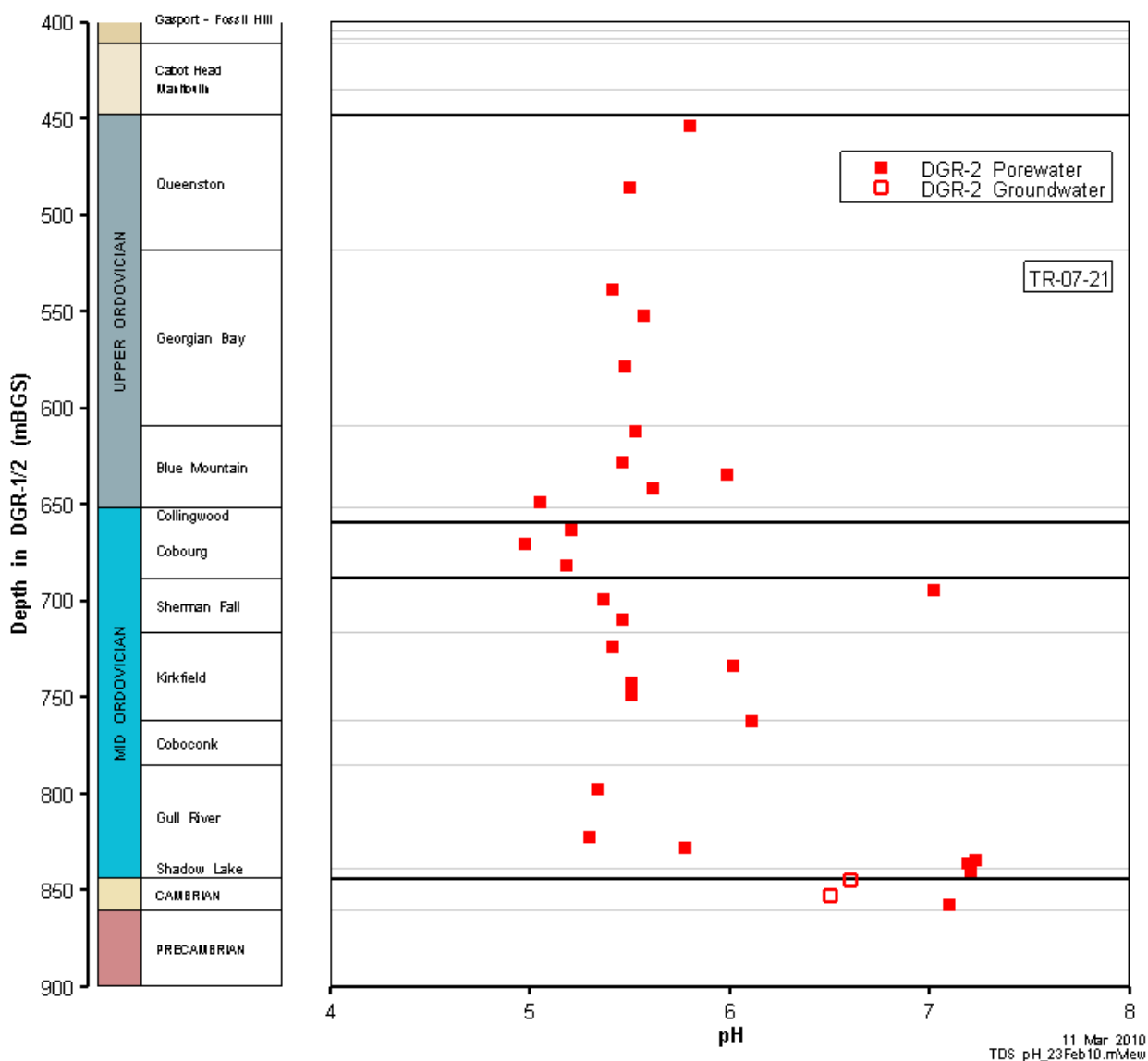


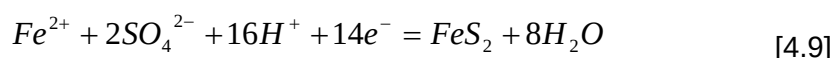
Figure 4.71 Profile of measured groundwater pH and calculated porewater pH from measured CO₂ in DGR-2

The calculated pH values for the DGR-2 porewaters are shown on Figure 4.71, and are in the range pH 5.0 – 6.0. By comparison, the artesian Cambrian brine of DGR-2 was measured on two occasions as having a pH = 6.5. The pH calculations in PHREEQC are carried out by a charge balance method and are subject to significant errors particularly associated with the assumption of carbonate (calcite)

equilibria. The calculated pH values should be considered estimates of porewater pH. For this reason, pH calculations were not carried out for DGR-3 or DGR-4. That notwithstanding, the high yields of CO₂ from the vacuum distillation and the low porewater yields, particularly for the limestones, indicate that the solution pH must be less than neutral. Further, calculated pH values for the Cambrian and Shadow Lake samples are very close to the measured pH of the Cambrian groundwater, suggesting that the calculated pH values are reasonable estimates.

It is also not possible to determine directly the redox state of porewaters from an analysis of their composition due to their method of extraction. However, available mineralogical and hydrogeochemical evidence points to the conclusion that the Paleozoic sequence of rocks beneath the Bruce nuclear site is an anoxic redox environment that is classifiable as either 'sulphidic', i.e., H₂S ≥ 1 µM, or 'methanic' (H₂S < 1 µM) in the terminology of Berner (1981). Because pyrite is ubiquitous in the DGR Paleozoic sequence it is reasonable to assume that the S(VI)-S(II-) redox potential is likely to provide a lower limit of Eh values that can be employed in geochemical modeling.

Langmuir (1997, p. 456) provides an Eh estimate based upon the assumption of ΣS(aq) = 0.01 mol/kg and ΣFe(aq) = 1x10⁻⁴ mol/kg for:



for which:

$$Eh(V) = 0.355 + 0.00423 \log[Fe^{2+}][SO_4^{2-}]^2[H^+]^{16}. \quad [4.10]$$

At pH = 6.0, which is approximately the estimated pH from PHREEQC simulations of pH in equilibrium with calcite as shown in Figure 4.44, ΣS(aq) = 0.3 mol/kg and ΣFe(aq) = 1x10⁻⁴ mol/kg, Eh = -0.07 V or pE = -1.2.

4.6.9 Helium

He profiles have been shown (Hendry et al., 2005; Rübel et al., 2002) to be important in understanding the mobility of dissolved gases in low-permeability formations and, therefore, the potential for formations to retain contaminants. However, the total concentration of He in pore fluids is very difficult to measure accurately in the presence of a free gas phase as may exist in the DGR Paleozoic rock column (see Section 4.3.3). Although total He per gram of rock is readily measured by the method employed, normalizing to pore fluid requires a precise measurement of both the brine volume and any separate gas phase that exists. The low solubility of He in brines makes this an important measurement in establishing the pore-scale partial pressure of He that would drive diffusion through the section. Therefore, this discussion is limited to the measured isotopic ratio of ³He/⁴He in DGR samples to that in air (xRa) as shown in Figure 4.72.

The DGR-2 profile is reproduced by the DGR-3/4 profile using a slightly modified method of micro-drilling cores in the field and encapsulating them in copper tubes. The remarkably good overlay of the two profiles in Figure 4.72 adds confidence to the interpretation that the lower Cobourg/upper Sherman Fall is characterized by exceedingly low gas permeability. This is consistent with the low diffusivity zone observed with the methane isotope profile (see Section 4.6.7.1) and the very low field measurements of hydraulic conductivity at this location in DGR boreholes (see Figure 4.82).

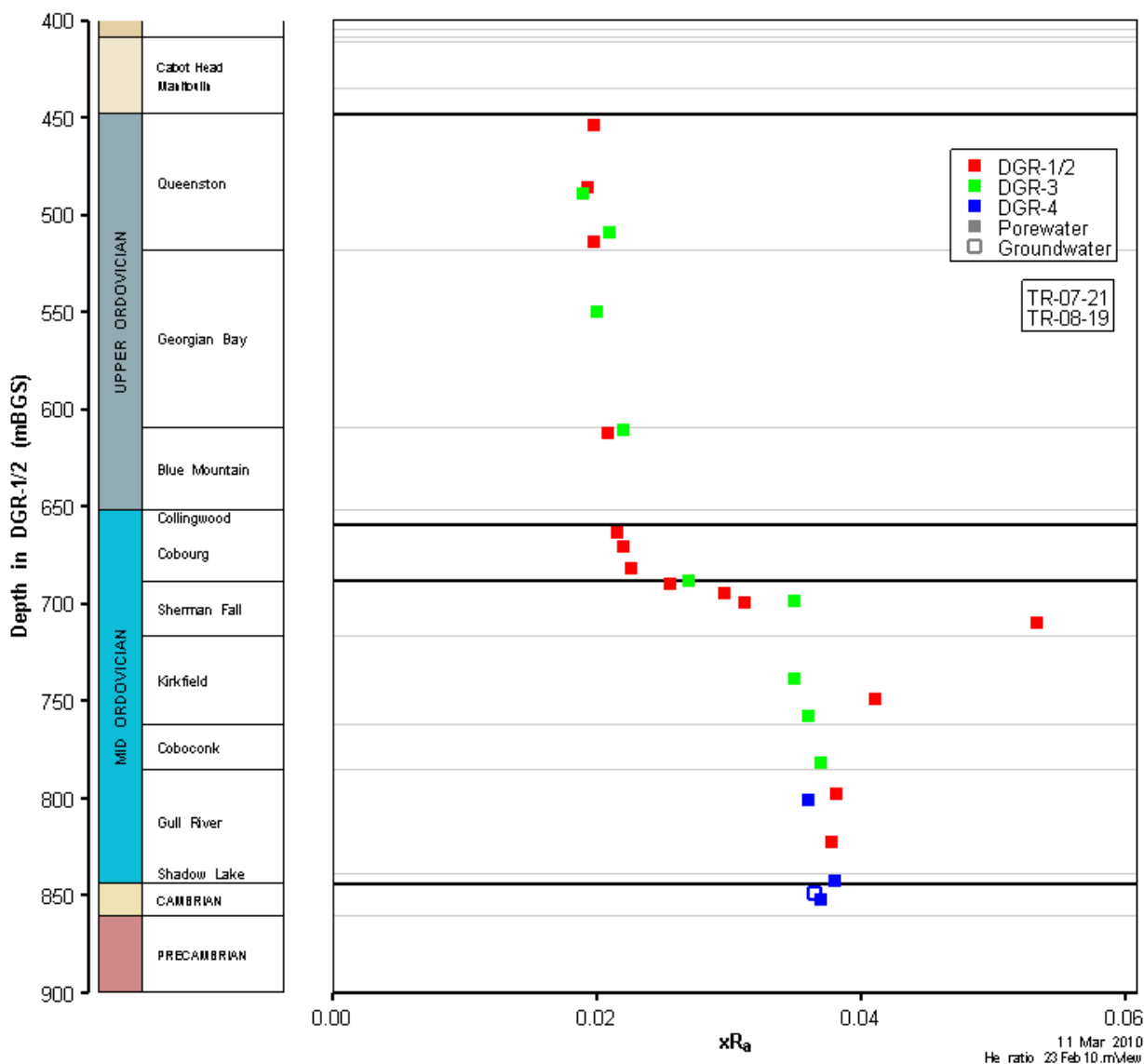


Figure 4.72 Profile of ratio $^3\text{He}/^4\text{He}$ in DGR porewater and groundwater normalized to He in air

The $^3\text{He}/^4\text{He}$ ratio profile brings a supporting perspective that is independent of the normalization uncertainties that affect the He concentration data. Consistent with the CH_4 isotope ratios, the $^3\text{He}/^4\text{He}$ ratio suggests a two component source for He in this section. The Ordovician shales have a relatively uniform ratio close to $x\text{Ra} \sim 0.02$, which transitions over less than about 50 m to a higher $^3\text{He}/^4\text{He}$ ratio ($x\text{Ra} \sim 0.04$) in the deeper limestones. This value for the Lower Ordovician porewaters is within the range reported for Cambrian gas field He in southwestern Ontario by Sherwood Lollar et al., (1994; mean $x\text{Ra} = 0.035$). Further, this transition is also found at the base of the Cobourg, providing further evidence for a diffusional barrier at this horizon. The $^3\text{He}/^4\text{He}$ gradient at the base of the Cobourg is similar to that observed in the methane isotopic data (see Figure 4.64) as well as that suggested by the gas entry pressure data (Section 4.3.6).

4.7 Radioisotopes in Groundwater and Porewater

The Geoscientific Site Characterization Plan was prepared making the assumption that the deep groundwater system in the shales and limestones is saline, stagnant, stable and ancient (Intera Engineering Ltd., 2008). The measured low permeability of the argillaceous sedimentary rocks

reported elsewhere in this DGSM (Section 4.9.2) suggests diffusion is the controlling process in solute transport throughout most of the Paleozoic bedrock sequence from Salina Formation down to the top of the Black River limestones as defined by the Coboconk Formation. Notable exceptions to this general observation are the permeable aquifers of the Salina Upper A1 Unit and the Guelph Formation. This general assumption has not been considered applicable to the shallow groundwater flow system in the Devonian and Upper Silurian formations for which there is strong evidence that they have been penetrated by recharge that occurred during the Quaternary period similar to that reported in Michigan by McIntosh and Walter (2005 and 2006).

Consequently, an independent means of estimating the ages of the porewater or groundwater in the depth profile modeled would help justifying the assumptions of diffusion controlled radionuclide migration in the Ordovician shales and limestones and modern recharge in the shallow dolostones. Given the range in potential ages of the groundwaters and porewaters in the Paleozoic rock sequence at the DGR, radioisotope dating provides an appropriate tool to estimate the ages of the groundwater and porewater and to improve our understanding of solute transport at the Bruce DGR site. The radioisotopes considered for use are ^{14}C ($t_{1/2}=5730$ yr), ^{36}Cl ($t_{1/2}=301,000$ yr) and ^{129}I ($t_{1/2}=1.6\times 10^7$ yr) because their long half lives permit estimation of solute residence times in the groundwaters and porewaters of the DGR rocks. TR-08-38 provides a detailed description and discussion of the characterization of radioisotopes in DGR groundwater and porewater.

4.7.1 ^{14}C in Shallow Groundwaters

The ages of shallow Devonian and Upper Silurian groundwaters present in fractures and solution cavities above the Salina F Unit shale have been investigated by ^{14}C dating. The $\delta^{13}\text{C}$ mixing model of Pearson (1965) and Pearson and Hanshaw (1970) was applied to correct the apparent radiocarbon ages as described by Clark & Fritz (1997, pp. 210-211). Table 4.11 presents the results from groundwater samples collected from the US series of Westbay multi-level wells.

Corrected ages suggest mid Holocene recharge at most depths. There is no general trend towards older ^{14}C ages with depth. The samples from 68.9 m and 158.0 m depth have comparatively greater corrected ages. The deeper (158.0 mBGS) sample was recovered from the Upper Silurian dolostones and has a depleted $\delta^{18}\text{O}$ value (-16.6‰) and the oldest ^{14}C age (7700 yrs BP) that indicate a component of glacial meltwater recharge.

Table 4.11 Apparent radiocarbon ages in years before present and the percent modern carbon (pmC) of selected shallow groundwater samples as well as radiocarbon ages corrected using the $\delta^{13}\text{C}$ mixing model.

<i>Borehole and Depth (mBGS)</i>	<i>Apparent ^{14}C Age (Years BP)</i>	<i>% Modern Carbon (pmC)</i>	<i>Corrected ^{14}C Age (Years BP)</i>
US3-32.30	12550 $\pm$ 70	20.96 $\pm$ 0.18	4741
US3-68.50	12100 $\pm$ 70	22.16 $\pm$ 0.19	4468
US7-68.90	14450 $\pm$ 80	16.54 $\pm$ 0.16	7290
US8-40.60	5810 $\pm$ 50	48.50 $\pm$ 0.30	4447
US8-120.80	8030 $\pm$ 60	36.79 $\pm$ 0.27	4666
US8-158.00	13270 $\pm$ 70	19.16 $\pm$ 0.17	7709
US8-179.40	12070 $\pm$ 70	22.25 $\pm$ 0.19	4732

4.7.2 ^{36}Cl and ^{129}I in Porewaters and Groundwaters

A means of estimating the age and tracing the potential migration of the porewater or groundwater in the depth profile is provided by other longer-lived radioisotopes. In particular, ^{36}Cl ($t_{1/2}=301,000$ yr) and ^{129}I ($t_{1/2}=1.6\times 10^7$ yr) were chosen because of their longer half lives and subsurface production that may permit estimation of residence times of solutes in the groundwaters and porewaters of the DGR rocks at the Bruce nuclear site. Measured concentrations can be attributed to in-growth towards secular equilibrium in the host formation, or to transport of ^{129}I and ^{36}Cl from higher or lower geogenic production zones in the subsurface (Bentley et al., 1986). Bottomley et al. (2002) employed ^{129}I to identify a residence time of greater than 80 million years for the Shield brine collected in the Con Mine, Yellowknife, NWT. The coupled use of these two radioisotopes has resulted in several successful hydrogeological studies according to Fabryka-Martin (1999). She also noted "that during normal operations of nuclear power stations, negligible amounts of ^{129}I are discharged to the environment", consequently contamination of DGR drilling fluids should also be negligible.

Measurements and analyses of ^{129}I and ^{36}Cl concentrations in DGR porewaters and groundwaters are incomplete at this time and will be provided when all measurements are available.

4.8 Fluid Density

Groundwater (GW) and porewater (PW) chemistry data and field and laboratory fluid density measurements were used to generate a profile of formation fluid density for the Paleozoic bedrock column at the Bruce nuclear site (TR-08-31). Figure 4.73 shows the fluid density versus depth and formation data, the recommended or reference density profile selected for the DGR bedrock sequence, and arithmetic formation averages. A reference density profile is required to calculate environmental water heads from fresh water heads in variable density fluid systems as exist at the Bruce nuclear site.

Figure 4.73 includes laboratory measurements of fluid density on groundwater samples collected during drilling of DGR boreholes (TR-07-11, TR-08-18), on groundwater samples collected from Westbay MP-38 casing completion in US-8 (TR-08-08) and calculations of fluid density from major ion analyses of porewater reported by University of Ottawa (TR-07-21, TR-08-19) discriminated based on charge balance (CB) error, and by University of New Brunswick (TR-07-17, TR-08-27). For groundwater samples collected from the Salina Upper A1 Unit aquifer in DGR-4, the fluid density was calculated from the measured TDS as the laboratory density value was judged to be unreliable.

Fluid densities reported from groundwater sampling and by the University of New Brunswick were in units of kg/m^3 of solution. Since porewater chemistries reported by the University of Ottawa were in units of g/kg of water, these units were converted to kg/m^3 of solution by scaling the porewater TDS in units of g/kg of water to the known average groundwater density of the Guelph Formation (1234 kg/m^3) and the calculated average groundwater TDS of the Guelph Formation (451.8 g/kg of water). The similarity of fluid densities reported for porewaters by different laboratories and from direct measurements on groundwater samples from non-Guelph aquifers to those calculated from porewater analyses provides confidence in the reference density profile.

Figure 4.73 shows a density profile that transitions from fresh water ($\rho=990\text{-}1000 \text{ kg/m}^3$) in the upper dolostone units (Lucas, Amherstburg, Bois Blanc and Bass Islands Formations) through brackish water ($\rho=1010 \text{ kg/m}^3$) in the Salina F Unit to the brine ($\rho=1070 \text{ kg/m}^3$) in Salina Formation B Unit. From the Salina B Unit down to the upper A1 Unit aquifer the water density significantly decreases to the saline water that characterises the upper A1 Unit aquifer ($\rho=1018 \text{ kg/m}^3$). There is then a significant increase in water density from the upper A1 Unit aquifer to the brine found within the Guelph Formation ($\rho=1234 \text{ kg/m}^3$) which is the highest TDS and density fluid measured at the DGR site.

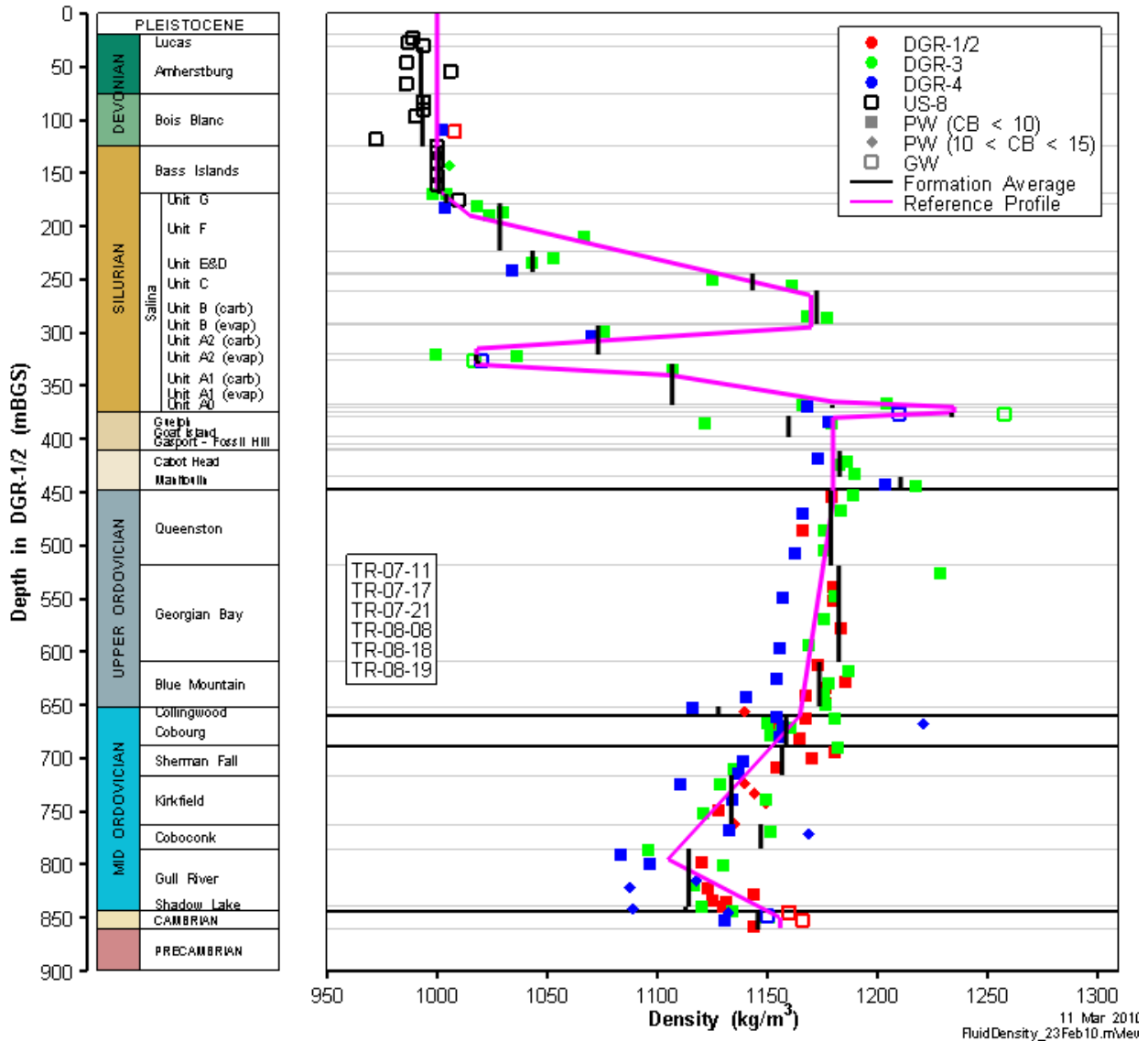


Figure 4.73 Reference fluid density profile and formation averages based on US-8 and DGR borehole groundwater and porewater data

From the Guelph downward the water density decreases to 1180 kg/m^3 in the Goat Island to Manitoulin Formations. Through the Ordovician shales the fluid density decreases from 1180 kg/m^3 in the upper Queenston Formation to 1160 kg/m^3 at the bottom of the Collingwood Member. Further reductions in porewater density occur down through the Ordovician limestones to the top of the Gull River Formation with fluid density of 1105 kg/m^3 . Fluid density then increases through the Gull River and Shadow Lake Formations to an average groundwater density of 1156 kg/m^3 within the Cambrian sandstone.

4.9 Formation Hydraulic Conductivity

4.9.1 Shallow Bedrock – US Wells

Data on formation horizontal hydraulic conductivity for the shallow bedrock (Lucas, Amherstburg, Bois Blanc and Bass Islands Formations) are available from summaries of geotechnical bedrock investigations and Bruce A and B cooling water intake tunnelling experience (Golder Associates Ltd, 2003), straddle packer testing of US-1 to US-7 (106 tests - Lukajic, 1988), slug testing of Westbay test intervals in US-5 and US-6 (14 tests - Golder Associates Ltd, 2003) and from drilling fluid loss observations made during drilling of US-8 (TR-07-19) and DGR boreholes (TR-07-06, TR-08-13). Packer test flowrates and injection pressures and drilling fluid loss rates and heads were converted to equivalent hydraulic conductivities assuming conditions of confined steady radial flow.

Table 4.12 summarizes recommended estimates of horizontal hydraulic conductivities for the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations, the basis/rationale for the estimate and the data source for their inclusion in this report. Of note are the very permeable sections (1×10^{-4} m/s) of the upper 20 m of Bass Islands Formation that created significant drilling fluid losses during drilling of all DGR boreholes and US-8.

Table 4.12 Summary of horizontal hydraulic conductivities for Lucas, Amherstburg, Bois Blanc and Bass Islands Formations

Formation	Hydraulic Conductivity (m/s)	Basis/Rationale	Source
Lucas and Amherstburg (<30 m)	6×10^{-9} to 3×10^{-5} 2×10^{-6}	Range, geometric mean from packer tests in US boreholes	Analysis of Lukajic (1988) Data
Lucas and Amherstburg (<30 m)	4×10^{-9} to 2×10^{-4} 5×10^{-7}	Range, geometric mean from Bruce A site investigations	Golder Associates Ltd. (2003)
Amherstburg (>30 m)	8×10^{-10} to 8×10^{-5} 8×10^{-8}	Range, geometric mean from packer tests in US boreholes	Analysis of Lukajic (1988) Data
Amherstburg (>30 m)	1×10^{-8} to 2×10^{-5} 2×10^{-7}	Range, geometric mean from Bruce A site investigations	Golder Associates Ltd. (2003)
Bois Blanc (to 100 m)	6×10^{-10} to 1×10^{-5} 1×10^{-7}	Range, geometric mean from packer tests in US boreholes	Analysis of Lukajic (1988) Data
Combined Amherstburg and Bois Blanc	1×10^{-6} to 1×10^{-4} 1×10^{-5}	Range, geometric mean from tunnel dewatering experience and slug testing of US-5 & US-6 casings	Golder Associates Ltd (2003)
Bass Islands (upper 20 m)	1×10^{-5} to 3×10^{-4} 1×10^{-4}	Analysis of drilling fluid losses in US-8 and DGR boreholes	TR-07-06, TR-07-19, TR-08-13
Bass Islands	1×10^{-5}	Estimated average representative value	Golder Associates Ltd (2003)

4.9.2 Deep Bedrock – DGR Boreholes

4.9.2.1 Field Testing

Field measurements of deep bedrock formation horizontal hydraulic conductivity were made in all DGR boreholes using a custom-built straddle-packer hydraulic testing tool (TR-08-32) as well as during opportunistic groundwater sampling using a bottom-hole, production-injection packer (PIP) during drilling. Hydraulic test responses were collected from 3 intervals (12 m test zone) in DGR-1, 15 intervals (30.5 m test zone) in DGR-2, 23 intervals (30.7 m test zone) in DGR-3, and 24 intervals (30.7 m test zone) in DGR-4. The hydraulic tests performed in DGR boreholes included pulse, slug, and drill-stem tests (DST) using a workover rig and drill tubing to position the test tool in the borehole (see

Figure 4.74.



Figure 4.74 Straddle-packer hydraulic testing at DGR-4 using workover rig and drill tubing

The testing in DGR-1 targeted selected intervals from 199.76 to 447.75 mBGS based on the stratigraphy and information obtained during fluid electrical conductivity logging (TR-07-14). The testing in DGR-2, DGR-3 and DGR-4 provided continuous coverage of the open sections of each borehole typically from the bottom of the steel casing in the Salina F Unit to near the top of the PIP set in the Shadow Lake Formation to control artesian flow from the Cambrian sandstone.

During each straddle-packer hydraulic test, pressures within, below and above the test interval (within drill tubing and borehole annulus), as well as pressures controlling packer inflation, the downhole open-close shut-in valve and the downhole pulse piston, and atmospheric pressure were continuously monitored in real time. Figure 4.75 provides an example of the pressure data obtained during each straddle-packer hydraulic test performed in DGR boreholes.

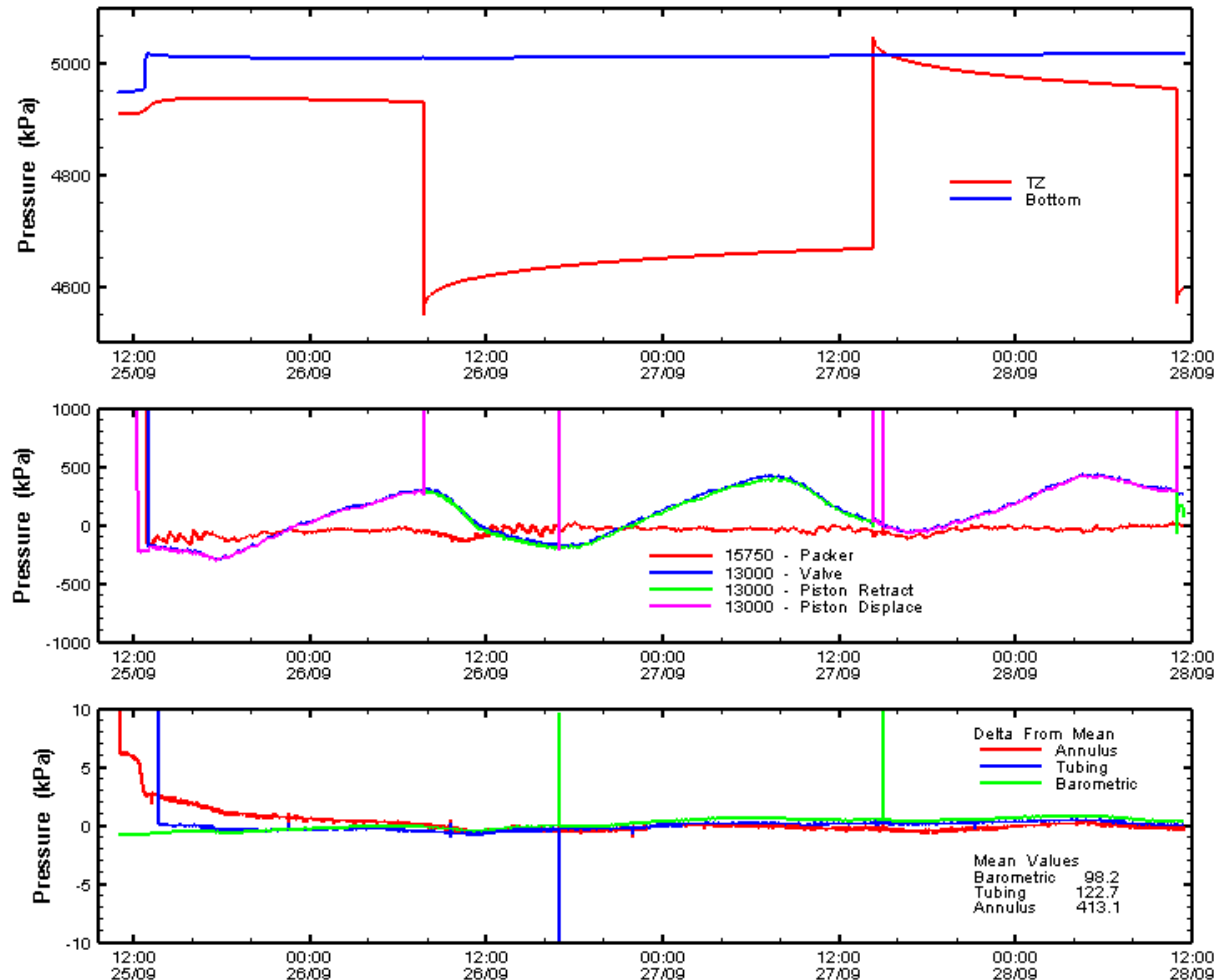


Figure 4.75 Pressure data recorded during pulse hydraulic testing of interval 471.41-502.15 mBGS in DGR-3 in Queenston Formation

The DGR borehole hydraulic test data were analysed to determine best-fit, minimum, maximum and mean estimates of formation hydraulic conductivity and formation pressure and other formation parameters including borehole skin thickness and hydraulic conductivity and formation specific storage. Test analyses included consideration of test interval pressure history based on drilling and drilling fluid density information and in-hole pressures recorded prior to packer isolation of the test interval.

The computer code used for analysis of the hydraulic tests was Sandia National Laboratories numerical hydraulic-test simulator, nSIGHTS (**n**-dimensional **S**tatistical **I**nverse **G**raphical **H**ydraulic **T**est **S**imulator), a numerical well-test analysis code. Description of the straddle-packer hydraulic testing program including testing and analysis methodologies, quantification of uncertainty using perturbation analyses and detailed analysis of DGR-1, DGR-2, DGR-3 and DGR-4 tests are given in TR-08-32.

Figures 4.76 to 4.79 show examples of simulated tests and field test data used to determine horizontal formation hydraulic conductivity and static formation pressure. Figure 4.76 shows the comparison of best-fit simulated and measured test pressure for the pulse test of the 471.41-502.15 mBGS interval of the middle of the Queenston Formation in DGR-3. Figure 4.77 is the XY-scatter plot for the same test showing the goodness of fit for different estimates of formation hydraulic conductivity and static formation pressure derived from the perturbation analysis of the test data.

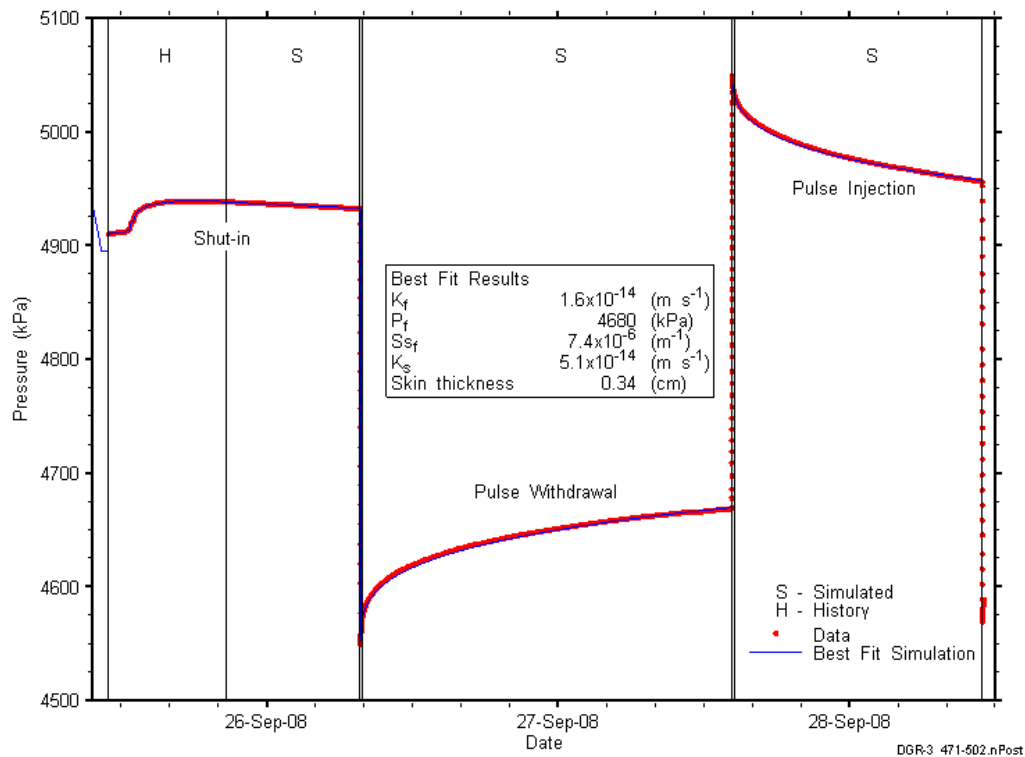


Figure 4.76 Annotated pulse testing sequence showing test data, best-fit simulation and parameter estimates. Test interval 471.41-502.15 mBGS in DGR-3 in Queenston Formation

Figure 4.76 shows the test sequence including pre-shut-in period (with quantified pre-test pressure history – H), and the post-shut-in simulated (S) test phase comprising a pulse withdrawal and pulse injection that were completed over a three-day period. Analysis of this straddle-packer hydraulic test indicates a horizontal formation hydraulic conductivity (K_f) of 1.6×10^{-14} m/s, negative skin of thickness 0.34 cm and hydraulic conductivity (K_s) of 5.1×10^{-14} m/s, and static formation pressure (P_f) of 4680 kPa. An estimate of test interval formation specific storage (S_{sf}) of 7.4×10^{-6} m⁻¹ is also generated from the test, however the analysis is not particularly sensitive to this parameter.

Figure 4.78 shows the comparisons of the best fit simulated and measured test pressure for the pulse test of the 658.46-689.120mBGS interval covering all of the Cobourg Formation limestone (the repository horizon) and the lower 3.0 m of the overlying Collingwood Member shale in DGR-4. Figure 4.79 is the XY-scatter plot for the same test showing the goodness of fit for different estimates of formation hydraulic conductivity and static formation pressure derived from the perturbation analysis of the test data.

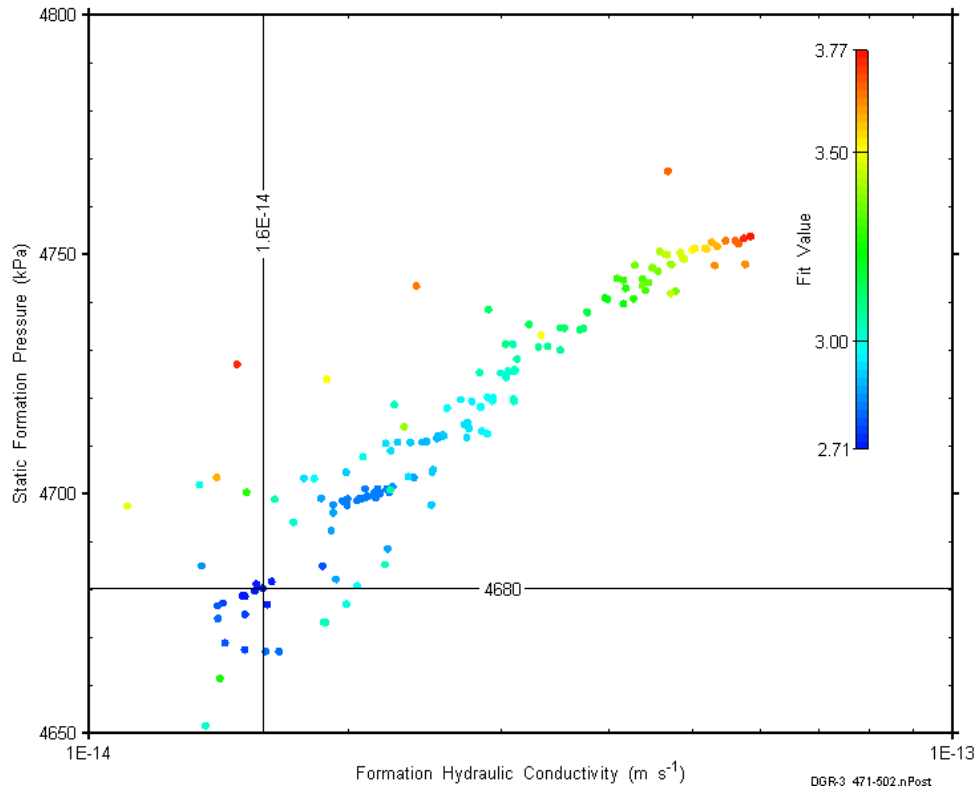


Figure 4.77 XY-scatter plot showing estimates of formation conductivity and raw static formation pressure derived from perturbation analysis. Test interval 471.41-502.15 mBGS in DGR-3 in Queenston Formation

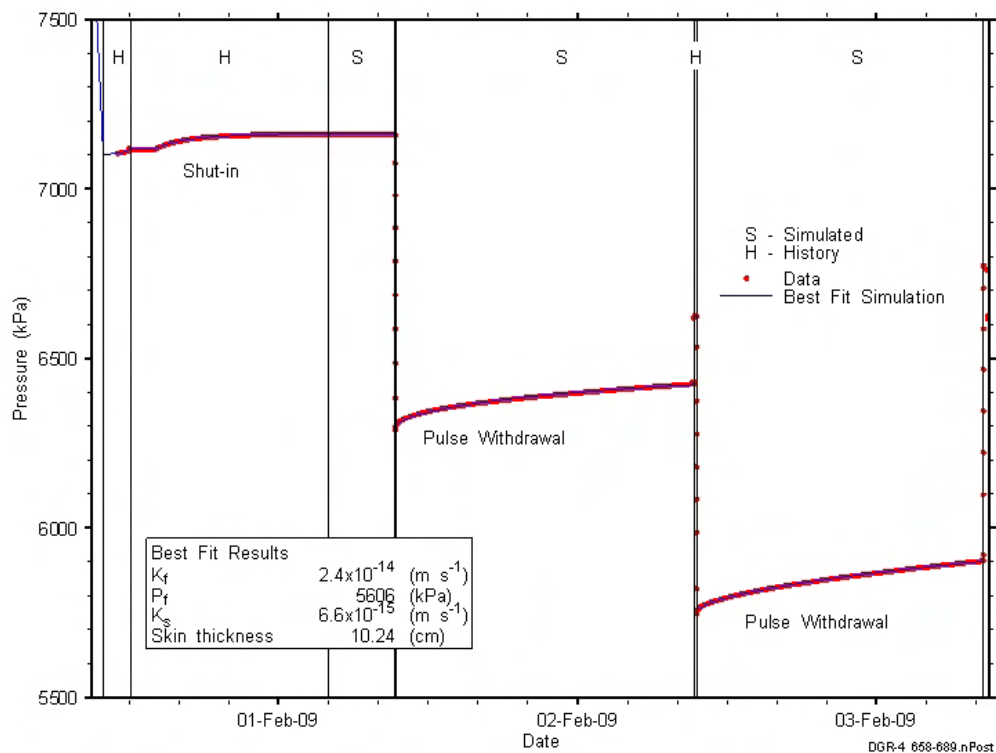


Figure 4.78 Annotated pulse testing sequence showing test data, best-fit simulation and parameter estimates. Test interval 658.46-689.20 mBGS in DGR-4 in Cobourg Formation

Similar to Figure 4.76, Figure 4.78 shows the test sequence including pre-shut-in period (with quantified pre-test pressure history – H), and the post-shut-in simulated (S) test phase comprising a pulse withdrawal and pulse injection that were completed over a three-day period. Analysis of this straddle-packer hydraulic test indicates a horizontal formation hydraulic conductivity (K_f) of 2.4×10^{-14} m/s, a positive skin of thickness of 10.2 cm and hydraulic conductivity (K_s) of 6.6×10^{-15} m/s, and static formation pressure (P_i) or 5606 kPa. The formation specific storage value for this test analysis was set at $1.0 \times 10^{-6} \text{ m}^{-1}$, a value estimated from preliminary perturbation analysis.

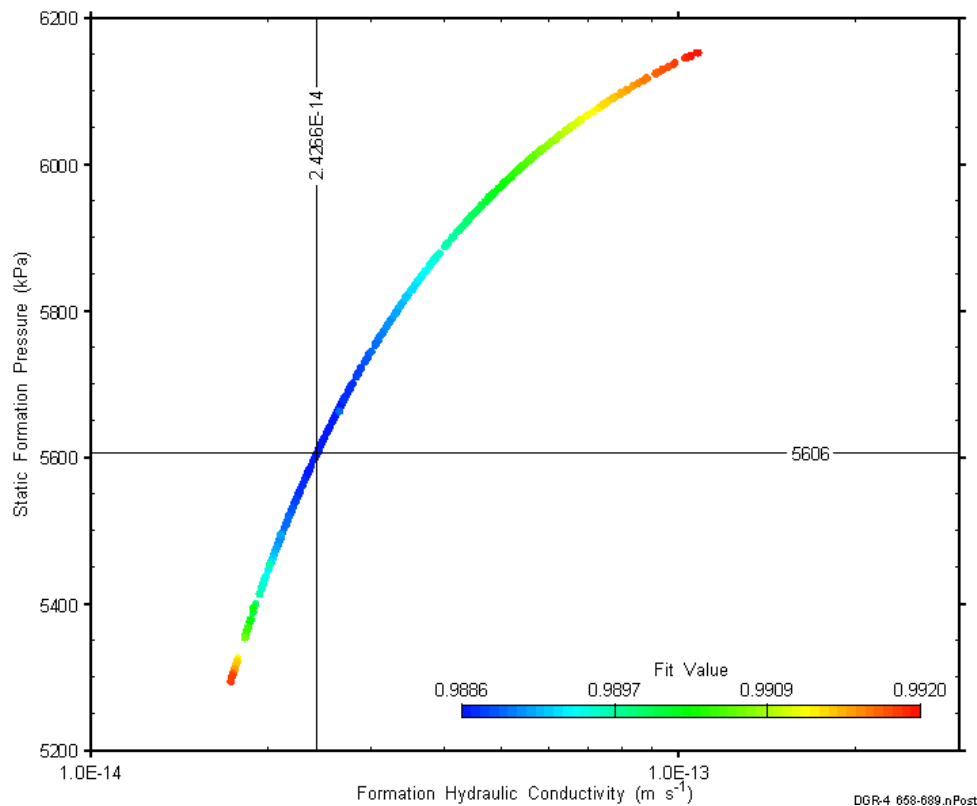


Figure 4.79 XY-scatter plot showing estimates of formation conductivity and raw static formation pressure derived from perturbation analysis. Test interval 658.46-689.20 mBGS in DGR-4 in Cobourg Formation

The results of the straddle-packer hydraulic testing of DGR boreholes are summarized versus depth and formation in Figures 4.80 and 4.81. Figure 4.80 shows calculated formation hydraulic conductivities and Figure 4.81 shows calculated test interval compressibilities. No straddle-packer hydraulic test results are available for the Shadow Lake Formation and Cambrian sandstone because of the installation of temporary PIPs to control formation fluid flow from the Cambrian sandstone. Results presented for DGR-2 are preliminary. Results for DGR-1, DGR-3 and DGR-4 are final.

Figure 4.80 shows that the calculated test interval hydraulic conductivities in DGR boreholes below the Salina G Unit range from 10^{-16} to 10^{-8} m/s. The lowest measured test interval hydraulic conductivities of less than 10^{-15} m/s were determined from testing of the Sherman Fall and Kirkfield Formations in DGR-2 (preliminary results). The highest test interval hydraulic conductivities of greater than 10^{-8} m/s were determined for tests that included the porous and permeable sections of the Salina Upper A1 Unit and the Guelph Formation. The bedrock below the Guelph Formation to the Queenston shale has test interval hydraulic conductivity between 4×10^{-14} and 2×10^{-11} m/s. The bulk of the Ordovician shales and all the Ordovician limestones from the Cobourg to the Kirkfield Formation

(i.e., the Trenton Group) have very low test interval hydraulic conductivity of less than 10^{-15} to 5×10^{-14} m/s. Slightly higher test interval hydraulic conductivities (9×10^{-14} to 3×10^{-13} m/s) attributed to identified single fractures or zones of closely spaced fractures were measured within one test interval in each DGR borehole (lower Georgian Bay in DGR-2 and DGR-4, Blue Mountain in DGR-3). The deeper Ordovician limestones of the Black River Group (Coboconk and Gull River Formations) have higher test interval hydraulic conductivity of between 1×10^{-13} and 5×10^{-11} m/s, which also may reflect the influence of thin, suspected increased permeability zones (e.g., the Coboconk ash layer).

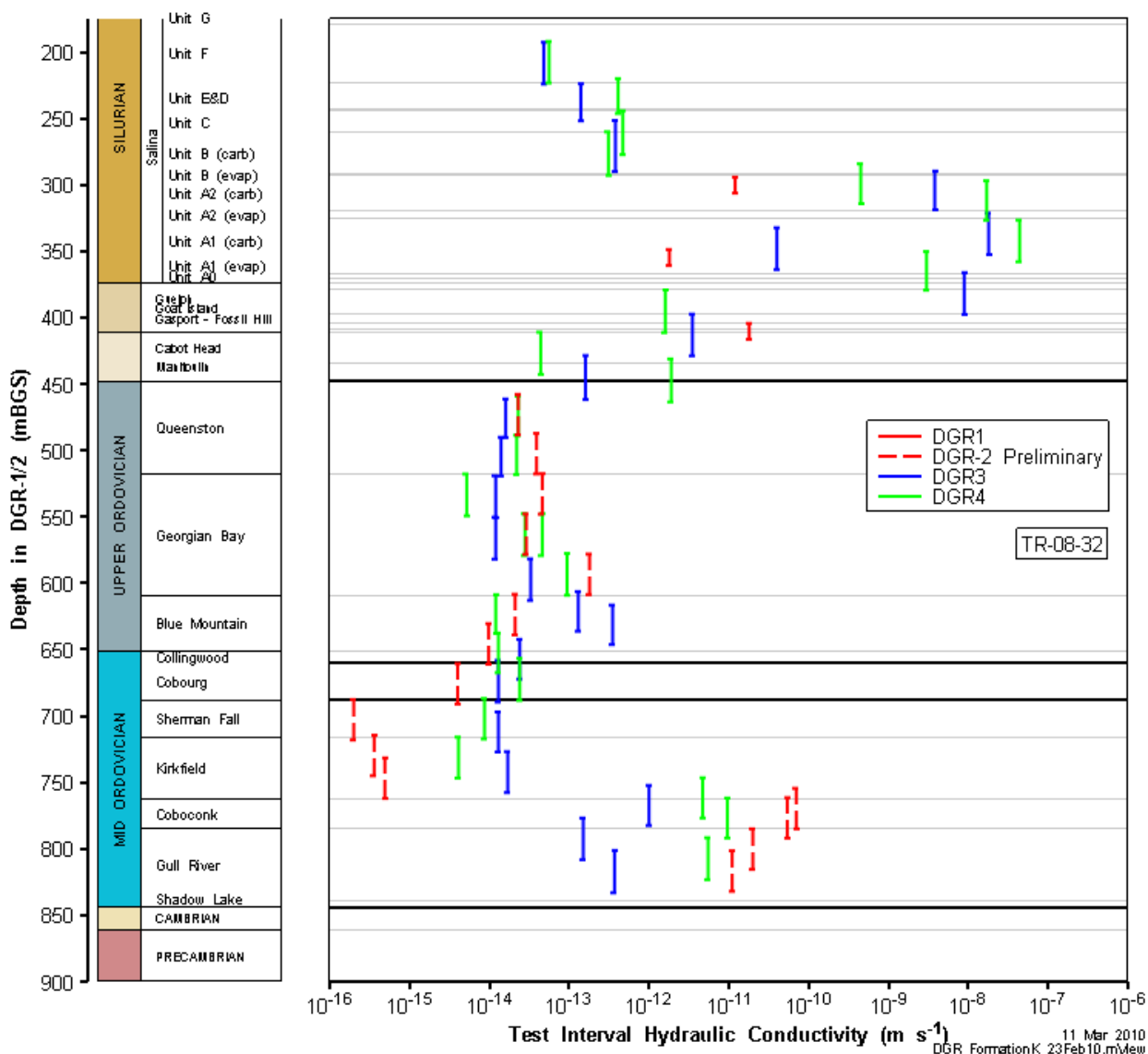


Figure 4.80 Profile of test interval hydraulic conductivity estimates determined from field straddle-packer testing in DGR boreholes

Figure 4.81 shows the calculated test interval compressibilities from known fluid volume displacements of the pulse piston, calculated test interval volumes and the measured test interval pressure pulse magnitudes. Test interval compressibility is reported because it can be a diagnostic measure of packer compliance, formation compressibility, presence of gas within the test interval and adjacent formation or fractures, and/or dilation/closure of fractures or other permeable planar features

that extend from the borehole into the formation.

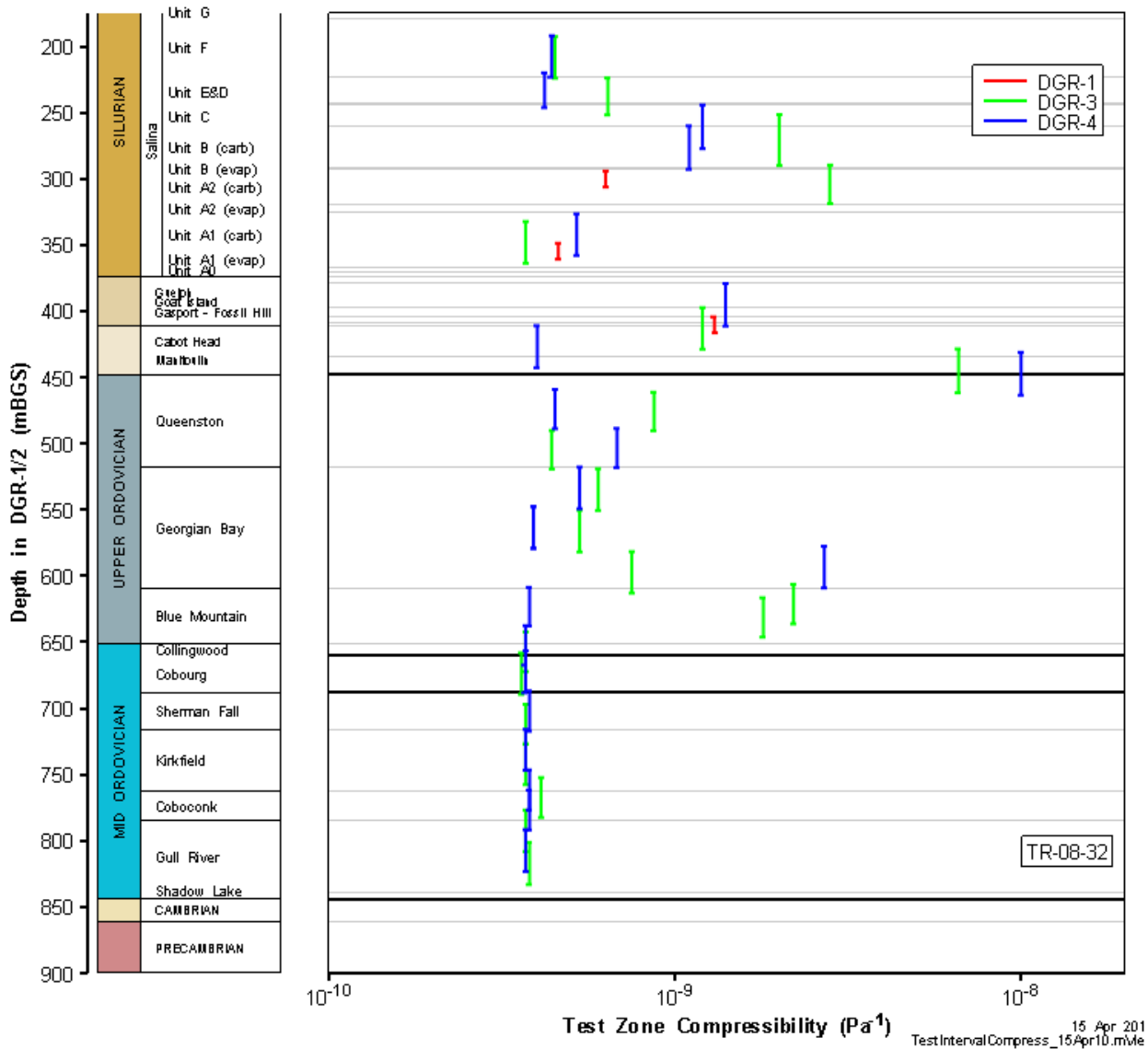


Figure 4.81 Profile of test interval compressibilities determined from field straddle-packer testing in DGR boreholes

Figure 4.81 shows that the test interval compressibilities are remarkably uniform and low within the Ordovician limestones and variable and larger within the overlying Ordovician shales and Silurian formations. The test interval compressibilities within the Ordovician limestones are all about $3\text{--}4 \times 10^{-10} \text{ Pa}^{-1}$, which is essentially the compressibility of brine (TR-08-10). These very low test interval compressibilities demonstrate the extreme rigidity of the test equipment and that packer compliance is negligible in the pulse hydraulic tests. Consequently, the increased test interval compressibilities observed for Ordovician shales and Silurian formations (up to $1 \times 10^{-8} \text{ Pa}^{-1}$) may be attributed to softer formations (e.g., Blue Mountain shales, Silurian evaporites), gas presence or permeable fractures/features that exhibit near-borehole pressure-dependent dilation or closure during pulse application.

4.9.2.2 Estimates of Average Formation Values

Figure 4.82 summarizes the estimates of formation horizontal hydraulic conductivity based on review of the consolidated results of DGR borehole hydraulic testing, hydraulic testing of US-series boreholes (Table 4.13), core inspection, observations of fluid loss during drilling of DGR boreholes and US-8 as discussed in Section 4.9.1, and observations on fluid volume production and drawdown during opportunistic groundwater sampling of DGR boreholes and other data as discussed in TR-08-10.

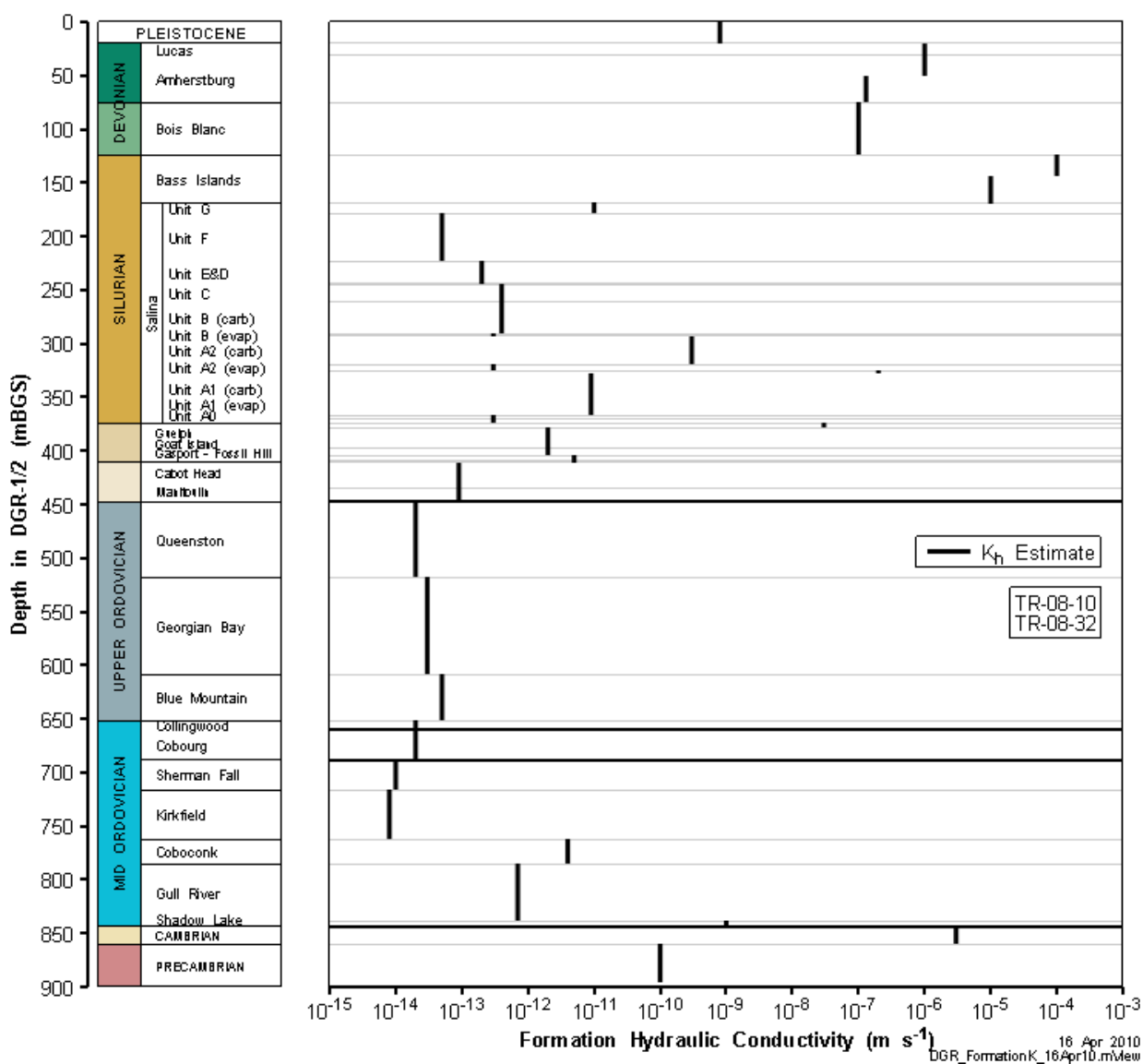


Figure 4.82 Estimates of formation horizontal hydraulic conductivity for overburden and bedrock formations at the DGR site.

Table 4.13 provides the tabular summary of the recommended estimates of formation horizontal hydraulic conductivity shown in Figure 4.82.

Inspection of Figure 4.82 and Table 4.13 shows that the Devonian and Upper Silurian dolostone formations (Lucas to Bass Islands) have moderate to high horizontal hydraulic conductivity typically larger than 10^{-7} m/s with an important high permeability (drill fluid loss) zone in the upper 20m of the Bass Islands Formation.

Table 4.13 Summary of recommended horizontal hydraulic conductivities of DGR formations

<i>Formation</i>	<i>Depth of Top in DGR-1/2 (mBGS)</i>	<i>$K_h (m s^{-1})$</i>
Clay till overburden	0	8E-10
Lucas	20.0	1E-06
Amherstburg (top 20 m)	30.4	1E-06
Amherstburg (lower 25 m)	50.0	1E-07
Bois Blanc	75.0	1E-07
Bass Islands (upper 20m)	124.0	1E-04
Bass Islands (lower 25 m)	144.0	1E-05
Salina G Unit	169.3	1E-11
Salina F Unit	178.6	5E-14
Salina E Unit	223.0	2E-13
Salina D Unit	243.0	2E-13
Salina C Unit	244.6	4E-13
Salina B Unit dolostone	260.3	4E-13
Salina B Unit anhydrite	291.2	3E-13
Salina A2 Unit dolostone	293.1	3E-10
Salina A2 Unit evaporite	319.7	3E-13
Salina A1 Unit upper dolostone	324.8	2E-07
Salina A1 Unit lower dolostone	328.5	5E-13
Salina A1 Unit evaporite	367.0	3E-13
Salina A0 Unit	370.5	5E-13
Guelph	374.5	3E-08
Goat Island	378.6	2E-12
Gasport	397.4	2E-12
Lions Head	404.2	5E-12
Fossil Hill	408.7	5E-12
Cabot Head	411.0	9E-14
Manitoulin	434.8	9E-14
Queenston	447.7	2E-14
Georgian Bay	518.0	3E-14
Blue Mountain	608.9	5E-14
Cobourg – Collingwood Member	651.6	2E-14
Cobourg - Lower	659.5	2E-14
Sherman Fall	688.1	1E-14
Kirkfield	716.1	8E-15
Coboconk	762.0	4E-12
Gull River	785.0	7E-13
Shadow Lake	838.6	1E-09
Cambrian	843.8	3E-06
Upper Precambrian	860.7	1E-10

The majority of the Upper Silurian Formations have very low horizontal formation hydraulic conductivities of 5×10^{-14} to 5×10^{-13} m/s, with the exception of G Unit dolostone and the upper A2 Unit dolostone with formation K_h of 1×10^{-11} and 7×10^{-11} m/s respectively, and a vuggy zone in the upper part of the A1 Unit dolostone, which has hydraulic conductivity of about 2×10^{-7} m/s. The hydraulic conductivity for the upper part of the A1 Unit dolostone was determined by assuming that all of the flow in the longer straddle-packer test interval occurred within the average 3.5 m length of vuggy and porous core. Figure 3.20 shows the core photograph of this permeable vuggy zone of the upper A1 Unit in DGR-4.

The Middle and Lower Silurian Formations have very low formation hydraulic conductivity of 9×10^{-14} m/s (Cabot Head and Manitoulin Formations) to 2×10^{-12} to 5×10^{-12} m/s (Goat Island, Lions Head and Fossil Hill Formations). The most permeable interval in the Middle to Lower Silurian Formations in DGR-1 is the vuggy Guelph Formation dolostone with K_h of 3×10^{-8} m/s, again based on an average effective zone length of about 5.1 m determined from core logging applied to the longer interval straddle packer test result (i.e., assuming all of the test flow occurs within this 5.1 m vuggy zone). Figure 3.23 shows the appearance of the Guelph Formation in DGR-1. Figure 4.83 shows this same permeable vuggy section of the Guelph Formation dolostone found in DGR-4.



Figure 4.83 Permeable vuggy core in Guelph Formation dolostone, 375 mBGS, DGR-4

The formation horizontal hydraulic conductivity of the Ordovician shales based on 30 m test interval lengths are very low ranging from 2×10^{-14} to 5×10^{-14} m/s with the highest value estimated for the Blue Mountain Formation. The Trenton Group limestones consisting of the Cobourg, Sherman Fall and Kirkfield Formations have estimated formation K_h values of 2×10^{-14} , 1×10^{-14} and 8×10^{-15} m/s, respectively. The Black River Group limestones consisting of the Coboconk and Gull River Formations have higher estimated formation K_h of 4×10^{-12} and 7×10^{-13} m/s, respectively. All of the current estimates of formation K_h are based on the final results of the analysis of straddle packer tests in DGR-3 and DGR-4. These results may change as the final results from DGR-2 become available. Based on the preliminary results given in Figure 4.80, decreases in formation K_h for the Trenton Group limestones and increases in formation K_h for the Black River Group may be expected considering DGR-2 data.

Formation K_h estimates for the Shadow Lake Formation and the upper several tens of metres of the Precambrian basement rocks are based on review of borehole test results completed and compiled by Raven et al. (1992a, 1992b). The Shadow Lake Formation has an estimated formation K_h of 1×10^{-9} m/s and the upper Precambrian basement has an estimated formation K_h of 1×10^{-10} m/s. The permeable Cambrian sandstone has an average K_h of 3×10^{-6} m/s based on completion of flow tests of the Cambrian during opportunistic groundwater sampling in DGR-2, DGR-3 and DGR-4 and general observations of produced formation fluids during drilling.

4.9.3 Comparison of Field and Laboratory K Data

Figure 4.84 shows comparison of the field and laboratory hydraulic test data expressed as hydraulic conductivity (K). For ease of presentation, field K data in Figure 4.84 are shown as the recommended best estimates of formation horizontal hydraulic conductivity (K_h) which are derived primarily from review of borehole hydraulic testing data. Figure 4.84 also shows the laboratory-derived estimates of horizontal and vertical permeability determined from gas pulse permeability testing of “as received” cores and from brine pulse permeability testing, which are the test results least affected by sample preparation (see Section 4.3.4). Lab results were converted from permeability to hydraulic conductivity assuming an average brine density of 1150 kg/m^3 and a dynamic viscosity of $0.002 \text{ Pa}\cdot\text{s}$. The clustering of K values at $5 \times 10^{-14} \text{ m/s}$ represents the lower testing limit of the Core Labs gas and brine pulse testing equipment. Actual lab K data for these tests will be less than the plotted values.

Figure 4.84 clearly shows the overestimation of in-situ K by laboratory gas and brine pulse testing for most of the samples tested within the Ordovician shales and to a lesser degree within the Ordovician Trenton limestones as discussed in Section 4.3.4. The overestimation of K for the Ordovician shales ranges from 1 to 4 orders of magnitude, whereas the overestimation for the Ordovician Trenton limestones typically ranges from 1 to 3 orders of magnitude. The Ordovician Black River limestones show comparable field and lab estimates of K with increasing lab K with depth in Gull River Formation. The estimated field result (Raven et al., 1992a – borehole OHD-1) and the lab data for the Shadow Lake Formation are comparable at about $1 \times 10^{-9} \text{ m/s}$.

Figure 4.84 also shows similar overestimation of K for the Salina F Unit shale and Cabot Head shale with lab data ranging up to 3 orders of magnitude larger than in-situ field estimates. The remaining Silurian dolostone, shale and evaporite rocks show significant scatter in lab test data but generally show the field best estimates represent the central tendency of the lab data. The notable exception to this general observation, is the Salina A2 Carbonate which shows higher field estimate than lab data. This is most likely due to the occurrence of several permeable fractures identified in the upper half of the carbonate unit that was subject to packer testing that are evident from review of hydraulic testing (TR-08-32), core logging (TR-07-06) and borehole geophysical logging (TR-07-08).

Comparison of the field and laboratory K data for the Cambrian sandstone shows that the field estimate is more than a 1000 times higher than the lab test. This difference is mostly a reflection of facies changes in the Cambrian (the upper Cambrian sample that was subject to lab testing is primarily fine grained dolostone) and the occurrence of open permeable fractures in the deeper Cambrian sandstone.

Figure 4.84 clearly shows that the best and most reliable estimates of hydraulic conductivity for the majority of low permeability DGR bedrock formations are derived from in-situ hydraulic testing.

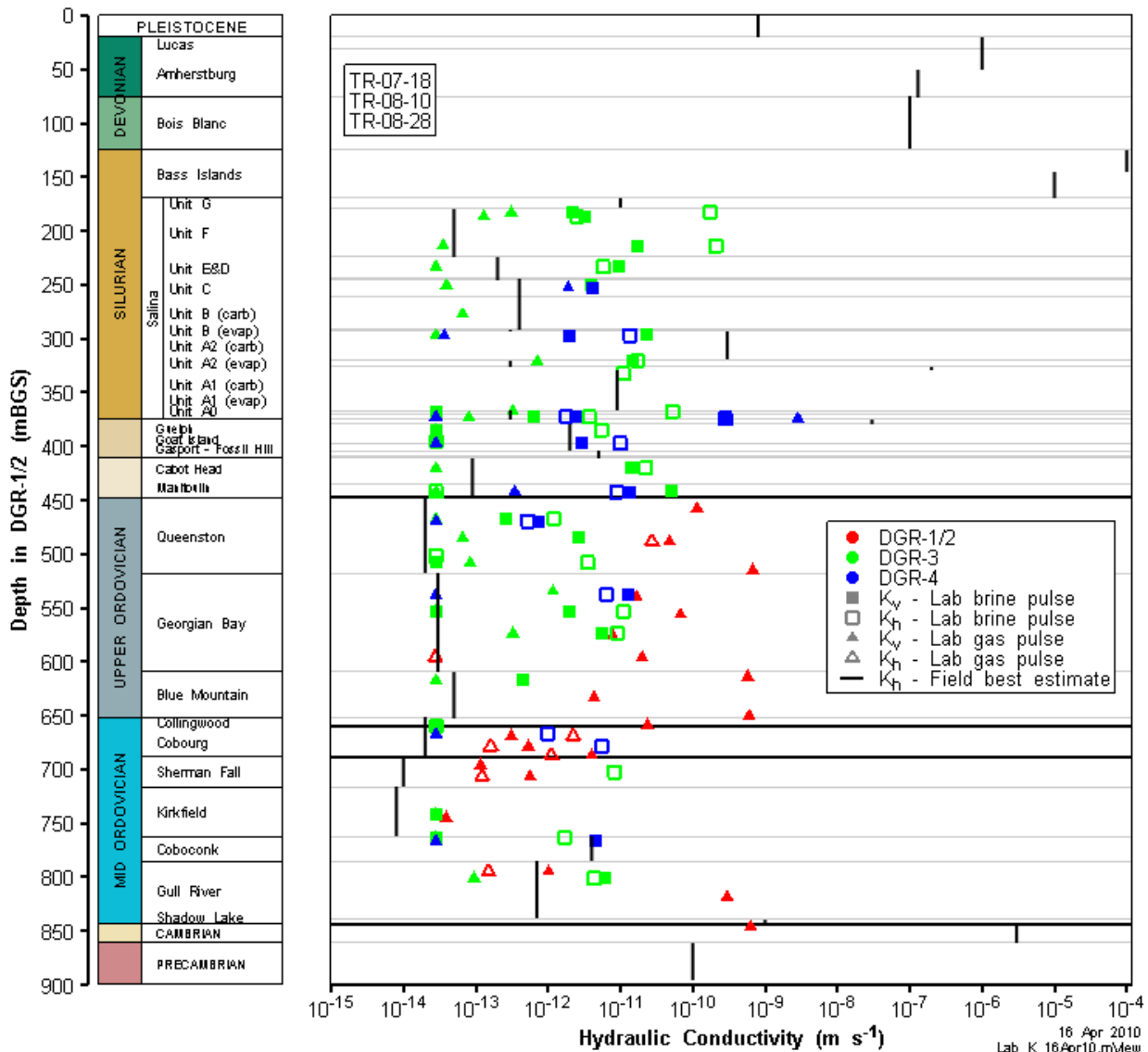


Figure 4.84 Comparison of best estimates of formation K_h based on field testing and laboratory K_h and K_v determined from “as received” gas pulse testing and brine-saturated pulse testing of DGR cores

4.10 Formation Compressibility and Specific Storage

Uniaxial compression testing (TR-07-03, TR-08-24, TR-08-39) and porosity characterization (Section 4.3.2) of intact cores collected from DGR boreholes allow estimation of formation matrix compressibility and specific storage properties (TR-08-10) (see Figure 4.85). Such matrix properties do not consider the effects of any fractures or presence of gas, and hence might be expected to underestimate overall formation properties if fractures or gas were present. Quantification of such poroelastic properties are important for understanding and predicting both short-term and long-term transient hydraulic responses of the Paleozoic bedrock sequence at the Bruce nuclear site to hydraulic and geomechanical perturbations such as DGR excavation and glacial and erosional unloading. Independent quantification of specific storage also allows for more accurate interpretation of straddle packer hydraulic tests and determination of formation hydraulic conductivity.

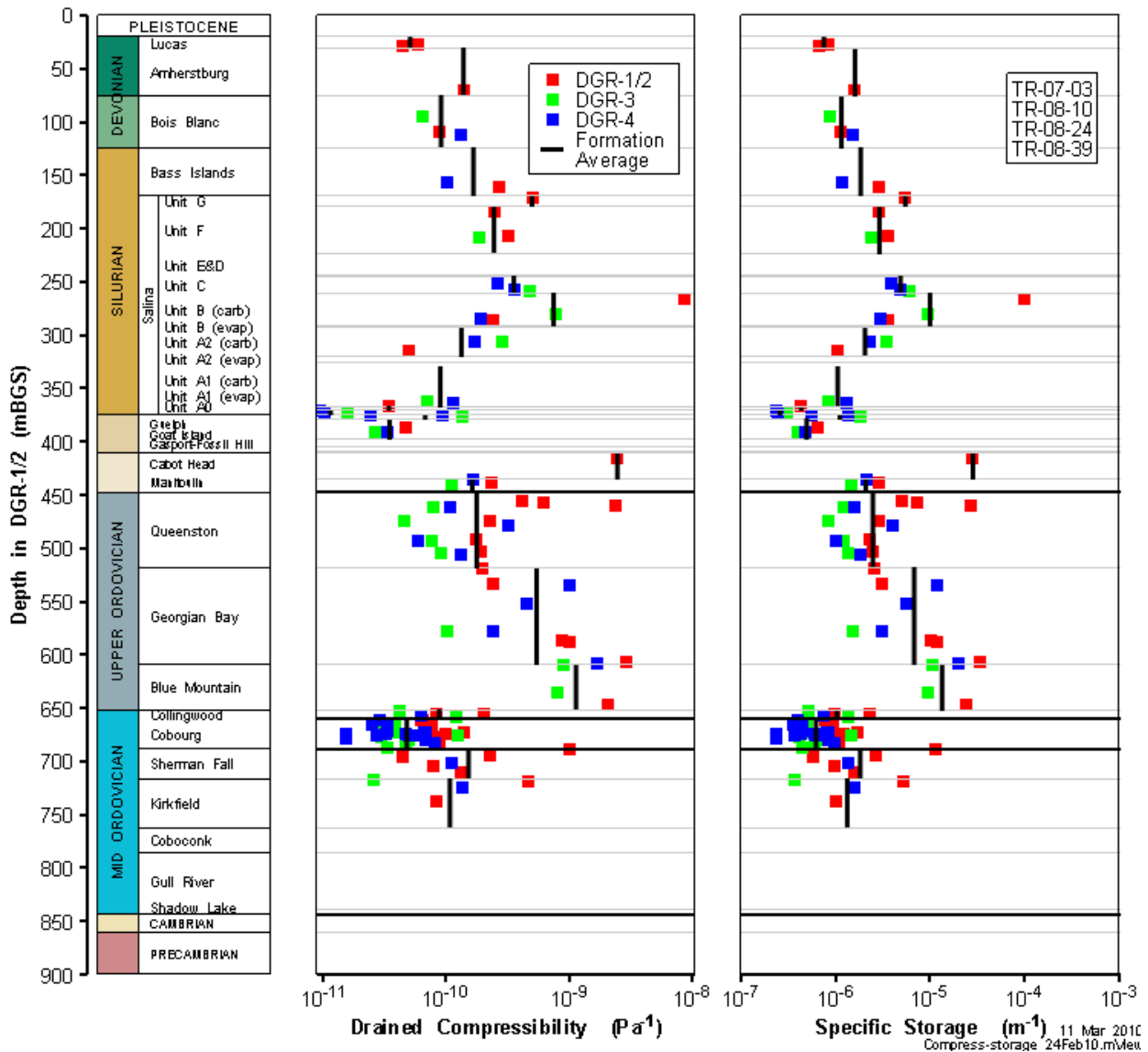


Figure 4.85 Profile of rock compressibility and specific storage in DGR boreholes showing point data and formation averages

Stress-strain data collected during uniaxial compression testing were analysed to determine undrained Young's moduli and Poisson's ratio (see Section 5), undrained and drained bulk moduli and undrained and drained rock compressibility. Specific storage values were then calculated from formation-averaged liquid porosity and pore fluid density values and individual core rock drained compressibility data. The methods and results of these calculations are provided in TR-08-10.

Figure 4.85 shows the calculated values of drained rock compressibility and specific storage by depth and formation from testing of DGR core as well as the geometric mean formation averages. Figure 4.85 shows that the competent Devonian and Silurian dolostones generally have drained formation compressibility of 9.6×10^{-12} to $2.4 \times 10^{-10} \text{ Pa}^{-1}$, and specific storage of 8.9×10^{-7} to $3.6 \times 10^{-6} \text{ m}^{-1}$. The Salina upper B Unit, Cabot Head shale and the Ordovician shales are more compressible with drained compressibility of about 1×10^{-10} to $8.6 \times 10^{-9} \text{ Pa}^{-1}$, and specific storage of 2.4×10^{-6} to $1.0 \times 10^{-4} \text{ m}^{-1}$. There is noticeable increase in both drained compressibility and specific storage with increasing depth within the Ordovician shales, with maximum values (specific storage = $3.4 \times 10^{-5} \text{ m}^{-1}$) evident within the Blue

Mountain Formation. The Cobourg, Sherman Fall and Kirkfield Formations have poroelastic properties similar to and less than those of the Devonian/Silurian dolostones with drained compressibility of 1.5×10^{-11} to $1.0 \times 10^{-9} \text{ Pa}^{-1}$, and specific storage of 2.4×10^{-7} to 1.2×10^{-5} . The compressibility and specific storage values for the Ordovician shales are typically an order of magnitude greater than those properties of the Ordovician limestones.

The most compressible formations in DGR boreholes are the Salina upper B Unit and the Cabot Head and Blue Mountain shales. Within the Devonian and Silurian strata, the rock compressibility and specific storage values are greatest within Salina B Unit decreasing both upward and downward from this unit. Within the Ordovician strata, the rock compressibility and specific storage values are greatest within the Blue Mountain Formation also decreasing both upward and downward from this formation.

4.11 Formation Pressures and Hydraulic Heads

4.11.1 Shallow Bedrock – US Wells

Shallow bedrock boreholes US-3, US-7 and US-8 instrumented with Westbay MP-38 multi-level monitoring casings (TR-07-20) provide profiles of formation pressures from 31 packer-isolated intervals in the shallow bedrock at the Bruce nuclear site to depths of 200 m (TR-08-08, TR-08-30). Formation pressures in US-3, US-7 and US-8 are analyzed and presented as freshwater hydraulic heads as the groundwater densities in these wells, based on groundwater sampling, are all about $990\text{--}1000 \text{ kg/m}^3$ or less (see Section 4.8).

Pressure profiles were completed in US-3, US-7 and US-8 in March, late May-early June and July, 2008 (Figure 4.86) following casing installation in US-3 and US-7 on December 10 and 11, 2007 and in US-8 on March 6, 2008. Subsequent to summer 2008, pressure profiles were completed on a quarterly basis.

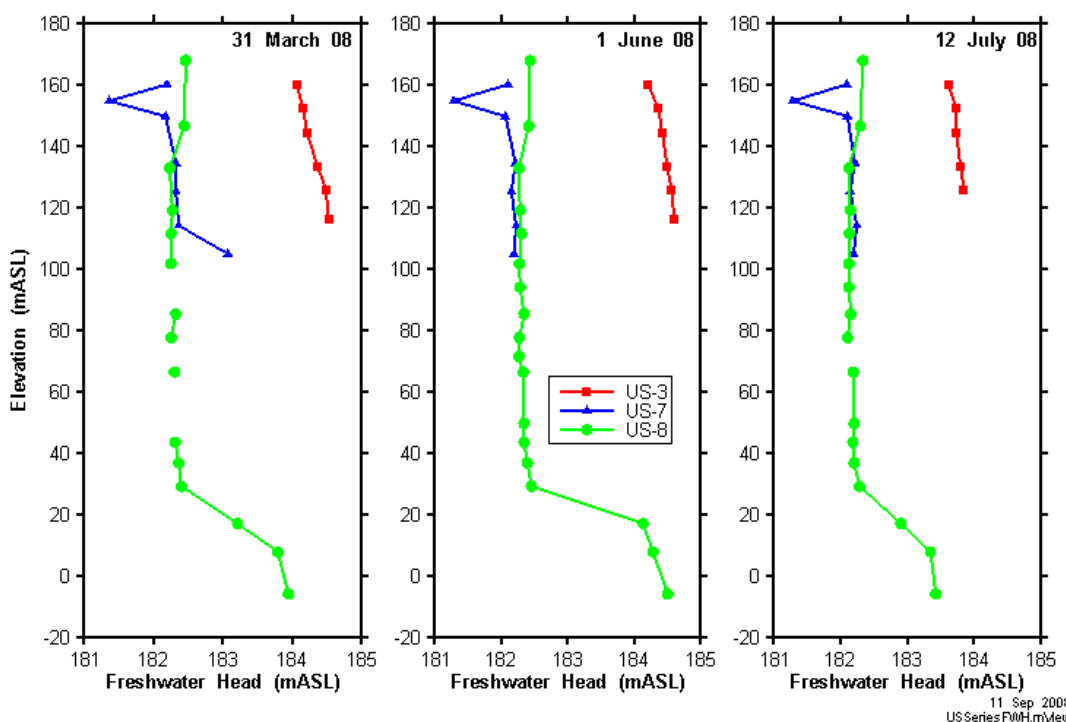


Figure 4.86 Hydraulic head profiles – US-3, US-7 & US-8 in March to July, 2008

Figure 4.86 shows stable hydraulic head profiles indicating slight upward hydraulic gradients (0.001 to 0.01 m/m) and lateral flow to the northwest toward Lake Huron. Quarterly pressure profiles completed after this spring/summer 2008 monitoring have shown similar hydraulic gradients and groundwater flow directions.

4.11.2 Deep Bedrock – DGR Boreholes

Boreholes DGR-1, DGR-2, DGR-3 and DGR-4 were completed with Westbay stainless steel and PVC MP55 multi-level monitoring casings, primarily to provide access for formation pressure measurement, but also to allow for future groundwater sampling. MP55 casings were installed in DGR-1 and DGR-2 on September 25 and December 13, 2007. MP55 casings were installed in DGR-3 and DGR-4 on September 28 and April 30, 2009. For reasons outlined below, the MP55 casing installed in DGR-2 on December 13, 2007 was successfully removed on June 5, 2009. An improved and upgraded MP55 casing system was installed in DGR-2 on December 2, 2009. Table 4.14 summarizes the design elements of the MP55 casing systems installed in DGR boreholes.

Table 4.14 Major design elements of MP55 casing systems installed in DGR boreholes

MP55 Casing Element	DGR-1	DGR-2 (old)	DGR-2 (new)	DGR-3	DGR-4
Monitored Depth Range (mBGS)	190.7 to 462.9	460.4 to 848.0	460.7 to 846.7	218.3 to 869.2	194.3 to 852.5
Number of Packers	23	28	27	43	43
Number of Formation Pressure Monitoring Intervals	22	25	24	42	42
Average Monitoring Interval Length (m)	11.3	14.4	14.7	14.0	14.3
Range of Monitoring Interval Lengths (m)	3.4 to 24.0	3.0 to 23.0	5.2 to 24.2	4.7 to 28.7	3.2 to 24.2
Number of Pressure Profiles Completed to End of 2009	12	6 + Continuous MOSDAX	1	2	4

Profiles of formation pressure were typically measured in DGR boreholes immediately following casing installation, on an approximate monthly basis for the next three months, and then on a quarterly basis. Table 4.13 lists the total number of continuous pressure profiles completed in each DGR borehole up to December 31, 2009. On March 4, 2008 a MOSDAX string of 10 pressure transducers was installed in DGR-2 to provide continuous records of formation pressure in 10 key test intervals. This MOSDAX system operated for approximately 13 months, when this pressure measurement system was removed from DGR-2 on April 2, 2009.

In the very low permeability formations that characterize large sections of all DGR boreholes, formation pressures are slow to equilibrate. Consequently, measured formation pressures in DGR boreholes are reported here for selected monitoring dates that provide a reasonable representation of the temporal evolution of formation pressures. For each DGR borehole the measured formation pressures are plotted relative to freshwater hydrostatic and density-compensated hydrostatic pressure lines. These measured in-situ pressures are also plotted with the best-fit estimates of test interval formation pressure from analyses of the straddle-packer hydraulic tests as described in TR-08-32.

In addition to pressure plots, the pressure data are converted to environmental head considering the reference formation fluid density profile provided in Figure 4.73. Calculated environmental heads are plotted with the vertical ground surface elevation line as a reference point for the calculated heads.

Fresh water and environmental heads were calculated from formation pressures following the methods of Luszczynski (1961) and Jorgensen et al. (1982) as described in TR-08-31. Environmental heads are suitable for assessing vertical groundwater flow potentials in variable-density groundwater flow systems. Detailed description of the calculations for determination of freshwater hydrostatic and density-compensated hydrostatic pressure lines, and of environmental heads is also provided in TR-08-31.

4.11.2.1 DGR-1 and DGR-2 (Old)

Figure 4.87 shows the temporal evolution of pressures and heads in DGR-1 over a four to 18 month period after casing installation. Figure 4.91 shows that stable formation pressures and heads occur in almost all of the Salina Formation after an equilibration period of about 5 months. The environmental head profile is arcuate with the minimum environmental head of about 170 mASL occurring in the middle of the formation at the bottom of the Salina B Unit. Formation pressures and heads for the permeable upper Salina A1 Unit and Guelph Formation aquifers are stable in all pressure profiles. Elevated pressures and environmental heads are observed within lower Salina A1 carbonate and the underlying Goat Island to upper Cabot Head Formations. These Westbay pressures measured in the Lions Head, Fossil Hill and upper Cabot Head formations are very similar to the estimated formation pressure from borehole hydraulic testing. The increasing and high pressures measured in these formations may be related to gas occurrence as hydrocarbons in the form of crude oil were observed in the bottom of the Salina A1 Unit. Gas occurrence and up-dip migration have been credible explanations for overpressures measured in tight Paleozoic rocks in southern Ontario (Raven et al., 1992a).

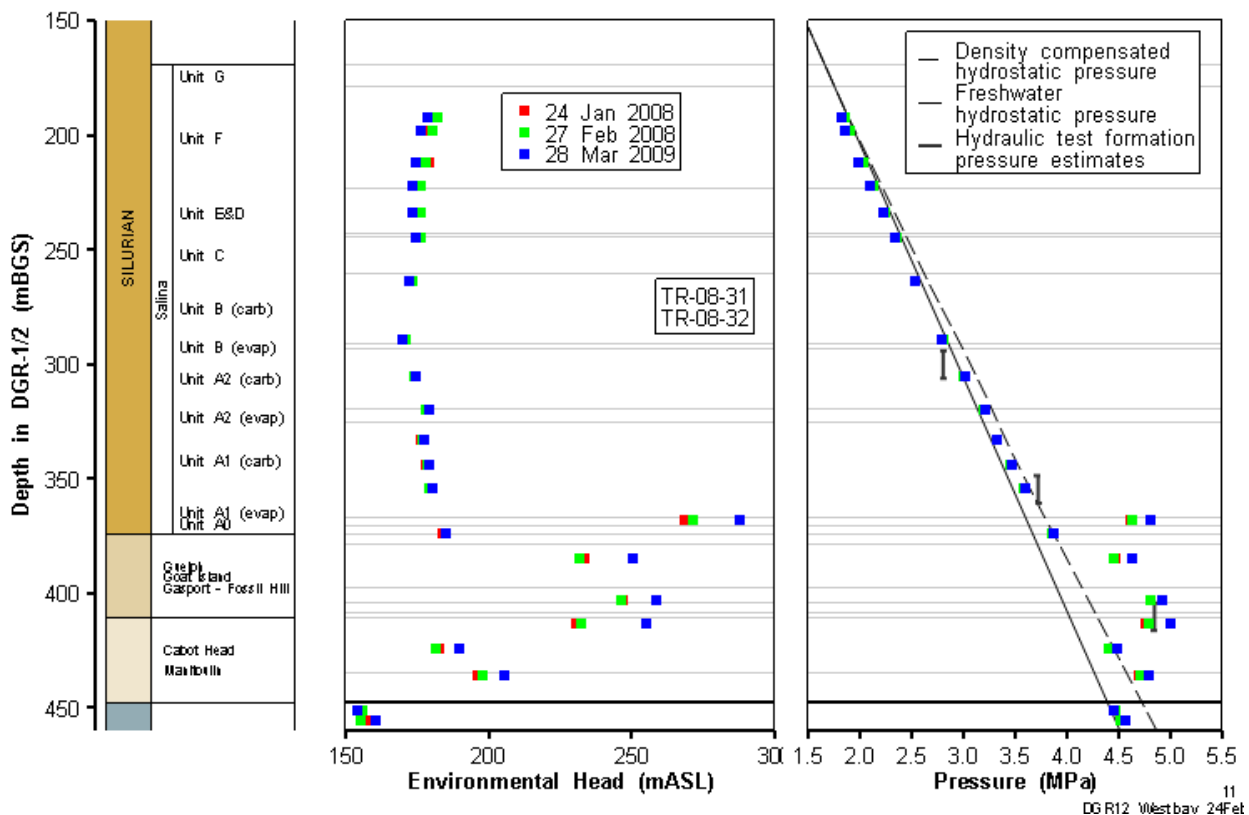


Figure 4.87 DGR-1 formation pressure and environmental head profiles, January 24 and February 27, 2008, and March 29, 2009

The very bottom of DGR-1 shows environmental heads that are underpressured relative to the vertical ground surface line and all other environmental heads in DGR-1. These underpressures and low environmental heads are entirely consistent with deeper data recorded in DGR-2.

Figure 4.88 shows the temporal evolution of pressures and heads in DGR-1 and DGR-2 over about a one to 15 month period after casing installation in DGR-2. Figure 4.88 shows the development of significant underpressures within the Ordovician shales and Trenton Group limestones with environmental heads approaching -70 mASL or 255 mBGS. Pressure data collected from DGR-2 also show the occurrence of a slightly overpressured zone within the lower part of the Georgian Bay that has elevated test interval compressibility from hydraulic testing and is suspected to be associated with gas-containing inclined fracture at 585.7 mBGS (see Figure 3.51). This slightly overpressured zone also shows interval hydraulic conductivity about 1 to 1.5 orders of magnitude greater than the surrounding rock mass.

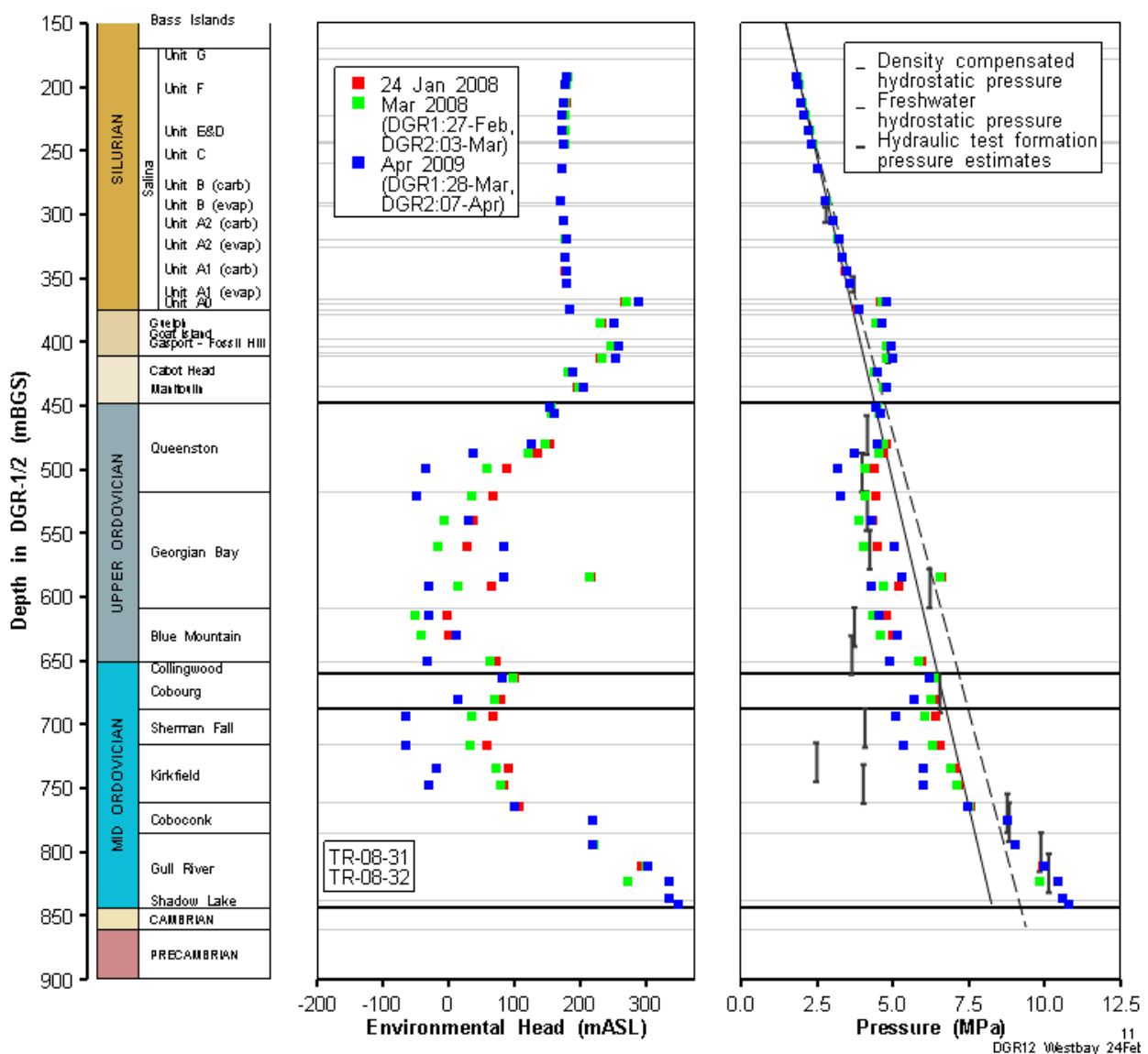


Figure 4.88 Combined DGR-1 and DGR-2 (Old) formation pressure and environmental head profiles, January 24, 2008, February-March, 2008 and March-April, 2009

Figure 4.88 also shows that large overpressure extends downward from the Coboconk Formation to the Cambrian sandstone. The deepest formation pressures in DGR-2 are equivalent to an environmental head of about 350 mASL or 165 m above ground surface (AGS). Both the under-pressures and over-pressures were also estimated from interpretation of borehole hydraulic tests.

In the period of March 2008 to April 2009, ten pressure transducers were installed in DGR-2 to continuously monitor formation pressures. Figure 4.89 shows the continuous pressure plots generated from this MOSDAX installation. This figure shows that even after 18 months, pressures within DGR-2 continue to show changes with decreasing pressures in the Georgian Bay, Cobourg and Kirkfield Formations and apparent stabilization of pressures within the Queenston, Blue Mountain and Coboconk/Gull River Formations. The step pressure increase and decrease shown in mid to late March is leakage of Cambrian pressure into the sealed casing and correction of this leakage by disconnecting the pressure transducer from the Cambrian measurement port. Figure 4.89 also shows periodic “bumps” or pressure increases for the upper Georgian Bay, Blue Mountain, Cobourg and Kirkfield Formations that are thought to be due to leakage around packer seals and/or leakage from the inside of the MP55 casing to these under-pressured formations.

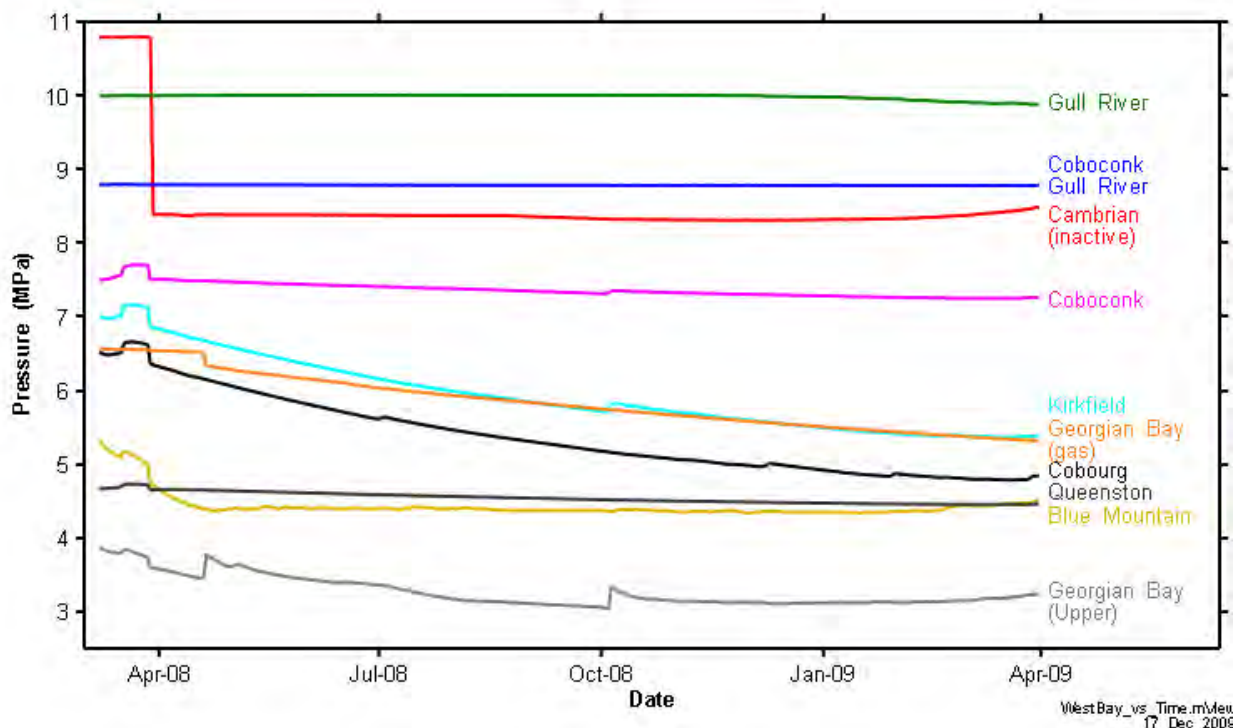


Figure 4.89 Continuous formation pressure measurements, March 2008 to April 2009 in DGR-2

Figures 4.88 and 4.89 show that the only truly stable environmental heads in DGR-2 during the monitoring period are in the deeper Coboconk and Gull River Formations, as well as the underlying Shadow Lake Formations, whose pressures are controlled by the stable high pressure measured in the Cambrian sandstone. While environmental heads in the Ordovician shales appear close to stabilizing, the heads in the Cobourg and Kirkfield Formations show near uniform pressure decreases throughout the 18-month monitoring period.

4.11.2.2 DGR-2 Casing Removal and Re-installation

Removal of the 848 m length of MP55 casing in DGR-2 was undertaken in early June 2009 for the following reasons:

- To eliminate the suspected MP55 casing leaks by upgrading the design of the system by increasing the amount of stainless steel components and the use of high pressure Geopro™ packers in zones expected to experience very high differential pressures.
- To allow for additional borehole acoustic televiewer logging of the borehole walls to further assess possible borehole breakouts for assessment of in situ stresses (see Section 5.4).
- To allow for retesting of DGR-2 to address concerns over possible test equipment leaks identified by comparison of test results between borehole DGR-2 and boreholes DGR-3 and DGR-4.
- To demonstrate retrieveability of MP55 casings in DGR boreholes, which was a requirement of the Phase 1 GSCP (Section 5.2.7.4), (Intera Engineering Ltd, 2006).

4.11.2.3 DGR-2 (New)

The new MP55 casing system was installed in DGR-2 on December 2, 2009. Other than the post-inflation pressure profile completed on December 3, no other pressure profiles are available for this new completion at the time of preparation of this report. Pressure and head profiles will be generated for this new DGR-2 casing installation early in 2010.

4.11.2.4 DGR-3

Figure 4.90 shows the November 15, 2009 profiles of formation pressures and environmental heads in DGR-3 1.5 months after casing installation in late September, 2009. Although only one pressure profile is available for this borehole after completion of the post-inflation profile, the pressure and head data illustrated in Figure 4.94 are remarkably similar to data for DGR-1 and DGR-2.

The pressure and head data for DGR-3 show minor underpressure in the Salina Formation that increases to over-pressure in the Gasport to Fossil Hill Formations and then rapidly transitions to significant underpressure within the Ordovician shales and the Trenton Group limestones. Similar to DGR-2, all of the deeper Black River Group formations are overpressured with the source of the over-pressure being the Cambrian sandstone. Figure 4.90 shows that the over-pressured and underpressured intervals measured in the MP55 casing were all reasonably well determined from borehole hydraulic testing. Comparison of the formation pressures determined from hydraulic testing to MP55 casing measurements indicates that final or stable underpressures and environmental heads in the Ordovician shales and limestones are likely to be much lower than those measured on November 15, 2009. Stable formation pressures are evident for the permeable sections of DGR-3, including the Salina Upper A1 Unit, the Guelph and the Cambrian sandstone.

What is also remarkable is that the development of the overpressures and underpressures are very similar in DGR-3 and DGR-2. For example, environmental head profile determined from the DGR-3 November 15, 2009 pressure measurements completed about 1.5 months after casing installation is very similar in both shape and magnitude to the environmental head profile determined from the DGR-2 January 24, 2008 pressure measurements, which was also completed about 1.4 months following casing installation.

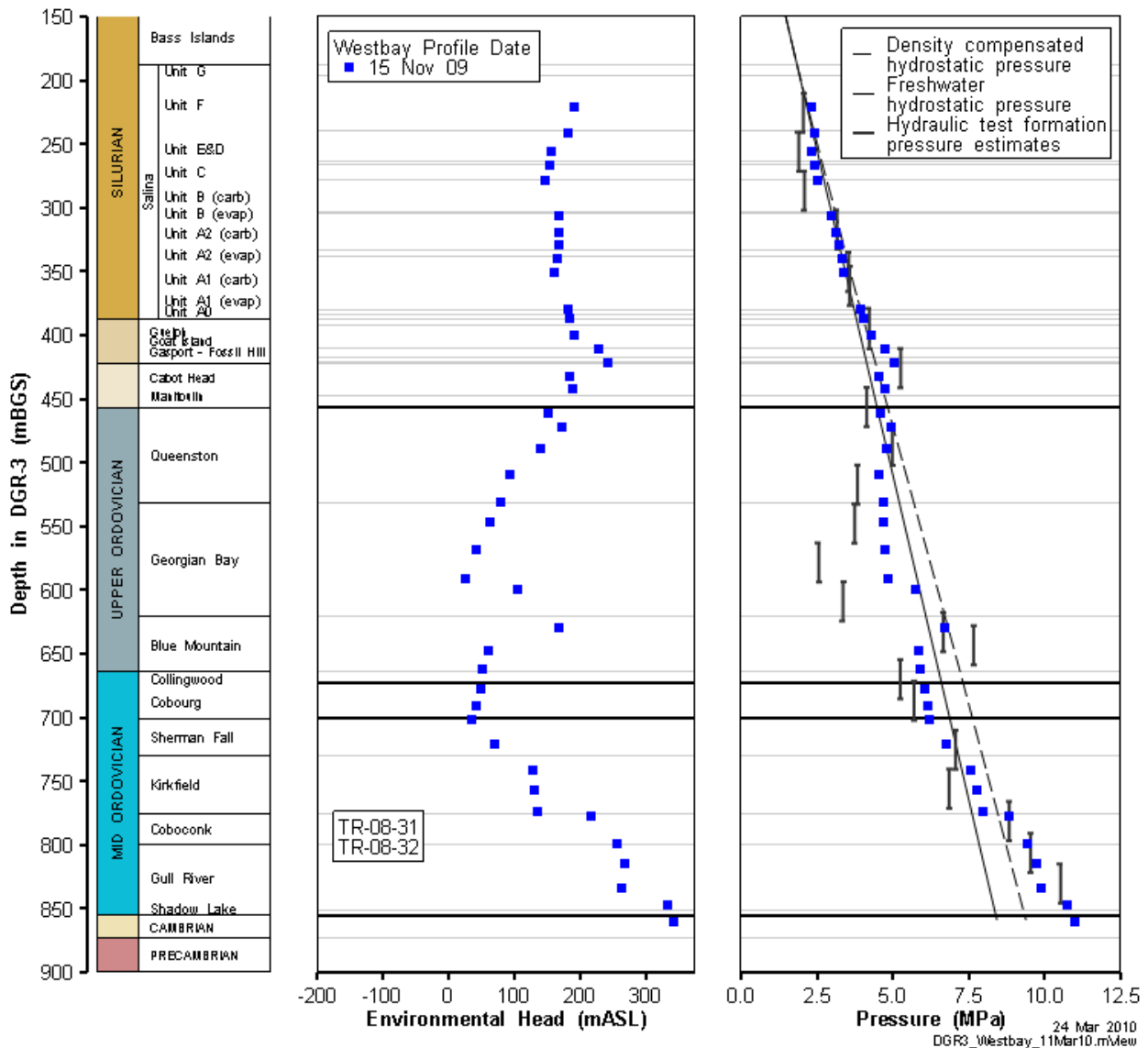


Figure 4.90 DGR-3 formation pressure and environmental head profiles, November 15, 2009

As in DGR-2, there is one normally-pressured interval in the Ordovician shales; in DGR-3 it occurs within the Blue Mountain Formation that has environmental head at least 200 m greater than heads in the surrounding shales and test interval hydraulic conductivity that is about 1.5 orders of magnitude greater than the surrounding rock mass. This higher pressure and permeability interval is attributed to a set of inclined, cm-spaced, calcite-infilled fractures found at 638 to 639 mBGS in DGR-3. Figure 4.91 shows a close-up of the appearance of these closely-spaced fractures. Borehole acoustic televiewer logs indicate that at least one of these inclined fractures has an identifiable trace on the borehole wall and hence may have increased permeability relative to the intact rock mass. In both core and borehole wall images these inclined fractures show pitting or minor breakage at the high and low points of the elliptical fracture traces. This normally-pressured interval also shows elevated test interval compressibility from straddle-packer hydraulic testing.



Figure 4.91 Closely-spaced, inclined, calcite-infilled fractures at 638.5 mBGS in Blue Mountain Formation, DGR-3. Note pitting or minor core breakage at the low point on the elliptical fracture trace.

4.11.2.5 DGR-4

Figure 4.92 shows the temporal evolution of pressures and heads in DGR-4 over the one to 5.5 month period following casing installation. The temporal development and spatial distribution of overpressures and underpressures in DGR-4 is essentially identical to that observed in boreholes DGR-1, DGR-2 and DGR-3.

As in other DGR boreholes, the pressure and head data for DGR-4 show underpressure in the Salina Formation that increases to overpressure in the Gasport to Fossil Hill Formations and then rapidly transitions to significant under-pressure within the Ordovician shales and the Trenton Group limestones. Similar to DGR-1, formation pressures within the permeable Upper A1 Unit and Guelph aquifers are stable in all pressure surveys. Similar to DGR-2 and DGR-3, all of the deeper Black River Group formations are overpressured with the source of the overpressure being the Cambrian sandstone. The pressure in the Cambrian sandstone in DGR-4 is equivalent to an environmental head of 165 mAGS.

The underpressures in DGR-4 are greater in magnitude than in DGR-1, DGR-2 or DGR-3, being equivalent to environmental heads of 117 mASL in the middle of the Salina Formation and -115 mASL (300 mBGS) in the Blue Mountain Formation. This observation is not unexpected as the MP55 casing in DGR-4 is a more robust design than casing in DGR-1 and DGR-2 (old) and has been in the ground longer than DGR-2 (new) and DGR-3. Figure 4.92 shows that the overpressured and underpressured intervals measured in the MP55 casing in DGR-4 were all reasonably well determined from borehole hydraulic testing. Again, comparison of the formation pressures determined from hydraulic testing to MP55 casing measurements indicates that final or stable underpressures and environmental heads in the Ordovician shales and limestones are likely to be much lower than those measured on November 15, 2009.

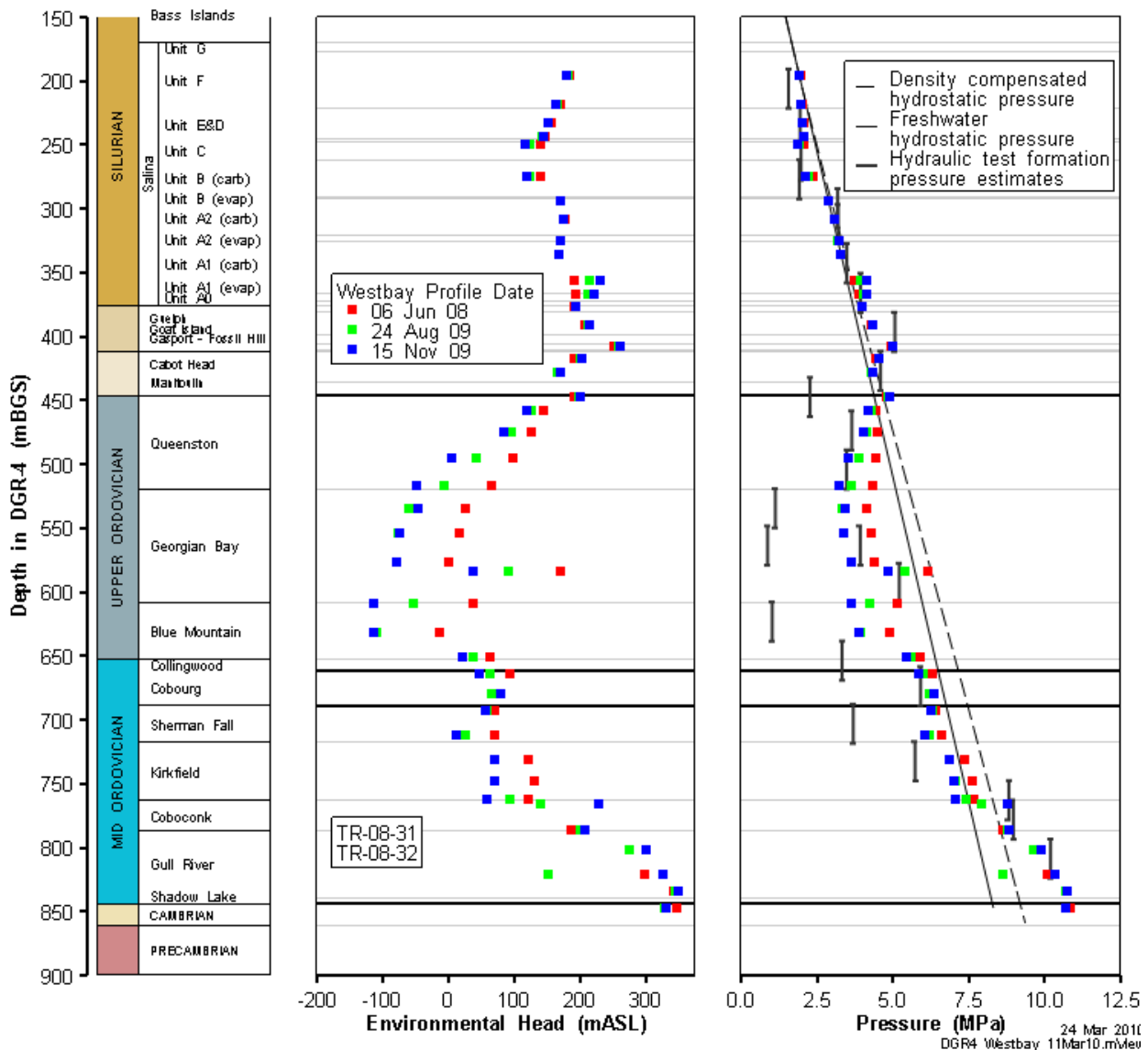


Figure 4.92 DGR-4 formation pressure and environmental head profiles, June 6, August 24 and November 15, 2009

As in DGR-2 and DGR-3, there is one normally-pressured interval within the Ordovician shales; in DGR-4 it occurs within the lower Georgian Bay Formation and has environmental head at least 200 m greater than heads in the surrounding shales. In DGR-4 this overpressured zone appears to have slightly elevated hydraulic conductivity relative to the surrounding rock mass. It appears to be associated with a sub-horizontal calcite-infilled fracture at 594.8 mBGS. Similar to other normally-pressured zones in the Ordovician shales in DGR boreholes, it shows elevated test interval compressibility from straddle-packer hydraulic testing.

4.11.2.6 Summary of Underpressures and Overpressures

The available pressure measurements from borehole hydraulic testing and monitoring of MP55 casings shows the following general environmental head conditions in DGR boreholes related to overpressures and underpressures:

- Underpressures in the Salina Formation with maximum underpressures occurring within the C and B Units with environmental heads of 70 mBGS.
- Overpressures in the Salina A1 and A0 Units, and Gasport to Fossil Hill Formations with maximum overpressures equal to environmental heads of 75 mAGS.
- Underpressures in the Ordovician shales and Trenton Group limestones with maximum underpressures occurring within the Blue Mountain Formation with environmental heads of 300 mBGS.
- Overpressures in the Black River Group limestones and siltstones and the Cambrian sandstone with maximum overpressures equal to environmental heads of 165 mAGS.

It is important to understand that for the majority of the underpressures, the currently available data provide indications of what the actual equilibrium formation pressures may be, assuming such equilibria exist. The formation pressures from straddle-packer testing are values determined from analysis of the pressure transient data similar to values of formation hydraulic conductivity. As illustrated in Figure 4.93, the actual time it would take to reach equilibrium formation pressures with the straddle-packer testing equipment is on the order of 1-2 years for a formation hydraulic conductivity of 9×10^{-15} m/s.

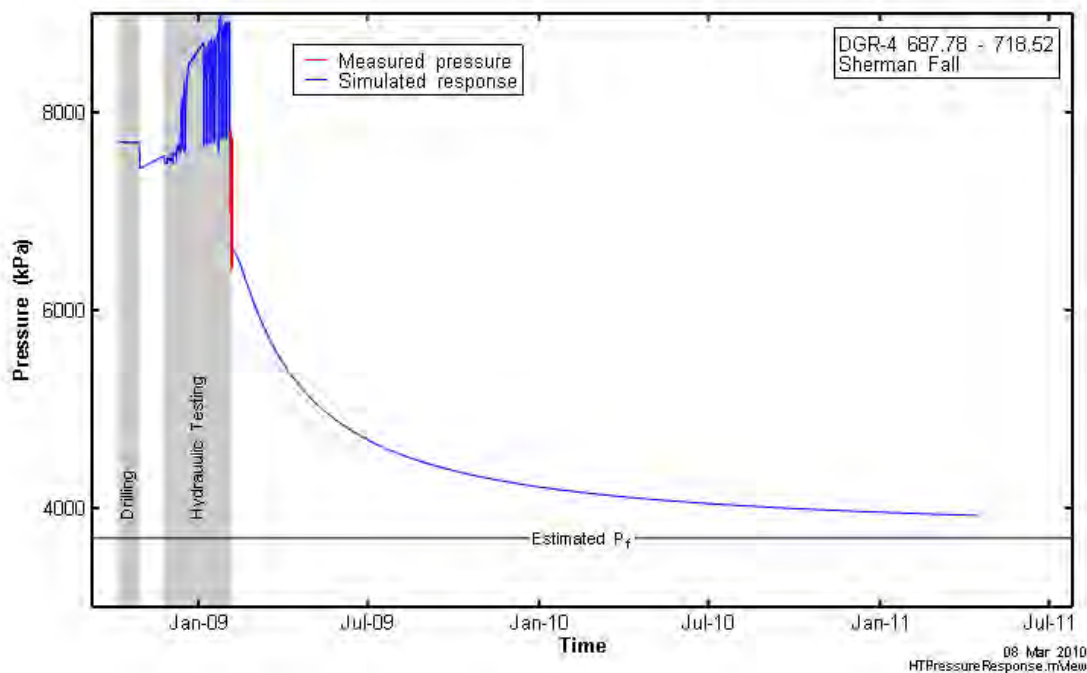


Figure 4.93 Calculated time to reach equilibrium formation pressure with straddle-packer testing equipment, Sherman Fall Formation in DGR-4

Because the test interval compressibility of MP55 casing is likely an order or magnitude greater than the very stiff straddle-packer test equipment, the time to reach equilibrium formation pressures with the MP55 installations is on the order of 5-10 years. Since pressure monitoring in the MP55 casing systems has only been undertaken for a maximum of 1.5 years, the bulk of the data from these installations are overestimates of actual formation underpressures. Given these constraints, the best current estimates of formation underpressures are likely those determined from analysis of straddle-packer hydraulic tests.

The cause of the observed underpressures and overpressures and heads in DGR boreholes are not evident at this time. Certainly both the underpressures and larger overpressures are not in hydrodynamic equilibrium with local topography and surface water elevations.

While the moderate overpressures observed within the Salina A1 and A0 Units, Goat Island, Gasport, Lions Head and Fossil Hill Formations and the middle of the Georgian Bay Formation (DGR-2 and DGR-3) and the Blue Mountain Formation (DGR-4) may be gas related, the Cambrian overpressure is much larger and is associated with a locally permeable formation (i.e., $K > 10^{-6}$ m/s). Possible explanations for the Cambrian overpressures include: hydraulic connection to a remote elevated regional recharge area (e.g., Niagara Escarpment, Canadian Shield); remnant overpressure from deep basin glacial meltwater recharge (Bense and Person, 2008), and/or up-basin regional fluid (brine or gas) migration and pressurization as has been reported by Bahr et al. (1994) for deep Middle Ordovician formations on the east side of Lake Huron near Saginaw Bay and by Raven et al. (1992a) for southern Ontario. The fact that the groundwater flow directions in the overpressured Cambrian today at the Bruce DGR site are outward from the centre of the Michigan Basin (see Section 4.11.3) suggests that the Cambrian overpressures are likely sourced from the centre of the Michigan Basin.

There is much more literature on the occurrence and genesis of underpressures, particularly in very low permeability argillaceous formations as exist at the Bruce nuclear site. Similar underpressures have been reported for the Pierre shale in South Dakota (Neuzil, 1993), the western Canada sedimentary basin (Corbet and Bethke, 1992) and the marl-shale aquitard at Wellenberg, Switzerland (Vinard, 1988). Neuzil (1995) provides a good summary of the various mechanisms for generation of abnormal pressures in hydrogeologic systems.

Based on available literature and considering the Bruce nuclear site geology/hydrogeology and geological history, possible explanations for the observed underpressures include: poroelastic response to glacial unloading; poroelastic response to Cenozoic erosional unburdening; capillary pressure effects due to likely presence of a separate gas phase; and/or chemical osmosis. Poroelastic response is an attractive explanation because the lowest pressures appear to occur within the most compressible formations (i.e., Georgian Bay and Blue Mountain shales, but also the Salina B and C Units). Presence of a gas phase within the Ordovician shales and limestone as suggested in Sections 4.3.3 and 4.6.7.3 is also a credible explanation based on recent brine-gas modeling (AECOM Canada Ltd., 2010) that shows similar underpressures within these formations. Osmosis cannot be eliminated from the list of potential explanations as water within the packer-isolated test intervals of DGR boreholes have lower salinity than most adjacent formation porewater. These chemical gradients may potentially create osmotically induced flow of water from the test interval to the formation resulting in under-pressuring of the test interval (Neuzil, 2000).

Regardless of which explanation is favoured, the occurrence of such underpressures implies that the formations in which they are measured must be of extremely low permeability in order for them to persist. Based on underpressure occurrences reported for the Pierre shale, which is quite analogous to the Bruce Ordovician shale and limestone sequence (i.e., 300 m thick shale sequence with similar underpressure head magnitude [130 m] and pattern [maximum underpressure at centre of sequence]), the Ordovician shale and limestone sequence at the Bruce nuclear site has formation-scale

permeabilities of less than 10^{-20} m^2 (hydraulic conductivity less than 10^{-13} m/s). These hydraulic conductivity estimates are very similar to those estimated from interpretation of field hydraulic test data discussed in Sections 4.9.2 and 4.9.3.

4.11.3 Groundwater Flow Directions in Permeable Units

As evident in Figure 4.82 and Table 4.13, there are four sections of the Paleozoic stratigraphic sequence at the Bruce nuclear site, with sufficient permeability (e.g., $> 10^{-10} \text{ m/s}$) to support active groundwater movement or flow. These aquifers and their reference depths include:

- the permeable Devonian and Upper Silurian dolostone aquifer of the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations At depths of 20 to 169.3 mBGS in DGR-1,
- the vuggy Salina Upper A1 Unit aquifer at depths of 325.5 to 328.5 mBGS in DGR-1;
- the vuggy Guelph Formation aquifer at depths of 374.5 to 378.6 mBGS in DGR-1; and
- the overpressured Cambrian sandstone at depths of 843.8 to 860.7 mBGS in DGR-2.

Groundwater flow directions in these four aquifers are estimated based on measurements of formation pressures and hydraulic heads in boreholes instrumented with MP38 and MP55 multi-level monitoring casings.

Groundwater flow in the permeable Devonian and Upper Silurian dolostones is discussed in Section 4.11.1. Formation pressure measurements in boreholes US-3, US-7 and US-8 show stable hydraulic head profiles indicating slight upward hydraulic gradients (0.001 to 0.01 m/m) and lateral flow to the northwest toward Lake Huron.

For the deeper permeable units intersected by DGR boreholes, horizontal groundwater flow directions are calculated from measured formation pressures obtained from MP55 casings considering the density of the aquifer fluids and the dip of the formations. Table 4.15 summarizes the results of this assessment.

Table 4.15 Formation pressures and groundwater flow directions in DGR deep permeable bedrock units

Parameter (Units)	Salina Upper A1 Unit	Guelph Formation	Cambrian Sandstone
Date of Pressure Measurements	October 30, 2009	October 30, 2009	December 8/9, 2009
Adjusted Pressures for Mid-Depth of Horizontal Permeable Unit (kPa)	DGR-1: 3408.98 DGR-3: 3348.85 DGR-4: 3297.48	DGR-1: 4051.09 DGR-3: 4103.91 DGR-4: 4060.99	DGR-2: 10990.64 DGR-3: 11015.98 DGR-4: 11010.58
Equipotential Line (Azimuth)	231°	327°	2°
Groundwater Flow Direction (Azimuth)	320°	57°	92°
Hydraulic Gradient (m/m)	0.0086	0.0045	0.0020

Groundwater flow directions and hydraulic gradients were calculated from measured in-situ pressures in MP55 casings with the following procedure:

- Correct measured absolute MP pressures for the interval that contains the permeable unit for atmospheric pressures measured at the time of the field survey.
- Express atmospheric-corrected MP pressures as the formation pressure at the mid-depth point of the permeable unit considering the density of the formation fluid and the elevation difference between the MP pressure measurement port the mid-depth point.
- Express the mid-point formation pressures as an equivalent pressure for a horizontal permeable unit considering the orientation of the unit as listed in Table 3.1 determined from TR-08-12. These equivalent horizontal unit pressures are listed in Table 4.16.
- Solve the three-point pressure problem to determine the strike and dip of the equivalent horizontal formation pressure surface considering true location of pressure measurement ports considering borehole tilts.
- Express the calculated formation pressure surface as equipotential lines, groundwater flow directions and hydraulic gradients.

The results of these calculations as listed in Table 4.15 show the groundwater flow directions in the Upper A1 Unit aquifer are the same as those in the shallow dolostones, being to the northwest toward Lake Huron. In contrast, the calculated groundwater flow directions for the Guelph Formation and the Cambrian sandstone are outward from the middle of the Michigan Basin being toward the northeast (Guelph Formation) and to the east (Cambrian sandstone).

4.12 Hydrostratigraphic Units

Because of natural variability, hydrogeological and geochemical properties can be expected to vary within and across every stratigraphic formation and unit beneath the Bruce nuclear site as defined in Section 3 of this report. For the purpose of preparation of the descriptive hydrogeological site model, the overburden and bedrock formations at the Bruce nuclear site have been categorized and grouped into hydrostratigraphic (HS) units.

Hydrostratigraphic units are formations, parts of formations or groups of formations which have similar hydrogeologic characteristics that allow for grouping into aquifers, aquitards and aquicludes. Hydrostratigraphic units are operational definitions that facilitate hydrogeologic assessment. Nine hydrostratigraphic units have been defined, as noted below and shown in Figure 4.94, based on data and reference stratigraphy depths at DGR-1 and DGR-2.

- HS Unit 1; Overburden Aquitard; 0 to 20 mBGS.
- HS Unit 2; Devonian and Upper Silurian Dolostone Aquifer, 20 to 169.3 mBGS.
- HS Unit 3; Silurian Shale, Dolostone and Anhydrite Aquitards, 169.3 to 447.7 mBGS, excluding Unit 4.
- HS Unit 4; Silurian Dolostone Aquifers, 325.5 to 328.5 mBGS (4A) and 374.5 to 378.6 mBGS (4B).
- HS Unit 5; Ordovician Shale Aquiclude, 447.7 to 659.5 mBGS.

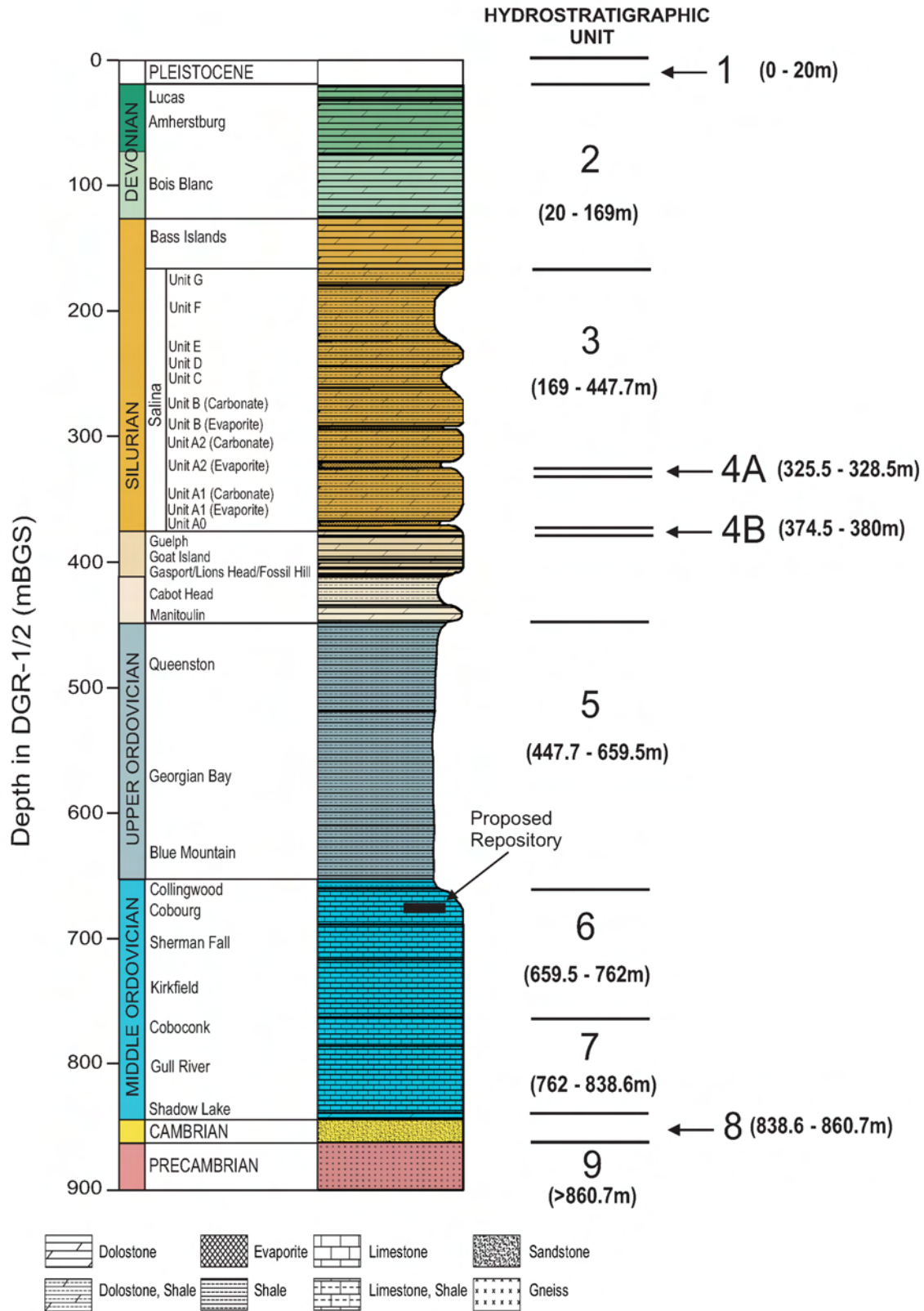


Figure 4.94 Reference stratigraphic column showing hydrostratigraphic units at the Bruce nuclear site

- HS Unit 6; Ordovician Limestone Aquiclude, 659.5 to 762.0 mBGS,
- HS Unit 7; Ordovician Limestone Aquitard, 762.0 to 836.6 mBGS.
- HS Unit 8; Cambrian Sandstone Aquifer, 838.6 to 860.7 mBGS.
- HS Unit 9; Precambrian Aquifer and Aquitard, >860.7 mBGS.

Within this DGSM report aquifer, aquitard and aquiclude are defined based on definitions provided in the OPG DGR project glossary (OPG, 2008b). Aquifers are defined as formations or units that are sufficiently porous and permeable to store, transmit and yield significant quantities of groundwater. For the Bruce DGSM, aquifers are practically defined as formations or units that yield sufficient water to allow for groundwater sampling. Aquitards are formations or units that retard but do not prevent flow of water to or from adjacent aquifers. Aquitards do not readily yield water, but over long periods of time may exhibit evidence of advection. Aquicludes are formations or units with very low permeability such that they are almost impermeable and do not exhibit evidence of advection even over very long periods of time.

4.12.1 HS Unit 1: Overburden Aquitard

HS Unit 1 comprises the overburden deposits at the Bruce nuclear site. Overburden at the Bruce nuclear site (Section 3.6.1) is of variable thickness ranging from a thin veneer near Lake Huron to upwards of 20 m in the southeastern part of the site near US-6 and DGR-1 (Figure 1.2). In the vicinity of the proposed DGR at DGR-1, the overburden consists of 2-3 m layers of granular fill and basal gravel overlying and underlying 15 m of sandy silt till, which classifies the overburden as an aquitard.

Although hydraulic testing of overburden deposits was not undertaken as part of the GSCP, there is an extensive database of hydraulic tests of the overburden at the Bruce nuclear site completed as part of radioactive and non-radioactive waste management investigations (Jensen and Heystee, 1987; Jensen and Sykes, 1995; Golder Associates Ltd., 2003). Based on these sources, the bulk horizontal hydraulic conductivity for unweathered sandy silt till at the Bruce nuclear site ranges from 1×10^{-10} to 6×10^{-9} m/s with an average or estimated value of 8×10^{-10} m/s. Horizontal:vertical K anisotropy has been evaluated at 2:1 with water loss porosity of 20% (Jensen and Heystee, 1995).

Specific storage values for HS Unit 1, based on literature review of similar soils and review of on-site hydraulic testing, are estimated to be about 1×10^{-3} m⁻¹.

Vertical hydraulic gradients are typically about 0.1 m/m in both upward and downward directions depending upon proximity to the regional groundwater discharge area of Lake Huron.

Effective diffusion coefficients (D_e , chloride) in HS Unit 1 have been reported as 6×10^{-10} m²/s (Golder Associates Ltd., 2003) with diffusion porosity equal to water loss porosity. Diffusion properties in the overburden are assumed to be isotropic.

Groundwater chemistry is typical fresh Ca:Na-HCO₃ with TDS less than 500 mg/L (Intera Engineering Ltd., 2007b) and with oxidizing redox conditions. Master variables of pH and Eh approximate 7-8 and +200 to +400 mV, respectively.

4.12.2 HS Unit 2: Devonian and Upper Silurian Dolostone Aquifer

HS Unit 2 comprises the permeable upper dolostone aquifer at the Bruce nuclear site from top of bedrock to reference depth of 169.3 m BGS at DGR-1. HS Unit 2 includes the Lucas Formation, where present, and the underlying Amherstburg, Bois Blanc and Bass Islands Formations. In DGR boreholes the Unit is 149 to 179 m thick. HS Unit 2 includes the regional groundwater supply aquifer that typically extends to depths of 50 to 100 m and the deeper less permeable bedrock to the top of the Salina Formation.

Extensive packer testing and observations of drilling fluid loss show that the average horizontal hydraulic conductivities in the upper 100 m range from 2×10^{-6} to 8×10^{-8} m/s, generally decreasing with depth. However, the upper part of the Bass Islands Formation in all DGR boreholes at DGR-1 reference depths of 140 to 145 mBGS contains very permeable sections with hydraulic conductivity approximating 1×10^{-4} m/s. Below 145 mBGS at DGR-1, the hydraulic conductivity of HS Unit 2 decreases to average values of about 1×10^{-6} m/s. The horizontal:vertical K anisotropy is assumed to be 10:1. Based on lab testing of the Bois Blanc and Bass Islands Formations in DGR boreholes, an average total porosity of 7% is assumed for HS Unit 2.

Specific storage values for HS Unit 2, based on literature review of similar rock, review of on-site hydraulic testing, and calculations from lab measurements of rock compressibility and liquid porosity (see Section 4.10) are estimated to be in the range of 8×10^{-7} to 3×10^{-6} m⁻¹, generally increasing with depth.

Vertical and horizontal hydraulic gradients in HS Unit 2 are low (i.e., 0.001 to 0.01 m/m) reflecting the high hydraulic conductivities with flow gradients directed upward and laterally to the northwest toward Lake Huron.

Diffusion testing was not undertaken in HS Unit 2 in Phase 1 or Phase 2. Based on core observations, measured porosities, results from testing on similar DGR core, and scientific literature, the vertical effective diffusion coefficient for iodide in HS Unit 2 is estimated at 1×10^{-11} m²/s. The horizontal:vertical D_e anisotropy is assumed to be 1:1 based on DGR core observations and the elevated formation hydraulic conductivities. Diffusion porosity is assumed equal to total porosity of 7%.

Groundwater and porewater chemistries in HS Unit 2 are transitional from fresh Ca:Mg-HCO₃ water (TDS ~500 mg/L) near the top of the bedrock to brackish Ca-SO₄ water (TDS ~5,000 mg/L) at the bottom of the Unit. Master variables of pH and Eh (field measured) approximate 7-8 and +400 to -100 mV respectively, with Eh decreasing with depth.

The deeper parts of HS Unit 2 including the Bass Islands Formation show a depleted ¹⁸O and D signature and ¹⁴C ages indicative of a glacial meltwater component. Vertically upward mixing and exchange of higher TDS Ca-SO₄ water from underlying HS Unit 3 is also evident in HS Unit 2.

4.12.3 HS Unit 3: Silurian Shale, Dolostone and Anhydrite Aquitards

HS Unit 3 comprises the low permeability Silurian shale, dolostone and anhydrite rocks at the Bruce nuclear site from DGR-1 reference depths of 169.3 to 447.7 mBGS. HS Unit 3 includes three aquitards: upper, middle and lower separated by two Silurian dolostone aquifers (HS Units 4A and 4B) which are found at DGR-1 reference depths of 325.5 and 374.5 mBGS. The upper aquitard comprises the Salina Units G, F, E, D, C, B and most of A2 found at reference depths of 169.3 to 325.5 mBGS. The middle aquitard includes the Salina A1 and A0 Units found at reference depths of 328.5 to 374.5 mBGS. The lower aquitard consists of the Goat Island, Gasport, Lions Head, Fossil Hill, Cabot Head and Manitoulin Formations found at reference depths of 378.6 to 447.7 mBGS. HS

Unit 3 has a combined thickness of 260.7 to 271.3 m in DGR boreholes.

Borehole straddle-packer testing shows that the average horizontal hydraulic conductivities for formations and units that comprise HS Unit 3 range from 5×10^{-14} to 3×10^{-10} m/s, with most values at or less than 1×10^{-12} m/s. Based on lab permeability testing (Figures 4.18 and 4.84), the horizontal:vertical K anisotropy is estimated to be 10:1. Based on lab testing (Section 4.3.2, Figure 4.3, Table 4.3), average liquid porosity for HS Unit 3 formations and units range from 1 to 20% with a calculated bulk HS Unit 3 average value of 8.9%. The upper aquitard and the Cabot Head shale of the lower aquitard have higher average porosity (~15%) than the middle aquitard and the remaining formations comprising the lower aquitard (average 3%).

Specific storage values for HS Unit 3, based on calculations from lab measurements of rock compressibility and liquid porosity are estimated to be in the range of 4×10^{-7} to 5×10^{-6} m⁻¹, generally decreasing with depth into the more competent Silurian dolostones. Elevated specific storages are noted for the Cabot Head shale with values of 3×10^{-5} m⁻¹.

Pressures in the upper and middle aquitards of HS Unit 3 are moderately underpressured with the maximum underpressure (~ 70 mBGS) occurring in the middle of the sequence in the Salina C and B Units. Based on environmental heads, vertical hydraulic gradients in the upper and middle aquitards of HS Unit 3 are moderate (0.1 to 0.5 m/m) upward and downwards to the maximum underpressure zone reflecting the low vertical hydraulic conductivities of the aquitard. However, vertical hydraulic gradients in the lower aquitard are much higher (1.0 to 3.0 m/m) being both upwards and downwards from the high pressure zone straddling the Salina A1 and A0 Units and the Goat Island, Lions Head and Fossil Hill Formations. These high vertical gradients suggest that the bedrock of the bottom part of the middle aquitard and lower aquitard must be of very low permeability in order to maintain such high hydraulic gradients.

Laboratory diffusion testing undertaken on shale, dolostone and anhydrite core samples collected from HS Unit 3 shows a wide range of vertical effective diffusion coefficients for iodide of about 3×10^{-14} m²/s for anhydrite to $1-2 \times 10^{-11}$ m²/s in the higher porosity shales. The available diffusion data indicate that the vertical effective diffusion coefficient for iodide in the upper aquitard and the Cabot Head shale of the lower aquitard is about 5×10^{-12} m²/s with horizontal:vertical D_e anisotropy of 2:1. The average iodide diffusion porosity in these rocks is 6% or about 67% of the total porosity. The vertical effective diffusion coefficient for iodide in the middle and lower aquitard (excluding the Cabot Head shale) is about 1×10^{-13} m²/s with horizontal:vertical D_e anisotropy of 2:1. The average iodide diffusion porosity in the middle and lower aquitard, excluding the Cabot Head shale, is 1.5% or about 50% of the total porosity.

Groundwater and porewater chemistries in HS Unit 3 are transitional from brackish Ca-SO₄ water (TDS ~10,000 mg/L) near the top of the Unit to Na-Cl brine (TDS ~325,000 mg/L) at the bottom of the Unit. The dramatic increases in TDS with depth in this unit is reflected in the major ion profiles (Figures 4.52, 4.53 and 4.54) and the fluid density profile (Figure 4.73). Master variables of pH and Eh approximate 7.0 and -100 to -150 mV, respectively, reflecting iron and/or sulphur reducing conditions.

Superimposed on this major ion chemistry profile are significant decreases and increases in the salinity and chemistry of groundwater measured in the Upper A1 Unit aquifer and the Guelph aquifer, respectively. The moderate salinity profile in the upper aquitard suggests that exchange or mixing of porewater from this part of the aquitard has occurred and that the upper aquitard is likely more permeable than the middle and lower aquitards. The salinity contrast in the middle aquitard from TDS of 30,000 mg/L at 328.5 mBGS to 330,000 mg/L at 374.5 mBGS is remarkable and suggests that the middle aquitard comprising the Salina A1 and A0 Units is of very low permeability, such that solute transport is likely by diffusion. Based on the changes in concentrations of major ions and TDS across

the lower aquitard, it is also likely of very low permeability.

4.12.4 HS Unit 4: Silurian Dolostone Aquifers

HS Unit 4 comprises two thin porous and permeable aquifers evident in core logging, borehole geophysical logging, hydraulic testing and groundwater sampling completed in DGR boreholes. The upper aquifer (4A) is found at reference depths 325.5 to 328.5 mBGS in DGR-1 and is the upper 3.0 to 3.7 m of the Salina A1 Unit dolostone in DGR boreholes. The lower aquifer (4B) is found at reference depths 374.5 to 378.6 mBGS in DGR-1 and is the entire thickness of the Guelph Formation dolostone. The lower aquifer ranges in thickness from 4.1 to 5.4 m thickness in DGR boreholes. Core photographs of these porous and permeable aquifers are given in Figures 3.20, 3.23 and 4.83.

Borehole straddle-packer testing and observations during targeted groundwater sampling in DGR-3 and DGR-4 show that the average horizontal hydraulic conductivities in these Silurian dolostone aquifers approximate 2×10^{-7} and 3×10^{-8} m/s, respectively (Table 4.13). Based on core observations, the horizontal:vertical K anisotropy is assumed to be 1:1. Again, based on core observations and limited lab testing (TR-08-10), an average total porosity of 7.0% is assumed for HS Unit 4A and 5.7% for HS Unit 4B.

Specific storage values for HS Unit 4B, based on calculations from lab measurements of rock compressibility and liquid porosity are estimated to be about 1×10^{-6} m⁻¹. This specific storage value is assumed to be applicable to HS Unit 4A, based on similarity of lithology and porosity.

Vertical hydraulic gradients in both dolostone aquifers of HS Unit 4 are negligible based on the observed high permeability and limited thickness. Horizontal hydraulic gradients for HS Unit 4A are calculated from MP55 casing pressure measurements at 0.0086 m/m with groundwater flow directed to the northwest toward Lake Huron (Table 4.15). Horizontal hydraulic gradients for HS Unit 4B, also calculated from MP55 casing pressure measurements, are 0.0045 m/m with groundwater flow directed to the northeast.

Diffusion testing was not undertaken in HS Unit 4 in either Phase 1 or Phase 2A. Based on measured or estimated, the vertical effective diffusion coefficient for iodide is estimated at 5×10^{-12} m²/s for MS Unit 4A and 3×10^{-12} m²/s for MS Unit 4B (TR-08-10). The horizontal:vertical D_e anisotropy is assumed to be 1:1 based on core observations. Diffusion porosity in these porous permeable aquifers is assumed equal to total porosity at 7% and 5.7% for Units 4A and 4B, respectively.

Groundwater and porewater chemistries in HS Unit 4 are remarkably different in each aquifer based on results of recent targeted groundwater sampling in DGR-3 and DGR-4. The aquifer of the Salina Upper A1 Unit contains saline Na-Cl water with TDS of 30,000 mg/L. The lower aquifer of the Guelph Formation contains Na-Cl brine with TDS of 370,000 mg/L. Master variable of pH for the upper and lower aquifers approximate 7.0 to 7.3 and 6.5 to 7.1 (field measured), respectively. Eh in the upper and lower aquifers is about -100 mV and -150 mV, respectively, reflecting iron and/or sulphur reducing conditions.

4.12.5 HS Unit 5: Ordovician Shale Aquiclude

HS Unit 5 comprises the very low permeability massive Ordovician shale sequence at the Bruce nuclear site from reference depths of 447.7 to 659.5 mBGS at DGR-1 and DGR-2. HS Unit 5 includes the Queenston, Georgian Bay and Blue Mountain Formation shales and Collingwood Member shale of the Cobourg Formation. The Unit is 211.8 to 216 m thick in DGR boreholes.

Borehole straddle-packer testing shows that the average horizontal hydraulic conductivities for formations and members that comprise HS Unit 5 range from 2×10^{-14} to 5×10^{-14} m/s, with several individual straddle-packer test results reported at values greater than and less than these average formation values. Based on laboratory petrophysical testing, the horizontal:vertical K anisotropy is assigned a value of 10:1. Based on extensive testing by different laboratories using different testing methods (Section 4.3.2, Figure 4.3, Table 4.3), an average total porosity of 7.1% is assumed for the massive shales of HS Unit 5. The siltstone and argillaceous limestone hard beds that occur within the shales have lower average total porosity of 2.7%.

Specific storage values for HS Unit 5, based on calculations from lab measurements of rock compressibility and liquid porosity are estimated to be in the range of 1×10^{-6} to 2×10^{-5} m⁻¹, generally increasing with depth into the softer Blue Mountain shales. Specific storage values for the Collingwood Member approximate 8×10^{-7} m⁻¹.

Formation pressures in the Ordovician shales are significantly under-pressured. As discussed in Section 4.11.2, after shut-in periods of up to 18 months, formation pressures in HS Unit 5 are not yet stable, with maximum underpressures of about 300 mBGS expressed as environmental water head occurring within the Blue Mountain Formation. Based on environmental heads, vertical hydraulic gradients in HS Unit 5 are generally strongly downward (~1.2 to 1.5 m/m) to the Blue Mountain Formation. Although the genesis of these underpressures is ambiguous, their occurrence and persistence are clearly indicative of very low formation permeability.

It is a characteristic of the HS Unit 5 that a normally-pressured zone of higher test interval compressibility and hydraulic conductivity occurs within the otherwise under-pressured and very low hydraulic conductivity aquiclude. These features appear to be associated with discrete inclined and subhorizontal fractures.

Laboratory diffusion testing undertaken on DGR shale core samples collected from HS Unit 5 shows vertical effective diffusion coefficients for iodide of about 4×10^{-13} to 3×10^{-12} m²/s generally decreasing with depth and showing a horizontal:vertical D_e anisotropy of about 2:1. A bimodal distribution of iodide effective diffusion coefficient and porosity is recognized from diffusion testing based on the presence of two distinct lithologies (shale and limestone/siltstone hardbeds) within HS Unit 5. The vertical effective diffusion coefficients for the HS Unit 5 hardbeds range from 3×10^{-14} to 4×10^{-13} m²/s. The estimated iodide diffusion porosity values are 4.5% for the massive shales and 2% for the siltstone/limestone hardbeds within those shales.

Porewater chemistries in HS Unit 5 are relatively uniform consisting of Na-Cl brine (average TDS ~300,000 mg/L, Figure 4.52) showing minor (up to 10%) decreases in TDS with depth through the Unit. This uniform chemistry profile is evident in the major ion profiles (Figures 4.52, 4.53 and 4.54), the ¹⁸O and D profiles (Figures 4.59 and 4.60) and the fluid density profile (Figure 4.73). Master variables of pH and Eh approximate 5.5 (computed from measured pCO₂) and -150 mV respectively, reflecting iron and/or sulphur reducing conditions.

The persistent formation underpressures and the uniform porewater chemistry profiles indicate that no significant fluid flow has occurred within HS Unit 5, supporting its designation as an aquiclude.

4.12.6 HS Unit 6: Ordovician Limestone Aquiclude

HS Unit 6 comprises the very low permeability argillaceous limestone of the Lower Member of the Cobourg Formation – the DGR repository horizon and the underlying limestones of Sherman Fall and Kirkfield Formations. Geologically, this HS Unit 6 is composed of the Trenton Group limestones. HS Unit 6 is found at reference depths of 659.5 to 762.0 mBGS at DGR-2. The Unit is 101.5 to 102.6 m thick in DGR boreholes.

Borehole straddle-packer testing and some laboratory petrophysical testing show that the average horizontal hydraulic conductivity for the formations that comprise HS Unit 6 range from 8×10^{-15} to 2×10^{-14} m/s, with bulk Unit average of 1×10^{-14} m/s. Based on laboratory petrophysical testing, the horizontal:vertical K anisotropy is assigned a value of 10:1. Based on extensive testing by different laboratories using different testing methods (Section 4.3.2, Figure 4.3), an average total porosity of 1.8% is assumed for the argillaceous limestones of HS Unit 6.

Specific storage values for HS Unit 6, based on calculations from lab measurements of rock compressibility and liquid porosity are estimated to be in the range of 2×10^{-7} to 3×10^{-6} m⁻¹, with an average value of about 8×10^{-7} m⁻¹.

Formation pressures in the Cobourg, Sherman Fall and Kirkfield Formations are under-pressured and very slow to achieve stable conditions. As discussed in Section 4.11.2, stable formation pressures in HS Unit 6 have not yet been measured following shut-in periods of 15 months after initial installation of MP55 casing systems in DGR-2. The current best estimates of underpressures in HS Unit 6 expressed as environmental heads approximate 250 mBGS. Based on environmental heads, vertical hydraulic gradients in HS Unit 6 are moderately to strongly upward (~0.5 to 1.0 m/m) to the Blue Mountain Formation. Although the genesis of these underpressures is ambiguous, their occurrence is clearly indicative of very low formation permeability.

Laboratory diffusion testing undertaken on DGR core samples collected from HS Unit 6 shows vertical effective diffusion coefficients for iodide of about 1×10^{-13} to 9×10^{-13} m²/s with an average values of about 3×10^{-13} m²/s. Similar to other low permeability HS units, a horizontal:vertical D_e anisotropy of about 2:1 is determined for HS Unit 6 from available diffusion testing. Average iodide diffusion porosity was measured at about 1.3%.

Porewater chemistries in HS Unit 6 are show minor decreases in concentration from the top to the bottom of HS Unit 6. Porewater in HS Unit consists of Na-Cl brine decreasing in TDS from about 270,000 mg/L at the top of unit to about 230,000 mg/L at the bottom of the unit (Figure 4.52). This chemistry profile is evident in the major ion profiles (Figures 4.52, 4.53 and 4.54), the ¹⁸O and D profiles (Figures 4.59 and 4.60) and the fluid density profile (Figure 4.75). Master variables of pH and Eh approximate 5.0 (computed from measured pCO₂) and -150 mV respectively, reflecting iron and/or sulphur reducing conditions.

The formation underpressures and the porewater chemistry profiles indicate that no significant fluid flow has occurred within HS Unit 6, supporting its designation as an aquiclude.

4.12.7 HS Unit 7: Ordovician Limestone Aquitard

HS Unit 7 comprises the low permeability Ordovician limestone sequence at the Bruce nuclear site from reference depths of 688.1 to 838.6 mBGS at DGR-2. HS Unit 7 includes the Coboconk and Gull River Formations (i.e., the Black River Group of limestones). In DGR boreholes, the Unit is 75.4 to 76.6 m thick.

Borehole straddle-packer testing and laboratory petrophysical testing show that the average horizontal hydraulic conductivity for HS Unit 7 ranges from 2×10^{-13} to 5×10^{-11} m/s, with some higher lab values reported in bottom of the Gull River Formation. The estimated average horizontal hydraulic conductivity for the HS Unit is 5×10^{-12} m/s. Based on laboratory petrophysical testing, the horizontal:vertical K anisotropy is assumed to be 10:1 throughout HS Unit 7. However this anisotropy estimate may be low within the Coboconk Formation if formation permeability is preferentially associated with some thin zones (i.e., volcanic ash and tan dolostone marker beds) that are suspected to have increased hydraulic conductivity based on interpretation of borehole geophysical logs. Based on extensive testing by different laboratories using different testing methods (Section

4.3.2, Figure 4.3), an average total porosity of 1.8% is assumed for the limestones of HS Unit 7.

Since there are no lab geomechanical tests on core collected from HS Unit 7, specific storage values for HS Unit 7 are estimated based on data from overlying HS Unit 6. Consequently, specific storages are estimated to be in the range of 2×10^{-7} to $3 \times 10^{-6} \text{ m}^{-1}$, with an average value of about $8 \times 10^{-7} \text{ m}^{-1}$.

Formation pressures and calculated fresh water and environmental heads in HS Unit 7 are normally pressured to overpressured and achieve stable conditions quickly within several weeks to a few months of casing installation (see Figures 4.61 to 4.63), reflecting the higher formation permeabilities relative to the overlying lower permeability units. Based on environmental heads, vertical hydraulic gradients in HS Unit 7 are strongly upward (~ 1.6 to 2.2 m/m) to the Kirkfield Formation reflecting overpressuring from the deeper Cambrian sandstone. These upward gradients, as per Darcy's Law, indicate upward advection of groundwater through HS Unit 7. If there was no upward advection through HS Unit 7, the hydraulic head profile through HS Unit 7 would be uniformly equal to that measured within the Cambrian sandstone.

Laboratory diffusion testing undertaken on DGR core samples collected from HS Unit 7 shows vertical effective diffusion coefficients for iodide of about 5×10^{-14} to $9 \times 10^{-13} \text{ m}^2/\text{s}$ with an average value of about $3 \times 10^{-13} \text{ m}^2/\text{s}$. Similar to other low permeability HS units, a horizontal:vertical D_e anisotropy of about 2:1 is determined for HS Unit 7 from available diffusion testing. Average iodide diffusion porosity in HS Unit 7 was measured at about 1.2%.

Porewater chemistries in HS Unit 7 are Na-Cl brine but are transitional with depth from the chemistry of the overlying Kirkfield Formation to that of the underlying Cambrian sandstone. TDS decreases from $\sim 230,000 \text{ mg/L}$ at the top of Coboconk Formation to $\sim 200,000 \text{ mg/L}$ in the top to middle of the Gull River Formation and then increases to $\sim 230,000 \text{ mg/L}$ at the bottom of the Gull River Formation (Figure 4.52). There are numerous excursions in porewater chemistry from this general trend, with both higher and lower concentrations evident in HS Unit 7. The changes in porewater TDS chemistry with depth are evident in the major ion profiles (Figures 4.52, 4.53 and 4.54 – especially for potassium), the ^{18}O and D profiles (Figures 4.59 and 4.60) and the fluid density profile (Figure 4.73). Master variables of pH and Eh approximate 5.5 (computed from measured pCO_2) and -150 mV respectively, reflecting iron and/or sulphur reducing conditions.

The porewater chemistry profiles and the observed hydraulic gradients indicate upward mixing and exchange of Cambrian groundwater into HS Unit 7.

4.12.8 HS Unit 8: Cambrian Sandstone Aquifer

HS Unit 8 comprises the permeable Cambrian sandstone and the overlying permeable Shadow Lake siltstone found at reference depths of 838.6 to 860.7 mBGS at DGR-2. In DGR boreholes the Unit is estimated to be 22.1 m thick. The hydraulic properties of HS Unit 8 are dominated by the high hydraulic conductivity and hydraulic heads of the middle to lower parts of the Cambrian rocks.

Borehole packer testing, opportunistic groundwater sampling and laboratory petrophysical testing show that the average horizontal hydraulic conductivity for HS Unit 8 range from $1 \times 10^{-9} \text{ m/s}$ for the Shadow Lake Formation (Raven et al., 1992a) and upper parts of the Cambrian sandstone to $3 \times 10^{-6} \text{ m/s}$ for the bulk of the Cambrian rocks. Given the permeable nature of HS Unit 8, the hydraulic conductivity of HS Unit 8 is assumed to be isotropic. Based on extensive testing by different laboratories using different testing methods (Section 4.3.2, Figure 4.2), an average total porosity of 13% is assumed for the Cambrian sandstones of HS Unit 8. Lower values of about 2 to 10% have been measured in the less permeable upper part of the Cambrian sequence that shows fine-grained dolostone facies and in the Shadow Lake Formation. The overall average total porosity for HS Unit 8 is 9.5%.

Since there are no lab geomechanical tests on core collected from HS Unit 8, specific storage values for HS Unit 8 are estimated based on data from overlying HS Units, known HS Unit 8 porosity and literature review. Consequently, specific storage is estimated to about $1 \times 10^{-6} \text{ m}^{-1}$.

Formation pressures and calculated fresh water and environmental heads in HS Unit 8 are significantly over-pressured with formation pressures of about 11,000 kPa and environmental heads of 350 mASL (165 m above ground surface). These pressures and heads have been consistently measured during opportunistic groundwater sampling, flow tests of the Cambrian sandstone and with Westbay MP55 casing installations in all DGR holes. These high Cambrian Formation pressures propagate upward into the overlying Shadow Lake, Gull River and Coboconk Formations. Vertical hydraulic gradients in HS Unit 8 are assumed to be negligible based on the observed high hydraulic conductivities. Horizontal hydraulic gradients for HS Unit 8 are calculated from MP55 casing pressure measurements at 0.002 m/m with groundwater flow directed to the east away from the centre of the Michigan Basin (Table 4.15).

Diffusion testing was not undertaken in HS Unit 8 in Phase 1 or Phase 2A. Based on core observations, known porosity, results from testing on comparable DGR core, and scientific literature, the vertical effective diffusion coefficient for iodide in HS Unit 8 is estimated at $5 \times 10^{-11} \text{ m}^2/\text{s}$, the same as for permeable HS Unit 4. The horizontal:vertical D_e anisotropy is assumed to be 1:1 based on core observations. Diffusion porosity is assumed equal to liquid porosity at 8.1%.

Groundwater and porewater chemistries in HS Unit 8 are Na:Ca-Cl brine (TDS ~235,00 mg/L) but of lower salinity than the porewater of the upper parts of HS Unit 7 and of HS Units 6 and 5. Master variables of pH and Eh approximate 6.5 to 7.3 (field measured) and -150 mV reflecting iron and/or sulphur reducing conditions.

The collection of reliable and representative samples of groundwater from the over-pressured Cambrian rocks allows assessment of the reliability and representativeness of the porewater chemistry data determined for the Cambrian strata and the Shadow Lake Formation. Where this comparison is possible, it shows that the major ion (Figures 4.52, 4.53 and 4.54), environmental isotope (Figures 4.59 and 4.60) and gas (Figures 4.64, 4.66 and 4.72) chemistries are quite similar, providing confidence in the porewater chemistry results.

4.12.9 HS Unit 9: Precambrian Aquitard

HS Unit 9 comprises the moderate to low permeability basement rock of the Precambrian granite gneiss underlying the Cambrian sandstone. At DGR-2 the Unit is found at reference depths of 860.7 mBGS. Based on appearance of the 1.55 m of core obtained from DGR-2, HS Unit 9 is comprised of competent moderately fractured felsic granite gneiss.

No field or laboratory testing of the hydraulic properties of the Precambrian basement has been performed as part of Phase 1 or 2A site characterization work. However, there is a large amount of information on both the hydraulic and diffusive properties of similar rock types at similar depths in the Canadian Shield based on Canadian and international studies completed in support of deep geological disposal of nuclear fuel wastes. Based on review of these studies (Raven et al., 1992b), recommended estimates of hydraulic conductivity and liquid porosity of the majority of HS Unit 9 are $1 \times 10^{-12} \text{ m/s}$ and 0.5%, respectively and the rocks are assumed to be isotropic. The upper several metres to tens of metres of the Precambrian basement is often weathered, fractured and more permeable than the deeper basement rocks. Based on testing reported by Raven et al. (1992a) for borehole OHD-1 at a depth of about 400 mBGS at the Lakeview Generating Station, the upper weathered and fractured part of the Precambrian may have hydraulic conductivity of about 10^{-10} to 10^{-9} m/s , with a higher total porosity equivalent to the 3.8% measured by testing of DGR-2 core (Figure 4.3) to reflect weathering and fracturing. Based on these estimated hydraulic properties the

Precambrian, relative to the overlying Cambrian sandstone aquifer is an aquitard, although the upper part of the Unit likely has sufficient permeability to be considered an aquifer as per the definitions provided in Section 4.12.

There is no information available on formation pressures or hydraulic heads within HS Unit 9 at the Bruce nuclear site. Based on review of scientific literature (Raven et al., 1992b), a hydraulic gradient of 1×10^{-3} m/m is likely appropriate for HS Unit 9. The actual magnitude and direction of this assumed gradient is unknown at the Bruce nuclear site.

Diffusion testing was not undertaken in HS Unit 9 in Phase 1 and will not likely be conducted in Phase 2. Based on core observations and review of international scientific literature (Raven et al., 1992b), the effective diffusion coefficient for iodide is estimated at 3×10^{-13} m²/s. The horizontal:vertical D_e anisotropy is assumed to be 1:1. Diffusion porosity is assumed equal to total porosity at 0.5%.

Groundwater and porewater chemistries in HS Unit 9 are not known at the Bruce nuclear site, but have been extensively characterized elsewhere in Ontario (Frape and Fritz, 1987; Gascoyne et al., 1987), including the Sudbury mining region. Canadian Shield groundwater from comparable depths (>860 m BGS) are typically Ca-Na:Cl brine with TDS greater than 50,000 mg/L towards an estimated Shield source brine of more than 350,000 mg/L (Gascoyne et al, 1987; Pearson, 1997). Based on literature review, master variables of pH and Eh approximate 6.0 and -150 mV respectively, reflecting iron and/or sulphur reducing conditions.

4.12.10 Summary of HS Unit Properties

Table 4.16 provides a summary of the recommended estimates of hydrogeologic properties of the hydrostratigraphic units identified for the Bruce nuclear site as discussed in Sections 4.12.1 to 4.12.9. Table 4.16 lists recommended estimates of formation-scale properties based on review of available Phase 1 and 2A site characterization data, experience from investigation of similar formations elsewhere and professional judgment. Table 4.16 lists single recommended estimates or ranges of recommended estimates for formations where changes with depth are apparent. Table 4.16 lists parameter values for specific storage (S_s), horizontal hydraulic conductivity (K_h), hydraulic conductivity anisotropy ratio ($K_h:K_v$), total porosity (ϕ_t), vertical effective diffusion coefficient (D_{e-v}), diffusion coefficient anisotropy ratio ($D_{e-h}:D_{e-v}$), iodide accessible diffusion porosity (ϕ_i) and groundwater/porewater chemistry.

Table 4.16 Summary of recommended estimates of hydrogeologic properties of Bruce nuclear site hydrostratigraphic units

HS Unit	Depth (mBGS)	Hydraulic Properties				Iodide Diffusive Properties			Groundwater/Porewater Properties			
		S_s (m^2)	K_h (m/s)	$K_h:K_v$ (-)	Φ_t (%)	D_{e-v} (m^2/s)	$D_{e-h}:D_{e-v}$ (-)	Φ_l (%)	TDS (mg/L)	Type	pH	Eh (mV)
1: Overburden Aquitard	0-20	1×10^{-3}	8×10^{-10}	2:1	20	6×10^{-10}	1:1	20	<500	Ca,Na-HCO ₃	7-8	+200 to +400
2: Dolostone Aquifer	20-169.3	8×10^{-7} to 3×10^{-6}	1×10^{-7} to 1×10^{-4}	10:1	7.0	1×10^{-11}	1:1	7.0	500 to 5000	Ca,Mg-HCO ₃ to Ca-SO ₄	7-8	+400 to -100
3: Silurian Aquitards	169.3-447.7	4×10^{-7} to 3×10^{-5}	5×10^{-14} to 3×10^{-10}	10:1	3.0 to 15	1×10^{-12}	2:1	1.5 to 6.0	10,000 to 350,000	Ca-SO ₄ to Na-Cl	7.0	-100 to -150
4A: Silurian Aquifer	325.5-328.5	1×10^{-6}	2×10^{-7}	1:1	7.0	5×10^{-12}	1:1	7.0	30,000	Na-Cl	7.1	-100
4B: Silurian Aquifer	374.5-380.0	1×10^{-6}	3×10^{-8}	1:1	5.7	3×10^{-12}	1:1	5.7	370,000	Na-Cl	6.8	-150
5: Ordovician Shale Aquiclude	447.7-659.5	5×10^{-6} to 3×10^{-5}	2×10^{-14} to 5×10^{-14}	10:1	2.7 & 7.1	1×10^{-13} & 1×10^{-12}	2:1	2.0 & 4.5	300,000	Na-Cl	5.5	-150
6: Ordovician Lmst Aquiclude	659.5-762.0	8×10^{-7}	1×10^{-14}	10:1	1.8	3×10^{-13}	2:1	1.3	270,000 to 230,000	Na-Cl	5.0	-150
7: Ordovician Lmst Aquitard	762.0-838.6	8×10^{-7}	5×10^{-12}	10:1 ²	1.8	3×10^{-13}	2:1	1.2	230,000 to 200,000	Na-Cl	5.5	-150
8: Cambrian Aquifer	838.6-860.7	1×10^{-6}	1×10^{-9} to 3×10^{-6}	1:1	9.5	1×10^{-11}	1:1	8.1	225,000	Na,Ca-Cl	6.7	-150
9: Precambrian Aquitard ¹	>860.7	1×10^{-6}	1×10^{-10} & 1×10^{-12}	1:1	3.8 & 0.5	3×10^{-13}	1:1	3.8 & 0.5	50,000 to 350,000	Ca,Na-Cl	6.0	-150

Notes: Unless otherwise flagged all data are derived or interpreted from investigations of the Bruce nuclear site as described in relevant Technical Reports and discussed in Section 4.11 and earlier sections of this report.

1. All hydraulic and iodide diffusive property values for HS Unit 9 are from Raven et al. (1992b). All groundwater porewater property data are from Gascoyne et al. (1997) and Pearson (1987)

2. Anisotropy may be higher if permeability is preferentially associated with thin marker beds in the Coboconk Formation

4.13 Hydrogeological Systems

Physical and chemical hydrogeological data presented and discussed in Sections 4.3 to 4.12 of this report indicate the presence of four hydrogeological systems or regimes at the Bruce nuclear site:

- Shallow System;
- Intermediate System;
- Deep Aquiclude System; and
- Deep Over-Pressured System.

4.13.1 Shallow System

The shallow freshwater to brackish hydrogeological system includes HS Units 1 and 2 and extends to reference depths of about 169.3 mBGS at DGR-1. Groundwater flow within the permeable bedrock system is upward and laterally toward Lake Huron. Groundwater and porewater chemistries are transitional from fresh Ca:Mg-HCO₃ water (TDS ~500 mg/L) near the top of the bedrock to brackish Ca-SO₄ water (TDS ~5,000 mg/L) at the bottom of the system. Solute migration within this permeable shallow groundwater system is principally by advection.

This shallow groundwater flow system contains stable-isotope evidence of circulation of glacial meltwater mixing with older brackish waters. Although redox potentials of up to 400 mV have been measured (with Pt electrodes) on collected groundwater samples, this flow system is predominately anoxic as is demonstrated by the presence of trace pyrite in core samples. The deepest penetration of water with significant amounts of dissolved oxygen (i.e., DO > 0.3 mg/L) is from 170 m BGS in US-8 in which DO=7 mg/L (TDS=2670 mg/L). Radiocarbon analyses of dissolved inorganic carbon in groundwater from 158 and 179 mBGS in US-8 indicate ($\delta^{13}\text{C}$ corrected) ¹⁴C ages of 4,000 to 8,000 years B.P. Both of these samples had non-detectable DO.

4.13.2 Intermediate System

The intermediate hydrogeological system includes much of HS Unit 3 and both Silurian aquifer zones that comprise HS Unit 4, and occurs at reference depths of 169.3 to 378.6 mBGS at DGR-1. This is a predominantly low permeability system ($K_h=5\times10^{-14}$ to 3×10^{-10} m/s) with groundwater flow likely restricted to the two permeable aquifer zones present at reference depths of 325.5 – 328.5 mBGS in the top of the Salina A1 Unit and at 374.5 – 378.6 mBGS in the Guelph Formation. Based on formation pressure measurements, flow in these two permeable units is not coupled as the flow direction in the Salina Upper A1 Unit is towards Lake Huron, whereas in the Guelph Formation the flow direction is eastwards or inland. Opportunistic groundwater samples from these two permeable zones contained ferrous iron and dissolved sulphide and were approximately neutral in pH. The Salina Upper A1 Unit aquifer shows evidence of deep meltwater recharge, i.e., OGW-8: $\delta^{18}\text{O}=-14.4$ and $\delta\text{D}: \text{‰} -104\text{‰}$. Groundwater and porewater chemistries in this intermediate system are transitional from saline Ca-SO₄ water (TDS ~10,000 mg/L) near the top of HS Unit 3 to Na-Cl brine (TDS ~370,000 mg/L) at the bottom of the system, i.e., the Guelph aquifer zone.

The salinity and tracer profiles (e.g., $\delta^{18}\text{O}$ and δD , Cl, Sr) in the upper part of the system (Salina G to A1 Units) suggest that diffusive exchange of porewater from this part of the aquitard with the meltwater in the overlying Bass Islands Formation and underlying Salina Upper A1 Unit aquifers has occurred. There is also a pronounced $\delta^{18}\text{O}$, δD , major ion, TDS and fluid density increases downward from the Salina Upper A1 Unit to the Guelph that is likely diffusional in origin. The TDS in this lower

part of the system increases by over an order of magnitude in a vertical distance of only 46 m from 30,000 mg/L at reference depth of 328.5 mBGS to 370,000 mg/L at reference depth of 374.5 mBGS.

4.13.3 Deep Aquiclude System

The deep aquiclude hydrogeological system includes the lower part of HS Unit 3 and HS Units 5, 6 and 7 and occurs at reference depths of 378.5 to 762.0 mBGS at DGR-1 and DGR-2. This deep system consists of the lower Silurian dolostones and shales from the Goat Island down into the Upper Ordovician shales and finally the Trenton Group limestones that include the Cobourg, Sherman Fall and Kirkfield formations. Porewater chemistries in this system are Na-Cl brine with 4500 to 6000 mmol Cl/kgw and TDS of 220,000 to 300,000 mg/L that decrease in concentration with depth. Below the Guelph Formation, the rocks are of exceptionally low hydraulic conductivity ($K_h=8 \times 10^{-15}$ to 5×10^{-12} m/s), are typically moderately overpressured in the Gasport to Fossil Hill Formations and significantly underpressured in the deeper Ordovician shales and Trenton Group limestones that contain a free gas phase of approximately 10% of the pore volume. These hydrogeological properties indicate an aquiclude with no advection of brine, and a system in which gas flow would also be diffusion controlled.

Within each DGR borehole monitoring the deep aquiclude system there is one normally-pressured horizon that appears to be associated with specific subvertical (DGR-2 and DGR-3) and subhorizontal fractures (DGR-4). This normally-pressured zone also shows formation hydraulic conductivity that is 1 to 1.5 orders of magnitude greater than the surrounding rock mass and increased test interval compressibility measured during packer testing.

Environmental isotope profiles from DGR boreholes indicate no significant migration of solutes from this system other than by diffusion upwards to the Guelph Formation and possibly downwards to the underlying more permeable limestones of the Black River Group. The limited number of fractures detected appear to have healed and infilled with halite and calcite. The presence of soluble halite throughout the 290 m of rocks above and occasionally in the 75 m of rocks below the proposed repository formation is a clear indicator of the absence of active fluid circulation in this system. This diffusion-dominated system has likely existed over a time scale of hundreds of millions of years (AECOM Canada Ltd., 2010).

Several lines of evidence point to the presence of capillary barriers to solute migration immediately above the proposed repository formation. Firstly, the estimated pore throat radii for the Cobourg and Lower Blue Mountain formations are < 4 nm and the gas entry pressures are in excess of 20 MPa, which is approximately the lithostatic confining pressure at that depth. Also, the helium gas isotope ratios and the methane isotope ratios show strong gradients at the shale-limestone contact represented by the Collingwood Member. These data indicate that upward migration of gaseous radionuclides would be inhibited by capillary effects while downward migration would be prevented by a combination of the extremely low hydraulic conductivity and a strong upward hydraulic gradient.

4.13.4 Deep Overpressured System

The deep overpressured hydrogeological system includes HS Units 7 and 8 and occurs at reference depths of 762.0 to 860.7 mBGS at DGR-2. This deep system includes the Middle Ordovician Coboconk, Gull River and Shadow Lake Formations and the Cambrian sandstone, which all exhibit increased permeability relative to the overlying deep aquiclude system, and overpressures sourced from the Cambrian sandstone. The formation hydraulic conductivities in this system decrease upwards from Cambrian sandstone ($K_h=3 \times 10^{-6}$ m/s) through the Shadow Lake Formation ($K_h=1 \times 10^{-9}$ m/s) to the Gull River and Coboconk ($K_h=7 \times 10^{-13}$ and 4×10^{-12} m/s), with locally higher estimates of up to 5×10^{-11} m/s reported from some straddle-packer testing. Groundwater and porewater chemistries in this regime are Na:Ca-Cl to Na:Cl brine with TDS of about 200,000 to 225,000 mg/L.

Groundwater flow appears to occur both horizontally and vertically in this deep over-pressured system. Groundwater flow within the permeable Cambrian sandstone occurs laterally with flow directed to the east away from the centre of the Michigan Basin. Based on Darcy's Law and the observed upward hydraulic gradients that approximate 2 m/m, upward vertical groundwater flow is also occurring from the Cambrian sandstone to the Coboconk Formation. If there was no upward vertical groundwater flow in this deep overpressured system, the overpressure within the Cambrian sandstone would propagate uniformly upward to the top of the Coboconk with a resultant negligible upward vertical hydraulic gradient. The upward vertical groundwater flow may be occurring within a sparse network of discrete interconnected vertical and horizontal fractures and/or through an interconnected matrix porosity.

Because of the very low hydraulic conductivity of the overlying Trenton Group limestones in the area of the DGR, the upward flux of groundwater from the deep overpressured system must be accommodated by lateral and vertical groundwater flow through these overlying formations. Some of this lateral groundwater flow may be occurring in the suspected permeable volcanic ash layer present within the upper part of the Coboconk Formation and within the tan dolostone marker bed also found within the Coboconk Formation.

The major ion and environmental isotope profiles from DGR boreholes show that the current groundwater and porewater chemistry in the Cambrian sandstone is significantly different than the porewater chemistry profile evident within the overlying formations from the Guelph Formation to the Black River Group of formations, that AECOM Canada Ltd., (2010) attribute to very old (275 million years) diffusional profile. The reversals of Cl, Br, TDS, δO^{18} , δD , deuterium excess, Sr and $^{87}\text{Sr}/^{86}\text{Sr}$ depth trends evident within the Gull River Formation suggest that this perturbation within the Cambrian occurred within the recent geological past.

4.14 Recommended Estimates of Descriptive Hydrogeological Model Properties

Tables 4.17 and 4.18 summarize the recommended estimates of the main hydrogeological properties of the 39 layers that comprise the descriptive hydrogeological model for the Bruce DGR site. Data given in Tables 4.17 and 4.18 are consistent with and provide a more detailed description of the hydrogeological information given in Table 4.16 on the nine hydrostratigraphic units that represent the Bruce DGR site.

The descriptive hydrogeological model includes three additional layers that were not included in the geological model. The hydrogeological model includes separate model layers to account for increased permeability associated with the upper parts of Amherstburg Formation, Bass Islands Formation and Salina Upper A1 Unit Aquifer (HS Unit 4A). The descriptive geological model does not differentiate the upper and lower parts of these formations and units.

Table 4.17 summarizes the estimates of wet bulk density, dry bulk density, grain density, liquid porosity, diffusion porosity, total porosity and gas saturation for the 39 layers that comprise the descriptive hydrogeological site model. Table 4.18 summarizes estimates of the main transport properties, including formation horizontal hydraulic conductivity, hydraulic conductivity anisotropy, specific storage, vertical effective diffusion coefficients for iodide, effective diffusion coefficient anisotropy and groundwater/porewater total dissolved solids (TDS) of the 39 model layers. These tables do not list all hydrogeological properties determined for the descriptive hydrogeological model, only those main properties for which data is available for the most of the model layers and for which recommended estimates are appropriate and reasonably calculated. For example, information on gas entry pressures, surface areas and gas-brine flow properties are available primarily for the Cobourg Formation and the Ordovician shales and are not summarized here. Similarly, estimates of porewater and groundwater geochemistry, and formation pressures and environmental heads are not given here because many of the model layers show important spatial and/or temporal changes within

layers that are poorly represented by single estimated values.

Table 4.17 Recommended estimates of rock density, porosity and gas saturation properties of hydrogeological model layers

Model Layer	Wet Bulk Density (g/cm³)	Dry Bulk Density (g/cm³)	Grain Density (g/cm³)	Liquid Porosity (%)	Diffusion Porosity (%)	Total Porosity (%)	Gas Saturation (%)
Clay till overburden	-	-	-	20	20	20	-
Lucas	2.60	2.49	2.70	7.0	7.0	7.0	-
Amherstburg (upper 20m)	2.60	2.49	2.70	7.0	7.0	7.0	-
Amherstburg (lower 20m)	2.60	2.49	2.70	7.0	7.0	7.0	-
Bois Blanc	2.60	2.49	2.70	7.7	7.0	7.7	-
Bass Islands (upper 20 m)	2.60	2.49	2.70	5.7	5.7	5.7	-
Bass Islands (lower 25 m)	2.60	2.49	2.70	5.7	5.7	5.7	-
Salina G Unit	2.58	2.48	2.70	17.2	0.9	17.2	-
Salina F Unit	2.53	2.30	2.76	12.8	4.8	10.7	16.1
Salina E Unit	2.60	2.49	2.83	13.5	5.5	11.9	21.7
Salina D Unit	2.89	2.87	2.93	9.8	0.7	8.8	-
Salina C Unit	2.45	2.29	2.75	20.5	8.5	19.4	18.0
Salina B Unit dolostone	2.56	2.37	2.81	16.5	8.7	15.7	0
Salina B Unit anhydrite	2.89	2.87	2.93	9.8	0.7	8.8	-
Salina A2 Unit dolostone	2.65	2.44	2.87	14.5	3.9	12.4	0.3
Salina A2 Unit evaporite	2.89	2.87	2.93	9.8	0.7	8.9	14.7
Salina Upper A1 Unit	2.63	2.63	2.72	7.0	7.0	7.0	-
Salina Lower A1 Unit	2.63	2.63	2.72	1.9	1.1	2.9	-
Salina A1 Unit evaporite	2.89	2.87	2.93	0.7	0.1	1.2	0.3
Salina A0 Unit	2.63	2.60	2.78	2.7	1.8	5.4	16.5
Guelph	2.65	2.60	2.81	5.7	5.7	7.5	-
Goat Island	2.67	2.60	2.73	2.0	1.2	2.1	0
Gasport	2.67	2.60	2.73	2.0	1.2	2.1	-
Lions Head	2.67	2.60	2.73	3.1	1.3	3.1	-
Fossil Hill	2.67	2.60	2.73	3.1	1.3	3.1	-
Cabot Head	2.62	2.54	2.80	11.6	6.8	7.6	-
Manitoulin	2.66	2.66	2.73	2.8	1.3	3.1	0
Queenston	2.66	2.58	2.77	7.3	3.7	6.7	8.0
Georgian Bay	2.64	2.61	2.76	7.1	3.4	5.3	3.9
Blue Mountain	2.64	2.56	2.76	7.8	4.3	6.5	6.3
Cobourg – Collingwood Member	2.63	2.58	2.69	1.2	1.7	2.9	31.6
Cobourg - Lower	2.68	2.66	2.71	1.5	1.3	1.7	10.1
Sherman Fall	2.70	2.66	2.72	1.6	0.45	1.7	17.0
Kirkfield	2.68	2.64	2.70	2.1	2.1	2.1	20.3
Coboconk	2.67	2.67	2.69	0.9	1.1	0.7	3.7
Gull River	2.71	2.67	2.73	2.2	1.4	1.8	21.4
Shadow Lake	2.61	2.53	2.75	9.7	9.7	8.3	-
Cambrian	2.55	2.40	2.66	7.1	7.1	10.1	3.5
Upper Precambrian	2.54	2.49	2.59	3.8	3.8	3.8	-

Table 4.18 Recommended estimates of hydraulic, diffusive and pore fluid density properties of hydrogeological model layers

Model Layer	K_h (m/s)	$K_h:K_v$ (-)	S_s (m^{-1})	Iodide D_{e-v} (m^2/s)	$D_{e-h}:D_{e-v}$ (-)	Fluid TDS (g/L)
Clay till overburden	8E-10	2:1	1E-03	6.0E-10	1:1	0.5
Lucas	1E-06	10:1	8E-07	6.0E-12	1:1	0.5
Amherstburg (upper 20m)	1E-06	10:1	2E-06	6.0E-12	1:1	1.0
Amherstburg (lower 20m)	1E-07	10:1	2E-06	6.0E-12	1:1	2.0
Bois Blanc	1E-07	10:1	1E-06	6.0E-12	1:1	3.2
Bass Islands (upper 20m)	1E-04	10:1	2E-06	1.3E-11	1:1	6.0
Bass Islands (lower 25m)	1E-05	10:1	2E-06	1.3E-11	1:1	6.0
Salina G Unit	1E-11	10:1	5E-06	4.3E-13	2:1	14.8
Salina F Unit	5E-14	10:1	3E-06	4.1E-12	2:1	59.6
Salina E Unit	2E-13	10:1	3E-06	4.7E-12	2:1	124
Salina D Unit	2E-13	10:1	8E-07	4.7E-12	2:1	200
Salina C Unit	4E-13	10:1	5E-06	1.1E-11	2:1	249
Salina B Unit dolostone	4E-13	10:1	3E-05	1.2E-11	2:1	321
Salina B Unit anhydrite	3E-13	10:1	9E-07	7.7E-14	2:1	321
Salina A2 Unit dolostone	3E-10	10:1	2E-06	1.2E-12	2:1	136
Salina A2 Unit evaporite	3E-13	10:1	7E-07	7.7E-14	2:1	45.6
Salina Upper A1 Unit	2E-07	1:1	1E-06	4.9E-12	1:1	28.6
Salina Lower A1 Unit	5E-13	10:1	1E-06	1.8E-13	2:1	192
Salina A1 Unit evaporite	3E-13	10:1	4E-07	3.0E-14	2:1	325
Salina A0 Unit	5E-13	10:1	2E-07	3.0E-14	2:1	360
Guelph	3E-08	1:1	1E-06	3.2E-12	2:1	370
Goat Island	2E-12	10:1	5E-07	1.5E-13	1:1	300
Gasport	2E-12	10:1	5E-07	1.5E-13	2:1	300
Lions Head	5E-12	10:1	7E-07	6.2E-12	2:1	300
Fossil Hill	5E-12	10:1	9E-07	1.6E-11	2:1	300
Cabot Head	9E-14	10:1	3E-05	3.1E-12	2:1	306
Manitoulin	9E-14	10:1	2E-06	1.5E-13	2:1	350
Queenston	2E-14	10:1	4E-06	1.0E-12	2:1	310
Georgian Bay	3E-14	10:1	1E-05	6.8E-13	2:1	308
Blue Mountain	5E-14	10:1	1E-05	8.2E-13	2:1	295
Cobourg – Collingwood Member	2E-14	10:1	1E-06	4.9E-13	2:1	225
Cobourg - Lower	2E-14	10:1	7E-07	3.7E-13	2:1	272
Sherman Fall	1E-14	10:1	3E-06	2.2E-13	2:1	270
Kirkfield	8E-15	10:1	2E-06	4.2E-13	2:1	234
Coboconk	4E-12	10-100:1	2E-06	2.7E-13	2:1	255
Gull River	7E-13	10:1	2E-06	2.6E-13	2:1	203
Shadow Lake	1E-09	10:1	1E-06	6.1E-12	2:1	200
Cambrian	3E-06	1:1	1E-06	7.7E-12	1:1	235
Upper Precambrian	1E-10	1:1	1E-06	3.0E-13	1:1	-

Table 4.17 lists the estimates of rock densities based on laboratory testing by Core Labs, University of New Brunswick and the University of Bern (TR-07-17, TR-08-18, TR-08-06, TR-08-27, TR-08-28 and TR-08-40). Estimates of rock densities were determined from arithmetic averages for layers presented in Figure 4.1. Where rock density data were not available for shallow layers and some thin layers (e.g., Lucas to Bass Islands, Salina D Unit anhydritic dolostone, B Unit evaporite, A0 Unit dolostone, Gasport, Lions Head and Fossil Hill dolostones), densities were estimated from lithologically similar units or formations.

Estimates of liquid and total porosity for each of the hydrogeological model layers are based on a coherent analysis and interpretation of testing completed by Core Labs, University of Ottawa, University of New Brunswick and University of Bern as summarized in TR-08-10 and TR-08-34. The Estimated values of liquid and total porosities for each model layers are the arithmetic averages shown on Figures 4.2 and 4.3 that are based testing of unconfined cores. Estimates of diffusion porosity are the arithmetic average values of iodide tracer-accessible porosity from University of New Brunswick testing completed normal to bedding planes (TR-07-17, TR-08-27) as listed in Figure 4.40. As with rock density, where porosity data were not available for shallow layers and some thin layers, porosities were estimated from lithologically similar units or formations.

Estimates of gas saturations, expressed as a percentage of the pore space, are determined from analysis and interpretation of testing completed by Core Laboratories (TR-07-18, TR-0828) as described in TR-08-34. The estimates are the arithmetic averages shown on Figure 4.8. Given the observed variability of these data, extrapolation of data to other layers that were not tested was not done.

Similar to the descriptive geological model, Table 4.18 provides estimates of properties mostly on a unit, member and formation basis, regardless of any major lithofacies changes within such units, members and formations. Thus for the Queenston and Georgian Bay Formations where two sets of lithofacies are evident (massive shale and limestone/siltstone hardbeds) the reported estimates of rock densities, porosities and gas saturations are averages of cores that sample these different lithofacies. Similarly for the Cambrian rocks that are comprised of an upper argillaceous dolostone facies and a lower quartzitic sandstone facies, the reported estimate values represent an average of these two different lithofacies.

The estimates of formation hydraulic conductivity (K) for each of the 39 hydrogeological model layers given in Table 4.19 are geometric mean values determined primarily from field testing of DGR and US boreholes (TR-08-10). The values listed in Table 4.19 are those listed in Table 4.13 and shown in Figure 4.82. Only data from boreholes DGR-3 and DGR-4 are considered in these determinations for layers below the Salina G Unit as final K values from testing of DGR-2 were not available at the time of data compilation. No weight was given to laboratory gas pulse permeability testing due the recognized effects of core damage on the reported results. Estimates of hydraulic conductivity anisotropy are based primarily on laboratory core testing, with the proviso that thin permeable layers (i.e., Salina Upper A1 Unit, Guelph and Cambrian aquifers) based on core observations are isotropic with respect to hydraulic conductivity.

The Estimates of effective diffusion coefficient listed in Table 4.18 are the geometric mean estimates for iodide testing normal to bedding planes based on University of New Brunswick X-ray radiography and conventional through-diffusion testing (TR-07-17, TR-08-27). The estimates given in Table 4.18 are the average values shown in Figure 4.37 and calculated values for other layers not subject to testing based on measured porosity using Equation 4.7 assuming $m=2$ as described in Section 4.4.3 and tabulated in TR-08-10. Anisotropy in effective iodide diffusion coefficients given in Table 4.19 are based on testing completed by the University of New Brunswick on intact low permeability DGR cores and the assumption that rocks with hydraulic conductivity equal to or greater than 10^{-8} m/s are isotropic with respect to diffusion.

Average salinity of each model layer is listed in Table 4.18 as TDS in units of g/L solution based on porewater and groundwater analyses of US and DGR boreholes from TR-07-11, TR-07-27, TR-07-21, TR-08-08, TR-08-18, TR-08-19 and TR-08-27. The conversion of these data which are given in mixed concentration units to common units of g/L solution is described in TR-08-34.

4.15 Confidence Assessment of Hydrogeological Data and Model

Confidence in the descriptive hydrogeological site model presented in Section 4 is assessed based on an evaluation of the quality and uncertainty in the key data that comprises the model, consistency of the data sets that comprise the model and consistency of the hydrogeological model with other geoscientific models presented in Section 3 (descriptive geological site model) and Section 5 (descriptive geomechanical site model).

The following key hydrogeological data sets are subject to confidence assessment:

- Rock densities
- Liquid and total porosities
- Gas saturations
- Gas-brine flow properties
- Diffusion properties
- Porewater characterization
- Formation hydraulic properties
- Formation pressures and heads
- Groundwater flows in bedrock aquifers

4.15.1 Rock Densities

Confidence in the reported wet bulk, dry bulk and grain densities of the 39 layers that comprise the descriptive hydrogeological model is judged to be high. The estimates are based on extensive testing of strata from the Salina F Unit shale to the Precambrian basement using different testing techniques on different sized core subsamples by different testing laboratories. The resultant scatter and range in the reported densities as evident in Figure 4.1 and Table 4.1 are minor and generally in accordance with expectations given the known formation mineralogies and porosities.

The highest standard deviations on wet bulk, dry bulk and grain densities for major groups of formations as given in Table 4.1 are for the Silurian formations and the Cambrian strata – rocks that show a wide range of mineralogy and porosity. The standard deviations for the reported densities of the Ordovician shales and limestones are all small at less than 0.05 reflecting the more uniform mineralogy and porosity of these strata. The agreement between observed scatter in densities and known variability in formation mineralogy and porosity provides confidence in these data sets.

The relative differences between wet bulk/dry bulk and grain densities are also in agreement with expectations given the magnitudes of porosity reported for the different model layers. The differences are greatest for those layers with the largest porosity. For example, within the higher porosity Silurian

and Ordovician shales, the difference between wet bulk density and grain density approximates 0.11 to 0.30 kg/m³. The differences between these densities for the low-porosity Ordovician limestones averages 0.02 kg/m³ or about 10 times less, which corresponds to the ratio of porosities for these different formations. A similar correspondence exists between dry bulk density and grain density and formation porosity. This agreement between observed difference in wet bulk/dry bulk and grain densities and expectations based on reported porosities increases confidence in the density data.

4.15.2 Liquid and Total Porosities

Confidence in the reported liquid and total porosities of the 39 layers that comprise the descriptive hydrogeological model is judged to be moderate. The initial assessment of confidence in the liquid and total porosity data was less than moderate due to observation that liquid porosity values were often greater than total porosity values, an occurrence that is physically impossible. This occurrence was thought, in part, to be due to application of different testing and data reduction and interpretation methods by different testing laboratories in the determination of liquid porosities (see Section 4.3.2.3).

In an effort to address the different data reduction and interpretation methods for liquid porosity determination, all basic water-loss measurements made by different testing laboratories upon sample heating were converted to liquid porosities based on a standardized approach (TR-08-34) considering the average density and TDS of porewater determined from porewater characterization studies. Detailed assessment of the standardized liquid porosity values, in conjunction with consideration of the effects of release of mineralogically-bound water (see Section 4.6.3), possible presence of a gas phase, variable testing procedures, lower testing limit errors, sample size, heterogeneity and anisotropy, indicates that confidence in liquid and total porosity is at least moderate for the DGR bedrock formations. Confidence is highest for the porosities determined for limestone, dolostone and sandstone layers with porosity greater than 2% (e.g., Devonian dolostones, Salina A2, A1 and A0 Unit dolostones, Guelph to Fossil Hill dolostones, Manitoulin dolostone, Kirkfield limestone, Shadow Lake siltstone and Cambrian sandstone).

Confidence in the determination of liquid and total porosity is most easily evaluated with data sets that minimize the number of confounding effects on the measurements. The porosity data set with the least number of potential confounding effects is the Core Labs data for liquid and total porosity based on unconfined testing of identical core plugs (i.e., Figure 4.6). These data show very good correlation between liquid and total porosity, where the higher total liquid porosities apparent in the Silurian and Ordovician rocks are attributed to presence of a separate gas phase. The next best comparable data set is that of the University of Bern, where different sub samples of different sizes collected from the same core were tested. These results, which are illustrated in combination with Core Labs results in Figure 4.4, show a much greater difference in liquid and total porosity values for cores of all DGR rocks. The observed larger liquid porosities compared to total porosities in this data set are most likely due to release of mineralogically-bound water for the samples of Silurian formations (i.e., gypsum and clays) and Ordovician shales (clays), and lower testing limit errors for the low porosity (<2%) Ordovician limestones.

4.15.3 Gas Saturations

Confidence in the reported gas saturations of the 39 layers that comprise the descriptive hydrogeological model, for which such data are available, is judged to be low. Confidence in gas saturations (S_g) is considered low, principally because of the concern that the generally small values reported (formation group means of 7-14%, formation means of 0-20%) may be artefacts due to sample drying and irrecoverable core relaxation effects during sample collection, handling and preparation for testing, and the difficulty of accurately measuring such properties in low porosity (<2%) formations. In Dean Stark testing of fluid saturations, gas saturations are determined as the difference between calculated total porosity and calculated brine and oil saturations. Thus the estimate of S_g

incorporates all of the errors accumulated in estimating total porosity and both S_w and S_o .

As discussed in Section 4.3.3, irrecoverable core damage cannot fully explain the resultant gas saturations, but sample drying and measurement error remain potential explanations for the reported gas saturations. Uncertainty in gas saturations due to measurement error associated with Dean Stark testing is significant (+/- 50 to 100%) for formations with porosity of <2%. Consequently, all of the reported gas saturations for the Ordovician limestones which have porosity of less than 2%, may be the result of measurement error. For the higher porosity Ordovician shales measurement error is not a reasonable explanation for the reported gas saturations.

In contrast to the sample drying and measurement error, the following data and observations support the occurrence of a discontinuously distributed gas phase in the DGR formations.

- Testing of brine and gas saturations using Nuclear Magnetic Resonance and He gas expansion on Ordovician shale and limestone cores from DGR-4 that confirm the Dean Stark results on the same core samples (Figure 4.9).
- Observation of presence of discontinuous oil, bitumen and petroliferous odours in DGR formations (Section 3.6.5) and the expectation that gas would also be associated such hydrocarbon presence.
- Carbon isotope signatures of methane (Figure 4.64) that indicate biogenic generation of methane gas within the Ordovician shales and underlying limestones.
- Comparison of measured methane concentrations in Ordovician shale and limestone cores from DGR-3 and DGR-4 (Figures 4.6.7 and 4.6.8, Section 4.6.7.3) against calculated methane solubility that show supersaturation and therefore likely presence of separate methane gas phase.
- Occurrence of low test interval compressibility from straddle-packer hydraulic testing (i.e., 11 of 51 test intervals show compressibility greater than $1 \times 10^{-9} \text{ Pa}^{-1}$ – see Figure 4.81), that is most likely due to the presence of gas within fractures which show increased permeability relative to the intact rock matrix.
- Results of TOUGH2 brine-gas modeling of the DGR formations (AECOM Canada Ltd., 2010, Section 5.5.4) that shows that transient brine-gas flow modeling can reproduce the general features of the underpressures and occasional normally-pressured zones observed in the DGR Ordovician shales and limestones.

On balance, the available data indicate that gas is likely present as a separate phase within the pore space of some of the Silurian, Ordovician and Cambrian formations, although confidence in this assessment remains low.

4.15.4 Gas-Brine Flow Properties

Confidence in the reported gas-brine flow properties of the layers that comprise the descriptive hydrogeological model, for which such data are available, is judged to be low to moderate depending upon the property considered. Confidence in pore size distributions, median pore throat sizes and gas entry pressures determined from high pressure mercury injection testing are considered moderate, whereas confidence van Genuchten fitting parameters for capillary pressure – liquid saturation curves and relative permeability – liquid saturation curves are considered low.

High pressure mercury injection testing is a well-established testing technique for determination of pore size distributions of rock cores and with extrapolation, the gas entry pressures for brine-filled pores. The results of the mercury injection testing shown as mercury saturation – injection pressure profiles (Figure 4.20), gas entry pressures (Figure 4.21) and median pore throat radii (Figure 4.22) are comparable between tests completed on cores collected from within the same formation and with core from different DGR boreholes and generally consistent with expectations based on core observations and other testing (e.g., lab porosity testing, field hydraulic conductivity testing). For example, mercury saturation – injection pressure profiles and gas entry pressures for the Salina A2 and A0 Units, the lower Gull River and Cambrian cores are distinctly different than those for the bulk of the Ordovician shales and limestones, and show results in accordance with the increased porosity and permeability of these horizons evident from other testing and core observations.

Brine-gas flow properties of capillary pressure – brine saturation and relative permeability – brine saturation were determined from fitting mercury injection porosimetry data, fluid saturation data and gas pulse permeability data for “as received” and “clean and dry” core samples to standard van Genuchten fitting parameters. Confidence in these data is judged to be low based on the low confidence assigned to the gas and brine saturations and the fact that the relative permeability – saturation curves are fit to only one relative permeability-saturation data point (the “as received” test results).

4.15.5 Diffusion Properties

Confidence in the reported diffusion properties (effective diffusion coefficients, coefficient anisotropy and tracer-accessible porosity) of the 39 layers that comprise the descriptive hydrogeological model, is judged to be high. The estimates of effective diffusion coefficients for iodide normal and parallel to bedding planes and iodide tracer-accessible porosity are based on University of New Brunswick (UNB) laboratory testing by X-ray radiography using iodide tracer and by conventional through-diffusion testing techniques using both iodide and tritium as tracers. A total of 113 diffusion experiments were completed to support the estimated values listed in Table 4.18. A cursory review of diffusion data plotted by DGR boreholes (Figure 4.37) shows that there are no discernable differences in D_e values between individual DGR boreholes, and hence the geometric mean D_e formation values are representative.

Although a new diffusion testing technique (X-ray radiography) was used for iodide diffusion testing of rocks other than the low-porosity Ordovician limestones, the results of this new technique were benchmarked against conventional through-diffusion testing also using iodide as a tracer. University of New Brunswick results for the Queenston shale and Cobourg limestone were also benchmarked against radioiodine (^{125}I) diffusion completed by Paul Scherrer Institute, Switzerland in an inter-laboratory comparison study using DGR core. All diffusion testing was completed by University of New Brunswick using synthetic porewaters designed to match porewater chemistries determined from porewater characterization studies (Section 4.6.5) and therefore minimizing mineral dissolution and precipitation during the testing and increasing confidence in the testing results.

The testing program completed by UNB also reported on comparison of water-loss (liquid) porosities measured on the same cores subject to diffusion testing and determination of iodide tracer-accessible porosity. This comparison, which showed that iodide-accessible porosity was typically 50% of liquid porosity in the Silurian and Ordovician shales, is in accordance with anion exclusion theory (Section 4.6.4) and provides confidence in the estimates of iodide-accessible porosity determined from UNB testing.

The results of the UNB diffusion testing using both tritium and iodide tracers were also compared to diffusion coefficient and porosity data generated for argillaceous rocks as part of the OECD Claytrac Project. Effective diffusion coefficients and tracer-accessible porosities for both tritium and iodide

compare very favourably with international data considering the lower porosity of the DGR rocks, and with the porosity-diffusion coefficient relationship derived from Archie's Law (see Section 4.4.3). These favourable comparisons show that the UNB diffusion property data are reliable, representative and of high quality.

4.15.6 Porewater Characterization

Confidence in the reported porewater chemistry profiles of the DGR rocks that comprise the descriptive hydrogeological model is judged to be low to high depending upon the porewater parameter considered (i.e., major/minor ions, environmental isotopes, strontium isotopes, and gases). Concentrations of major/minor ions in porewater were reported by University of Ottawa, University of New Brunswick and University of Bern using different laboratory methods that allow for inter-laboratory comparisons. Environmental isotopes, strontium isotopes and gases in porewaters were only determined by the University of Ottawa. However measurement of all porewater parameters were also completed on groundwater samples from permeable aquifers (e.g., Salina Upper A1 Unit, Guelph and Cambrian) allowing for direct comparison of porewater and groundwater concentrations.

Confidence in major and minor ion profiles (Na, Ca, K, Mg, Sr, B, Cl, Br, SO₄, TDS) presented as part of the descriptive hydrogeological model (Section 4.6.5) range from low to moderate. Confidence in Na, K, B, Cl, Br and TDS porewater profiles is considered to be moderate, based on similarity of the concentration depth profiles for these analytes, inter-laboratory comparisons (Figure 4.95) and expectation that for Na, Cl and TDS, the reported results may only be influenced by halite presence and release of mineralogically bound water during heating. Dissolution of halite during crush and leach experiments will result in overestimation of these parameters, whereas release of mineralogically bound water will result in underestimation of the parameters in porewater due to overestimation of the volume of water within the pore that contains the parameters.

Confidence in Ca, Mg, Sr, and SO₄ profiles are judged to be low due to potential effects of dissolution of anhydrite, gypsum and celestite and oxidation of pyrite during leaching experiments and the effects of solubility controls exerted by these minerals as well as calcite and dolomite on reported concentrations. The reported concentrations of these ions only account for mineral dissolution for anhydrite and calcite. As evident in Figures 4.53 and 4.54, the depth profiles of Ca, Mg, Sr and SO₄ do not follow the same general concentration trends of Cl and Br. Consequently, the Ca, Mg, Sr and SO₄ concentrations in porewater should be interpreted with caution.

Confidence in profiles of the environmental isotopes of $\delta^{18}\text{O}$, deuterium (δD) and deuterium excess (d) presented as part of the descriptive hydrogeological model (Section 4.6.6.1) is judged to be high. The depth profiles of these parameters are smooth with some variability between DGR boeholes that is interpreted to reflect site conditions and not analytical uncertainty. These porewater parameters are not significantly influenced by rock interactions during vacuum distillation, and a laboratory test program completed by the University of Ottawa (TR-08-37) demonstrated that a standard extraction temperature of 150°C and extraction time of 6 hours produced reliable estimates of porewater isotope and major ions (Na, Cl) concentrations. Additional explanations for the high confidence in environmental isotopes data determined by vacuum distillation by the University of Ottawa, including international experience (Altinier et al., 2006) is provided in TR-07-21.

Confidence in profiles of the strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) in porewater, groundwater and rock presented as part of the descriptive hydrogeological model (Section 4.6.6.1) is judged to be moderate at this time. Reproducibility between measured strontium isotopes in different DGR boreholes and between rapid and 60 day leaches shows there is little to no influence of the carbonate matrix on the measured strontium isotopes in porewater, increases confidence in the analytical results. Confidence in the whole rock strontium isotope results is also evident from the similarity between reported values and both marine strontium and rock measurements from eastern Ontario. However,

the contribution of clastic materials (e.g., sheet silicates) to whole rock strontium isotope values remains to be quantified, which results in the overall moderate confidence assessment in the strontium isotope data.

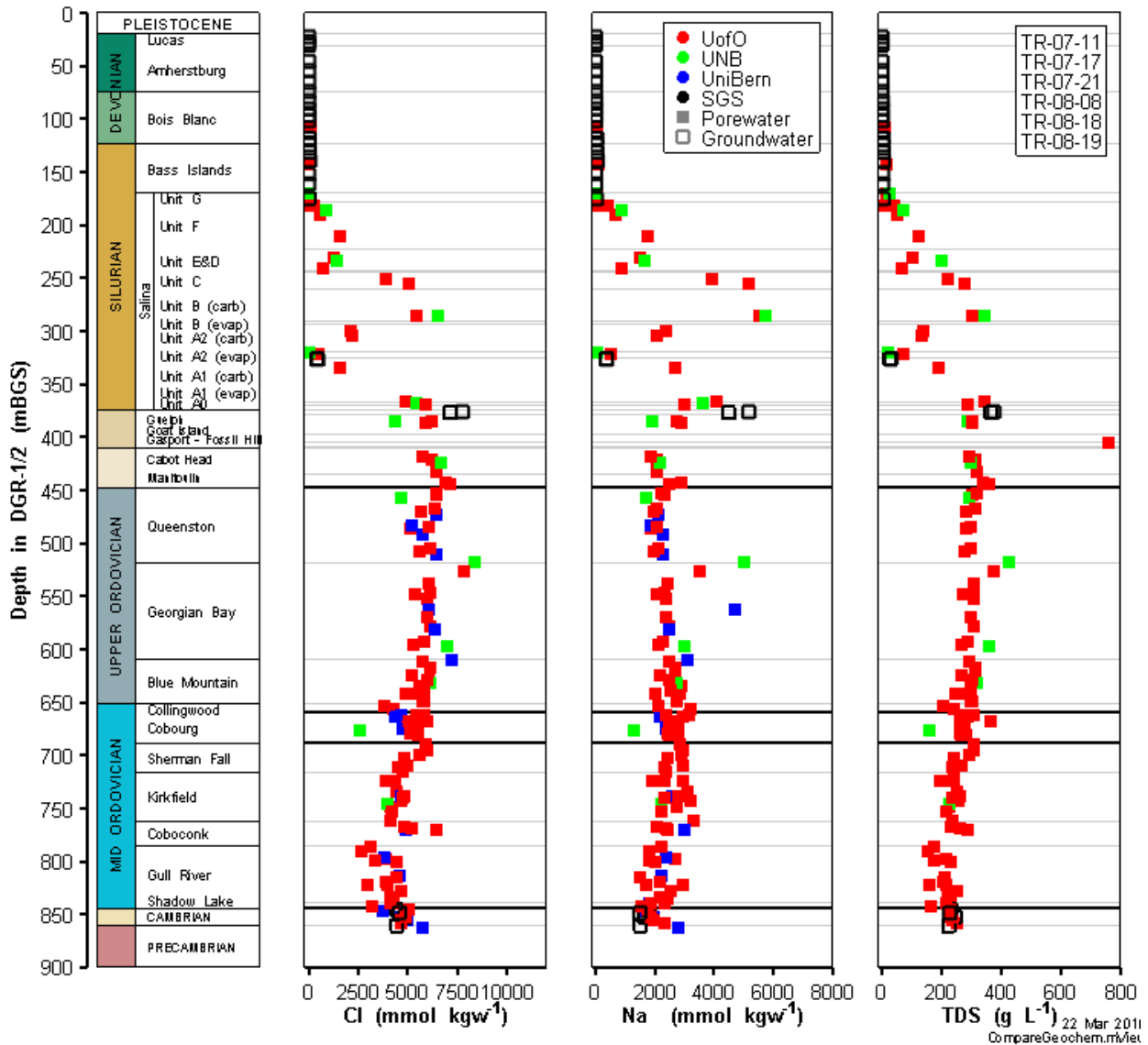


Figure 4.95 Profiles of porewater and groundwater Cl, Na and TDS profiles in DGR boreholes distinguished by analytical laboratory

Confidence in reported profiles of apparent methane concentrations and isotopes ($\delta^{13}\text{C}_{\text{CH}_4}$, $\delta\text{D}_{\text{CH}_4}$) are interpreted to moderate based on confidence in the analytical methods, reproducibility of analytical results between boreholes, and similar smooth depth profiles for these parameters in DGR boreholes. Confidence in reported profiles of carbon dioxide concentrations and isotopes ($\delta^{13}\text{C}_{\text{CO}_2}$) are judged to be low, based on the scatter in observed profiles and the uncertain role of the carbonate rock matrix in controlling CO_2 concentrations and isotopes, especially within the Ordovician limestones. Confidence in reported helium concentrations and isotope ratios are judged to be low and moderate respectively. The low confidence in helium concentrations is due to recognized difficulty in retaining this highly volatile gas in core samples (TR-07-21) and the associated difficulties in

partitioning helium to brine and any separate gas phase that may be present in the pore space due to low solubility of helium in brine. To overcome these difficulties in reporting helium concentrations, the measured isotopic ratio of $^3\text{He}/^4\text{He}$ in DGR samples is reported relative to that in air. This reporting approach increases the confidence in the helium isotope data to moderate.

4.15.7 Formation Hydraulic Properties

Confidence in the reported hydraulic properties (hydraulic conductivity, conductivity anisotropy and specific storage) of the 39 layers that comprise the descriptive hydrogeological model is judged to be moderate to high depending upon the property considered.

The recommended estimates of formation hydraulic conductivity (K) are based entirely on historical packer testing of the shallow Devonian dolostones, observation during DGR drilling, and continuous-profile field hydraulic testing using a custom-fabricated straddle-packer testing tool (TR-08-32). The resultant K estimates range from 10^{-15} to 10^{-4} m/s and are consistent with expectations based on formation lithology, field testing in similar formations remote from the Bruce nuclear site (Raven et al., 1992a; Neuzil, 1993; 1994; Golder Associates Ltd., 2003) and controlled lab testing of cores from the same formations elsewhere in Ontario (Vilks and Martin, 2007). Typically, confidence in very low hydraulic conductivity estimates ($<10^{-12}$ m/s) is difficult to achieve and demonstrate. Such confidence was achieved in the DGR borehole hydraulic testing program by use of very stiff, high-pressure hydrofracturing packers, completion of leak testing in steel casing installed in each DGR borehole, and detailed analyses of the pulse test results using a numerical well test simulator (nSIGHTS) developed by Sandia National Laboratories.

Quantification of the lower testing limit of straddle-packer testing equipment provides confidence in the reported K values above the testing limit. Leak testing completed in the steel casing of DGR boreholes shows the lower testing limit of the test tool approximates 5×10^{-15} to 2×10^{-14} m/s, however these limits include threaded steel casing joints that likely have finite permeability. An alternate method of defining the lower testing limit is the lowest reported K value from field testing. Based on preliminary analysis of testing of the Sherman Fall formation in DGR-2 the lower testing limit of the test tool is about 2×10^{-16} m/s. Given this lower testing limit it is reasonable to conclude that K values of greater than and equal to 10^{-15} m/s can be reported with high confidence.

Confidence in the K anisotropy assigned to the 39 layers that comprise the descriptive hydrogeological model is judged to be moderate to high. For the thin permeable aquifer units and the Precambrian basement, confidence in the assumption of isotropic K is high. For the majority of low to intermediate K model layers, the assumption of 10:1 horizontal:vertical K is based principally on lab petrophysical testing and core observations of the occurrence of cm-scale low K bedding layers in these DGR rocks. Confidence in this assumption is moderate. For parts of the Black River formations where thin higher permeability zones are suspected (e.g., ash layer in Coboconk Formation), the assumed anisotropy value of 10:1 is likely underestimated because the horizontal hydraulic conductivity for most the rock is overestimated.

Confidence in the specific storage reported for the 39 model layers that comprise the descriptive hydrogeological model is judged to be moderate. Specific storage values are difficult to reliably measure during hydraulic testing as the test results are not particularly sensitive to changes in this parameter. Given this difficulty, recommended estimates of formation specific storage values were calculated as geometric means of component values including drained compressibility from geomechanical testing and formation averages of porosity and pore fluid density. Moderate confidence in the reported specific storages are supported by the observation that the values calculated from component values were generally similar to those values determined from analyses of field hydraulic tests.

4.15.8 Formation Pressures and Heads

Confidence in the reported profiles of formation pressure and environmental head that comprise the descriptive hydrogeological model is judged to be low for zones of underpressure and high for zones of normal to overpressure.

Low confidence is assessed for the values of formation underpressure and associated environmental head because such pressures are associated with formations of very low hydraulic conductivity and equilibrium values of such underpressure have not been measured with MP55 casing systems, but rather inferred from estimates determined from nSIGHTS analyses of straddle-packer hydraulic tests. Based on the analysis and discussion presented in Section 4.11.2.6, the time to reach formation pressure equilibration in the MP55 casings is on the order of 5-10 years. As this time frame is longer than the current monitoring period, measurement of stable formation pressures with MP55 casing have not reported to date.

In contrast, high confidence is associated with the stable normal and overpressured formation pressures found in the DGR boreholes. Where comparisons are possible, there is coincidence of stable formation normal pressure and overpressures from monitoring of MP55 casings and from interpretation of straddle-packer hydraulic tests. This coincidence is evident for the overpressured Cambrian and Black River Group formations as well as the single isolated zones of normal pressure found within the Ordovician shales. As evident from repeated formation pressure profiles of the MP55 casings installed in DGR boreholes and the dedicated DGR-2 MOSDAX transducer installation in DGR-2, stable formation pressure are attained in these more permeable intervals within several days to weeks following casing installation. Based on the elevated hydraulic conductivity of the Silurian aquifers of the Salina Upper A1 Unit and Guelph and repeated stable formation pressures measured in these aquifers using MP55 casing, there is also high confidence in the formation pressures and environmental heads of these horizons in DGR boreholes.

4.15.9 Groundwater Flow Directions and Gradients in Bedrock Aquifers

Confidence in the reported groundwater flow directions and gradients in bedrock aquifers that comprise the descriptive hydrogeological model is judged to be moderate to high depending upon the aquifer considered. Confidence is based on accuracy of formation pressure measurements and accuracy in known depths and horizontal positions of the pressure measurement ports

There is high confidence in the groundwater flow directions and gradients within the permeable Devonian dolostone bedrock that is monitored via the MP38 multi-level monitoring casings installed in boreholes US-3, US-7 and US-8. Pressures within these permeable units are stable and reproducible based on quarterly pressure profiling using a pressure transducer sensitive to 0.07 kPa and accurate to about 1 kPa. Positions of the measurement ports are known to within an accuracy of 1 to 3 cm and related uncertainty in these positions does not affect the calculated groundwater flow directions and gradients.

Groundwater flow directions and gradients within the Salina Upper A1 Unit and Guelph are reported (Table 4.15) with moderate confidence based on similar transducer sensitivity of 0.07 kPa and accuracy of about 3 kPa and the observation that the difference in adjusted pressures between the DGR boreholes at 110 kPa (Upper A1 Unit) and 52 kPa (Guelph) is much greater than the accuracy or sensitivity of pressure measurement. Because the true borehole depths and horizontal positions are used in the calculation of groundwater flow directions in these aquifer units, the only uncertainty in measurement port position is that associated with stretch of MP55 casing. This uncertainty is estimated at a maximum of 10 cm given the depth of ports, which translates to a pressure uncertainty of 1.0 kPa. While these computations suggest high confidence in the accuracy of the calculated flow directions and gradients in these aquifers, moderate confidence is assigned based on the fact that

formations pressures were recorded in the MP55 casings when borehole DGR-5 was open. Such an open borehole in proximity to borehole DGR-1 would allow drainage from the Guelph aquifer to the Upper A1 Unit aquifer and potentially affect the measured pressures in these formations in DGR-1. Future pressure measurements to be obtained following sealing of boreholes DGR-5 and DGR-6 will allow for more accurate assessment of groundwater flow directions and gradients within these thin Silurian aquifers. Borehole DGR-5 is currently sealed and borehole DGR-6 is planned to be sealed by end of June, 2010.

Groundwater flow directions and gradients within the Cambrian sandstone aquifer are reported (Table 4.15) with moderate confidence. Although the transducer sensitivity and accuracy are similar for pressure measurements in the Cambrian to those made in the Salina Upper A1 Unit and Guelph aquifers, the difference in adjusted pressures (25 kPa) is less and the uncertainty in depth location of the measurement ports is greater at about 30 cm or 3 kPa.

5 DESCRIPTIVE GEOMECHANICAL SITE MODEL

5.1 Model Elements and Scope

The geomechanical site model describes and summarizes our current understanding of the principal geomechanical properties of the rock materials and rock mass beneath the Bruce DGR site. The geomechanical site model focuses on presentation of quantitative estimates of physical properties that will control the geomechanical behaviour of the rock mass beneath the Bruce nuclear site during and after construction of the sub-surface infrastructure required for development of the DGR. Estimated values are based on combining the specific quantitative values of various parameters derived from field and laboratory testing with expert judgement, where appropriate. Thus, while taking full account of all relevant test data, recommended estimate values may or may not be synonymous with simple average or median values of test results, and are intended to provide guidance as to values of geomechanical parameters that may be reasonably relied upon for purposes of preliminary design.

The descriptive geomechanical site model has been divided into five broad units for the purposes of presentation of summary data and recommended parameter values, as discussed below.

5.1.1 Mechano-Stratigraphic Units

Because of natural variability, geomechanical properties can be expected to vary within and across every stratigraphic rock unit beneath the Bruce nuclear site. However, it would be neither useful nor necessary for the purposes of site description to present geomechanical data separately for every stratigraphic unit, and detailed data is available from within the data sources listed in Section 5.2, if required. The intent of this part of the report is to summarize the geomechanical data in a manner that is meaningful within the context of overall development and performance of the sub-surface infrastructure. For this purpose, five mechano-stratigraphic (MS) units have been defined, as noted below and shown in Figure 5.1, based on data from DGR-1, DGR-2, DGR-3 and DGR-4. Depths of these MS units are described below and throughout this section based on reference stratigraphy as defined in boreholes DGR-1 and DGR-2 (Figure 5.1).

- MS Unit 1. Comprising principally dolostones, this MS Unit includes all Devonian formations encountered at the Bruce nuclear site, as well as the Upper Silurian Bass Islands Formation and the Salina G Unit dolostone. In DGR-1, MS-1 lies from 20 to 178.6 mBGS.
- MS Unit 2. Comprising a sequence of interbedded shales, dolostones and anhydrites, this MS Unit includes the strata from the top of the Silurian F Unit to the base of the Silurian Fossil Hill Formation. In DGR-1, MS-2 lies from 178.6 to 411 mBGS.
- MS Unit 3. Comprising principally the sequence of shales that overlie the repository horizon, this MS Unit includes the strata from the top of the Lower Silurian Cabot Head Formation, through all of the Upper Ordovician strata, to the base of the Middle Ordovician Collingwood Member. In DGR-1 and DGR-2, MS-3 lies from 411 to 659.5mBGS.
- MS Unit 4. This MS Unit includes the repository horizon and comprises the Middle Ordovician Cobourg Formation argillaceous limestone. In DGR-2, MS-4 lies from 569.5 to 688.1 mBGS.
- MS Unit 5; This MS Unit comprises all units below the Cobourg Formation, including Middle Ordovician Sherman Fall Formation and deeper Cambrian and Precambrian units. In DGR-2 , MS-5 lies below 688.1 mBGS.

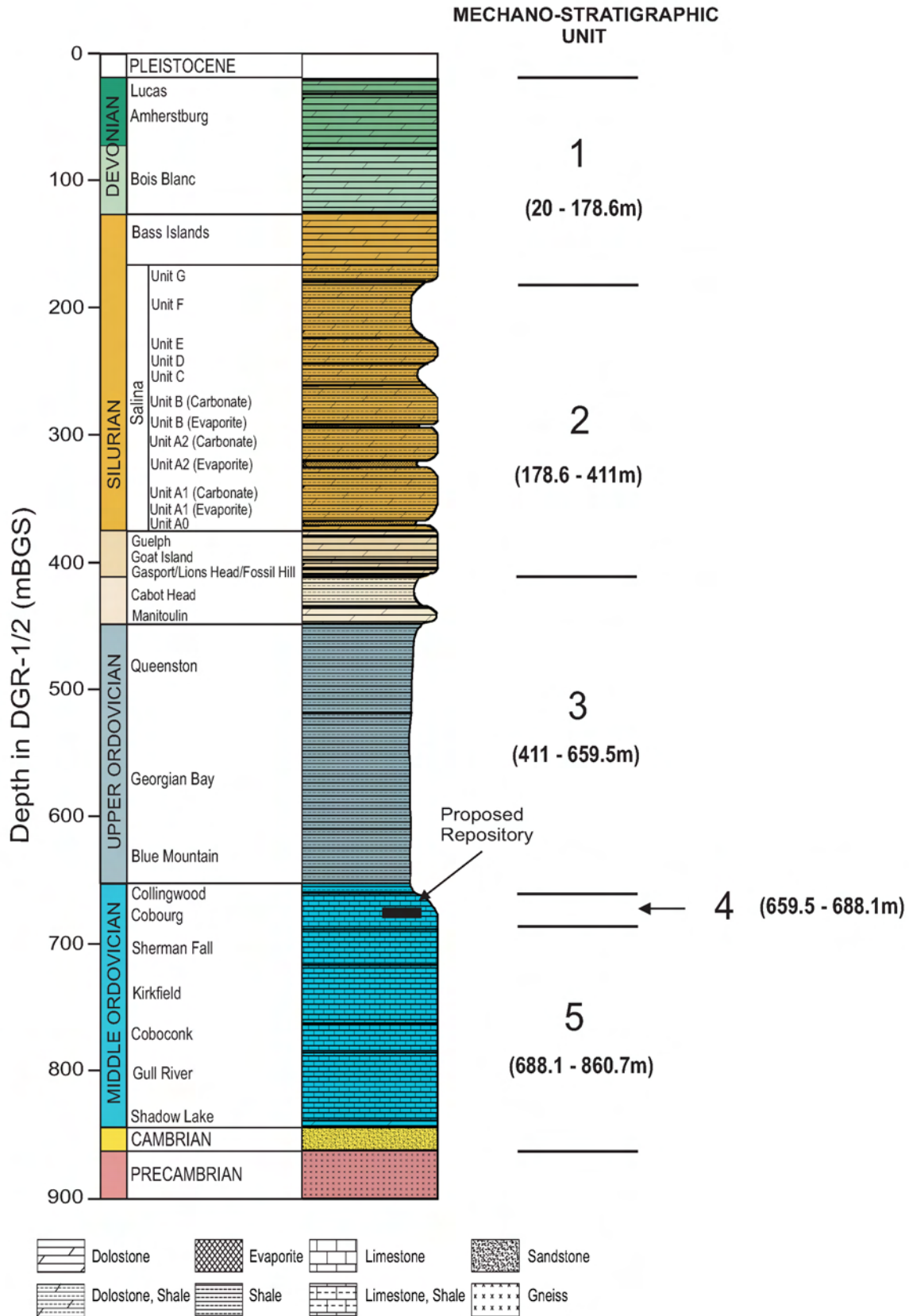


Figure 5.1 Reference stratigraphic column showing mechano-stratigraphic units at the Bruce nuclear site

The rock formations lying above the target host horizon for the repository have been grouped into the upper three MS units. These units will house the vertical access penetrations (shafts) and associated seals to the repository horizon. The fourth unit will house the repository itself, and the fifth unit comprises the rocks lying below the repository. Portion of the shaft sumps will extend into the fifth unit. Each unit has been defined on the basis that the overall geomechanical properties of the rocks in the unit can be presented and discussed in a context that is meaningful to the geomechanical issues associated with repository design and performance.

For each MS Unit, descriptive geomechanical site data are presented under two broad headings – rock material characteristics and rock mass characteristics, respectively. At the current stage, available site data deal primarily with characteristics of the rock material itself, derived from field and laboratory tests on core from DGR-1, DGR-2, DGR-3 and DGR-4. Data concerning rock mass characteristics at the site are relatively limited at the current stage of investigation.

5.1.1.1 MS Unit 1: Devonian and Upper Silurian Dolostones

The MS-1 Unit has a total thickness of approximately 159 to 179 m in DGR boreholes. At DGR-1, MS-1 Unit comprises the fossiliferous limestone/dolostone of the Devonian Lucas and Amherstburg Formations from ~ 20 to 75 mBGS, the cherty dolostone of the Devonian Bois Blanc Formation from ~75 to 124 mBGS, the argillaceous dolostone of the Upper Silurian Bass Islands Formation from ~124 to 169 mBGS, and the Salina G Unit argillaceous dolostone from 169 to 179 mBGS (Sections 3.7.2; 3.7.3). This MS unit will house the uppermost bedrock portion of the shaft excavations (approximately 159-179 m thickness). From a geomechanical viewpoint, the lithology (dolostone) is relatively consistent within this unit. Although variation in geomechanical parameter values does occur between different stratigraphic horizons, such variation is not anticipated to have major impacts on the design or performance characteristics of the shafts (Section 5.5).

5.1.1.2 MS Unit 2: Upper and Middle Silurian Shales, Dolostones and Anhydrite

The MS-2 Unit has a total thickness of approximately 226 to 234 m in DGR boreholes. It consists primarily of the alternating dolostones, shales and anhydrites of most of the 190.3 to 198.2 m thick Upper Silurian Salina Formation, underlain by 33.4 to 36.5 m of dolostones and limestones in the Middle Silurian Guelph/Goat Island/Gasport/Fossil Hill Formations (Sections 3.7.3, 3.7.4). Geomechanically, properties within this 226 to 234 m thick unit can be expected to be highly variable due to frequent lithological changes, giving rise to local variation in the performance of the rock units around the shaft excavations (Section 5.6).

5.1.1.3 MS Unit 3: Lower Silurian and Upper Ordovician Shales and Dolostones

The MS-3 Unit has a total thickness of approximately 248 to 251 m. With the exception of the included Lower Silurian Manitoulin Formation, the MS-3 Unit was defined primarily for the purpose of including the shale formations overlying the repository horizon (Section 5.7). In descending order, MS-3 includes:

- 23.8 to 24.7 m of Cabot Head Formation shale (Lower Silurian);
- 9.5 to 12.9 m of Manitoulin Formation dolostone (Lower Silurian);
- 70.4 to 74.4 m of Queenston Formation shale (Upper Ordovician);
- 88.7 to 90.9 m of Georgian Bay Formation shale (Upper Ordovician);
- 42.7 to 45.6 m of Blue Mountain Formation shale (Upper Ordovician); and

- 7.9 to 8.7 m of Collingwood Member, Cobourg Formation shale (Middle Ordovician).

5.1.1.4 MS Unit 4: Middle Ordovician Cobourg Formation.

The MS-4 Unit comprises only the 27.5 to 28.6 m thick argillaceous limestone of the lower part of the Cobourg Formation, i.e., the host horizon of the repository. In terms of the DGR itself, the geomechanical properties within this MS Unit will be critical to design and performance assessment issues of the repository rooms (Section 5.8).

5.1.1.5 MS Unit 5: Middle Ordovician Sherman Fall and Deeper Formations

All rock formations encountered in DGR boreholes lying beneath the repository horizon are included in this MS unit. While the geomechanical properties of the different lithological units within MS-5 may vary widely, in practical terms this variation will have little or no impact on the design and performance issues of the DGR (Section 5.9).

5.2 Data Sources

Primary data sources for the descriptive geomechanical site model include:

- the descriptive geological site model given in Section 3 of this report;
- observations during drilling, logging and sampling of DGR-1 and DGR-2 (TR-07-06) and DGR-3 and DGR-4 (TR-08-13);
- field geomechanical testing of DGR-1 and DGR-2 core (TR-07-07) and of DGR-3 and DGR-4 core (TR-08-14);
- laboratory geomechanical strength testing of DGR-1 and DGR-2 core (TR-07-03) and of DGR-3 and DGR-4 core (TR-08-24, TR-08-39);
- laboratory abrasiveness testing of DGR-2 core (TR-07-04) and of DGR-3 and DGR-4 core (TR-08-25);
- borehole geophysical logging of DGR-1 & DGR-2 (TR-07-08) and of DGR-3 and DGR-4 (TR-08-15);
- laboratory swell testing of DGR-2 core (TR-07-16) and of DGR-3 and DGR-4 core (TR-08-26);
- laboratory long-term strength degradation testing of DGR-2 core (TR-08-11) and of DGR-3 and DGR-4 core (TR-08-36);
- assessment of in-situ stresses from analyses of borehole wall behaviour in DGR boreholes (TR-08-35);
- field in-situ stress measurements in MS Unit 1 in US -6 (McKay, 1989); and
- regional geomechanics of southern Ontario geosynthesis study (Gartner Lee Limited, 2008c) and Phase 2 geosynthesis updates to these studies (AECOM Canada Ltd., 2010).

5.3 Local Seismicity

Seismic monitoring at and in the vicinity of the Bruce nuclear site is undertaken to obtain understanding of the contemporary seismic activity within a few hundred kilometres of the Bruce nuclear site, which in turn will be used to conduct a seismic hazard evaluation for the DGR. As described in the GSCP, such an evaluation also provides information on the contemporary seismicity and microseismicity that can be used in identification of seismogenic features in the region surrounding the Bruce nuclear site.

Seismic monitoring has historically been completed for the Bruce nuclear site for magnitude 2.0 (M2.0) and above. The Canadian National Seismic Network (CNSN) provided an earthquake detection threshold of magnitude 3.0. With the expended POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) network in 2002, the detection threshold in the region has reduced to M2.0. To further lower the earthquake detection threshold to M1.0, University of Western Ontario, under contract to OPG, installed three POLARIS-type surface and bedrock borehole microseismic monitoring stations approximately 40 km from the Bruce nuclear site during the summer of 2007. The seismic monitoring network for the Bruce nuclear site includes the following stations, the locations of which are shown in Figure 5.2:

- Station BRCO (existing Bruce nuclear station) near Tiverton;
- Station BWLO at Walkerton;
- Station BASO at Ashfield; and
- Station BMRO at Maryville Lakes.

(Circles around Bruce represent 50 km and 150 km radius.)



Figure 5.2 Earthquakes in the vicinity of Bruce nuclear site, 2008 (after CHIS, 2009)

CHIS (2009) also reviews historical seismicity for the Bruce area (see Figure 5.3). CHIS notes that only three earthquakes have historically been detected within 50 km of the Bruce nuclear site prior to 2008. Including the M1.2 event recorded in 2008, the four events occurred in Lake Huron about 20 km northwest of Southampton with M1.2 to M2.1. These current and historical monitoring data show that the Bruce nuclear site is located in a seismically quiet area.

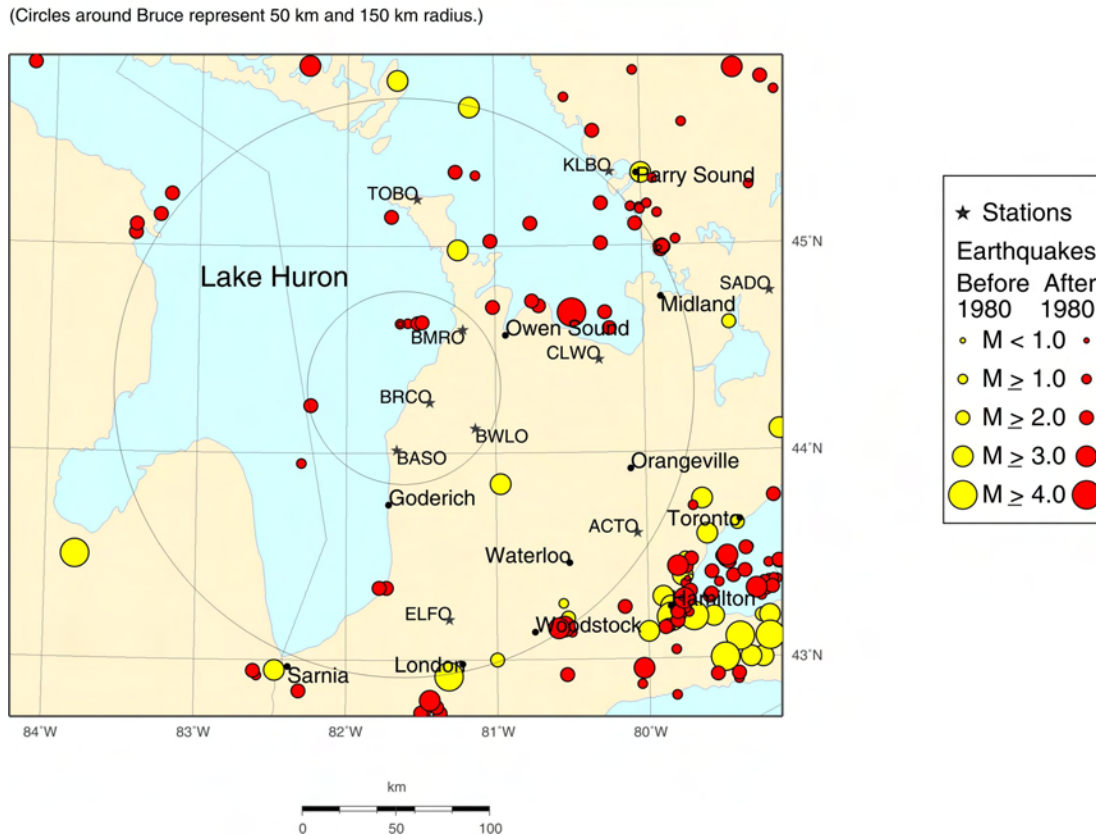


Figure 5.3 Historical earthquakes in the vicinity of Bruce nuclear site (after CHIS, 2009)

5.4 In Situ Stresses

The in situ state of stress below the DGR site, and particularly at the repository elevation, is a key geomechanical parameter affecting the design of the repository facilities. The vertical stress magnitude and orientation will closely match the gravitational stress caused by the weight of rock above any elevation of interest, and this magnitude can be accurately estimated. The challenge lies in trying to evaluate the magnitudes and orientations of the horizontal stress components at depth.

Unfortunately, there are great challenges in trying to obtain, with confidence, direct measurements of in situ stresses at the depths of interest from a surface-based exploratory borehole. This is particularly true in horizontally bedded formations where the vertical stress is less than the horizontal stresses, as hydrofracture techniques cannot be used with confidence in this situation. While traditional strain-relief methods (e.g. overcoring) are suitable for relatively shallow measurements, such testing from within an exploration borehole at the ~ 680m depth of the DGR would provide uncertain results, while being extremely expensive. Consequently, no direct measurements of the in situ stresses at the depth of the proposed repository at the Bruce nuclear site have been undertaken during the Phase 1 and 2 site characterization investigations.

Although no direct stress measurements are available at repository depth beneath the Bruce nuclear site, indirect evidence is available from three primary sources:

- compilation of regional stress measurement data undertaken as part of the Phase 1 Regional Geomechanics Report (Gartner Lee Limited, 2008c);
- modelling of the Bruce nuclear site as a layered series of rock units subjected to imposed horizontal compression of a magnitude that matches stresses that have been measured at a depth of 680 mBGS in the Norton Mine in Ohio; and
- behaviour of the DGR-1, DGR-2, DGR-3 and DGR-4 borehole walls and recovered core (TR-08-35).

The Phase 1 Regional Geomechanics Report provides detailed presentation and discussion of regional stress data, derived from numerous sources. Virtually all of the data at depths beyond 100 mBGS have been derived from hydrofracture testing, and there is uncertainty regarding the validity of these data in horizontally bedded rock formations with relatively high horizontal stresses – a condition that is well known to exist widely throughout the sedimentary rocks of Southern Ontario. However, there are some stress measurements that have been made from the deep Norton Mine in Ohio using short overcoring holes from within the mine, and these measurements are particularly valuable in helping to evaluate the probable stress conditions at similar depth beneath the Bruce nuclear site.

Figure 5.4 summarizes the results of this regional database evaluation (using a 7-point moving median technique), showing the potential variation with depth of the maximum horizontal stresses respectively, expressed as a ratio of the vertical (gravity) stress. Confidence in these regional data is low, as noted above. This view is further supported by the observation that the plot of regional data in Figure 5.4 does not appear to indicate that the in situ stresses vary as a function of the stiffness (modulus) of the various rock units, as would be expected. In fact, there seems to be an inverse relationship, suggesting that stresses increase in the softer shale units compared to the stiffer dolostone units. This is unlikely.

A second line of reasoning is based on numerical modeling of the Bruce nuclear site as a series of rock layers of different elastic modulus values (as determined from laboratory testing of rock cores) that have been subjected to an imposed horizontal compression sufficient to cause the same in-situ stresses that were actually measured at the Norton Mine. Stresses in the various rock strata will then vary as a function of their stiffness (modulus). The results of this modelling, conducted by Itasca, are also shown in Figure 5.4.

The third, and most important, line of reasoning concerning the horizontal stresses at depth at the Bruce nuclear site comes from careful examination of the borehole wall behaviour during and after drilling of DGR exploratory boreholes. These boreholes are, in fact, small diameter trial excavations, around which concentration of the in situ stresses will occur. If the in situ stresses are sufficiently high relative to the strength of the rock in the borehole wall, then borehole breakouts will occur, and these will be visible from optical and acoustic downhole logging of the holes.

This phenomenon is well known, and can be used to provide some bounds on the possible magnitude of the in situ stresses, depending on whether or not such breakouts have occurred. In a significant sense, observation and analysis of this mechanism provides very direct evidence of the actual stress-to-strength situation in the rock formations at depth. Importantly, no evidence of stress-induced borehole breakouts was found at any location throughout boreholes DGR-1, DGR-2, DGR-3 or DGR-4. Of particular note is the fact that down-hole televiewer logs were re-run after the exploratory holes had been open for about 24 months in DGR-2 and for 6 months in DGR-3, and no break-out damage was evident. As noted below, it is considered probable that if the induced stresses in the borehole

walls had exceeded the “crack initiation” threshold for the rock materials, then visible breakout damage would be expected after these time periods.

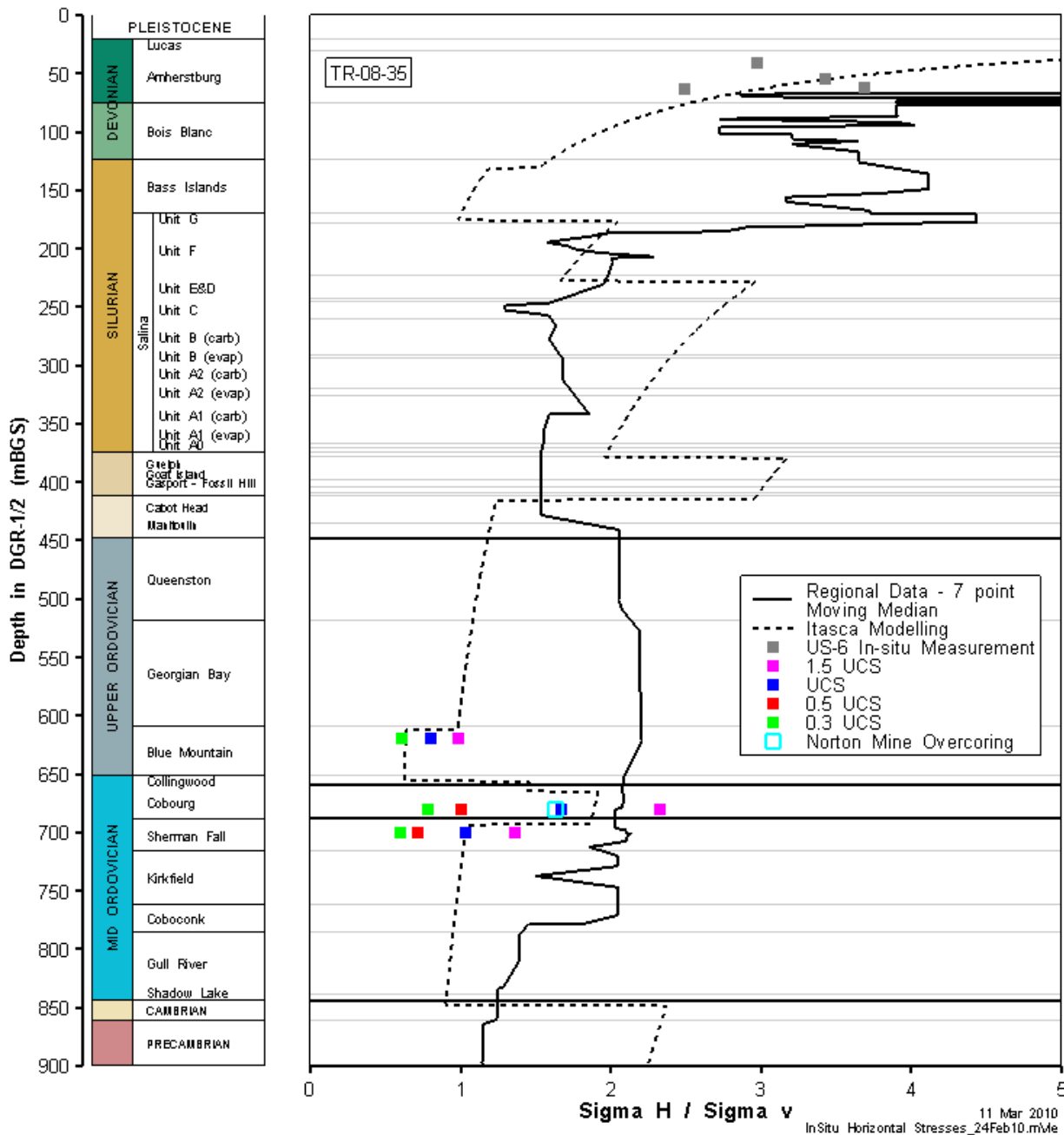


Figure 5.4 Potential magnitudes of maximum in-situ horizontal stresses (σ_H) compared to vertical stress (σ_v). Note UCS is mean peak uniaxial compressive strength and the listed values are the assumed borehole wall strengths for borehole breakout analyses.

Results from analysis of the downhole images from DGR-1 to DGR-4 for the purpose of characterizing or limiting the in situ state of stress at the DGR location are reported in TR-08-35. In undertaking these analyses, one critical parameter is the effective magnitude of the rock material strength at the borehole wall and, in particular, the strength value at which borehole breakout will occur if it is

exceeded by the stresses induced around the borehole.

As there is uncertainty regarding the “correct” value to use for the borehole wall strength, analyses were conducted for a number of possible values:

- Mean value of peak uniaxial compressive strength (UCS - laboratory measured on cores) available at the time of completion of the analyses.
- 150% of UCS, assuming that borehole wall breakout strength is actually 50% higher than UCS.
- 75%, 50%, and 30% of UCS, assuming that borehole wall breakout strength is actually lower than UCS.

The results of these analyses are shown below in Table 5.1 for depths corresponding to the repository horizon (within the Cobourg Formation at 680 mBGS), just above the repository horizon (in the Blue Mountain Formation at 620 mBGS), and just below the repository horizon (in the Sherman Fall Formation at 700 mBGS). Based on the absence of borehole breakouts, and on a number of assumptions regarding the ratio of principal stresses in the earth’s crust under various faulting regimes (TR-08-35), these analyses are capable only of evaluating:

- a) the maximum possible magnitude of the larger of the two horizontal in situ stresses (σ_H), beyond which borehole breakout would occur.
- b) the corresponding range of minimum-to-maximum possible magnitudes of the smaller of the two horizontal stresses (σ_h).

Table 5.1 Constraints on the horizontal stress magnitude at depths of 620, 680 and 700 mBGS, assuming various scenarios for the borehole wall strength. Vertical stress at repository depth (680 mBGS) is about 18 MPa

Formation and Depth	Assumed Borehole Wall Strength	~Vertical Stress, σ_v, MPa	Bounding Horizontal Stress Values		Maximum Ratio σ_H/σ_v
			Maximum Value of σ_H	Range: Minimum-to-Maximum Value of σ_h	
Blue Mountain 620 mBGS	1.5 UCS	16.4	16	8-16	0.98
	UCS (20 MPa)	16.4	13	8-13	0.80
	0.75 UCS	16.4	11	8-11	0.68
	0.5 UCS	16.4	10	8-10	0.61
	0.3 UCS	16.4	10	8-10	0.61
Cobourg 680 mBGS	1.5 UCS	18.0	42	9-42	2.33
	UCS (107 MPa)	18.0	30	9-30	1.67
	0.75 UCS	18.0	24	9-24	1.33
	0.5 UCS	18.0	18	9-18	1.00
	0.3 UCS	18.0	14	9-14	0.78
Sherman Fall 700 mBGS	1.5 UCS	18.5	25	9-25	1.36
	UCS (70 MPa)	18.5	19	9-19	1.03
	0.75 UCS	18.5	16	9-16	0.86
	0.5 UCS	18.5	13	9-13	0.71
	0.3 UCS	18.5	11	9-11	0.60

Table 5.1 shows that the assumptions of UCS used on the analyses are slightly different than those recommended based on formation estimates (see Section 5.10, Table 5.18). The UCS values listed in Table 5.1 and used in the stress analyses were based on depth-specific statistical analysis of the available UCS data (TR-08-35) whereas recommended formation estimates are based on simple formation averages.

The results indicate that the ratio of the maximum horizontal stress to vertical stress (σ_H/σ_V) at the repository horizon depth (680 mBGS) could potentially lie between 0.78 to 2.33, depending on the actual breakout strength of the rock at the borehole wall. However, both ends of the quoted range of results (i.e. for assumed borehole wall strengths of 150% of UCS and 30% of UCS) are considered to be unlikely, as they represent cases in which the assumed borehole wall strength is very significantly different from the laboratory measured values. Removing these outer bounds, a range of $1.67 < \sigma_H/\sigma_V < 1.00$ is considered more realistic at the repository horizon, based on a range of borehole wall strengths from UCS to 50% UCS.

It is important to note that the lower bound of this range (i.e. assuming 50% UCS) is roughly equal to (slightly higher than) the “crack initiation stress” measured in the laboratory, which has a consistent value of 40% UCS in the rock at the repository horizon (see Section 5.8.1.1). In our opinion, it is probable that borehole breakout would occur if the induced stresses at the borehole walls exceeded the crack initiation stress level, particularly after the holes had stood open for several to many months. No such damage was observed.

Maximum possible stresses immediately above and below the repository horizon (at 620 and 700 mBGS, respectively) are indicated to be much lower, due to lack of borehole damage in the weaker rocks of the Blue Mountain and Sherman Fall Formations.

The results of these lines of reasoning regarding in situ stress levels are summarized in Figure 5.4 for the maximum horizontal stress magnitude and for the range of assumptions noted above re: borehole wall strength.

Based on review of the available data and the lines of argument summarized above, the following in situ stress levels are indicated as current recommended conservative values at the elevation of the DGR (~680 mBGS):

- Vertical stress (σ_V) ~ gravity load of super-incumbent materials, ~18 MPa.
- Maximum horizontal stress (σ_H): $1.5 < \sigma_H/\sigma_V < 2.0$.
- Minimum horizontal stress (σ_h): $1.0 < \sigma_h/\sigma_V < 1.2$.

Detailed measurements of the borehole dimensions indicated a consistent trend for the boreholes to deform by elongating in a SE direction, indicating a high probability that the major horizontal in situ stress was acting perpendicular to this, in a NE-SW direction.

5.5 MS Unit 1: Devonian and Upper Silurian Dolostones

The geomechanical data available from within MS-1 (20 to 178.6 mBGS in DGR-1) is relatively limited, as the geomechanics focus of the Phase 1 and 2A site investigation has been, primarily, on the rock units hosting or immediately overlying the DGR.

5.5.1 Rock Material Geomechanical Characteristics

5.5.1.1 Uniaxial Compression

Nine laboratory test specimens were prepared from DGR core recovered in the MS-1 interval, then tested in uniaxial compression. Key results are summarized in Figure 5.5 for each specimen in terms their peak uniaxial compressive strength (UCS), the percentage of UCS at which crack initiation and crack damage occurred, and the Modulus of Elasticity and the Poisson's Ratio values (measured at 40% of UCS).

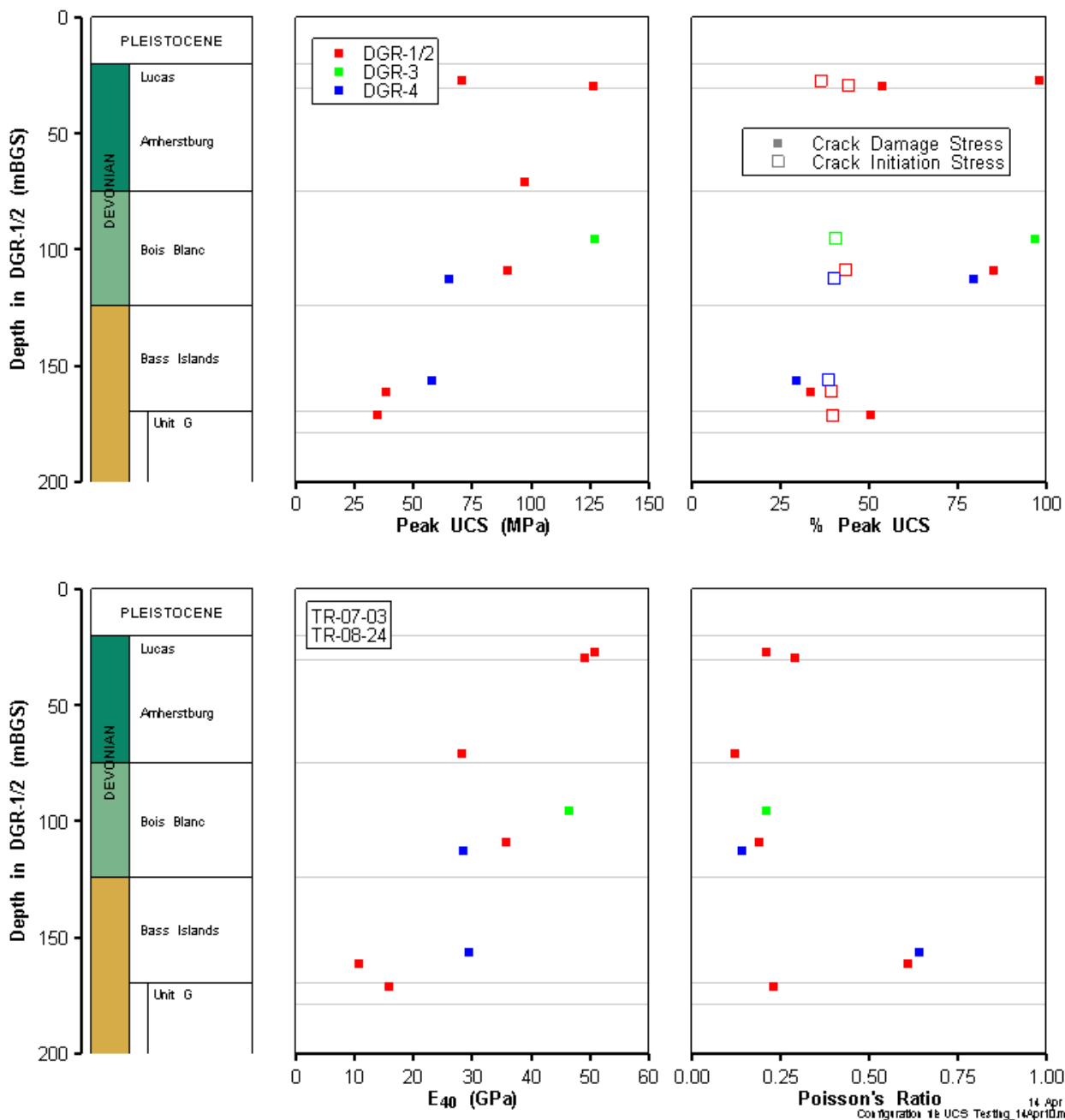


Figure 5.5 MS-1: uniaxial compression test data

Figure 5.6 summarizes the Point Load Test (PLT) data from field tests on core recovered in the MS-1 Unit, in terms of axially oriented tests (left), and in terms of the ratio of diametral-to-axial PLT values (right).

Laboratory test data in the MS-1 Unit are relatively sparse. The more frequent point load testing was conducted in an attempt to provide more extensive index information concerning the variability of rock strength throughout MS-1. It was recognized, and is emphasized here, that individual test results from point load testing are intended to provide a qualitative indication of strength variability only, and should not be used for direct estimation of compressive strength.

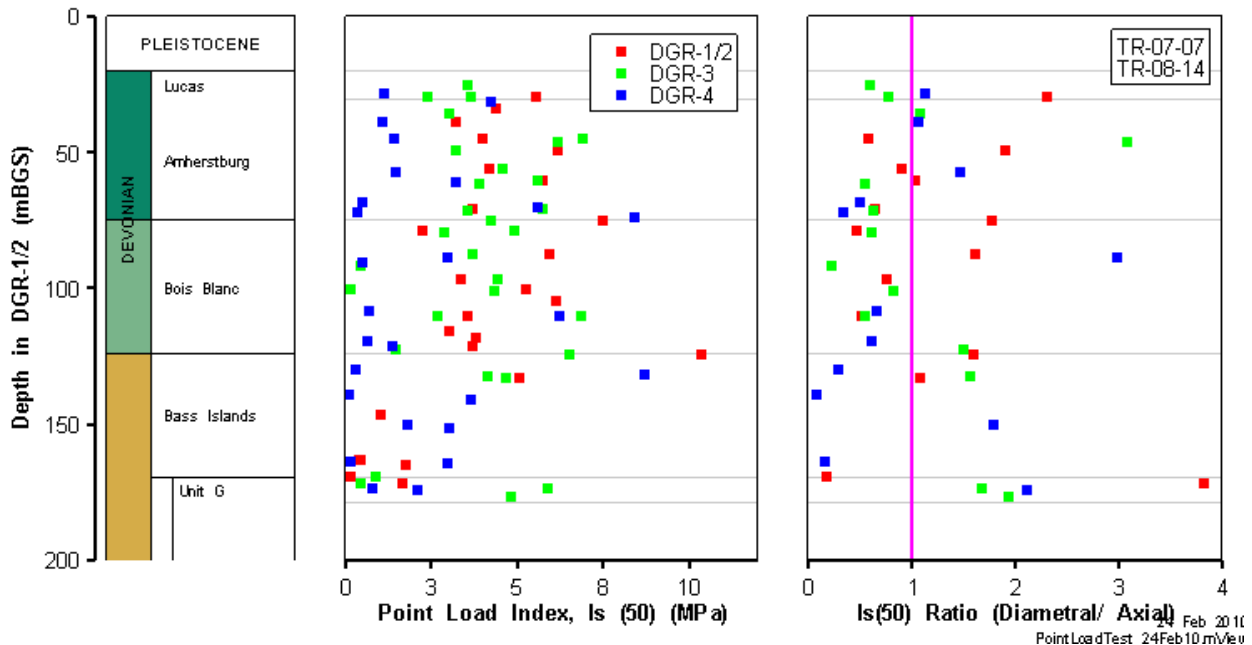


Figure 5.6 MS-1: point load test data

Overall, the data indicate there is an apparent distinction between the relatively stronger upper formations (Lucas, Amherstburg and Bois Blanc), and the lower Bass Island Formation and Salina G Unit. This distinction is visible both in the laboratory based peak UCS values, which average ~95 MPa in the upper units (range 70-126 MPa) and fall to ~36 MPa in the lower Bass Island -G Unit (range 34-38 MPa), as well as in the overall PLT test results which indicate an $I_{s(50)}$ value of ~5 MPa in the upper units, falling to ~1 MPa in the Bass Island – Salina G Unit

Although the peak UCS varies as noted above, the relative stress level at which internal cracking is initiated is remarkably consistent (defined as the point at which internal cracking causes the volumetric strain curve to deviate from linear contraction), remaining virtually constant at ~40% of the peak UCS (range 36%-44%). However, the stress level at which significant crack damage has accumulated in each sample is highly variable as a percentage of the peak UCS, ranging from ~35% to ~98% (defined as the point at which the incremental volumetric expansion caused by crack opening becomes greater than the incremental volumetric contraction of the rock material). These results indicate that whereas crack initiation as a proportion of peak UCS is a robust and useful parameter, crack damage cannot be reliably predicted.

As expected, Modulus of Elasticity values (measured at 40% of UCS) are generally higher in the higher strength materials, and lower in the weaker materials, averaging ~40 GPa in the upper Amherstburg/Bois Blanc units (range 28-51 GPa), and 13 GPa in the lower Bass Island – G Unit (range 11-16 GPa).

Poisson's Ratio (computed at stress levels of 40%UCS) does not generally show significant variability in MS-1 except in two samples near the base of the Bass Islands Formation. Other than this anomalous zone, the Poisson's Ratio is fairly constant in all units at ~0.20, which is somewhat lower than might be expected, although not significantly so. Testing results for the two samples at the base of the Bass Island are distinctly anomalous, as both cases show very early onset of significant crack damage (at about 30% of peak strength), leading to rapid volume expansion and consequent Poisson Ratio values greater than 0.5 when measured at 40% UCS.

Based on the ratio of diametral-to-axial PLT results, rock materials in MS-1 do not appear to be strongly anisotropic. However, this conclusion should be treated with caution, due to the uncertainties that are inherent in PLT data.

There are no data available for the rocks in MS-1 regarding possible relationships between short-term strength and the stress threshold at which long-term strength degradation (LSD) may commence.

Based on the available data, Table 5.2 summarizes estimated values of geomechanical parameters associated with behaviour under uniaxial compression for the rock materials in MS-1.

Table 5.2 MS-1: estimated geomechanical parameters in uniaxial compression

<i>Parameter</i>	<i>Mean</i>	<i>Range</i>	<i>Estimate</i>
Peak UCS	20-124 mBGS: 96MPa 124-178 mBGS: 43MPa	20-124 mBGS: 65-127MPa 124-178 mBGS: 34-58MPa	20-124 mBGS: 90 MPa 124-178 mBGS: 35 MPa
Crack Initiation	40% (UCS)	36-44% (UCS)	40% (UCS)
Crack Damage	Data inconsistent	33-98% (UCS)	No consistent estimate.
Modulus of Elasticity (E_{40})	20-124 mBGS: 40 GPa 124-178 mBGS: 18.6GPa	20-124 mBGS: 28-51 GPa 124-178 mBGS: 11-29 GPa	20-124 mBGS: 35 GPa 124-178 mBGS: 12 GPa
Poisson's Ratio	0.19	0.1 –0.29 (excl outlier)	0.20
PLT Strength Anisotropy (Diametral/Axial)	Low (~1)	Large scatter	~0.8
Long-Term Strength Degradation (initiating stress level as %UCS)	No data	No data	No data

5.5.1.2 Tension

No data regarding behaviour of MS-1 rock materials under tension were generated during Phase 1 and 2A site investigations.

5.5.1.3 Shear

No data regarding behaviour of MS-1 rock materials under shear were generated during Phase 1 and 2A site investigations.

5.5.1.4 Slake Durability

In general, standard slake durability tests were run in the field only on specimens from core samples that, based on visual inspection, contained significant argillaceous (clayey) material. In the MS-1 interval, however, slake durability tests were conducted not only on two samples of argillaceous dolostone from the Salina G Unit, but also on two samples of dolostone that did not appear to be argillaceous.

The results, summarized in Figure 5.7, indicated that as expected the non-argillaceous materials showed no significant degradation when subjected to slaking (wetting-drying) cycles (Slake Durability Index 95-100%), whereas argillaceous dolostones can be expected to show some degradation, with the degree dependent on both the quantity and the nature of the clay content (Slake Durability Index 30-80%). No overall estimated values are presented as these would be meaningless - susceptibility to slaking degradation is completely specific to the clay content (amount and type) which is variable within each rock unit (see Figures 3.5 and 3.6 in Section 3.6.1).

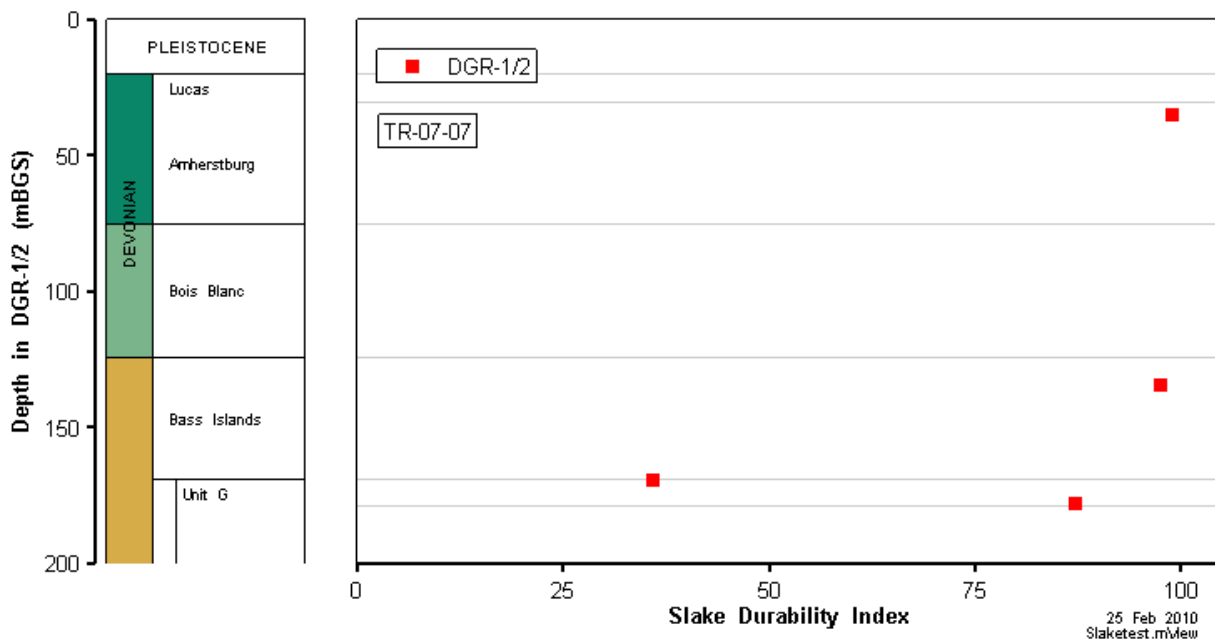


Figure 5.7 MS-1: slake durability index data

5.5.1.5 Free Swell

No data regarding the swelling behaviour of MS-1 rock materials were generated during Phase 1 and 2A site investigations.

5.5.1.6 Abrasiveness

No data regarding the abrasive behaviour of MS-1 rock materials were generated during Phase 1 and 2A site investigations.

5.5.1.7 Dynamic Properties

Compression wave (P-wave) and shear wave (S-wave) velocities were measured on core samples both in the field (TR-07-07, TR-08-14) and in the laboratory (TR-07-03, TR-08-24), from which dynamic elastic constants were calculated. Variations between field and laboratory results occur, and this is not unusual. However, as noted in Section 5.5.1.1, there appears to be a distinct change in character between the upper Amherstburg/Bois Blanc Formations and the lower Bass Island – Salina G Unit, with the latter showing significantly reduced P- and S-wave velocities.

Dynamic elastic constants are calculated from P-wave and S-wave velocities using the following relationships (ASTM, 2005):

Dynamic Modulus of Elasticity:

$$E_d = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \quad [5.1]$$

where: E_d = dynamic Young's modulus
 V_s = S-wave velocity
 V_p = P-wave velocity
 ρ = bulk density of specimen

Dynamic Shear Modulus:

$$G_d = \rho V_s^2 \quad [5.2]$$

where: G_d = dynamic shear modulus
 V_s = shear wave velocity
 ρ = bulk density of specimen

Dynamic Poisson's Ratio (based on velocity data):

$$\nu_d = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad [5.3]$$

where: ν_d = Poisson's Ratio
 V_s = S-wave velocity
 V_p = P-wave velocity

Based on review of the data, estimated values of wave velocities and dynamic elastic constants for the intact rock materials in MS-1 are summarized in Table 5.3.

Table 5.3 MS-1: estimated dynamic properties

<i>Parameter</i>	<i>Estimated Value</i>
P-wave Velocity	20-124 mBGS: 5.1 km/s 124-178 mBGS: 4.3 km/s
S-wave Velocity	20-124 mBGS: 2.7 km/s 124-178 mBGS: 2.2 km/s
Dynamic Modulus of Elasticity	20-124 mBGS: 51 GPa 124-178 mBGS: 36GPa
Dynamic Shear Modulus	20-124 mBGS: 20 GPa 124-178 mBGS: 13.6 GPa
Dynamic Poisson's Ratio	~ 0.30

5.5.2 Rock Mass Geomechanical Characteristics

Access for geomechanical mapping of the rock mass beneath the Bruce nuclear site was not available during the Phase 1 and 2 site investigations. Consequently, information regarding the characteristics of the overall rock mass has been derived only from the relatively small diameter, one-dimensional penetrations provided by the DGR boreholes, and the resulting core. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns (discontinuities) within the mass, information on the overall rock mass characteristics is limited at the current stage.

5.5.2.1 Rock Quality Designation (RQD) and Fracture Frequency

Measurements of Rock Mass Quality Designation (RQD) and fracture frequency were conducted routinely throughout the drilling of DGR boreholes, as reported in Section 3.5. Results of the RQD and natural fracture frequency measurements are summarized in Table 3.3 and Figures 3.2 and 3.3. Overall, for the units comprising MS-1, the RQD and fracture frequency measurements indicate a rock mass that is *moderately fractured and of generally poor-to-fair quality*. However, RQD results suggest that the lower portion of MS-1 comprising the Bass Islands Formation is of lower overall quality, with a mean RQD of 33% indicating a rock mass of *poor quality*. Locally, extreme variations in quality are encountered, with RQD values from 0% to 100%. Some of these low RQD values are in part due to difficult drilling conditions where some grinding of core was reported.

5.5.2.2 Bulk Properties from Geophysical Logging

Elastic dynamic properties of a bulk in-situ sample of the rock mass are derived from downhole sonic logging. A uniform wet bulk density of 2.63 g/cm³ (Figure 4.1), was used in all modulus calculations. Downhole sonic logging was not completed in within MS-1 in DGR-1, DGR-2 or DGR-3 due to presence of grouted steel casing. However such logging was performed in DGR-4 prior to steel casing installation and is the basis for the rock mass dynamic properties listed in Table 5.4. Results are summarized in Table 5.4 for various depth intervals within the MS-1 Unit. The depth intervals were selected on the basis that the sonic velocities were relatively constant within the interval.

Table 5.4 MS-1: estimated rock mass dynamic properties

<i>Formation</i>	<i>Depth Range (mBGS)</i>	<i>V_p (m/s)</i>	<i>V_s (m/s)</i>	<i>E_d (GPa)</i>	<i>G_d (GPa)</i>
Lucas	27.00 - 30.39	4863	2263	36.7	13.5
Amherstburg	30.40 – 74.99	4805	2750	33.9	19.9
Bois Blanc	75.00 – 123.99	4376	2674	45.4	18.9
Bass Islands	124.00 – 169.29	4378	2706	46.0	19.3
Salina G Unit	169.30 – 178.59	3666	2040	28.3	11.1

5.5.2.3 Rock Mass Classification

Rock mass classification systems in common usage for geomechanics purposes include Bieniawski's (1974) Rock Mass Rating (RMR) system, Barton et al. (1974) Tunneling Quality Index (Q-system), and Hoek's (1994) Geological Strength Index (GSI). Subsurface data obtained from the vertical DGR boreholes in the Phase 1 and 2A investigations are not sufficient to provide reliable or complete estimates of all the parameter values required to determine the classification categories under these systems. Preliminary descriptive comments regarding rock mass quality are included under Section 5.5.2.1 above, based on the limited parameters of Rock Quality Designation (RQD) and one-dimensional fracture frequency.

5.6 MS Unit 2: Upper and Middle Silurian Shales, Dolostones and Anhydrite

The MS-2 Unit (178.6 to 411 mBGS in DGR-1) consists primarily of the 190.3 to 198.2 m thick sequence of evaporite and evaporite-related carbonates and shales of the Salina Formation, underlain by 33.4 to 36.5 m of dolostones.

5.6.1 Rock Material Geomechanical Characteristics

5.6.1.1 Uniaxial Compression

Twenty-five laboratory test specimens were prepared from core in the MS-2 interval, then tested in uniaxial compression. Key results are summarized in Figure 5.8 for each specimen in terms of their peak uniaxial compressive strength (UCS), the percentage of UCS at which crack initiation and crack damage occurred, and the Modulus of Elasticity and Poisson's Ratio measured at 40% of UCS.

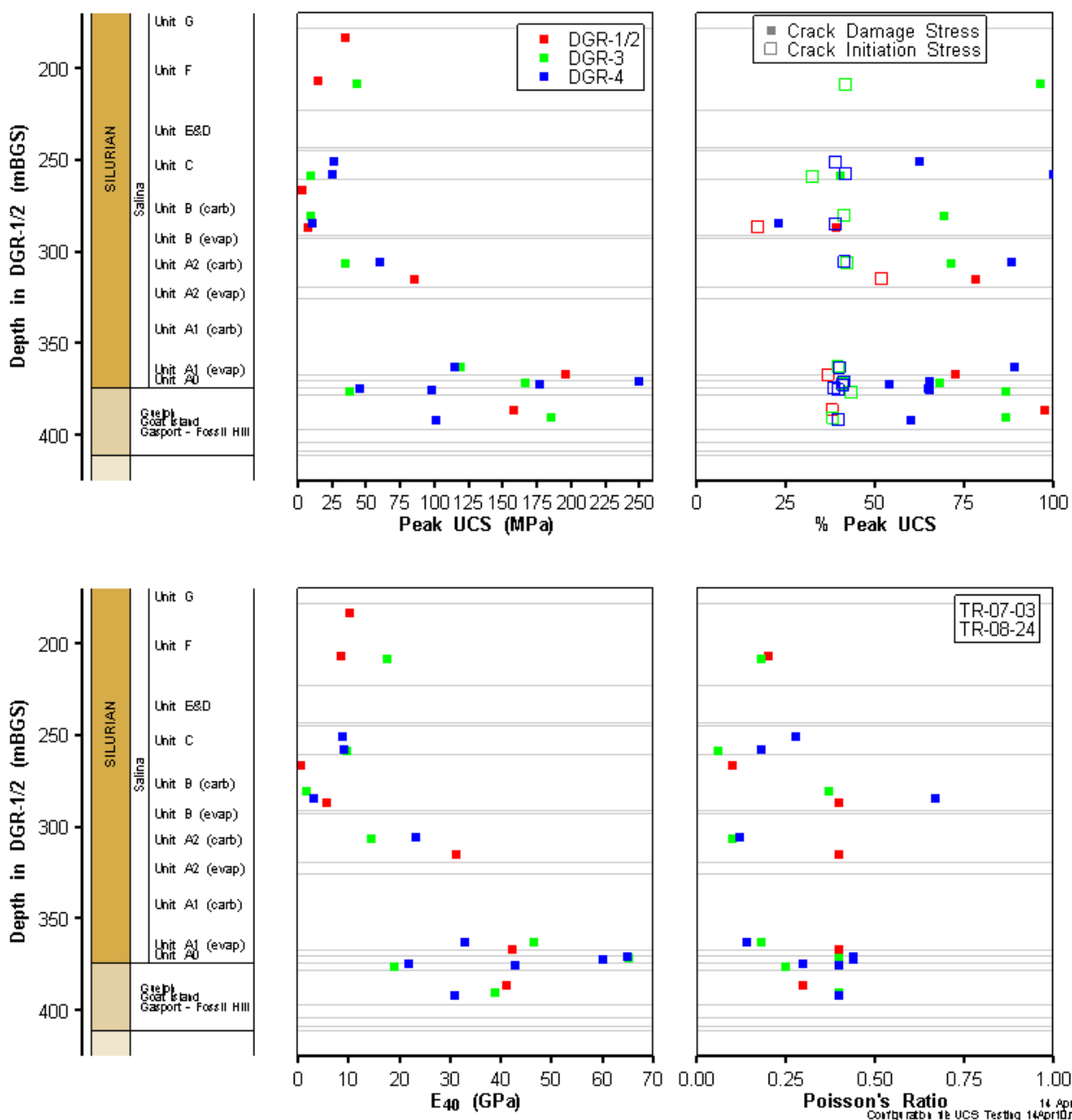


Figure 5.8 MS-2: uniaxial compression test data

Figure 5.9 summarizes the Point Load Test (PLT) data from field tests on core recovered in the MS-2 Unit, in terms of axially oriented tests (left), and in terms of the ratio of diametral-to-axial PLT (right).

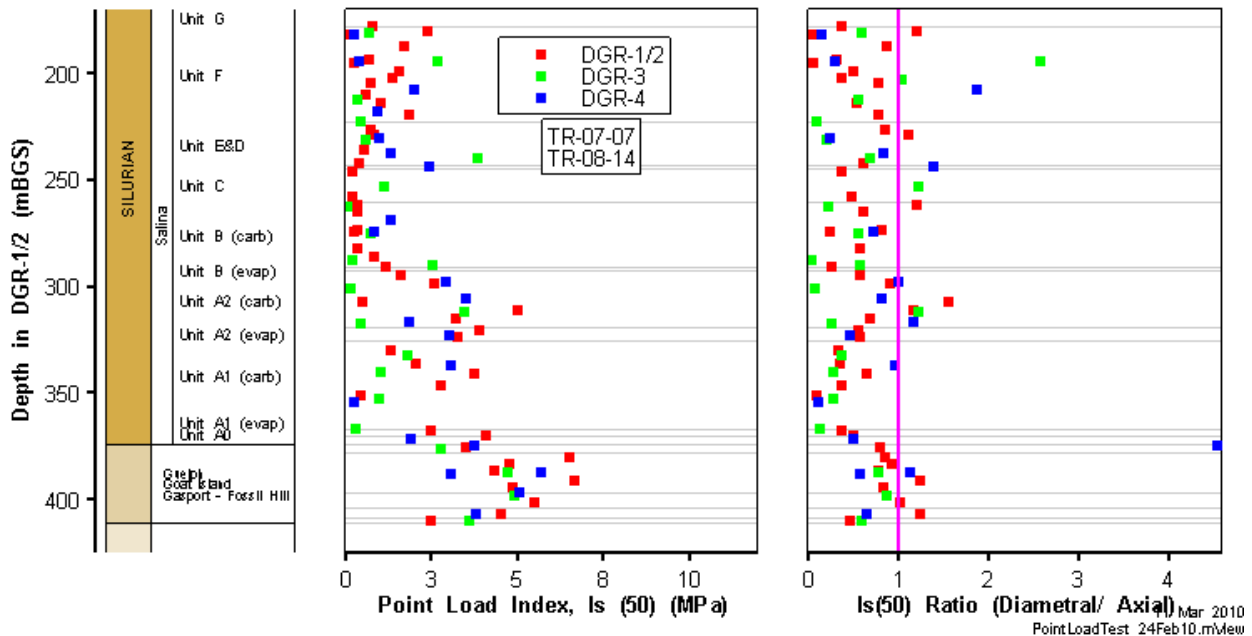


Figure 5.9 MS-2: point load test data

The detailed lithological make-up of the rocks that comprise the 190.3 to 198.2 m thick Salina Formation F to A0 Units varies substantially, including at the scale of the core samples from which laboratory test samples were prepared. For instance, local layers of anhydrite, gypsum and shale may be interspersed among argillaceous or brecciated dolostones within a single test specimen, giving rise to significant heterogeneity within the test specimen. Consequently, even though the core recovery throughout this Formation is generally excellent (Section 3.7.3), implying only minor in-situ fracturing, laboratory and field testing of the core often indicates low compressive strengths due to heterogeneities in the core.

This effect was particularly pronounced in the upper 115 m of the MS-2 Unit (from 178.6 to 293 mBGS in DGR-1; Salina B, C, D, E and F units), and is evident in both the uniaxial compression test results (Figure 5.8) and in the point load test results (Figure 5.9). Within the lower ~118 m of the MS-2 Unit, comprising the Salina A1 and A2 Units and the underlying Middle and Lower Silurian dolostones, this effect appears less prevalent, resulting in higher apparent compressive strengths of the tested core samples. Based on these results, the peak compressive strength and modulus of elasticity values for the MS-2 Unit have been grouped into two broad zones, from 178.6 to 293 mBGS, and from 293 to 411 mBGS, respectively. Broadly, the upper 115 m of MS-2 consist of weaker and lower modulus materials compared to the lower 118 m of the MS-2 Unit.

Poisson's Ratio also shows more variability than might be expected, probably due to the lithological variability noted above, and expert judgement has been used to provide a general estimated value.

Based on the ratio of diametral-to-axial PLT results, rock materials in MS-2 are quite strongly anisotropic with diametral-to-axial ratios of 0.1 to 1.5. While this conclusion should be treated with some caution due to the uncertainties that are inherent in PLT data, the nature of the formations in MS-2 are such that strength anisotropy should be expected.

There are no data available for the rocks in MS-2 regarding possible relationships between short-term strength and the stress threshold at which long-term strength degradation (LSD) may commence.

Results for uniaxial compression parameters are summarized in Table 5.5 below. With respect to the parameters summarized in Table 5.5, it is important to recognize – particularly for the upper zone (178 to 293 mBGS) – that a single estimated value of any parameter can be used only as a very general guideline, as substantial local variability can be expected to occur.

Table 5.5 MS-2: estimated geomechanical parameters in uniaxial compression

<i>Parameter</i>	<i>Mean</i>	<i>Range</i>	<i>Estimate</i>
Peak UCS	178-293 mBGS: 18MPa 293-411 mBGS: 123MPa	178-293 mBGS: 3-43MPa 293-411 mBGS: 35-250MPa	178-293 mBGS: 20MPa 293-411mBGS: 100MPa
Crack Initiation	39% (UCS)	17-52% (UCS)	35% (UCS)
Crack Damage	Data inconsistent	23-100% (UCS)	No consistent estimate.
Modulus of Elasticity (E_{40})	178-293 BGS: 6GPa 293-411 BGS: 38GPa	178-293 mBGS: 0.5-18GPa 293-411mBGS: 15-65GPa	178-293 mBGS: 7GPa 293-411 mBGS: 35GPa
Poisson's Ratio	0.31	0.10-0.44	0.30
PLT Strength Anisotropy (Diametral/Axial)	High	Large scatter	~0.5
Long-Term Strength	No data	No data	No data

5.6.1.2 Tension

No data regarding behaviour of MS-2 rock materials under tension were generated during Phase 1 and 2A site investigations.

5.6.1.3 Shear

No data regarding behaviour of MS-2 rock materials under shear were generated during Phase 1 and 2A site investigations.

5.6.1.4 Slake Durability.

Slake durability tests were run in the field only on specimens selected from core samples that appeared to contain significant argillaceous (clayey) material, based on visual inspection. In the MS-2 interval, a total 8 tests were conducted. The results are summarized in Figure 5.10 and indicate that, as expected, some slaking deterioration can be expected to occur in materials with shale content. Slake durability index results range from ~33 to 90% for the 8 samples tested. No general estimated value is given, as the results are highly specific to the clay content of the specimens selected.

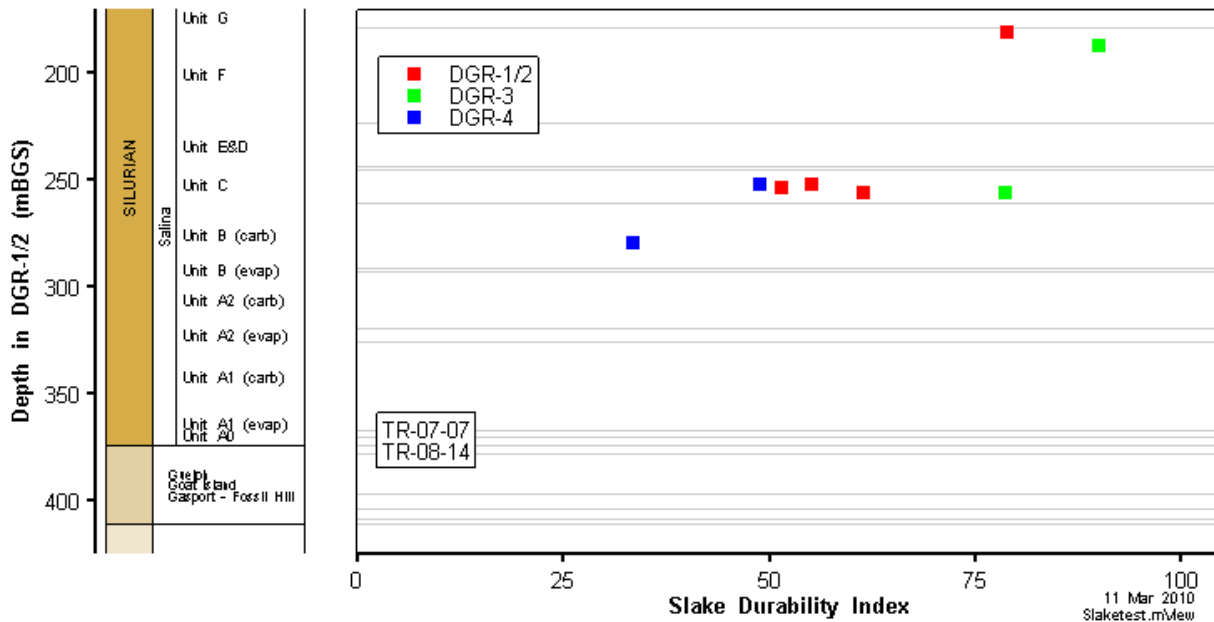


Figure 5.10 MS-2: slake durability index data

5.6.1.5 Free Swell

Free swell testing of core samples from the Salina Unit of MS-2 was undertaken by K. Y. Lo Inc (TR-08-26, Figure 5.11). The samples were tested using fresh water to determine swelling potential in the vertical and horizontal directions, respectively. Swelling potential was shown generally to increase with decreasing calcite content. Swelling potential in the horizontal direction was generally low, ranging from 0% per log cycle of time for all samples from DGR-4, to a maximum of 0.9% per log cycle for one DGR-3 sample taken from within the F Unit of the Salina Formation.

In the vertical direction, swelling potential was variable, ranging from 0% to 3.4% per log cycle of time, related to the calcite content of the material, which ranged from 48.6% to a low of 4.6% in the sample with the maximum swell potential.

5.6.1.6 Abrasiveness

No data regarding the abrasive behaviour of MS-2 rock materials were generated during Phase 1 and 2A site investigations.

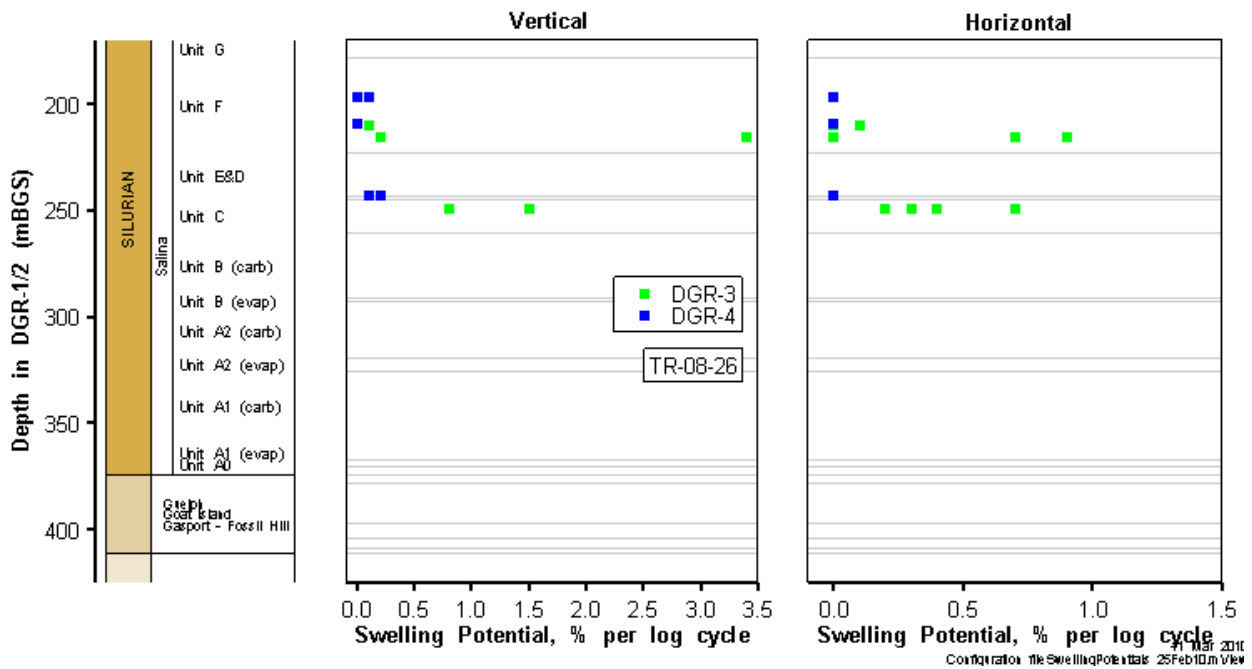


Figure 5.11 MS-2: swelling potential in fresh water

5.6.1.7 Dynamic Properties

Compression wave (P-wave) and shear wave (S-wave) velocities were measured on core samples both in the field (TR-07-07, TR-08-14) and in the laboratory (TR-07-03, TR-08-24), from which dynamic elastic constants were calculated for the rock material. Variations between field and laboratory results occur, and this is not unusual. However, as noted in Section 5.6.1.1, there appears to be a distinct change in character between the upper 115 m thick zone (from 178.6 to 293 mBGS) and the lower 118 m thick zone (from 293 to 411 mBGS), with the lower zone showing increased compression and shear wave velocities, reflecting their generally stiffer nature. Based on review of the test data, estimated values of wave velocities and dynamic elastic constants for the intact rock materials in MS-2 are summarized in Table 5.6.

Table 5.6 MS-2: estimated dynamic properties

<i>Parameter</i>	<i>Estimated Value</i>
P-wave Velocity	178-293 mBGS: 3.7 km/s 293-411mBGS: 5.0 km/s
S-wave Velocity	178-293 mBGS: 2.1 km/s 293-411 mBGS: 2.7 km/s
Dynamic Modulus of Elasticity	178-293 mBGS: 27 GPa 293-411 mBGS: 52 GPa
Dynamic Shear Modulus	178-293 mBGS: 11 GPa 293-411 mBGS: 20 GPa
Dynamic Poisson's Ratio	~ 0.26

5.6.2 Rock Mass Geomechanical Characteristics

Access for geomechanical mapping of the rock mass beneath the Bruce nuclear site was not available during the borehole site investigations. Consequently, information regarding the characteristics of the overall rock mass has been derived only from the relatively small diameter, one-dimensional penetrations provided by the DGR boreholes, and the resulting core. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns (discontinuities) within the mass, information on the overall rock mass characteristics is limited at the current stage.

5.6.2.1 Rock Quality Designation (RQD) and Fracture Frequency

Measurements of Rock Mass Quality Designation (RQD) and fracture frequency were conducted routinely throughout the drilling of DGR boreholes, as reported in Section 3.5 and summarized in Table 3.3 and Figures 3.2 and 3.3. Core recovery throughout the MS-2 Unit was generally 100%, RQD measurements averaged 92-100% with very little local variation, and fracture spacing was generally greater than 3 m. These data indicate a rock mass that is *very sparsely fractured* and of *excellent quality*.

5.6.2.2 Bulk Properties from Geophysical Logging

Elastic dynamic properties of a bulk in-situ sample of the rock mass are derived from downhole sonic logging. A uniform wet bulk density of 2.63 g/cm³ (Figure 4.1), was used in all modulus calculations. Results are summarized in Table 5.7 for various depth intervals within the MS-2 Unit. The depth intervals were selected on the basis that the sonic velocities were relatively constant within the interval. The bulk properties shown in Table 5.7 are reasonable and comparable to laboratory data (TR-07-03, TR-08-24).

Table 5.7 MS-2: estimated rock mass dynamic properties

Formation	Depth (mBGS)	V_p (m/s)	V_s (m/s)	E_d (GPa)	G_d (GPa)
Salina F Unit	177.00 – 182.99	5031	2754	28.3	11.1
Salina F Unit	183.00 – 218.49	5030	2750	35.3	14.3
Salina F Unit	218.50 – 222.99	4900	2820	35.7	21.4
Salina E Unit	223.00 – 242.99	4890	2640	47.4	18.4
Salina C&D Units	243.00 – 260.29	3820	1930	27.5	16.5
Salina B Unit	260.30 – 283.68	4010	2140	31.4	12.1
Salina B Unit	283.69 – 293.09	5720	2560	31.4	23.2
Salina A2 Unit	293.10 – 327.99	4470	2380	38.7	15.2
Salina A1 Unit	328.00 – 365.97	5110	2810	53.2	20.7
Salina A1 Unit	365.98 – 370.49	5940	3020	54.8	24.0
Salina A0, Guelph, Goat Is	370.50 – 393.37	5113	2750	51.7	19.9
Goat Island, Gasport	393.38 – 404.24	5540	2880	57.3	21.8
Lions Head, Fossil Hill	404.25 – 411.00	5740	2960	60.9	23.1

5.6.2.3 Rock Mass Classification

Rock mass classification systems in common usage for geomechanics purposes include Bieniawski's Rock Mass Rating (RMR) system, Barton's (1974) Tunneling Quality Index (Q-system), and Hoek's Geological Strength Index (GSI). Subsurface data obtained from the vertical DGR boreholes in the Phase 1 and 2A investigations are not sufficient to provide reliable or complete estimates of all the parameter values required to determine the classification categories under these systems. Preliminary descriptive comments regarding rock mass quality are included under Section 5.6.2.1 above, based on the limited parameters of Rock Quality Designation (RQD) and one-dimensional fracture frequency.

5.7 MS Unit 3: Lower Silurian and Upper Ordovician Shales and Dolostones

The 249 to 250 m thick MS-3 Unit (411 to 659.5 mBGS in DGR-1 and DGR-2) was defined as a single mechano-stratigraphic unit in order to group together the thick sequence of shale rocks that directly overlies the repository horizon, although contained within the unit there is one relatively minor (9.5 to 12.9 m thick) layer of dolostone, the Manitoulin Formation. The MS-3 Unit also includes the Collingwood Shale, which is the Upper Member of the Middle Ordovician Cobourg Formation (Figure 5.1).

5.7.1 Rock Material Geomechanical Characteristics

5.7.1.1 Uniaxial Compression

With the exception of the cherty dolostone of the Manitoulin Formation (434.8 to 447.7 mBGS in DGR-1), the 249 to 250 m thick MS-3 Unit comprises shale rocks of the Cabot Head, Queenston, Georgian Bay and Blue Mountain Formations and the Collingwood Member.

Thirty-eight laboratory specimens for uniaxial compression testing were prepared from core recovered from the MS-3 Unit. Key results are summarized in Figure 5.12 for each specimen in terms of their peak uniaxial compressive strength (UCS), the percentage of UCS at which crack initiation and crack damage occurred, and the Modulus of Elasticity and Poisson's Ratio values (measured at 40% of UCS).

Figure 5.13 summarizes the Point Load Test (PLT) data from field tests on core recovered from the MS-3 Unit, in terms of axially oriented tests (left), and in terms of the ratio of diametral-to-axial PLT values (right).

In general, and as expected, the peak compressive strength and the modulus of elasticity values for these shale rocks are significantly lower than for the primarily carbonate rocks within the other MS units. Although considerable care was taken to preserve the shale core samples shipped to the laboratory in order to avoid deterioration, some variability in results may be ascribable to the sensitivity of these materials to moisture changes (Sections. 5.7.1.4, 5.7.1.5).

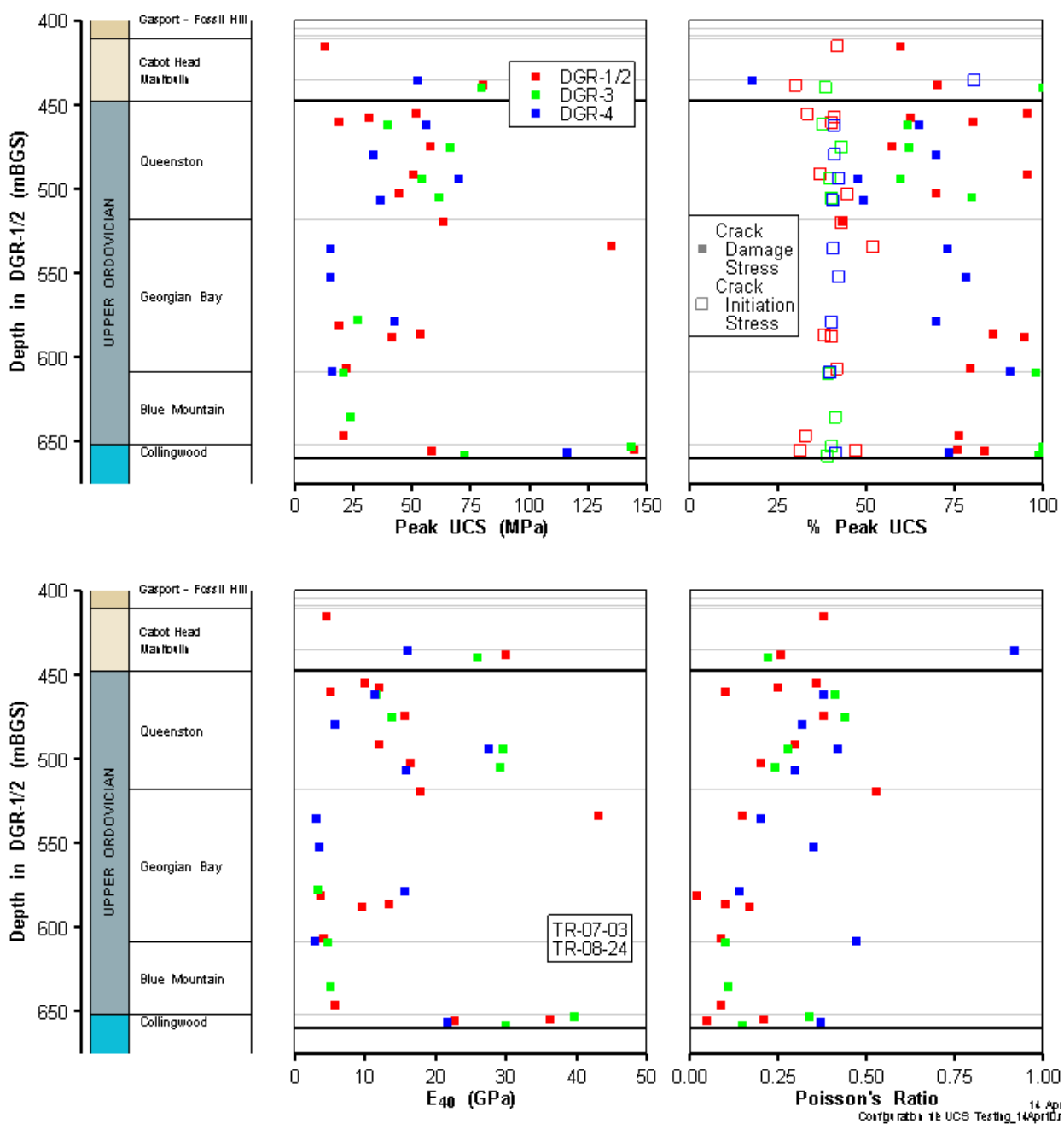


Figure 5.12 MS-3: uniaxial compression test data

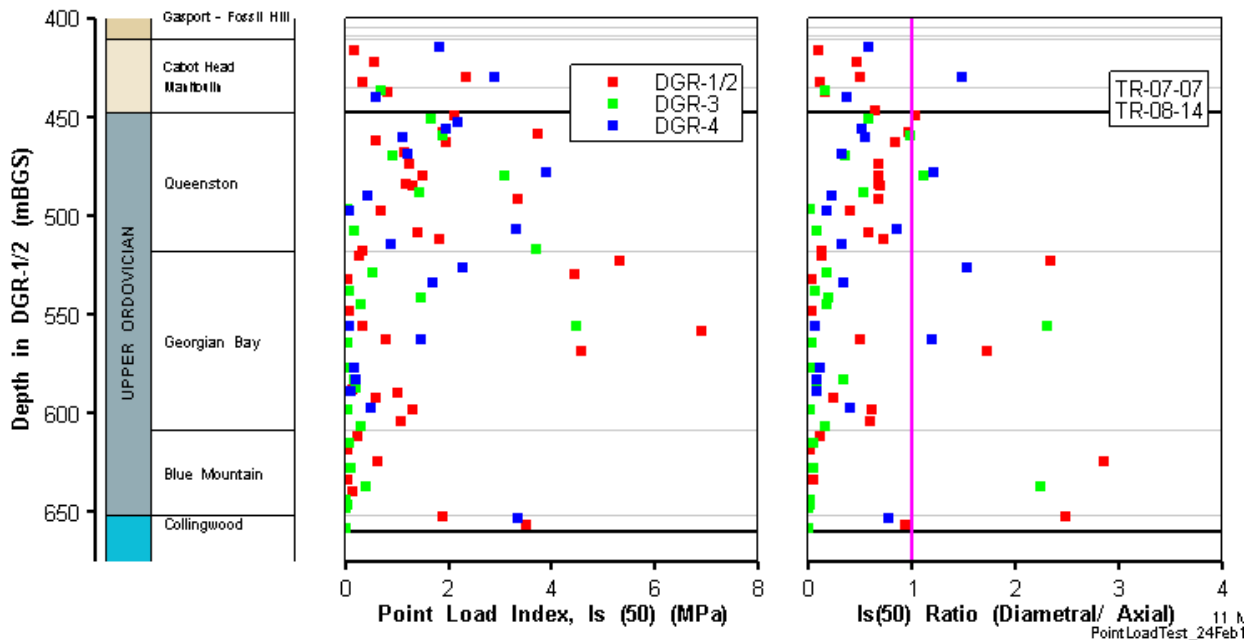


Figure 5.13 MS-3: point load test data

In general, the peak strength, stiffness and Poisson's Ratio values decline in the lower part of the unit (Georgian Bay; Blue Mountain; Collingwood) compared to the upper part (Queenston). It is also noted that the Blue Mountain Formation is indicated to be a particularly weak material, with a UCS of ~20 MPa. Despite these variations in the properties of the shale materials (with the exception of the included Manitoulin Formation dolostone) that comprise the MS-3 Unit, the geomechanical properties have been grouped together into a single unit for the purposes of this summary site descriptive report. If required for purposes of detailed design analyses – for instance for shaft seals at specific elevations - details of the specific test data are available in the reference documents TR-07-03 and TR-08-24.

Based on the ratio of diametral-to-axial PLT results (Figure 5.13), the rock materials in MS-3 are quite strongly anisotropic. While this conclusion should be treated with some caution due to the uncertainties that are inherent in PLT data, the relatively fissile nature of the shale formations in MS-3 are such that strength anisotropy should be expected (see Section 5.7.1.3 below).

There are no data available for the rocks in MS-3 regarding possible relationships between short-term strength and the stress threshold at which long-term strength degradation (LSD) may commence. However, it has been demonstrated in other units (see MS-4) that no long-term strength degradation is likely to occur at stress levels below crack initiation which consistently occurs at 40% of UCS in the MS-3 units.

Results for uniaxial compression parameters are summarized in Table 5.8 below, excluding the dolostone of the Manitoulin Formation.

Table 5.8 MS-3: estimated geomechanical parameters in uniaxial compression

<i>Parameter</i>	<i>Mean</i>	<i>Range</i>	<i>Estimate</i>
Peak UCS	53 MPa	13-145 MPa	50 MPa
Crack Initiation	40% (UCS)	30-52% (UCS)	35% (UCS)
Crack Damage	74% (UCS)	42-100% (UCS)	~75% (UCS)
Modulus of Elasticity (E_{40})	16 GPa	3-43 GPa	15 GPa
Poisson's Ratio	0.25	0.12-0.47	0.25
PLT Strength Anisotropy (Diametral/Axial)	High	Large scatter	~0.5
Long-Term Strength	No data	No data	No data

5.7.1.2 Cross-Anisotropic Uniaxial Compression

In order to obtain some comparison of compressive strength parallel and perpendicular to bedding, two core samples from the Queenston Shale unit were sub-cored at 90 degrees to the borehole axis (one each from DGR-3 and DGR-4) and tested in uniaxial compression (TR-08-24). Surprisingly, the core from DGR-3 (at 487.1.mBGS) indicated that UCS parallel to bedding was actually greater than perpendicular to bedding (75.2 MPa vs 47.5 MPa). However, the core from DGR-4 (at 477.9 mBGS) indicated that strength parallel to bedding was 42% of strength perpendicular to bedding (19.2 MPa vs 46.2 MPa). The results are inconclusive. Experienced judgement would indicate that the fissile nature of the shale rocks in MS-3 will generally result in reduced compressive strength when loaded parallel to bedding. This conclusion is supported by the Point Load Test results, which also indicate a high degree of strength anisotropy (Figure 5.13).

5.7.1.3 Triaxial Compression

Three core samples from the Georgian Bay Formation were tested under triaxial confinement of 5, 10 and 15 MPa respectively.. The results are shown in Figure 5.14., which also shows the best-fit Hoek-Brown envelope for the data. The data is limited, comprising only three triaxial points, giving relatively low confidence in the calculated Hoek-Brown parameters noted below.

- $\sigma_c = 42$ MPa
- $m_i = 14.7$
- $s = 1.0$
- $a = 0.5$

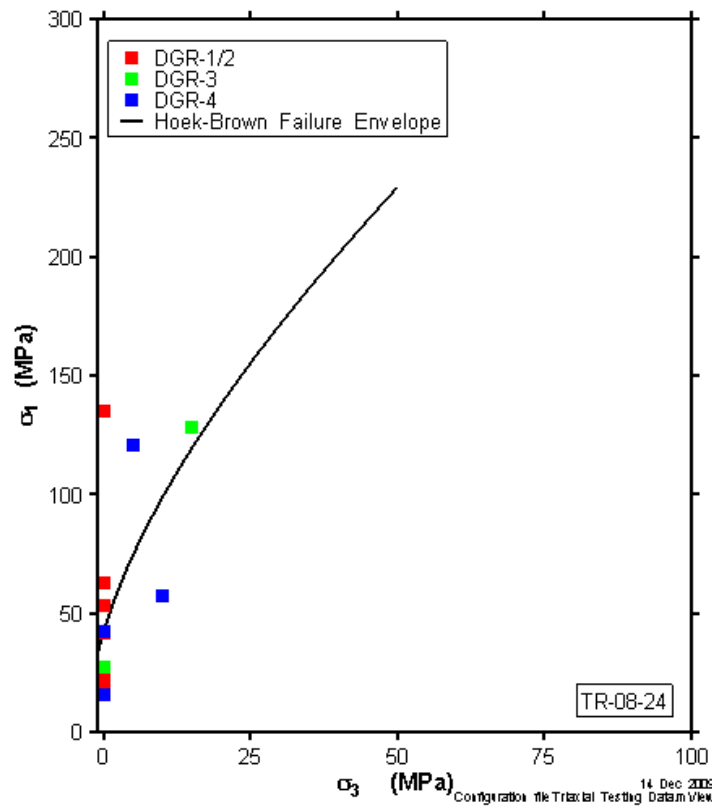


Figure 5.14 MS-3: triaxial compression test data for Goergian Bay Formation

5.7.1.4 Tension

A limited number of Brazilian tests were conducted to determine indirect tensile strength values for the MS-3 rocks (Figure 5.15). Figure 5.15 shows the results of this tensile strength testing including the style of failure mode recorded by the testing laboratory (TR-07-03, TR-08-24). Failure modes include diametral (Mode 1 - normal to bedding), slabbing (Mode 2- parallel to bedding) or mixed (Mode 3 – normal and parallel to bedding).

While Brazilian test results in rock often display significant variability, it is particularly difficult to obtain valid results in fissile shales, due in part to inconsistency in the modes of failure that occur (e.g., parallel or perpendicular to the core axis, or in combined mode). Estimated values of the indirect tensile strength should be treated with caution. For purposes of this DGSM, a value of 4.0 MPa is considered to a reasonable estimate of the indirect tensile strength. It is noted that values of indirect tensile strength derived from Brazilian tests tend to give results that are 30-40% higher than those from direct tension tests. The ratio of indirect and direct tension test results could be much higher than 30% in interbedded limestone and shale formations like the Georgian Bay. The direct tensile strength is strongly dependent on the presence of weak bedding partings within a specimen.

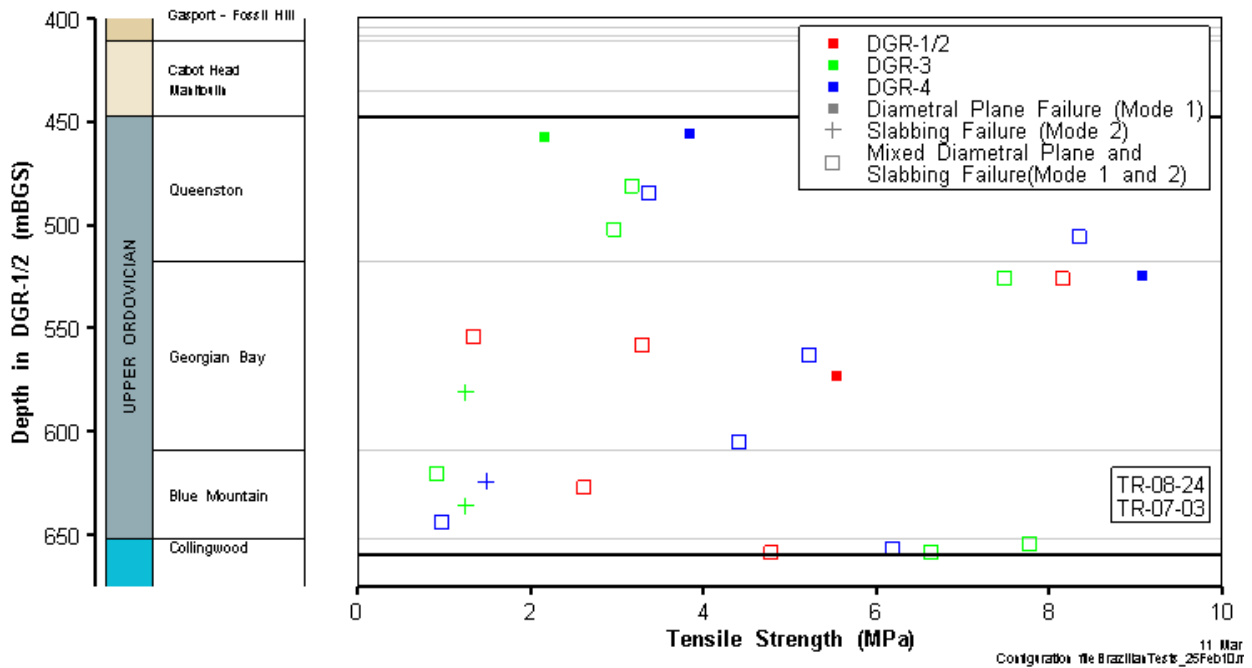


Figure 5.15 MS-3: Brazilian tests - indirect tensile strength data

5.7.1.5 Shear

Direct shear tests were conducted on samples from the Georgian Bay, Blue Mountain and Collingwood Formations, located in the lower part of the MS-3 Unit. The specimens were sheared along the direction of bedding (i.e. along a horizontal plane). In each case, staged tests were conducted at increasing normal stress in order to define the residual shear strength envelope. In addition, direct shear tests were conducted on one intact core specimen from the Georgian Bay Formation, one from the Blue Mountain Formation, and five from the Collingwood Formation. Test results are summarized in Figure 5.16.

Residual shear strength parameters appear to be relatively consistent. For purposes of this DGSM, proposed recommended values of the residual shear strength parameters are:

- residual cohesion = 0 MPa, and
- residual friction angle = 29 degrees.

Residual shear strength envelope: $\tau_r = \sigma_n(\tan 29^\circ)$, MPa, where:

τ_r = residual shear strength, and

σ_n = normal stress.

For intact material from MS-3, the data regarding peak shear strength are relatively limited, comprising seven tests conducted at a maximum normal stress of 2 MPa. The best fit line through these intact shear strength test data implies a very high apparent angle of internal friction at these relatively low normal stresses. This phenomenon is common for direct shear tests of intact rock, and it is generally observed that as the normal stress increases, the apparent friction declines and the apparent cohesion increases, due to the effect of asperities on the newly formed shear plane (Hoek and Bray,

1974).

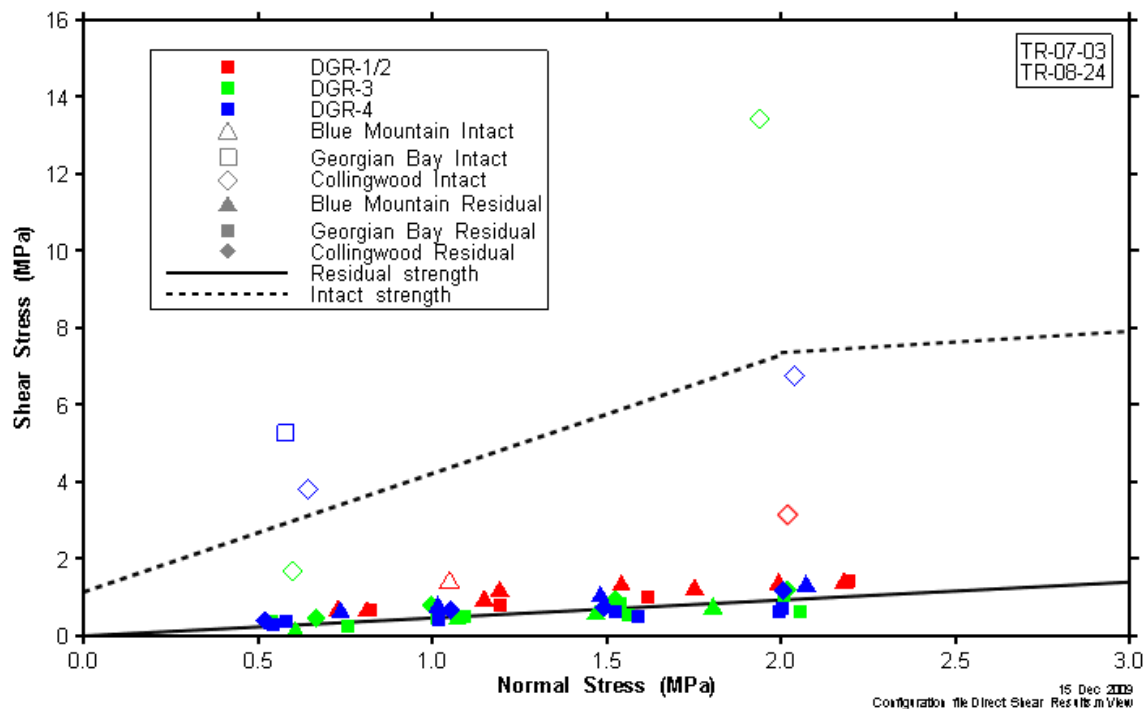


Figure 5.16 MS-3: direct shear test results for Blue Mountain and Georgian Bay Formations and Collingwood Member

At low normal stresses, the asperities contribute a major geometric effect which effectively increases the apparent friction angle. At high normal stresses, shear occurs through the asperities, increasing the effective cohesion intercept, while the apparent friction angle declines, ultimately reaching the value of the residual friction angle. For this reason, a bi-linear shear strength envelope is proposed for the peak shear strength of these intact materials. At normal stresses below 2 MPa, the best fit line to the test data is used directly to evaluate apparent cohesion and friction. At normal stresses above 2 MPa, it is conservatively assumed that the friction angle becomes equal to the residual friction angle, as noted above.

For normal stresses (σ_n) in the range: $0 < \sigma_n < 2 \text{ MPa}$:

- apparent cohesion intercept = 1.1 MPa,
- apparent friction angle 72 degrees, and
- peak shear strength envelope: $\tau_p = 1.1 + \sigma_n(\tan 72^\circ)$, MPa.

For normal stresses (σ_n) greater than 2 MPa:

- apparent cohesion = 6.3 MPa,
- apparent friction angle = 29 degrees, and

- peak shear strength envelope: $\tau_p = 6.3 + \sigma_n(\tan 29^\circ)$, MPa.

5.7.1.6 Slake Durability

The MS-3 Unit consists largely of shaley materials, and a total of 32 slake durability tests were conducted in the field on selected core samples. The results are summarized in Figure 5.17, and show a range of Slake Durability Index (SDI) from 41.5% in the Cabot Head Shale to almost 100% in a sample from the Collingwood Member. In general, it is expected that clay shale units will show some degradation under wetting-drying cycles, and the results indicate that this is the case, with a mean SDI of 80% for the MS-3 unit. However, it is noted that the mean SDI value is significantly higher in the Queenston Shale (~90%) than in the underlying Georgian Bay Shale (~76%), indicating that the Queenston Formation will be relatively resistant to slaking degradation compared to the Georgian Bay Formation materials. The Blue Mountain Formation materials are also relatively resistant to slaking degradation, with a mean SDI of ~90%.

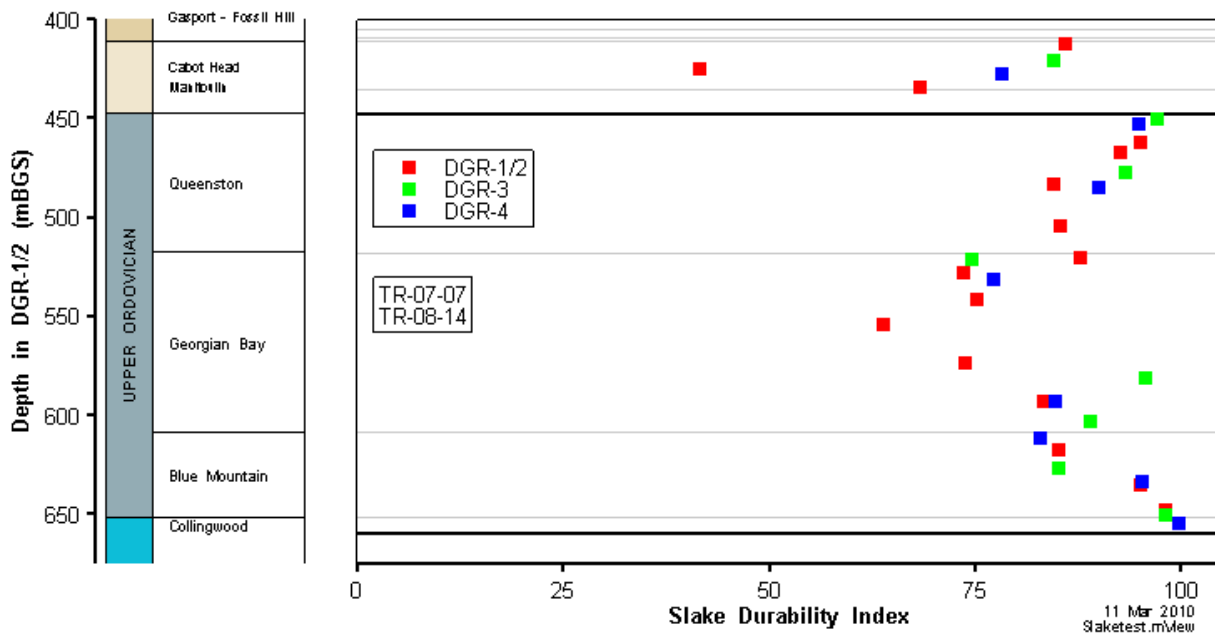


Figure 5.17 MS-3: slake durability index data

For purposes of this report, the following estimated values of Slake Durability Index are recommended:

- 411 to 447 mBGS (Cabot Head + Manitoulin): SDI~75%
- 448 to 518 mBGS (Queenston): SDI~90%
- 518 to 608.9 mBGS (Georgian Bay): SDI~75%
- 608.9 to 652 mBGS (Blue Mountain): SDI~90%
- 652 to 659.5 mBGS (Collingwood): SDI ~95%.

5.7.1.7 Free Swell

Time-dependent swelling deformation of several shaley rock formations in Ontario is a well known phenomenon. The testing methods for determining swelling potential developed by Lo et al. (1978) have become the *de facto* standard methodology for evaluating swelling potential, and these methods were utilized for this project. Swelling potential is expressed as the percent swelling strain that occurs per log cycle of time, in either the vertical (perpendicular to bedding) or horizontal (parallel to bedding) directions.

As the swelling phenomenon appears to be related to ion exchange between the rock porewater and the surrounding water, tests were conducted using both fresh water and artificial (i.e. re-constituted) formation water. A total of 27 swell tests in freshwater and 11 in formation water were run on samples of MS-3 rocks, principally from the Queenston, Georgian Bay and Blue Mountain Formations. Where possible, both the Vertical Swelling Potential (VSP) and Horizontal Swelling Potential (HSP) were recorded. Some difficulties regarding sample preparation and preservation were encountered with samples from the Blue Mountain Formation. Details of the testing results are presented in TR-07-16 and TR-08-26, and are summarized below in Figure 5.18 in terms of VSP and HSP.

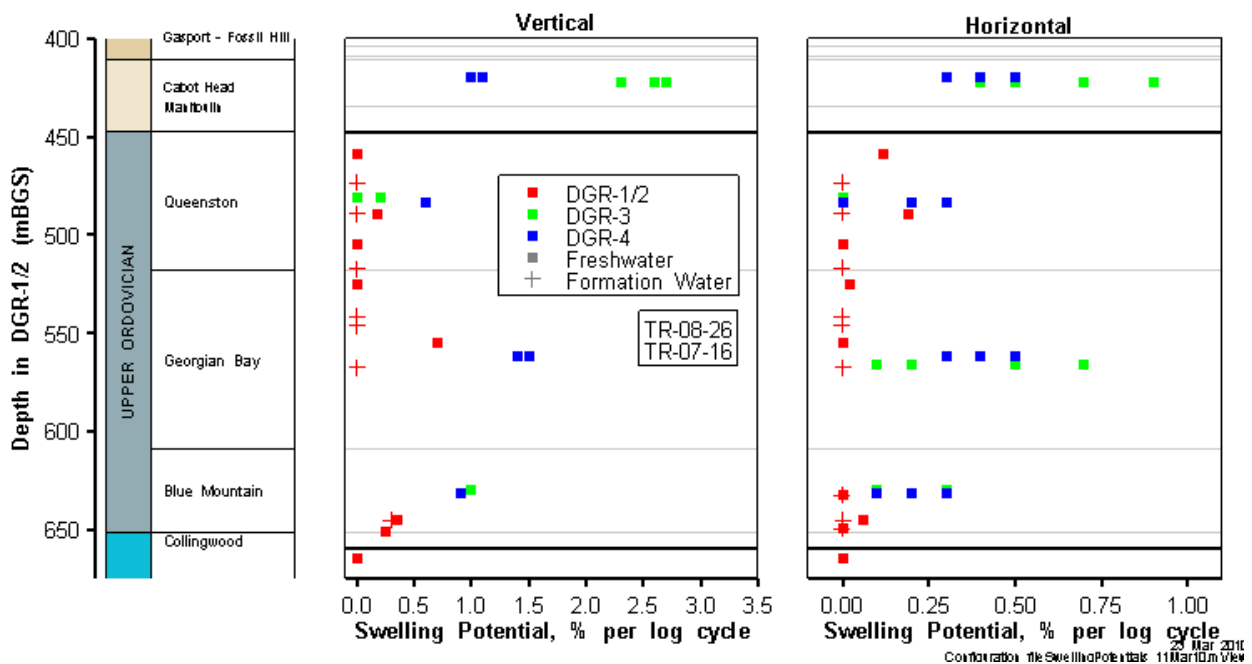


Figure 5.18 MS-3: swelling potential in fresh water and in formation water

In formation water, the swelling potential for MS-3 rocks is essentially zero, as expected. For practical purposes, both the VSP and the HSP can be considered to be zero in formation water.

When exposed to fresh water, the measured swelling potential was found to decrease with increasing calcite content. The vertical swelling potential results were generally consistent with data from precedent projects (TR-07-26), as indicated in Table 5.9 below. However, the Cabot Head Formation – for which no precedent data is available - exhibited significant swelling potential, up to a maximum of 2.7% VSP and up to 0.9% HSP. Except for the Cabot Head, horizontal swelling potential was generally minor.

Table 5.9 MS-3: vertical and horizontal swelling potential in fresh water.

Formation	VSP (DGR data)	VSP (precedent)	HSP (DGR data)	HSP (precedent)
Cabot Head	~2%	No data	~0.6%	No data
Queenston	~0.3%	0.02% - 0.54%	~0.1%	0 – 0.34%
Georgian Bay	~1%	0.2% - 1.4%	~0.3%	0 – 0.34%
Blue Mountain	~1%	0.9% - 1.05%	~0.15%	0.15%

5.7.1.8 Abrasiveness

No data regarding the abrasive behaviour of MS-3 rock materials were generated during Phase 1 and 2A site investigations.

5.7.1.9 Dynamic Properties

Compression wave (P-wave) and shear wave (S-wave) velocities were measured on intact core samples both in the field (TR-07-07, TR-08-14) and in the laboratory (TR-07-03, TR-08-24), from which dynamic elastic constants were calculated for the rock material. Variations between field and laboratory results occur, and this is not unusual. Overall, although the Georgian Bay Formation materials appear to have somewhat higher P-wave and S-wave velocities, these differences are not considered to be significant in practical terms. Based on review of the test data, estimated values of wave velocities and dynamic elastic constants for the intact rock materials in MS-3 are summarized in Table 5.10.

Table 5.10 MS-3: estimated rock material dynamic properties

Parameter	Estimated Value
P-wave Velocity	4.0 km/s
S-wave Velocity	2.1 km/s
Dynamic Modulus of Elasticity	34 Pa
Dynamic Shear Modulus	18 GPa
Dynamic Poisson's Ratio	0.31

5.7.2 Rock Mass Geomechanical Characteristics

Access for geomechanical mapping of the rock mass beneath the Bruce nuclear site was not available during the Phase 1 and 2A site investigations. Consequently, information regarding the characteristics of the overall rock mass has been derived only from the relatively small diameter, one-dimensional penetrations provided by the DGR boreholes, and the resulting core. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns (discontinuities) within the mass, information on the overall rock mass characteristics is limited at the current stage.

5.7.2.1 Rock Quality Designation (RQD) and Fracture Frequency

Measurements of Rock Mass Quality Designation (RQD) and fracture frequency were conducted routinely throughout the drilling of DGR boreholes as reported in Section 3.5 and summarized in Table 3.3 and Figures 3.2 and 3.3. Core recovery and RQD values throughout the MS-3 Unit were generally excellent, and fracture frequency measurements indicated a generally very sparsely fractured rock mass. Based on these borehole-derived measurements, and with the exception of a few localized zones located primarily within the Queenston and Georgian Bay Formations, the rock mass comprising the MS-3 Unit can be characterized as *very sparsely fractured* and of *excellent quality*.

5.7.2.2 Bulk Properties from Geophysical Logging

Elastic dynamic properties of a bulk in-situ sample of the rock mass are derived from downhole sonic logging. A uniform bulk density of 2.63 g/cm³ (Figure 4.1) was used in all modulus calculations. Results are summarized in Table 5.11 for various depth intervals within the MS-3 Unit.

Table 5.11 MS-3: estimated rock mass dynamic properties

Formation	Depth Range (mBGS)	V_p (m/s)	V_s (m/s)	E_d (GPa)	G_d (GPa)
Cabot Head	411.00 – 431.49	3810	2170	31.2	12.4
Manitoulin	431.50 – 447.64	5140	2860	54.8	21.5
Queenston	447.65 – 517.99	4170	2220	33.7	12.9
Georgian Bay	518.00 - 579.42	3970	1990	27.6	10.8
Georgian Bay, Blue Mountain	579.43 – 616.49	3670	2000	25.5	10.6
Blue Mountain	616.50 – 649.42	3540	1980	17.5	19.2
Blue Mountain, Collingwood	649.43 – 651.99	4890	2650	17.5	18.9
Collingwood	652.00 – 659.49	4898	2504	44.3	16.7

5.7.2.3 Rock Mass Classification

Rock mass classification systems in common usage for geomechanics purposes include Bieniawski's Rock Mass Rating (RMR) system, Barton's (1974) Tunneling Quality Index (Q-system), and Hoek's Geological Strength Index (GSI). Subsurface data obtained from the vertical DGR boreholes in the Phase 1 and 2A investigations are not sufficient to provide reliable or complete estimates of all the parameter values required to determine the classification categories under these systems. Preliminary descriptive comments regarding rock mass quality are included under Section 5.7.2.1 above, based on the limited parameters of Rock Quality Designation (RQD) and one-dimensional fracture frequency.

5.8 MS Unit 4: Middle Ordovician Cobourg Formation

The 27.5 to 28.6 m thick Lower Member of the Cobourg Formation is MS Unit 4 (659.5 to 688.1 mBGS in DGR-2) and comprises a fossiliferous argillaceous limestone. This is the target horizon to host the DGR (Figure 5.1).

5.8.1 Rock Material Geomechanical Characteristics

5.8.1.1 Uniaxial Compression

A total of 39 laboratory specimens (Figure 5.19) were tested in standard short-term uniaxial compression tests, nine as part of the initial work by CANMET (TR-07-03, TR-08-24) and a further 11 samples were tested to provide input data for the Long-term Strength Degradation (LSD) testing (TR-08-11, TR-08-36). In addition, six LSD samples were tested after being subjected to long-term static loading at stress levels below the anticipated crack initiation levels.

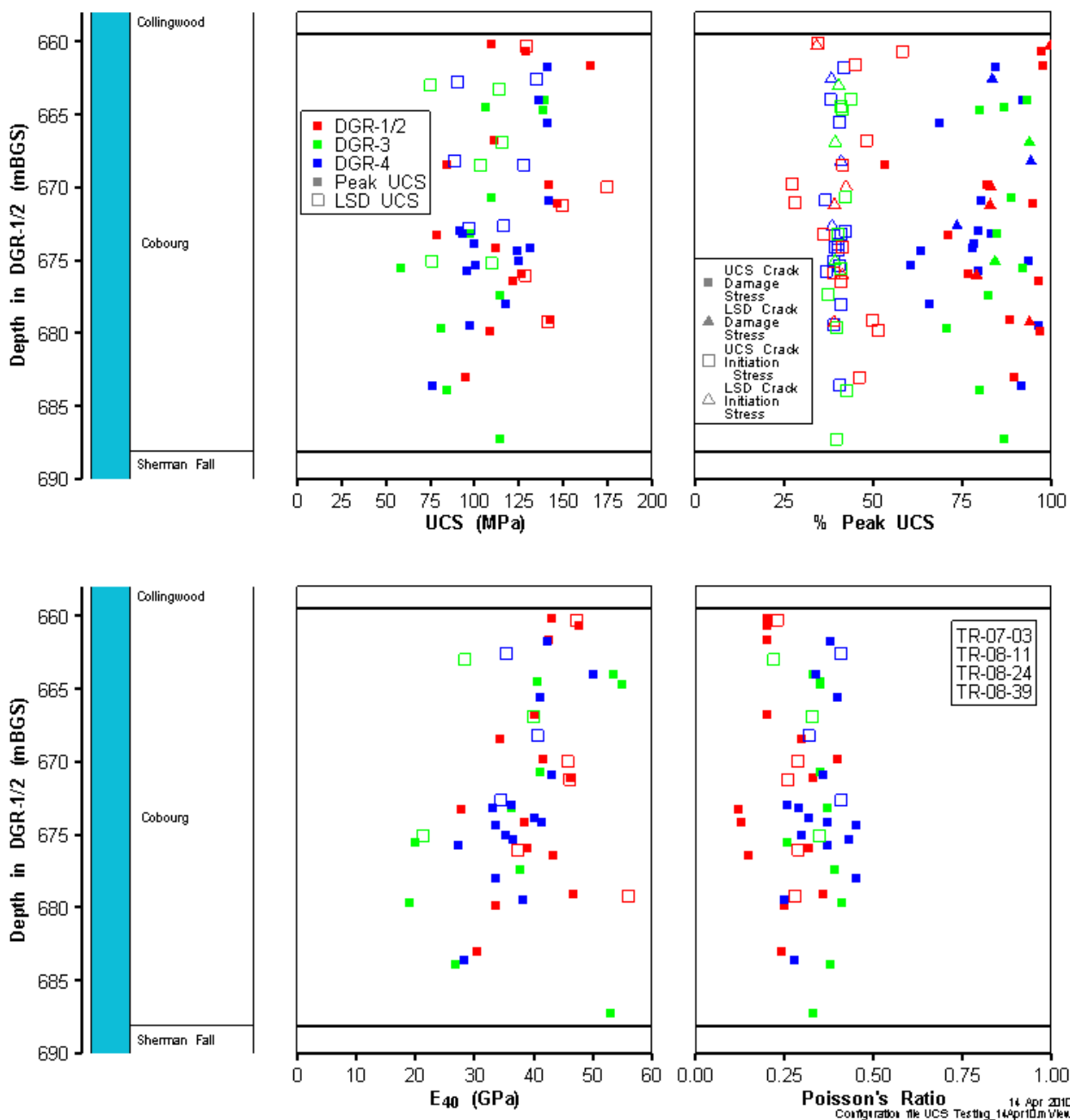


Figure 5.19 MS-4: uniaxial compression test data

The results of the LSD tests did not indicate that any strength degradation had occurred for samples that had been statically loaded for 100 days to stress levels that averaged 70% of the crack initiation stress level (range from 43 to 100%). Consequently, these results have been included in the data summary along with the short-term results, giving a total of 56 uniaxial compression strength (UCS) results. Results are summarized in Figure 5.19 for each specimen in terms of peak uniaxial compressive strength (UCS), the percentages of UCS at which crack initiation and crack damage, respectively, occurred, and the Modulus of Elasticity and Poisson's Ratio values measured at 40% of UCS.

Figure 5.20 summarizes data from the Point Load Tests that were conducted on core recovered from the MS-4 Unit. The axial tests gave consistent results with the $PLT \sim 3.75 \text{ MPa}$, and the ratio of diametral to axial results indicates a very low degree of anisotropy.

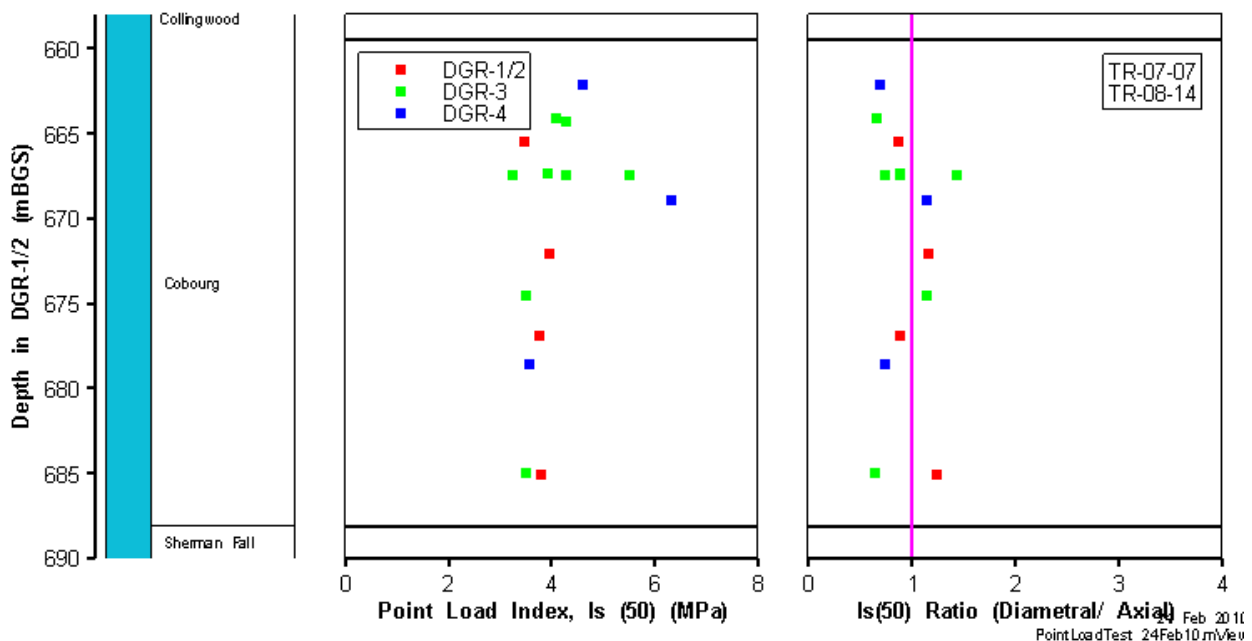


Figure 5.20 MS-4: point load test data

As indicated in Figures 5.19 and 5.20., uniaxial compression test results indicate that the compression parameters display relatively little variability, except for a few outliers. Table 5.12 summarizes the uniaxial compression parameters for the MS-4 Unit rock materials. Due to the large number of compression test results available from the MS-4 Unit (56), the results have been summarized in terms of their mean and standard deviation values.

Table 5.12 MS-4: geomechanical parameters in uniaxial compression (Note: includes results from long-term strength degradation tests)

<i>Parameter</i>	<i>Mean</i>	<i>Std Deviation</i>
Peak UCS (all tests)	114 MPa	26 MPa
Crack Initiation	40% (UCS)	10% (UCS)
Crack Damage	86% (UCS)	23% (UCS)
Modulus of Elasticity (E_{40})	39 GPa	7 GPa
Poisson's Ratio	0.30	0.08
PLT Strength Anisotropy (Diametral/Axial)	Low	Minor scatter
Long-Term Strength Tests (Peak after 100 days)	124 MPa	-

Figure 5.21 below shows the relationship between the peak uniaxial compressive strength data gathered from throughout the region as part of the Phase 1 Regional Geomechanics Report, (Gartner Lee Limited, 2008c), and the Phase 1 and 2A data from the Bruce nuclear site. The figure indicates that the site specific data lies at the upper range of the regional data. In part, this may reflect the rigorous quality control procedures and the state of the art testing procedures utilized for handling of the core samples from the DGR site, or the fact that most regional data are obtained from shallow depths where weathering and stress relief act to decrease rock strengths.

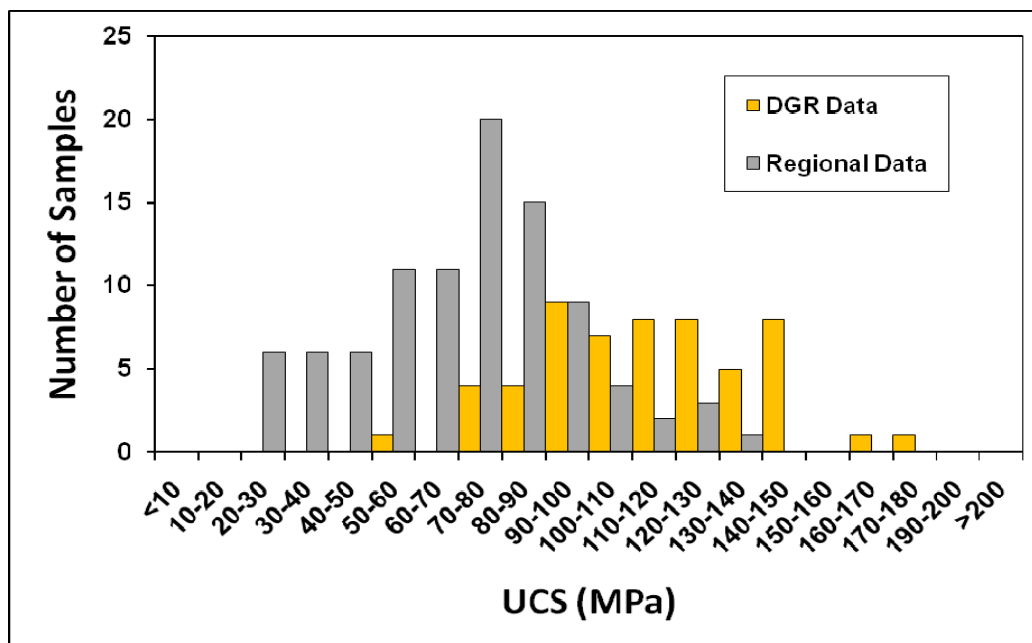


Figure 5.21 MS-4: peak uniaxial compressive strength (UCS) - site specific and regional data

5.8.1.2 Cross-Anisotropic Uniaxial Compression

In order to obtain some comparison of compressive strength parallel and perpendicular to bedding,, two core samples were sub-cored at 90 degrees to the borehole axis (one each from DGR-3 and 4) and tested in uniaxial compression (TR-08-24). The core from DGR-3 (at 678.7.mBGS) indicated that UCS parallel to bedding was 60% of the UCS perpendicular to bedding (87.6 MPa vs 144.0 MPa). However, the core from DGR-4 (at 671.7 mBGS) indicated no change in strength relative to bedding direction (148.9 MPa vs 148.7 MPa). As bedding planes are generally poorly expressed in this unit, it is anticipated that UCS values generally will not be strongly directionally dependent. This conclusion is supported by the Point Load Test results, which also indicate a very low level of strength anisotropy (Figure 5.20).

5.8.1.3 Triaxial Compression

Twelve core samples from the Lower Cobourg unit were tested under triaxial confinement ranging from 7.5 – 30 MPa.

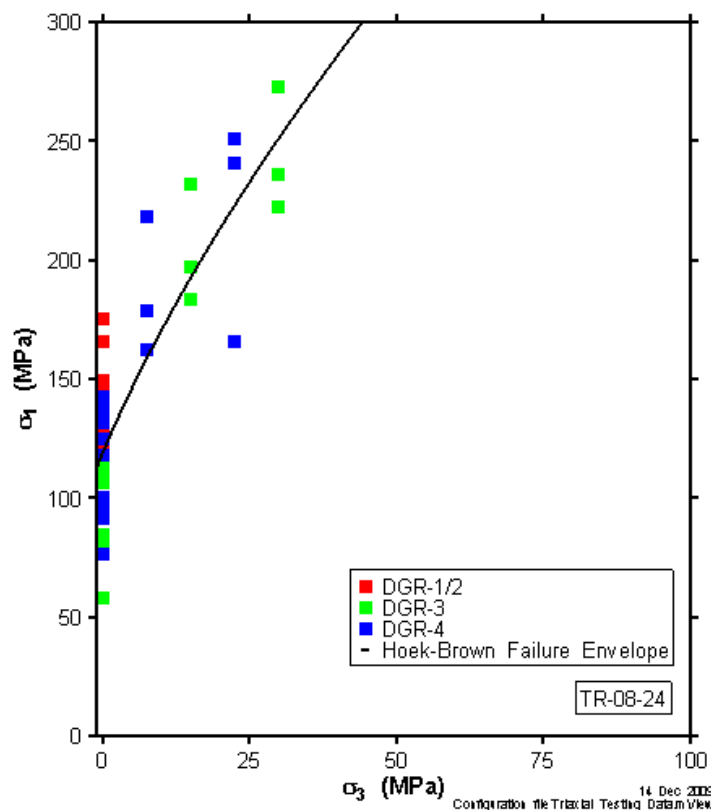


Figure 5.22 MS-4: triaxial compression test data for Cobourg Formation

The results are shown in Figure 5.22, which includes the best-fit Hoek-Brown envelope for the data, and indicates the following Hoek-Brown parameters for the intact rock.

- $\sigma_c = 120$ MPa
- $m_i = 10.0$
- $s = 1.0$

- $a = 0.5$

5.8.1.4 Tension

Nine valid indirect tension tests (Brazilian tests) were conducted on core from MS-4. The results (Figure 5.23) give a mean value of the estimated tensile strength of ~6.4 MPa.

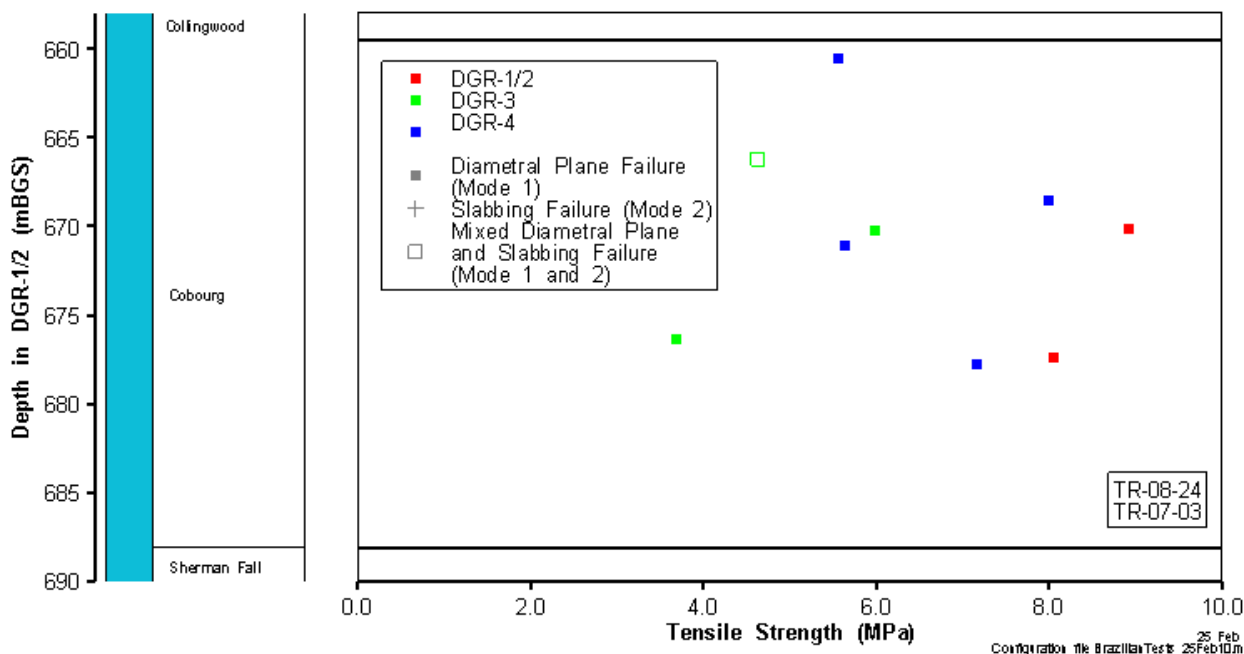


Figure 5.23 MS-4: Brazilian tests – indirect tensile strength data

5.8.1.5 Shear

Direct shear tests were run on 12 samples of intact rock from the Lower Member of the Cobourg Formation. Peak shear strength parallel to bedding was first determined prior to running staged shear tests at increasing normal stress levels to determine the residual strength parameters. Results are summarized in Figure 5.24.

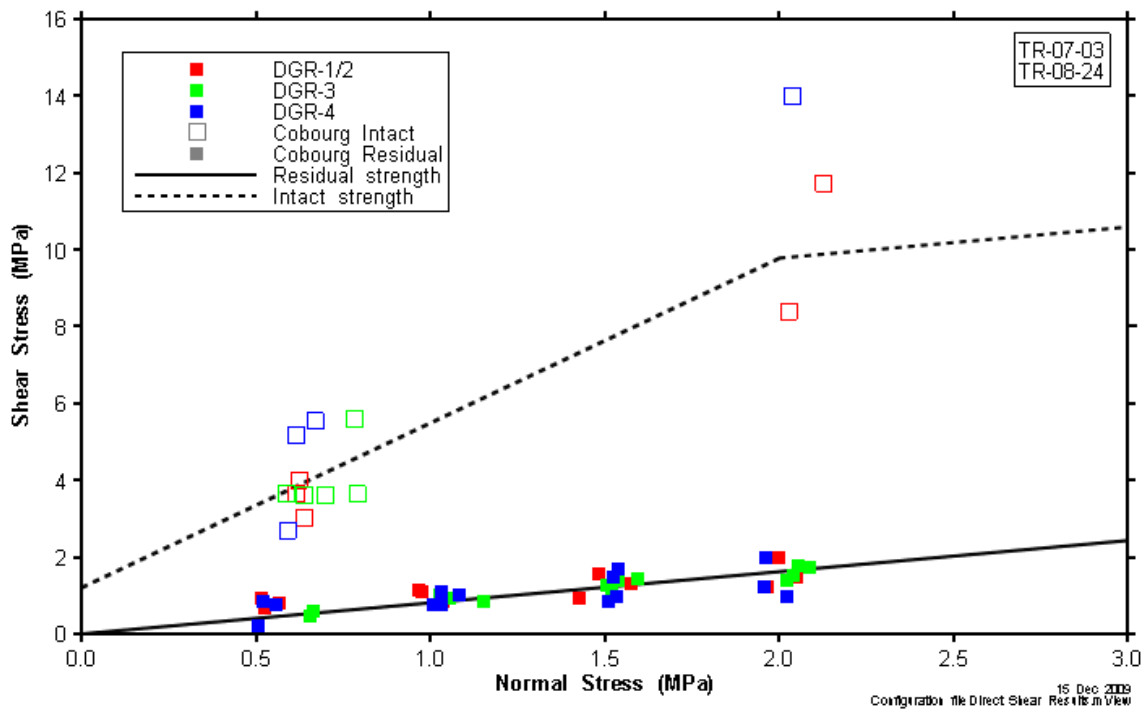


Figure 5.24 MS-4: direct shear test results for Cobourg Formation

For residual shear strength, based on the best-fit line through the test data, the proposed estimated values of the shear strength parameters are:

- residual cohesion = 0 MPa, and
- residual friction angle = 39 degrees.

Residual shear strength envelope: $\tau_r = \sigma_n(\tan 39^\circ)$, MPa, where:

- τ_r = residual shear strength, and
- σ_n = normal stress

As discussed in Section 5.7.1.5 (MS-3 Unit), data regarding peak shear strength of the intact material only extends to normal stresses of approximately 2 MPa. Within this range of relatively low normal stress, the data indicate a high apparent friction angle, due to the geometric effect of asperities along the freshly formed shear plane. As normal stresses increase, apparent friction will decrease and apparent cohesion will increase as the effect of the asperities changes from contributing to apparent friction to adding to apparent cohesion. For this reason, a bi-linear shear strength envelope is proposed for the peak shear strength of these intact materials. At normal stresses below 2 MPa, the best fit line to the test data is utilized to evaluate apparent cohesion and friction. At normal stresses above 2 MPa, it is conservatively assumed that the friction angle becomes equal to the residual friction angle noted above.

For normal stresses (σ_n) in the range: $0 < \sigma_n < 2 \text{ MPa}$:

- apparent cohesion intercept = 1.2 MPa,
- apparent friction angle = 75 degrees, and
- peak shear strength envelope: $\tau_p = 1.2 + \sigma_n(\tan 75^\circ)$, MPa.

For normal stresses (σ_n) greater than 2 MPa:

- apparent cohesion = 8.7 MPa,
- apparent friction angle = 39 degrees, and
- peak shear strength envelope: $\tau_p = 8.7 + \sigma_n(\tan 39^\circ)$, MPa.

5.8.1.6 Slake Durability

Two slake durability tests were conducted on samples from the MS-4 Units that appeared to be somewhat argillaceous. Neither sample indicated any significant sensitivity to slaking degradation, as indicated below in Figure 5.25.

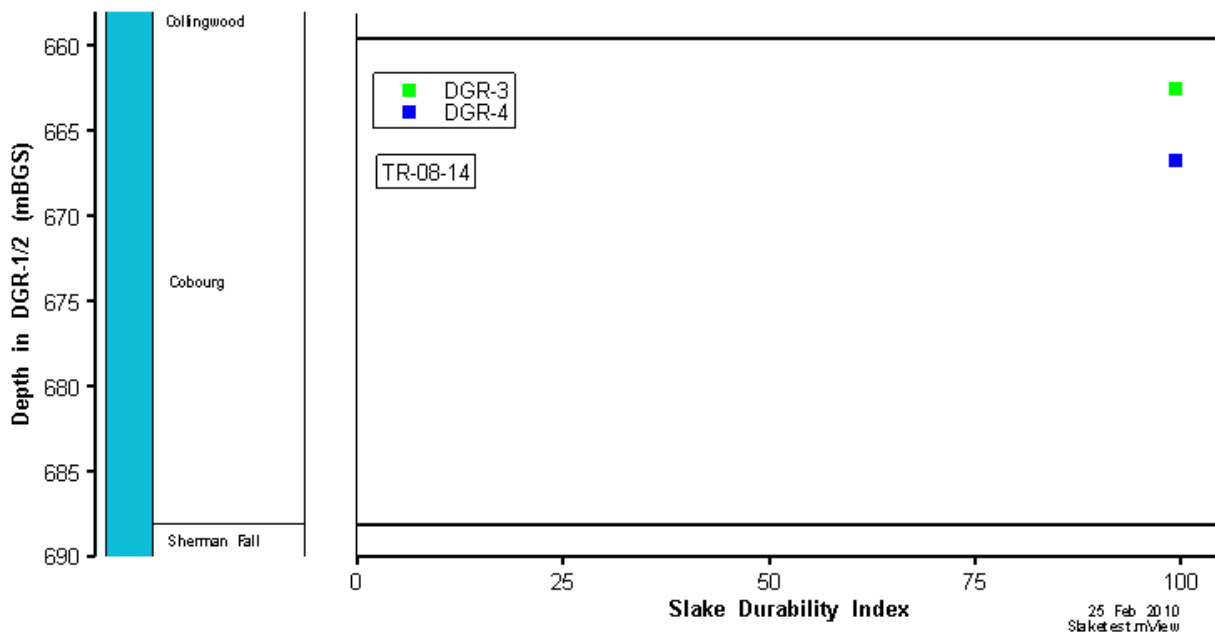


Figure 5.25 MS-4: slake durability index data

5.8.1.7 Swelling Potential

Four tests of swelling potential were conducted on MS-4 Unit rocks during the Phase 1 investigation (DGR-2), two in fresh and two in formation water, respectively. The vertical and the horizontal swelling potentials were zero for all tests. No further tests were conducted during Phase 2A (DGR-3 and DGR-4).

5.8.1.8 Abrasiveness

A series of abrasivity tests were performed on samples from the Lower Member of the Cobourg Formation (MS-4) as well as within the lower part of the Collingwood Member of the Cobourg Formation. Details are reported in TR-07-04 and TR-08-25. Testing was based on the standard CERCHAR scratch test (Plinninger et al, 2003) with the results expressed as CERCHAR Abrasivity Index for the smooth surfaces tested (CAI_s). Results, which are shown in Figure 5.26, indicate that the materials would be classified as displaying slight to medium abrasivity with average CERCHAR Abrasivity Index on smooth (saw-cut) surfaces of approximately 0.85. As noted in TR-08-25, these results are consistent with typical values reported in the literature for limestone and marlstone.

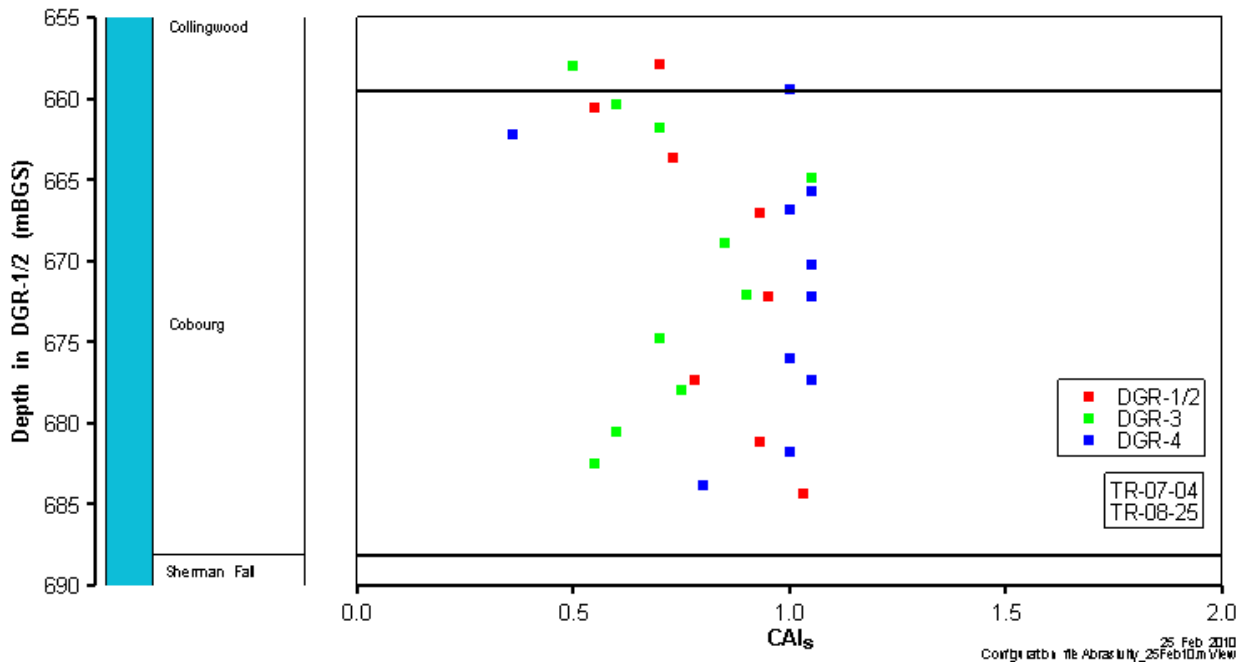


Figure 5.26 MS-4: CERCHAR abrasivity index data

5.8.1.9 Dynamic Properties

Compression wave (P-wave) and shear wave (S-wave) ultrasonic pulse velocities were measured on intact core samples in the field (TR-07-07, TR-08-14)) and in the laboratory (TR-07-03, TR-08-24), from which dynamic elastic constants were calculated for the rock material. As is commonly the case, field and laboratory results show differences, possibly due to factors such as sample disturbance during shipping. Based on overall review of the data, Table 5.13 summarizes estimated values for the dynamic properties.

Table 5.13 MS-4: estimated rock material dynamic properties

<i>Parameter</i>	<i>Estimated Value</i>
P-wave Velocity	5.3 km/s
S-wave Velocity	2.7 km/s
Dynamic Modulus of Elasticity	55 GPa
Dynamic Shear Modulus	21 GPa
Dynamic Poisson's Ratio	0.31

5.8.2 Rock Mass Geomechanical Characteristics

Access for geomechanical mapping of the rock mass beneath the Bruce nuclear site was not available during the Phase 1 and 2A site investigations. Consequently, information regarding the characteristics of the overall rock mass has been derived only from the relatively small diameter, one-dimensional penetrations provided by the DGR boreholes, and the resulting core. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns (discontinuities) within the mass, information on the overall rock mass characteristics is limited at the current stage.

5.8.2.1 Rock Quality Designation (RQD) and Fracture Frequency

Measurements of Rock Mass Quality Designation (RQD) and fracture frequency were conducted routinely throughout the drilling of DGR boreholes, as reported in Section 3.5 and summarized in Table 3.3 and Figures 3.2 and 3.3. Core recovery and RQD values throughout the MS-4 Unit were excellent (see Figure 3.35) and fracture frequency measurements indicated a very sparsely fractured rock mass. Based on these borehole-derived measurements, the rock mass comprising the MS-4 Unit can be characterized as *very sparsely fractured* and of *excellent quality*.

5.8.2.2 Bulk Properties from Geophysical Logging

Elastic dynamic properties of a bulk in-situ sample of the rock mass are derived from downhole sonic logging. A uniform wet bulk density of 2.63 g/cm³ (Figure 4.1) was used in all modulus calculations. Results are summarized in Table 5.14 for various depth intervals within the MS-4 Unit.

Table 5.14 MS-4: estimated rock mass dynamic properties

<i>Formation</i>	<i>Depth Range (mBGS)</i>	<i>V_p (m/s)</i>	<i>V_s (m/s)</i>	<i>E_d (GPa)</i>	<i>G_d (GPa)</i>
Cobourg (Lower Member)	659.50 – 686.49	5640	2850	57.9	21.8

5.8.2.3 Rock Mass Classification

Rock mass classification systems in common usage for geomechanics purposes include Bieniawski's Rock Mass Rating (RMR) system, Barton's (1974) Tunneling Quality Index (Q-system), and Hoek's Geological Strength Index (GSI). Subsurface data obtained from the single deep borehole location in the Phase 1 investigations are not sufficient to provide reliable or complete estimates of all the parameter values required to determine the classification categories under these systems. Preliminary descriptive comments regarding rock mass quality are included under Section 5.8.2.1 above, based on the limited parameters of Rock Quality Designation (RQD) and one-dimensional

fracture frequency.

5.9 MS Unit 5: Middle Ordovician Sherman Fall and Deeper Formations

The MS-5 Unit (688.1 to 860.7 mBGS in DGR-2) comprises all rock units lying beneath the repository horizon, to the bottom of each deep exploratory DGR borehole (Figure 5.1). Within MS-5, approximately 150 m of limestone lie immediately below the repository horizon. Of these rocks, the principal unit of interest from a geotechnical perspective is the 28.0 to 29.0 m thick Sherman Fall Formation located directly beneath the repository horizon. Towards the base of MS-5, Cambrian sandstones lie immediately above the Precambrian granitic gneiss.

Geotechnically, the formations below the Sherman Fall are of little interest to the design or performance of the DGR. Consequently, the limited laboratory data obtained within MS-5 is focussed almost exclusively on the upper zone of the unit, in the Sherman Fall Formation (688.1 to 716.1 mBGS in DGR-2).

5.9.1 Rock Material Geomechanical Characteristics

5.9.1.1 Uniaxial Compression

Nine uniaxial compression tests were conducted on samples recovered from the Sherman Fall Formation, and three on samples within the Kirkfield Formation. Key results are summarized in Figure 5.27 for each specimen in terms of peak uniaxial compressive strength (UCS), the percentage of UCS at which crack initiation and crack damage occurred, and the Modulus of Elasticity and Poisson's Ratio values (measured at 40% of UCS).

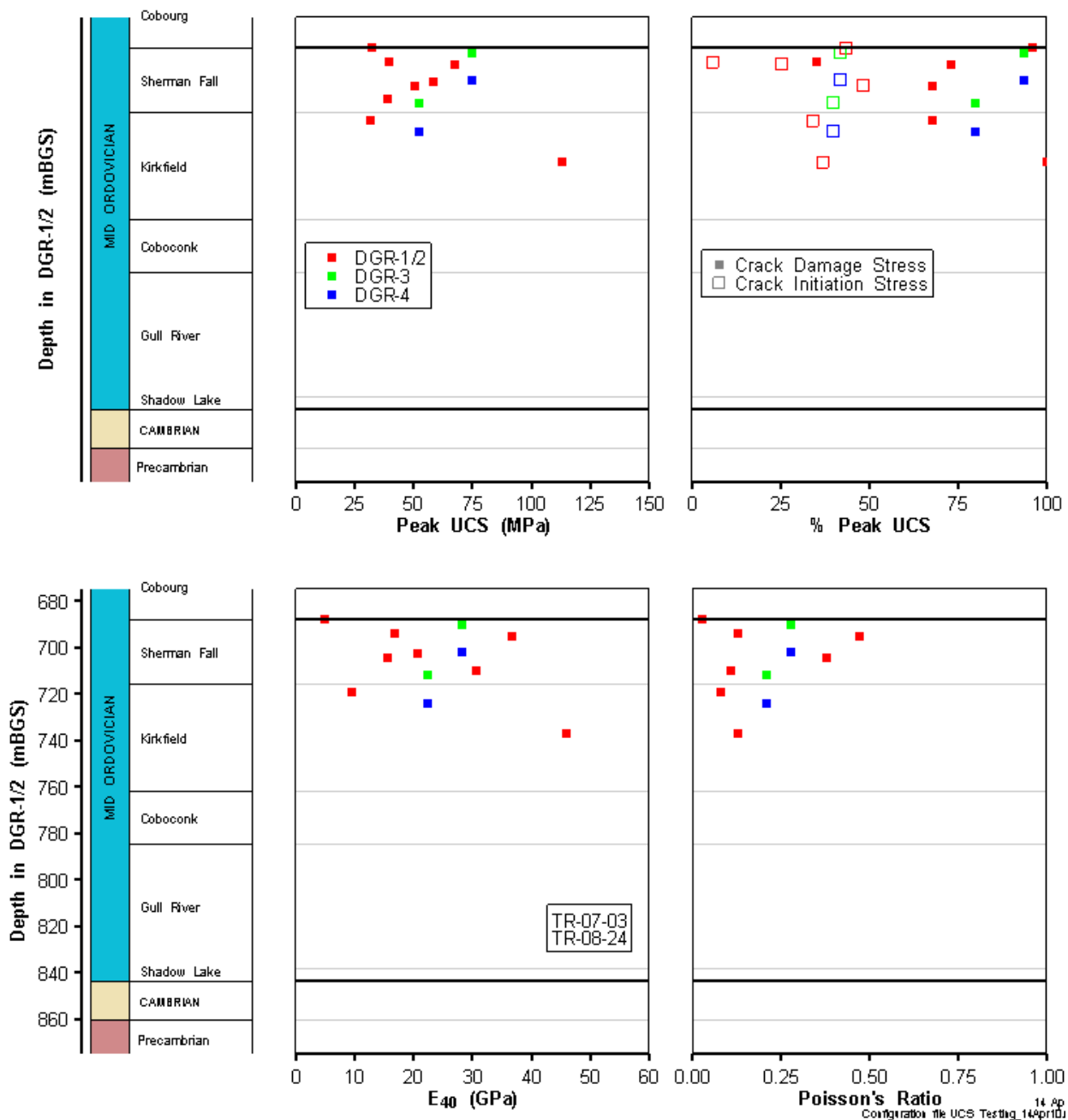


Figure 5.27 MS-5: uniaxial compression test data

Figure 5.27 summarizes data from the Point Load Tests (PLT) that were conducted on core recovered from the MS-5 Unit. Table 5.15 summarizes estimated uniaxial compression parameters for only the Sherman Fall and Kirkfield Formations of the MS-5 Unit, as laboratory data are not available for other formations.

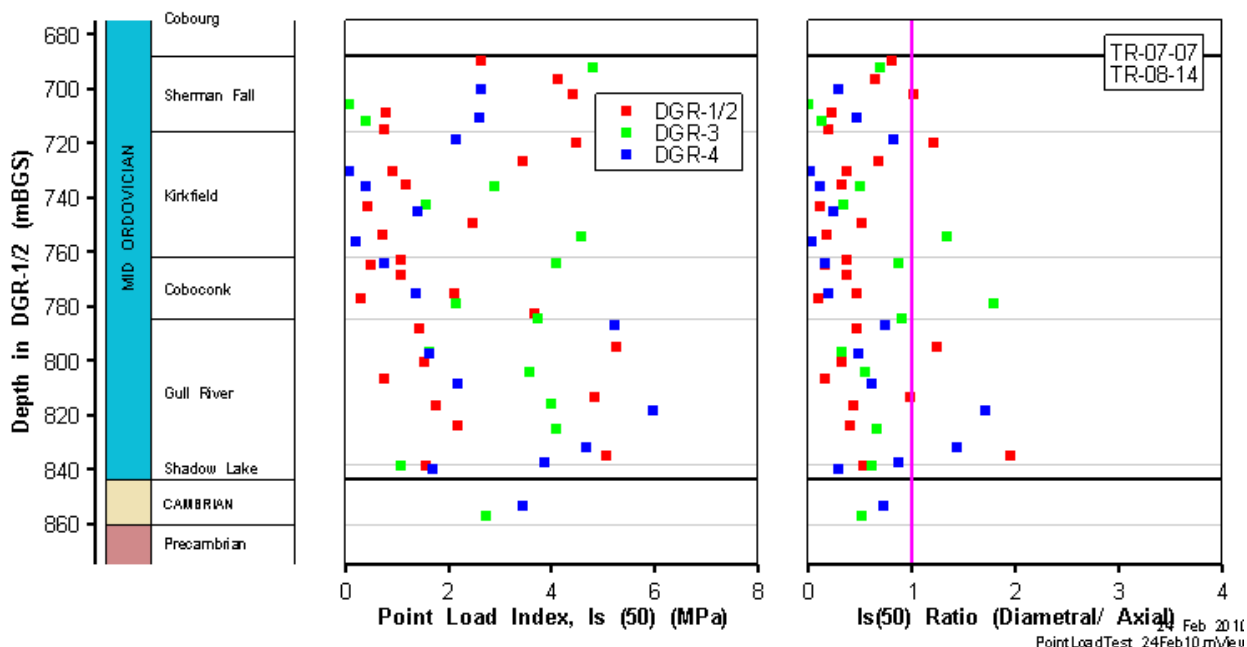


Figure 5.28 MS-5: point load test data

Table 5.15 MS-5 (Sherman Fall and Kirkfield Formations): estimated geomechanical parameters in uniaxial compression

Parameter	Mean	Range	Estimate
Peak UCS	55 MPa	32 - 113 MPa	45 MPa
Crack Initiation	35% (UCS)	6 – 48%%(UCS)	25%(UCS)
Crack Damage	73% (UCS)	35 - 100% (UCS)	~65%(UCS)
Modulus of Elasticity (E_{40})	24 GPa	5 – 46 GPa	15 GPa
Poisson's Ratio	0.21	0.03 – 0.47	0.25
PLT Strength Anisotropy throughout MS-5. (Diametral/Axial)	High	0.1 – 2.0	~0.4
Long-Term Strength	No data	No data	No data

The data show that the Sherman Fall and Kirkfield Formation materials have a peak (mean) UCS of approximately 45 MPa, and are therefore significantly weaker than the overlying rocks of the Cobourg Formation which hosts the DGR (mean UCS ~125 MPa). The crack initiation stress levels are less predictable in these materials as a percent of UCS than in MS-4 materials, and the elastic modulus shows much greater variation. These measures indicate a relatively weak and variable material in contrast to the limestone in the repository host rock horizon (Lower Cobourg). Throughout the 150 m of limestones in MS-5, the point load test (PLT) data show also considerable scatter, ranging from 0.3 to 6.0. In general, significant strength anisotropy is indicated, with diametral PLT generally less than 1/3 of the axial PLT.

5.9.1.2 Tension

A total of six indirect (Brazilian) tension tests were conducted on rock cores from the Sherman Fall Formation, five of which resulted in mixed-mode failure as shown in Figure 5.29. With one exception, results were relatively consistent, indicating indirect tensile strength for the intact material of approximately 4 MPa.

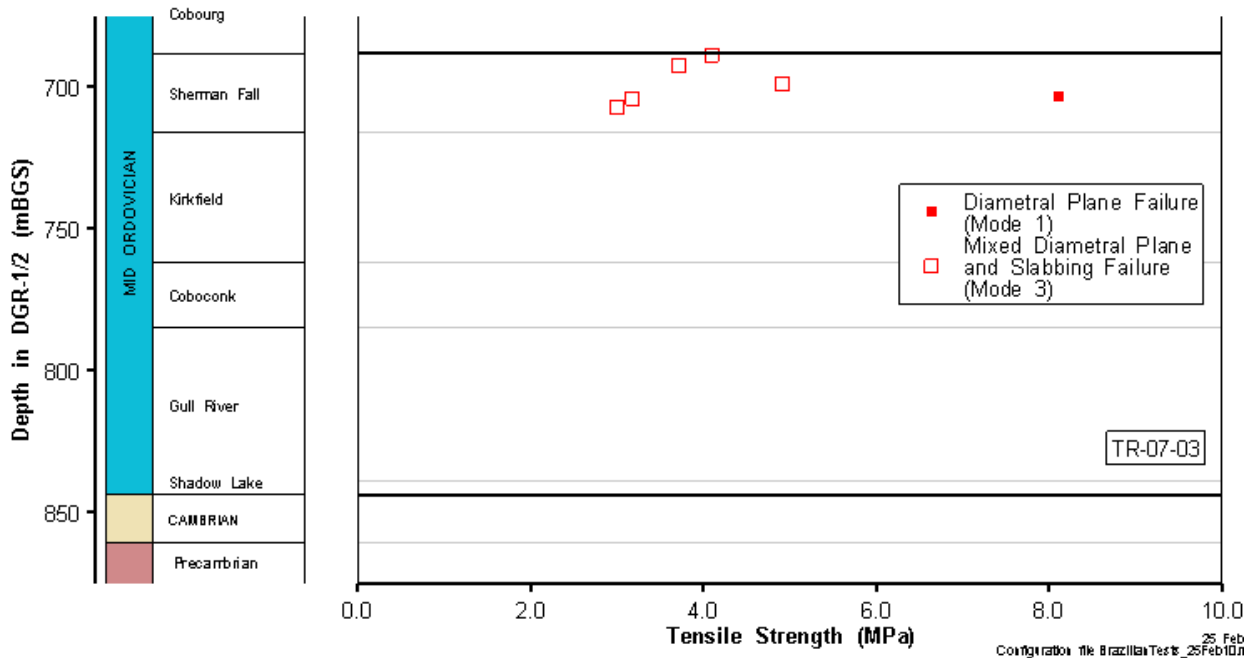


Figure 5.29 MS-5: Brazilian tests - indirect tensile strength data

5.9.1.3 Shear

Results from five direct shear tests on core samples from the Sherman Fall Formation, two of which were intact, are summarized in Figure 5.30. Peak shear strength parallel to bedding was determined for the two intact samples, and staged shear tests were conducted on all samples to evaluate residual shear strength parameters.

The best-fit line for the residual shear strength indicates zero apparent cohesion, but a relatively high residual friction angle of ~42 degrees. These data suggest that while there is little or no cohesion along the bedding planes in this argillaceous limestone formation, there may be a significant geometric component to the apparent residual friction angle due to waviness of the bedding planes. Under conditions of higher normal stress, the residual friction angle may decrease, with a related increase in the apparent cohesion. Estimate residual shear strength parameters for normal stresses within the testing range are:

- apparent cohesion = 0 MPa, and
- residual friction angle = 40 degrees.

For the intact samples, tested under a normal stress of ~1MPa, a cohesion value of ~3 MPa appears reasonable. Test data for intact shear strength are too limited to allow a separate best-fit envelope to be determined for peak shear strength. For purposes of this DGSM report, it has been conservatively assumed that the angle of internal friction is equal to the residual angle noted above, with a cohesion intercept of 3MPa, giving an estimated peak shear strength envelope of:

- peak shear strength envelope: $\tau_p = 3.0 + \sigma_n(\tan 40^\circ)$, MPa.

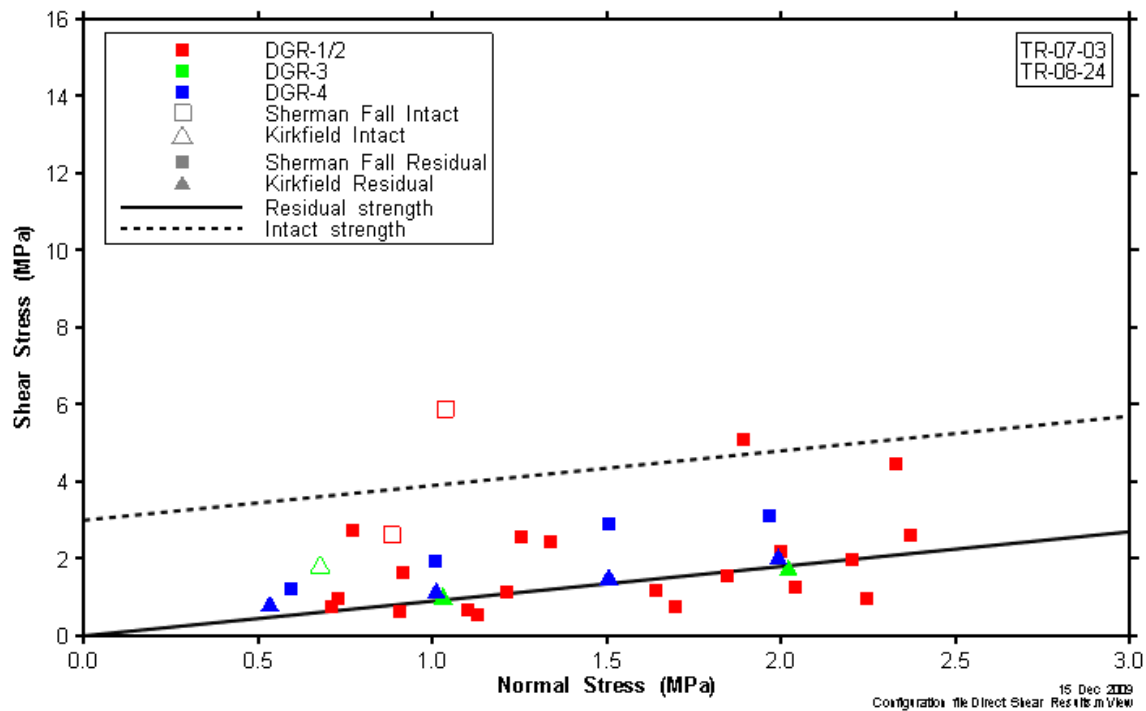


Figure 5.30 MS-5: direct shear test results for Sherman Fall and Kirkfield Formations

5.9.1.4 Slake Durability

Six samples from within MS-5 were selected for slake durability testing. The results, summarized in Figure 5.31 indicate minor to negligible susceptibility to slaking degradation.

In the Sherman Fall Formation, the slake durability index (SDI) value was approximately 85%, whereas in the lower units beneath the Sherman Fall, the SDI was close to 100%.

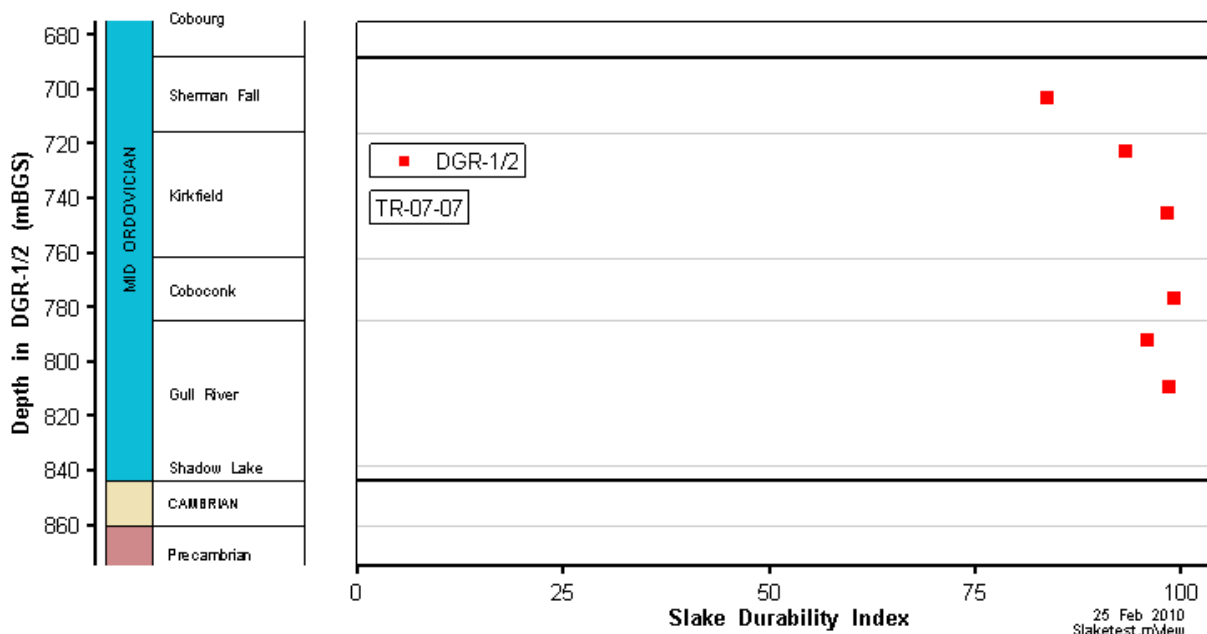


Figure 5.31 MS-5: slake durability index

5.9.1.5 Swelling Potential

Single swelling potential tests were conducted on Sherman Fall rock material in fresh water and in formation water respectively. Swelling potential was observed to be zero in both cases.

5.9.1.6 Abrasiveness

No data were obtained regarding abrasivity of rock materials in MS-5 as part of Phase 1 and 2A site investigations.

5.9.1.7 Dynamic Properties

There are relatively few data available regarding dynamic elastic properties based on ultrasonic pulse velocity testing of intact core samples from the MS-5 unit. Eight core samples from the Sherman Fall Formation were tested in the CANMET laboratory (TR-07-03), and 10 core samples from the deeper Gull River Formation were tested in the field. Based on overall review of the data, estimated values are given in Table 5.16 for rock material from these two formations.

Table 5.16 MS-5: estimated rock material dynamic properties

<i>Parameter</i>	<i>Estimated Value</i>
P-wave Velocity	4.5 km/s
S-wave Velocity	2.3 km/s
Dynamic Modulus of Elasticity	38 GPa
Dynamic Shear Modulus	15 GPa
Dynamic Poisson's Ratio	0.31

5.9.2 Rock Mass Geomechanical Characteristics

Access for geomechanical mapping of the rock mass beneath the Bruce nuclear site was not available during the Phase 1 and 2A site investigations. Consequently, information regarding the characteristics of the overall rock mass has been derived only from the relatively small diameter, one-dimensional penetrations provided by the DGR boreholes, and the resulting core. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns (discontinuities) within the mass, information on the overall rock mass characteristics is limited at the current stage.

5.9.2.1 Rock Quality Designation (RQD) and Fracture Frequency

Measurements of Rock Mass Quality Designation (RQD) and fracture frequency were conducted routinely throughout the drilling of DGR boreholes as reported in Section 3.5 and summarized in Table 3.3 and Figures 3.2 and 3.3. Core recovery and RQD values throughout the MS-5 Unit were generally excellent, with the exception of some local zones in the Sherman Fall Formation where the RQD dropped to as low as 25 % over a short section in DGR-2 due to core grinding during drilling. Fracture frequency measurements indicated a generally very sparsely fractured rock mass, with the exception of the deep lying Cambrian sandstone, which appeared to be sparsely to moderately fractured. Based on these borehole-derived measurements, the overall rock mass comprising the MS-5 Unit can be characterized as *very sparsely fractured* and of *excellent quality*. However, it is noted that minor local zones of lower quality may occur in the Sherman Fall Formation.

5.9.2.2 Bulk Properties from Geophysical Logging

Elastic dynamic properties of a bulk in-situ sample of the rock mass are derived from downhole sonic logging. A uniform bulk density of 2.63 g/cm³ (Figure 4.1) was used in all modulus calculations. Results are summarized in Table 5.17 for various depth intervals within the MS-5 Unit.

Table 5.17 MS-5: estimated rock mass dynamic properties

Formation	Depth Range (mBGS)	V_p (m/s)	V_s (m/s)	E_d (GPa)	G_d (GPa)
Sherman Fall, Kirkfield	688.10 – 731.99	5280	2760	51.6	19.5
Kirkfield	732.00 – 761.99	5150	2660	49.8	18.9
Coboconk	762.00 – 768.62	5750	3160	68.7	26.8
Coboconk	768.63 – 778.74	6380	3380	69.6	30.7
Coboconk, Gull River	778.75 – 843.69	5740	3080	65.7	25.3

5.9.2.3 Rock Mass Classification

Rock mass classification systems in common usage for geomechanics purposes include Bieniawski's Rock Mass Rating (RMR) system, Barton's (1974) Tunneling Quality Index (Q-system), and Hoek's Geological Strength Index (GSI). Subsurface data obtained from the single deep borehole location in the Phase 1 investigations are not sufficient to provide reliable or complete estimates of all the parameter values required to determine the classification categories under these systems. Preliminary descriptive comments regarding rock mass quality are included under Section 5.9.2.1 above, based on the limited parameters of Rock Quality Designation (RQD) and one-dimensional fracture frequency.

5.10 Recommended Estimates of Descriptive Geomechanical Model Properties

Tables 5.18, 5.19 and 5.20 summarize the recommended estimates of the main geomechanical properties of the 34 layers that comprise the descriptive geomechanical model for the Bruce DGR site. The descriptive geomechanical model includes the 36 model layers that comprise the descriptive geological model minus the overburden and Precambrian layers. However for some model layers (i.e., those below the Kirkfield Formation) there is very limited to no geomechanical data available as these layers are deeper than planned excavation. Data given in Tables 5.18, 5.19 and 5.20 are consistent with and provide a more detailed summary description of the geomechanical information given in Sections 5.5 to 5.9 on the five mechano-stratigraphic units that represent the Bruce DGR site.

Table 5.18 Recommended estimates of uniaxial compression strength properties of geomechanical model layers

<i>Model Layer</i>	<i>Peak UCS (MPa)</i>	<i>Crack Initiation (% UCS)</i>	<i>Crack Damage (% UCS)</i>	<i>Modulus of Elasticity (GPa)</i>	<i>Poisson's Ratio (-)</i>	<i>PLT Anisotropy (Dia/Axial)</i>
Lucas	98	40	76	50	0.20	1.0
Amherstburg	98	40	76	28	0.20	1.0
Bois Blanc	94	41	87	37	0.20	1.0
Bass Islands	48	39	32	20	0.50	0.95
Salina G Unit	34	40	50	16	0.23	1.0
Salina F Unit	30	42	95	12	0.20	0.70
Salina E Unit	-	-	-	-	-	0.65
Salina D Unit	-	-	-	-	-	1.0
Salina C Unit	20	38	68	9	0.20	0.70
Salina B Unit dolostone	8	32	44	3	0.40	0.55
Salina B Unit anhydrite	-	-	-	-	-	-
Salina A2 Unit dolostone	60	45	80	23	0.20	0.85
Salina A2 Unit evaporite	-	-	-	-	-	0.55
Salina A1 Unit dolostone	117	40	90	40	0.15	0.40
Salina A1 Unit evaporite	-	-	-	-	-	0.35
Salina A0 Unit	198	41	63	63	0.43	1.0
Guelph	60	40	72	28	0.30	0.80
Goat Island	148	39	81	37	0.37	0.90
Gasport	-	-	-	-	-	0.95
Lions Head	-	-	-	-	-	0.95
Fossil Hill	-	-	-	-	-	0.50
Cabot Head	13	42	60	4	0.38	0.55
Manitoulin	70	50	63	24	0.45	0.35
Queenston	48	40	68	15	0.31	0.60
Georgian Bay	41	42	77	11	0.22	0.50
Blue Mountain	22	38	87	10	0.10	0.55
Cobourg – Collingwood Member	107	40	86	5	0.22	1.0
Cobourg - Lower	114	41	83	39	0.30	0.95
Sherman Fall	54	35	77	23	0.24	0.45
Kirkfield	66	37	83	26	0.15	0.45
- Not measured or not determined						

Table 5.18 summarizes the estimates of strength properties of intact core from each model layer based on uniaxial compression testing (TR-07-03, TR-08-24, TR-08-39), including some long-term strength testing results (TR-08-11, TR-08-36). Table 5.18 lists estimates of peak uniaxial compression strength (UCS), crack initiation and crack damage stress (as a percentage of peak UCS), modulus of elasticity (E_{40}), Poisson's ratio and estimates of strength anisotropy based on results of diametral and axial point load testing (PLT) based on arithmetic averages of these parameters. No uniaxial strength data are available for model layers below the Kirkfield Formation and for several thin units (Salina E, D, B anhydrite, A2 evaporite and A1 evaporite) and formations (Gasport, Lions Head and Fossil Hill).

Table 5.19 Recommended estimates of slaking, swelling and abrasivity properties of geomechanical model layers

<i>Model Layer</i>	<i>Slake Durability Index (%)</i>	<i>Fresh Water Swelling Potential (% per log cycle)</i>		<i>CERCHAR Abrasivity Index – Smooth Surfaces</i>
		<i>Vertical</i>	<i>Horizontal</i>	
Lucas	-	-	-	-
Amherstburg	100	-	-	-
Bois Blanc	-	-	-	-
Bass Islands	95	-	-	-
Salina G Unit	50	-	-	-
Salina F Unit	80	1.5	0.5	-
Salina E Unit	-	-	-	-
Salina D Unit	55	-	-	-
Salina C Unit	-	1.0	0.4	-
Salina B Unit dolostone	-	-	-	-
Salina B Unit anhydrite	-	-	-	-
Salina A2 Unit dolostone	-	-	-	-
Salina A2 Unit evaporite	-	-	-	-
Salina A1 Unit dolostone	-	-	-	-
Salina A1 Unit evaporite	--	-	-	-
Salina A0 Unit	-	-	-	-
Guelph	-	-	-	-
Goat Island	-	-	-	-
Gasport	-	-	-	-
Lions Head	-	-	-	-
Fossil Hill	-	-	-	-
Cabot Head	75	2.0	0.6	-
Manitoulin	-	-	-	-
Queenston	90	0.3	0.1	-
Georgian Bay	75	1.0	0.3	-
Blue Mountain	90	1.0	0.15	-
Cobourg – Collingwood Member	95	-	-	0.6
Cobourg - Lower	100	0	0	0.85
Sherman Fall	85	0	0	-
Kirkfield	90	-	-	-
- Not measured or not determined				

Table 5.20 Recommended estimates of rock mass quality, natural fracture frequency and dynamic moduli properties of geomechanical model layers

<i>Model Layer</i>	<i>RQD (%)</i>	<i>Natural Fracture Frequency (m⁻¹)</i>	<i>Dynamic Modulus of Elasticity (GPa)</i>	<i>Dynamic Shear Modulus (GPa)</i>
Lucas	47	5.4	36.7	13.5
Amherstburg	47	5.4	33.9	19.8
Bois Blanc	68	3.6	45.4	18.9
Bass Islands	33	2.7	46.0	19.3
Salina G Unit	54	3.8	28.3	11.1
Salina F Unit	92	1.1	35.3	14.3
Salina E Unit	98	0.6	47.4	18.4
Salina D Unit	100	0.3	27.5	16.5
Salina C Unit	100	0.3	27.5	16.5
Salina B Unit dolostone	100	0.1	31.4	12.1
Salina B Unit anhydrite	100	0.1	31.4	23.2
Salina A2 Unit dolostone	99	0.2	38.7	15.2
Salina A2 Unit evaporite	99	0.2	38.7	15.2
Salina A1 Unit dolostone	100	0.2	53.2	20.7
Salina A1 Unit evaporite	100	0.2	54.8	24.0
Salina A0 Unit	100	0.2	51.7	19.9
Guelph	100	0.3	51.7	19.9
Goat Island	100	0.3	51.7	19.9
Gasport	100	0.3	57.3	21.8
Lions Head	100	0.3	60.9	23.1
Fossil Hill	100	0.3	60.9	23.1
Cabot Head	100	0.1	31.2	12.4
Manitoulin	99	0.1	54.8	21.5
Queenston	97	0.3	33.7	12.9
Georgian Bay	97	0.1	27.6	10.8
Blue Mountain	100	0.1	17.5	19.2
Cobourg – Collingwood Member	100	0.2	44.3	16.7
Cobourg - Lower	100	0.2	57.9	21.8
Sherman Fall	100	0.3	51.6	19.5
Kirkfield	98	0.6	49.8	18.9
Coboconk	98	0.7	69.6	30.7
Gull River	100	0.3	65.7	25.3
Shadow Lake	99	0.3	65.7	25.3
Cambrian	99	1.7	-	-
- Not measured or not determined				

Table 5.19 summarizes the estimates of slaking, swelling and abrasivity properties of each model layer, where such data are available. Estimates of slaking potential are presented as slake durability indices based on field testing (TR- 07-07, TR-08-14) of layers with abundant sheet silicates or clays. Estimates of swelling potential are presented as vertical and horizontal swelling in fresh water in % per log cycle (TR-07-16, TR-08-26) for major shale-containing layers. Estimates of rock abrasivity are presented only for the Collingwood Member and the Cobourg Formation as CERCHAR abrasivity

indices for smooth surfaces (TR-07-04, TR-08-25).

Table 5.20 summarizes the estimates of rock mass geomechanical properties each layer of the geomechanical site model. Table 5.20 provides estimates of rock quality as RQD and natural fracture frequency from Table 3.3 based on core logging (TR-07-06, TR-08-13). Estimates in-situ rock mass dynamic elastic and shear moduli are given in Table 5.20 based on analysis of P-wave and S-wave velocities measured during borehole geophysical logging of DGR boreholes.

5.11 Confidence Assessment of Geomechanical Data and Model

Confidence in the descriptive geomechanical site model presented in Section 5 is assessed based on an evaluation of the quality and uncertainty in the key data that comprises the model, consistency of the data sets that comprise the model and consistency of the geomechanical model with other geoscientific models presented in Section 3 (descriptive geological site model) and Section 4 (descriptive hydrogeological site model).

The following key geomechanical data sets are subject to confidence assessment:

- In situ stresses
- Rock material strength properties
- Rock slaking properties
- Rock swelling properties
- Rock abrasivity properties
- Rock mass geomechanical properties

5.11.1 In Situ Stresses

Confidence in the reported in situ stresses of the model layers that comprise the descriptive geomechanical model is judged to be moderate to low. This assessment of confidence is due to the fact that in situ stresses have not been directly measured, rather they have been estimated based on compilation of regional stress measurement data, on geomechanical modeling, and on the observed lack of borehole breakouts in DGR boreholes based on certain assumptions concerning the long-term strength of the borehole walls.

Although confidence in the reported in situ stresses are moderate to low, these stress estimates represent the best available at this time. The fact that no rock failure has been observed in the boreholes, which represent “trial excavations”, provides empirical confidence that the in-situ stresses are moderate relative to the in-situ strength of the rock materials.

5.11.2 Rock Material Strength Properties

Confidence in the reported strength properties of intact rock material of the model layers that comprise the descriptive geomechanical model is judged to be moderate to high. All laboratory strength testing was completed by CANMET Mining and Mineral Science Laboratories following Standard Operating Procedures based on established ASTM testing procedures.

Strength testing was completed on core samples recovered from all DGR boreholes. Review of the strength data shows that there is no significant variation in strength properties between different DGR boreholes. Consequently, the reported strength properties are judged to be representative of conditions at the DGR site. In general the measured strength properties correlate well with expectations based on precedent data for similar lithologies.

For the majority of model layers where collection of intact rock cores suitable for laboratory testing was easily undertaken, the resulting strength parameters are of high quality. For those formations that were subject to extensive diskings of core that influenced the ability to collect intact core samples suitable for testing (e.g., parts of the Georgian Bay Formation, the Blue Mountain Formation and the Collingwood Member) the resultant strength properties may be biased towards stronger materials and hence overall confidence in the strength properties of these model layers is considered moderate.

5.11.3 Rock Slaking Properties

Confidence in the reported slaking properties of intact rock material of the model layers that comprise the descriptive geomechanical model is judged to be high. All slaking tests were completed in the field in accordance with ASTM testing and analysis procedures.

Slake durability testing was completed on samples collected from all DGR boreholes. Review of the slake durability test data shows that there is no discernable variation in slaking properties between different DGR boreholes. Consequently, the reported slaking properties are judged to be representative of conditions at the DGR site. In general the measured slaking properties correlate well with expectations based on precedent data for rock units with sheet silicate or clay contents.

5.11.4 Rock Swelling Properties

Confidence in the reported swelling properties of intact rock material of the model layers that comprise the descriptive geomechanical model is judged to be moderate to high. All laboratory swell testing was completed by K.Y. Lo Inc. following standard testing procedures that were pioneered by Dr. Lo in the late 1970s. These testing procedures have been routinely used in assessment of swelling potential of clay-rich rocks throughout Ontario. Swelling potential was originally assessed with both synthetic formation water and fresh water for DGR-2 core and later only in fresh water for DGR-3 and DGR-4 core due to lack of observed swelling with formation water.

Swell testing was completed on samples from all DGR boreholes. Review of the swelling test data shows that there is no discernable variation in swelling properties between different DGR boreholes. Consequently, the reported swelling properties are judged to be representative of conditions at the DGR site. In general the measured swelling properties correlate well with expectations based on precedent data on the reported calcite contents of different rocks.

Similar to rock strength testing, a high confidence rating is assigned to formations that did not show extensive diskings (i.e., Salina F Unit, Salina C Unit, Cabot Head, Queenston, Georgian Bay, Cobourg and Sherman Fall Formations) and hence allowed for sample preparation for swell testing. A moderate confidence assessment is provided for the swelling potential of the Blue Mountain shales due to the difficulties in maintaining sample integrity during sample preparation and swell testing.

5.11.5 Rock Abrasivity Properties

Confidence in the reported abrasivity properties of intact rock material of the Collingwood Member and Cobourg Formation is judged to be high. All laboratory abrasivity testing was completed by Mirarco/Geomechanics Research Centre, Laurentian University following the widely accepted and standard CERCHAR testing procedures.

Abrasivity testing was completed on samples from all DGR boreholes. Review of the abrasivity test data shows that there is no discernable variation in abrasivity properties between different DGR boreholes. Consequently, the reported abrasivity properties are judged to be representative of conditions at the DGR site.

5.11.6 Rock Mass Geomechanical Properties

Confidence in the reported rock mass geomechanical properties of the model layers that comprise the descriptive geomechanical model is judged to be moderate. The rock mass geomechanical properties considered here are rock quality, discontinuity characteristics and bulk elastic properties.

While currently available data on rock quality and discontinuity occurrence as expressed by reported RQD and natural fracture frequency are of high quality, these data have only been collected from vertical boreholes. As the overall geomechanical characteristics of the rock mass depend in part on the three-dimensional characteristics of the fracture patterns within the rock mass, additional information on the characteristics of inclined discontinuities is necessary to improve confidence in the assessment of overall rock mass characteristics.

As described in the descriptive geological site model (Section 3.4.15), confidence in the characterization of minor structural features, such as simple fractures (e.g., joints) is judged to be high for subhorizontal features and low to moderate for inclined and subvertical features based on current borehole data. These data have been reported for all DGR boreholes and the available data do not show any discernable variability between boreholes. Consequently, the reported rock quality and natural fracture frequency based on logging of subhorizontal discontinuity properties are judged to be representative of conditions at the DGR site.

Bulk elastic properties of the rock mass are reported based on interpretation of sonic borehole geophysical logging. Although not reported here on an individual borehole basis, the bulk estimates of elastic properties are similar in all DGR boreholes and comparable to estimates reported from P- and S-wave testing of intact cores. As the bulk elastic properties of the rock mass are unlikely to be anisotropic, confidence in the estimates of bulk elastic properties of the layers that comprise the geomechanical site model is judged to be high.

6 REFERENCES

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