CHARACTERISING THE GEOMECHANICS PROPERTIES OF THE SEDIMENTARY ROCKS FOR THE DGR EXCAVATIONS

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ABSTRACT
Ontario Power Generation (OPG) is currently conducting site characterization program for a Deep Geologic Repository (DGR) for the long-term management of operational Low and Intermediate Level Radioactive Wastes at the Bruce Nuclear site near Tiverton, Ontario. The proposed repository will be located at approximately 680 m depth in a sedimentary sequence of carbonates, shales and evaporites. The host horizon will comprise argillaceous limestones of Cobourg Formation underlain by the Sherman Fall Formation. To support the understanding of the geomechanical properties of Paleozoic bedrock formations in southern Ontario and the regional rock stress conditions around the Michigan Basin, information from over 700 geomechanical test measurements collected at 29 sites and in-situ stress measurements from 25 sites in southern Ontario and northern U.S. were assembled and reviewed.

RÉSUMÉ
Ontario Power Generation (OPG) est en train de mener des études de caractérisation afin de développer un dépôt pour la gestion à long-terme des déchets radioactifs de faible et de moyenne activité dans des couches géologiques profondes sur le site de Bruce, près de Tiverton en Ontario. Le dépôt sera construit à une profondeur d'environ 680 m dans une séquence sédimentaire composée de carbonates, schistes et évaporites. L'horizon encaissant sera constitué de calcaire ardileux de la formation de Cobourg, localisé au dessus de la formation de Sherman Fall. Les propriétés géomécaniques de la formation paléozoïque du sud de l'Ontario et les contraintes régionales autour du bassin du Michigan sont supportées par l'analyse de plus de 700 mesures géomécaniques provenant de 29 sites du sud de l'Ontario ainsi que des mesures de contraintes in-situ provenant de 25 sites du nord des États-Unis et du sud de l'Ontario.

1 INTRODUCTION

Ontario Power Generation (OPG) is proposing the development of a Deep Geologic Repository (DGR) for the long-term management of Low and Intermediate Level Radioactive Waste (L&ILW) from OPG owned nuclear generating facilities. A Site characterisation program is currently underway to determine the suitability of the Bruce Nuclear Site as the location to construct the underground repository. As part of the site characterization work, information regarding the geomechanical properties of the sedimentary formations intersected at the DGR and regional in-situ stresses was assembled and reviewed. This compilation of available rock strength and in-situ stress data from Southern Ontario and surrounding Great Lake region was used to establish input parameters for preliminary engineering analyses of the DGR facility. These parameters will be verified or modified by data from on-going site-specific field and laboratory investigations. The Bruce site Geoscientific Site Characterisation Plan and the activities associated with the L&ILW DGR work program are described in detail by Jensen et al. (2007).

This paper provides a summary of the compilation of the geomechanical rock properties for Ordovician rock formations relevant to the DGR concept as they occur in southern Ontario, and on in-situ rock stresses within the Appalachian and Michigan Basins. This work is a portion of a much larger database on the subject collected by OPG as a part of the DGR project. Figure 1 shows the stratigraphy of bedrock formations beneath the proposed DGR site.

2 REGIONAL ROCK STRENGTH DATABASE

A large database of test results has been assembled to assess various regional geomechanical properties of the Ordovician rocks of southern Ontario. The data comprise over 700 test results from 29 sites as described in public domian literature and laboratory reports (both published and proprietary). Except for western OPG sites and an anonymous site south of the Bruce facility, all sites are located along the shore or in the vicinity of Lake Ontario. Figure 2 shows the regional bedrock geology and distribution of these sites. The database contains a wide range of information on bedrock formations of interest to the DGR project ranging in age from Devonian to Ordovician as depicted on Figure 3.

The geomechanical database includes unconfined compressive strength (UCS), triaxial compressive strength, direct tensile strength, Brazilian (split) tensile strength and shear strength of bedding partings. The data from these tests described in the following sections are mainly confined to the shale and carbonate rocks of Upper and Middle Ordovician ages, which are the proposed host and cap rock units of the DGR.

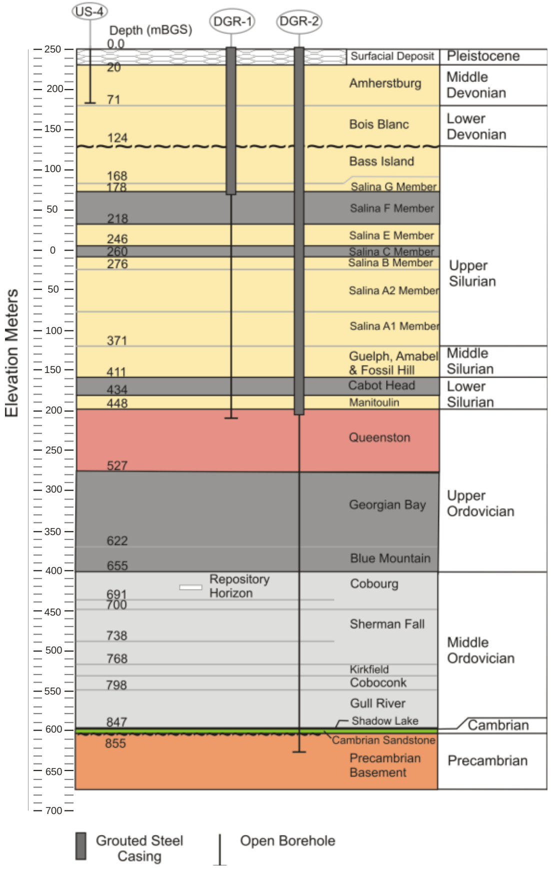

Figure 1. Bedrock stratigraphy with deep boreholes DGR-1 and DGR-2

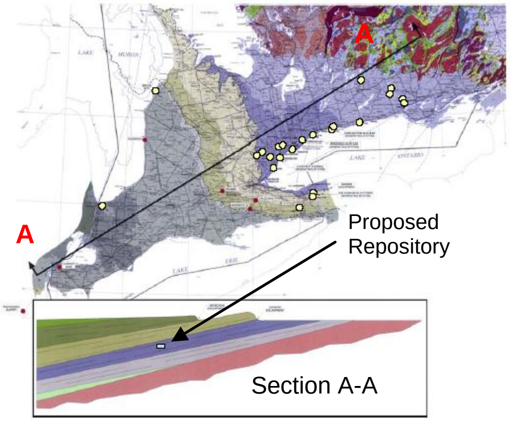

Figure 2. Sampling sites for geomechanical property study

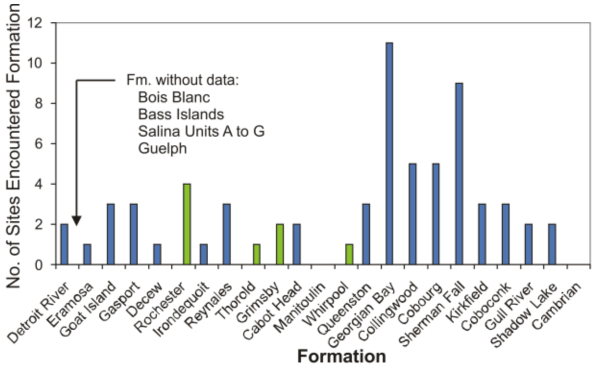

Figure 3. Bedrock formations encountered at the studied sites [existing at Bruce site (blue); elsewhere (green)]

2.1 Unconfined Compression Test

Because of the nature of sedimentary rock, rock strength data were divided into two general groups, tests involving loading i) perpendicular; and ii) parallel to bedding planes. All data presented in this paper are from samples that were loaded perpendicular to bedding planes.

For the argillaceous limestone of the Cobourg Formation, results from 94 samples subjected to compressive loading were used in rock strength determination. These specimens were mainly N and H size cores (45 mm and 61 mm in diameter) and were retrieved from sites at Mississauga, Pickering, Bowmanville, Wesleyville and Port Hope, Ontario. A well-defined unimodal distribution of strength measurements that range from 22 to 140 MPa is shown on Figure 4. The arithmetic mean is 72 MPa. Figure 5 illustrates a histogram of the corresponding elastic modulus of the limestone. It has a mean of 31.5 GPa.

Similarly, for the interbedded limestone and shale of the Sherman Fall Formation the characteristics of the rock can be illustrated by the bimodal distribution of the UCS data. It is inferred from Figure 6 that the average strength values for shale and limestone layers are 51 (13 samples) and 116 MPa (31 samples), respectively. All tests were loaded perpendicular to bedding with samples of diameters ranging from 32 to 61 mm. As there is insufficient information to separate the shale and carbonate in the elastic modulus data, both limestone and shale were analysed as one rock group with a mean elastic modulus of 40 GPa.

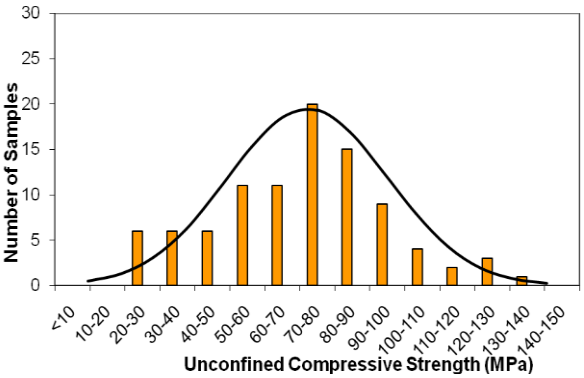

Figure 4. Unconfined compressive strength of Cobourg Formation (argillaceous limestone)

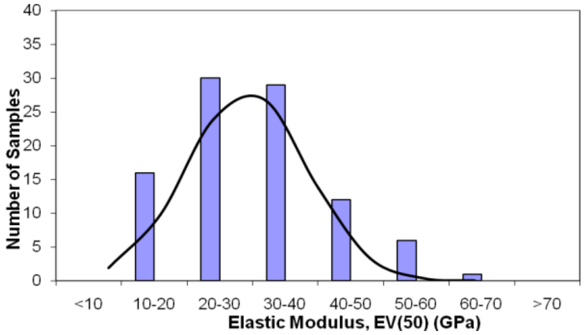

Figure 5. Elastic modulus of Cobourg Formation (argillaceous limestone)

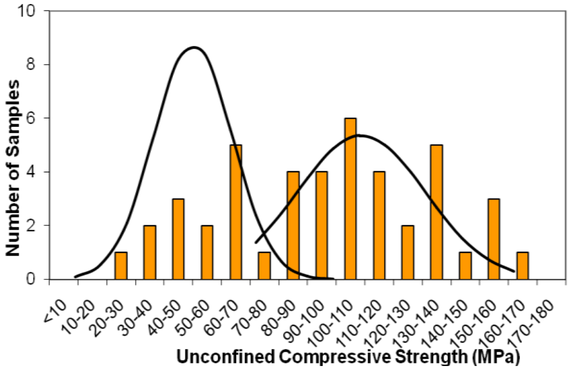

Figure 6. Unconfined compressive strength of Sherman Fall Formation (interbedded limestone & shale)

The UCS and elastic modulus data of the limestones of the remaining Middle Ordovician units, the Coboconk and Kirkfield Formations, are insufficient to produce representative mean values.

A summary of selected geomechanical properties of these two formations is presented in Table 1.

Table 1: Selected Geomechanical properties of Cobourg and Sherman Fall Formations

	Cobourg Fm.		Sherman Fall Fm.			
	Mean	Range	Mean		Range	
			Sh.	Ls.	Sh.	Ls.
UCS (MPa)	72	22 – 140	51	116	23 - 69	71 - 161
E_v (GPa)	32	10 – 67	40		1 – 73	
ν	0.3	0.1 – 0.6	0.3		0.1 – 0.4	
ρ (g/cm^3)	2.7	2.6 – 2.9	2.7		2.5 – 2.7	

2.2 Deere's Classification and GSI

The UCS results of limestones are plotted against the corresponding elastic modulus values in Figures 7 and 9. These plots indicate that the Ordovician limestones can be classified as average-to-high strength with average modulus ratio. The cluster of data appears to fall within the zone identified as sedimentary rock group in Deere and Miller's classification system. Attempts have been made to establish relationships between the elastic modulus, UCS and Geologic Strength Index (GSI). The test data are plotted with the GSI ranging from 70 to 90 in Deere's classification system (Martin et. al. 2003). Figure 7 shows these relationships for the limestones.

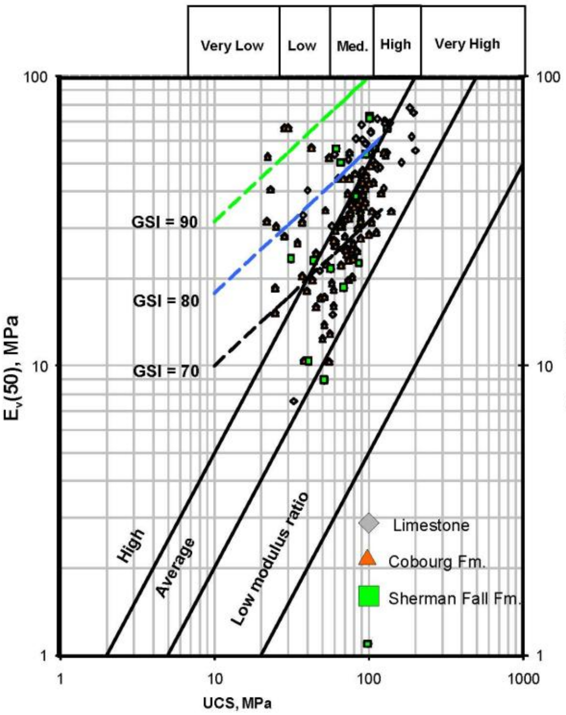

Figure 7. Deere's classification for limestones

2.3 Other Physical Property Relationships

Rock strength can be determined indirectly from geophysical log data if a strength-physical property relationship of the rock formation is established. The following parameters can be utilized to develop correlations with UCS:

1. P-wave velocity,
2. Elastic modulus, and
3. Effective porosity (absorption).

Figures 8 to 10 present plots exploring possible relationship between these parameters and UCS for all rock formations in the database. Despite a large scattering, approximate but notable trends are apparent when UCS is plotted against either the P-wave velocity or the elastic modulus. No correlation was found to exist between effective porosity and UCS

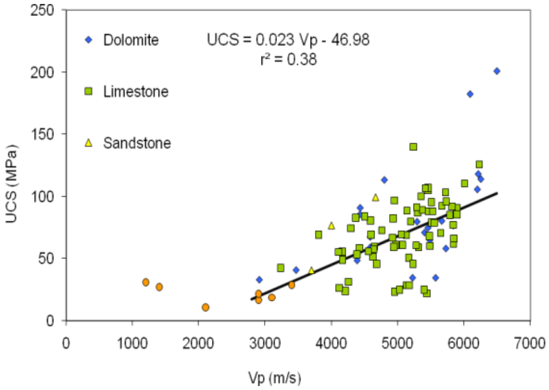

Figure 8. UCS data vs. P-wave velocity for all rock groups

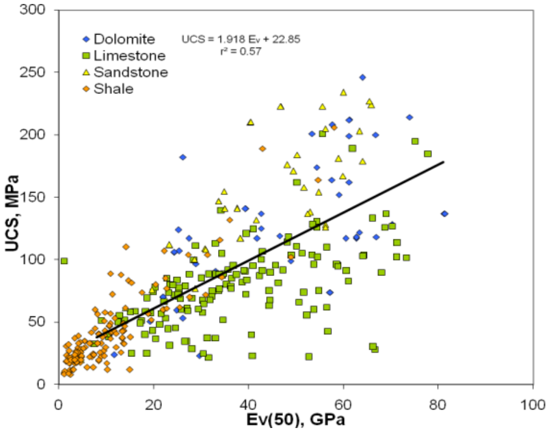

Figure 9. UCS data vs. elastic modulus for all rock groups

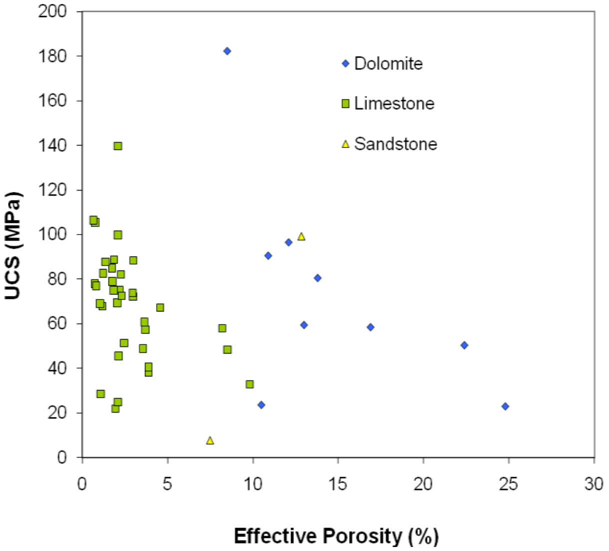

Figure 10. UCS data vs. effective porosity for all rock groups

3 BRAZILIAN AND DIRECT TENSION TESTS

In addition to the UCS data, the Brazilian and direct tension test data for the Cobourg and Sherman Fall Formations were also compiled. Figures 11 and 12 present the histograms of these data. It is noted that the direct tensile strength of both rocks are lower than those derived from Brazilian tests. The cause for such discrepancy is mainly due to the effect of bedding plane on the direct tension tests Table 2 summarized the tensile strengths of both formations.

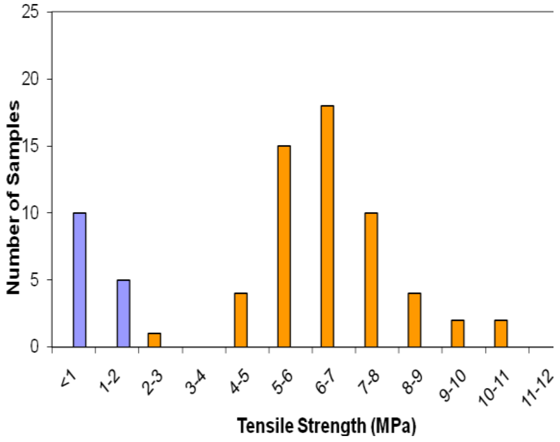

Figure 11. Direct tensile (blue) and Brazilian (orange) strength of Cobourg Formation

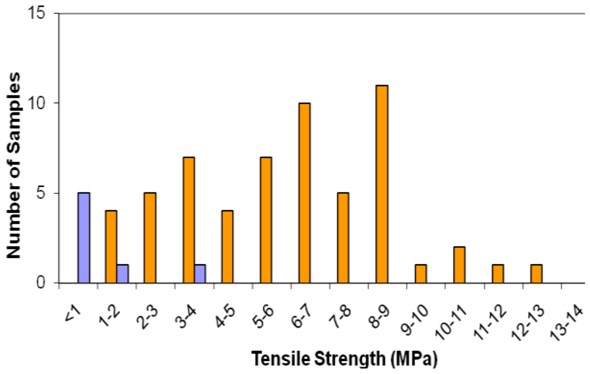

Figure 12. Direct tensile (blue) and Brazilian (orange) strength of Sherman Fall Formation

Table 2. Tensile strength (MPa) of Cobourg and Sherman Fall Formations

Type of Test	Cobourg Formation		Sherman Fall Formation	
	Mean	Range	Mean	Range
Direct Tension	1	0.04 – 2	1	0.1 – 3
Brazilian	6.5	3 – 10	6	1 – 12

4 TRIAXIAL COMPRESSION TESTS

Triaxial test data for the Cobourg argillaceous limestone were obtained from rock samples retrieved from the Darlingtion Cooling Water Intake Tunnel and deep borehole, UN-1. By using these 18 triaxial test data together with the UCS data described earlier, a regression analysis of rock strength was carried out to determine the Hoek-Brown failure criterion parameters for the limestone. The results obtained from the Brazilian and direct tension tests are not included in this analysis as the strengths from these tests generally represent the tensile strength of the bedding partings and the values are relatively low in comparison with the rock mass itself. Figure 13 presents the plot of these data. Data from the Cobourg and the Sherman Fall Formations give very similar results, and these data have been combined for evaluation of the Hoek-Brown strength parameters. Regression analysis (r^2=0.62) gives Hoek-Brown parameters for the intact rock material in these formations as:

σ_c = 72 MPa, s = 1.0 and m = 10.3

where σ_c is the UCS and s and m are material constants for Hoek-Brown Criterion.

For sedimentary formations such as these, it is probable that the Hoek-Brown envelope tends to overestimate the actual tensile strength of the rockmass in a direction normal to bedding planes.

For the Coboconk and Kirkfield Formations, test data are insuficient for meaningful analysis. However, a preliminary estimation of the Hoek-Brown material constant, m for the failure criterion appear to be 27.8 (Figure 13).

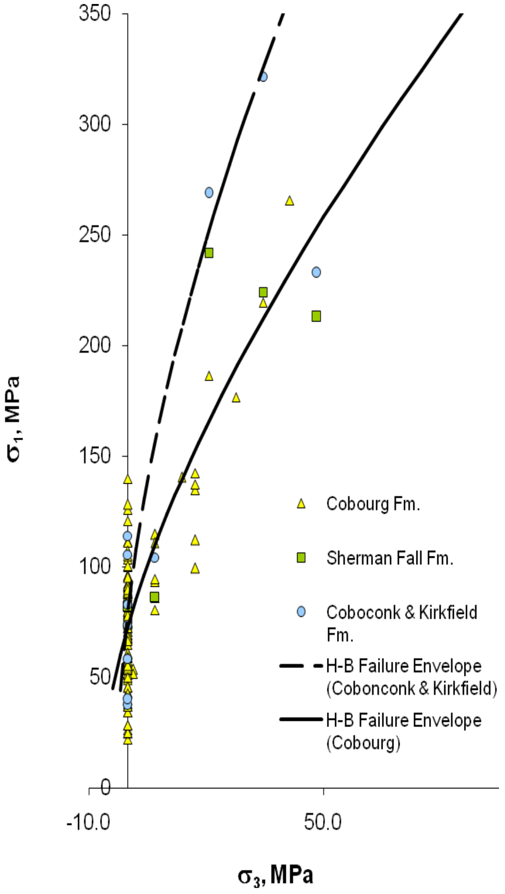

Figure 13. Hoek-Brown Failure Envelopes with Middle Ordovician Limestone Data

5 DIRECT SHEAR TEST

Shear test results were available for the Sherman Fall Formation from samples recovered at OPG's hydraulic stations along the Trent and Otonabee Rivers. Specimens containing various shear plane surface conditions, ranging from natural to cut and ground surfaces, were tested. Figure 14 presents the results of these tests. Normal test pressure was limited to 0.7 MPa because of the loading requirement of hydraulic structures. After correction for the effects of surface roughness, the minimum base friction angle was 32^o.

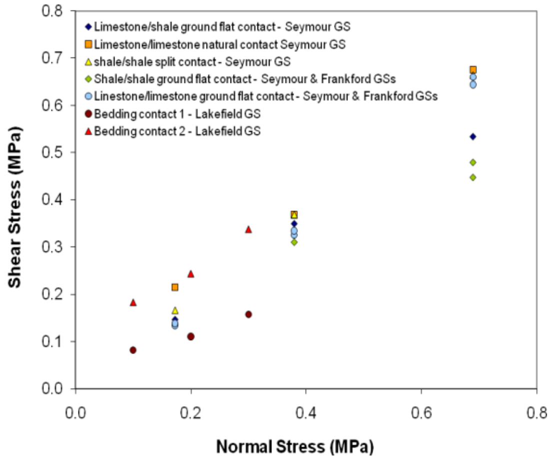

Figure 14. Direct shear test results on Sherman Fall Formation (interbedded limestone and shale)

6 REGIONAL IN-SITU STRESS DATABASE

Ontario is located in the Mid-Plate stress province, the largest stress province in North America and is characterized by high horizontal compressive stress (Adam and Bell 1991). The existence of high horizontal stresses in many sedimentary and shield rocks of Ontario has been well documented (Lo 1978 and Lee 1981). This section summarizes the available rock stress measurements made in southern Ontario and northern US within the Great Lakes region. Figure 15 shows the locations of the 25 test sites involved. Almost all of the measurements were obtained from tests conducted in rock formations of Silurian and Ordovician age at various depths.

6.1 In-Situ Stress in Appalachian and Michigan Basins

The maximum and minimum horizontal stresses (σ_H & σ_h) are plotted as a function of depth in Figure 16. The diamond symbol indicates the magnitude of the maximum stress at a given horizon and the square symbol corresponds to minimum horizontal stress. The coloured symbols represent measurements from hydraulic fracturing tests, whereas the open symbol represent results obtained from overcoring tests.

The majority of the stress measurements are limited to about 300 m depth. It is important to note that virtually all of the deeper measurements were conucted using hydrofracture technique. Overcoring tests were conducted only to depths of about 200 m except at the Norton Mine where tests were performed at the 700 m level (Bauer et al. 2005). The deepest stress measurement within the data set is 5.1 km (Haimson 1978a). Within each rock group, the stress gradients for the two horizontal stresses appear very consistent. Figure 16 also shows the relationship between the two horizontal stresses with depth as proposed by Haimson (1978a) from depth below 1 km.

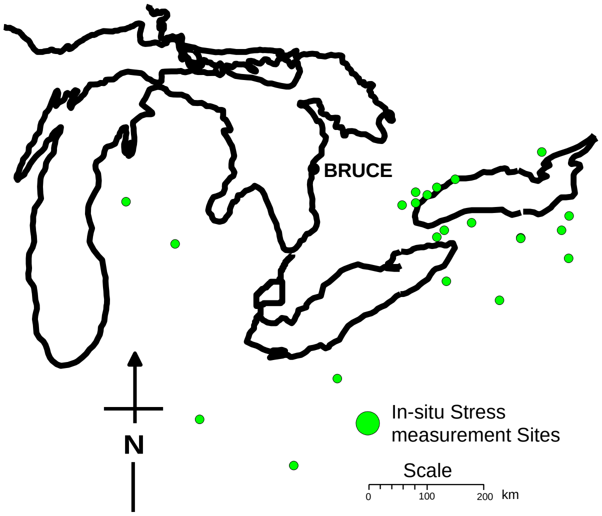

Figure 15. Site location plan for regional in-situ stress database

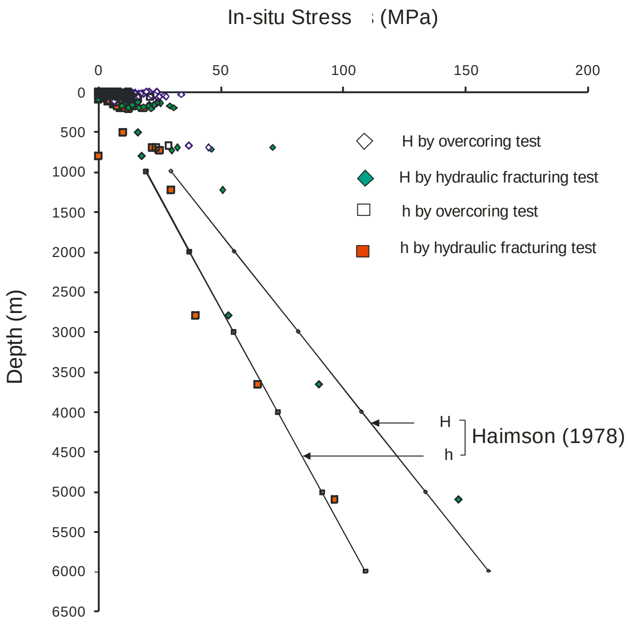

Figure 16. Summary of regional stress measurement verus depth

6.2 In-situ Stress ratios

Figures 17 to 19 present plots of stress ratio between the maximum and minimum horizontal stresses and vertical stresses (σ_{vert}, computed and measured) against depth below surface. A moving median technique was used to smooth in-situ stress data that resulted in the following approximate stress ratios at repository depth.

σ_H/σ_{vert} = 2.0 to 2.5, σ_h/σ_{vert} = 1.5, and σ_H/σ_h = 1.5.

The drop of approximately 0.4 in the stress ratio between 650 and 700 m depth in Figure 17 is likely attributed to: i) different stress measurement techniques; and ii) mine induced stress redistribution influencing measurement results. All these data were measured at the Norton Mine in Ohio. Below 200 m, rock mass stress anisotropy is virtually constant for σ_h/σ_{vert} and σ_H/σ_h as shown in Figure 18 and Figure 19, respectively.

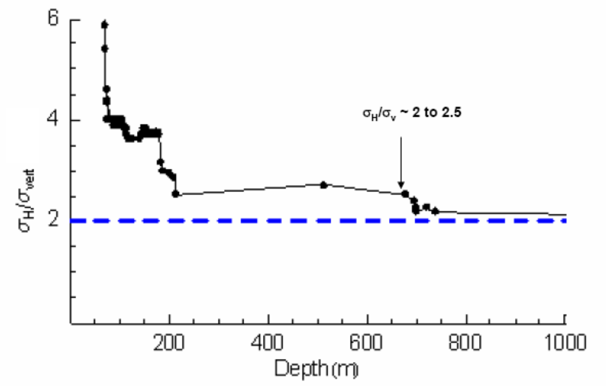

Figure 17. Data smoothing of σ_H/σ_{vert} **ratio**

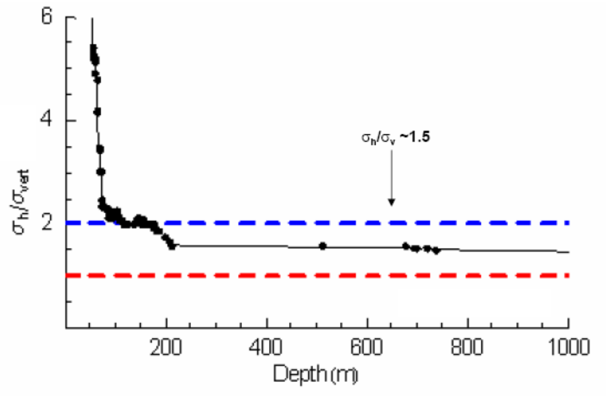

Figure 18. Data smoothing of σ_h/σ_{vert} **ratio**

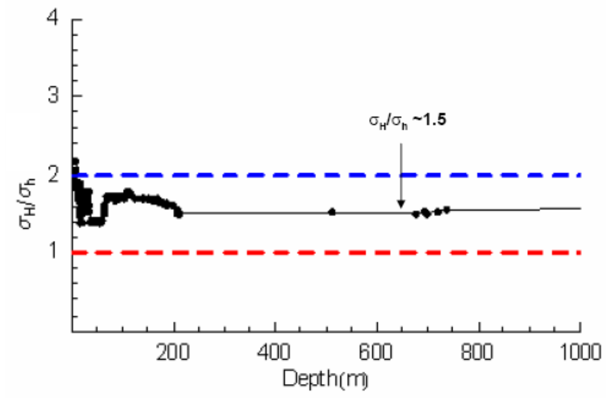

Figure 19. Data smoothing of σ_H/σ_h **ratio**

6.3 In-situ Stress Orientations

Figure 20 presents over 300 data on the orientation of the maximum horizontal stress derived from in-situ stress measurements, interpretation of oil well breakout information, focal mechanism and geological observation (Adams 1985). Despite data scattering, it appears that the orientation of the stress field at depths less than 200 m is consistent within the Michigan and Appalachian Basins. The directions of maximum horizontal stress cluster closely in a NNE to E direction.

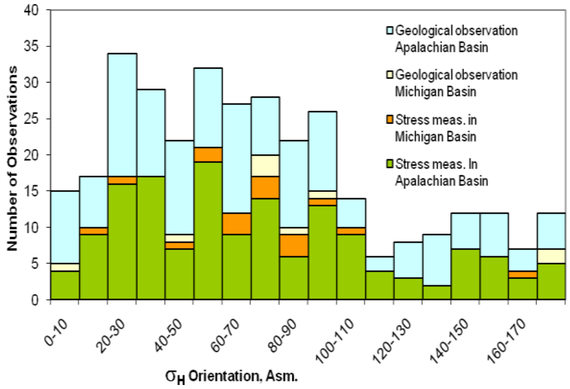

Figure 20. Orientation of Maximum Horizontal Stress in Appalachian and Michigan Basins

Hamsion (1978b; 1982) compiled regional stress orientation data for the Michigan Basin. It overwhelmingly appears that the maximum horizontal stress is in a NE to ENE direction (Figure 21).

6.4 Regional Joint Orientations

Four major sub-vertical joint sets have been mapped at 142 sites situated on the northern Michigan Basin rim. As described by Holst (1982), the orientation of these joint sets is consistent with depth, regardless of bedrock formation age (Figure 22). A similar observation was noted in the deep boreholes at Darlington GS (where the ENE joint set persists throughout the Paleozoic sequence and into the Precambrian), as well as by Engelder (1982) on the jointing of western New York State. Engelder suggested that there is a strong correlation between the in-situ stress field and this set of regional joints (Engelder 1982 and Engelder and Geiser 1980). Andjelkovic, Cruden and Armstrong, 1998, carried out numerous joint measurements, from Orillia to Kingston in Ontario, in the Paleozoic and the Precambrian rock formations and found a correlation between the two sites, indicating a continuity from Precambrian into Paleozoic. Eyles and Scheidegger, 1999, found a strong correlation between the joints found in the Pleistocene-aged glacial sediments of the Scarborough Bluffs, on the shores of Lake Ontario in eastern Toronto, and those in the underlying bedrock. It therefore appears that at least some joint sets translate through the Precambrian, Paleozoics and into the glacial sediments above.

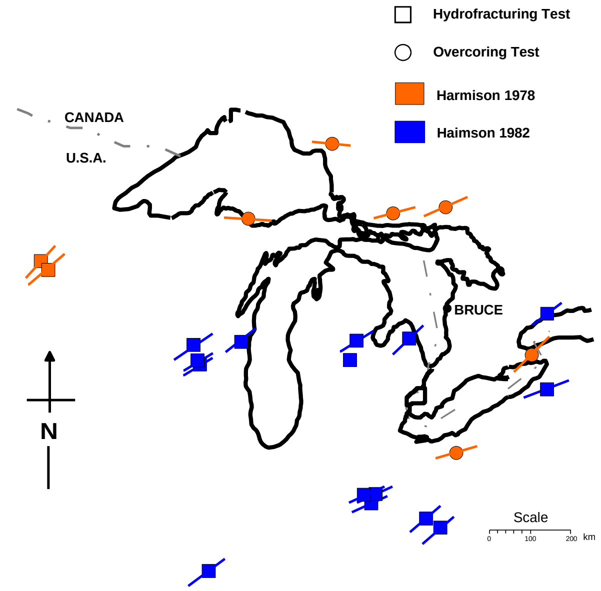

Figure 21. Maximum horizontal stress orientations in Michigan Basins

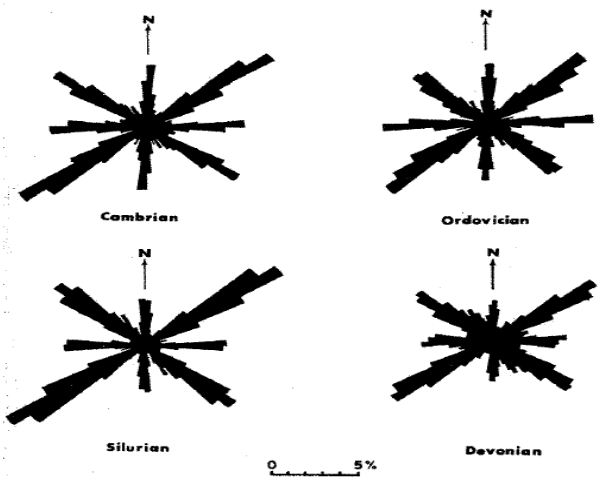

Figure 22. Rose Diagrams of Joints in Cambrian, Ordovician, Silurian and Devonian Formations in Northern Michigan Basin (Holst 1982)

7 SUMMARY

In support of the DGR site characterization work program, a database of regional geomechanical properties for the Ordovician rocks and regional in-situ stresses relevant to the DGR concept has been assembled. This database provides a basis for the initial selection of rock strength and in-situ stress parameters for preliminary repository design prior to obtaining site specific data. Mean values of various strength parameters were determined for the Cobourg, Sherman Fall and other formations.

The compilation of in-situ stress measurements by overcoring and hydraulic fracturing suggest a state of relatively high horizontal compressive stress in Paleozoic bedrock formations. At the proposed repository horizon, the stress ratio, σ_H/σ_{vert}, is estimated to be between 2.0 to 2.5 and, the ratios σ_h/σ_{vert} and σ_H/σ_h, both being approximately 1.5. Based on these stress ratios, the maximum and minimum horizontal stress magnitudes at the proposed Deep Geologic Repository depth of can be estimated for use in preliminary design.

The orientation of the maximum horizontal stress in the Michigan Basin appears to be in a NE to ENE direction.

OPG is currently conducting its initial phase of site characterisation activities. Data obtained from these investigations will be presented in the future.

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