HYDROGEOLOGICAL EVIDENCE OF LOW ROCK MASS PERMEABILITIES IN ORDOVICIAN STRATA: BRUCE NUCLEAR SITE

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ABSTRACT

One of the key attributes contributing to the suitability of the Bruce nuclear site to host a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) is the low permeability of the Ordovician host rock and of the overlying and underlying strata. The permeability of these rocks is so low that diffusion is a much more significant transport mechanism than advection. Hydrogeological evidence for the low permeability of the Ordovician strata comes from two principal sources, direct and indirect.

Direct evidence of low permeability is provided by the hydraulic testing performed in deep boreholes, DGR-2 through DGR-6. Straddle-packer hydraulic testing was performed in 57 Ordovician intervals in these five holes. The testing provided continuous coverage using ~30-m straddle intervals of the Ordovician strata exposed in boreholes DGR-2, DGR-3, DGR-4, and DGR-5, while testing was targeted on discontinuous 10.2-m intervals in DGR-6. The average horizontal hydraulic conductivities of these intervals determined from the tests ranged from 2E-16 to 2E-10 m/s. The Lower Member of the Cobourg Formation, which is the proposed host formation for the DGR, was found to have a horizontal hydraulic conductivity of 4E-15 to 3E-14 m/s. The only horizontal hydraulic conductivity values measured that were greater than 2E-12 m/s are from the Black River Group, located at the base of the Ordovician sedimentary sequence.

Indirect evidence of low permeability is provided by the observed distribution of hydraulic heads through the Ordovician sequence. Hydraulic head profiles, defined by hydraulic testing and confirmed by Westbay multilevel monitoring systems, show significant underpressures relative to a density-compensated hydrostatic condition throughout most of the Ordovician strata above the Black River Group, whereas the Black River Group is overpressured. Pressure differences of 1 MPa or more are observed between adjacent intervals in the boreholes. The observed underpressures and gradients in the Ordovician strata can only persist if permeabilities are so low that vertical advection is insignificant. Thus, both lines of evidence converge on a conclusion that the Ordovician strata at the Bruce nuclear site are characterized by extremely low permeabilities.

1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to construct a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the Western Waste Management Facility at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The DGR is planned as an engineered facility, comprising a series of 31 underground emplacement rooms at a depth of approximately 680 m below ground surface within the Ordovician-age argillaceous limestone of the Cobourg Formation.

As part of the geoscientific characterization activities at the site, six deep boreholes were drilled, five of which (DGR-2, -3, -4, -5, and -6) penetrated most or all of the Ordovician strata at the site. DGR-5 and 6 were inclined boreholes, intended to detect high-angle features such as potential faults. Among other objectives, these boreholes allowed:

1. the performance of hydraulic tests to assess the hydraulic properties of the Silurian and Ordovician strata beneath the Bruce nuclear site; and
2. the installation of long-term multilevel monitoring systems to define hydraulic heads and gradients.

Both of these activities have provided information pertinent to a demonstration of low permeability in the Ordovician strata, which is a key element in the safety case for the proposed repository.

2. BACKGROUND

Low permeability is a desirable property for the host and surrounding rocks of a radioactive waste repository because it limits the amount of groundwater that may contact the waste and transport radionuclides away from the repository. Consequently, low permeability is commonly a siting criterion for any repository. Demonstrations of low permeability may take two forms: direct and indirect. A direct demonstration of low permeability is provided by hydraulic testing designed to measure the permeability of the confining rock mass. Indirect demonstrations are provided by the measurement of other properties, such as hydraulic head, combined with reasoned arguments that the observed properties are consistent only with a low-permeability system and could not otherwise exist. Both direct and indirect demonstrations of low permeability in the Ordovician strata at the Bruce nuclear site are discussed below.

3. STRADDLE-PACKER HYDRAULIC TESTING

Straddle-packer hydraulic testing is intended to stress the rock being tested in such a way that the response reflects the permeability of the rock. Two inflatable packers are used to isolate a section of borehole (the test interval) for testing. For low-permeability media (hydraulic conductivity less than 1E-10 m/s), the most suitable type of test is known as a pulse test [1], in which the pressure in the test interval is changed nearly instantaneously by the introduction or removal of a solid (or liquid) volume, followed by monitoring of the pressure return to equilibrium.

3.1. Test Equipment

The testing equipment used at the Bruce nuclear site was custom designed based on years of experience designing and using similar equipment in support of program activities at the Waste Isolation Pilot Plant (WIPP) site in New Mexico. The test equipment consisted of downhole and surface components. The downhole equipment consisted of two inflatable packers, a shut-in valve, a pulse tool, a slotted section, feedthroughs to connect the transducers to the intervals to be monitored, gauge carriers to house the transducers, and miscellaneous subs to connect the various pieces, as shown in Figure 1 (not to scale).

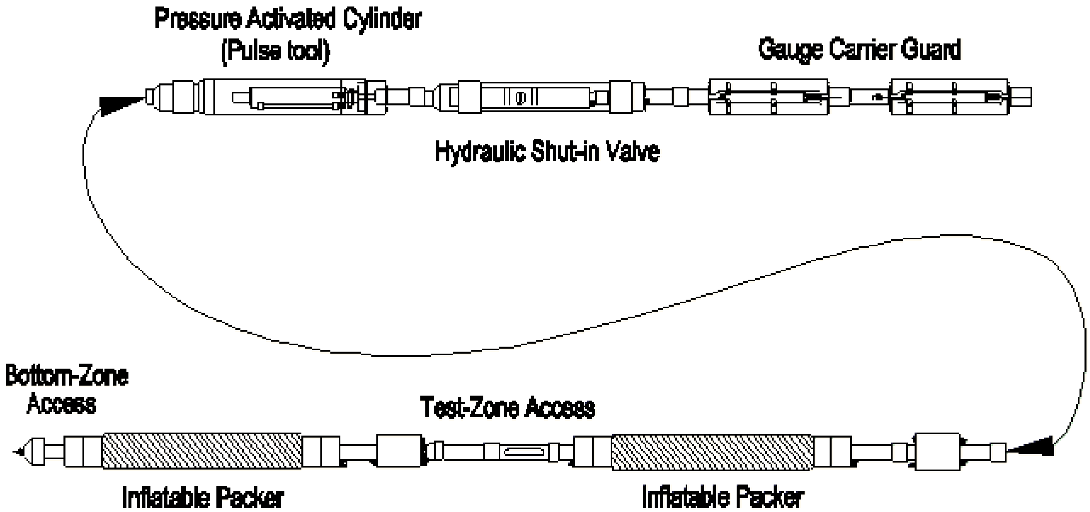

Figure 1. Schematic of Straddle-Packer Test Tool

The packers isolated the section of formation to be tested. The shut-in valve separated the test interval from the tubing string. When the packers were fully inflated, closing the shut-in valve isolated the test interval. Pressure transducers were mounted above the shut-in valve on gauge carriers and were connected to measurement points by stainless steel lines and feedthroughs.

The pulse tool was a hydraulic piston mounted in a chamber connected to the test interval. In an isolated, or shut-in, test interval, extending the piston creates a near-instantaneous pressure pulse. As the volumes of the piston and test zone are known, the magnitude of a pulse could be used to directly calculate test-zone compressibility (C_{tz}), which is a critical value for test analyses. Pulse withdrawals could be created by extending the piston prior to shut-in, and subsequently retracting the piston after the shut-in valve was closed.

The downhole equipment was connected to surface with hydraulic lines and an armoured umbilical cable with transducer power and communication lines. The hydraulic lines and umbilical cable were clamped to the outside of a 2-3/8 inch tubing string which provided the overall mechanical connection between the service rig at surface and the downhole tool. Numerous centralizers were included between tool elements and throughout the tubing string in the inclined boreholes to reduce abrasion as the tool and tubing slid along the boreholes.

With the exception of reels for the stainless steel hydraulic lines and the umbilical cable, all surface equipment was contained within a customized trailer. The trailer contained the data-acquisition system (DAS) computer and equipment, intensifier pumps, and the hydraulic line control panel. The DAS acquired data from the downhole probes, as well as additional transducers measuring barometric pressure and pressures on each hydraulic line. Data could be queried and viewed on-site, or could be accessed remotely over a secure web-based interface.

3.2. Test Methodology

For the testing of DGR-2, DGR-3, DGR-4, and DGR-5, test intervals of approximately 30 m in length were overlapped to provide continuous coverage of the open portion of the borehole to as great a depth as was feasible. The intervals were designed principally to cover (portions of) single formations, with minimal inclusion of the overlying or underlying formations. Testing in DGR-6 used a shorter straddle interval (10.23 m) in order to allow for discontinuous, targeted testing of different lithologies within individual formations, as well as to test fractured and unfractured portions of formations. The short straddle interval also allowed the Collingwood Member of the Cobourg Formation to be tested with minimal contributions from the overlying Blue Mountain and underlying Cobourg Formations, in contrast to the testing in the other deep DGR boreholes.

The majority of tests performed in the DGR boreholes were pulse tests. A pulse injection (PI) or withdrawal (PW) test is an instantaneous (within the limitations of the equipment) pressure increase/decrease induced in the test zone that is allowed to dissipate back toward static pressure conditions. The rate of pressure decay is used to infer the hydraulic properties of the tested geologic unit. During a pulse test, the test zone is shut-in (i.e., it is isolated from the fluid column in the tubing by closing the shut-in valve).

The pressure response observed during a pulse test is directly proportional to the wellbore storage coefficient of the test interval. The wellbore storage coefficient has two components: the volume of fluid contained within the test zone (V_{tz}), and the compressibility of all the materials within or in contact with the test zone (C_{tz}). V_{tz} includes the volume of fluid between the packers, within any tubing or equipment components below the shut-in valve, and within the feedthrough line connected to the test-zone transducer. C_{tz} is a composite compressibility that includes contributions from the test equipment, the borehole fluid, and the geomechanical response of the borehole wall. To minimize the time required to complete a pulse test, the DGR equipment was carefully designed and selected to minimize both V_{tz} and C_{tz}. During the DGR borehole testing, V_{tz} ranged from 0.17 m^3 (DGR-6) to 0.62 m^3 (DGR-2). C_{tz} was minimized through use of extremely stiff packers and strong interconnecting components. Most tool feedthroughs and connections were custom-machined stainless steel components.

The test tool was assembled from individual components as it was lowered into the borehole. An extensive gas and liquid pressure testing program was conducted during tool assembly to eliminate leaks, which can mask the actual hydraulic response of a formation being tested. A final leak test of the fully assembled tool was performed by conducting a pulse test within the surface conductor casing. Note that any undetected leaks within the test equipment would lead to overestimates of hydraulic conductivity.

Figure 2 shows typical test-zone and bottom-zone responses to a typical test sequence, consisting of a stabilization period followed by two pulse-withdrawal tests. Figure 2 shows the data from the DGR-2 test of the interval between 660.50 and 691.00 m, covering the Cobourg Formation and spanning the proposed repository horizon. Each pulse test was approximately one day in duration, with a total testing time of three days (one day of stabilization, followed by two tests at one day each). Due to the low permeability of the strata, relatively little pressure recovery occurred during the 24-hr period allotted to each test, and the observed response was significantly affected by the pretest borehole pressure history to which the test interval had been subjected since drilling of the borehole occurred. Consequently, a robust numerical approach was used to estimate the hydraulic rock mass properties of the tested intervals.

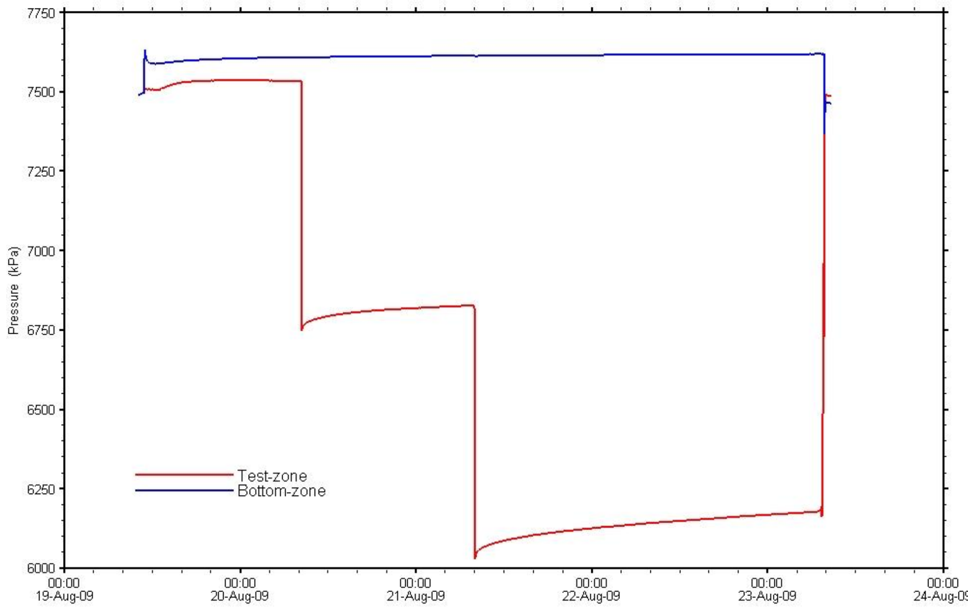

Figure 2. DGR-2 660.50-691.00 m Test Interval and Bottom Zone Response

3.3. Analysis Approach

Pressure data collected during the hydraulic tests were analyzed using the well-test simulator nSIGHTS (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator) developed by Sandia National Laboratories [2] to estimate hydraulic conductivity and formation pressures of the tested intervals. nSIGHTS has been used in radioactive waste repository programs around the globe, including Canada (OPG), the USA (WIPP), Sweden (SKB), France (Andra), Switzerland (Nagra), and Japan (JNP). The code has unique capabilities that allow the analyst to incorporate complex borehole pressure histories into the simulations. The nSIGHTS code uses non-linear parameter estimation methods to find the optimal values of the model fitting parameters (typically hydraulic conductivity, specific storage, formation pressure, and skin properties) that provide the best match to the observed test data. It also allows for quantification of the uncertainty in the hydraulic parameter estimates.

Preliminary analyses were performed to determine an appropriate conceptual model and obtain baseline estimates of the fitting parameters for each tested interval. Perturbation analyses were then performed in multiple stages to obtain the final best-fit parameter values and the corresponding uncertainty ranges. Perturbation analysis consists of randomly perturbing the baseline fitting-parameter values a specified number of times and then re-optimizing those perturbed values. This allows multiple minima within the parameter space to be located in the search for the global minimum (i.e., the true optimal solution). To begin, 250 perturbations were performed. At least one subsequent perturbation run followed, where the initial parameter values to be perturbed were updated using the best-fit values obtained from the initial 250 perturbations. If these new best-fit values indicated that the initial baseline parameter values were contained within the global minimum, then a final run of between 500 and 5000 perturbations was performed, with the number of perturbations being dependent upon the complexity of the parameter space. If the initial 250 perturbations indicated that a new global minimum had been found, then another 250 perturbations were run using the new best-fit values as the initial values to be perturbed. This process was repeated until the results indicated that the global minimum had been found and the final perturbation run could be initiated.

After the final perturbation run was completed, a cumulative distribution function (CDF) was calculated using the fit values (measure of the goodness of fit) associated with each perturbation. The characteristics of this fit-value CDF along with a visual assessment of parameter-space plots for each fitting variable, and a visual assessment of the fits themselves were all used to determine the value of the "fit discriminant". The fit discriminant is used to reduce the perturbations under consideration to only those within the best-fit minimum, and sufficiently close to be subjectively considered "acceptable" fits. All perturbation results for which the fit value was less than the fit discriminant were deemed acceptable solutions and are included in the final range of reported values for each fitting parameter.

Results from the testing of the Cobourg Formation in DGR-2 (interval 660.50-691.00 m) are presented as an example of the analysis approach. Figure 3 shows the pre-test borehole pressure history used in the analysis of the testing in this interval. The pressure history was developed from knowledge of the fluid level and density in the borehole during drilling and from bottom-hole pressure measurements made while testing higher intervals in the DGR-2 borehole.

Figure 4 shows the cumulative distribution function for the fit value derived from 1000 simulations of the DGR-2 660.50-691.00 m test. Almost no change is seen in the fit value below a cumulative probability of 0.69, so the fit value at that probability (0.40) was selected as the fit discriminant. Figure 5 shows the fit values and hydraulic conductivity estimates for the 1000 simulations, with 314 simulations rejected for having fit values greater than the fit discriminant. The range of uncertainty in hydraulic conductivity for this test is only 2.3E-13 to 4.8E-13 m/s.

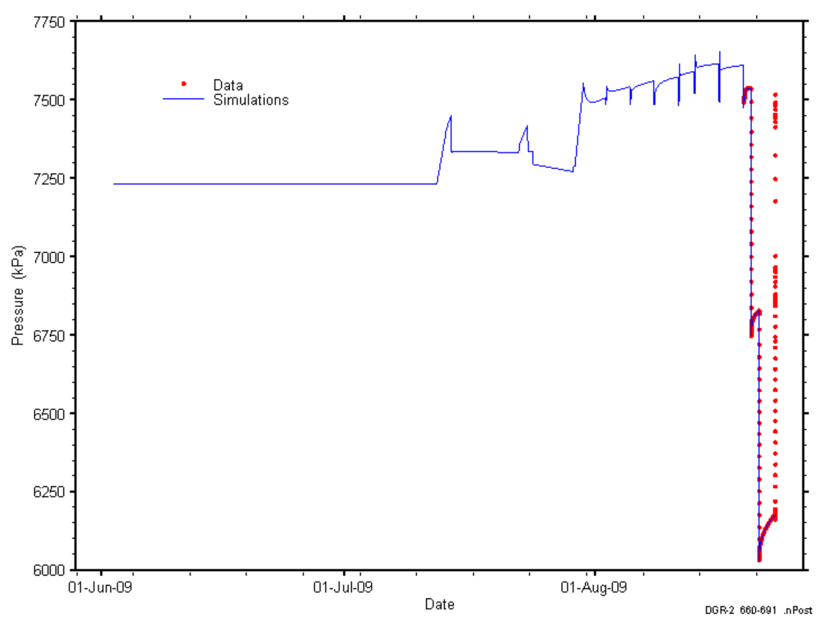

Figure 3. Pressure History and Test Data for the DGR-2 660.50-691.00 m Testing Sequence Showing Best-Fit Simulations

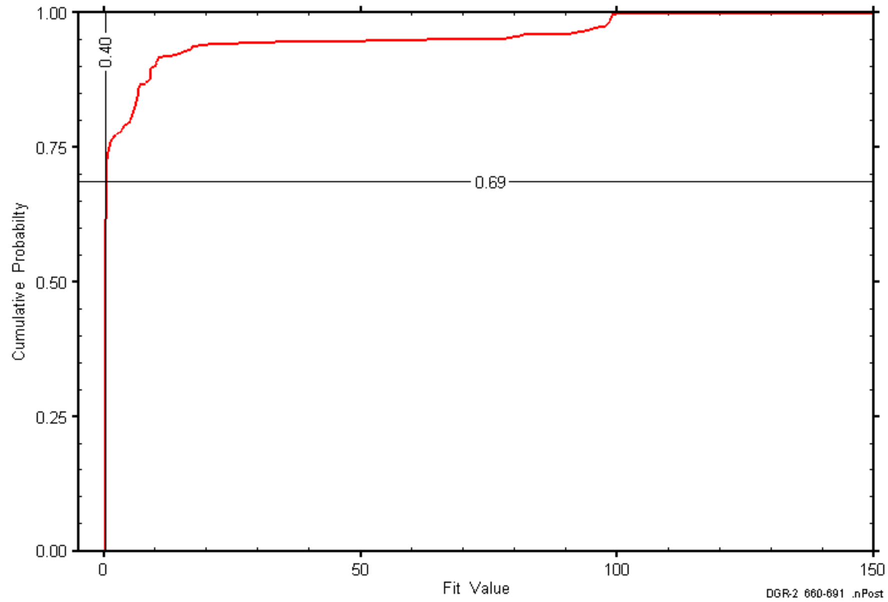

Figure 4. Fit Value Cumulative Distribution Function for the DGR-2 660.50-691.00 m Perturbation Analysis

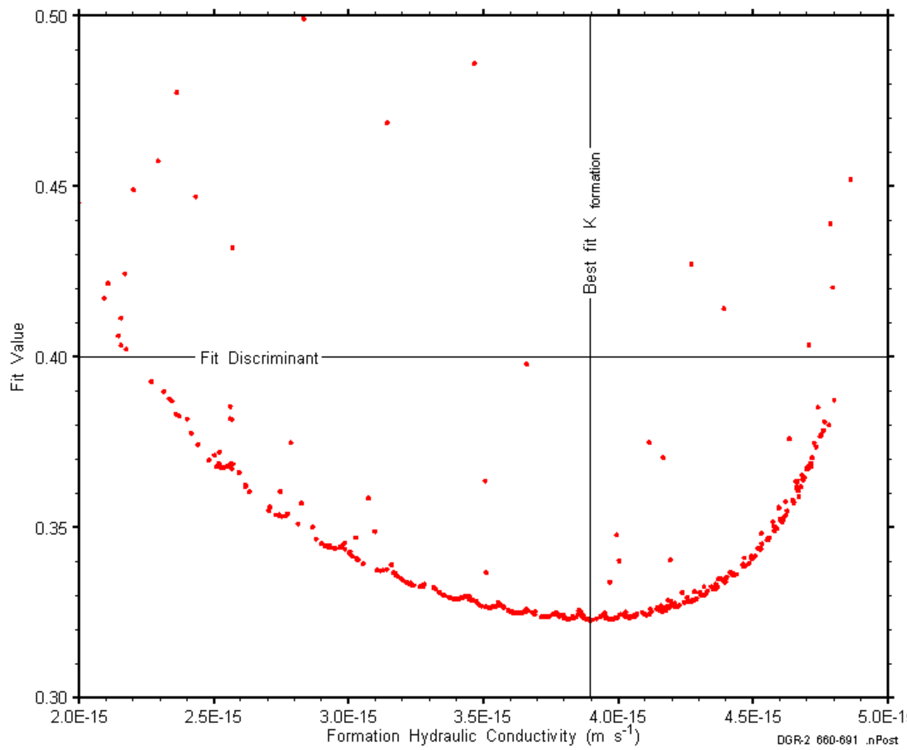

Figure 5. XY-Scatter Plot Showing the Formation Hydraulic Conductivity Parameter Space Derived from the DGR-2 660.50-691.00 m Perturbation Analysis Along with the Fit Discriminant and Best-Fit Value

Figure 6 shows an example of how correlations between fitting parameters can be examined through the perturbation analysis approach. Estimates of formation specific storage and skin properties are always highly correlated. For some tests, estimates of formation pressure are correlated with hydraulic conductivity and/or specific storage. Hydraulic conductivity is typically the most tightly constrained of the fitting parameters, and is estimated with high confidence.

Figure 7 shows the testing sequence performed in the interval along with the best-fit nSIGHTS parameter estimates and the 686 simulations with fit values less than the fit discriminant. The simulations overlie each other so closely that they appear as a single line on the figure. Note that the inferred formation pressure for this interval is lower than the initial pressure during the first pulse test; the pressure increase following the first pulse withdrawal was caused by the elevated pressures to which the test interval had been exposed during the history period (Figure 3).

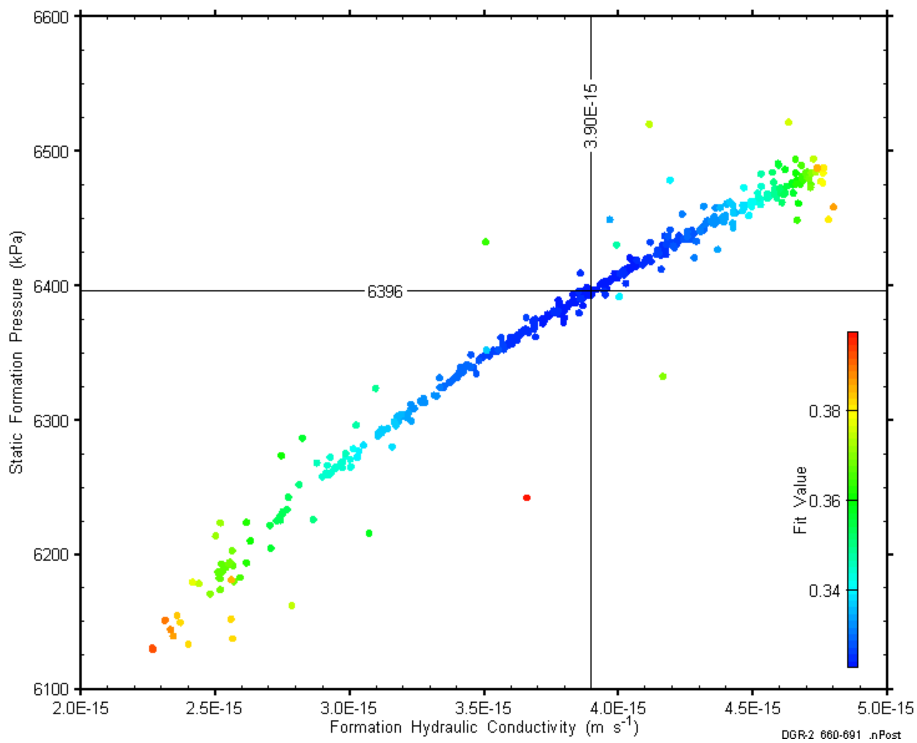

Figure 6. XY-Scatter Plot Showing Estimates of Formation Hydraulic Conductivity and Raw Static Formation Pressure Derived from the DGR-2 660.50-691.00 m Perturbation Analysis

3.4. Results

The best-fit hydraulic conductivity (K) estimates inferred from the straddle-packer tests in the DGR boreholes by Roberts et al. [3] are presented in Figure 8. In all but a few cases, the uncertainty on K derived from perturbation analyses is less than an order of magnitude. Estimated formation hydraulic conductivities have been calculated as the geometric mean of tests conducted within the formations. The horizontal K values estimated from the straddle-packer tests in the Upper Ordovician strata are generally less than 1E-12 m/s, with estimated formation averages of less than 1E-13 m/s. The horizontal K values estimated from the straddle-packer tests in the Middle Ordovician Trenton Group strata (Kirkfield-Sherman Fall-Cobourg) are all less than 1E-13 m/s, with estimated formation averages of approximately 1E-14 m/s or less. Horizontal K values estimated from the straddle-packer tests in the Middle Ordovician Black River Group (Coboconk-Gull River-Shadow Lake) are higher, ranging from approximately 1E-13 to 1E-10 m/s, with formation averages of 2E-11 m/s for the Coboconk Formation and 2E-12 m/s for the Gull River Formation. Because of the bedded sedimentary nature of the Ordovician strata, vertical K values are expected to be at least an order of magnitude lower than the already low horizontal K values. With hydraulic conductivities this low, advective transport through the Ordovician strata must be virtually nonexistent, and molecular diffusion must be the dominant transport mechanism.

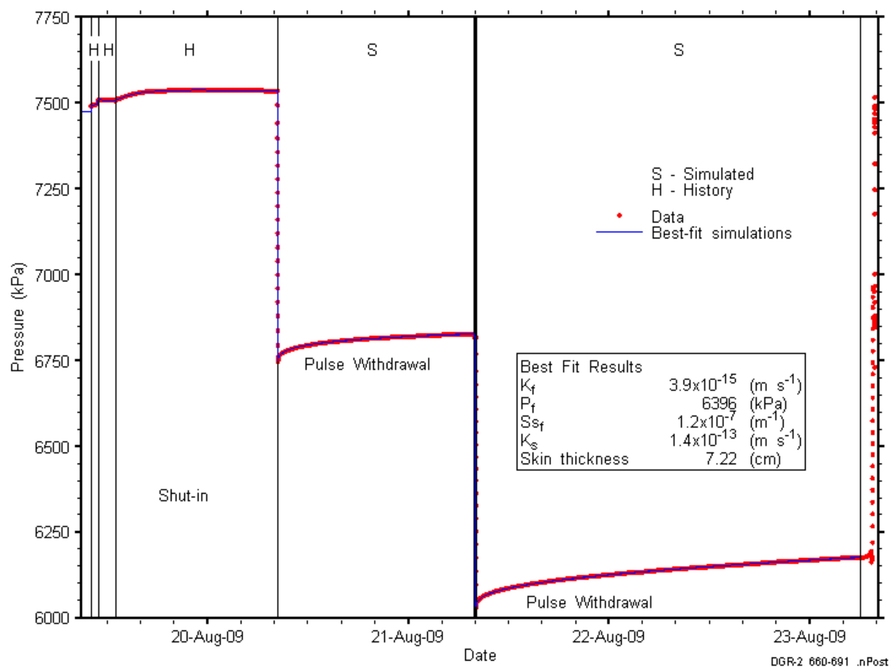

Figure 7. Annotated DGR-2 660.50-691.00 m Testing Sequence Showing Best-Fit Parameter Estimates and 686 Accepted Simulations

4. LONG-TERM PRESSURE MONITORING

In low-permeability formations, installing monitoring wells and measuring water levels is not a practical method of determining hydraulic heads; water levels may take decades or even centuries to stabilize because the formations produce so little water. Measuring pressures in packer-isolated intervals is a more feasible approach, but even under isolated conditions, pressures may take months to years to stabilize. To facilitate long-term monitoring, boreholes DGR-2, DGR-3, and DGR-4 were completed with Westbay stainless steel MP55 multi-level monitoring systems. Westbay systems are built around a central casing that provides access for a transducer, or string of transducers, that connects to monitoring ports installed in the casing. The monitoring ports provide access to intervals isolated by inflatable packers that are part of the casing string. The Westbay system in DGR-2 has 27 packers with 24 intervals being monitored, while the systems in DGR-3 and DGR-4 both have 43 packers to monitor 42 intervals. Westbay systems were not installed in DGR-5 and DGR-6.

Pressure profiles have been completed in the Westbay systems a number of different times since installation in order to monitor pressure equilibration in the various stratigraphic intervals. Figure 9 shows the measured Westbay pressures and estimated environmental head profile for borehole DGR-4 between April 2009 and February 2011, along with the formation pressure estimates derived from the straddle-packer testing. Environmental head, as defined by Lusczynski [4], accounts for changes in fluid density that occur with depth in a stratigraphic sequence, allowing for the determination of vertical, but not horizontal, hydraulic gradients. Similar profile figures for the Westbay installations in boreholes DGR-2 and DGR-3 are given in Intera Engineering Ltd. [5]. The Westbay intervals are generally shorter than the straddle-packer intervals, and so provide more detail and involve less averaging of pressures.

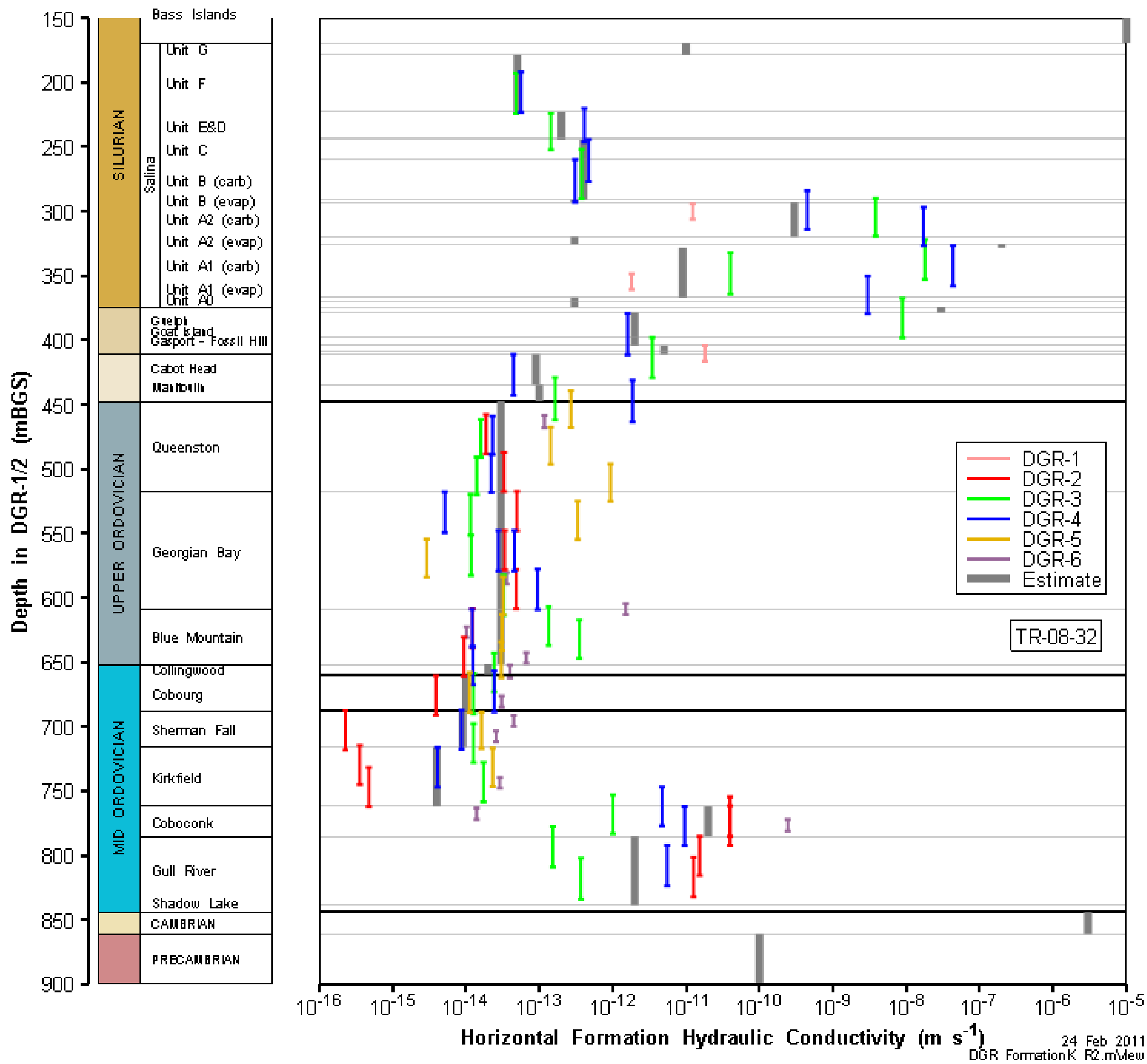

Figure 8. Best-Fit Interval Horizontal Hydraulic Conductivities from Borehole Straddle-Packer Tests and Estimated Formation Average Values

Pressures in most of the Ordovician strata are seen to be decreasing toward the values estimated from the hydraulic testing, and do not appear to have reached fully stabilized values. The

Ordovician strata above the Black River Group are clearly underpressured relative to either a freshwater or density-compensated hydrostatic condition. The Black River Group strata (Coboconk, Gull River, and Shadow Lake) and the underlying Cambrian, in contrast, are overpressured relative to a hydrostatic condition. Recent indications of underpressures in the Gull River and Coboconk are believed to be an artifact of difficulties in connecting the transducer to the Westbay monitoring port, leading to temporary and non-representative depressurization of the intervals. In addition, significant vertical hydraulic gradients are observed between adjacent intervals.

These observations constitute indirect evidence of extremely low permeability. The observed underpressures and gradients in the Ordovician strata can only persist if permeabilities are so low that vertical advection is insignificant. If the Ordovician permeabilities were not low, advective flow from the overlying Silurian and underlying Cambrian would have eliminated the underpressures in the Upper and Middle Ordovician strata, as well as the steep and abrupt hydraulic gradients between adjacent intervals.

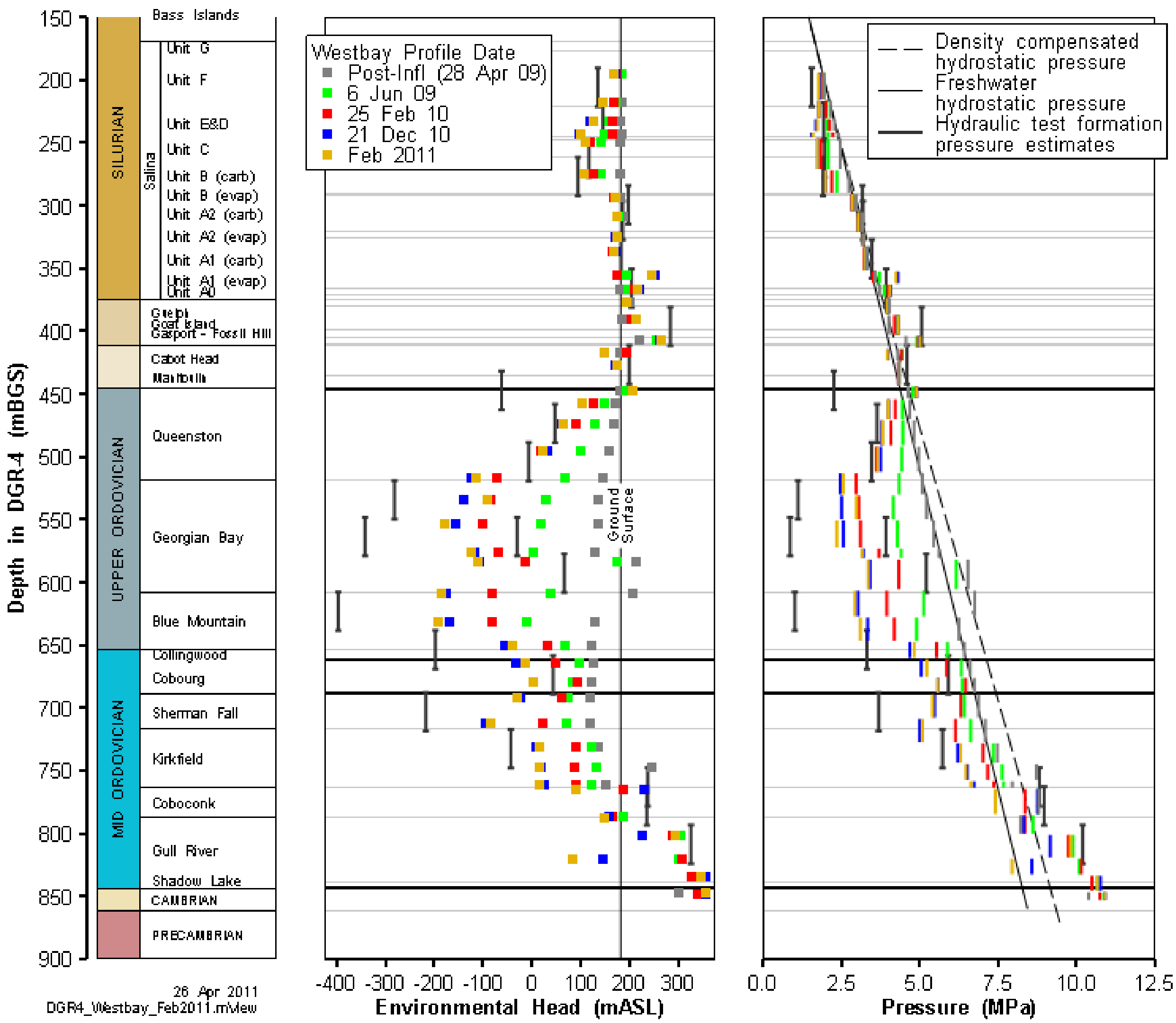

Figure 9. Measured Westbay Pressures and Estimated Environmental Head Profile for Borehole DGR-4

5. SUMMARY AND CONCLUSIONS

The straddle-packer hydraulic testing of the Ordovician strata conducted in the DGR boreholes shows consistently low values of horizontal hydraulic conductivity, always below 1E-9 m/s. The proposed DGR horizon in the Cobourg Formation is overlain by over 200 m of Upper Ordovician sediments with horizontal hydraulic conductivities of less than 2E-12 m/s, and underlain by over 100 m of Middle Ordovician Trenton Group sediments with horizontal hydraulic conductivities less than 1E-13 m/s. Long-term pressure monitoring in the Ordovician strata shows that the Upper Ordovician and Middle Ordovician Trenton Group are significantly underpressured relative to a density-compensated hydrostatic condition and relative to the overlying Silurian strata and underlying Black River Group and Cambrian strata. These underpressures could not persist if hydraulic conductivities were not as low as those measured. Thus, both direct and indirect lines of hydrogeological evidence indicate that the Ordovician strata at the Bruce nuclear site are characterized by very low permeabilities.

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