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Preliminary characterization of fracturing at the site of the chalk river laboratories

By:

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MANAGEMENT PERSPECTIVE

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Author(s): Piggott, A., Moltyaner, G., Yamazaki, L., and Novakowski, K.

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Citation: 50th Canadian Geotechnical Conference

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Current Status: The Chalk River Laboratories (CRL) of Atomic Energy of Canada Limited are located on the Ottawa River, 150 km northwest of Ottawa, and are situated within a fractured granitic rock mass. Groundwater flow in this setting is largely confined to an interconnected system of fractures. It has been proposed that a repository for the disposal of historic, low level radioactive wastes presently in storage at locations across Ontario be constructed at the CRL site. Demonstration of an adequate geologic barrier to radionuclide migration by groundwater transport will be a key issue in estimating the performance of the repository. This paper presents preliminary results of the application of advanced methods of site characterization to estimate the geometry of the fracture system at the CRL. These results will provide a defensible basis for determining the distribution and rate of groundwater flow within the in situ rock mass, and ultimately the suitability of the site relative to the disposal of radioactive waste materials.

Next Steps: Continuing research will focus on finalizing the conceptual model introduced in this paper and on developing a method of predicting groundwater flow at the site.

ABSTRACT

A three-dimensional conceptual model of fracture system geometry based on a uniform and isotropic distribution of disc-shaped fractures and a fractal relation between the frequency and dimension of the fractures is developed for the site of the Chalk River Laboratories of Atomic Energy of Canada Limited. The model is applied to site and outcrop scale fracture trace length data and is consistent with the data for trace lengths in the range of 1 to 1000 m. Probabilistic results derived from the model confirm the accuracy of the plotting and interpretation of the in situ data and illustrate the three-dimensional form of the estimated fracture system.

PRELIMINARY CHARACTERIZATION OF FRACTURING AT THE SITE OF THE CHALK RIVER LABORATORIES

Andrew Piggott, Greg Moltyaner, Lucy Yamazaki and Kent Novakowski

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CARACTÉRISATION PRÉLIMINAIRE DE LA FRACTURATION SUR LE SITE DES LABORATOIRES DE CHALK RIVER

Andrew Piggott, Greg Moltyaner, Lucy Yamazaki et Kent Novakowski

RÉSUMÉ

On a développé, pour le site des laboratoires de Chalk River d'Énergie atomique du Canada limitée, un modèle théorique tridimensionnel de la géométrie d'un système de fractures, basé sur une distribution uniforme et isotropique de fractures en forme de disque et sur un rapport de type fractal entre la fréquence et les dimensions des fractures. On a appliqué ce modèle à ce site, et les données sur les longueurs des traces obtenues pour les fractures dans les affleurements concordent avec celles obtenues pour la plage de 1 à 1 000 m. Les résultats probabilistes obtenus grâce à ce modèle confirment l'exactitude des courbes obtenues et l'interprétation des données *in situ* , et ils illustrent la forme tridimensionnelle du système de fractures modélisé.

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Next Steps:	Continuing research will focus on finalizing the conceptual model introduced in this paper and on developing a method of predicting groundwater flow at the site.

INTRODUCTION

The Chalk River Laboratories (CRL) of Atomic Energy of Canada Limited are located 150 km northwest of Ottawa, on the Ottawa River, and have been an important centre for nuclear research for more than 50 years. In 1995, a referendum held in the town of Deep River indicated public support for assessment of the CRL site relative to the disposal of historic, low level radioactive wastes. The CRL are located within a fractured, granitic rock mass where the most likely pathway for radionuclide transport from a subsurface repository to the biosphere is through an interconnected system of fractures. Methods of predicting radionuclide transport in fractured rock have been developed for the geologic disposal of high level radioactive wastes, and form a defensible basis for the performance assessment of a repository constructed at the CRL site. This paper summarizes progress in developing a conceptual model of the fracture system at the site of the CRL that will be used to predict the distribution and rate of groundwater flow at the site.

CONCEPTUAL MODEL OF FRACTURE SYSTEM GEOMETRY

Numerous conceptual models of fractured rock masses have been proposed over the past 20 years. These models span a wide range of complexities and respond to a variety of factors such as the geologic setting, persistence and frequency of the fractures, and relative permeabilties of the fracture system and intact rock matrix. Granitic rock masses are frequently represented as a network of discrete fractures within an impermeable matrix where a shape, location, orientation, and hydraulic and transport properties are assigned to each of the constituent fractures.

Analyses of discretely fractured rock masses are often based on two-dimensional geometry where the idealized fractures approximate the fracture traces that are visible in outcrop and are assumed to be continuous with respect to depth. This representation does not address the connectivity of the fractures at depth and may not accurately predict groundwater flow. A three-dimensional model where each fracture is assumed to be planar and circular, or disc-shaped, is a reasonable compromise between geometric detail and the difficulty of estimating the parameters of the model from sparse in situ data. In this application, the disc-shaped fracture model is implemented subject to the further assumptions that the fractures are distributed in a uniform and isotropic manner. In other words, the density of fracturing does not vary spatially, or with depth, and the fractures are not distributed among sets with statistically related orientation.

Examination of a rock mass at virtually any scale reveals some degree of fracturing, and sampling of the fracture system assumes an implicit scale dependence. For example, the statistics of a population of fractures detected using remote sensing are very likely to differ from the statistics of the same population measured in thin section. An objective of this paper is to characterize the geometry of the fracture system at the site of the CRL across a broad range of sampling scales. The concept of fractal geometry (Mandelbrot 1983) is a useful approach to the representation of single fractures and fracture systems with respect to scale that has been widely applied elsewhere in the rock mechanics literature. In this application, a population of disc-shaped fractures is considered to be fractal if the number of fractures per unit volume of the rock mass with a diameter greater than D may be approximated using

$$N(D) = \frac{a_D}{D^{F_D}} \quad [1]$$

where a_D and F_D are the fractal coefficient and dimension of the population. Characterization of a fracture system using Eq. 1 requires a sample of fracture diameters. It is not possible to directly measure the diameters of fractures using existing methods of subsurface reconnaissance. As a result, the fractal parameters must be determined using an indirect approach which relates fracture diameters to fracture trace lengths, which are more readily measurable in situ.

Fracture traces result from the intersection of a fracture system with an outcrop surface. Analytic relations exist between the fractal parameters of an isotropic population of disc-shaped fractures and the statistics of the population of trace lengths resulting from the intersection of the fracture system with a planar outcrop surface (Piggott 1996). These relations indicate that the distribution of trace lengths is fractal and has the form

$$N(L) = \frac{a_L}{L^{F_L}} \quad [2]$$

and that the fractal coefficient and dimension of the two distributions are related using

$$F_D = F_L + 1 \quad [3]$$

and

$$a_D = a_L \sqrt{\pi} \frac{F_L}{F_L + 1} \frac{\Gamma(\frac{3+F_L}{2})}{\Gamma(\frac{2+F_L}{2})} \quad [4]$$

where Γ denotes the Gamma function. It is therefore possible to characterize a fracture system in terms of a fractal distribution of fracture diameters provided that the corresponding population of fracture trace lengths may be approximated using Eq. 2.

CHARACTERIZATION OF THE IN SITU FRACTURE SYSTEM

The data that are presently available to support the characterization of the fracture system at the site of the CRL include 303 fracture traces measured from air photographs and geophysical data and 368 fracture traces measured along 9 scan lines applied to 4 outcrop surfaces (Siting Task Force 1994). The first set of traces is referred to as site scale data and has a sampling dimension of approximately 6000 m. Figure 1 shows the distribution of these traces across the site. Each of the traces has been assigned a measure of confidence varying from confirmed or very high probability through high, moderate, and low probability. Traces with the highest measure of confidence are not used in this analysis as these features are aligned with the Ottawa River and the various lakes that occur across the site and therefore are more appropriately handled as

deterministic features that may be accurately located in a siting or groundwater modelling exercise. Trace lengths listed in the site scale data vary from 75 to 10,200 m and are most populous in the range of 100 to 1000 m. The second set of traces is referred to as outcrop scale data and has a sampling dimension of approximately 20 m. Trace lengths listed in the outcrop scale data vary from 0.3 to 15 m and are most populous in the range of 1 to 10 m.

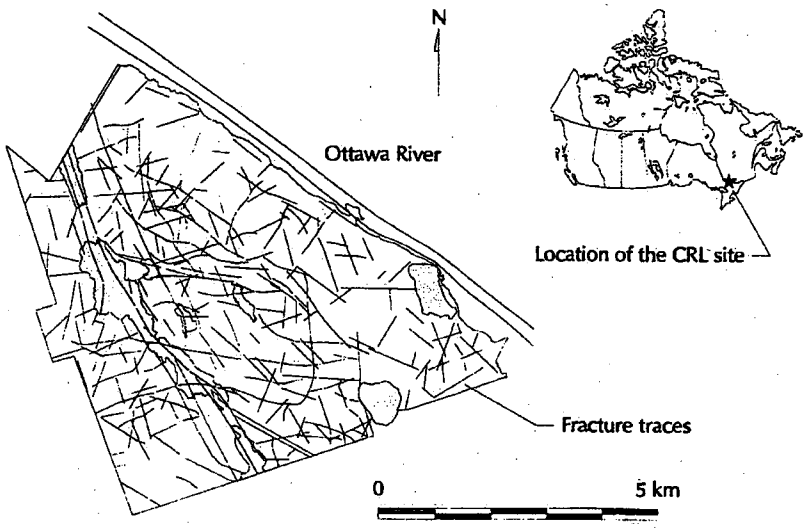

FIGURE 1. Map of the CRL site showing the site scale fracture trace data.

Many of the traces listed in the site and outcrop scale data are truncated by intersection with an obstruction such as the property boundary, a lake, or overburden. It is estimated that 75 of the 282 site scale traces selected for analysis are truncated while 213 of the 349 outcrop scale traces selected for analysis are truncated. Many outcrop scale traces with lengths of several metres are truncated at both ends. This suggests that the outcrop surfaces are partly obstructed by remnants of overburden or vegetation where these smaller obstructions occur with a spacing of several metres. While it is possible to statistically represent the truncation of the fractures, this requires prior knowledge of the geometry of the obstructions and the underlying distribution of trace lengths. This information is presently not available and therefore the truncation of the data must be recognized as a factor limiting the certainty of the characterization results.

The fractal coefficient and dimension of the trace length data may be most conveniently determined by plotting the data in a logarithmic form where Eq. 2 is reduced to

$$\log N(L) = \log a_L - F_D \log L \qquad [5]$$

and the relation of log N(L) to log L is linear. In order to prepare this plot, the site and outcrop scale data were sorted into descending order to yield two lists of trace lengths, L_i. Next, the weights for each of the observations were computed using

$$W_i = \frac{1}{A_S} \qquad [6]$$

for the site scale data and

$$W_i = \frac{\pi}{2L_i L_s} \qquad [7]$$

for the outcrop data where $A_s = 3.9\text{x}10^7$ m^2 is the total area of the site and $L_s = 166.5$ m is the total length of the 9 scan lines. Equation 7 corrects for the bias that is associated with sampling fracture traces along a scan line and is based on the assumption of an isotropic distribution of traces. Finally, the weights of the observations were accumulated using

$$N(L_i) = \sum_{j=1}^{i} W_j \qquad [8]$$

which is a discrete approximation of Eq. 2. The two sets of data may be plotted independently because the accumulated weight of site scale data is nominal relative to the weight of the outcrop scale data. This plotting procedure was applied to the complete sets of site and outcrop scale data, including truncated traces, and to subsets of these data consisting of only non-truncated fractures. Figure 2 compares the measured data to the fractal relation where the histograms positioned above the results indicate the distribution of the data.

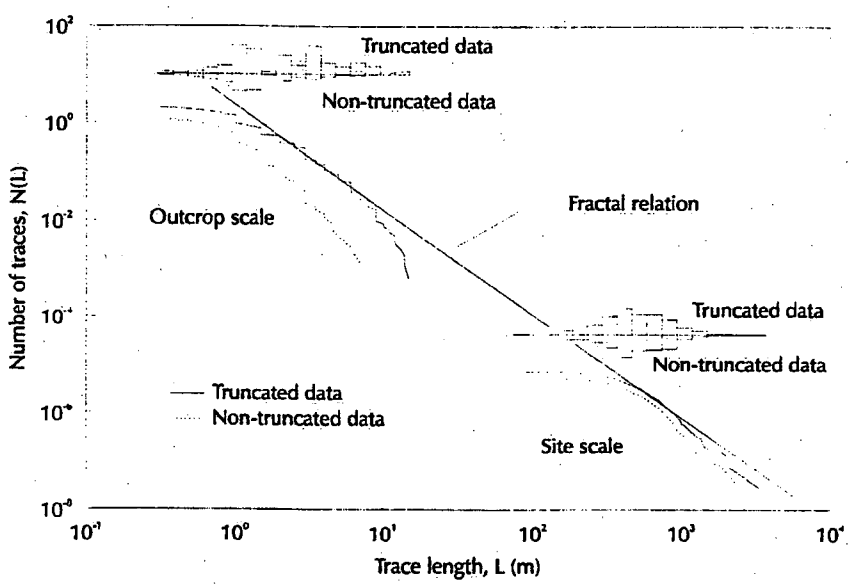

FIGURE 2. Interpretation of the trace length data in terms of a fractal relation.

The fractal relation shown in Figure 2 was fit to the truncated data by matching the two sets of data over the populated portions of the ranges of values that are most consistent with a linear relation. The parameters of the indicated relation are $a_L = 2.40$ and $F_L = 2.16$. The discrepancy

between the truncated and non-truncated site scale data is relatively small and suggests a decrease in the fractal coefficient (i.e., a downward shift of the results) due to the loss of the truncated trace lengths. In contrast, the discrepancy between the truncated and non-truncated outcrop scale data is more distinct and suggests a decrease in the fractal coefficient and dimension (i.e., a downward shift and rotation of the results). Departure of the trace length data from the fractal relation at the upper end of each of the ranges of data may be due to inadequate sampling and an increased probability of truncation. At the lower end of the ranges of data, this departure may be the result of selective sampling of the traces. It is likely that fracture traces measured from air photographs and geophysical data are subject to a lower limit below which traces cannot be consistently resolved. Similarly, it is not possible to map each of the large number of small, faint traces that are exposed in outcrop.

The reasonable match between the trace length data and fractal relation suggests that the distribution of trace lengths is both fractal and consistent at the site and outcrop scales. It is therefore reasonable to conclude that the fracture system at the site of the CRL conforms to the conceptual model in at least an approximate sense. The fractal parameters for the distribution of fracture diameters determined using Eqs. 3 and 4 and the parameters estimated from Figure 2 are $a_D = 3.95$ and $F_D = 3.16$. These findings are not sufficient to prove the accuracy of the model over all sampling scales; indeed, the model is likely to deviate from in situ conditions beyond lower and upper threshold values where the mechanics and history of fracture system formation are different than those at the outcrop and site scales. It may be most appropriate to use the model to estimate fracturing between the site and outcrop scales. This is an important range of values as it approximates the depth at which an excavated repository may be constructed and therefore is characteristic of the probable scale of radionuclide transport to the biosphere.

THREE-DIMENSIONAL RENDERING OF FRACTURE SYSTEM GEOMETRY

Probabilistic renderings of fracture system geometry at the two sampling scales were generated using the procedure described by Piggott (1996). Site and outcrop scale systems with dimensions of 18000 and 60 m, respectively, were generated using the estimated values of the fractal parameters and a lower limit for the sizes of the generated fractures of 600 and 2 m. Next, the intersections of the fracture systems with planar surfaces were computed to form two populations of fracture traces. These traces were then cropped to conform to sampling areas with dimensions of 6000 and 20 m in order to match the dimensions of the in situ samples. The resulting patterns of fracture traces are shown in Figure 3 and are plotted relative to the in situ data and estimated fractal relation. The synthetic outcrop scale data plotted in Figure 3 were sampled by intersecting the traces with 4 scan lines directed through the cropped area. There is a reasonable match between the synthetic and in situ data and the fractal relation at both scales, and the departure of the synthetic data from the fractal relation at the upper and lower limits of the data is similar to that of the in situ data. Further, the synthetic data most accurately match the fractal relation over a similar range of values as the in situ data. These results confirm the accuracy of the plotting and interpretation of the data and the assertion that the departure of the in situ data from the fractal relation may be due to sampling limitations as the synthetic results, which precisely conform to the conceptual model, display a similar departure from the fractal relation.

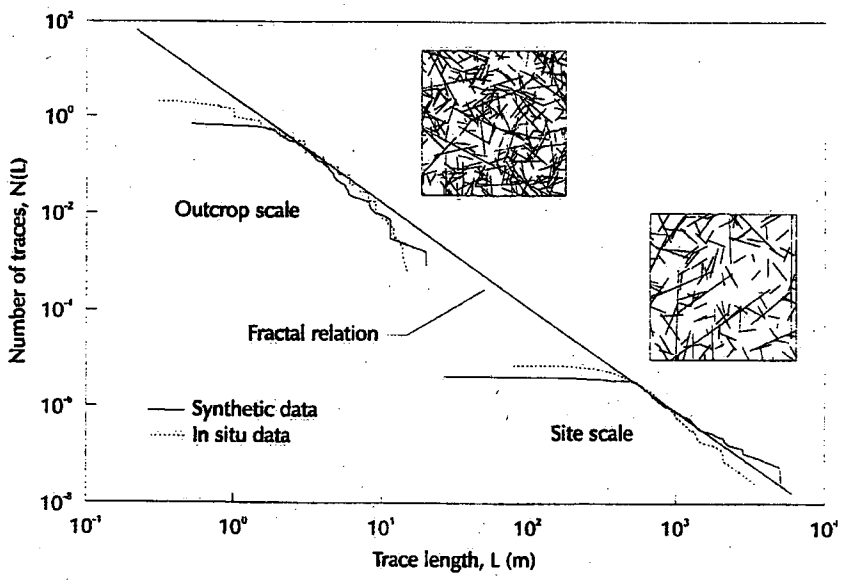

FIGURE 3. Comparison of the synthetic trace length data to the in situ data and fractal relation.

Figure 4 is a three-dimensional depiction of the geometry of a fracture system at the scale of the CRL site. Again, only fractures with diameters greater than 600 m, one tenth the dimension of the site, are represented. Fracture centres were generated within a volume with horizontal dimensions of 10,000 m and a vertical dimension of 2000 m. The resulting fracture traces, the boundary of the site, and the various surface obstructions shown in Figure 4 are displaced relative to the fracture system so that the geometry of the system is more clearly visible. The synthetic pattern of fracture traces is similar to the measured pattern shown in Figure 1. Figure 4 also shows a sample of the fracture system with dimensions of 2000 m. The three-dimensional connectivity of the system is defined by linear intersection segments between the fractures and is very different than the connectivity apparent in sections through the system. Numerous fractures are entirely isolated and do not conduct groundwater while others are only locally connected and conduct groundwater over limited distances. It is evident that a two-dimensional representation of the fracture system based on fractures that match the traces exposed in outcrop and are continuous with respect to depth would conduct groundwater in a very different manner than the three-dimensional representation shown in Figure 4.

CONCLUSIONS AND RECOMMENDATIONS FOR CONTINUING RESEARCH

The results reported in this paper indicate that a conceptual model of fracture system geometry based on a uniform, isotropic, three-dimensional distribution of disc-shaped fractures and a fractal relation between the frequency and diameter of the fractures is a reasonable approximation of the fracture system at the site of the CRL. This model predicts fracturing across a range of sampling scales and will be useful in the prediction of groundwater flow.

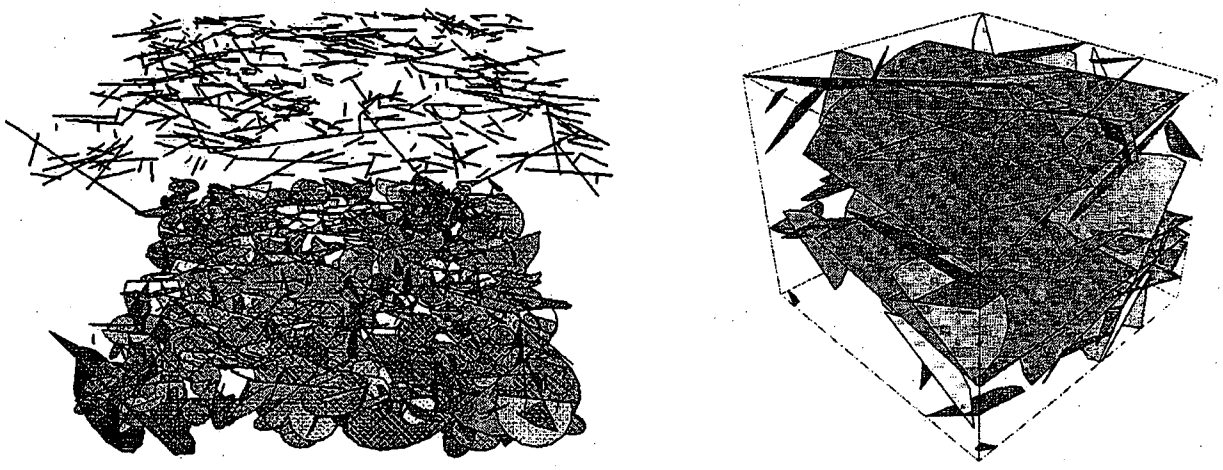

FIGURE 4. Site scale (left) and detailed (right) views of a synthetic fracture system.

Additional research will be required prior to completion of the characterization effort introduced in this paper. In particular, the impact of the truncation of fracture traces at the outcrop scale must be determined in order to reduce the uncertainty associated with the estimated values of the fractal parameters. Further, collection of trace length data at an intermediate sampling scale would allow the continuity of fracturing between the outcrop and site scales to be evaluated. Finally, comparison of the conceptual model to borehole fracture mapping data would allow the continuity of fracturing with respect to depth to be determined. There is evidence that fracturing at the CRL site may be directionally and spatially variable (Raven 1986). The implications of these deviations from the conceptual model must also be determined. Again, it is necessary to maintain a reasonable compromise between meaningful geometric detail, the limited in situ data that is available to support this detail, and the compatibility of the resulting model with subsequent analyses such as simulation of groundwater flow within the fracture system.

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