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INTRODUCTION

An important problem in the storage of radioactive waste in fractured crystalline rock is the characterization of natural fractures for both thermomechanical and hydrologic purposes. From a thermomechanical standpoint fractures can introduce nonlinear behavior in the rock mass response to heating. Hydrologically, fractures represent the principal flow paths for radionuclide transport away from a repository. In the Swedish-American Radioactive Waste Storage Program at Stripa, Sweden, the fracture system is being characterized over either the local or large scale according to the needs of the experiment.[1] The large scale studies are hydrologically oriented and are described elsewhere in the symposium.[2] This paper presents the methodology and preliminary results of analyzing the local fracturing around the underground heater tests at Stripa, focusing on the "time-scale" experiment.[3] This particular test is designed to simulate the thermal effects of an array of eight waste canisters, and a detailed description of it is given by Cook, et al.[5] Interpretation of the test data is proceeding, and the fracture information provided here should facilitate future analyses.

SITE DESCRIPTION

A general description of the geology and fracture system at Stripa is given by Olkiewicz, et al.,[5] and only a brief summary is supplied here. Situated in south-central Sweden, the Stripa iron ore body lies in a synclinal formation of leptite, which is a gray to brownish metavolcanic rock of Precambrian age. The syncline plunges 20° to the northeast, and the underground site is in fine-grained granite in contact with the northwestern limb. The granite post-dates the leptite, and may be associated with several post-orogenic Precambrian plutons in the region. Fracturing in the test area, located at a depth of about 335 m, is pervasive, yet the absence of gneissic structures suggests that tectonism since the intrusion has been relatively mild. A geological study is in progress to investigate the origin and structure of the granite body in more detail.

METHODOLOGY AND RESULTS

Two approaches are used here to characterize the local fracture system. First, major discontinuities are identified in the test area so that they can be modeled as discrete elements of weakness.[6] While these features probably have a major role in the rock mass behavior, they comprise only a small percentage of the fracturing. Most of the other fractures are discontinuous in their own planes, hence the second aspect of the characterization involves defining all fracturing in terms of orientation, spacing, and length of joints. While it is presently impracticable to define or model such ubiquitous joints as they actually exist, techniques are being developed to represent them stochastically.[7]

An important part of fracture characterization is validation; i.e., the various findings must be compatible with each other and with other information concerning the rock mass. A discussion of this aspect will be given in a following section.

Characterization of Major Discontinuities

The success to which major discontinuities can be delineated within a rock mass depends on their continuity and the quality of subsurface information from which they can be identified. Surficial mapping is an aid in assessing the continuity of fractures, and at Stripa, the walls and floors of the heater experiment drifts have been mapped in detail to show all fractures longer that about 0.3 m. The outcrops of features were mapped at a scale of 1:20, using a 1-by-1 m reference grid painted on the rock surface. Information such as rock type variations, fracture fillings, or clear signs of faulting was noted during the mapping. The detailed fracture map developed in this manner for the time-scale drift floor is shown in Fig.1.

Heaters for the experiment are placed 10 m below the drift floor, therefore only the most prominent and continuous features in the map are likely to extend through the heated region and affect the rock mass behavior. Accordingly, only the prominent faults striking transverse to the drift were extrapolated downward and correlated with features in the borehole fracture logs. The correlation of the features was based on observational evidence;

Fig. 1. Detailed fracture map of the floor of the time-scale experiment drift.

i.e., similarity of orientations, coatings, and surface characteristics and proximity to the extrapolated position. Other significant discontinuities may exist near the heaters and not intersect the drift; however, none could be identified with confidence using the observational technique. Results of the discrete characterization are illustrated by Fig. 2, which shows the inferred profile of four shear surfaces that pass through the heater array. These features offset or truncate other discontinuities, and their filling minerals of chlorite, calcite, epidote, and clay are several times thicker than the fillings of other fractures. Fault number 3, which is the most prominent and well-defined of the set, apparently offsets a 20 cm-wide pegmatite dike as shown in the figure.

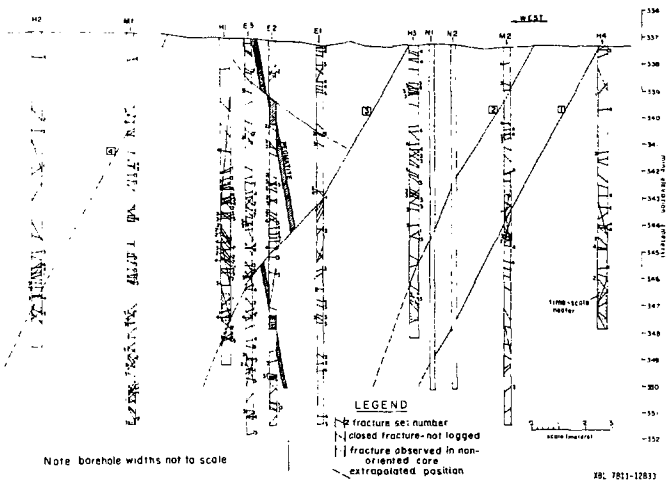

Fig. 1. Profile of fractures along centerline of time-scale drift.

Characterization of Jointing

In order to describe the abundant jointing between the major features, it is preferable to adopt a statistical approach that incorporates both borehole and surficial data. The important parameters are the dominant joint orientations, i.e., joint sets, and the distributions of joint spacings and trace lengths. Fracture logs of the oriented core from the instrumentation boreholes in the time-scale experiment supplied orientation and spacing data. Figure 1 yielded trace length information.

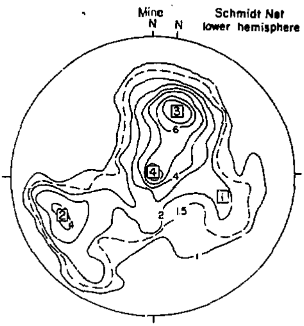

Fig. 3. Stereonet plot of fractures poles
for time-scale experiment.

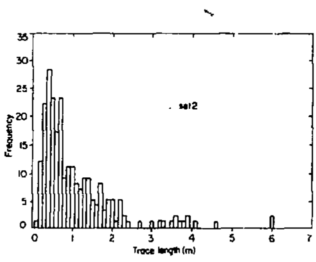

Fig. 4. Histogram of joint lengths.

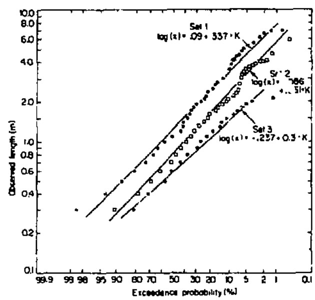

Fig. 5. Lognormal joint length distribution.

The jointing can be separated into four distinct sets according to the pole clusters in Fig. 3. Assigning these set designations to fractures in Fig. 1 allows a compilation of trace lengths to be made. A typical histogram of the data for one joint set is shown in Fig. 4. When these values are plotted in lognormal probability form, the cumulative frequency distributions in Fig. 5 are obtained. The least-squares linear fit through each distribution is of the form

$$\log x = \overline{\log x} + K \cdot \sigma_{\log x}$$

where x is the trace length in meters, $\overline{\log x}$ is the logarithmic mean and $\sigma_{\log x}$ is the standard deviation. K is related to the normal probability function by

$$P(X>x) = (1/\sqrt{2\pi}) \cdot \int_{-\infty}^{K} \exp(-k^2/2)dk$$

where P(X>x) is the probability of exceeding the value x.

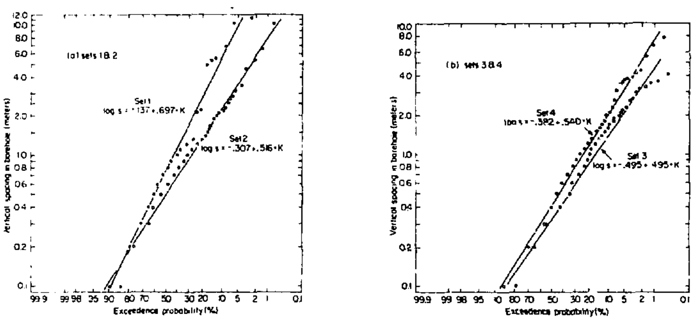

Fig. 6. Lognormal plots of joint spacings for (a) sets 1 &2 and (b) sets 3 & 4.

Joint spacing distributions can be described in a similar manner by assigning appropriate set designations to fractures logged in the boreholes. Vertical spacings are then computed as the distance between consecutive fractures of the same set. Fig. 6 is a lognormal probability plot of the data with the respective distribution equations shown.

Several errors are inherent in the above approach. First, inclined fractures are under-represented by vertical boreholes.[8] This bias could be reduced by incorporating the floor map in the spacing analysis. For the data presented here, the spacing normal to joints is found by multiplying the vertical spacing by the cosine of the mean dip angle of the set. Similarly, horizontal features are missing from the floor map, hence their length distributions are not given. Also, there are biases in the trace length data caused by (a) the minimum length of fractures that were mapped (0.3 m) and (b) the dimensions of the drift. These biases prevent the distributions from being used to predict extreme values outside the range of data upon which they are based.

DISCUSSION

The virgin state of stress has been measured in the underground test site,[9] and this information helps to validate the above findings. Fig. 7 is a stereographic plot of the principal stresses and the mean pole directions to the four fracture sets in the time-scale experiment. The pole of joint set 1, $\hat{n}_1$, corresponds to that of the four faults traced through the rock mass. Resolving the principal stresses into shear and normal components on the mean fault plane,[5] as shown in Fig. 8 yields a theoretical shearing azimuth of 242°. The azimuth of slickensiding on the faults was measured as 240° by field observation and inspection of the fracture intercepts in the core. Reconstruction of the inferred configuration of the fractures by orthographic projection and physical modeling shows the intercept points to be nearly colinear in this direction.[3] In light of this corroboration, the results seem quite reasonable.

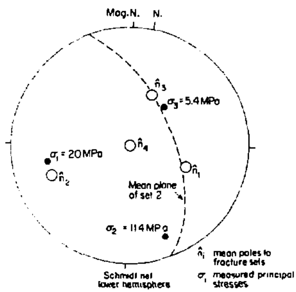

Fig. 7. Stereographic plot of principal stresses and joint set poles in the time-scale experiment.

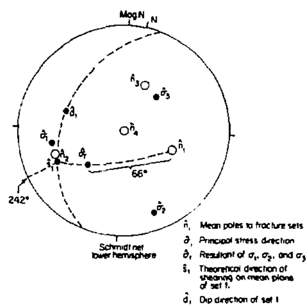

Fig. 8. Stereographic determination of stress components on mean plane of joint set 1.

The origins of the jointing are still uncertain, but it appears likely that set 3 is the youngest of the four sets and may be associated with continuing post-glacial uplift. Three observations in support of this claim are offered: (1) The set lies perpendicular to the existing minimum principal stress (Fig. 7). (2) Joints of this set are predominantly filled with calcite rather than the more common chlorite found in other joints, which suggests a relatively recent transport and deposition. (3) The joints tend to cross or offset nearly all other joints when observed in the core samples.[3]

Statistically, joints of set 3 are shorter and more closely spaced than are the others (Figs. 5 and 6). A shear-to-normal stress ratio of 4.70 has been calculated for the mean plane of the set, which is over twice that for the other joint sets.[3] Thus, if thermal loading or some other perturbation were to propagate or coalesce these fractures, stability problems might arise. The likelihood of this has not yet been addressed in the Stripa analysis, but it appears that some attention is warranted.

The origins of joint sets 1,2 and 4 are also uncertain in the absence of structural information on the Stripa granite. Fractures in set 2 tend to be rough or irregular, suggesting an extension mechanism. Clearly, these could not result from the state of stress reported here, but more likely from a condition where the major principal stress was perpendicular to its present orientation. Such conditions could occur by (a) glacial loading, in which the major principal stress would be closer to vertical, (b) stress changes during cooling of the pluton, or (c) viscous drag during the intrusion process.[10] The othogonality of the joint sets indicates that there is probably a simple explanation for their occurrence, yet it is tenuous to speculate on this with limited knowledge of the regional geology.

Regardless of their genesis, certain observations can be made regarding the engineering significance of joint sets 1,2, and 4. First, with set 2 lying perpendicular to the major principal stress it would be unlikely for these joints to deform appreciably or otherwise affect the stability of the rock mass under moderate stress perturbations. Secondly, radial stress relief around the opening has reduced the compression across the horizontal joints, which should increase the nonlinearity of their deformation behavior. The third point concerns the modeling of joint set 1. The set is effectively represented by the four faults in Fig. 2, since most instability along planes at this orientation would be accommodated by these major weaknesses. The faults are anisotropic, however, due to their lack of planarity transverse to the direction of slickensiding.[3] This anisotropy will be properly represented if numerical models utilize the irregular surface configurations that have been developed,[3] or alternatively, if strength parameters that vary with direction are assigned.

CONCLUSIONS

It is clear that the characterization of the fracture system in a repository is important, and it appears that the purpose of the characterization should dictate the scale over which measurements must be made. The results discussed here pertain to nearfield behavior of a rock mass, and as such they represent a practical limit to the degree to which discrete subsurface discontinuities can be defined by surface mapping and cross-correlation of observational borehole data. It can be stated that discontinuities on the scale of the rock mass being studied can dominate its response, and should therefore be described according to their influence on the stability of the opening and local groundwater regime. Alternatively, if the size or continuity of a feature is much less than the scale of the rock mass in question, there will be insufficient data with which to validate a discrete characterization, hence a statistical approach is required.

It has been demonstrated that in addition to facilitating a discrete characterization of major features, detailed mapping of fractures and thorough logging of core samples can yield valuable statistical information. Efficient collection of data requires prior knowledge of the engineering significance of parameters to be measured. The experience gained at Stripa in characterizing fractures and determining their behavior will contribute to this knowledge.

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