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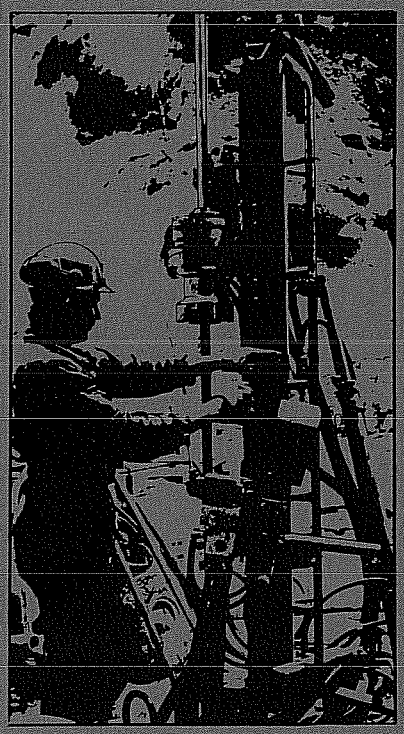
SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Information Report No. 15

AN APPROACH TO THE FRACTURE HYDROLOGY AT STRIPA: PRELIMINARY RESULTS

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May 1979

A Joint Project of

Swedish Nuclear Fuel Supply Co.
Fack 10240 Stockholm, Sweden

Operated for the Swedish
Nuclear Power Utility Industry

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720, USA

Operated for the U.S. Department of
Energy under Contract W-7405-ENG-48

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A03

Presented at the Organization for Economic Cooperation and Development (OECD) seminar on in situ heating experiments in geological formations, held at Ludvika, Sweden, September 1978. To be published in the seminar proceedings.

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This work was prepared under the auspices of the U.S. Department of Energy working in collaboration with the Swedish Nuclear Fuel Supply Company.

PREFACE

This report is one of a series documenting thé results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L. B. Nilsson and O. Degerman for SKBF, and N. G. W. Cook, P. A. Witherspoon, and J. E. Gale for LBL. Other participants will appear as authors of the individual reports.

Previous technical reports in this series are listed below.

1. Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns by P. A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).

2. Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test by Lars Lundstrom and Haken Stille. (LBL-7052, SAC-02).

3. The Mechanical Properties of the Stripa Granite by Graham Swan. (LBL-7074, SAC-03).

4. Stress Measurements in the Stripa Granite by Hans Carlsson. (LBL-7078, SAC-04).

5. Borehole Drilling and Related Activities at the Stripa Mine by P. J. Kurfurst, T. Hugo-Persson, and G. Rudolph. (LBL-7080, SAC-05).

6. A Pilot Heater Test in the Stripa Granite by Hans Carlsson. (LBL-7086, SAC-06).

7. An Analysis of Measured Values for the State of Stress in the Earth's Crust by Dennis B. Jamison and Neville G. W. Cook. (LBL-7071, SAC-07).

8. Mining Methods Used in the Underground Tunnels and Test Rooms at Stripa by B. Andersson and P. A. Halen. (LBL-7081, SAC-08).

9. Theoretical Temperature Fields for the Stripa Heater Project by T. Chan, Neville G. W. Cook, and C. F. Tsang. (LBL-7082, SAC-09).

10. Mechanical and Thermal Design Considerations for Radio-active Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Wastes by Neville G. W. Cook; Part II: In Situ Heating Experiments in Hard Rock: Their Objectives and Design by Neville G. W. Cook and P. A. Witherspoon. (LBL-7073, SAC-10).

11. Full-Scale and Time-Scale Heating Experiments at Stripa: Preliminary Results by Neville G.W. Cook and Michael Hood. (LBL-7072, SAC-11).

12. Geochemistry and Isotope Hydrology of Groundwaters in the Stripa Granite: Results and Preliminary Interpretation by P. Fritz, J.F. Barker, and J.E. Gale. (LBL-8285, SAC-12).

13. Electrical Heaters for Thermo-mechanical Tests at the Stripa Mine by R. H. Burleigh et al. (LBL-7063, SAC-13).

14. Data Acquisition, Handling, and Display for the Heater Experiments at Stripa by Maurice B. McEvoy (LBL-7062, SAC-14).

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SUMMARY

There are two main problems associated with the concept of geologic storage of radioactive waste in fractured crystalline rock: (1) the thermo-mechanical effects of the heat generated by the waste, and (2) the potential for transport of radioactive materials by the groundwater system. In both problems, fractures play a dominant role. An assessment of the hydraulic and mechanical characteristics of fractured rock requires a careful series of laboratory and field investigations. The complexity of the problem is illustrated by the field studies in a fractured granite that are currently underway in an abandoned iron-ore mine at Stripa, Sweden. Much information is being gathered from an extensive series of boreholes and fracture maps. The approach being taken to integrate these data into an analysis of the fracture hydrology is reviewed and preliminary results from the hydrology program are presented.

1. INTRODUCTION

There are two main problems associated with the concept of geologic storage of radioactive waste in fractured crystalline rock: (1) the thermo-mechanical effects of the heat generated by the waste, and (2) the potential for transport of radioactive materials by movement of groundwater through the rock system. In both of these problems, fractures play a dominant role. In the first case, fractures have non-linear deformation characteristics that can modify the displacements induced by thermal loading from a repository. In the second case, in a properly selected repository site, matrix porosity and permeability should be such that no flow can occur through the rock blocks, and hence the fracture system will provide the only pathway for radionuclides to migrate away from the repository. Hence, it is essential to characterize the fracture system in order to properly interpret the thermally induced displacements and stresses around large-scale repositories as well as to provide the framework within which to interpret the fracture hydrology of both local and large-scale flow systems in fractured rock mass.

Figure 1 illustrates the different kinds of discontinuities that are usually present in fractured crystalline rock. These discontinuities reflect to a large degree the nature and number of tectonic disturbances to which the rock mass has been subjected. Joints are usually the most common feature observed because they tend to occur in sets, with the individual joints in any given set being more or less parallel to one another. It is extremely important to recognize that joints are discontinuous in their own planes and tend to extend only over

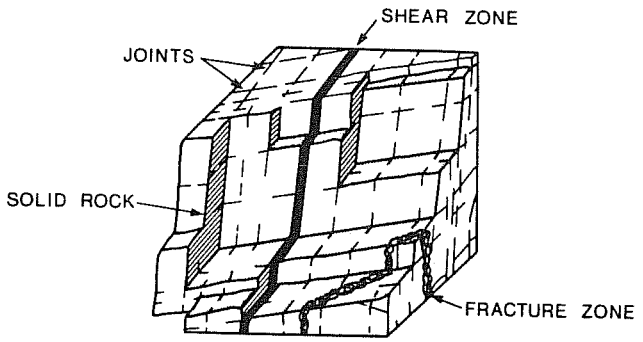

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Fig. 1. Discontinuities in a fractured rock mass.

relatively short distances of a few meters to a few tens of meters. The interconnection of different joint sets is a major factor controlling the hydraulic characteristics of rock masses that are dominated by this kind of discontinuity. Fracture zones are defined as zones of closely spaced and highly interconnected discrete breaks. Such zones range in width from meters to tens of meters, and need not be continuous throughout the rock mass. Shear zones are usually the most pervasive features in that they are usually continuous and, as a result of the shearing action that formed them, are generally filled with broken and crushed rock, which may be embedded in a clay matrix. Such large-scale features can extend for kilometers, but their hydraulic characteristics can vary considerably from point to point.

An assessment of such a rock system requires a very careful series of field investigations. The problem is to gather sufficient information to be able to describe the geometry and characteristics of the fractured crystalline rock. Since the discontinuities are mechanically the most compliant parts of the rock mass, their location and behavior will certainly be a controlling factor in determining the overall

thermo-mechanical effects. Very little is known about the methods that one should use in predicting such effects in connection with the design of an underground waste repository.

Several approaches have been taken in attempting to determine the hydraulic characteristics of fractured rock masses (Witherspoon and Gale 1977). Early work (Romm and Pozinenko 1963; and Snow 1965) was based on a statistical analysis of the rock discontinuities. Two of the key problems have been to determine the fracture aperture distribution and to develop a permeability tensor to describe the hydraulics of the rock mass. Louis and Pernot (1972) have developed an elaborate system of packer tests in oriented boreholes with a number of piezometer points around the injection borehole as an approach to calculating the permeability tensor.

Another approach consists of drilling orthogonal boreholes oriented with respect to the fracture system, and testing the boreholes with increasing packer spacing. It is assumed that as packer spacing increases, the permeability should approach an average value (Maini 1971). A third approach that we are attempting to develop requires careful mapping of the fracture system, drilling boreholes approximately perpendicular to the principal fracture sets, oriented cores, detailed logging of fracture planes, injection tests to determine effective fracture apertures, and the integration of these data into a permeability tensor. This method will be described in more detail below, using results from the Swedish-American cooperative project at Stripa, Sweden to illustrate some of the concepts.

2. PERMEABILITY OF A FRACTURED ROCK MASS

2.1 Basic Equations

The approach that we propose here to determine the permeability of a fractured rock mass assumes that fractures (joints) can be represented as two-dimensional planar conduits with appropriate consideration for roughness and contact area, and that fractures are not randomly distributed in orientation but form sets. Fractures are assumed to be infinite in extent and of constant aperture within their plane; further work to assess the effect of finite fracture lengths has yet to be included. In a given rock system, there can be a number of such fracture sets. If the direction of the normal to the fracture plane (pole) is used to describe the orientation of the fracture plane, then we find that the dispersion of orientations can be described in terms of a standard deviation about some mean value for each fracture set. Data on the spacing of fractures within each set can be obtained from surface outcrops, underground excavations, oriented drill core, and TV-camera surveys of the borehole walls. It is assumed that under similar stress conditions, the apertures of each fracture set can be represented by a log-normal distribution (Snow 1965).

The mathematics of calculating directional permeabilities from fracture orientation and aperture data, assuming that permeability is a function of the aperture squared, was first published by Romm and Pozinenko (1963). Extensive work in this area has been performed by several others (Snow 1965; Louis and Pernot 1972; Parsons 1972; and Caldwell 1971). Kiraly (1969) presents a related contribution

on fracture orientation and density analysis. The basic approach used in calculating direction of permeabilities of a fracture system is discussed below, and follows that of Snow (1965). For single-phase, non-turbulent flow of an incompressible Newtonian fluid, the parallel plate analogy for flow through a fracture is:

$$q = \frac{(2b)^3}{12\mu} \rho g I \qquad (1)$$

where:	q	= discharge per unit width of conduit	L^2/T
	$2b$	= fracture aperture	L
	ρ	= fluid density	M/L^3
	g	= acceleration of gravity	L/T^2
	I	= effective potential gradient	-
	μ	= fluid viscosity	M/LT

Snow defines flow in a single conduit under a general field gradient as:

$$q_j = - \frac{(2b)^3}{12\mu} \rho g \, (\partial_{ij} - M_{ij}) \, I_i \qquad (2)$$

where:	q_j	= discharge vector per unit width of conduit	L^2T
	∂_{ij}	= kronecker delta	-
	M_{ij}	= 3x3 matrix formed by direction cosines of the normal to the conduit	
	I_i	= potential gradient vector	-

Snow further assumes that for a large number of fractures intersecting a sample line, each fracture has its image at a distance L equal to the length of the sample line and in the direction of the sample line. Thus, the spacing between the fracture and its repetition

is given by Bianchi and Snow (1969).

$$w = L|n_i \cdot D_i| \tag{3}$$

where: w = spacing between fractures — L

L = length of sample line — L

n_i = direction cosines of normal to fracture plane — -

D_i = direction cosines of sampling line — -

The permeability of a fracture is then given by:

$$k_{ij} = \frac{2}{3L} \frac{b^3}{|n_i \cdot D_i|} (\partial_{ij} - M_{ij}) \tag{4}$$

where k_{ij} = intrinsic permeability tensor — L^2

The equivalent permeability of the medium at a given sampling station is obtained by summing the contributions from the individual fractures (Bianchi and Snow 1969). Where more than one sampling station is used, the average of all the stations is calculated. Having obtained the permeability tensor for a given rock mass, we must then determine the principal components of the tensor and their directions. This is equivalent to finding the eigenvalues and eigenvectors of the tensor, and has generally involved solving a cubic equation. An analytical solution to the eigenvalue problem based on the analogy with the stress tensor (Ford 1963) should be used to calculate the principal components of the permeability tensor.

2.2 Overall Approach at Stripa

The program of investigations currently underway in the Swedish-American cooperative project at Stripa, Sweden will serve to illustrate the problems involved in determining the permeability of a fractured rock mass. Part of our approach is an extension of earlier work by others (Snow 1965; Parsons 1972; and Kiraly 1969). The overall program (summarized in Fig. 2) consists of five basic field components: (1) calculation of directional permeabilities, (2) geochemical studies, (3) tracer tests, (4) an underground ventilation experiment to measure in situ seepage, and (5) pump tests. All five components will be integrated with and supported where needed by mathematical modeling. The two most unique parts of this program are the calculation of directional permeabilities and the underground ventilation experiment. These will be described in more detail below.

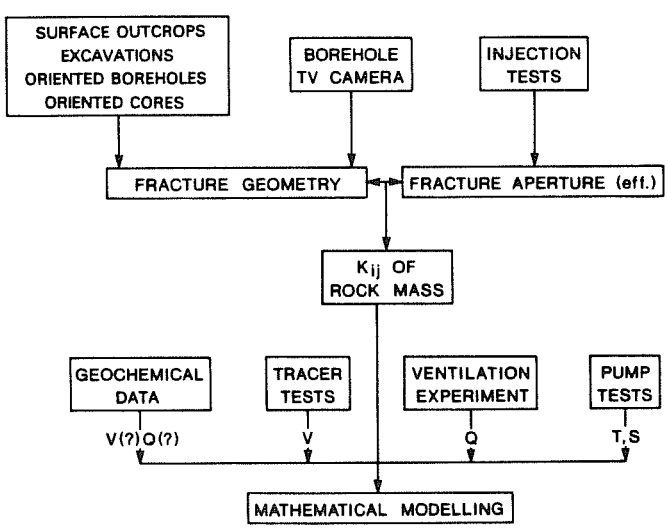

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Fig. 2. Overall approach to determination of fracture permeability.

2.3 Calculation of Directional Permeabilities

Fracture orientations and fracture spacings for the calculation of directional permeabilities are being measured along the walls of subsurface excavations. In addition the drill core from three oriented boreholes will be reconstructed so that the true strikes and dips of fractures can be determined. Each borehole will be treated as a line sample or a series of line samples. The surface and subsurface borehole locations are shown in Figs. 3 and 4.

Figure 3 also shows the distribution of surface outcrops of granite and leptite (metasedimentary rocks) in the area above the test excavations. In this area the contact between the two main rock types trends approximately east-west and plunges about 45° south (Olkiewicz et al. 1978). Figure 5 shows a vertical cross-section along line AB including the

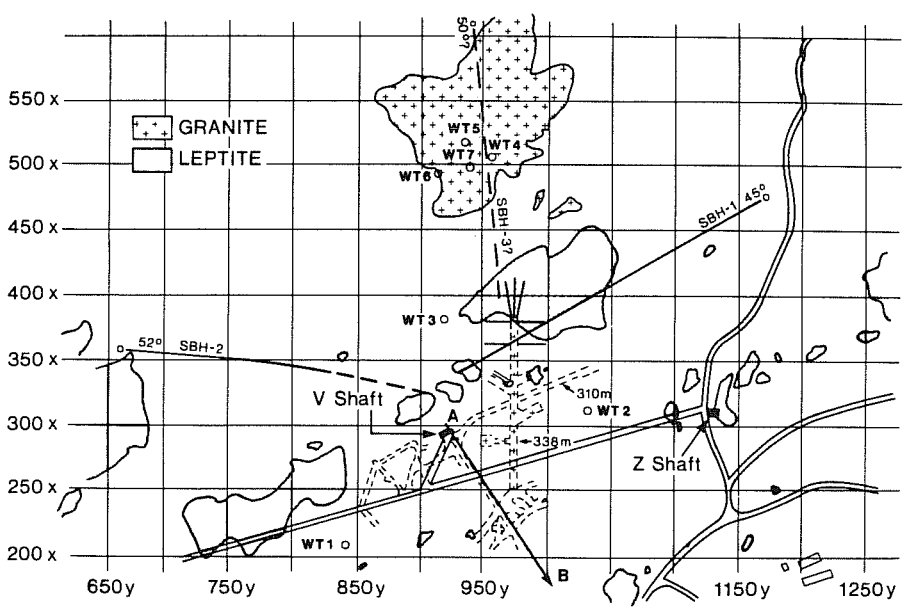

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Fig. 3. Areal geologic map showing general layout of Swedish-American cooperative project at Stripa, Sweden. Glacial deposits prevail except where leptite and granite outcrop.

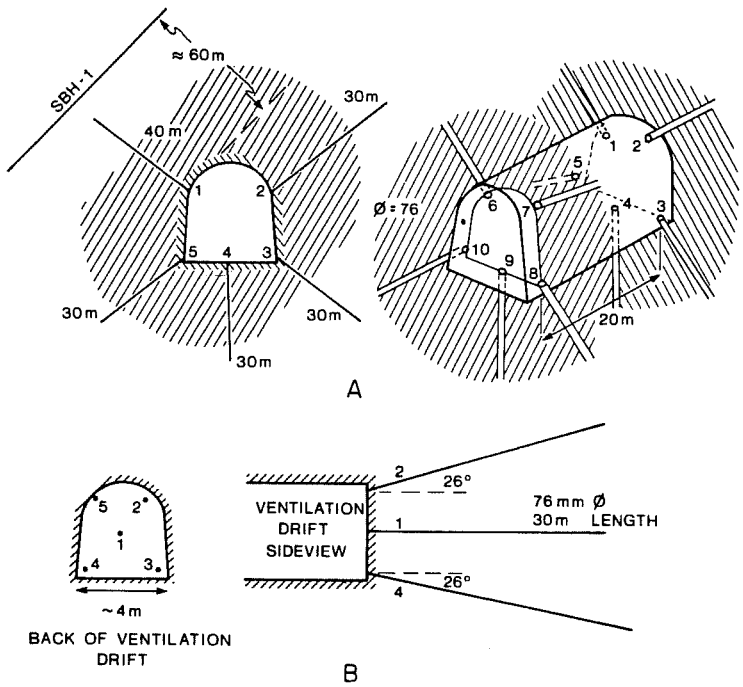

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Fig. 4. Arrangement of subsurface boreholes in the tunnel section used for ventilation experiment.

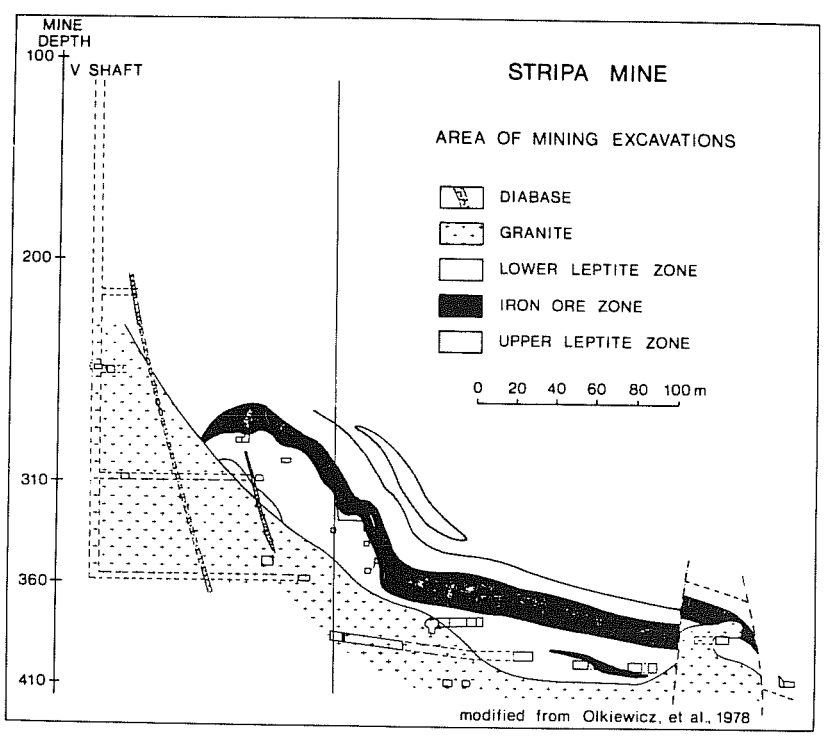

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Fig. 5. Vertical section showing general attitude of granite beneath the leptite (Olkiewicz et al. 1978). Section is along A-B of Fig. 3.

"V" shaft indicated on Fig. 3. The location of test excavations that have been mined at an elevation of 338 m for this project are shown by the dashed outline in Fig. 3. More details of these excavations are shown in Fig. 6.

The surface boreholes consist of six water table wells, WT-1 through WT-6; a pump test well, WT-7; and two long inclined boreholes, SBH-1 and SBH-2 (Fig. 3). A third long borehole, SBH-3, is planned in the location shown on Fig. 3. SBH-1 (an open, 76-mm diameter, diamond-cored borehole, 385 m in length) angles downward at 45°, passes over the top of the test excavations, and terminates at approximately the 290-m level. SBH-2, also diamond cored, was drilled from the west

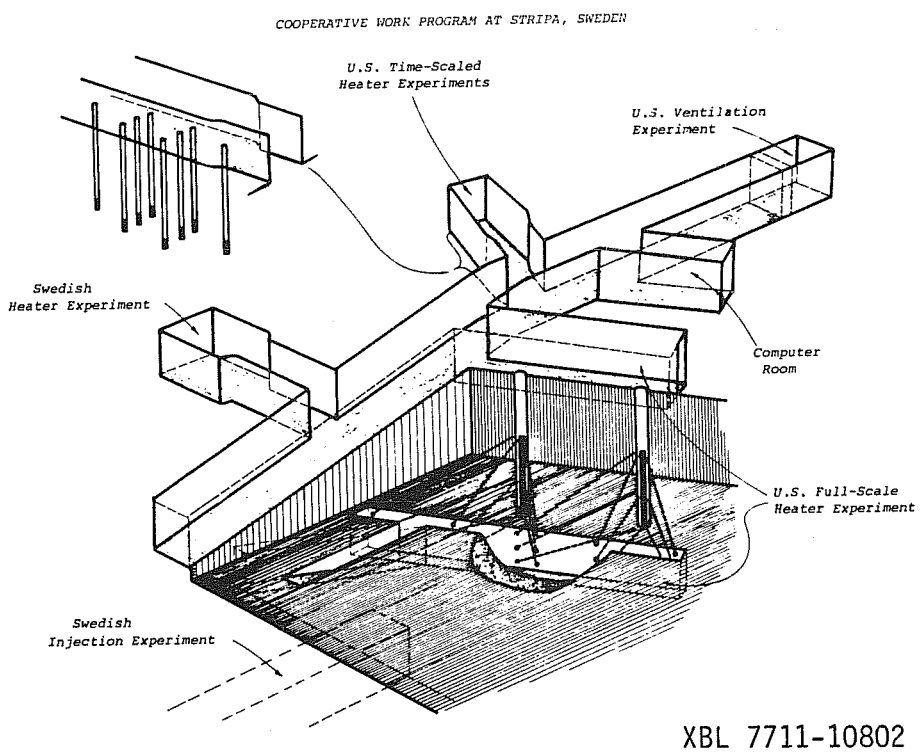

Fig. 6. Isometric view of test excavations in granite rock mass at Stripa.

towards the test excavations. This borehole is 365 m in length, angles downward at 52°, and terminates in the position shown on Fig. 3 at approximately the 290-m level. SBH-3 will be drilled from the north at an angle of approximately 50° south towards the underground test excavations.

The cores from SBH-1 and SBH-2 have already been reconstructed, and both boreholes will be logged with a TV-camera. This will provide two independent checks on the determination of the true strikes and dips for individual fracture planes. Each of the boreholes will be tested with a double packer assembly in three steps: (1) a fixed packer spacing of approximately 2-m length, (2) selected zones using a variable packer spacing, and (3) a fixed packer spacing of 0.3 m in order to test selected fractures. The same approach will be used in drilling and testing SBH-3. This program will provide the necessary geometry and aperture data for calculating directional permeabilities of the fractured rock mass at Stripa, using the equations discussed in Section 2.

2.4 Ventilation Experiment

It is recognized (Olkiewicz et al. 1978) that the surfaces of underground openings in "dry" mines appear to be dry because the permeability of the rock mass is so low that the mine ventilation system can evaporate the water that is slowly seeping into the underground opening. If one could determine the volume of water being removed in this manner from a section of the mine by the ventilation system, one would have a direct measure of the volume of water seeping

into that section of the mine. Furthermore, if the groundwater pressure gradients near the mine opening were known, then it should be possible to determine the rock mass permeability.

The underground ventilation experiment at Stripa is designed to measure the amount of water that is seeping into a 30-m section of tunnel at the end of the main drift (Fig. 6). This section will be sealed off with airtight and watertight bulkheads. A controlled amount of heated air will be pumped into and out of the sealed room, and the change in the water content of the air will be measured. After steady state conditions are reached, the change in water content will give the rate of in situ seepage.

In order to measure fluid pressure gradients in the rock mass adjacent to the ventilation section, two groups of 76-mm-diameter boreholes have been drilled. Ten boreholes approximately 30 m in length have been drilled in two radial patterns, as shown in Fig. 4A. Five boreholes, 30 m in length, have been drilled in a diverging pattern from the end of the ventilation drift, as shown in Fig. 4B. These boreholes will also provide data on the fracture system and fracture permeability in the rock mass surrounding the ventilation experiment.

It should be possible to compare the rock mass permeability calculated from the ventilation experiment with the directional permeabilities discussed above that will be calculated from the injection test and fracture geometry data. Supplementary data will also be obtained from pump tests, tracer tests, geochemical studies, and laboratory studies. These data, when added to the results from directional permeability studies and the in situ ventilation experiment, should provide

the necessary iterative framework within which to interpret the fracture hydrology of the Stripa granite.

3. PRELIMINARY RESULTS

As in any detailed field study, all of the boreholes must be drilled, tested, and the bulk of the supporting studies completed before general conclusions can be drawn. Individual pieces of data can be misleading when considered out of the context of the total data base. In this paper we will restrict ourselves to the presentation of preliminary results that reflect: (1) the general hydrologic and fracture conditions at Stripa; (2) general groundwater ages as determined from isotopic analysis; and (3) the fracture conditions in the rock mass near the time-scaled heater experiment.

3.1 General Fracture Conditions

Figures 7 and 8 show--for SBH-1 and SBH-2--the distribution of rock units and fracture zones identified, RQD (Rock Quality Designations; Deere 1963) values based on 4-m core intervals, and in situ fluid pressures measured during drilling. Both SBH-1 and SBH-2 trend subparallel to the granite-leptite contact, and hence intersect substantial sections of leptite. The RQD values give a qualitative picture of the degree of fracturing; more quantitative data will be presented in subsequent reports. There appears to be a reasonable correlation between RQD values and the fracture zones identified during core logging.

The bottom-hole fluid pressures were measured during drilling, using a single packer assembly to isolate the bottom 3 to 4 m of borehole. The fluid pressures in SBH-1, expressed as pressure at the mid-point of the cavity, were approximately hydrostatic over the first 150 m

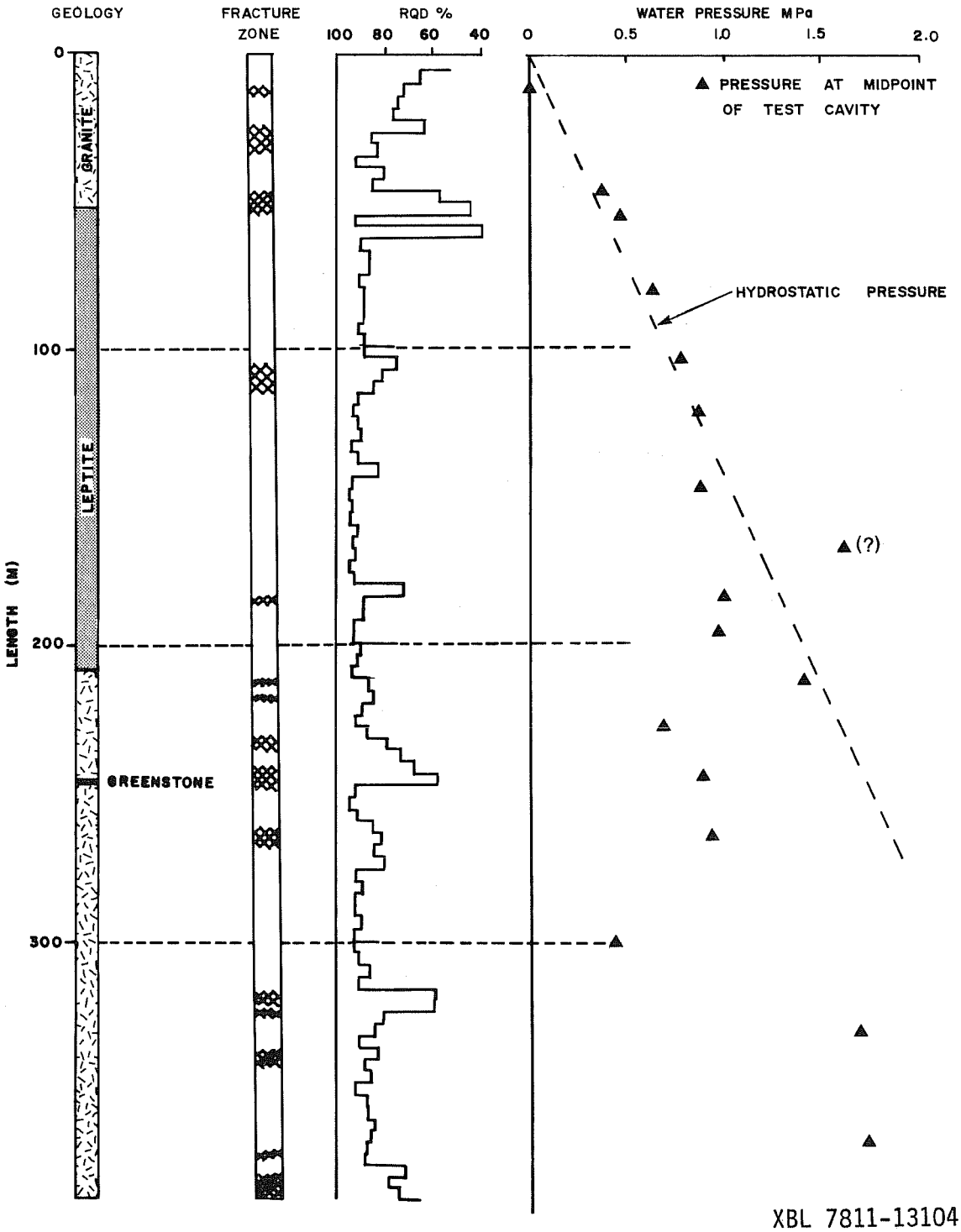

Fig. 7. Results of fracture and pressure measurements in SBH-1.

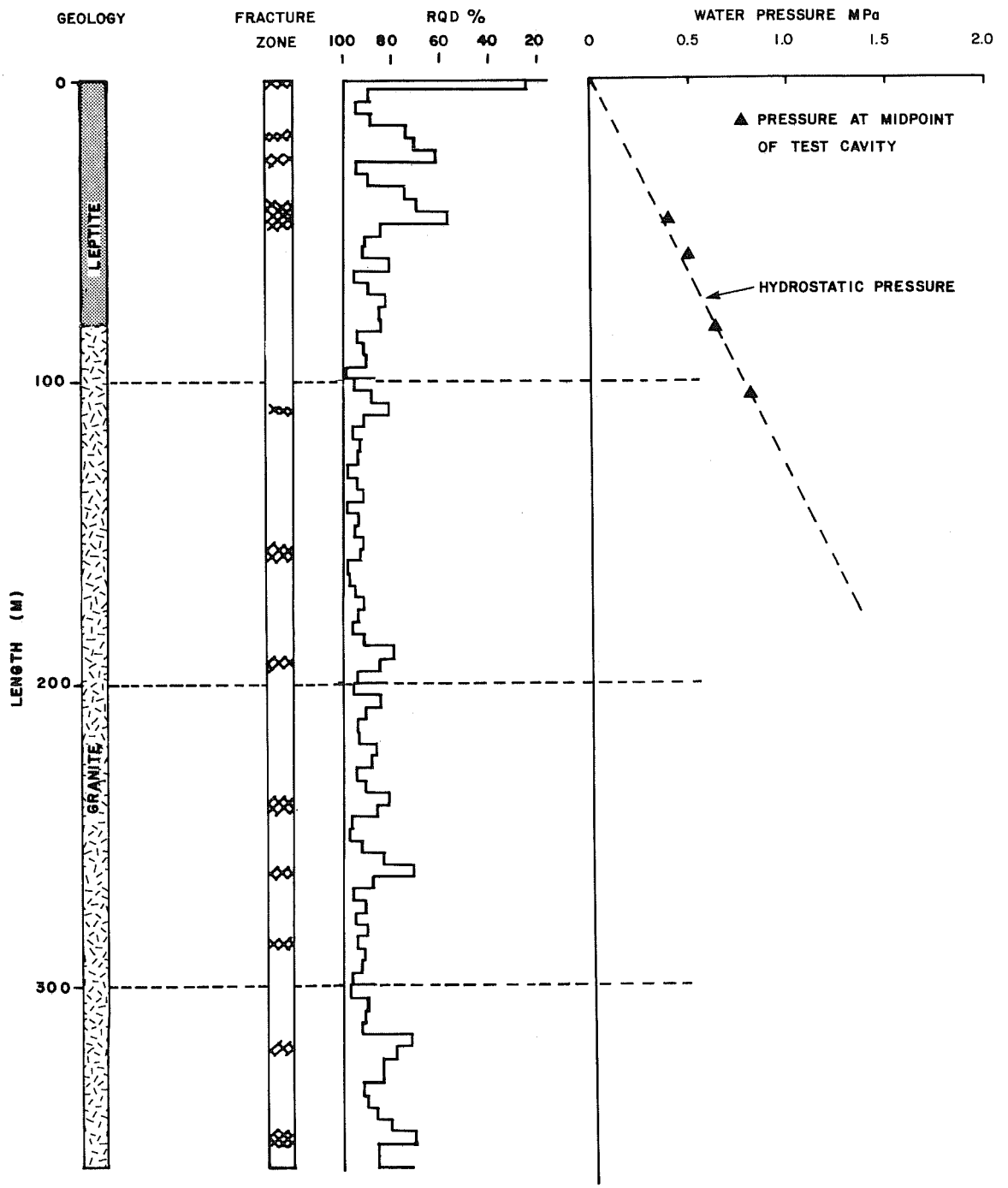

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Fig. 8. Results of fracture and pressure measurements in SBH-2.

of borehole length (Fig. 7). Below 200 to 225 m of borehole length, the fluid pressures were substantially less than hydrostatic. This presumably reflects the perturbation of the flow system by the previous mining activities. The standing column of water in SBH-1 decreased by some 50 m or more of borehole length within 6 months after the hole was drilled.

The in situ fluid pressures in SBH-2, measured during drilling in the upper 100 m of borehole length, also were approximately hydrostatic (Fig. 8). Fluid pressure data were not collected from the lower part of the borehole because of an equipment malfunction, but the water level in SBH-2 has dropped approximately 30 m of borehole length since the hole was drilled.

3.2 Isotope Hydrology Results

The preliminary results from isotope hydrology studies (Deere 1963) are shown in Fig. 9. Figure 9 is an approximate geological cross-section along line A-B of Fig. 3, showing the key groundwater sampling locations for isotopic studies. Groundwater samples have been analyzed for tritium, oxygen-18, oxygen-16, carbon-14, carbon-13, uranium 234/238, helium, and argon. In general the groundwater flowing out of a borehole located at the end of the time-scaled heater room at the 338-m level appears to be about 25,000 years old. Similar ages were obtained from the upper level of a deep vertical borehole drilled from the 410-m level, although some confusion is created by a carbon-14 date obtained from an intermediate depth in this borehole. Note the preliminary result of 90,000 years based on helium, argon, and uranium analysis of a water sample collected at the bottom of

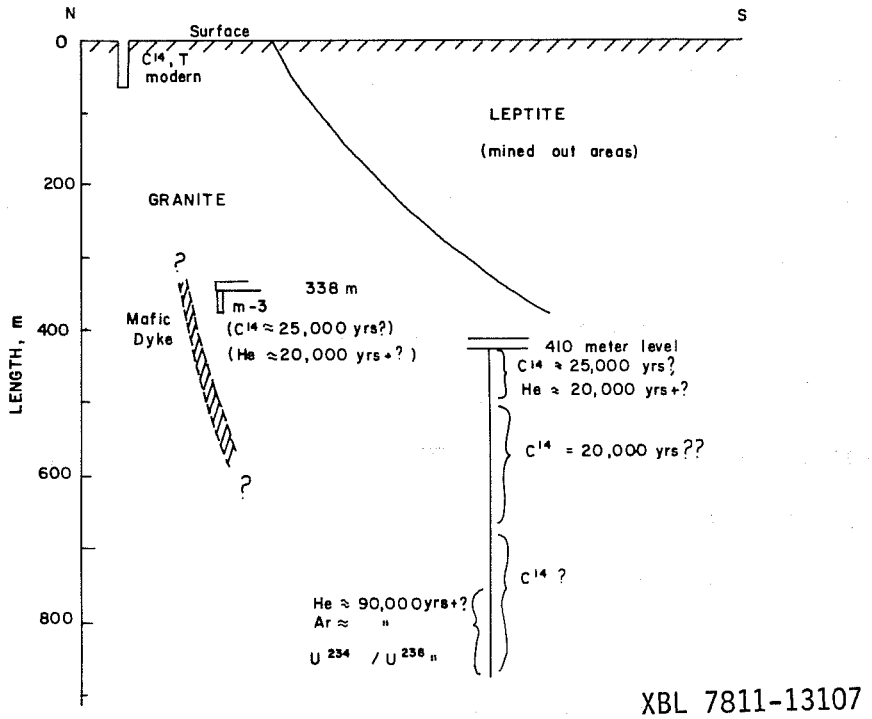

Fig. 9. Preliminary results of isotope age dating of groundwater samples.

this borehole. In the absence of rock analyses showing the potassium content, one can only say that the water is presumed to be fairly old, ranging in age from 10^4 to 10^5 years. In general, the ages determined from helium and argon analyses of water samples collected from the upper part of the 410-m borehole and the 338-m borehole tend to verify the ages determined from carbon-14 samples from the time-scaled heater room and the three depths in the 410-m borehole. Hopefully, further analyses of the rock fracture minerals and additional isotope analyses of water samples will allow us to further pinpoint the age of the water.

Groundwater samples collected from boreholes within the heater rooms (Fig. 6) will be analyzed to determine if the oxygen isotopes are affected by the increasing groundwater temperatures. Preliminary results of the overall geochemical and isotopic hydrology program

will be published in a separate report (Fritz, Barker, and Gale--in preparation).

3.3 Fracture Hydrology Studies Related to Heater Experiments

A series of heater experiments are also underway at Stripa as part of the Swedish-American cooperative program (Witherspoon and Degerman 1978). Part of the fracture hydrology program consists of trying to determine how fluid pressure and permeabilities in fractured rocks are affected by increasing temperatures. This work has involved drilling two 76-mm-diameter boreholes (S-1 and S-2) parallel to the time-scaled room (Figs. 3 and 6). S-1 and S-2 are located on the north side of the time-scaled heater room and are drilled from the main drift at an angle of approximately 30° from the horizontal and parallel to the axis of the room. Each borehole is located north (S-1 is 1 m north; S-2 is 3 m north) of the heater nearest to it in the cluster of heaters shown in Fig. 6.

The general nature of the fracture systems encountered, as well as the in situ pressures and outflow rates prior to the start of the time-scaled experiment on June 1, 1978, are shown in Fig. 10 for S-1 and in Fig. 11 for S-2. These results indicate a considerable variation in the hydrologic conditions within the rock mass in which the time-scaled heater study is being conducted. It should be noted that a dewatering system was operating in the time-scaled room when the in situ pressures were being measured.

All of the eight heater holes in the time-scaled room have been instrumented to permit removal of any water that flows into the boreholes during the experiment. Figure 12 shows the water inflow rates in

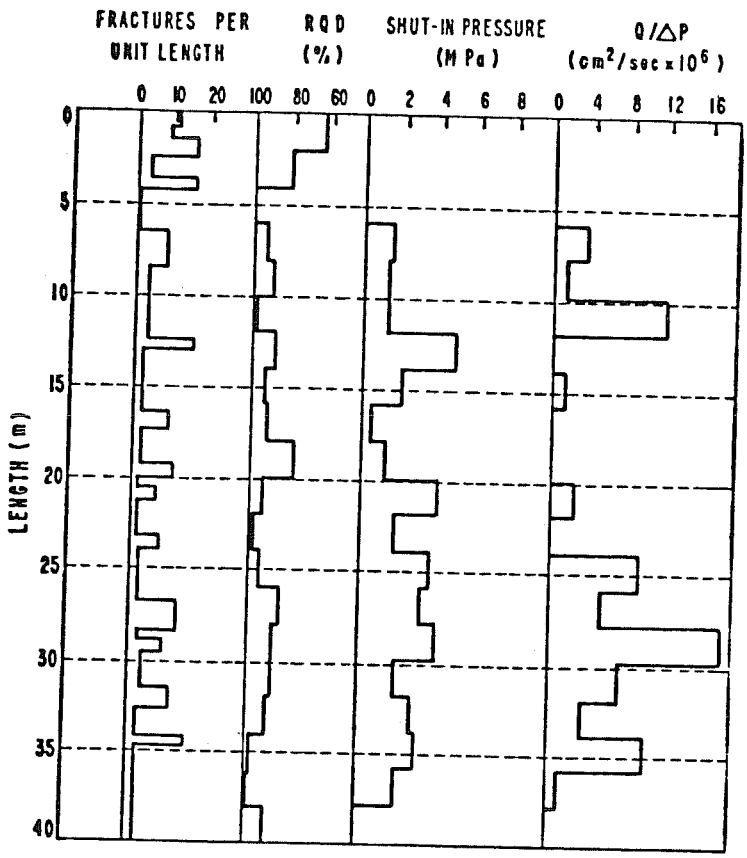

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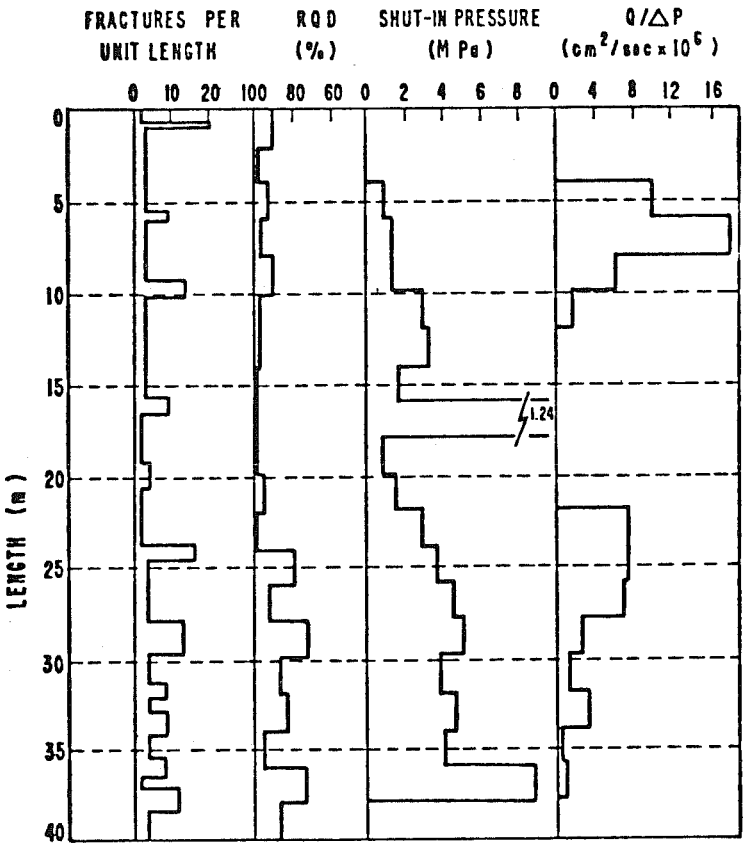
Fig. 10. Results of fracture hydrology measurements in S-1.

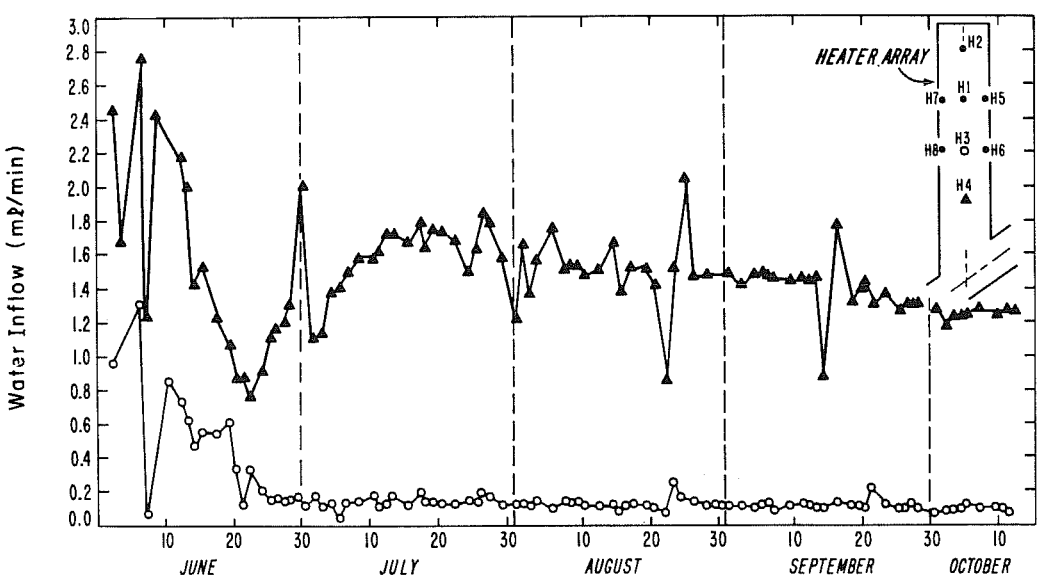
ml/min for two of the heater holes, H3 and H4. After some initial fluctuations in flow rate which occurred shortly after June 1, 1978, when the heaters were turned on, the curves have become reasonably stable.

Inflow rates for H3, on the order of 0.2 ml/min, are typical for most of the heater holes. H4 is located near the entrance to the time-scaled room (Fig. 12), and its much higher inflow rates--ranging from 1.2 to 1.8 ml/min--result from seepage through the disturbed



XBL 793-8919

Fig. 11. Results of fracture hydrology measurements in S-2.

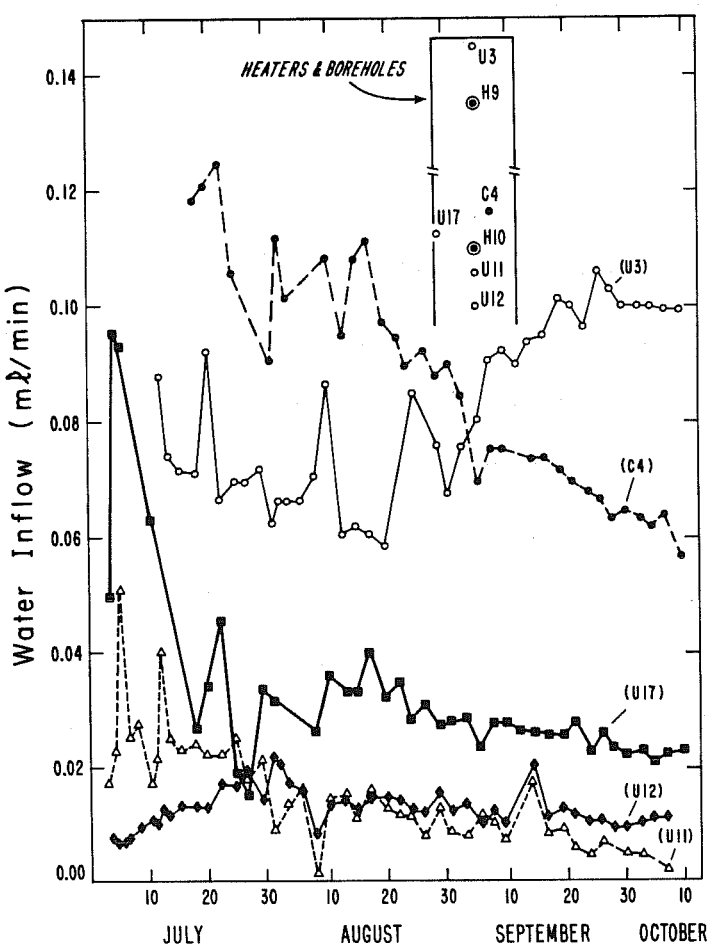


XBL 7811-2143

Fig. 12. Water inflow rates for two heater holes in time-scaled heater room (H-4 shown by triangles, H-3 by circles).

rock mass beneath the floor of the nearby main drift. This observation is supported by the fact that most of the water entering H4 does so from the upper part of the borehole.

Water inflow rates in five instrument boreholes in the full-scale heater room are shown in Fig. 13. Heater H10 was turned on July 3, 1978; heater H9, August 24, 1978. Note that the inflow rates are much smaller than has been observed in the time-scaled heater room



XBL 7811-2145

Fig. 13. Water inflow rates for five instrument boreholes in full-scale heater room.

and range from 0.01 to 0.10 ml/min. With the exception of instrument hole U3, the general trend in the inflow rates has been downward since heater H10 was turned on.

Borehole inflow rates will be monitored in both the time-scaled and full-scale heater rooms on a continuing basis. Some consideration is being given to continuing the time-scaled experiment with no dewatering for a short period of time in order to determine the impact on the temperature field and the groundwater gradients.

4. CONCLUSION

The analysis of fracture hydrology in a discontinuous rock mass is a very complex problem that needs much more investigation. The complexity of the problem is illustrated by the situation at Stripa, Sweden. In order to understand the results of the heater studies, the fracture geometry and mechanical behavior must be integrated. The thermal loading effects involve the coupled problems of heat flow, fluid flow, and stress changes. This coupling inevitably involves the behavior and properties of the network of fractures, a phenomenon under investigation at Stripa.

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This report is part of a cooperative Swedish-American project supported by the U.S. Department of Energy and/or the Swedish Nuclear Fuel Supply Company. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory, the Department of Energy, or the Swedish Nuclear Fuel Supply Company.

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