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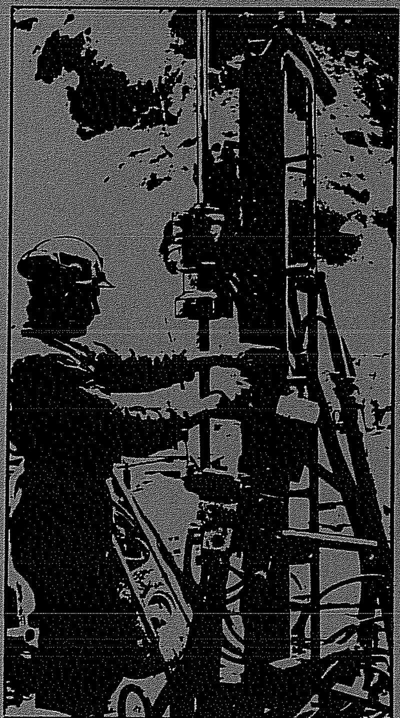
SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Information Report No. 18

ROCK MASS CHARACTERIZATION FOR STORAGE OF NUCLEAR WASTE IN GRANITE

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February 1979

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Paper to be presented to the 4th Congress of the International Society for Rock Mechanics, Montreux, Switzerland, September 2-8, 1979.

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February, 1979

PREFACE

This report is one of a series documenting the 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 Lundström and Håken 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. Halén. (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 Radioactive 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).

15. An Approach to the Fracture Hydrology at Stripa: Preliminary Results by J. E. Gale and P. A. Witherspoon. (LBL-7079, SAC-15).

16. Preliminary Report on Geophysical and Mechanical Borehole Measurements at Stripa by P. Nelson, B. Paulsson, R. Rachiele, L. Andersson, T. Schrauf, W. Hustrulid, O. Duran, and K. A. Magnusson. (LBL-8280, SAC-16).

17. Observations of a Potential Size-Effect in Experimental Determination of the Hydraulic Properties of Fractures by P. A. Witherspoon, C. H. Amick, J. E. Gale, and K. Iwai. (LBL-8571, SAC-17).

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1. INTRODUCTION

1.1 Basic Data Requirements

The underground storage of nuclear waste requires assurance of long-term hydrologic containment of potential contaminants and structural integrity of the rock mass during the operational phase of the repository. For storage sites in crystalline rocks such as granite, the success of the repository will depend largely on the behavior of the fracture system during the thermal cycle associated with radioactive decay of the waste. The basic fracture system parameters that require identification are spacing, orientation, aperture (opening), and continuity. In addition to these basic factors, the effect of stress either from tectonic and lithostatic loads or from temperature changes on the apertures of existing fractures and the creation of new fracture surfaces must be considered.

Lawrence Berkeley Laboratory, in conjunction with the Swedish Nuclear Fuel Safety Board (KBS), is conducting a program of heater tests, hydrologic tests, and fracture system characterization studies in granite adjacent to an iron mine at Stripa, Sweden. Test chambers at the 338-m level of the mine have been excavated for tests involving heaters for waste-canister simulation, and boreholes have been drilled from both surface and subsurface locations for fracture mapping and testing. Rock mass characterization is being pursued by four different methods:

1) mechanical characterization - including monitoring the responses to thermal loading of jointed rock in situ, and mechanical tests on cores from 25 mm to 1.0 m in diameter.
2) geological characterization - including detailed surface mapping, subsurface mapping, and core mapping.

3) geophysical characterization - using a variety of borehole techniques, with emphasis on sonic methods.

4) hydrologic characterization - through injection tests, pump tests, water pressure measurements, and controlled inflow tests to tunnels.

1.2 Geology of Stripa Mine and Configuration of Boreholes

The Stripa mine, located in south-central Sweden, is an inactive iron mine which drew its ore from hematite-rich zones in leptite, a quartzo-feldspathic metamorphic rock of the granulite facies. This leptite was intruded by a medium-grained granite in which a considerable part of the mine accessways are located. It is from such drifts at the 360-m level of the mine that drifts were excavated for the in situ heater tests and other experiments at the 338-m level (Fig. 1). The location of the surface holes relative to surface geology and the experiment drifts is shown in Fig. 2.

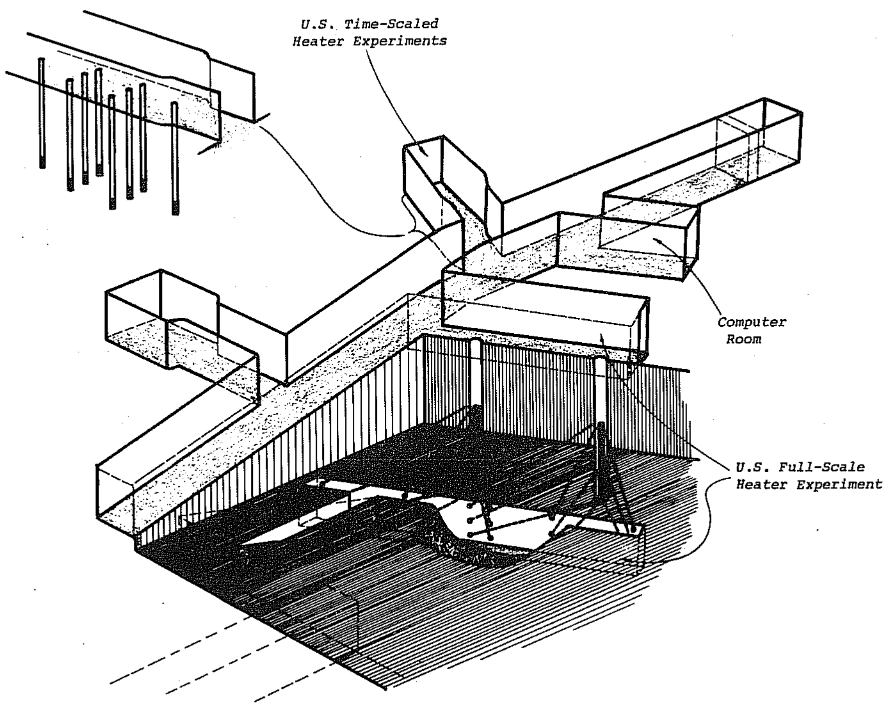

Fig. 1. Isometric view of test excavations at Stripa. (XBL 7711-10802A)

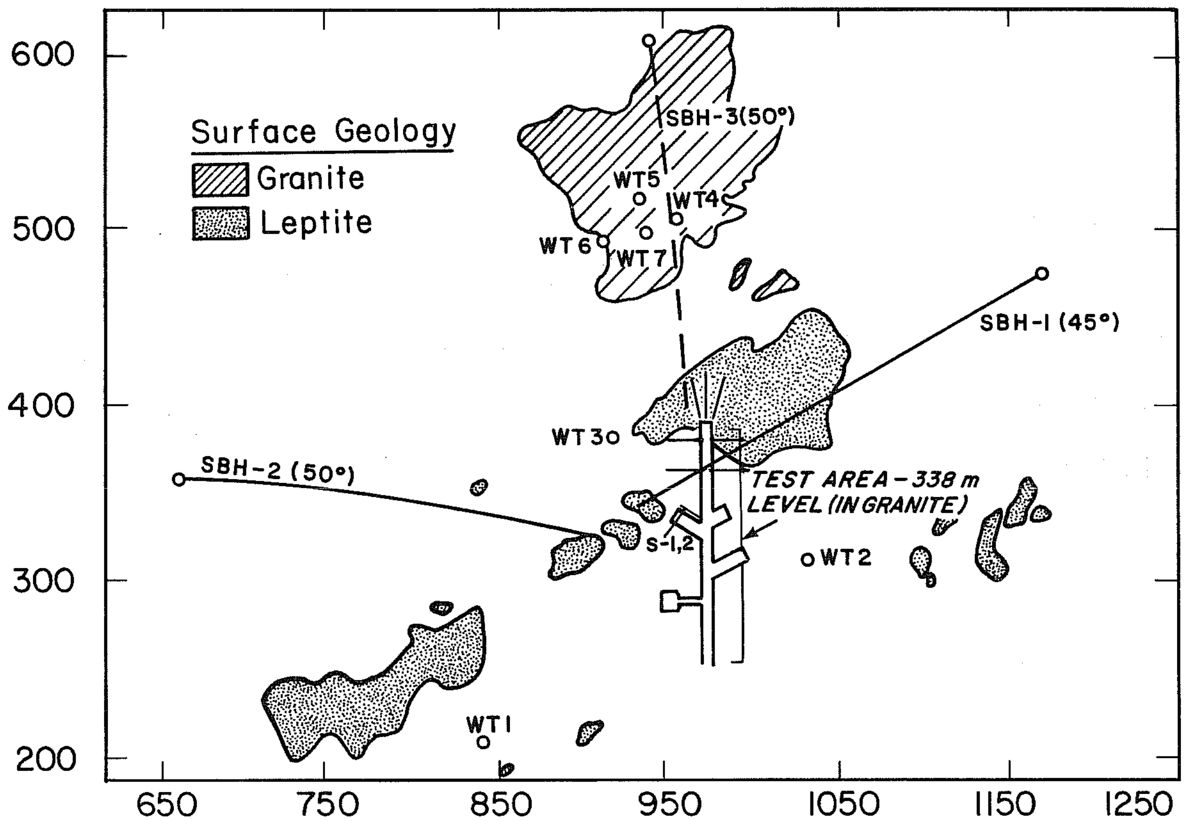

Fig. 2. Relative locations of bedrock outcrops, surface boreholes, and test excavations. (XBL 792-7380A)

In addition to the boreholes and rooms associated with the heater tests, a 40-m-long drift was excavated for a controlled ventilation test to determine the magnitude of the water flow into a portion of the mine both as liquid and as vapor. In this drift two sets of five holes were drilled radiating from the drift axis (Fig. 2). Five additional holes radiating from the end of the drift have been drilled for use in crosshole water pressure pulse tests and crosshole geophysical work. All fifteen of these ventilation drift holes are being equipped with packers to isolate five separate zones in each hole for pressure measurements to determine the effect of the drift on the hydraulic potential field.

The surface boreholes consist of six water wells, WT-1 through WT-6, a pump test well WT-7, and two long inclined boreholes, SBH-1 and SBH-2 (Figu. 2). A third long borehole SBH-3 is planned in the location shown on Fig. 2. SBH-1 is an open, 76-mm-diameter, diamond corehole, 385-m in length, that angles downward at 45° and passes over the top of the test excavations terminating at approximately the 290-m level. SBH-2, also diamond cored, was drilled from the west towards the test excavations. This borehole is 365-m in length, angles downward at 52° and terminates in the position shown in Fig. 2 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.

2. MECHANICAL CHARACTERIZATION

Mechanical characterization of the rock mass has been pursued mainly by in situ heater tests in chambers especially excavated for experimental purposes (Fig. 1). Two sets of heater tests are underway - a full-scale test and a time-scaled test (Witherspoon and Degerman 1978).

The full-scale experiments are designed in granite using two heater canisters 3-m long and 0.3-m in diameter which simulate proposed radioactive waste canisters both in size and energy output. The rock surrounding the heaters has been thoroughly instrumented, as discussed in another paper (Pratt et al, in press). The first heater was started July 3, 1978, the second on August 24, 1978.

The time-scaled experiment was designed to investigate long-term effects and consists of an array of eight 1-kW heaters. Whereas transient heat conduction calculations depend on a dimensionless quantity - the ratio of linear distance to the square root of the product of thermal diffusivity and time, the distance between the heaters has been reduced to $1/\sqrt{10}=0.32$ of the scale of an actual repository; this scaling allows a ten-fold compression in the time dimension so that one year of experimental data simulates ten years of repository life. The time-scaled experiment began June 1, 1978 (Cook and Witherspoon 1978).

Details of the experiment results are discussed in Cook and Hood (1978). Preliminary findings indicate that temperature data closely follow predicted results based on continuum modeling; stress values are about 80 percent of the prediction; however, displacements are lower than predicted, possibly due to thermal expansion of the rock into spaces between joint surfaces.

3. GEOLOGIC CHARACTERIZATION

3.1 Basic Objectives

Geological characterization is the process of defining the geometry of fracture systems using data from core and mapped surfaces. The results are used to better understand the results of the thermal experiments and - when combined with fracture aperture - to provide directional hydraulic conductivities.

3.2 Core Orientation

As core was removed from the split inner barrel of the triple tube assembly, it was reconstructed, i.e., open fracture surfaces were mated to one another to restore the core pieces to their proper relative orientation. The core was then scribed with a permanent marking pen along the side of the core parallel to an orientation mark. This mark was made at the begining of each core run using a wireline "indentor" which would follow the lowest side of the hole. The use of the indentor was similar to the use of paint markings by Rosengren (1967). In the shallower vertical holes drilled for the heater experiment instrumentation, a guide was used to direct the indentor which was oriented relative to a surveyed line at the top of each borehole. This method was used for holes as long as 14 m.

3.3 Core Logging

Core-logging process included recording of fracture orientation, roughness amplitude, planarity, mineralogy and hardness of fillings, weathering, slickensiding, and whether the fracture was open, closed, or induced by drilling. Triple tube, split inner barrel equipment was used for all 76-mm holes; a very high degree of recovery and preservation of fracture features was achieved. Polaroid photos were taken as soon as the core was exposed, and color slides were taken after logging for permanent records. Calculations were also made of mean core length and RQD.

3.4 Mapping and 3-D Characterization

Detailed mapping was done in the heater experiment drifts in order to define discontinuities which would affect the local rock-mass behavior. Virtually all fractures with traces greater than about 0.5-m length were mapped from the drift floors, using a 1:20 scale (Fig. 3). This degree of detail reduced interpretive bias and provided an accurate representation of the complexity of the joint system. Stereophotos were taken of the drift walls, from which prominent features were traced. From the detailed floor maps and the wall tracings, certain "major" features were delineated on the basis of length, thickness, and continuity. The general selection criteria were (a) thickness greater than about 1 cm and (b) continuous lengths

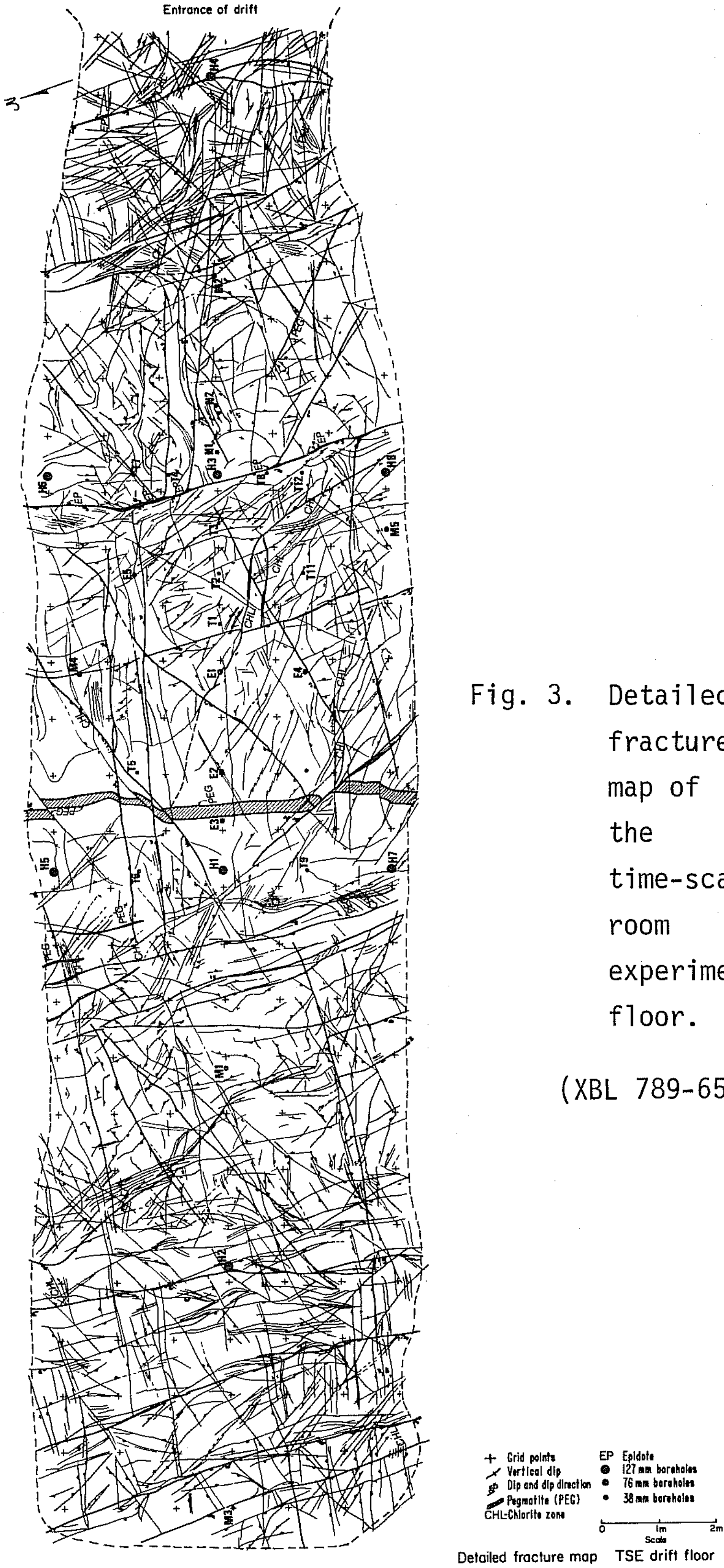

Fig. 3. Detailed fracture map of the time-scale room experiment floor.

(XBL 789-6535)

greater than about 3 m. The principal objective was then to locate these features beneath the drift floors by means of correlation with core samples and corresponding detailed fracture logs. An effort was also made to delineate major subsurface features not intersecting the drift floors by crosshole correlation of fracture logs. Criteria for the crosshole correlations were based on a similarity of (1) extrapolated and actual position, (2) orientation, and (3) mineralization characteristics.

The most prominent set, based on thickness and continuity, strikes roughly perpendicular to the drift centerline and dips westerly at 60 to 70°. The fact that other features appear to be truncated or offset by this set implies faulting, but the amount of apparent displacement is less than 2 m. Because of their prominence, fractures of this set were extrapolated numerically, then correlated with reasonable success to fractures identified in the core samples.

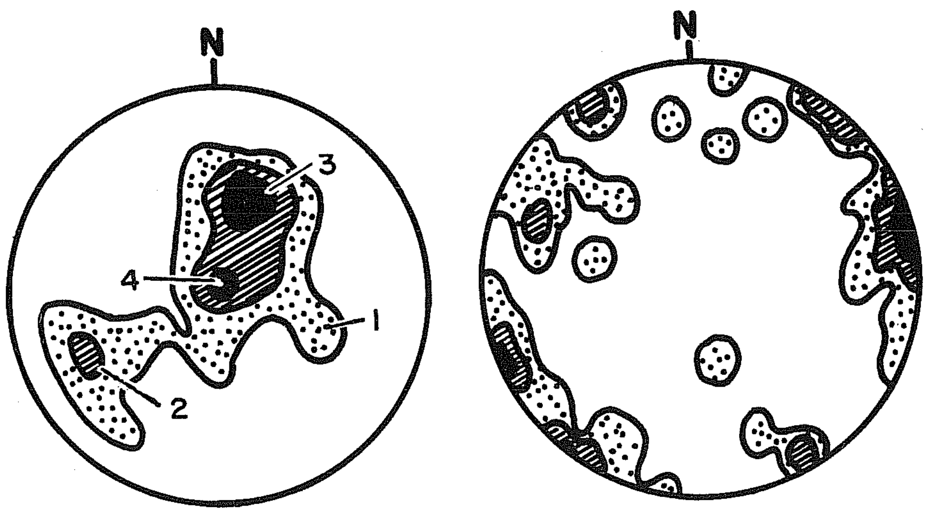

Fig. 4. Equal area projection of joints from the time-scale room core (left) and surface exposures (right). Contours are 1.5, 5, and 10 percent. (XBL 7812-13227)

Figure 4, an equal-area contour plot of all fractures logged in the time-scaled-room core samples, shows that these discontinuous fractures fall into three relatively distinct joint sets labeled 2, 3, and 4. Set number 1 is poorly defined in the stereoplot; however, it is significant that it correlated well with the major features shown in Fig. 3. Set 2 likewise is represented in Fig. 3, yet set 3 is not expressed by the mapping. This suggests that joints in set 3 may be less than 0.5 in dimension, and thus not shown in the map. Mapping of set 4 is clearly biased by its subhorizontal orientation. Set 2 correlates well with the major fracture orientation on the surface (Fig. 4b).

3.5 Effect of Fractures on Heaters

The set 1 joints have two attributes that suggest they may undergo significant shear due to thermal loads. First, the set 1 joints have large trace lengths relative to the other sets (Fig. 3); and second, the set 1 joints are oriented obliquely relative to the major axis of the heater array. Sets 2 and 3 should also be subject to shearing, but to a lesser degree due to their discontinuous nature. Set 4 should be significant in terms of measured rock deformation, since these nearly horizontal joints should experience considerable vertical (normal) compression.

4. GEOPHYSICAL CHARACTERIZATION

4.1 Introduction

Both surface and borehole geophysical techniques promise to play an important role in the characterization for a waste repository. Our work has concentrated on borehole methods due to difficulty in interpreting surface data in a geological setting complicated by the proximity of iron-bearing formations. The Stripa project has emphasized geophysical borehole methods for the following: definition of fractures, providing information pertinent to the assessment of permeability, indicating the physical and chemical homogeneity of the rock, quantitative measurement of the water content and porosity, and locating fractures or other major inhomogeneities between boreholes. Each of these tasks has been addressed before in other geophysical applications such as hydrology (Keys and McCary 1971), mining (Glenn and Nelson, in press), and engineering (Van Schalkwyk 1976), as well as petroleum engineering. However the combination of the crystalline rock environment and repository criteria impose new problems for borehole measurements. For example the tight pore structure of unaltered crystalline rock means exceptionally high electrical resistivity and low water content, conditions not commonly investigated by electrical and neutron methods. Furthermore the expected stringent requirements on fluid flow properties require an extremely high degree of resolution in locating fracture discontinuities and in determining their properties. The geophysical borehole investigations at Stripa represent an initial step in assessing the applicability of available techniques in achieving these ends.

4.2 Borehole Instrumentation

The geophysical logging system used was capable of working with a wide variety of logging tools both on surface to depths of 380 m and in holes underground (Nelson et al., in press).

Signal transmission from the probes to the electronics in the logger is either pulse or analog, with subsequent conditioning and conversion to time-averaged analog output for recording on the chart recorder.

Certain modifications were necessary to adapt individual probes to the exploration of an unweathered granite. For example, the neutron-thermal neutron probe was carefully calibrated in a granite block with a water porosity which could be artificially varied over 1 to 3 volume percent range, yielding a calibration of -80 counts per second per 1 volume percent porosity change in a 76-mm water-filled borehole. In the case of the caliper probe, a special set of arms was ordered which gave extremely good sensitivity in the 76-mm holes, such that diametral irregularities of a fraction of a millimeter could be observed.

4.3 Discussion of Specific Methods and Examples

Gamma logs reflect the amount of radioactive uranium, thorium, and potassium in the rock and are useful for assessing the background radioactivity for later repository modeling, water age dates, and rock-chemical homogeneity. An unusual feature of the Stripa granite is the high content of uranium and thorium; both occur at concentrations roughly 10 times greater than that considered normal for a granite (Clark 1966). The uranium and thorium content is also quite variable within a single borehole. Individual features which are anomalous in uranium and thorium can be tracked across the boreholes of the heater test areas, as shown in Fig. 5. The ultimate cause of such geologic inhomogeneities can only be resolved by detailed petrographic and elemental analysis; but, in any case, the probe can clearly demarcate zones which may have different mechanical or flow properties, either in the geological past or in the potential future of a repository.

Another parameter of interest in the site investigation for a repository is the water content of the rock, including the water which is mineralogically bound as well as the water in the pore spaces. Ideally what is sought is the water present in each of four categories: mineralogically bound water, water in pore spaces which are interconnected, water in cracks

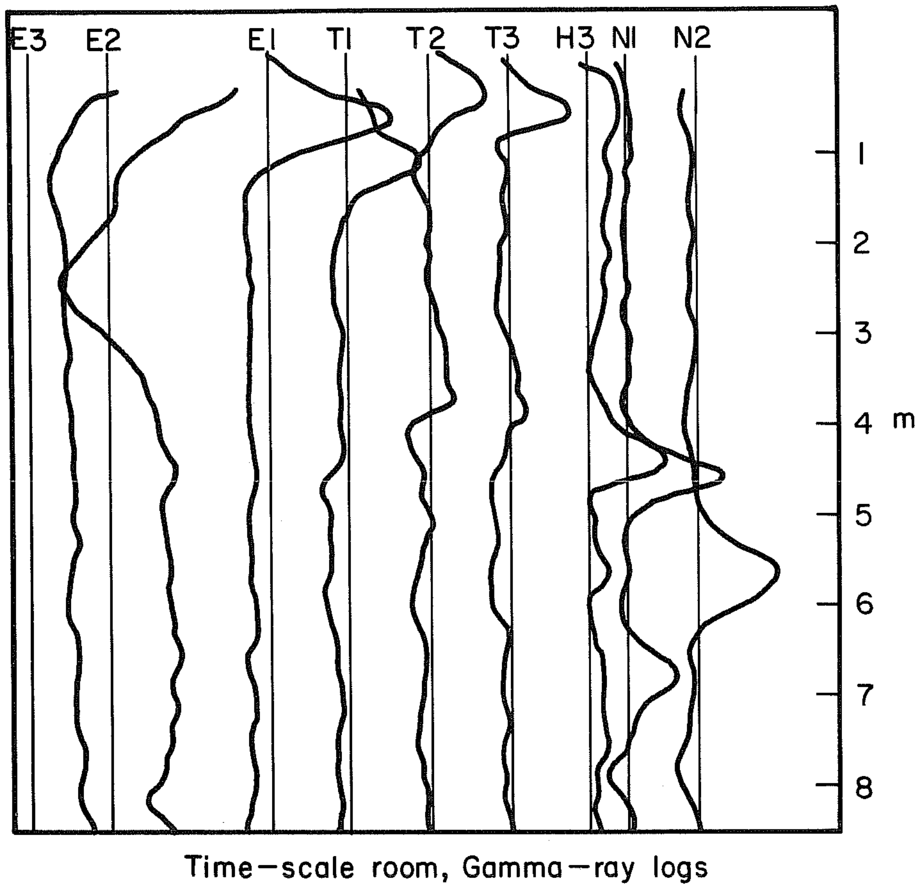

Fig. 5. Gamma-ray logs, time-scale room holes. (XBL 785-910)

and fractures which are interconnected, and water in cracks and fractures which is relatively free to move. As a rough approximation, the quantities of water in these four categories are 1 percent, .5 percent, 1 percent, and 0.1 percent, respectively, in unaltered igneous rock (Norton and Knapp 1977). At present there is no method of recovering this information, especially at such low volumetric percentages. At Stripa emphasis was placed on the neutron-thermal neutron measurement, which measures the water content through the moderating influence of the hydrogen atoms upon the high-energy neutrons. Using a 1-Ci americium-beryllium source and a helium-3 thermal neutron detector, a sensitivity of better than 0.5 percent was obtained in the continuous logging mode; in the stationary mode, counting for 30 sec., the standard deviation in the water estimate is about 0.1 percent. An example of the neutron logs in Fig. 6 demonstrates the character of inhomogeneities detected with the neutron-tool probe. The logs in holes N1 and N2 indicate fluctuations in the water content of about 1-1/2 percent, attributed to the concentrations of chlorite in the rock. As in the case of the gamma-ray log, a side benefit is the identification of the location and scale of inhomogeneities in the rock mass.

Another common log that responds to water content is the electrical resistivity which in igneous rock appears to respond to the inverse second

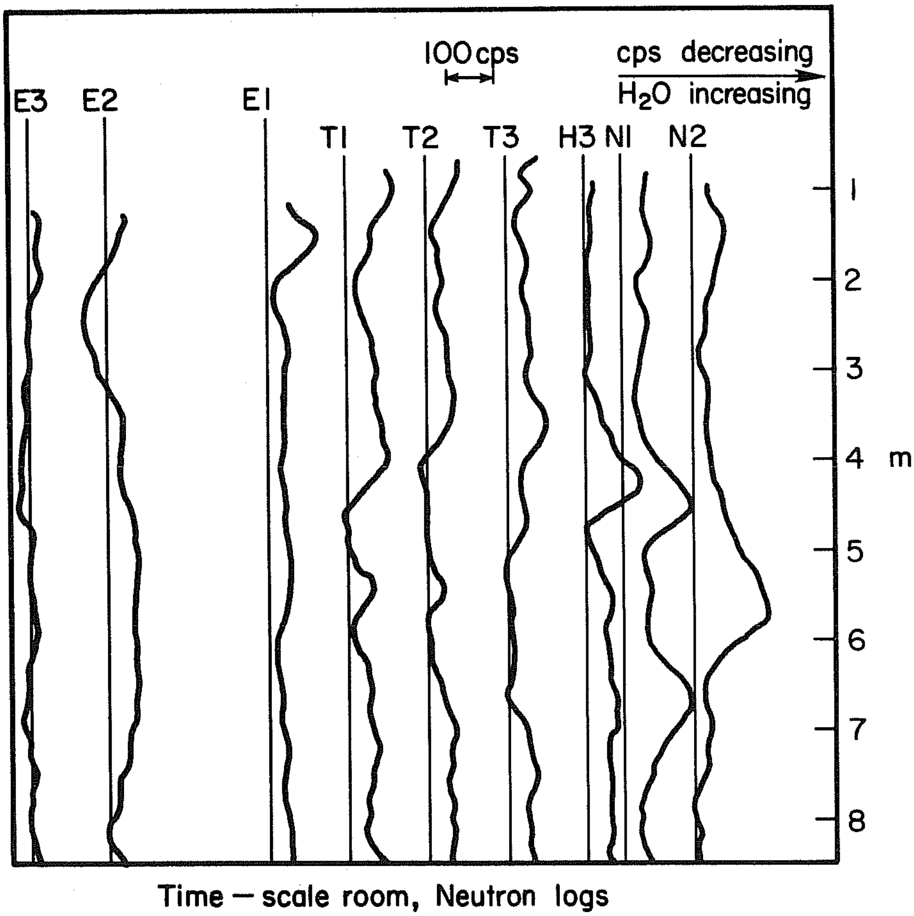

Fig. 6. Neutron logs, time-scale room holes. (XBL 785-909)

power of porosity (Brace and Orange 1968) although the data for igneous rock is quite limited. Figure 7 shows the neutron and the electrical resistivity logs obtained in borehole SBH-1 at Stripa, demonstrating the correlation of the two measurements in this case. In other cases a lack of correspondence can indicate that one of the measurements has been adversely influenced by other effects and may not be usable. For instance, the neutron probe is particularly susceptible to the presence of small amounts of those elements which possess a very high thermal neutron absorption cross-section. Such effects become especially tricky to evaluate when such small amounts of water are to be measured. These considerations emphasize the importance of obtaining as many different types of logs as is practical in new situations. As is obvious from the emphasis of this paper, any geophysical method that can assist in the location of fractures and the quantitative evaluation of their characteristics will be of prime interest in the site evaluation of repository development. Figure 7 illustrates the application of the foremost candidate for fracture evaluation, the borehole sonic tool. This probe was operated in the continuous logging mode with a source-receiver separation of 30 cm. The waveforms are recorded on film by intensity modulating an oscilloscope in such a manner that the dark bands correspond to the negative portions of the waveform. In Fig. 8 the interval 316 to 326 m displays a significant amount of distortion in the shear wave portion of the record, indicating considerable fracturing in the interval. The interval 350 to 360 m, on the other hand, is free of distortion except for the single fracture delineated at 358 m. Another representation of the sonic information is given in Fig. 7, where the arrival time of the initial compressional wave is presented as a single trace.

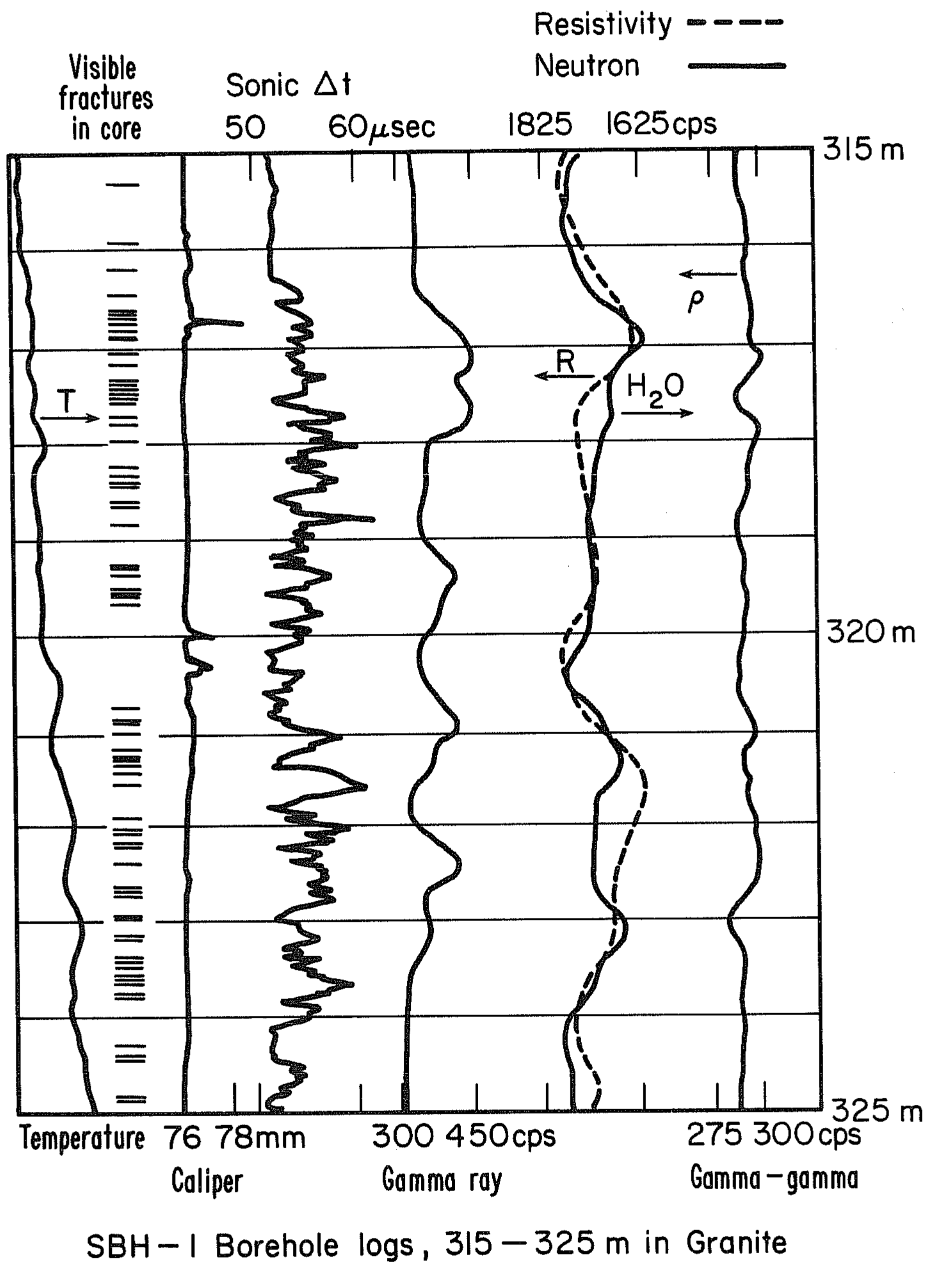

Fig. 7. Comparative logs for a portion of surface hole SBH-1 (315 m to 325 m). (XBL 785-906)

Both the waveform and arrival time presentations are extremely useful in the evaluation of a borehole prior to hydrological testing. The next important steps will consist of improving the instrumentation, particu-

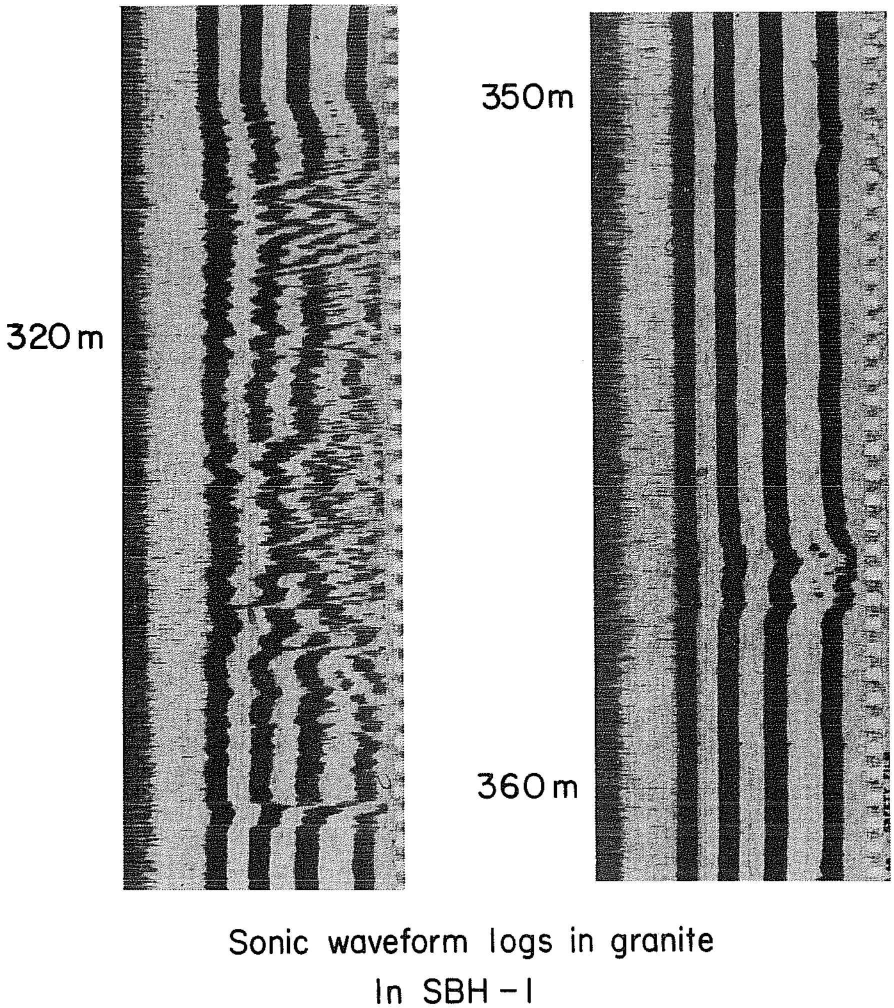

Fig. 8. Sonic log for a fractured zone (left) and an unfractured zone (right) in SBH-1. (XBB 785-6469)

larly for shear energy, and improving our understanding of how fracture openings affect the transmission of acoustic waves.

Other probes were used at Stripa for fracture delineation and deserve mention here. The trace from a high sensitivity caliper is shown in Fig. 7, where three openings of 1 mm or more are depicted. The caliper provides a simple corroboration of events observed on other logs. Also shown in Fig. 7 is a gamma-gamma log from a probe designed to provide high resolution by means of a close spacing between the source and detector.

Results thus far have been disappointing in terms of the resolution of narrow fractures, and the main use of such logs lies in aiding the interpretation of other probe measurements. Finally, a technique of considerable interest is the differential resistance probe used at Stripa (Nelson et al., in press) and elsewhere (Magnusson and Duran 1978) by members of the Swedish Geological Survey. This method relies on measuring the voltage required to force a small electrical current through a narrow annulus formed by an insulating element of the probe and the borehole wall. In this way small openings or conducting fractures are detected through decreases in electrical resistance.

In progress at Stripa are ultrasonic and electro-magnetic crosshole propagation experiments which will rely on the core analysis described above for verification of their effectiveness. The ultrasonic method, using piezoelectric transducers in a housing that is mechanically pressed against the borewall, is being run in conjunction with the heater tests to determine changes in rock properties with temperature. Crosshole experiments are also being carried out over 4-m spans in the holes at the end of the ventilation drift. The electromagnetic experiments are utlizing equipment and analysis techniques developed in other geological environments (Lytle et al. 1978), using a ray-path technique to locate inhomogeneities between holes.

5. HYDROLOGIC CHARACTERIZATION

5.1 Overall Approach

Flow of water through fracture systems depends on fracture geometry hydraulic gradient. For waste repositories one needs additionally a model for predicting changes in these parameters due to heating and other stress changes. The following sections summarize the Stripa work which consists of:

- determination of directional permeability from fracture data;
- determination of permeability from large-scale tests (pump tests, ventilation experiments);
- influence of temperature on permeability;
- determination of water pressure around the mine;
- groundwater chemistry for obtaining estimates of age and origin of water;
- determining stress permeability relationships in laboratory tests.

5.2 Permeability Based on Fracture System Analysis

The basic approach being used at Stripa (Fig. 9; Gale and Witherspoon 1978) to determine permeabilities is to quantify the factors that control

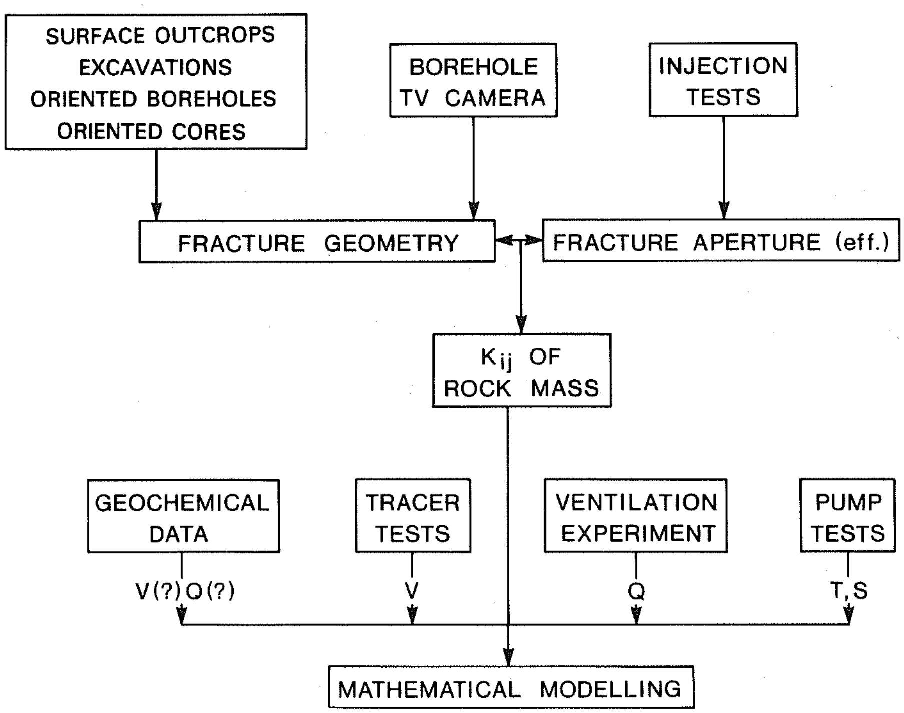

Fig. 9. Block diagram of steps in calculating directional permeabilities from fracture data. (XBL 7811-2144)

permeability in three dimensions - orientation, spacing, aperture, and continuity - and from these derive the permeability tensor. The results of this approach are then checked against the results of larger scale tests such as pump tests, geochemical data, and a ventilation experiment in part of the mine, details of which are presented in later sections. The surface program consists of drilling boreholes SBH 1, 2, and 3 (Fig. 2) normal to the major joint sets, and performing the following well tests:

(1) Injection tests of the entire length of each surface hole with 2-m packer spacings.

(2) Injection tests of prominent fractures noted in the TV logging.

(3) Injection tests on zones showing pronounced geophysical anomalies.

Data for the geometry of the fracture system come from the core logging and TV logging. Continuity can be estimated from the underground mapping. Aperture data come from the injection tests in the boreholes. Although it is possible to estimate joint aperture from optical data such as TV camera logs or surface photography (Bianchi and Snow 1969), the parameter required for permeability calculations is the aperture of a smooth-walled parallel-plate with the same hydraulic characteristics as the rough, possibly coated, natural fracture. The extension of the parallel-plate analogy to rough fractures has been demonstrated by Iwai (1976). This effective aperture can be calculated from injection tests in boreholes by methods described by Gale (1975, p. 125). Results from Canadian granites (Gale 1975) show that apertures estimated from borehole optics are considerably more than the calculated effective apertures.

TV logs have been made for all holes, and are useful mainly in constructing fracture system geometry and in selecting zones for injection tests.

Injection equipment in use in Sweden consists of a two-packer assembly with a downhole housing for a temperature sensor and three pressure transducers. The pressure transducers are designed to monitor fluid pressures in the injection zone, and above and below the packers, thus enabling monitoring of packer leakage and eliminating the need to correct for pressure losses in the injection line. All sensors are continuously monitored during testing.

The mathematics of calculating directional permeabilities from fracture orientation and aperture data using the parallel-plate analogy of fracture flow was first published by Romm and Pozinenko (1963). Extensive work in this area has been performed by several others (Snow 1965; Caldwell 1971; Parsons 1972; Louis and Pernot 1972). A related contribution on fracture orientation and density analysis has also been made (Kiraly 1969). The basic approach used in calculating directional permeabilities of a fracture system follows that of Snow (1965) and is discussed further by Gale and Witherspoon (1978). It consists of developing a permeability tensor from the measured orientations of the fractures and from the apertures of the fracture determined by well tests. Principal permeabilities and their directions can be calculated from the eigenvalues and eigenvectors of the tensor following procedures discussed by Ford (1963).

5.3 Pressure Data from Surface Holes

In addition to permeability measurements, repository site characterization requires knowledge of the hydraulic potential field. These pressure measurements not only are useful in determining directions of groundwater flow, but also can provide a qualitative assessment of fracture continuity, as some of the data from SBH-1 shows (Fig. 10).

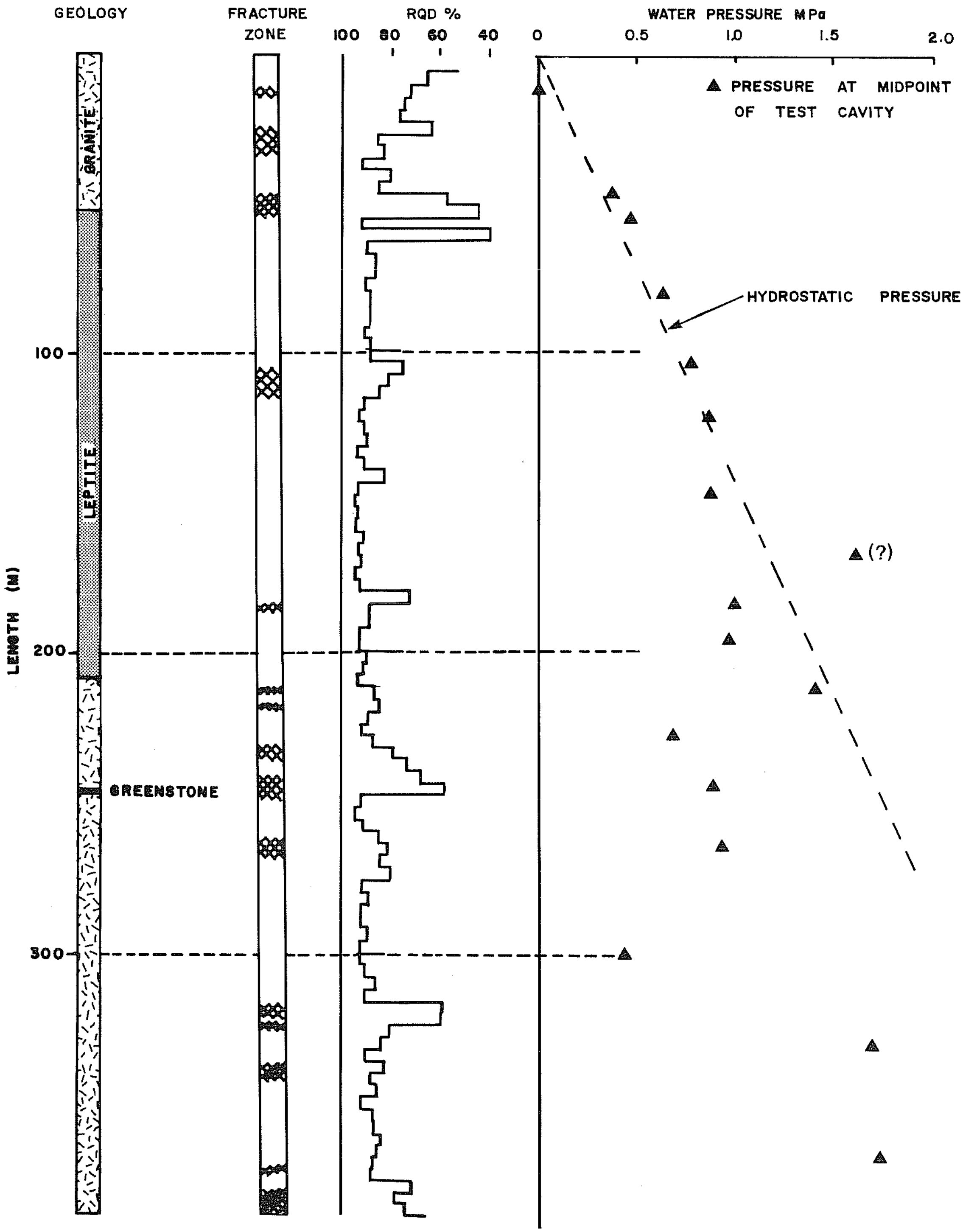

Fig. 10. Results of fracture and pressure measurements in surface hole SBH-1. (XBL 7811-13104)

Pressure data in SBH-1 were taken using a single packer with a housing containing a pressure transducer. This assembly was lowered to within 3 m of the bottom of the hole at 15- to 20-m intervals during the drilling. At depths less than 150 m the pressures follow a normal hydrostatic path. Below this depth the influence of mine drainage begins and pressures are lower than the hydrostatic gradient values. There are, however, local variations especially in a zone at 300 m which was considerably lower than the general trend. A more direct hydraulic connnection with the mine could cause the lower pressure value.

5.4 Fracture Hydrology Studies Related to Heater Experiments

A part of the fracture hydrology program consists of trying to determine how fluid pressures and permeabilities in fractured rocks are affected by increasing temperatures of the heater experiment. This work has involved the drilling of two 76-mm-diameter boreholes (S-1 and S-2), parallel to the time-scaled room (Fig. 2). S-1 and S-2 are located on the north side of the time-scale heater room and are drilled from the main drift at an angle of approximately 30^{o} from the horizontal and parallel to the axis of this room. Both S-1 and S-2 pass through a horizontal plane defined by the center elevation of the time-scaled heaters, which is 10.5 m below the floor of the room. At this elevation S-1 and S-2 are located 1 m and 3 m, respectively, in a northerly direction from the two nearest heaters.

S-1 has been instrumented with five water-inflated packers that define five separate cavities along the borehole. Stainless-steel tubes provide access to each cavity for water pressure measurements and the collection of water samples. Data are not yet available from S-1; however, it is expected that fracture deformation as a result of the heating should be reflected in the water pressures, the flow rates during sampling, and possibly in the chemistry of the outflowing water.

Water inflow rates in five instrument boreholes in the full-scale room are shown in Fig 11. Inflow rates are much smaller than those obser-

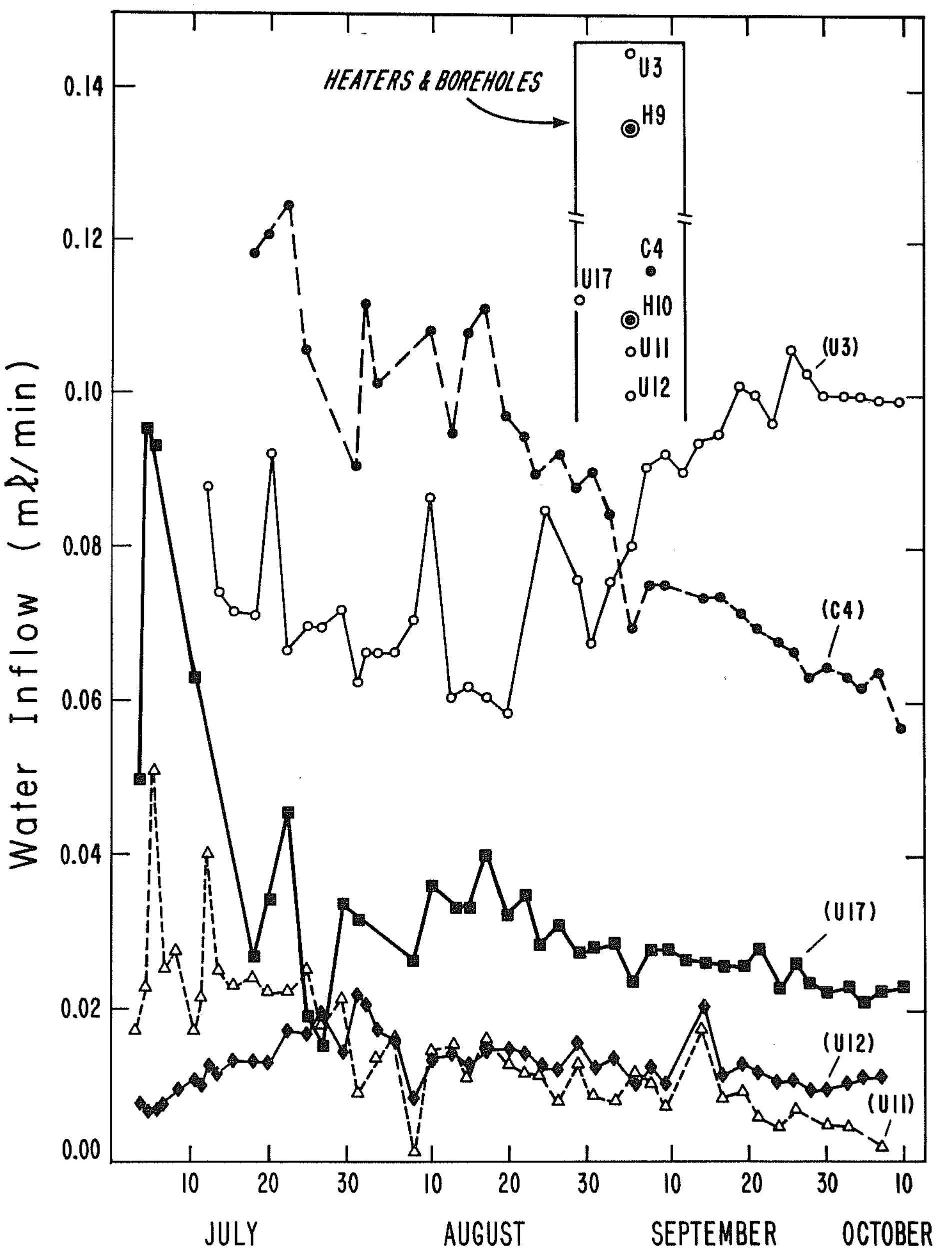

Fig. 11. Water inflow data for five instrument holes in the full-scale heater room. (XBL 7811-2145)

ved in the time-scaled heater room and range from 0.01 to 0.10 ml/min. With the exception of instrument hole U-3, the general trend in inflow rates has been downward since the turn-on of heater H10 in July 1978. If the displacement data are indeed a reflection of fracture closing, an effect observed experimentally by Summers, Winkler, and Byerlee (1978) in tests on small cores at elevated temperature, then this flow behavior should be expected.

5.5 Isotope Hydrology Data

Groundwater samples from surface wells and underground wells are being analyzed for age (carbon 14, tritium, helium, uranium) and source (carbon 13, oxygen 16 and 18). Results are discussed in detail by Fritz, Barker, and Gale (in press). Groundwater ages based on carbon isotopes in subsurface holes vary from 25,000 years for a hole in the time-scale experiment room to 90,000 years for a hole at the 410-m level of the mine.

5.6 Pump Tests

In the fall of 1977, wells WT 4, 5, 6, and 7 were drilled on the surface for use in pump testing. The wells were 4 inches (102 mm) in diameter and drilled in a pattern based on the dominant fracture orientation measured in the surface outcrop around the site (Fig. 2). Well WT-7 was drilled to a depth of 100 m and was designed to be the pumping well. Wells WT 4 and 6 were 50-m deep and located 15 m and 30 m, respectively, from WT-7; they were designed to be observation wells and were positioned along the strike of the major joint set relative to WT-7 (Fig. 4). Well WT-5 was positioned 15 m from WT-7 normal to direction of the strike of the dominant joint set. The primary goal of this layout was to determine anisotropy of the flow regime due to the dominant set. All wells are vertical.

Three pump tests were run, two in WT-7 and one in WT-6. The pump tests in WT-7 yielded permeabilities averaging 2.0 x 10^{-5} cm/sec. A major fracture zone 6 m below the initial water level was postulated based on differences between the drawdown and recovery curves. WT-4 was the only observation well to show significant connections with WT-7. To check the lack of communication between WT-7 and the observation wells WT-5 and WT-6, a pump test was run in WT-6, which was very brief due to a rapid drawdown of the well. Analysis of the water-level recovery in WT-6 for three months following the pumping, using slug test techniques (Cooper, Bredeshoeft, and Papadapoulos 1967), suggests a permeability of 1.0 x 10^{-8} cm/sec. These preliminary results indicate a high degree of variability in permeability over the scale of the pump-test well configuration (20 to 40 m).

5.7 Ventilation Experiment

It has been recognized that walls 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 slowly seeping into the underground openings (Witherspoon et al., in press). By measuring the amount of water vapor being removed from a section of the mine by the ventilation system, a direct measure of the volume of water seeping into an isolated section of a mine can be obtained. Furthermore, knowledge of the groundwater pressure gradients near the mine opening allows calculation of the rock-mass permeability.

The underground ventilation experiment at Stripa is designed to measure the total amount of water that is seeping into a 30-m section of tunnel at the end of the main drift (Fig. 1). This section is being sealed off with airtight and watertight bulkheads. A controlled amount of heated air is circulated into and out of the room, and the change in the water content of the air is measured to determine the rate of groundwater seepage. Construction of the bulkheads is underway and the experiment is scheduled to begin in the summer of 1979.

5.8 Laboratory Determination of Stress-Aperture Relationships

Reliable predictions of the mechanical and hydrological behavior of a repository are not complete with only an accurate description of the fracture system. Whereas fracture aperture has a major effect both on hydrology and on the displacements due to the thermal loading, an accurate means of determining the relationship of stress to fracture aperture is essential. Work has been done at the University of California to investigate the effect of sample size on the measurement of stress-aperture characteristics (Gale 1975; Witherspoon et al., in press). The core samples used for testing were medium-grained granite containing an axial drill hole and a single horizontal fracture normal to the core axis. Water was pumped through the drill hole and out the fracture at constant head. These tests have been run on samples ranging from 155 mm to 1.0 m in diameter over a range of normal stresses from 0.1 to 30 MPa. The tests on the 1-m-diameter core were performed on the University of California Richmond Field Station, 1 M-Newton test system (Fig 12). Smaller-diameter samples showed a decrease in fracture permeabilities from 10^{-3} to 10^{-5} cm/sec as the normal stress was increased. Permeabilities in the larger-diameter core, however, decreased from 10^{-3} to only 10^{-4} cm/sec -- an order of magnitude higher than the smaller core. Comparison of these results with those of Pratt et al. (1977) suggests that stress-permeability relationships based on tests on smaller cores give permeabilities that are low compared to those found

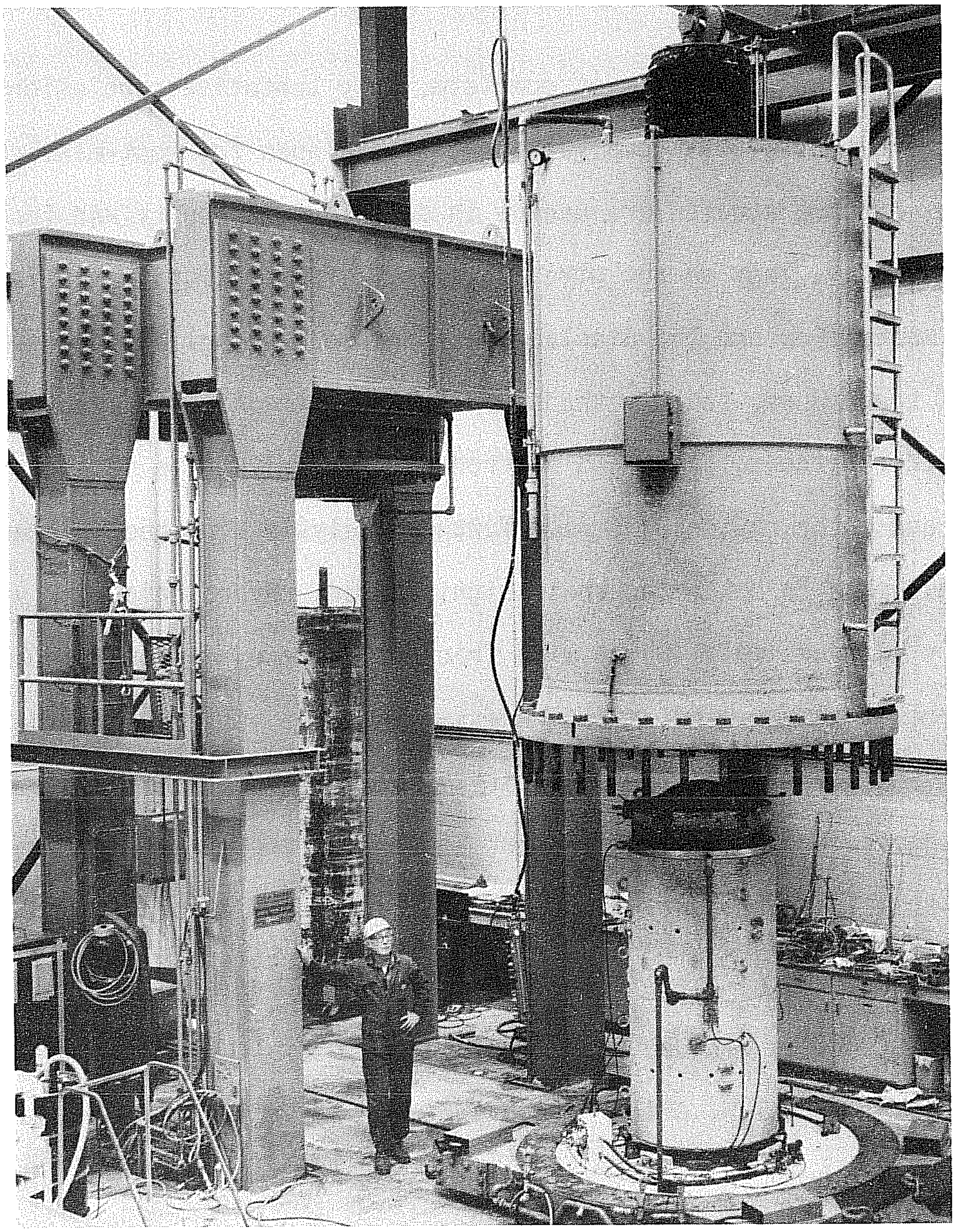

Fig. 12. One-meter-diameter core being readied for fracture flow testing. (XBB 753-1977)

in natural conditions. In view of these results a one meter diameter core containing a natural fracture has been extracted from the 360-m level of the Stripa mine for use in fracture flow versus normal stress testing.

6. DISCUSSION

Since the data are not yet complete, only tentative conclusions can be drawn regarding the best combinations of techniques for rock-mass characterization. Mapping studies are useful in defining continuity and fracture-system geometry. They do not give aperture, a factor significant in terms of both water flow and the displacements due to heating. Of the geophysical techniques, sonic methods appear most effective in fracture definition; other methods, gamma and neutron particularly, give data on radionuclide and water content and need further analysis with geologic and hydrologic data to determine their significance. Hydrologic work yields primarily aperture data, which with fracture geometry can be used to calculate directional permeabilities. Pressure measurements may provide one means of assessing fracture continuity. Finally, laboratory tests on large cores suggest considerable refinement in testing techniques may be needed before stress-aperture data can be extrapolated from laboratory to field.

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