PROGRESS WITH FIELD INVESTIGATIONS AT STRIPA

Witherspoon, P.A.

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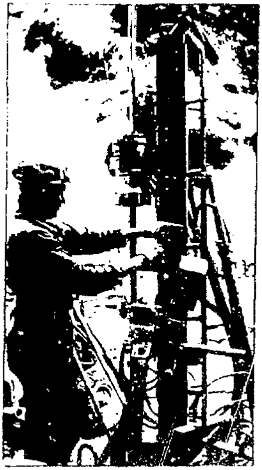
SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Information Report No. 27

PROGRESS WITH FIELD INVESTIGATIONS AT STRIPA

MASTER

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This report is a revision of a paper presented at the "Waste Management '80" conference held at the University of Arizona, Tucson, Arizona, March 10-14, 1980. It was prepared by the Lawrence Berkeley Laboratory under the University of California contract W-7405-ENG-48 with the Department of Energy. Funding for this project is administered by the Office of Nuclear Waste Isolation at Battelle Memorial Institute.

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 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 Radioactive Waste Repositories in Hard Rock. Part I: An Appraisal of Hard Rock for Potential Underground Repositories of Radioactive Waste* 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. Frtiz, 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, E. P. Binnall, A. O. DuBois, D. O. Norgren, and A. R. Ortiz (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. Magnussen (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).

18. *Rock Mass Characterization for Storage in Nuclear Waste in Granite* by P.A. Witherspoon, P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J. E. Gale, and C. Forster (LBL-8570, SAC-18).

19. *Fracture Detection in Crystalline Rock Using Ultrasonic Shear Waves* by K.H. Waters, S.P. Palmer, and W.F. Farrell (LBL-7051, SAC-19).

20. *Characterization of Discontinuities in the Stripa Granite--Time Scale Heater Experiment* by R. Thorpe (LBL-7083, SAC-20).

21. *Geology and Fracture System at Stripa* by A. Olkiewicz, J.E. Gale, R. Thorpe, and B. Paulsson (LBL-8907, SAC-21).

22. *Calculated Thermally Induced Displacements and Stresses for Heater Experiments at Stripa* by T. Chan and N.G.W. Cook (LBL-7061, SAC-22).

23. *Validity of Cubic Law for Fluid Flow in a Deformable Rock Fracture* by P.A. Witherspoon, J. Wang, K. Iwai and J.E. Gale (LBL-9557, SAC-23).

24. *Determination of In-Situ Thermal Properties of Stripa Granite from Temperature Measurements in the Full-Scale Heater Experiments, Pt. I: Methods and Primary Results* by J. Jeffry, T. Chan, N.G.W. Cook and P.A. Witherspoon (LBL-8424, SAC-24).

25. *Instrumentation Evaluation, Calibration, and Installation for Heater Tests Simulating Nuclear Waste in Crystalline Rock, Sweden* by T. Schrauf, H. Pratt, E. Simonson, W. Hustrulid, P. Nelson, A. DuBois, E. Binnall, and R. Haught (LBL-8313, SAC-25).

26. *Part I: Some Results from a Field Investigation of Thermo-Mechanical Loading of a Rock Mass When Heater Canisters are Emplaced in the Rock* by M. Hood. *Part II: The Application of Field Data from Heater Experiments Conducted at Stripa, Sweden for Repository Design* by M. Hood, H. Carlsson, and P.H. Nelson (LBL-9392, SAC-26).

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ABSTRACT

It is generally agreed that the most practicable method of isolating nuclear wastes from the biosphere is by deep burial in suitable geologic formations. Such burial achieves a high degree of physical isolation but raises questions concerning the rate at which some of these wastes may return to the biosphere through transport by groundwater. Any suitable repository site will be disturbed first by the excavation of the repository and second by the thermal pulse caused by the radioactive decay of the wastes. To assess the effectiveness of geologic isolation it is necessary to develop the capability of predicting the response of a rock mass to such a thermal pulse. Ultimately, this requires field measurements at depths below surface and in media representative of those likely to be encountered at an actual repository. Access to a granitic rock mass adjacent to a defunct iron ore mine at Stripa in Sweden at a depth of about 350 m below surface has provided a unique opportunity to conduct a comprehensive suite of hydrological and thermo-mechanical experiments under such conditions virtually without delay. The results of these field tests have shown the importance of geologic structure and the functional dependence of the thermo-mechanical properties on temperature in developing a valid predictive model. The results have also demonstrated the vital importance of being able to carry out large scale investigations in a field test facility.

1. INTRODUCTION

Although a number of concepts for the isolation of radioactive wastes has been proposed, the idea of using underground excavations for deep geological disposal is receiving increasing attention (U.S. Department of Energy 1979). Design of an underground repository to isolate radioactive wastes from the biosphere constitutes a unique problem for scientists and engineers. Three main types of rocks are now being investigated: granites, evaporites, and clays.

The need for a basic understanding of rock behavior under the special conditions that will arise in an underground repository in the presence of heat-generating, radioactive wastes, and the complex processes of waste migration (deMarsily et al.1977) in slowly moving groundwaters cannot be overstated. Whatever laboratory and theoretical research is done, field investigations will be needed in order to understand the magnitude and scope of such problems, and to expedite the timely development of the technology necessary to resolve this matter.

Over the past three years, the Lawrence Berkeley Laboratory (LBL) has been involved in a comprehensive series of field tests in an abandoned iron-ore mine at Stripa, Sweden, about 150 km west of Stockholm. A suite of experimental rooms has been excavated in an extensive mass of granite (quartz monzonite) adjacent to the iron-ore body (high-grade metavolcanics) and at a depth of 338 m below surface (Fig. 1). This work is part of a Swedish-American cooperative program (Witherspoon and Degerman 1978) of investigations on radioactive waste disposal between LBL and their counterpart in Sweden, the Nuclear Fuel Safety Program (KBS). The LBL activities are under the direction of Battelle Memorial Institute, Office of Nuclear Waste Isolation,

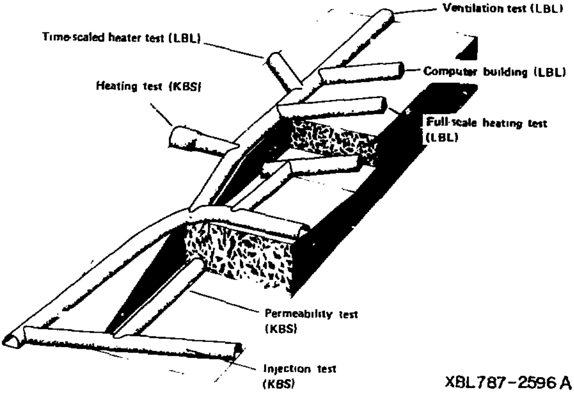

Fig. 1. Location of experimental rooms excavated in granite rock mass at Stripa.

and are funded by the U.S. Department of Energy. The KBS activities are under the direction of the Swedish Nuclear Fuel Supply Company (SKBF).

The mining operations carried out for many years at Stripa by Stållbergsbolagen revealed a massive body of granite adjacent to the underground workings. Abandonment of Stripa as a mining operation provided an invaluable and virtually unique opportunity to conduct field experiments in water-saturated granite at a depth and under other conditions comparable with those expected at the site of an actual repository. SKBF took over the Stripa mine soon after mining ceased so that KBS could carry out a series of tests (see Fig. 1) that were expected to be completed by the end of 1977. A formal agreement between SKBF and ERDA (now DOE) was signed July 1, 1977. The LBL program began immediately and the first major experiment was in operation on June 1, 1978, only eleven months later.

A coordinated series of tests have been carried out on two key problems that arise in using granite for underground waste isolation. One of these problems is that of predicting the thermo-mechanical behavior of a heterogeneous and discontinuous rock mass. This is being accomplished using a series of electric heater tests to simulate the energy released by the decay of nuclear waste. The other problem involves fracture hydrology, that is, predicting the movement of groundwater that can transport radionuclides through the granite. A combination of borehole measurements and geochemical studies forms the basis of these hydrology tests. A new method of measuring the permeability of very large rock masses using a length of drift is also being developed to compare with results by conventional methods.

2. THERMO-MECHANICAL INVESTIGATIONS

2.1 Importance of Thermo-Mechanical Effects

After a geologic site suitable for a radioactive waste repository has been identified, the site will be subjected to two principal perturbations if it is used for that purpose. First, it will be necessary to sink shafts to the depths of the proposed repository and then make the excavations for the repository at this depth. With careful design and the wealth of related experience in civil and mining engineering, it should be practicable to accomplish this without impairing the ability of the site to isolate wastes from the biosphere to any significant degree.

Second, as a result of the radioactive decay of the wastes, the subsurface media in the vicinity of the repository will undergo a thermal pulse. The system will be heated to a maximum temperature at the depth of the repository within a century, depending upon the waste form, and subsequently will cool over a much longer period of time. To ensure that the repository will provide adequate isolation of nuclear wastes from the biosphere over these long periods of time, it is necessary to assess the effects of this thermal pulse. In general, this pulse will increase compressive stresses and water pressures in the heated zone of the rock mass around the repository and induce corresponding tensile stresses outside this zone.

An estimate of the magnitude of these effects can be calculated readily using a linear theory of thermoelasticity. First, temperature fields can be calculated as a function of time using conduction of heat. From the temperature field at any time, the thermally induced displacements and stresses can be calculated using the coefficient of thermal expansion, Poisson's ratio and Young's modulus. Values for these coefficients as determined from laboratory measurements on small specimens of rock are available in handbooks (Clark 1966). However, it is well known that the behavior of a large rock mass is seldom the same as that of small specimens of rock (Hoek 1979). Accordingly, it is important to develop and verify models for predicting the thermomechanical response of an underground repository for nuclear wastes. To ensure that this is done in a meaningful and realistic way, relevant experiments must be done under conditions of rock stress, groundwater pressure and other conditions typical of those likely to be encountered at the depth of a repository.

The availability of a site at depth in water-saturated granitic rock at Stripa provided a unique opportunity for conducting three thermo-mechanical experiments under conditions encountered at representative depths: (a) two full-scale heater tests in which the near-field response of the rock mass was studied under simulated short-term and long-term conditions, and (b) an intermediate term time-scaled experiment covering the major part of the heating up period of the thermal pulse and interaction between adjacent heaters. By instrumenting these experiments so as to obtain comprehensive measurements of temperature fields, displacements, and stresses as functions of time and space, we have identified the data needed to predict the thermo-mechanical response of a repository. These results have shown that it is necessary to take into account the geologic structure of the rock mass and the functional dependence of the coefficients of thermal expansion, Poisson's ratio, and Young's modulus if predictions are to provide an accurate description of the response of a rock mass to the heat produced by the decay of radioactive wastes.

2.2 Full-Scale Heater Experiments

The energy output from U.S. canisters containing high level reprocessed radioactive waste could be as much as 5 kW per canister. This output drops significantly in the first few years after emplacement, but an energy release of this magnitude when coupled to the rock mass can produce temperature increases of several hundred degrees. It is therefore important that definitive field experience be gained concerning the thermal effects on the rock mass immediately adjacent to the canister.

Full-scale heater experiments have been designed to permit the investigation of the short-term effects of heat in granite. Electric heaters housed in a canister 3 m (10 ft) in length and 0.3 m (1 ft) in diameter have been used to simulate the power output of radioactive waste. Two such canisters, each containing four heating elements, have been positioned in 406-mm vertical holes drilled to a depth of 5.5 m in the floor of the full-scale heater drift

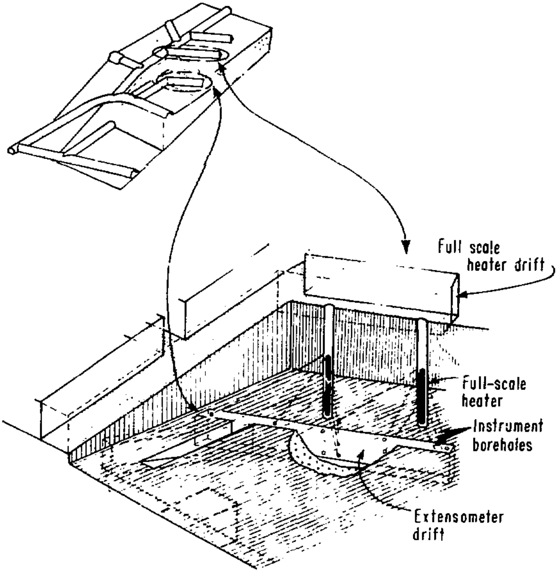

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Fig. 2. Arrangement of electric heaters in full-scale experiment room in granite showing location of instrument boreholes from adjacent extensometer drift.

as shown in Fig. 2. Details of the design and construction of these electrical heaters have been reported by Burleigh et al. (1979).

Figure 2 shows a cutaway drawing of the two full-scale heaters and some of the horizontal boreholes that have been instrumented from an adjacent lower level drift. The two heater holes are spaced 22 m apart so that the canisters have remained thermally isolated from each other for the duration of the experiment. This has enabled two separate experiments to be conducted in parallel. Power output for the canister-heater on the left side of Fig. 2 has been adjusted to 5 kW in order to represent a typical power level of reprocessed fuel after some three years. The other canister-heater, on the right, has been set at a power output of 3.6 kW to represent similar waste products approximately five years old at the time of emplacemnt.

The response of the mass adjacent to these two canisters has been monitored extensively. Rock displacements have been measured using extensometers, and thermally induced stresses have been determined from strain measurements using USBM borehole deformation gages and IRAD (Creare) vibrating-wire gages. Each of these instruments has a thermocouple associated with it, and additional thermocouples have been positioned around each heater to obtain the temperature field in three dimensions.

Because of the low thermal conductivity of rock, it is known that temperatures, and therefore the temperature gradients, within the rock in the immediate vicinity of the heaters will approach maximum values in a period of a few months. Consequently, within a relatively short period, this test program has been able to provide important data for two values of power output in a typical hard crystalline rock.

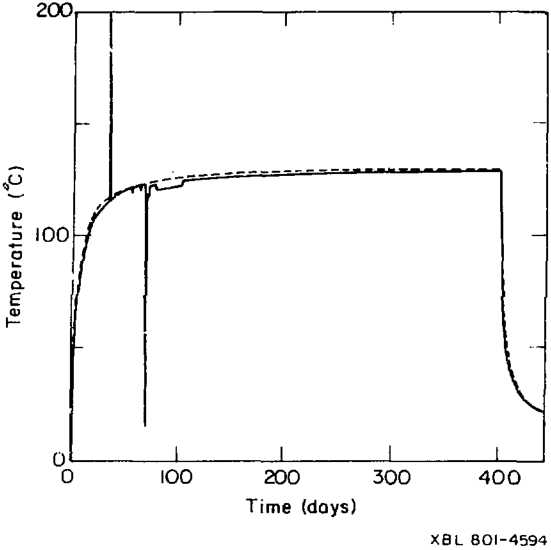

Fig. 3. Predicted (dashed) and measured (solid) temperatures plotted as *a function of time at a radius of 0.4 m from 3.6 kW heater along* heater midplane. Variations in measured signals at early time caused by corrosion of stainless steel thermocouple sheath.

Figure 3 shows an example of temperatures as predicted versus those that have been measured for the 3.6 kW heater in granite as a function of time. The length of the heating period was 398 days; the total length of this experiment was about 1-1/2 years. Temperatures were calculated before the experiment started based on a semi-analytic solution assuming intact rock and using laboratory measurements of rock properties (Chan, Cook, and Tsang 1978). The laboratory data were as follows: density, 2600 kg/m^3; specific heat, 837 J/(kg°C); thermal conductivity, 3.2 W/(m°C); and thermal diffusivity, 1.47 x 10^{-6} m^2/sec.

Figure 4 shows the spatial distribution of temperatures measured on the midplane passing through the center of the 5 kW heater compared with the predicted isotherms at 190 days after turn on. As will be described below, this granite rock mass is extensively fractured and jointed. Careful examination of Fig. 4 reveals that, despite the presence of these discontinuities and the water that fills them, there is little if any effect on the thermal field. Note the excellent agreement between predicted and measured values in all directions away from the axes of the heater. This is typical of the results that have been obtained throughout both full-scale heater experiments.

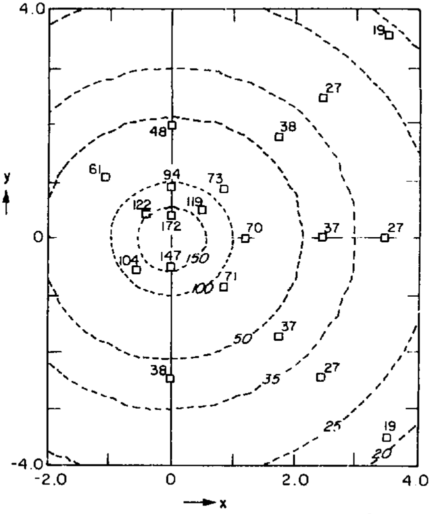

Fig. 4. Predicted (dashed) isotherms and measured temperatures in a horizontal plane through the center of the 5.0 kW full-scale heater 190 days after starting experiment. Distances are in meters and temperatures are in degrees centigrade.

2.3 Time-Scaled Heater Experiment

One of the more important factors in repository design is the effect on the rock mass of long-term thermal loading. A time-scaled experiment was designed to permit investigation of this long-term effect through the use of a scaled array of heaters. Calculations show that thermal interactions begin to occur between full-scale canisters in an actual repository within a period of three years if the canister spacing is 10 m. Thereafter, the effect of individual canisters diminishes and, in a period of 10 to 100 years, heat should flow upward and downward from a plane containing the canisters such that the 100°C isotherm will have migrated distances of the order of 50 m from the plane of the repository. The resulting thermal expansion of the roughly oblique spheroid of rock with these temperatures will be of the order of 10^{-3}, which is significant.

It is impractical to check these thermo-mechanical effects in the critical period of from 10 to 100 years using a full-scale heater experiment. Fortunately, the laws of heat conduction allow for compressing the time-scale. The dimensionless quantity used in solutions of heat conduction calculations is the ratio of the linear distance to the square root of the product of time and the thermal diffusivity of the material. Therefore, the time-scaled experiment was initiated at Stripa in which the times have been compressed in the raio of 1:10, that is, each year of data from the time-scaled experiments is equivalent to 10 years of data from the full-scale setup. In order to accomplish this, the linear scale must be reduced to $1/\sqrt{10} = 0.32$ of the full scale which still allows for realistic dimensions in the field. Measurements of rock temperatures and deformations have also been made in the time-scaled experiment so that these data can be compared with the full-scale results and with theoretical predictions of a repository over a period of several decades.

An array of 8 heaters, spaced 7 m apart along the axis of time-scaled heater room and 3 m apart in the other direction has been used in this investigation (Fig. 5). Appropriate scaling of the power output of these heaters shows that 1 kW is representative of an initial power output of 3.12 kW; this power level has been decreased during these tests to simulate the decay in energy output of radioactive waste.

The configuration of the heaters in the array shown in Fig. 5 was chosen to establish a three-dimensional pattern of thermal interaction between heaters and surrounding rock, such as may be found in a practical repository. It was calculated that this interaction would occur within a few months of the start of this experiment. Figure 6 shows how this interaction has taken place. Predicted isotherms are compared with measured temperatures in a horizontal plane passing through the centers of all eight heaters 190 days after starting the experiment. As in the case of the full-scale heater experiment, a remarkably good agreement between measured and predicted rock temperatures is seen again.

2.4 Rock Decrepitation

High temperatures were expected to occur in the rock immediately surrounding the electric heaters resulting in large thermal compressive stresses in directions parallel to the axis and tangential to the surface of the borehole containing the canister (Cook 1978). If these stresses exceed the uniaxial compressive strength of the rock, failure of the borehole wall will result. While such failure is not likely to damage a well-designed

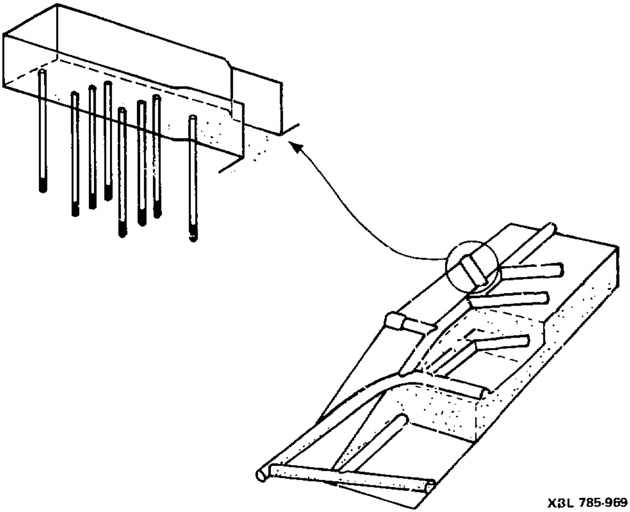

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Fig. 5. Arrangement of 1.0 kW electric heaters in time-scaled heater experiment. Heaters are 1.0 m in length and have been placed so that the heater midplane is 10.5 m below the floor.

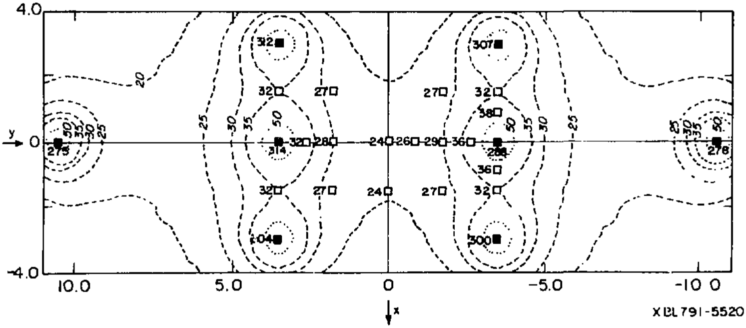

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Fig. 6. Predicted (dashed) isotherms and measured temperatures in a horizontal plane through the center of the time-scaled heaters 190 days after starting the experiment. Distances are in meters and temperatures are in degrees centigrade.

canister, it may make retrieval of the canister a difficult operation. Thus the strength of the rock is likely to be the factor that limits the canister power output and therefore the minimum age before burial.

Theory predicts that the stresses at the borehole wall asymptotically approach a maximum value about 30 days after the start of the experiment; in the case of the 5 kW heater, this maximum stress is tangential and was calculated to be about 215 MPa at the heater midplane (Chan and Cook 1980). This value is in the same range as the mean uniaxial compressive strength of the rock which by laboratory measurement was found to be 208 MPa at room temperature with only small variations from this mean value at elevated temperatures (Swan 1978). If the borehole were subject only to mechanical loading, failure would be expected to occur when the induced maximum compressive stress exceeded the uniaxial strength of the rock (Jaeger and Cook 1979).

A special experiment was conducted with the 5.0 kW full-scale heater that produced very definite evidence of borehole decrepitation. During the installation of the 5.0 kW heater, a series of eight 1.0 kW electric heaters were equally spaced around a circle with a radius of 0.9 m from the axis of the full-scale heater. These peripheral heaters were switched on at Day 204 in order to raise the ambient temperature of the rock mass by approximately 100°C in the vicinity of the full-scale heater. This also had the effect of increasing the compressive stresses on the surface of the heater hole.

Observations using a borescope revealed that serious deterioration of the 5.0 kW heater borehole occurred within a few days after the turn on of the peripheral heaters. Initially this spalling was concentrated about the heater midplane and was characterized by the formation of rock chips 20-30 mm in diameter and 2-3 mm in thickness. Step increases in canister skin temperatures of 10° to 30°C were noted and evidently reflect the increased impedence to heat flow from the heater to the borehole wall as a result of the accumulation of rock chips in the annulus. Borehole decrepitation continued to increase both in extent of damage along the length of the borehole and in the size of rock chips. Much larger rock chips were observed, up to 150 mm in length, and eventually the annulus between the canister and the borehole became completely blocked with rock fragments resulting in an increase in the skin temperature of the canister, for the same power output, of some 100°C. Calculated temperatures on the rock wall were in the range of 300°C to 350°C during this period.

These results indicate that two distinct mechanisms are involved in this spalling phenomenon. First, the time-dependent behavior obviously is not explained by thermoelastic theory. Cook (1978) has suggested other mechanisms for thermal deterioration of rock including dehydration of clay minerals and differential thermal expansion of individual crystals within the rock. At the present time this behavior is not well understood and further investigation is required. Second, the gross failure appears to be a stress related event that was precipitated by a buildup in compressive stresses when rock temperatures exceeded 300°C. Further work will be necessary to better define the stress conditions beyond which rock decrepitation will occur.

2.5 Rock Displacements and Stresses

The thermocouple readings show that, in general, the rock temperatures are symmetrical about the heater midplanes and heater axes (Fig. 4), and thus, the heat flow is little affected by discontinuities in the rock mass

(Hood 1980). Furthermore, analysis demonstrates that the dominant mode of heat transfer is by conduction and for this reason the temperature field is amenable to prediction using relatively simple semi-analytical methods (Chan, Cook, and Tsang 1978).

Unlike the temperature results, the rock displacements are not consistent with values predicted prior to heater turn on using linear thermoelastic theory (Chan and Cook 1980). Six vertically oriented, multiple-rod extensometers, each with four anchor points, have been mounted in boreholes adjacent to each full-scale heater at different radial distances. In addition nine horizontally mounted extensometers of similar design extend into the near vicinity of each heater through boreholes as illustrated in Fig. 7. Details of this and other instrumentation are given by Kurfurst, Hugo-Persson and Rudolph (1978).

The extensometer readings have yielded some puzzling results which reveal the complex problem one faces in attempting to predict thermo-mechanical behavior of a discontinuous rock mass. As a first approach, the limiting case of a homogeneous intact rock was assumed and displacements were predicted prior to heater turn on using the following constant material properties: thermal expansion, $\alpha = 11.1 \times 10^{-6}/°C$; Young's modulus, $E = 51.3$ GPa; Poisson's ratio, $\nu = 0.23$; and thermal conductivity, $k = 3.2$ W/m°C. These values are representative of average results over a temperature range of 100-150°C.

The rock displacements show two distinct types of behavior. During the first few weeks, the measured displacements were very much less than that predicted by the theory of linear thermoelasticity. After this initial

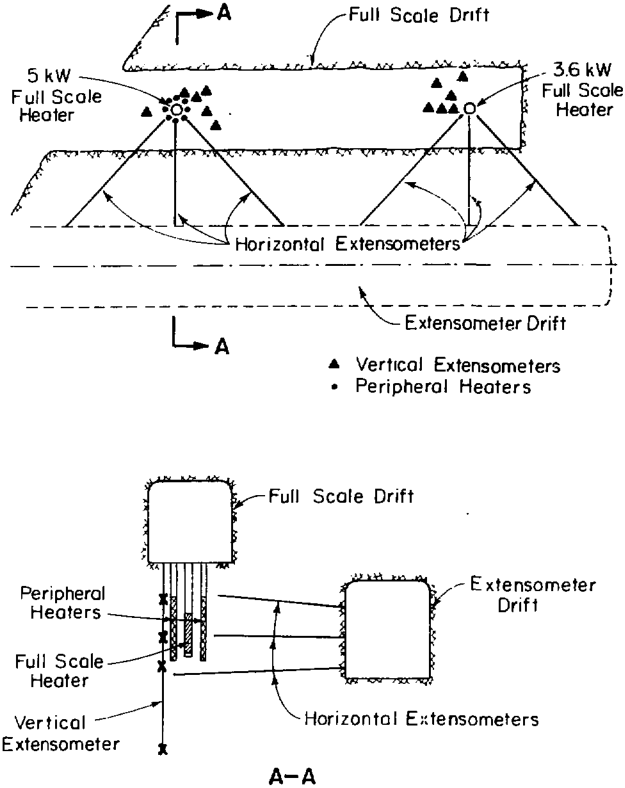

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Fig. 7. Diagram illustrating arrangement of full-scale heaters, locations of extensometers in both vertical and horizontal boreholes, and locations of peripheral heaters surrounding 5.0 kW full-scale heater.

period, the measured displacements increased uniformly but at a more or less constant percentage of the predicted values. For many of the extensometers, the ratio of measured to predicted displacements during this second phase has been 0.4 (Hood 1980).

An example of measured and predicted displacements for a vertical extensometer at a radial distance of 1.0 m from the 3.6 kW heater is shown in Fig. 8. Note that the experimental results show far less rock movement than one would predict from the theory of linear thermoelasticity for intact rock (Chan and Cook 1980). The temperature dependence of the material properties of Stripa granite is now being studied (Chan, Hood, and Board 1980). Based on a limited number of laboratory tests on intact samples, a

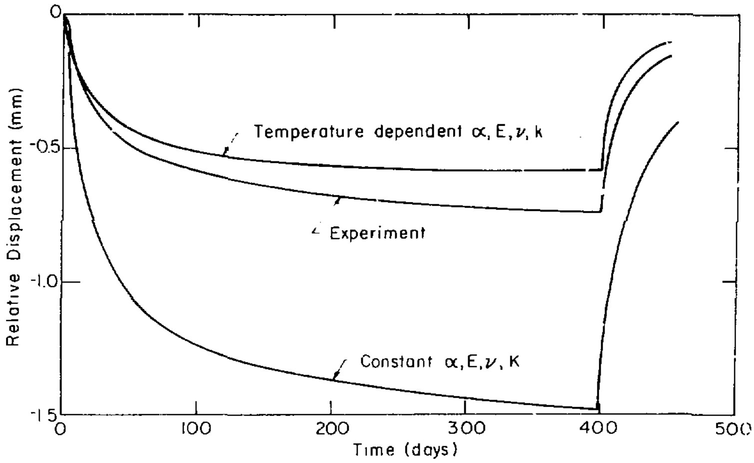

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Fig. 8. Plot showing measured rock displacements in a vertical direction between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1.0 m from the 3.6 kW full-scale heater. Also included are displacements predicted using constant as well as temperature dependent properties.

second set of displacements has been predicted using temperature dependent values of α, E, ν and k with results as shown in Fig. 8. Note that although much better agreement with field data has been obtained, the predicted vertical displacements are now less than the measured results. This work is continuing, especially the study of the thermo-mechanical behavior of Stripa granite samples obtained from the careful core drilling of all boreholes at the test site.

The nonlinear deformation behavior of the rock observed shortly after the activation of the heaters deserves special attention. Some of this nonliner rock behavior may be a result of the effects of the pre-existing discontinuities. This thesis is supported by independent experimental evidence from cross-hole ultrasonic measurements in the rock adjacent to the 3.6 kW full-scale heater. Figure 9 shows some results from ultrasonic

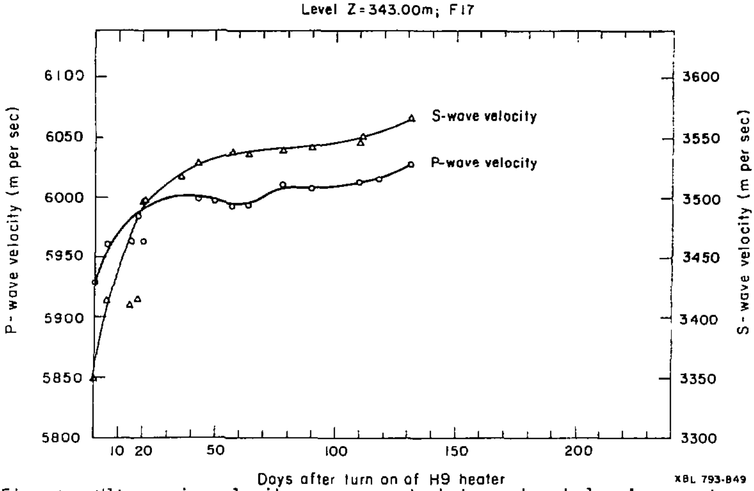

Fig. 9. Ultrasonic velocity measurements between boreholes 4 m apart at the heater midplane elevation in the rock mass adjacent to the 3.6 kW full-scale heater.

measurements where a marked increase in wave velocities was observed during the early time period when rock displacements were exhibiting a nonlinear behavior (Hood, Carlsson, and Nelson 1980). The increase in both S- and P-wave velocities probably indicates closure of fractures, especially in the rock between the transducer and the receiver.

Changes in stress in the rock mass computed from strain measurements using vibrating-wire Creare gauges show a trend somewhat similar to that of the extensometer results. The experimental values of stress have been consistently about one half or less of the values predicted using linear thermoelasticity and the constant values for thermo-mechanical properties cited above. Here too, a review of the material properties and their temperature dependence is needed. There is some indication that the predicted stresses are still significantly higher than the measured values even after the temperature dependence of rock properties has been taken into account (Chan, Hood, and Board 1980). Nevertheless, the stress results support the conclusion from extensometer measurements that the induced thermo-mechanical effects in the rock mass (away from the decrepitation effects at the heater hole) are significantly less than predicted by available theory for intact rock.

2.6 Fracture Mapping

The above results clearly indicate that the granite rock mass at Stripa, when subjected to a thermal pulse, does not behave in a linear isotropic manner. The reason, of course, is that the system discontinuities play a major role in controlling thermo-mechanical behavior. To understand the behavior of the rock mass in situ raises the difficult question, at what level of detail must one investigate the geometry of the fractures? A comprehensive program of fracture mapping has therefore been carried out in addition to a general description of the geology at Stripa (Olkiewicz et al. 1979).

Thorpe (1979) has described the methods he has employed in studying the rock fracture system in the time-scaled heater room. First, major discontinuities were identifed in the test area so that they can be modeled as discrete elements of weakness (Goodman 1976). Although these features probably play a major role in the rock mass behavior, they comprise only a small percentage of the total fracture system. Most of the other fractures are discontinuous in their own planes. Hence the second aspect of the characterization has involved defining all fractures through careful measurement of orientation, spacing, and joint length. It is presently impractical to model such ubiquitous joints as they actually exist; techniques are being developed to represent them stochastically (Glynn, Veneziano, and Einstein 1978).

Heaters for the time-scaled experiment were placed 10 m below the floor of the drift (see Fig 5), and the results of the fracture mapping indicate that only the most prominent and continuous features are likely to extend through the heated region. Accordingly, only the major fractures striking transverse to the drift were extrapolated downward and correlated with discontinuities found in the boreholes. Results of this discrete characterization are illustrated in Fig. 10, which shows the inferred profile of four shear surfaces that pass through the heater array. These fractures offset or truncate other discontinuities, whose positions are shown in each borehole,

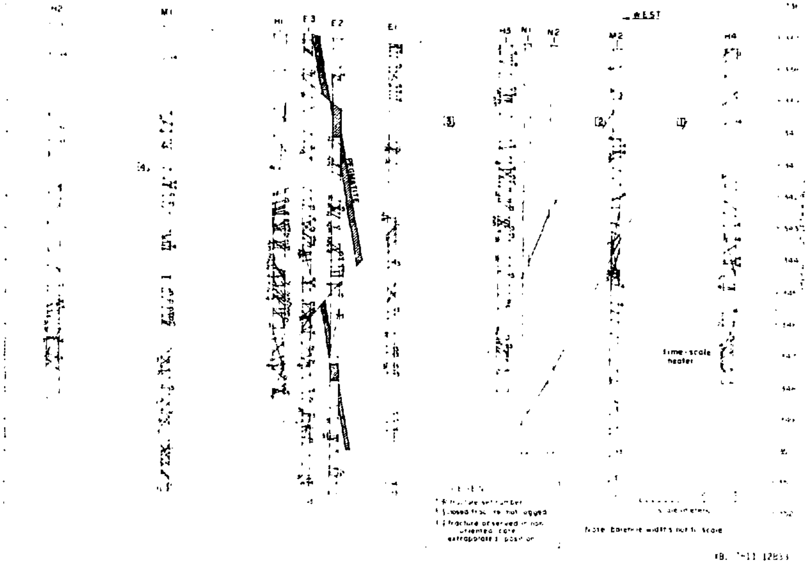

Fig. 10. Vertical profile of major fractures along centerline of time-scaled heater room.

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 pegmatite dike, 20 cm wide.

Thorpe (1979) has also made a statistical analysis of joint geometries using results from both borehole and surficial mapping. The jointing can be separated into four distinct sets, and these in turn have been found to correlate to a degree with the principal stresses as measured in the underground by Carlsson (1978). The mean pole of one of these joint sets corresponds to that of the four faults shown on Fig. 10. Resolving the principal stresses into shear and normal components on the mean fault plane yields a theoretical shearing azimuth of 242°. From field observations, the azimuth of slickensiding on the faults was found to be 240°.

It is clear from the above that characterization of the fracture system is an important component in understanding the overall thermo-mechanical response in a discontinuous rock mass. Without the level of detail described above, it will not be possible to carry out an analysis (now underway) of those fracture displacements that control the near field behavior of the overall system. Obviously, the comprehensive fracture analysis described above can only be carried out where one has access to an underground test facilty, such as at Stripa.

2.7 Instrument Problems

The heater experiments at Stripa have created some severe operating conditions for the instruments that were installed and expected to operate over a period of one and a half years (Binnall, DuBois, and Lingle 1979).

Measured heater skin temperatures approached 500°C, rock temperatures in the immediate vicinity of the heaters exceeded 300°C, and mechanical response had to be measured with rock temperatures exceeding 150°C. Few of the available instruments for measuring mechanical response are designed to operate with accuracy and reliability under such conditons.

Four types of instruments have been used at Stripa: 389 thermocouples for temperature, 35 rod extensometers for displacement, 30 U.S. Bureau of Mines (USBM) borehole deformation gauges and 26 IRAD (Creare) vibrating wire gauges for stress determination. These sensors have been installed in vertical and horizontal boreholes strategically located around the vertical heater boreholes (Schrauf et al. 1980). The sensor signals (>750) were digitized and transmitted to a Modcomp IV computer (McEvoy 1979) located in a nearby building underground (Fig. 1).

The major instrument problem has been with the USBM gauges, which utilize pairs of opposed cantilever beams to sense changes in borehole dimensions from which stress may be computed. The gauge was originally designed to operate at ambient temperature (Hooker, Aggson, and Bickel 1974), and it was thus necessary to incorporate high temperature components for operation up to 200°C. Sixteen of the twenty gauges installed in vertical holes and two of the ten gauges installed in horizontal holes have failed in service, some of these more than once. The failures have been caused by water entering the gauge housings, causing short circuits and open circuits due to corrosion. These leaks occurred in spite of a regular dewatering operation which ensured that water levels in the instrument boreholes remained below that of the gauges. Corrective measures have been taken to provide soldered internal connections and improved hermetic seals at cable connections. After passing a leak test, the improved gauges have been reinstalled, and we are now gathering data to assess whether performance will be improved.

The second method of determining stress using the IRAD (Creare) vibrating wire gauge (Hawkes and Bailey 1973) has experienced only three failures in operation. However, these gauges must be individually calibrated and the calibrations are temperature dependent. Once installed, the gauges can only be used to detect a change in stress, and thus, an independent measure of in situ stress is needed when information on the total stress field is required. In spite of the calibration, considerable uncertainties remain in the calculated stress change, particularly under conditions of varying temperature and cylic loading (Binnall, DuBois, and Lingle 1979).

The rod extensometer is a common device for measuring changes in the axial length of a borehole (Committee on Field Tests, International Society for Rock Mecnanics 1978). Basically these instruments have performed well with interim maintenance and minor field modifications. The major elements of these extensometers (Fig. 11) are: (1) the anchor system, (2) the anchor-to-collar rod connection mounted inside of a waterproof flexible conduit, (3) a head assembly which includes the rod tensioning system and the displacement sensors, and (4) several thermocouples for measuring the temperature profile along the connecting rods.

An arrangement with four downhole anchor points to measure displacements over a range of ± 13 mm has been installed. Superinvar rods, heat treated at 225°C for five hours, were found to have a reproducible thermal expansivity, and thus corrections for rod expansion during temperature buildup

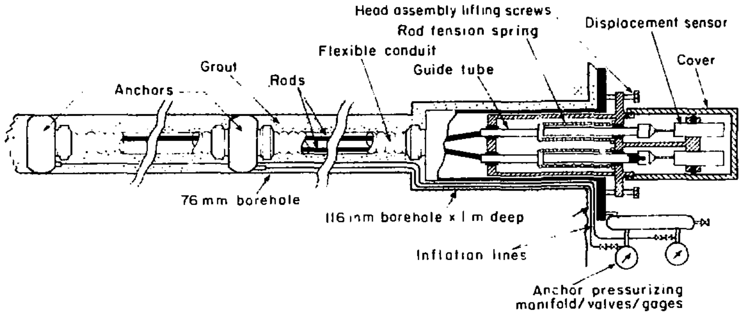

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Fig. 11. Sectional view of rod extensometer, two anchor version.

could be incorporated into the data reduction process. At Stripa, this correction was as much as 20% of the gross displacement.

A few problems with the extensometers have arisen that will require attention. One difficulty has been an internal friction that caused stepwise displacements of up to 0.08 mm. This friction could be released by simple tapping of the covers (Fig. 11), and a routine of releasing the stored displacements several times per week in this fashion was found necessary. Another problem is the precision of the instrument to measure very small displacements. The present lower limit in the precision of the extensometer is about 0.1 mm, and since heater experiments in the future may operate at significantly lower temperatures, a much greater accuracy will be required.

3. FRACTURE HYDROLOGY INVESTIGATIONS

3.1 Importance of Fracture Hydrology

The most likely way by which radionuclides may migrate away from a deep geologic repository is in the groundwater that slowly seeps through the site after burial. Once the wastes are able to dissolve in groundwater, retardation in their rate of movement will depend on three basic properties; (a) permeability, (b) effective porosity, and (c) sorptive properties of the host rock. Research in fracture hydrology at Stripa has been concerned with the permeability aspect of this migration problem.

Determining the permeability of a crystalline rock, such as granite, is essentially a problem of understanding the hydrological behavior of a complex network of fractures. Migration through the matrix will be relatively insignificant, and presumably a site with major zones of potential leakage (shear zones, faults, etc.) will be carefully avoided. Our knowledge of the permeability of fractured rocks has, until recently, been limited to borehole investigations in the upper few hundred meters of the earth's crust. In general, these investigations have been conducted under the assumption that the fracture system can be treated as a slightly different form of porous media. The needs of the nuclear waste isolation program require that investigations now be extended down to 1000 meters or more in an effort to locate rock systems that are "nearly" impermeable (Office of Waste Isolation 1977 and Lawrence Berkeley Laboratory 1979). Under these conditions, the porous media assumption also needs to be justified.

These new programs require an accurate description of the hydrology of fractured rocks. Thus, one must develop a data base to provide answers to such questions as: (1) what is the role of discontinuities in determining the nature (isotropic or anisotropic) of fractured rock permeability, and (2) under what conditions, if any, can fractured rock masses be treated as an "equivalent" porous media. The first question requires that we develop methods of characterizing a fracture system and its role in determining the hydrology of such systems in order to provide a framework within which to interpret local and large scale groundwater movements. Answers to the second question determine the type of borehole testing programs that must be undertaken in concept verification studies. These testing programs must provide the data needed to develop the hydraulic parameters that clearly describe how fluids move through fractured rock. Both of these questions become increasingly difficult to pursue in the field as permeability of the rock mass becomes vanishingly small.

In any crystalline rock mass, the fracture or joint system consists of several sets of planar openings, relatively parallel in orientation, most of which are involved in the flow properties of the rock. Several such groups of different orientations as well as randomly distributed fractures may exist at a given location. Velocity through a fracture is proportional to the square of the fracture aperture and flux is proportional to aperture cubed (Witherspoon et al. 1979). If all fractures in a particular volume of rock could be described in terms of their location, orientation, aperture and continuity, then it would be possible to develop a discrete model and analyze flow through that volume of rock.

It is essentially impossible to measure each and every fracture involved in regional groundwater movement. Since the actual three dimensional system of fracture flow paths cannot be fully described in practice, this discrete approach has a significant limitation. However, in order to use a continuum analysis we must be able to demonstrate that equivalent porous media values will provide an accurate prediction of the flow system. Then, we must be able to measure the equivalent porous media properties in situ.

A comprehensive program of investigations has been organized at Stripa (Gale and Witherspoon 1979) in an effort to understand the fracture hydrology of the granite mass. Three of the most important parts of this program will be discussed below: (1) assessing directional permeabilities, (2) large-scale permeability measurements, and (3) geochemistry and isotope hydrology.

3.2 Assessing Directional Permeabilities

The mathematics of calculating directional permeabilities from fracture orientation and aperture data, using the parallel plate analogy for fracture flow, was first developed by Romm and Pozinenko (1963). Extensive work in this area has been performed by several others (Snow 1965; Caldwell 1971; Parsons 1972; and Louis and Pernot 1972). The approach consists of developing a permeabilty tensor from measured orientations and spacings of fractures and assumed aperture distribution models. Principal permeabilities and their directions can be calculated from the eigenvalues and eigenvectors of the tensor following procedures outlined by Westergard (1964).

Our approach to assessing directional permeabilities of the fractured granite at Stripa is based on this earlier work. An attempt is being made to incorporate the effects of fracture continuity and fracture interconnection in the calculation of directional permeabilities. Basic data on fracture orientations, spacings and continuity have been obtained by mapping the fractures in the surface outcrops and in the walls and floors of the subsurface excavations (Thorpe 1979).

Another source of data has been obtained in a group of three oriented boreholes that were drilled from the surface down to the level of the experimental heater tests discussed above. Careful core drilling, core reconstruction and core orientation have been carried out in these boreholes in order to determine the variations in fracture geometry within the rock mass. The surface and subsurface data are now being combined with the borehole data in an attempt to define the three dimensional fracture system.

Figure 12 shows the distribution of outcrops at Stripa and the locations of these hydrology boreholes in relation to the underground heater tests at 338 m. SBH-1, SBH-2, SBH-3 are 76 mm diamond coreholes that were drilled at

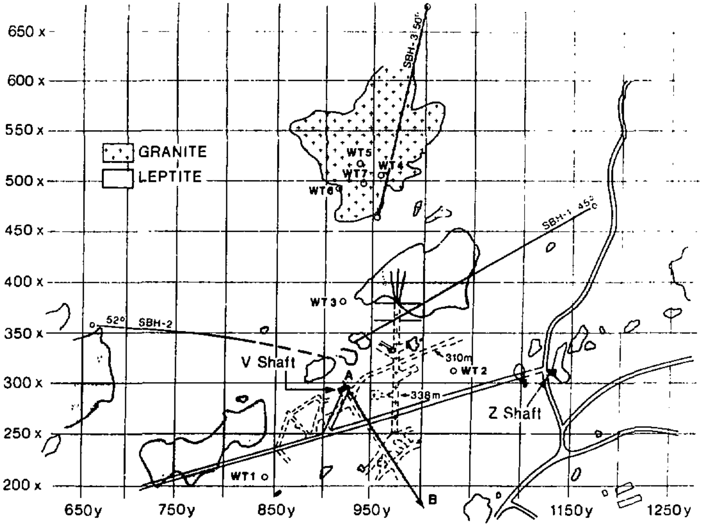

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Fig. 12. Map showing general geology at Stripa mine and locations of hydrology boreholes relative to underground (dashed) experiments.

various angles from the horizontal as indicated on Fig. 12. Additional information has also been obtained from a series of seven relatively shallow, vertical boreholes (WT-1 to WT-7). The inclined surface boreholes were oriented to optimize their intersection with the major fracture sets. An example of results from SBH-1 is given in Fig. 13. Note that the effect of years of drainage into the nearby mine workings has decreased the water pressures below hydrostatic as depths increase below 100 m.

A borehole injection test program has also been developed to provide information on the distribution of effective fracture apertures. The basic test equipment consists of a two packer assembly with downhole pressure and temperature probes. An example of injection test results and fracture data from the interval 325 m to 355 m in SBH-1 is given in Fig. 14. By combining different flow rates with different packer spacings, it should be possible to develop fracture aperture distribution data for different parts of the rock mass from a statistical analysis of fluid pressures, flow rates and fracture frequencies. This work is now underway (Gale et. al 1979), and the results will be incorporated into the analysis of directional permeabilities.

3.3 Large-Scale Permeability Measurement

Three problems arise in determining flow parameters for low permeability fractured rock. The first is to determine the minimum volume of rock for which the permeability tensor is representative of a larger rock mass and is amenable to a porous media method of analysis. The second problem is to determine this permeability tensor from field tests, such as those described above. The third problem is to assign permeabilities to the volumes of rock that are not directly examined in the field. The large-scale permeability

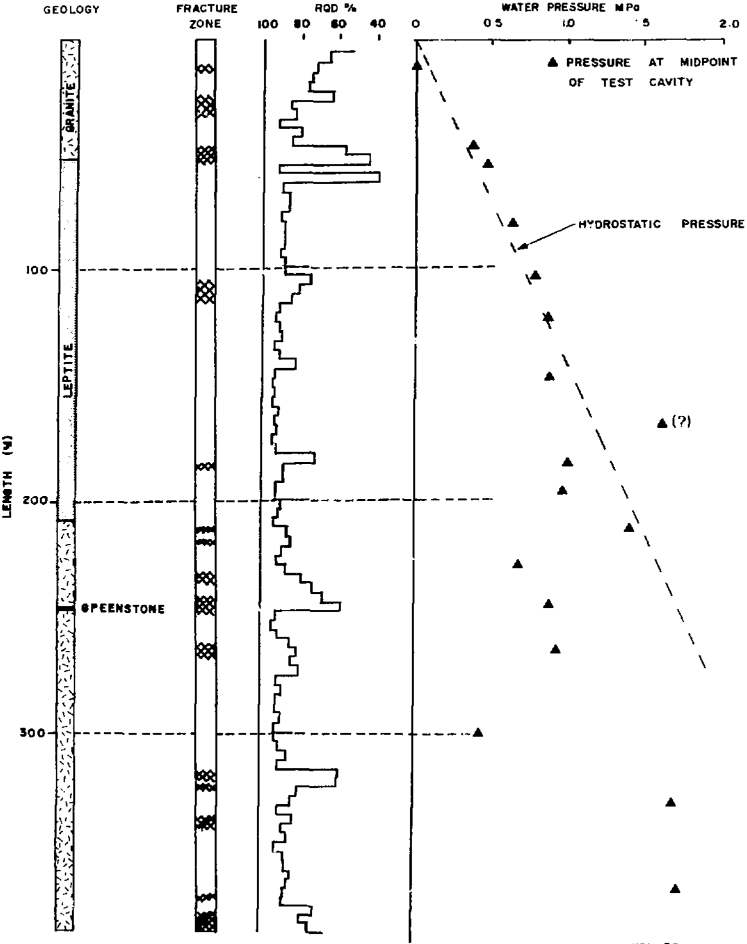

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Fig. 13. Fracture hydrology results from SBH-1 showing general geology, fracture zones, RQD values, and bottom hole hydrostatic pressures measured during drilling.

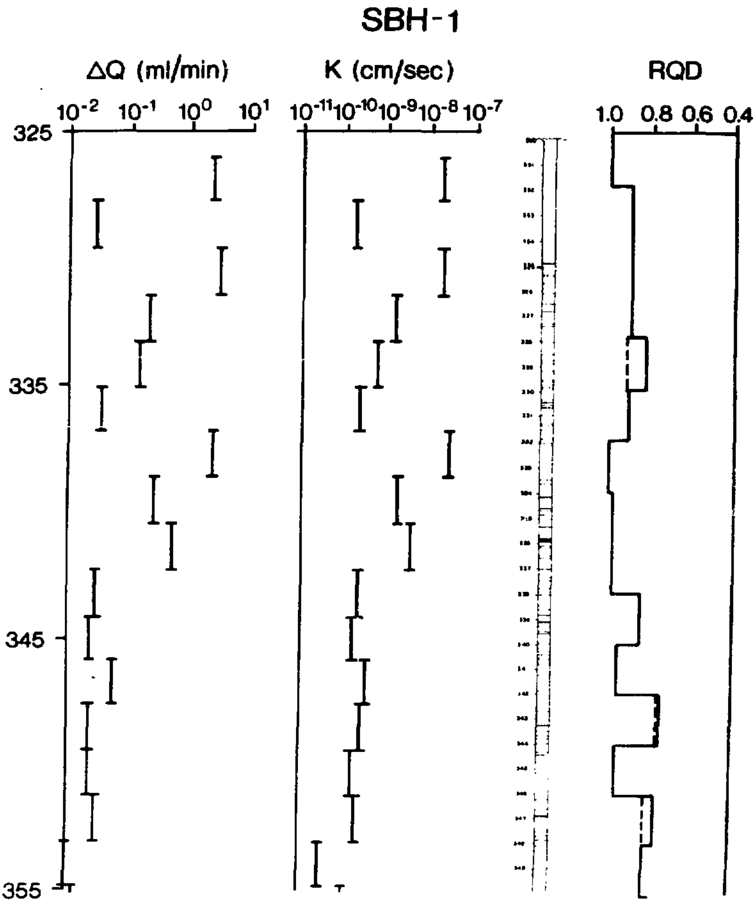

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Fig. 14. Injection test results and fracture data for the interval 325 m 355 m in SBH-1.

experiment at Stripa is an attempt to increase our understanding of the first two of these problems.

As the volume of the fractured rock sample increases from zero, the average permeability will oscillate as either fractured or solid rock is added to the sample. When the volume of rock becomes sufficiently large that permeability is no longer sensitive to the effects of individual fractures, the oscillations will be subdued. An average permeability can then be assigned to that volume of rock which is called the representative elementary volume (REV). Theoretically, volumes of rock the size of the REV can be treated as porous media for regional groundwater flow analyses. Increasing the volume further may ultimately cause additional oscillations if a different realm of fracturing is encountered. When a single permeability measurement is made in an arbitrary volume of rock, there is no way of knowing a priori whether or not the measured permeability lies on the oscillating portion of the curve. A series of measurements on different scales must be made to determine if there is an REV smaller than the rock mass itself, and to determine the permeabilities associated with that volume.

In fractured rocks, where the discontinuities themselves may occupy areas on the order of 10^2 m^2, it is reasonable to expect REV's, if they exist, to be on the order of 10^4 or 10^5 m^3 of rock. The large-scale permeability experiment at Stripa will permit a measurement of the average permeability of 10^5 to 10^6 m^3 of rock. There is no assurance that this volume will be as large as the REV; however, the experiment, taken along with other small-scale tests performed at the same site, should provide an indication of the size and existence of the REV.

The second problem is to determine the permeability of these large rock volumes from in situ tests. In high permeabilty soils or rocks, conventional well tests suffice because they perturb a large volume of the flow system. In rocks of very low permeabilty, however, such tests may only affect the flow system within a few meters of the well. A determination of large scale values of permeability can therefore be attempted in two ways. The first way is to synthesize large scale values from an appropriate number of conventional (small scale) tests in boreholes. The second way is to create a large scale sink (or source) which will perturb a large volume of the flow system, i.e., a macroscopic permeability test.

At Stripa, a macroscopic permeability test is now being carried out using the arrangement shown in Fig. 15. A 33 m length of the ventilation drift (Fig. 1) has been sealed off and equipped with a ventilation system whose temperature can be controlled to evaporate all water seeping into the room. The water seepage is being determined from careful measurements of the

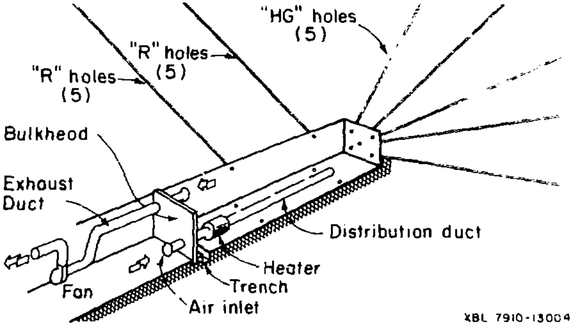

Fig. 15. Large-scale permeability experiment showing instrumentation boreholes and system to capture water seepage through evaporation into a controlled pattern of air flow.

mass flow rate and the difference in the humidities of entering and exiting air streams.

The pressure gradients in the rock walls are being measured in 15 holes that radiate out from the sealed room in all directions (Fig. 15). Two groups of five "R" holes each have been drilled from the walls out to distances of 30 m to 40 m. One group of five "HG" holes has been drilled at the end of the room. Each borehole has been sealed off with six packers placed so as to enable pressure and temperature measurements at intervals of approximately 5 m. Details of this experimental setup are given elsewhere (Witherspoon et al. 1980).

The results to date indicate that the experiment is developing in a very satisfactory manner. A dramatic indication of the degree of communication within this huge rock mass occurred in November, 1979, just as the last of the fifteen boreholes, R01, was packed off. Before instrumentation, when all the holes were draining freely, R01 produced about as much water as all the other 14 holes combined. Earlier injection tests in R01 resulted in pressure responses in many of the other boreholes in the ventilation drift. Consequently we instrumented R01 last and monitored the effects in all other boreholes of the pressure buildup in R01.

Figure 16 illustrates the pressure profiles in radial holes, R01-R05. Note that pressures increase with distance from the drift and are all about 1 MPa (145 psi) when measured 30 m out. These unusually low pressures are a result of the drainage that has been taking place into the adjacent mine workings for some years. The dashed lines represent pressures measured on October 30, 1979, and the solid lines represent pressures measured on November 8, 1979. R01 was packed off October 31, 1979, so the stippled areas show

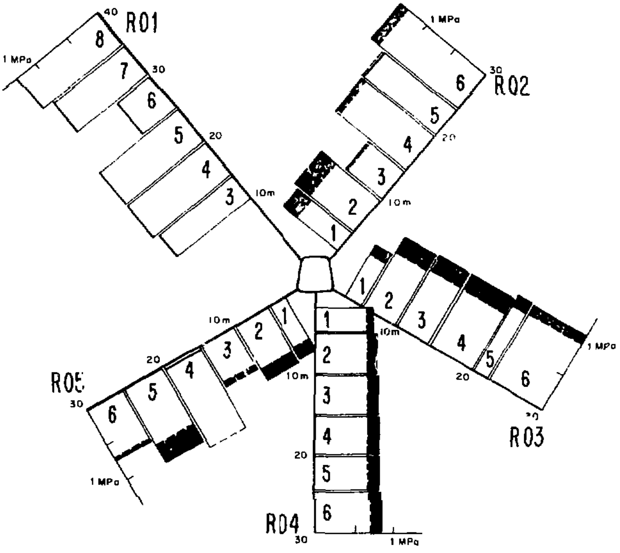

Fig. 16. Pressure measurements in radial boreholes of ventilation drift at Stripa. Stippled area shows pressure increases eight days after packing off R01. 1 MPa = 145 psi.

how pressure increases occurred more or less uniformly through out this fractured granite. Similar pressure increases were noted in all the other boreholes. This hydraulic response illustrates the complex nature of the fracture system in the granite at Stripa.

After all boreholes were packed off, a marked increase in drips and wet spots has been observed. Concurrently, the seepage rate is about 50 ml/min, and on the basis of the observed pressure gradients, the average hydraulic conductivity of the surrounding rock is about 10^{-11} m/s. This new method of measuring permeability in situ could well provide an important advance in fracture hydrology. Obviously, an experiment such as this could never be carried out without access to a test facility such as at Stripa.

3.4 Geochemistry and Isotope Hydrology

Another important component of the investigations at Stripa is the geochemistry and isotope hydrology of the groundwaters. This work provides an independent approach to the problem of the overall permeability of a rock system. If there is rapid communication of surface waters to the 338 m level where the heater experiments were placed, similarities in chemistry and age between shallow and deep waters should exist. On the other hand, if the deep waters entered the groundwater system many thousands of years ago and have percolated downward at very low velocities because of inherently low hydraulic conductivities in the rock mass, there should be significant differences between waters at different depths. This approach must, of course, take the geochemistry of these systems into account because changes in the environment of groundwaters can also produce signficant effects.

A comprehensive program of investigations on the geochemistry and isotope hydrology of the Stripa groundwaters has been carried out by Fritz, Barker, and Gale (1979a). Water samples were collected from the surface, shallow private wells, and in boreholes drilled at the 338 m level where the heater tests were carried out. In addition, a deep borehole drilled by the Swedish Geological Survey from 410 m (the deepest operating level in the mine) to about 840 m below surface provided a further opportunity to examine the concept of whether evidence can be gathered for an increasing isolation of the groundwaters with depth. Analysis of the results has provided important information on the geochemical evolution, origin and age of Stripa groundwaters (Fritz, Barker and Gale 1979a, 1979b).

Geochemical analyses of the groundwaters show an increase in total dissolved solids with depth. This increase is due to a few elements only, notably calcium, sodium, and chloride. Bicarbonate (or total inorganic carbon) decreases dramatically below 100 m depth, and both magnesium and potassium contents drop from higher levels (2-10 ppm) in the shallow groundwaters (>100 m) to below 1 ppm in the mine waters.

Especially remarkable, however, is the rise in pH from around 7.0 in the shallow waters to as high as 9.8 in the deepest groundwaters (801-838 m). This rise in pH is probably linked to the dissolution of primary silicates such as feldspars and the formation of clay minerals. These processes release calcium which causes continuous saturation of the mine waters with respect to calcite.

The increased sodium concentrations at depth could be explained by plagioclase dissolution, but is difficult to determine the origin of chloride, whose concentrations increase from 2-5 ppm in shallow waters to over 400 ppm in the deepest groundwaters. Simple mixing of freshwater and fossil seawater cannot explain the observed chemistry. The geochemical history of the deep groundwaters at Stripa is more complex than that of groundwaters from other localities in similar rocks (Jacks 1973). It is tentatively concluded that the deep groundwaters at Stripa have a different origin and are not related to fossil seawater which would have infiltrated less than 10,000 years ago.

The abundances of the stable isotopes ^{18}O, ^{2}H, and ^{13}C were determined to obtain information on the origin of these waters. The results of the ^{18}O and ^{2}H analyses are shown in Fig. 17, which illustrates that all groundwaters sampled except the surface waters, fall close to the global meteoric water line. They are thus "normal" groundwaters for which ^{18}O and ^{2}H contents reflect climatic conditions in the original recharge area.

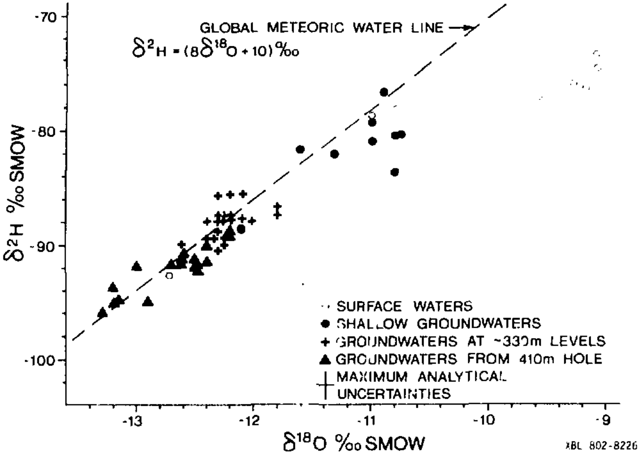

Fig. 17. Comparison of $\delta^{18}O$ and $\delta^{2}H$ values for Stripa groundwaters. The analyses are reported as δ°/₀₀ values with reference to SMOW. A $\delta^{18}O$ of -10°/₀₀ signifies that the sample has 10°/₀₀ (per mil) less ^{18}O than the reference standard which closely reflects average seawater.

As a general rule, lower heavy isotope concentrations signify lower average annual temperatures at the recharge area. Therefore, the deep "saline" groundwaters, which have the lowest ^{18}O and ^{2}H contents, must have recharged at lower average annual temperatures than the shallower groundwaters. This has been confirmed by rare gas analyses performed on all samples (Fritz, Barker, and Gale 1979a). One must therefore conclude that the deep groundwaters have an origin different from that of the shallower ones.

This conclusion is further substantiated by comparing ^{18}O with the chloride concentrations as shown in Fig. 18. Here, it is apparent that the deep groundwaters, especially those at the bottom of the 410 m hole, are

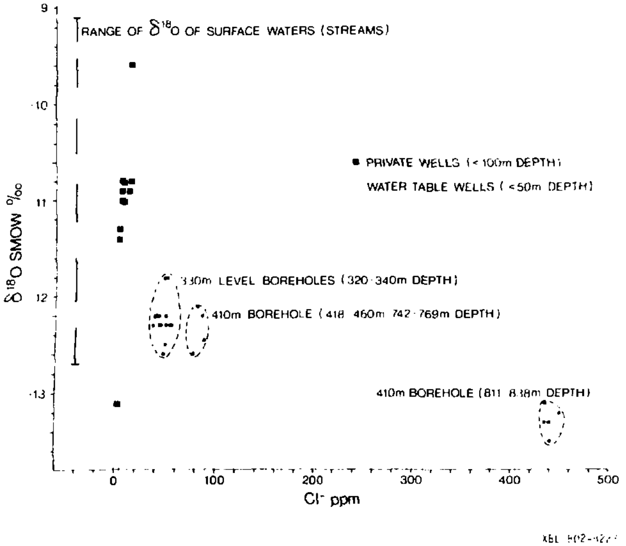

Fig. 18. Comparison of chloride with $\delta^{18}O$ values show that the different fracture systems in the Stripa granite carry different types of water.

distinctly different from the shallow groundwaters. In other words, the different fracture systems in the granite at Stripa carry different types of water because they are isolated from each other.

Because of the lower ^{18}O isotope contents in the deeper groundwaters, one could argue that this is an indication of subglacial recharge. This is not supported by the ^{13}C analyses; all waters from the mine levels have $\delta^{13}C$ levels close to or below -15°/₀₀. This indicates that biogenic carbon is present in the dissolved organic carbon, which would signify that these groundwaters infiltrated through soil horizons, that is, were generated during an interglacial period.

The most difficult and inconclusive part of this geochemical investigation was the attempt to date the groundwaters from the different mine levels (Fritz, Barker, and Gale 1979a). Tritium levels approaching 100 TU were found in all shallow groundwater (<100 m) and, interestingly enough, even in the mine waters of the old workings. However, tritium was not encountered (<0.5 TU) in any of the deep groundwaters from the granite despite the drainage mentioned above that has decreased water pressure below hydrostatic (see Fig. 13). This lack of tritium indicates that deep waters do not contain any surface water component younger than 30-40 years.

Major problems were encountered in attempting ^{14}C age dating because of the very low content of dissolved inorganic carbon. This required the treatment of 2,000 to 3,000 liters of water to obtain sufficient carbon for analysis. The results obtained indicate that waters at the 330 m level, and probably also from the 410 m borehole, exceed 20,000 years in age. Contamination problems with water samples from the 410 m borehole prevented a better result.

Three different approaches to age dating based on the uranium decay series were also investigated: (1) uranium activity rations, (2) helium contents, and (3) radium-radon relationships (Fritz, Barker, and Gale 1979a). The $^{234}U/^{238}U$ activity ratios in the groundwaters decrease from 10.4 at the 330 m level to about 6 at the top of the 410 m borehole to almost 4 in the high "saline" waters (Fig. 18) at the bottom of this hole. This decay in activity ratio can be used to date waters according to a method proposed by Barr and Carter (1978). Although the method is still under development and subject to some uncertainties, ages exceeding 100,000 years are obtained for the groundwaters from the 410 m borehole.

Somewhat lower ages were determined from the He concentrations. The atmospheric concentration at 5°C is 4.9×10^{-8} cm^3 He/cm^3 H_2O, whereas the concentrations in the groundwaters at Stripa are five orders of magnitude higher ranging from 0.3×10^{-3} cm^3 He/cm^3 H_2O at the 330 m level to 1.4×10^{-3} cm^3 He/cm^3 H_2O in the 410 m borehole. Based on a method proposed by Marine (1976), ages can be computed from these data that range from tens to hundreds of thousands of years.

If ^{222}Ra accumulates as a recoil product and is in equilibrium with ^{226}Ra, then ^{234}U and ^{222}Rn activities will eventually reach equilibrium. Ages calculated by this model indicate 10,000 to 35,000 years for the different mine waters. An extension of this approach considers the ^{226}Ra concentrations in the rock minerals and the ^{226}Ra in the water. If equilibrium between the two exists, that is, if the recoil rate from the rock equals decay in the solution, then the waters must be at least 8,000 years old (five half-lives of ^{226}Ra). There is evidence that this is the case, again supporting the earlier results that the waters presently found in the deep granite rock mass at Stripa are indeed many thousands of years old. It is apparent that a careful investigation of the geochemistry and isotope hydrology provides an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the Stripa groundwater system.

4. CONCLUSIONS

A defunct iron-ore mine at Stripa, Sweden has provided access to a large granitic rock mass for a series of investigations on the problem of isolating radioactive wastes in the underground. A coordinated series of tests are being carried out on two key problems that arise in using granite for underground waste isolation. One of these problems is that of predicting the thermo-mechanical behavior of a heterogeneous and discontinuous rock mass. This is being accomplished using a series of electric heater tests to simulate the energy released by the decay of radioactive waste. The other problem involves fracture hydrology, that is, predicting the movement of groundwater that can transport radionuclides through the granite. A combination of borehole measurements and geochemical studies forms the basis of these hydrology tests. A new method of measuring the permeability of very large rock masses is also being developed.

The thermo-mechanical investigations were designed to study the in situ behavior of granite under thermal loadings equivalent to that produced by reprocessed wastes after 3.5 and 5.0 years of surface storage. The results indicate that the temperature variations with time and space within the rock mass can be reasonably well predicted using available theory and appropriate values of material properties. The mechanical response, on the other hand, has been significantly less than that predicted from an application of the theory of linear thermoelasticity for intact rock. As one might expect, the discontinuities play an important role as thermal expansion of the rock blocks takes place. This is a complex problem that will require much more analysis.

High temperatures were expected to occur in the rock immediately surrounding the electric heaters resulting in large thermal compressive stresses approaching the strength of the granite. This has been investigated by increasing temperatures in the borehole surrounding one of the full-scale heaters. The resulting thermal decrepitation, along the vertical walls of the borehole has been severe, and the analysis to date indicates that this failure has been aggravated as rock temperatures exceed 300°C.

The fracture hydrology program at Stripa is essentially a problem of understanding the hydrological behavior of a complex network of fractures. Three of the most important components of this program involve: (1) assessing directional permeabilities, (2) large-scale permeability measurements, and (3) geochemistry and isotope hydrology. Basic data on fracture orientations, spacings and continuity have been obtained by careful mapping at the surface, in boreholes and in subsurface openings. A borehole injection test program has also been developed to provide information on the distribution of effective fracture apertures. An analysis of these data is now underway in an effort to assess directional permeabilities for the granite mass.

The large-scale permeability test is an attempt to develop a method of determining: (1) the minimum volume of rock for which the permeability tensor is representative of a larger rock mass, and (2) the permeability of a very large rock volume approaching 10^6 m^3. A 33 m length of drift has been sealed off and the mass of water that seeps into the room is being measured using an air ventilation scheme. Pressure gradients in the water saturated network of fractures in the rock walls of the drift are also being measured. Analysis of these data indicate that a preliminary value for the average permeability is about 10^{-11} m/s.

A comprehensive program of investigations on the geochemistry and isotope hydrology of the Stripa groundwaters has been carried out using samples collected from the surface, shallow private wells and underground boreholes. The geochemical analyses show that the total dissolved solids increase steadily with depth down to 840 m, which was the deepest point reached in one borehole. A comparison at ^{18}O with the chloride concentrations, which increase from 2-5 ppm in shallow waters to over 400 ppm in the deepest groundwaters (801-838 m), reveals distinct differences as depth increases. In other words, the different fracture systems in the granite at Stripa carry different types of water because they are isolated from each other. The results of age dating using ^{14}C indicate that waters at the 330 m level, and probably also in the deep borehole that extends down to 840 m, exceed 20,000 years in age. Three other approaches to age dating based on the uranium decay series were also investigated. Although these methods are still under development, the results support the ^{14}C data that the waters presently found in the fractures of the deep granite rock mass at Stripa are many thousands of years old. It is apparent that a careful investigation of the geochemistry and isotope hydrology provides an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the Stripa groundwater systems.

The results of these field tests have shown the importance of geologic structure and the functional dependence of the thermo-mechanical properties on temperature in developing a valid predictive model. The results have also demonstrated the vital importance of being able to carry out large scale investigations in a field test facility.

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