RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK— RESULTS OF FIELD INVESTIGATIONS AT STRIPA, SWEDEN

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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 excavation 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 below the surface 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, 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. 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 carrying out large-scale investigations in a field test facility.

1. INTRODUCTION

Although several ideas for isolating radioactive wastes have been proposed, the idea of using underground excavations for deep geological disposal is receiving increasing attention (U.S. Department of Energy 1979). Designing 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 cannot be overstated. These conditions include the presence of heat-generating, radioactive wastes, and the complex processes of waste migration (deMarsily et al. 1977) in slowly moving groundwaters. 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 problem.

Since 1977 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 an iron-ore body (high-grade metavolcanics) at a depth of 338 m below surface (Fig. 1). This work is part of a Swedish-American cooperative program of investigations on radioactive waste disposal (Witherspoon and Degerman 1978). LBL's counterpart in Sweden is the Nuclear Fuel Safety Program (KBS).
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Energy. The KBS activities are under the direction of the Swedish Nuclear Fuel Supply Company (SKBF).

A coordinated series of tests have been carried out on two key problems in using granite for underground waste isolation. The first is that of predicting the thermo-mechanical behavior of a heterogeneous and discontinuous rock mass. To do this, a series of electric heater tests is being used to simulate the energy released by the decay of nuclear waste. The second problem involves predicting the movement of groundwater that can transport radionuclides through fractures in the granite. A combination of borehole measurements and geochemical studies forms the basis of these hydrogeology tests. A new method of measuring the permeability of very large rock masses using a length of drift is also being developed. Results will be compared with those from conventional methods.

2. THERMO-MECHANICAL INVESTIGATIONS

2.1 Importance of Thermo-Mechanical Effects

A geologic site identified as suitable for a radioactive waste repository 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 practical to accomplish this without significantly impairing the ability of the site to isolate wastes from the biosphere.

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 geologic 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 where rock stress, groundwater pressure, and other conditions are 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 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 consider 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 as shown in Figure 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 about 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 U.S. Bureau of Mines 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 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.

Figure 3 compares predicted versus measured temperatures 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 heater turn-on. As will be described below, this granite rock mass is extensively fractured and jointed. Careful examination of Figure 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.

2.3 Time-Scaled Heater Experiment

One of the more important factors in repository design is the effect of long-term thermal loading on the rock mass. 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, in the time-scaled experiment at Stripa the times have been compressed in the ratio 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 $1/\sqrt{10} \approx 0.32$ 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 eight 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 Figure 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. We 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, there is a remarkably good agreement between measured and predicted rock temperatures.

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 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 installation, 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 5.0 kW 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 thick. Step increases in canister skin temperatures of 10° to 30°C 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 long, 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 present, 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 before 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 Figure 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 of 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 before 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, ν = 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 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 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 Figure 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 second set of displacements has been predicted using temperature dependent values of α, E, ν, and k with results as shown in Figure 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 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. Studies of the behavior of the rock mass in situ raises a 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 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 could 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 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, 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 surface 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 Figure 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 under way) 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 facility, 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 1 1/2 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 use 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 failed only three times. 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 cyclic 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 Mechanics 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 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 5 hours, were found to have a reproducible thermal expansivity, and thus corrections for rod expansion during temperature buildup 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 extensometer precision 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 in 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: permeability, effective porosity, and 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 to depths of 1000 m 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? To answer the first question, we need 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. We are attempting 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, and SBH-3 are 76 mm diamond core-holes that were drilled at various angles from the horizontal as indicated on Figure 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 Figure 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 Figure 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 under way (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 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 REVs, 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 permeabilty 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 indicate 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 permeability 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 Figure 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 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 pressure and temperature measurements can be made 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 15 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. Pressures increase with distance from the drift and are all about 1 MPa (145 psi) at a distance of 30 m. 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 how pressure increases occurred more or less uniformly throughout 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 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 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 it 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 Figure 17, which illustrates that except the surface waters, all groundwaters sampled 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.

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 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 $-15°/_{oo}$. 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, which 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 indicate that waters at the 330 m level, and probably also from the 410 m borehole, were more than 20,000 years old. 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 ratios, (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. A careful investigation of geochemistry and isotope hydrology is an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the Stripa groundwater system.

4. IMPORTANCE OF FULL-SCALE FIELD TESTING

The results obtained at Stripa would not have emerged unless the experiments had been carried out underground at depths comparable with those envisaged for an actual repository. However, this creates unexpected and sometimes difficult problems, which must be resolved if deep geologic disposal of radioactive waste is to become a reality. Scientific advances are needed in the laboratory but these must be supported by meaningful field experiments.

The mechanical, thermal, hydraulic, and chemical behavior of a repository in a crystalline rock mass of low permeability is determined by the rock matrix properties and, more importantly, by discontinuities that pervade the rock mass. This raises a critical question, Can one determine the geometry of fractures in sufficient detail using surface measurements? Studies by Kendorski and Mahtab (1976) and Raven and Gale (1977) suggest that fracture orientations between surface and subsurface are similar. However, no data demonstrate that length and continuity of such features can be predicted reliably from surface measurements.

Fractures must be mapped so that the orientation, spacing, continuity, and aperture distribution are determined in sufficient detail to enable us to predict the total behavior of the rock mass. Over long time periods, this complex problem involves the thermo-mechanical response of the rock system and the hydraulic-chemical behavior of aqueous solutions migrating through the discontinuities. The magnitude of the thermo-mechanical response depends on the thermal loads imposed on the system and the material properties of the rock mass. The hydraulic-chemical behavior depends on the permeability and porosity of the system, the hydraulic gradients (natural and/or thermally induced, and geochemical reactions. These coupled effects are also influenced by the magnitude of the in situ stresses. The repository must be deep enough to keep the fractures closed and to maintain low permeabilities (even in a perturbed rock mass containing discontinuities) yet not so deep as to generate stresses that cause stability problems.

Much more work will be required to develop a reliable basis for predicting the thermally induced behavior of discontinuous rock masses. The mechanical and hydrologic effects of the discontinuities are not yet understood. After a repository has been filled with waste canisters, the rock will undergo a thermal pulse of increasing temperature extending out to distances well beyond the limits of the excavations. The magnitude of this effect is, of course, primarily dependent on the energy and spacing of the canisters. However, for high-level waste from light water reactors, this pulse reaches a maximum temperature in the plane of the repository between 10 and 100 years.

This thermal perturbation caused by the repository raises a second critical question. How can we develop the technology to reliably predict the global thermal response of a repository in a discontinuous rock mass? This can only be carried out in an underground test facility that has been properly designed and instrumented. Whether or not more than one type of crystalline rock needs to be tested in this fashion is difficult to answer because the physics of the thermomechanical and hydraulic-chemical behavior of large rock masses are not yet adequately understood. Since granite and basalt have distinctly different types of fracturing and are examples of massive versus bedded forms of igneous rock, they would appear to be prime candidates for underground investigations.

Because the heat output of radioactive waste decays with time, the magnitude of the thermal perturbation depends on how long the emplaced waste was stored at the surface. This raises a critical question, What are the tradeoffs between minimizing the thermally induced effects and long-term surface storage of waste? The decrepitation results observed at Stripa when rock temperatures near the 5.0 kW heater exceeded 300°C could undoubtedly be eliminated by keeping the temperature below some maximum value. This would be an important component of the field experiments suggested above. Low temperatures would also minimize effects on backfill materials and the possibility of generating thermal convection in the groundwater system. The answer to this third critical question will not be forthcoming until the ability to predict thermally induced effects is perfected through appropriate field tests underground.

Another area of investigation must be the hydrogeology of the rock mass and the geochemical behavior of aqueous solutions, including radionuclides, as they migrate through that mass. This hydraulic-chemical respose is coupled to the thermo-mechanical response through the discontinuities. Fractures in any type of rock will deform under the influence of changes in rock stress, affecting the permeability of the rock mass. The magnitude of these changes in permeability may be very important and will depend on the effects of the thermal perturbation and the disturbance caused by the excavation itself.

All of these concerns raise a fourth critical question, How should we make field measurements of the rock properties we need to understand the hydraulic-chemical effects, specifically permeability (hydraulic conductivity), total and effective porosity, and sorption behavior?

At Stripa, a careful measure of the permeability tensor is being attempted using conventional methods in inclined boreholes drilled from the surface. These methods seem to be working well, but the hydraulic conductivity at Stripa is about 10^{-11} m/s. Less permeable rock masses may have values two to three orders lower than this, and whether conventional methods will still give reliable results remains to be seen. On the other hand, the large-scale method, of measuring permeability (Witherspoon et al. 1980) should easily be adaptable to rock masses with permeabilities far less than at Stripa. Thus, the accuracy of borehole methods must be assessed by comparing the results with those from the large scale method, which will certainly yield a good measure of the bulk permeability in the immediate vicinity of the repository. This information is needed to confirm the degree of isolation at a potential site. Conceptually, one could use this method to measure the permeability of the rock mass around individual drifts during their excavation. However, in the far field, where it is not practical to use the large-scale method, one needs to know the reliability of the various borehole testing techniques in measuring permeability.

In a rock mass with very low permeability, the problem of measuring the effective porosity using in situ tracer tests is not easily resolved. Because they involve rock at great depths and large enough to be representative of the total mass, the tests may take months or years to complete. Under such circumstances, conventional tracer tests in deep boreholes drilled from the surface are not likely to yield reliable results. On the other hand, an underground room, similar to that at Stripa (Fig. 15), creates significant pressure gradients at the depths where a repository will be constructed. Movement of groundwater through the fracture system toward such an underground opening is greatly enhanced, and tests using tracers can be designed for use in very large volumes of rock. Actual velocities can be measured by introducing such a tracer at a point along a known flow path and observing time of arrival downstream. Although standard borehole tracer tests contribute to an understanding of fracture flow in higher permeability rock masses, it is our conclusion that the only feasible approach in rocks with very low permeabilities is an underground tracer experiment run in conjunction with a large-scale permeability test.

Predicting the geochemical sorption behavior of aqueous solutions of radionuclides in contact with mineral surfaces is complicated by a lack of basic data. Much work is needed on the behavior of the actinide aqueous and solid species that are important in groundwater transport processes; there is also a dearth of information on the potential for actinides to form colloids in groundwater. Actinides may form complexes with organic materials that occur naturally in groundwater (Means and Hastings, 1979). The movement of dissolved species involves several mechanisms for retardation, such as sorption on mineral surfaces, precipitation, ion exchange, and diffusion into the rock matrix. Because of the small scale of these phenomena, they can be studied very effectively in the laboratory, and a large effort in this direction is now under way. Eventually geochemists will require field tests to validate their laboratory findings. If underground test facilities are already in operation for other purposes, various geochemical tests could be incorporated conveniently; such tests are already being planned for the Stripa project.

The critical importance of being able to determine the velocity of groundwater movement through a rock mass with very low permeability cannot be overstated. A good understanding of the geochemistry and of the ages of the groundwaters at different points in the total system provides important data. There is also the need to integrate geochemical and isotopic data with the physical hydrology results, as is being done at Stripa. This raises a fifth critical question. How should one gather groundwater samples for these investigations?

The conventional approach to this problem is to collect water samples in vertical boreholes drilled from the surface. Drilling procedures normally cause contamination of the natural waters because the pressures required for fluid circulation often exceed those of the fluids in the rocks being drilled. This is usually overcome before sampling by producing a sufficient volume of water from such rocks until the contaminants are removed. In rocks with very low permeability this may not be practicable because the influx of groundwater into boreholes may be very slow.

Experience at Stripa, however, has shown clearly the superiority of collecting groundwater samples from boreholes drilled from underground drifts and rooms. Hydrostatic water pressures in rock are about 1 MPa per 100 m of depth, whereas the pressure within the mined openings is only about 0.1 MPa (1 atm). Thus, any borehole that is drilled from an underground excavation into the rock mass around the opening encounters hydrostatic pressures that far exceed the pressure necessary to circulate the drilling fluids. This creates an artesian condition that minimizes contamination and greatly simplifies the subsequent problem of collecting water samples. Furthermore, both horizontal and vertical boreholes can be drilled from an underground location to provide data in three-dimensions of the hydraulic environment. This approach to collecting water samples for geochemical and isotopic groundwater studies is far more effective than methods using boreholes drilled from the surface.

The effectiveness of backfill materials in isolating canisters of radioactive waste and plugging off underground openings is still another problem that must be investigated. This raises the sixth critical question, What is the proper way to demonstrate the effectiveness of backfill materials? As in the case of sorption behavior for aqueous solutions of radionuclides, many fundamental aspects can be investigated very effectively in the laboratory, especially in conjunction with the study of naturally occurring geological materials. A large effort in this direction is already under way. Ultimately, however, field tests will be required to demonstrate how such materials can be used best under repository conditions. It will be necessary to carry out field demonstrations on selected materials under appropriate levels of stress, temperature, and moisture content. This can be done meaningfully only in an underground test facility.

Answers to the above six questions cannot be found in terms of current experience or through numerical modeling alone; these problems will require investigations conducted in full-scale underground test facilities at depths and other conditions expected to be encountered in an actual repository. For speed and economy, preference may be given to the process of evaluating a repository site on the basis of detailed exploration and testing carried out at the surface or in boreholes drilled from the surface. Such techniques, however, cannot yield the data needed to assess the total behavior of discontinuous rock masses when subjected to the perturbations of an underground waste repository. Experience with underground experiments at Stripa indicates that site evaluation must include extensive subsurface experiments, carried out in conjunction with measurements made at the surface. Much effort is needed at this stage to generate the technology that is required. The Stripa investigations are a beginning.

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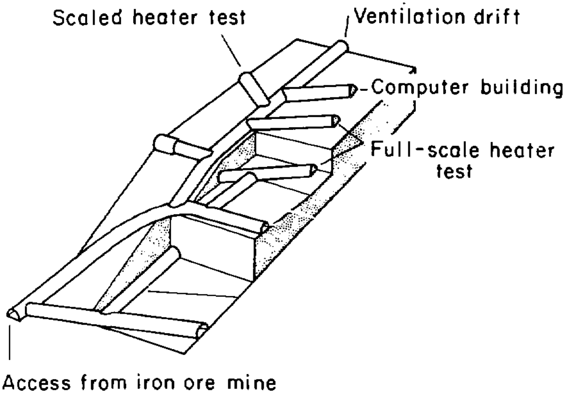
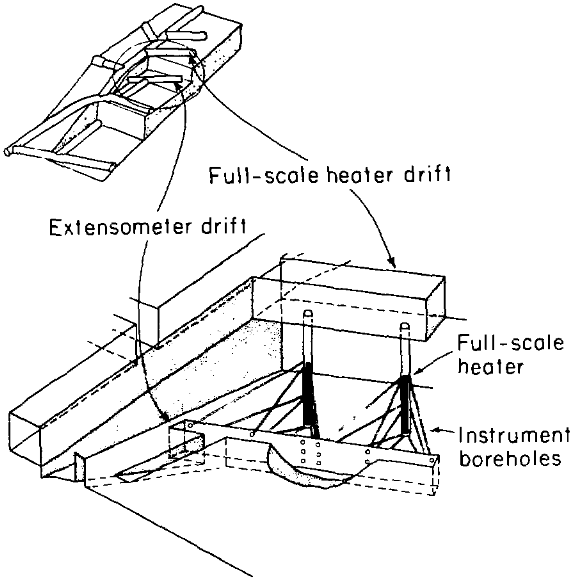


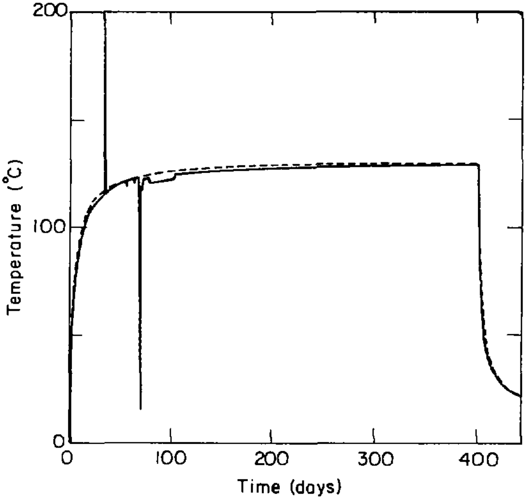
XBL 803-6853

Fig. 1. Location of experimental rooms excavatated in granite (quartz monzonite) rock mass at Stripa.



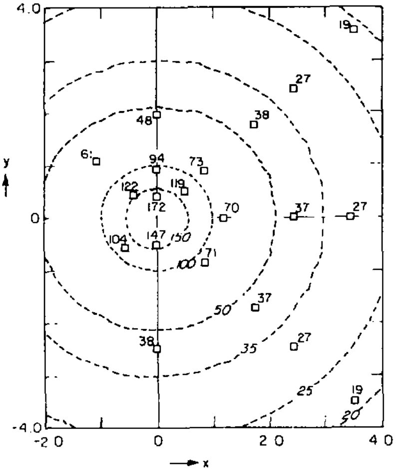
XBL 803-6854

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



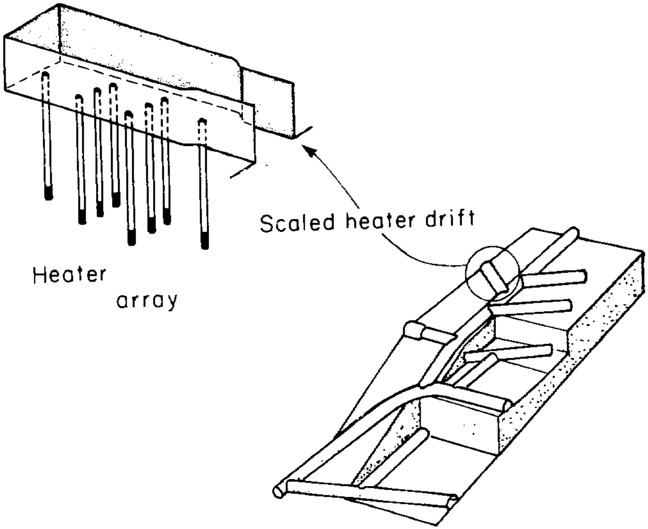
XBL 801-4594

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.



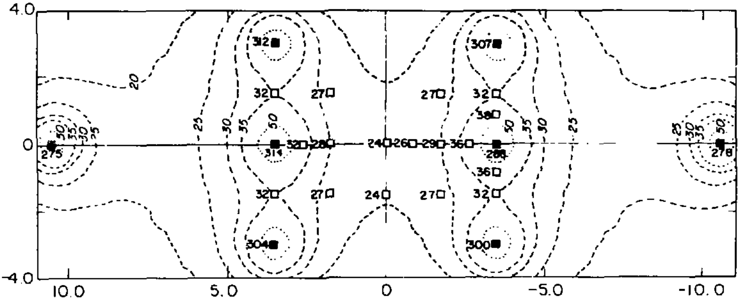
XBL 791-5519

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.



XBL 785-969A

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



XBL791-5520

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.

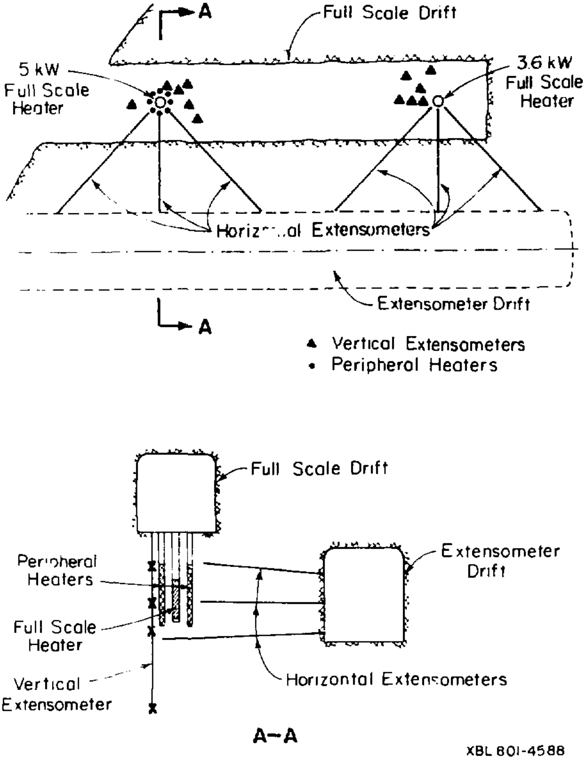
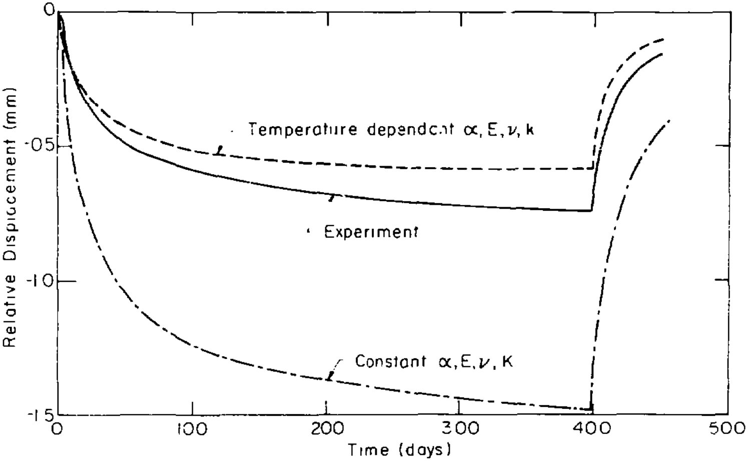


Fig. 7. Diagram illustrating arrangement of full-scale heaters, locations of extensometers in both vertical and horizontal boreholes, and locations of peripheral heaters surrounding 5.0 kW full-scale heater.



XBL801-4611

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.

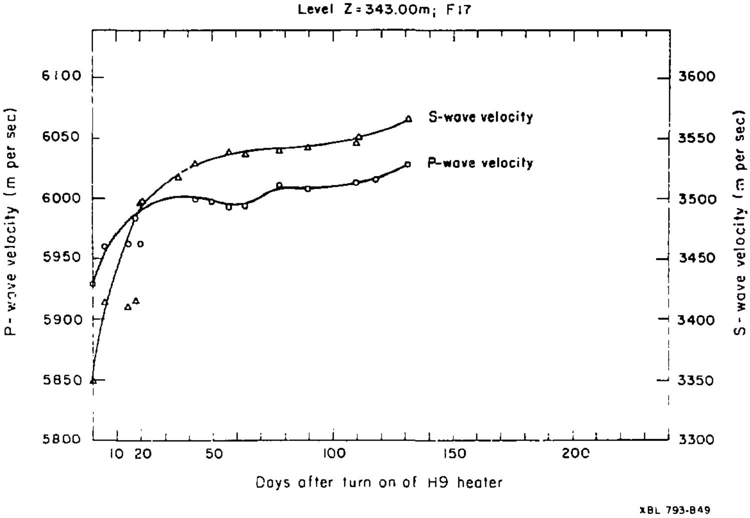
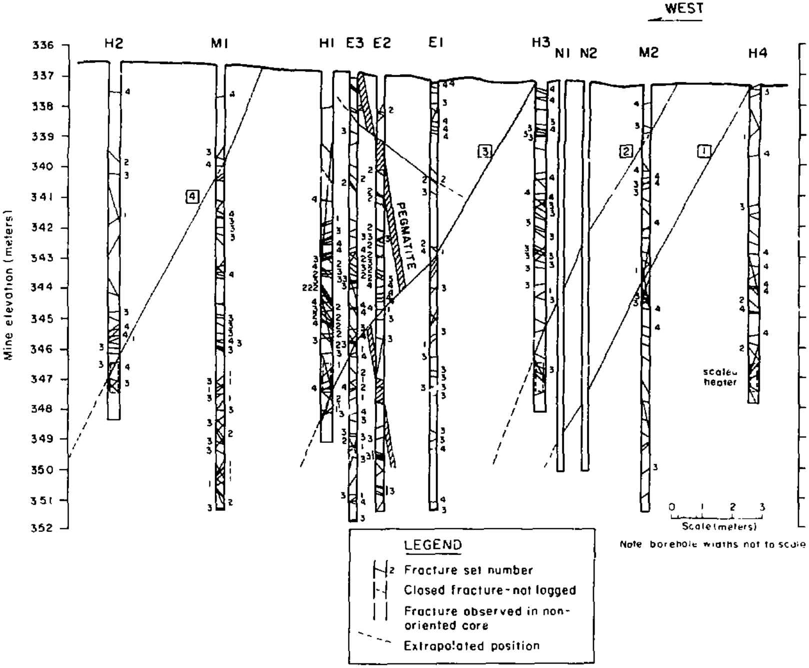
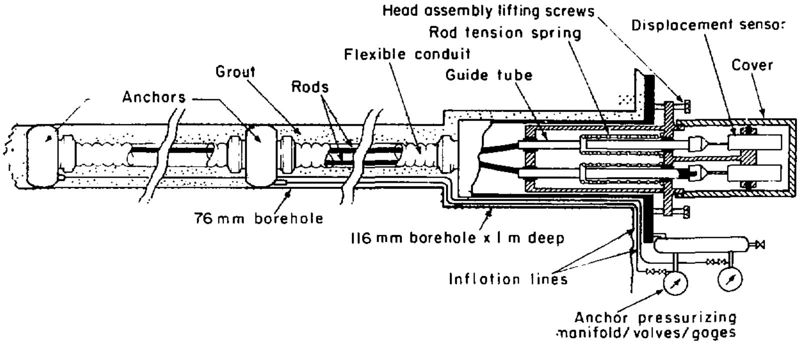


Fig. 9. Ultrasonic velocity measurements between boreholes 4 m apart at the heater midplane elevation in the rock mass adjacent to the 3.6 kW full-scale heater.



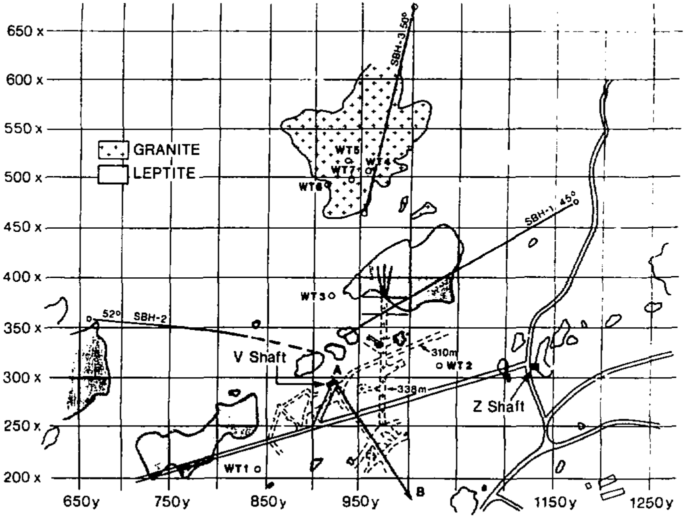
XBL 7811 12833A

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



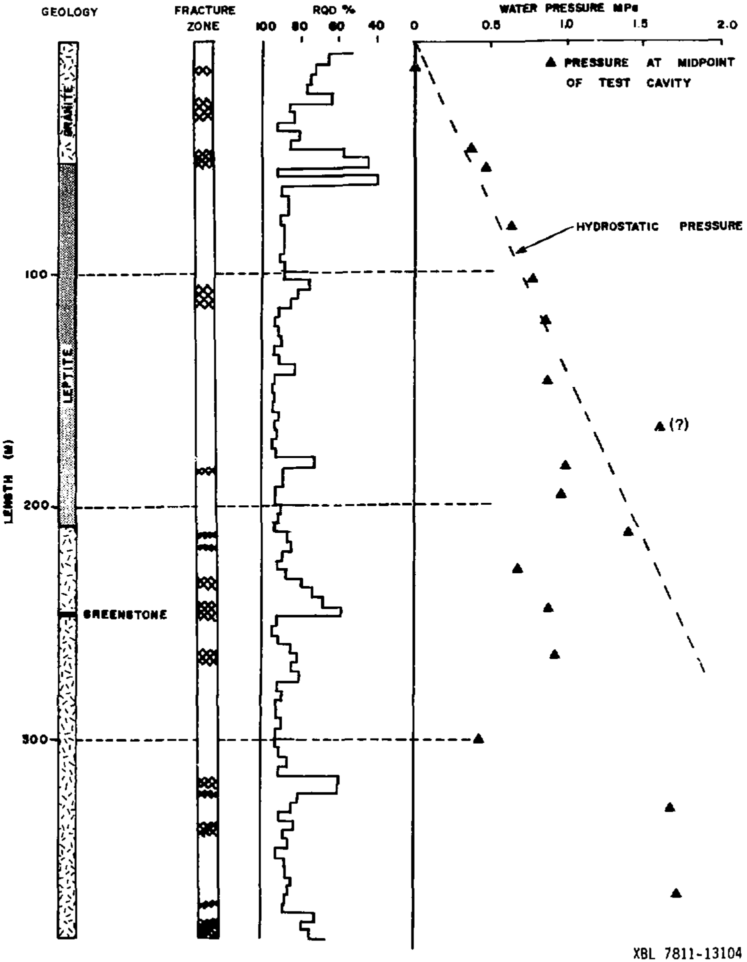
XBL 7910-4441

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



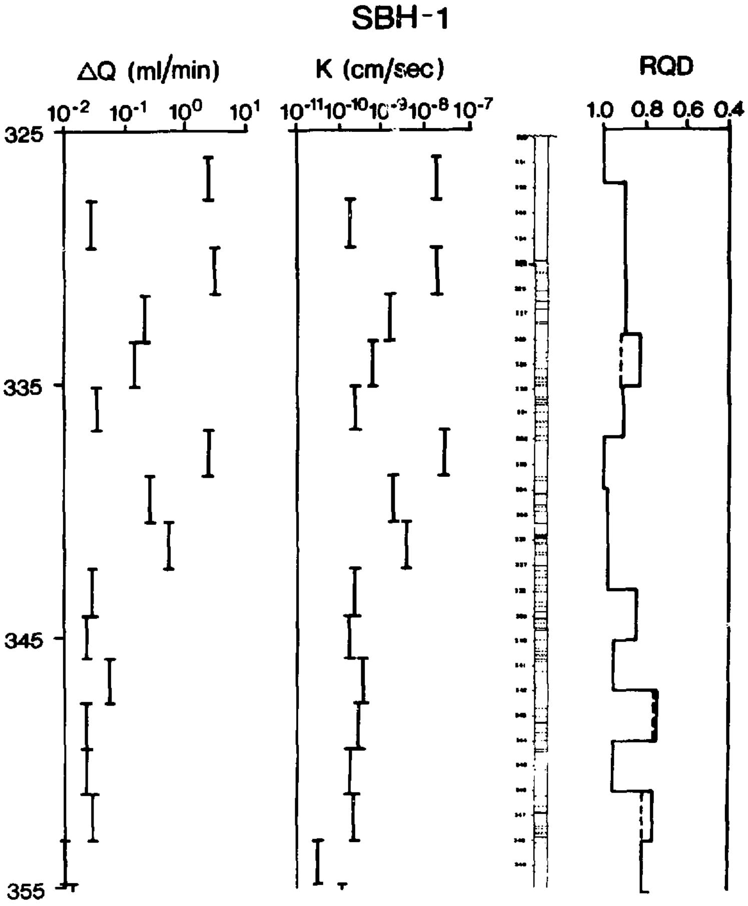
XBL 804-9434

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



XBL 7811-13104

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



XBL 802-8225

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

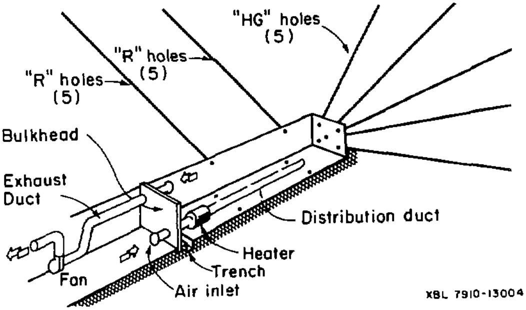
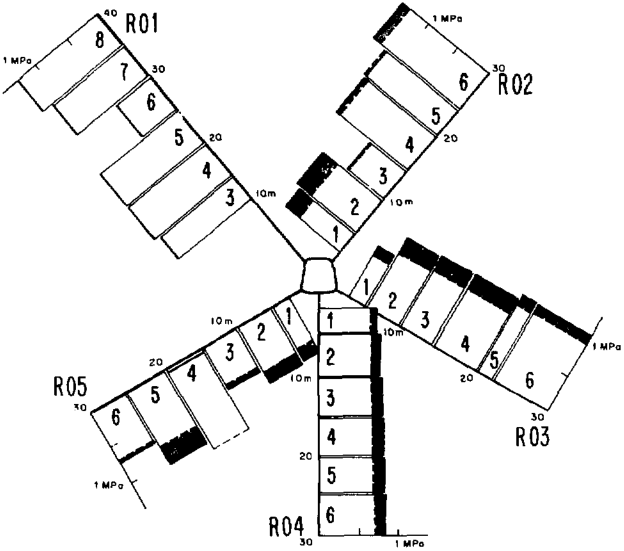


Fig. 15. Large-scale permeability experiment showing instrumentation boreholes and system to capture water seepage through evaporation into a controlled pattern of air flow.



XBL 7911-13436

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.

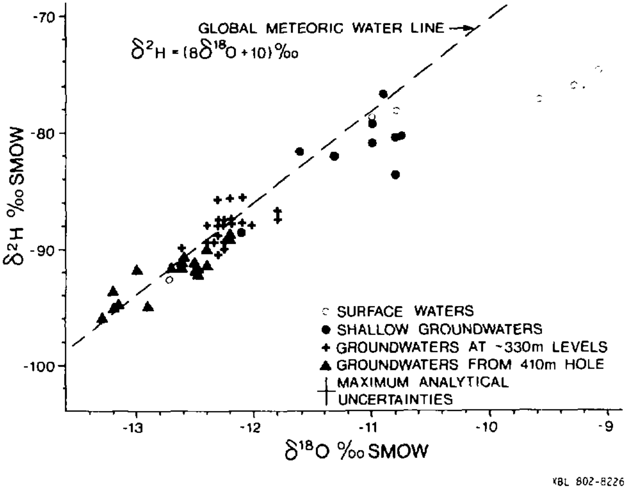


Fig. 17. Comparison of $\delta^{18}O$ and $\delta^{2}H$ values for Stripa groundwaters. The analyses are reported as δ°/₀₀ values with reference to SMOW. A $\delta^{18}O$ of -10°/₀₀ signifies that the sample has 10°/₀₀ (per mil) less ^{18}O than the reference standard, which closely reflects average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

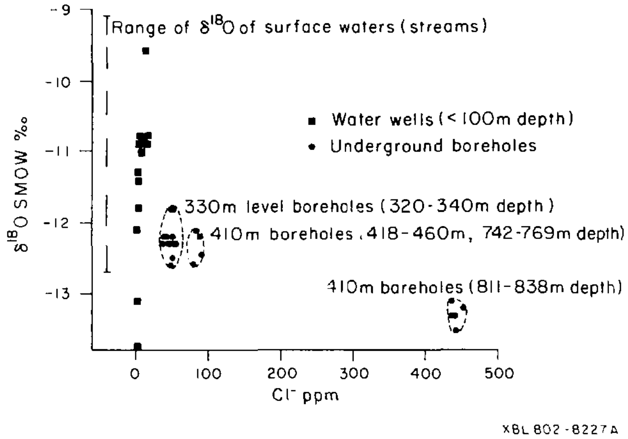


Fig. 18. Comparison of chloride with $\delta^{18}O$ values show that the different fracture systems in the Stripa granite carry different types of water.