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GEOTECHNICAL ASPECTS OF INVESTIGATIONS AT STRIPA ON RADIOACTIVE WASTE ISOLATION

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ABSTRACT

Access to a granitic rock mass in an iron ore mine in Sweden has provided a unique opportunity for a series of investigations on problems involved in geologic storage of radioactive waste. Important results have been obtained that would not have emerged if these experiments had not been carried out underground at depths comparable with those envisaged for an actual repository. It was observed that as the rock mass was heated, the temperature variations over time and space could be reasonably well predicted using available theory and appropriate values of material properties. However, because the rock is fractured, predicting the thermomechanical behavior is much more involved. The role of the discontinuities is a key factor and is not yet well understood. The fracture network is also the dominant factor in controlling rock mass permeability. A new method of measuring average permeability on a very large scale is reported. Investigations on the geochemistry and isotope hydrology of groundwater samples have also been carried out. This work has revealed a number of geotechnical problems that must be pursued and has also demonstrated the vital importance of being able to carry out large scale investigations underground in a field test facility.

RÉSUMÉ

D'avoir pu atteindre un volume de roche de granit dans une mine de fer en Suède a fourni une occasion unique de faire des recherches au sujet de problèmes concernant le stockage géologique des déchets radioactifs. On a ainsi obtenu des résultats importants qui n'auraient pu être générés si ces expériences n'avaient eu lieu sous terre à une profondeur comparable à celle d'un véritable dépot. On a noté que sous l'influence de la chaleur les changements de température en fonction du temps et de l'espace peuvent être prévus assez facilement en se servant de la théorie accessible et des valeurs appropriées des fonctions matérielles. Pourtant, parce que la roche est fissurée, il est beaucoup plus difficile de prévoir le comportement thermomécanique. Le role des discontinuités est primordial, car il est encore assez méconnu. Le réseau de fissures est le trait dominant qui controle la perméabilité de la masse rocheuse. On étudie ici une nouvelle méthode pour mesurer la perméabilité moyenne en grand. On a aussi fait des recherches sur la géochimie et l'isotope de l'hydrologie des échantillons souterrains. Ces recherches ont conduit à un nombre de problèmes géotechnique qui doivent être étudiés et ont aussi démontré qu'il est absolument essentiel de pouvoir poursuivre des recherches souterraines en grand dans un vrai champ d'essai.

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INTRODUCTION

Safe disposal of radioactive waste away from the biosphere has become a topic of much concern in the United States, particularly within the past decade. Over the past four years, the Lawrence Berkeley Laboratory has been responsible for carrying out a comprehensive series of field tests to study certain aspects of this problem in an abandoned iron-ore mine at Stripa, Sweden, about 150 km west of Stockholm. Lead organizations for this work are the Nuclear Fuel Safety Program (KBS) for Sweden and Lawrence Berkeley Laboratory (LBL) under the Battelle Office of Nuclear Waste Isolation for the U.S. Department of Energy (Witherspoon and Degerman, 1978).

Mining at Stripa began in 1485 and continued intermittently until late 1976. The underground workings are 250 km in length in 15 levels down to 410 m below the surface. The banded hematite ore at Stripa is situated almost entirely in leptite, predominantly a silica-rich, high-grade metamorphosed volcanic rock of Precambrian age (Olkiewicz et al., 1979). The leptite was subjected to east-west compression, during which the north-northeast-trending Vikern syncline, containing the ore deposit, was formed. Late in a second period of folding, caused by north-south compression, the plutonic rock at Stripa intruded the leptite. The plutonic rock, 1.7 billion years old, is predominantly quartz monzonite. A series of pegmatitic and aplitic dikes transect the reddish, medium grained massive quartz monzonite, which has been fractured in at least two stages. Some of the workings for mining the ore intersected the quartz monzonite,

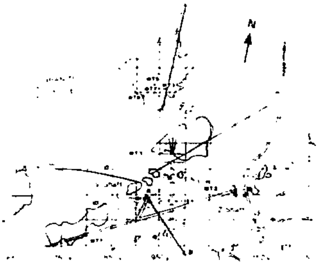

Fig. 1. Map showing general geology at Stripa mine, locations of inclined hydrology boreholes (SBH-1, SBH-2, SBH-3), and underground test rooms (dashed lines) at 338 m level.

hence the easy access for these investigations.

The general geology at the Stripa mine and the location of the experimental investigations for radioactive waste purposes are shown in Fig. 1. A coordinated series of tests were carried out on two key problems that arise in using granite for underground waste isolation. One of these problems is that of predicting the thermomechanical behavior of a heterogeneous and discontinuous rock mass. This was 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 formed the basis of these hydrology tests. A new method of measuring the permeability of very large rock masses in a sealed-off length of drift was also developed to compare with results by conventional methods. Important findings have been obtained in this work, and the purpose of this paper is to discuss their significance from the geotechnical standpoint.

THERMOMECHANICAL INVESTIGATIONS

Importance of Thermomechanical Effects

After a geologic site suitable for a radioactive waste repository has been identified, the site will be subjected to two principal perturbations. First, it will be necessary to sink shafts to the depths of the proposed repository and then make the required excavations to hold the waste canisters. 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 insure 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. An estimate of the magnitude of these effects can be calculated readily using a linear theory of thermoelasticity. This requires a prediction of the temperature fields and appropriate values of rock properties to be used in determining thermal induced displacements and stresses. Unfortunately, the required material properties are normally measured only on small cores, and it is well known that the behavior of a large rock mass is seldom the same as that of small samples of rock (Hoek, 1979). Accordingly, it is important to develop and verify models for predicting the thermomechanical response of an underground waste repository.

The availability of the test facility in the Stripa mine in water-saturated granitic rock provided a unique opportunity for conducting thermomechanical experiments. 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 thermomechanical 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.

Full-Scale Heater Experiments

Full-scale heater experiments were 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 were used to simulate the power output of radioactive waste. Two such canisters, each containing four heating elements, were 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 Fig. 2.

Fig. 2 shows a cutaway drawing of the two full-scale heaters and some of the horizontal boreholes that were instrumented from an adjacent lower level drift. The two heater holes were spaced 22 m apart so that the canisters remained thermally isolated from each other for the duration of the experiment. This enabled two separate experiments to be conducted in parallel. Power output for one canister-heater was adjusted to 5 kW to represent a typical power level of reprocessed fuel after some three years. The other canister-heater was set at 3.6 kW to represent similar waste products approximately five years old at the time of emplacement. These power levels were selected four years ago; currently, somewhat lower levels are preferred.

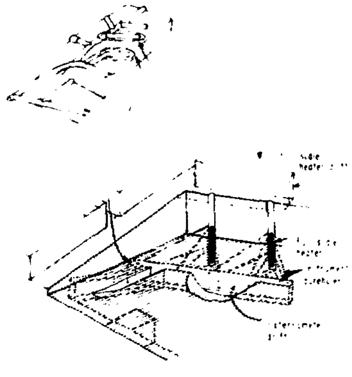

Fig. 2. Arrangement of experiments [illegible] in quartz monzonite rock mass some [illegible] below the surface, showing details of full-scale heater drift and location of instrument boreholes from adjacent extensometer drift.

The response of the mass adjacent to the two canisters was monitored extensively. Rock displacements were measured using extensometers, and thermally induced stresses were determined from strain measurements using USBM borehole deformation gages and IRAD (Create) vibrating wire gages (Schrauf et al., 1979). Each of these instruments had a thermocouple associated with it, and additional thermocouples were positioned around each heater to obtain the temperature field in three dimensions.

Within a relatively short period of time, these heater tests provided important data on the thermal behavior of typical hard crystalline rock (Chan et al., 1980a). Fig. 3 shows an example of temperatures predicted versus those that were measured for the 3.6 kW heater as a function of time. The length of the heating period was 398 days; the total length of the experiment was about 1½ years. Temperature predictions were based on a semi-analytical solution assuming intact rock and laboratory measurements of rock properties (Chan et al., 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, 1.47×10^{-6} m^2/sec.

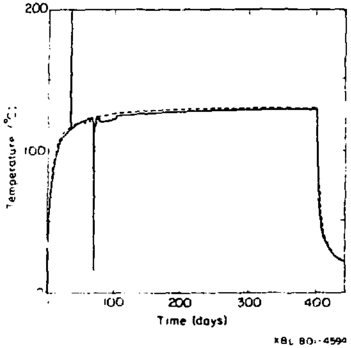

Fig. 3. Predicted (dashed) and measured (solid) temperatures plotted as a function of time at a radius of 0.4 m from 3.6 kW heater along heater midplane. Variations in measured signals at early time caused by corrosion of stainless steel thermocouple sheath.

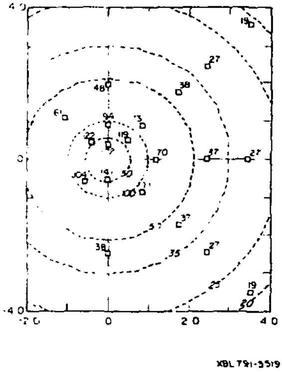

Fig. 4. Predicted (dashed) isotherms and measured temperatures in a horizontal plane *through the center of* the 5.0 kW full-scale heater 190 days after starting experiment. Distances are in meters and temperatures in degrees centigrade.

Fig. 4 shows the spatial distribution of temperature 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.

Scaled Heater Experiment

In the scaled heater experiment at Stripa, times were compressed in the ratio of 1:10 by using laws of heat conduction. Each *year of data is therefore equivalent to* ten years of data from the full-scale system. The linear scale, which must be reduced to $1/\sqrt{10} = 0.32$ of the full scale, still allows for realistic field dimensions. 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 was used in the investigation (Fig. 5). Appropriate scaling of the

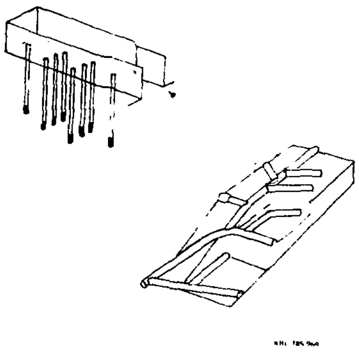

Fig. 5. Experimental rooms in quartz monzonite rock mass showing detail of scaled *heater* drift with eight 1.0 kW electric heaters. Heaters are 1.0 m long and have been placed so that the heater midplane is 10.5 m below the floor.

power output of these heaters shows that 1 kW is representative of an initial power output of 3.12 kW; this power level was 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. We calculated that thermal interaction would occur within a few months of the start of this experiment, and this was confirmed by field observation (Hood et al., 1979). As in the case of the full-scale heater experiments, remarkably good agreement was found between measured and predicted rock temperatures. We concluded that the dominant mode of heat transfer in a discontinuous rock mass is conduction. The temperature field is therefore amenable to prediction by relatively simple semianalytical methods (Chan et al., 1978).

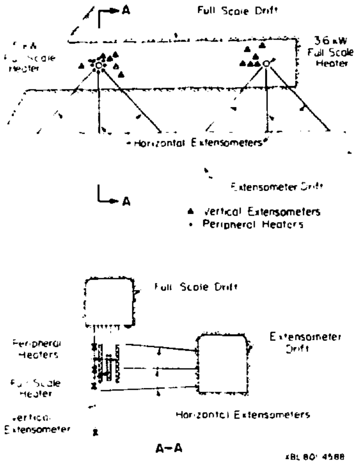

Fig. 6. Diagram illustrating arrangement of full-scale heaters, locations of extensometers in both vertical and horizontal boreholes, and locations of peripheral heaters surrounding 5.0 kW full-scale heater.

<u>Rock Displacements and Stresses</u>

Extensometer measurements in the rock adjacent to each full-scale heater reveal the complexity of attempting to predict thermomechanical behavior in a discontinuous rock mass. 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, 1979). Six vertically oriented multiple rod extensometers, each with four anchor points, were mounted in boreholes adjacent to each full-scale heater at different radial distances. In addition nine horizontally mounted extensometers of similar design extended into the near vicinity of each heater through boreholes, as illustrated in Fig. 6. Details of the instrumentation are described by Kurfurst et al., 1978).

The extensometer readings yielded some puzzling results which reveal the complex problem one faces in attempting to predict thermomechanical behavior of a discontinuous rock mass. As a first approach, the limiting case of homogeneous intact rock was assumed and displacements were predicted prior to heater turn on using the following constant material properties: thermal expansion, α = 11.1 × 10^{-6} /°C, Young's modulus, E = 51.5 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 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 period, the measured displacements increased uniformly but at a more or less constant percentage of the predicted values. For some of the extensometers, the ratio of measured to predicted displacements during this second phase was 0.4 (Hood et al., 1979).

An example of measured and predicted displacements for a vertical extensometer at a radial distance of [illegible] m from the 3.6 kW heater is shown in Fig. 7. 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, 1979). An explanation may be the temperature dependence of the rock properties. Displacements predicted from temperature dependent values of α, E, ν, and k for intact rock and based on limited laboratory tests (Chan et al., 1980b) are shown in Fig. 7. Although much better agreement with field data has been obtained, the laboratory values are too few to be regarded as representing the properties of the rock at Stripa sufficiently well. Accordingly, laboratory measurement of the thermomechanical property of cores from the Stripa quartz monzonite is receiving high priority.

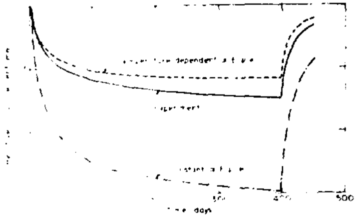

Fig. 7. Plot showing measured rock displacements in a vertical direction between anchor points 2.24 m above and below the heater midplane for an extensometer at a radial distance of 1.0 m from the 3.6 kW full-scale heater. Also included are displacements predicted using constant as well as temperature dependent properties.

Measurements of stress changes in the rock mass with vibrating-wire Creare gauges show trends similar to those of the extensometer results. The observed stress values were at most half of those predicted from the averaged thermomechanical properties cited above. Predicted stresses are still considerably higher than measured values when the temperature dependence of the rock properties is taken into account (Chan et al., 1980b). Nevertheless, the stress results support the conclusion that thermomechanical effects induced in the rock mass are significantly less than predicted (Chan and Cook, 1979) from published values for the properties of intact laboratory specimens of rock. The role of discontinuities in controlling the thermomechanical behavior of rock masses needs much more study.

Fracture Mapping

The disparities between measured displacements and those predicted from the linear theory of thermoelasticity indicate that the quartz monzonite, when subjected to a thermal pulse, does not behave in a linear isotropic manner with constant thermoelastic properties. Discontinuities in the system probably play a major role in controlling thermomechanical behavior, and this raises the difficult question of the level of detail at which fracture geometry must be investigated to understand the behavior of the rock mass. A comprehensive program of fracture mapping was initiated at the beginning of these experiments in anticipation of the need to answer this question.

The methods employed in studying the fracture system in the scaled heater experiment have been described (Thorpe, 1979). First, major discontinuities were identified so that they could be modeled as discrete elements (Goodman, 1976). Second, all fractures were defined through careful measurement of orientation, spacing, and joint length. At present, it is impractical to model such ubiquitous joints as they actually exist; techniques are being developed to represent them stochastically (Glynn et at., 1978; Hudson and Priest, 1979).

Since heaters for the scaled experiment were placed 10.5 m below the floor of the drift, only the most prominent and continuous features are likely to persist from the floor through the heated region. Accordingly, only the major features striking transverse to the drift were extrapolated downward and correlated with discontinuities found in the boreholes. Four shear surfaces probably pass through the heater array (Fig. 8) and offset or truncate other discontinuities, which are filled with chlorite, calcite, epidote, and clay. The most prominent and well-defined fault of the set apparently offsets a pegmatite dike some 20 cm wide.

Statistical analyses of joint geometries, based on results from logging of underground boreholes and comprehensive surficial mapping of the underground drifts, show four distinct sets of joints (Thorpe, 1979). The directions of three of these sets can be correlated with the directions of the current principal stresses (Carlsson, 1978). Detailed fracture mapping such as this cannot be accomplished by conventional methods with boreholes drilled from the surface only.

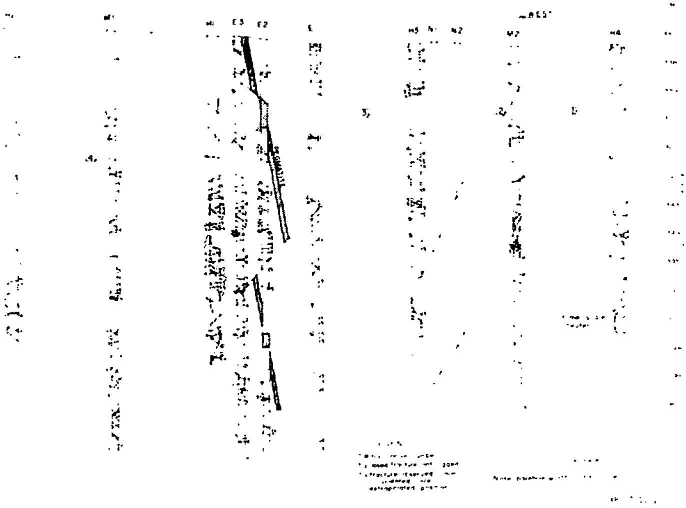

Fig. 8. Vertical profile of major fractures along centerline in scaled heater experiment.

Instrument Problems

The heater experiments at Stripa created some severe operating conditions for the instrument that were installed and expected to operate over a period of one and a half years (Binnall et al., 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 conditions.

Four types of instruments were 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 were installed in vertical and horizontal boreholes strategically located around the vertical heater boreholes (Schrauf et al., 1979). The sensor signals (>750) were digitized and transmitted to a Modcomp IV computer (McEvoy, 1979) located in a nearby building underground.

The major instrument problem was 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 et al., 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 failed in service, some of these more than once. The failures were caused by water entering the gauge housings, causing short circuits and open circuits due to corrosion. These leaks occurred in spite of a regular de-watering operation which insured that water levels in the instrument boreholes remained below that of the gauges. Corrective measures were taken to provide soldered internal connections and improved hermetic seals at cable connections.

The rod extensometer is a common device for measuring changes in the axial length of a borehole. Basically these instruments performed well with interim maintenance and minor field modifications. The major elements of these extensometers (Fig. 9) 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.

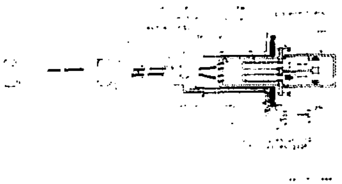

Fig. 9. Sectional view of rod extensometer, [illegible] version.

A few problems with the extensometers have arisen that will require attention. One difficulty was an internal friction that caused stepwise displacements of up to 0.05 mm. This friction could be released by simple tapping of the covers (Fig. 9), 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.

FRACTURE HYDROLOGY INVESTIGATIONS

Assessing Directional Permeabilities

Migration of radionuclides away from a repository may occur by solution in groundwater seeping through the site. The rates of nuclide movement depend on three basic rock properties: (1) permeability, (2) effective porosity, and (3) capacity for sorption. Research at Stripa was concerned only with the first of these properties.

Evaluating the permeability of a rock such as the quartz monzonite at Stripa is essentially a problem of understanding the hydraulic behavior of a complex network of fractures. A permeability tensor for the rock mass can be developed from measured orientations and spacings of fractures and an assumed model of aperture distributions. This approach has been used by a number of workers (Romm and Pozinenko, 1963; Snow, 1965; Parsons, 1972; Louis and Pernot, 1972).

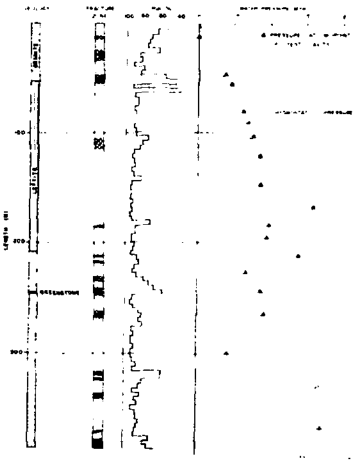

Fig. 10. Fracture hydrology results from SBH-1 showing general geology, fracture zones, RQD values, and bottom hole hydrostatic pressures measured during drilling.

Basic data on fracture orientations, spacings, and continuity were obtained by mapping the fractures in surface outcrops and underground rooms (Thorpe, 1979). Data have also been obtained from three boreholes (see Fig. 1) that were drilled from the surface down to the level of the heater experiments at angles of 38° to 45°

from the vertical. An exampl. of results from SBH-1 is given in Fig. 10.

Each hole was carefully cored so the rock samples could be orientated and the fracture geometries reconstructed. Borehole injection tests were made to obtain hydraulic measurements of the effective fracture apertures. All of these data are being combined in an attempt to define a permeability tensor for the rock mass (Gale et al., 1979). This work is not yet complete.

Large Scale Permeability Measurement

The investigations described above represent the conventional approach to fracture hydrology for a discontinuous rock mass, but the bulk permeability of the Stripa quartz monzonite is not particularly low. The permeability of the rock mass at a preferred repository site could be two to three orders of magnitude less than that at Stripa. To obtain meaningful measurements for such low permeabilities in a very large rock mass, special techniques are required.

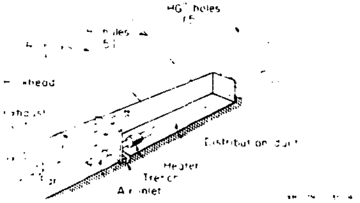

Fig. 11. Large scale permeability experiment showing instrumentation boreholes and system to capture water seepage through [illegible] into a controlled pattern of [illegible].

To investigate this problem, a new concept [illegible] a large-scale permeability test was carried out at Stripa (Witherspoon et al., 1980). A 33 m length of drift was sealed off and equipped with a ventilation system with which the air temperature could be controlled to evaporate all water seepage into the room (Fig. 11). The flow of water into this drift was determined from careful measurements of the airflow rate and the differences in humidity and temperature between the entering and exiting airstreams. This new technique enables measurement of the average permeability of a large volume of rock (of the order of $10^{?}$ to $10^6 m^3$) over a range of air temperatures from about 20 to 40°C.

Hydraulic pressures in the rock mass around this drift were measured at 90 points in 15 holes that radiate out from the drift in different directions. Two groups of five holes each were drilled radially outward, and one group of five holes was drilled at the end of the room to distances of 30 to 3? m (Fig. 11). Figure 12 shows the orientation of one of the radial groups of five holes. Each borehole was sealed off with six packers placed so that pressures and temperatures could be measured over six intervals.

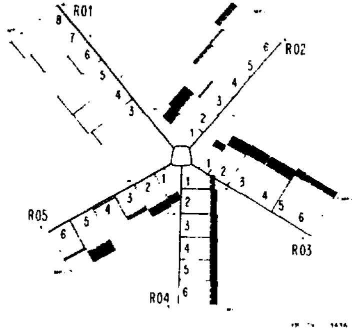

Fig. 12. Pressure measurements in radial boreholes of ventilation drift at Stripa. Stippled area shows pressure increases eight days after packing off R01. 1 MPa = 145 psi.

Before the installation of packers, all holes had been draining freely. Borehole R01 (Fig. 12) 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 drift. Consequently, R01 was packed off and instrumented last so that the effects of pressure buildup in the other boreholes could be monitored, as shown in Fig. 12. The dashed lines represent pressures measured just before R01 was packed off on 31 October 1979. The solid lines represent pressures measured on 8 November 1979, and the stippled areas show how pressure increases occurred more or less uniformly throughout this fractured rock after instrumentation of R01. Similar effects were noted in all the other boreholes. Note that the pressures increase with distance from the drift and are all about 1 megapascal (145 pounds per square inch) at a distance of 30 m from the drift. These unusually low pressures are the result of the effects of drainage into the adjacent mine workings over many years.

After all the boreholes were packed off, a marked increase in drips and wet spots in the drift was observed. The temperature and mass flow rate of the circulating air were adjusted to evaporate all incoming water, and an initial seepage rate of about 50 milliliters per minute was measured. On the basis of this rate and the observed pressure gradients, a preliminary value for the average hydraulic conductivity of the order of 10^{-11} m/sec has been calculated. This new method of measuring permeability in situ is an important advance in fracture hydrology.

Geochemistry and Isotope Hydrology

Geochemistry and isotope hydrology provide 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 significant effects.

A comprehensive program of investigations on the geochemistry and isotope hydrology of the Stripa groundwaters was carried out by Fritz et al., (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 et al., 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 formation of clay minerals. These processes release calcium which causes continuous saturation of the mine waters with respect to calcite.

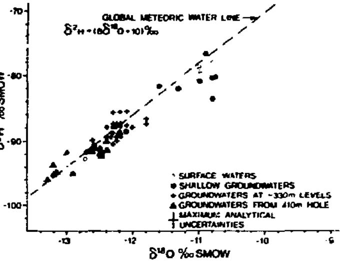

Fig. 13. Comparison of $\delta^{18}O$ and $\delta^{2}H$ values for Stripa groundwaters. The analyses are reported as δ °/₀₀ values with reference to standard mean ocean water (SMOW). A $\delta^{18}O$ of -10°/₀₀ signifies that the sample has 10°/₀₀ (per mil) less ^{18}O than the reference standard which closely reflects average seawater.

The abundance 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. 13, 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.

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 et al., 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. 14. Here, it is apparent that the deep groundwaters, especially those at the bottom of the 410 m hole, are distinctly different from the shallow ground waters. In other words, the different fracture systems in the granite at Stripa carry different types of water because they are isolated from each other.

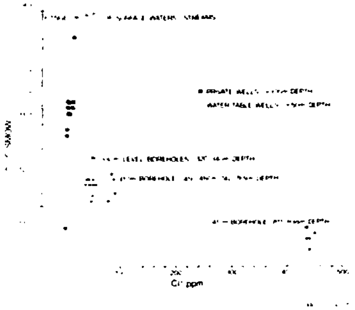

Fig. 14. Comparison of chloride with $\delta^{18}O$ values show that the different fracture systems in the Stripa granite carry different types of water. Oxygen isotopic values are referenced to standard mean ocean water (SMOW).

The most difficult and inconclusive part of this geochemical investigation was the attempt to date the groundwaters from the different mine levels (Fritz et al., 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. 10). 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 ratios, (2) helium contents, and (3) radium-radon relationships (Fritz et al., 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. 15) at the bottom of this hole. This decay in activity ratio can be used to date water 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 were 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.

All of the evidence from those investigations on geochemistry and isotope hydrology support the concept that waters presently found in the deep granite rock mass at Stripa are many thousands of years old. It is apparent that a careful investigation of this kind provides an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the groundwater system at Stripa.

SUMMARY AND CONCLUSIONS

A defunct iron-ore mine at Stripa, Sweden has provided access to a large granitic rock mass for a series of investigations on problems involved in geologic storage of radioactive waste. A coordinated series of tests were carried out on two key problems. One of these problems is that of understanding the thermomechanical behavior of a heterogeneous and discontinuous rock mass. This was investigated using electric heater tests to simulate the energy released by the decay of radioactive waste. The other problem involves fracture hydrology, that is, measurement of the transport properties of a discontinuous rock mass. A combination of borehole measurements and geochemical studies were made as part of this approach. Another part has led to a new method of measuring in situ permeability of very large rock masses.

Important results have been obtained from these investigations that would not have emerged if these experiments had not been carried out underground at depths comparable with those envisaged for an actual repository. Experiments at such depths give rise to unexpected and sometimes difficult problems which must be resolved if deep geologic disposal of radioactive waste is to become a reality.

From the geotechnical standpoint, a key issue is that of developing a method for predicting the thermomechanical behavior of the rock layers in which the repository will be constructed. The results from Stripa provide important input to this problem. It has been demonstrated that the temperature variations over time and space within the rock mass can be reasonably well predicted using available theory and appropriate values of material properties. The mechanical displacements, however, were significantly less than that predicted from an application of linear thermoelasticity for intact rock. The reason, of course, is that the effects of the fractures, which are not yet well understood, were a significant factor in reducing rock movements.

Discontinuities are prevalent in all rock masses. This is certainly the case on the scale of an underground repository, which will occupy an area of a few square kilometers. Thus, the geotechnical problem arises of mapping the discontinuities in sufficient detail for the purposes of underground storage. Although some preliminary studies (Kendorski and Mahtab, 1976; Raven and Gale, 1977) suggest that fracture orientations between surface and subsurface are similar, there are still no data to demonstrate that the important characteristics of length and continuity of such features can be predicted reliably from surface measurements. Similar difficulties exist in predicting the geometry and properties of other kinds of discontinuities in underground rock masses. To overcome these difficulties will probably require access to underground workings where the required mapping can be carried out.

Closely related to this problem is the much tougher question of the role that discontinuities play in controlling the thermomechanical behavior of a rock mass. Calculations of temperature effects reveal the very large rock volumes that will be heated to varying levels over long periods of time. Many investigators are now developing numerical methods to predict the effects of such temperature increases. But a major obstacle that all such efforts must face is to be able to predict how the discontinuities in the rock mass affect its thermal response. This is a problem of scale. How large a rock mass must be instrumented and tested to provide the data to validate these computer codes? No one really knows because this kind of underground testing in different rock types has never been done before. This is a geotechnical problem of first order importance.

The fracture hydrology program was essentially aimed at understanding the hydrological behavior of a complex network of fractures. The three most important components of this program involved: (1) assessing directional permeabilities, (2) development of a large-scale in situ method of measuring permeability, and (3) geochemistry and isotope hydrology.

The investigation of directional permeability required the compilation of a very large data base on fracture geometry and fracture aperture. These data had to be obtained from the surface domain 1 using the inclined boreholes (Fig. 1) and, of course, are augmented by the detailed mapping performed in the underground rooms. The analysis of these results will provide a measure of the complexity of the problems in evaluating the permeability tensor for a rock mass extending from the surface down to a depth of almost 400 m. An inherent problem in such an analysis is to develop evidence to support the conclusion that for flow purposes the rock system can be treated as though it were porous media. Long et al. (1981) are currently examining this problem to establish the criteria that must be satisfied in establishing porous media equivalence. This is another important geotechnical problem.

The large-scale permeability test has demonstrated that in situ measurements of the hydraulic properties of very large rock masses can easily be carried out in the underground. A 33 m length of drift was sealed off and the mass of water seeping into the room was measured using an air ventilation scheme. Pressure gradients in the water saturated network of fractures in the rock walls of the drift were measured, and a preliminary value for the average permeability of 10^{-11} m/s was obtained. The method should be applicable to rock masses with permeabilities several orders of magnitude lower than this. Introduction of non-sorbing tracers would further enhance this new technique by providing information on effective porosity. Data on the critical parameter of fluid velocities through large rock masses could be verified in this manner.

The program on geochemistry and isotope hydrology was carried out at Stripa using groundwater samples collected from the surface, shallow wells, and underground boreholes. The results provide an independent and powerful approach to the critical problem of elucidating the degree of isolation that has developed in the Stripa groundwater systems. The importance of such data raises the geotechnical problem of the procedures to be followed in gathering groundwater samples.

The conventional approach to this problem is to collect water samples in vertical boreholes drilled from the surface. Drilling procedures normally contaminate natural waters because the pressures required for circulation of the drilling fluids often exceed those of the fluids in the rocks being drilled. This is usually overcome before sampling by producing 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 has shown the superiority of collecting groundwater samples from boreholes drilled from underground drifts and rooms. The hydrostatic water pressure in rock is about 1 MPa per 100 m of depth, whereas the pressure within the mined openings is only about 0.1 MPa (1 atmosphere). Thus, a borehole drilled from an underground excavation into the rock mass around the opening encounters a hydrostatic pressure that far exceeds the pressure necessary to circulate the drilling fluid. This creates an artesian condition that minimizes contamination and greatly simplifies the collection of groundwater samples for geochemical and isotopic studies.

The results of the Stripa investigations have revealed a number of geotechnical problems that must be pursued further in developing a full understanding of the technology required for the geologic disposal of radioactive waste. The results have also demonstrated the vital importance of being able to carry out large scale investigations underground in a field test facility.

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