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Determination of the characteristics of crystalline rocks by field experiments: a review

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Crystalline rocks, particularly granitic rocks and basalts, are one of the principal rock types under consideration as a potential host rock for a high-level radioactive waste repository. Permeability in such rocks is related to discontinuities of various scales, and the quantification and prediction of groundwater flow within both the fractures and the intact rock between the fractures is the major goal of field experiments. The Canadian Underground Research Laboratory is unique in that the hydrogeological conditions within a large volume of rock surrounding the experimental shaft are being monitored before, during and after excavation and the results compared with model predictions. In Switzerland twelve deep boreholes are being drilled to over 1000 m to investigate crystalline basement rocks beneath a cover of sediments. The Stripa Mine in Sweden has hosted a major experimental programme including heater tests to stimulate the thermal effect of radioactive waste and hydrogeological tests at various scales down to individual fractures. The United States of America, the United Kingdom, France and Finland have also embarked on major experimental programmes. Continuing research is needed, with an emphasis on field experiments and research in underground rooms, to provide the data on which detailed risk assessments can be based.

Introduction

Most rocks are formed of mineral crystals and are therefore crystalline in the strict sense; however, in the radioactive waste disposal field, the term crystalline rocks has been reserved for those rocks formed by volcanic and plutonic processes. Of particular interest have been the large masses of granitic and basic igneous rocks and the extensive and thick accumulations of basic lavas that occur in some parts of the world. Metamorphic rocks such as gneisses and quartzites have similar properties and have also received attention as potential host rocks for a repository.

Most of the research has been concentrated on the granitic rocks and the compositionally similar acid gneisses and migmatites. Granitic rocks are generally coarse-grained and consist predominantly of quartz, feldspars, amphiboles and micas with subsidiary amounts of many other minerals. They are texturally and compositionally variable, often within a single body of rock, and were formed either by differentiation of primary magmas or by melting of other rocks at various depths within the Earth's crust. They occur as extensive masses known as batholiths and as smaller dome-like plugs or plutons. Gneisses have undergone plastic deformation and recrystallization, often resulting in compositionally banded rocks. Migmatites are an intimate admixture of a molten and a metamorphic component and may occur either at the margins of intrusive bodies or on a regional scale.

The most significant property of a rock mass from the point of view of preventing the migration of radioactive species is its low permeability. Permeability in granitic rocks is related to discontinuities of various scales. Cracks and joints are more important to considerations of the near field and faults to the far field. In such rock masses there are commonly zones of concentrated cracks or major fault or fracture zones between which occur blocks almost free from such fractures. Depending on regional and local stress patterns, even these few fractures can be effectively closed so that within these low-permeability blocks a repository might be constructed such that groundwater movement is exceedingly slow. Moreover, fractures themselves are often filled by clay minerals, which will make the granite even less permeable and provide sites for the adsorption of migrating radioactive species. Among other advantages of granite are its structural strength, which means that rooms and tunnels can be constructed underground with minimal support, and its moderately high thermal conductivity. Apart from their fracture permeability, which makes hydrogeological modelling complex, disadvantages of granites and associated rocks are the relatively poor adsorption properties of the bulk of the rock and the fact that they were formed at high temperatures and pressures, which makes them particularly susceptible to change and alteration by low-temperature circulating fluids.

Studies have been initiated in a number of countries into the suitability of granite and associated rocks for the disposal of long-lived and highly radioactive wastes. Argentina, Canada, Finland, France, Sweden, Switzerland, the United Kingdom and the United States of America all have active research programmes that have involved site investigations.

The basalts of interest occur in continental areas where laterally extensive and thick flows have accumulated to form plateau-like masses. Compositionally, the basalts are dominated by feldspar, pyroxene and iron ore minerals and are fine-grained with glassy textures. Basalts have a high compressive strength and commonly exhibit columnar jointing. Porosites at the top and bottom of individual flows tend to be enhanced by the presence of gas vesicles formed during rapid cooling at the margins, and erosion surfaces are developed between flows. These features result in enhanced permeabilities and individual flows therefore have to be thick enough for a repository to be constructed within the mass of basalt without encountering the higher-permeability marginal zones. At present the only country with a major programme in basalt is the United States of America, where the Columbia River Basalts of the Pacific Northwest are being investigated in detail.

A review of crystalline rocks would not be complete without reference to the work on volcanic ash, or tuff, that is going on in both the U.S.A. and Japan. The permeability of the more consolidated tuffs is low and they have excellent sorption characteristics. However, they have more affinities with argillaceous rocks than with the other igneous and metamorphic rocks discussed in this paper and will not be considered further here.

Objectives of field experiments

The only credible way by which radionuclides can reach the biosphere from an underground repository is via circulating groundwater. Therefore the major emphasis of any field research programme is to quantify and predict the behaviour of groundwater within the rock mass and its effect on the release and migration of radionuclides. For crystalline rocks the flow of groundwater is largely governed by the presence of fractures or fracture zones, and much of the experimental work has concentrated on the definition and prediction of these fractures in

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three dimensions and on how the hydraulic conductivity of these fractures and the overall rock mass are affected by the construction of a repository and the emplacement within it of heat-emitting wastes.

More specifically, field observations and experiments have been conducted with the following aims in mind:

to develop a model for groundwater flow and mass transport in a rock mass as it is now;

to determine how this will be changed by the construction and filling of a repository;

to develop models to perform an environmental and safety analysis of geological disposal that takes into account the uncertainties of the measurements and predictions;

to demonstrate that a repository can be designed, constructed and operated safely.

These objectives have been met by developing methods and techniques to define the physical and chemical properties of large rock masses and of the fluids within them, and by using these techniques in selected field areas to calibrate and evaluate models developed to calculate fluid flow and mass transport through such rock masses containing a hypothetical repository. Procedures have also been established to evaluate rock masses quantitatively and thereby acquire the capability to compare different sites.

In most countries, the selection of sites for generic research has been decided on the basis of both technical and political considerations. Thus, in some cases, field sites have been less than ideal but were the only ones available. From the technical viewpoint, the sites fall into two general categories: disturbed sites such as existing mines and tunnels, and undisturbed 'green-field' sites. Field observations and underground experiments at both types of site have provided vital information.

Currently most countries are conducting generic rather than site-specific field experiments on crystalline rocks. The major exception is the U.S.A., where the way in which a disposal site will be selected is determined by the Waste Policy Act. With the emphasis on generic work a major issue to be resolved is the applicability of information gained at generic research sites to other sites and the usefulness of such research in the selection of a final site for a repository. The following sections outline various field programmes that are completed, under way or at an advanced stage of planning in the various countries active in research on crystalline rocks, and review the significance of some of the results obtained.

Field experiments

Canada

The Canadian Nuclear Fuel Waste Management Programme is assessing the concept of the disposal of either immobilized fuel or vitrified waste from a future reprocessing plant, 500–1000 m deep in crystalline plutonic rocks. Deep exploratory drilling and detailed surface mapping have been carried out at designated field research areas in the Canadian Shield. Geoscience work at research areas had the twofold purpose of (i) testing new and existing exploration techniques for the evaluation of rock masses and (ii) through application of these airborne, surface and subsurface techniques, providing the field data necessary for the development of concepts and models that form the basis for site-selection criteria and safety analyses.

Research areas have been established at Atikokan, Ontario, an area underlain by granitic rocks, and at East Bull Lake north of Massey, Ontario, where gabbroic rocks are the dominant type. These research areas complement previously established research areas developed on granitic rocks at Atomic Energy of Canada Ltd (AECL) properties at Chalk River, Ontario, and Pinawa, Manitoba, and a research area, also in granitic terrain, near White Lake, Ontario, where work was done early in the programme to test geophysical exploration equipment. The White Lake area is no longer in active use. Approval has also been obtained for development of a research area on gabbroic rock at Denmark Lake, southeast of Kenora, Ontario.

The ability to predict subsurface geology and hydrogeology for site evaluation is being tested by means of the Underground Research Laboratory (URL) project being constructed by AECL within a granite batholith near the town of Lac du Bonnet, Manitoba, and close to the Whiteshell Nuclear Research Establishment (WNRE). Once constructed, the URL will provide researchers with representative geological environments in which to carry out a variety of *in-situ* geotechnical experiments (Simmons & Soonawala (eds) 1982; Davison & Simmons 1983; Simmons 1984; Thompson *et al.* 1984).

The main technical objectives established for the URL are:

(1) to assess the extrapolation of air, surface and borehole survey data to the geosphere;
(2) to study the hydrogeological and geochemical conditions in an undisturbed rock mass;
(3) to conduct a large-scale hydrogeological drawdown experiment;
(4) to study the response of a rock mass to excavation;
(5) to study the rock mass response to varying loads and temperatures;
(6) to emplace and test buffers, backfills, shaft seals and borehole seals;
(7) to study mass transport through fractured rock;
(8) to study complex, multi-component systems that are being developed for repositories at ambient and elevated temperatures and pressures.

The URL facility, including a vertical access shaft, a ventilation raise bore and a main horizontal experimental level, has been excavated to a depth of 254 m, approximately 245 m below the water table in a previously undisturbed rock mass. One of the unique features of the URL project, compared with similar experimental facilities in other countries, is that hydrogeologists are monitoring the hydrogeological conditions within a large volume of rock surrounding the URL excavation site before, during and after the excavation of the shaft and underground workings. The information obtained from investigations carried out before any excavation has been incorporated into various numerical computer models that describe the hydrogeology of the study area. These models have been used to predict the three-dimensional piezometric drawdown that will occur in the rock mass during and after excavation of the underground facility. When these predictions are compared with the results of the continuous hydrogeological monitoring being done during and after excavation, researchers will be able to assess how well the models have actually represented the three-dimensional hydrogeological conditions of the rock mass surrounding the URL excavation site. This validation exercise is a major step towards the development of reliable models with which to predict solute transport through large volumes of plutonic rocks.

Detailed investigations have been going on since 1980 to determine the three-dimensional physical and chemical hydrogeological characteristics to depths of 500 m within a study area 4.8 km^2 in size encompassing the URL excavation site (Davison 1984). Over 130 boreholes, including 25 to depths ranging from 160 to 1090 m, have been drilled, logged, tested and instrumented to accomplish this.

Assimilation of the fracture information obtained from the entire network of boreholes revealed that three major extensive sub-horizontal fracture zones were present within the rock mass. It has been found that these zones largely control the movement of groundwater at the study area. Except for these distinct extensive fracture zones, the rock mass is relatively unfractured, with fracturing being slightly more pronounced near the ground surface. The URL shaft has been excavated through the upper fracture zone, which was encountered between 110 and 113 m in the shaft, but stops above the second zone of intense fracturing. The hydrogeology of these two fracture zones has been studied in considerable detail, with a wide variety of borehole-testing techniques, including single-borehole straddle-packer tests and large-scale multiple-borehole hydraulic pressure interference tests (Davison 1984). The results of this work have revealed that a complex pattern of permeability exists within each of the two fracture zones, and that these permeability distributions control the patterns of hydraulic head and groundwater chemistry.

Comparison between the recorded inflow rates to the shaft and the calculated values indicates that the model overestimates the inflow rates by approximately a factor of three (Davison & Guvanasen 1984). Also, the model indicates that the inflow rates will reach a maximum when the uppermost fracture zone is intersected by the shaft. Subsequently the model predicts that the inflow rates will gradually decline to a constant value. This overall trend appears to agree well with the recorded data. A comparison between predicted drawdowns and field measurements was made for boreholes within a 400 m radius from the shaft. In most boreholes, the drawdown rate, the magnitude of the drawdown, and the temporal variation of the drawdown are fairly accurately predicted by the model (figure 1). At any given time, discrepancies between the model's predictions and field measurements appear in general to be proportional to the radial distance from the shaft; the further away from the shaft, the smaller the discrepancy.

During shaft sinking, four instrument arrays, at depths of 15, 62, 185 and 218 m, were used

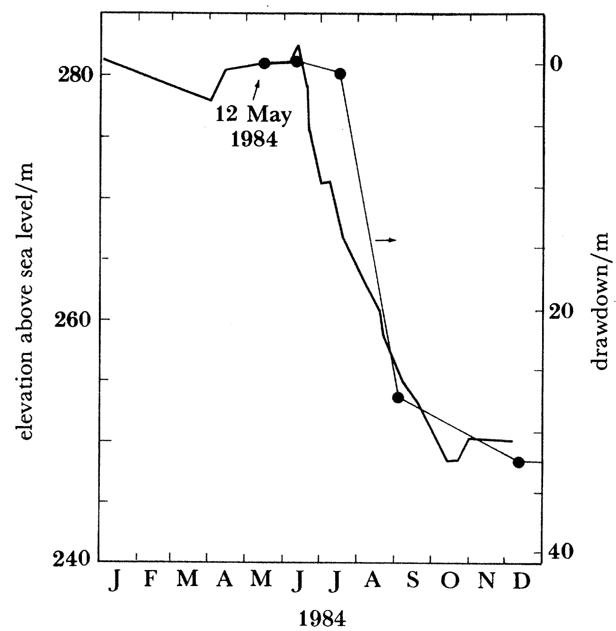

Figure 1. Measured (heavy line) and predicted (●) drawdown in a monitored interval of borehole URL-1, approximately 150 m from the shaft, as a result of shaft construction. The monitoring interval was 93.4–131.0 m below ground surface.

to monitor excavation-induced displacements, excavation-induced stress changes and rock temperature (Chan *et al.* 1985). These depths were chosen on the basis of borehole geological information. The major objectives of this monitoring were (1) to evaluate and improve the ability of numerical models to predict the mechanical response of the rock-mass, (2) to assess the validity of the concept of a rock-mass deformation modulus and, if possible, to back-calculate this modulus as a function of depth, and (3) to evaluate the quality of the geomechanical instrumentation to determine further instrumentation needs for future field experiments. It can be concluded that in the rock mass at the URL, where the fracture spacing is comparable with the excavation dimensions, the concept of a single rock-mass deformation modulus may not be valid and some of the discrete fractures should be modelled by using, perhaps, a discontinuum approach. More accurate extensometers are essential for geomechanical measurements in future URL experiments.

France

Following the investigation of several granite massifs in the western part of France (CEC 1978), including measurements in boreholes drilled to a maximum depth of 100 m (Feates *et al.* 1980), a granite near Auriat, in the Massif Central was selected for detailed investigation. Two boreholes, 1000 m and 500 m in depth, respectively, and 10 m apart, have been drilled. The density of fractures is high, but they are nearly all filled with secondary and/or alteration minerals such as quartz, calcite and clays. Permeability tests indicate that the granite has a very low permeability, of the order of 10^{-11} to 10^{-12} m s^{-1}, with two localized horizons with a higher permeability of 10^{-9} m s^{-1} between 300 and 400 m depth. A transfer experiment has shown that there is no hydraulic connection between the two boreholes, and the very low rate of movement of intraformational groundwater into the boreholes after the completion of drilling confirms that groundwater circulation is extremely slow (Derlich & Michelet 1983). However, the use of bentonite mud during the drilling of the boreholes means that the results are subject to interpretation difficulties as a consequence of the introduction of drilling mud into fractures.

The French Atomic Energy Commission has commissioned an underground research laboratory in the Fanay-Augères uranium mine, near Limoges, in the granite terrain of the Massif Central, to improve knowledge of the properties and behaviour of fissured materials. Two main programmes are presently going on in this laboratory in the framework of shared-cost contracts with the CEC: a hydrothermomechanical experiment, which is at an early stage, and an experiment to examine the influence of scale on measured values of permeability and dispersion coefficients. The scale problem arises when fracture density is so high that a discrete approach becomes impractical, owing to the large amount of data that would be required to define fracture geometry, but the observation scale is not large enough to guarantee that a continuum approach is valid.

The scale-effect study has been undertaken in a drift at a depth of 170 m. Initial studies involved the detailed characterization of fractures on the drift walls and the control, in boreholes, of the distribution of water pressure in the rock around the gallery. Local permeability has been determined between packers and the permeability of the medium on a large scale evaluated by the measurement of the drained flow rate along a delimited part of the drift. The average permeability is between 10^{-7} and 10^{-8} m s^{-1}. The scale-effect experiment itself consists of injection permeability tests between two packers at increasing spacings within ten 50 m long boreholes radiating from the drift. The same instrumented boreholes have been used for the determination of dispersion coefficients by the injection of different tracers at increasing packer spacing. Two hundred and fifty injection tests with the packers at various spacings confirm a scatter of individual permeability values from 2×10^{-5} to below 10^{-10} m s^{-1}. The results are being interpreted by using a three-dimensional model of water flow around the drift, to obtain a relation between the permeability tensor and the fracture network.

A third major French study has investigated the evolution of fracturing from the surface downwards to produce guidelines for the extrapolation of shallow data to depth. As well as data from the Auriat 1000 m borehole, data have been collected from the Saint-Sylvestre granite, near Limoges, and by a study of the available literature on the Bassies granite in the French Pyrenees and two large alpine tunnels. All the granite massifs were found to be crossed by large faults, between which were smaller fractures formed when the granite magmas crystallized and solidified or by later tectonic events. The smaller fractures were not significantly influenced by depth, and a distribution model of the smaller-scale fractures and their relation to the larger faults was prepared. The study concluded that it was possible to estimate deep fractures with the help of surface data but that, in addition to the mapping of the larger faults, it was necessary to analyse the orientation and density of the small fractures to characterize a site adequately.

Finland

In November 1983, the Government of Finland made a decision, in principle, on the final disposal of spent fuel from the Finnish nuclear programme, that requires the power companies to undertake research on the final disposal of spent fuel from their own plants. Before initiating their main site investigations, the Industrial Power Company Ltd (Teollisuuden Voima Oy (TVO)), which owns two units in Olkiluoto in southwestern Finland, drilled a deep borehole to gain experience of both the drilling and testing of such deep holes (Vuorela & Äikäs 1984). The borehole was drilled in the spring of 1984 to a depth of 1001 m and with a diameter of 56 mm into a granite intrusion near Lavia in southwestern Finland. Geophysical, hydrogeological and mineralogical investigations have been made both in the borehole and its immediate vicinity. Hydraulic conductivity is generally low, in the range of 10^{-9} to 10^{-11} m s^{-1}, except in the upper and lowermost parts of the hole, where it exceeds 10^{-7} m s^{-1}.

One of the major tasks of the investigation has been to evaluate the reliability and representativeness of the results and, in particular, the effect of the drilling method. Iodine was used as a tracer in the borehole flushing water and, despite a major pumping operation performed after the completion of drilling, remnants of the flushing water were retained within fractures, influencing the composition of groundwater samples. The tube wave technique of identifying fractures open to fluid flow shows a correlation with hydraulic conductivity, suggesting that the observed poor correlation between fracture frequency and hydraulic conductivity is not the result of rock flour blocking fractures. The study has concluded that the core drilling method employed in the investigation of these fractured rocks needs special care and attention if representative results are to be obtained.

The owners of the other two units in Finland, the Imatra Power Company, have initiated research into the Precambrian granitic bedrock in the area of the Louiisa Power Station about 80 km east of Helsinki. Eight boreholes have been drilled to a depth of about 200 m by conventional diamond core-drilling techniques to examine the feasibility of the final disposal of intermediate waste, including some long-lived wastes (Gardemeister & Rouhiainen 1984). The hydraulic conductivity of intact bedrock is low (below 10^{-8} m s^{-1}) but it is cut by broken zones with values in the range 10^{-6} to 10^{-5} m s^{-1}. Effective porosities vary from about 0.05% in intact rock to 0.4% in the broken zones.

Switzerland

The Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA) has initiated an experimental programme to investigate the stable crystalline basement underlying the northern part of Switzerland. Approval has been given for the drilling of 12 boreholes within an area where the available information indicated a sedimentary cover of less than 1000 m overlying crystalline basement. Six boreholes have so far been drilled but only results from the first of these boreholes, at Boettstein, have been widely reported. There, drilling in the crystalline basement began at a depth of 315 m below ground level in November 1982 and was completed in June 1983 at 1501 m. The testing phase commenced in June and was completed in December 1983.

The hydrogeological testing programme comprised single-packer tests conducted during the drilling, reconnaissance logging and double-packer tests conducted after completion (Gartner Lee AG 1984). Reliable hydraulic heads were obtained from nine tests in the Boettstein borehole. The data suggested that fractures are hydraulically influenced by the drilling activity, and reliable hydraulic heads are measured only after a long time (tens of days). Generally the hydraulic test data from the Boettstein borehole match equivalent porous medium analyses. This suggests that the conditions tested are at a larger scale than individual single fractures.

Hydraulic conductivity values for the crystalline rock portion of the borehole ranged from 10^{-12} to 10^{-5} m s^{-1}, and the profile shows discrete zones of high permeability that decrease with depth penetrated by the borehole. The higher permeability zones are of two types: (1) zones of crushed and altered granite, which are essentially planar, and (2) aplite–pegmatite dykes. Hydraulic conductivity in the weak zones at depth is orders of magnitude greater and porosity more than a factor of 10 higher than in the adjacent bulk crystalline rock.

On 20 June 1984 the Grimsel underground test site was officially opened. The most important research objectives are to gain practical experience in the development, testing and use of instrumentation and measurement techniques in underground laboratories; to carry out some specific experiments; and to check to what extent foreign research can be applied to the geological conditions in Switzerland (NAGRA 1984).

The Grimsel Rock Laboratory is situated under the Juchlistock Massif, about 1 km inside the mountain at an elevation of 1730 m above sea level. The laboratory host-rock is granite intruded by lamprophyre veins, which represent weak zones and can be water-bearing. Over 900 m of circular tunnel have been excavated with a diameter of 3.5 m by using a full-face cutting machine. Intersections and caverns were broken out by explosives and over 1000 m of cored boreholes have been drilled for rock-mass characterization. A carefully designed ventilation system allows the use of sophisticated measuring equipment and computers throughout the laboratory. NAGRA is working in close cooperation with the Federal Republic of Germany, which is bearing approximately half the costs of the experiments.

The following experiments are planned or under construction:

1. An excavation test to understand the effects of tunnel excavation on the surrounding rock.
2. A rock stress experiment to measure how stresses hold up in a rock mass. The rock stresses

in individual sections of a 200 m borehole will be measured by setting specially developed probes in pilot holes of 46 mm diameter and overcoring them.

3. A heating test in which the residual heat of high-level waste is simulated by the use of electrical heaters placed in a borehole 12–18 m below the tunnel floor.

4. The detection of weak zones, such as fractures or lamprophyres, by the use of borehole radar and seismic crosshole techniques.

5. A fracture system flow test to investigate water circulation in fractured rock. Water containing a tracer will be injected into a central injection borehole and the speed and direction with which this water flows within the fracture system will be observed by using packers in adjacent boreholes.

6. A ventilation test in which air with a known temperature and moisture content is pumped into a section of tunnel that is sealed off as an experimental chamber. When equilibrium has been reached between this air and the humidity conditions of the surrounding rock, the air will be extracted and the change in moisture content established.

Sweden

Current Swedish legislation gives owners of nuclear power plants the responsibility for the safe management of the radioactive wastes that they produce. This responsibility covers both the research and the eventual construction and operation of the disposal facilities and is managed by a jointly owned organization, the Swedish Nuclear Fuel Supply Company, SKBF. As part of the research programme a number of sites have been characterized to demonstrate that areas exist in Sweden where a safe final repository can be located. In the early stages of the project three sites were investigated at Finnsjön (granodiorite), Kråkemåla (granite) and Sternö (sedimentary gneisses). More recently four further sites have been examined at Fjällveden (veined gneiss), Gideå (veined gneiss), Kamlunge (gneisses and red granite) and Svartboberget (migmatites). The latter investigations have all been based on a standard programme, which is adapted to local conditions (SKBF/KBS 1983).

Detailed investigations on the surface, covering an area of 4–5 km^2, are used as a basis for a drilling programme with both hammer-drilled boreholes, to a depth of around 200 m and 56 mm diameter, and cored boreholes to 700 m. Up to 15 such deeper boreholes have been drilled at each site and several of them are inclined at an angle of 60° to internal fracture zones at a depth of 300–500 m (Olsson & Ahlborn 1984). Detailed investigations of the drill cores have been made and a comprehensive geophysical logging campaign has been carried out in the boreholes. Hydraulic conductivity profiles have been obtained by using constant-head water injection tests in packered-off sections of the boreholes. A packer spacing of 25 m has been used except where fracture zones are intersected, where this spacing has been reduced to 10, 5 or 2 m. In association with the water-injection tests, piezometric measurements are made at different levels in the boreholes and groundwater samples are taken for chemical analysis (Carlsson *et al.* 1984; SKBF/KBS 1983).

The Fjällveden site is bounded by regional fracture zones with a spacing of 2.5–3 km. Within these major zones local fracture zones, of lesser width and persistence, occur 300–900 m apart. These narrow local fracture zones show an overall decrease in hydraulic conductivity with depth and have a hydraulic conductivity of about 5×10^{-10} m s^{-1} at 500 m. This compares with a permeability for the rock mass between fractures of 5×10^{-11} m s. However, sub-vertical granite veins give the rock a directional hydraulic conductivity. They comprise about 3% of the rock mass and have a hydraulic conductivity of 3×10^{-9} m s^{-1} at 500 m depth. The situation at Gideå is comparable. The local fracture zones have a hydraulic conductivity of about 9×10^{-11} m s^{-1} at 500 m depth, which is twice that for the rock mass. However, veins of granite gneiss have a hydraulic conductivity of 10^{-9} m s^{-1} and therefore have hydraulic properties similar to the local fracture zones. Dolerite dykes also occur, which have a higher fracture frequency. At Kamlunge, local fracture zones have a hydraulic conductivity at 450 m depth of 10^{-9} m s^{-1}, which is 40 times greater than that of the rock mass. Local fracture zones at Svartboberget have a hydraulic conductivity of about 8×10^{-10} m s^{-1} at 500 m depth (about 17 times greater than the rock mass), dip at about 45° and are located 30–300 m apart. It was concluded that at all but Svartboberget there was a possibility of locating a repository within sound rock. At Svartboberget, the bedrock contained fracture zones oriented and distributed in such a way that a final repository would have to be split up into several small parts, which was not economically viable.

Since 1977, a major experimental programme related to the disposal of high-level radioactive waste in granite has been undertaken at the Stripa Mine in Sweden. From 1977 to 1980 the main part of the investigations was performed by the Lawrence Berkeley Laboratories (LBL) of the University of California sponsored by the U.S. Department of Energy in cooperation with SKBF. The aim of these investigations was to develop techniques to determine rock mechanics and far-field hydrogeological, geochemical and geophysical parameters at potential waste repository sites. Since 1980 the mine has been the focus of the International Stripa Project sponsored by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD). Phase 1 of the project concerned geochemical and hydrogeological studies, migration experiments and studies of the operation of engineered barriers. Phase 2 began in 1983 and includes the development of cross-hole geophysical and hydrogeological techniques, shaft and borehole sealing, fracture hydrology tests and a three-dimensional tracer migration test. A programme for phase 3 is currently under discussion.

The Stripa Mine is an abandoned iron ore mine within which granite is adjacent to the ore excavations and is accessible at a depth of 350 m. The rock is a grey to light red medium-grained granite; it contains several fracture sets, but most of these fractures are closed and filled with chlorite and occasionally calcite (OECD/NEA 1983).

Three experiments to simulate the thermal effect of radioactive waste have been carried out at a depth of 340 m in the mine. One experiment involved an array of eight electrical heaters scaled to simulate, in one year, the thermal conduction field around radioactive waste canisters over a period of a decade. The other two experiments involved a single electrical heater to simulate the short-term effects in the rock. The temperature distributions have proved to be consistent with predictions on the basis of thermal conduction through the rock matrix. However, measurements of displacements associated with thermal expansion have shown discrepancies between observed values and those calculated on the assumption of an unfractured monolithic rock matrix. The modelling efforts so far have not been successful in being able to duplicate all of the experimental findings.

Hydrogeological measurements have included permeability measurements over various scales, from tests on individual fractures to a large-scale macropermeability experiment. In this latter experiment water inflow was measured as the net moisture pickup of the ventilation system inside a sealed portion of a specially constructed room measuring 5 m × 5 m × 33 m. A comparison of these results has shown reasonable agreement with an average hydraulic conductivity of the order of 10^{-10} m s^{-1}, although fracture zones with hydraulic conductivities exceeding 10^{-8} m s^{-1} exist to considerable depth.

Groundwaters have been investigated by geochemical and isotopic techniques with particular attention given to discharges from a fracture system at 800 m depth. Although isotopic analysis shows conclusively that the waters are old and originate in an environment that differs markedly from the modern environment at Stripa, these deep waters have a complex history and it has not proved possible to quantify all the sources and processes that participate in their genesis. The work clearly illustrates the difficulty of interpreting such results in terms of groundwater residence times and flow paths when a significant amount of mixing occurs between different waters.

Migration experiments conducted in a single fracture within the granite demonstrate that groundwater flows in a few separate channels rather than uniformly over the fissure area. The travel times in separate channels can be different even for non-absorbed tracers, and the flow rates within the channels can vary considerably. It is clear from this work that groundwater pathways are considerably more complex than implied by a single-fissure concept.

United Kingdom

In the U.K. research was initiated in 1976 when the Institute of Geological Sciences (now the British Geological Survey) was commissioned to undertake a research programme into the feasibility of disposing of high-level radioactive wastes into crystalline igneous and metamorphic rocks. The programme was abandoned by the Government in 1981, by which time only one research site, within the Strath Halladale Granite of Cathness, had been investigated in detail. Three continuously cored deep boreholes (to around 300 m) and 24 shallow boreholes (to around 40 m) were drilled into a large, easterly-dipping, granite sheet emplaced within PreCambrian metasediments (Mather 1984).

Hydraulic conductivity profiles have been measured in the deep boreholes by using a 5 m test section. In common with research in other countries, the borehole testing has shown that the granite is characterized by discrete zones of higher hydraulic conductivity separated by blocks within which little movement occurs (Holmes 1981). There is a significant relation between hydraulic conductivity and depth below ground level, with a general decrease of hydraulic conductivity with depth which seems to apply to both fracture zones and the bulk rock (figure 2). Geochemical studies have demonstrated that most groundwater is dominated by recent recharge, but one borehole zone yielded water with an age of around 10^4 years. The programme has also included a comprehensive programme of borehole logging in which the geophysical logs have been calibrated against known geological conditions derived from the borehole cores. This has demonstrated that the full wave-train sonic logs and the acoustic logs show most promise for the assessment of crystalline rocks (McCann *et al.* 1981).

In parallel with the work in Caithness, an experimental research site within a granite quarry at Troon, near Camborne in Cornwall, has been developed by the U.K. Atomic Energy Authority to investigate both thermal effects produced by high-level waste and fracture hydrology. The thermal experiments used a 18 kW heater at a depth of 50 m monitored by 72 thermocouples within the surrounding 25 m radius sphere of granite (Bourke *et al.* 1978). An initial experiment in an open hole resulted in spalling of the wall of the hole once the temperature reached 300 °C, as a result of rupture of fluid inclusions within quartz crystals.

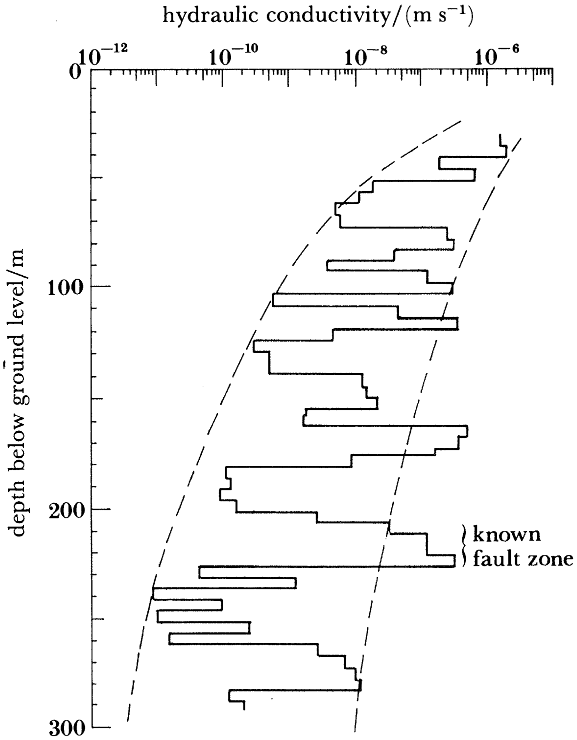

FIGURE 2. Plot of hydraulic conductivity against depth for results of packer testing in borehole A at Altnabreac, Caithness, showing general decreasing trend of hydraulic conductivity with increasing depth in both fracture zones and the bulk rock.

Subsequent tests were carried out in a lined borehole and showed reasonable agreement between measured heat transfer and predictions from transient conduction calculations with a constant thermal conductivity of 4 W mK^{-1}.

The purpose of the fracture hydrology work at Troon has been to investigate generic characteristics that control flows over long distances through intersecting fractures (Bourke *et al.* 1984). Hydraulic conductivity measurements in boreholes, examination of borehole walls and cores, and inter-borehole tracer tests have been used to estimate fracture separations, orientations, effective apertures, and lengths or frequency of intersections. Satisfactory methods have been developed, and work continues to investigate experimentally the channelling of flow in fractures and diffusion and sorption in the rock so that realistic predictions of radionuclide transport can be made.

United States of America

Field experiments within crystalline rocks in the U.S.A. have been conducted at two Department of Energy sites, the Nevada Test Site and the Hanford Reservation, and at the Colorado School of Mines facility at the Edgan Mine at Idaho Springs in Colorado (Stein & Collyer 1984). These all involve experiments in underground rooms and galleries. In addition, extensive preliminary surveys have been made of crystalline rock formations throughout the country, but no fieldwork has been carried out.

The Spent Fuel Test–Climax is located 420 m below the surface in the Climax Stock Granite at the Nevada Test Site. The facility used a number of existing tunnels and shafts previously constructed for the nuclear weapons underground testing programme. The facility was constructed in stages so that the effects of construction of one drift could be monitored by using previously constructed drifts. North and south heater drifts were constructed first and the volume of rock between them was extensively instrumented with various stress gauges and extensometers. The central, larger, used-fuel canister drift was then constructed with various drill and blast techniques and the effects of this construction were monitored in the earlier drifts (figure 3).

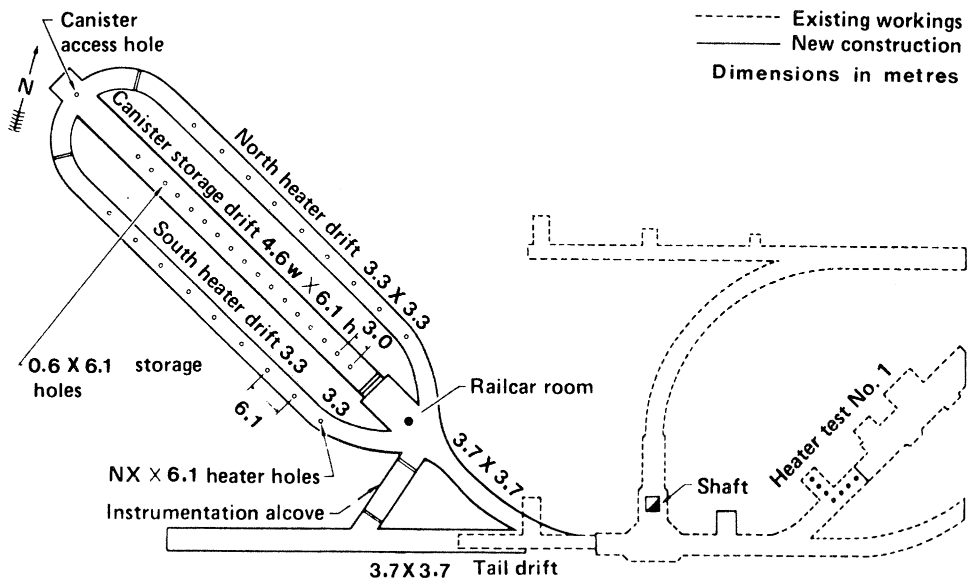

Figure 3. Layout of the Spent Fuel Test–Climax showing the canister storage drift and the earlier north and south heater drifts.

The canister drift was subsequently instrumented to measure changes in stress, dimensions and temperature. During the spring of 1980, 11 spent-fuel canisters were emplaced in boreholes beneath the drifts. The effects of the heat and radiation from these, together with heat effects from electrical heaters, were continuously monitored on over 900 channels for the 3 year duration of the fuel storage part of the test. After removal of the fuel, the monitoring was continued for 6 months to measure the thermal and mechanical responses during cooling of a simulated repository environment.

Near-field and intermediate-field temperature measurements show that conditions in the simulated environment closely approximate those calculated, indicating a high level of success in modelling heat transfer in the rock mass. Thermomechanical responses have not proved as easy to model but quite good agreement has been obtained between measured and calculated displacements (Patrick *et al.* 1983).

The programme (Simmons 1984; Hustrulid & Ubbes 1983) at the Colorado School of Mines facility, funded by the U.S. Department of Energy, has the following objectives:

to demonstrate and evaluate careful excavation techniques in crystalline rock;

to characterize the disturbance zone around the excavation;

to assess the suitability of a heated block test for characterizing hard rock; and

to create an underground research laboratory in which a wide variety of geomechanics experiments can be performed.

The facility is 100 m below the surface and above the water table. The excavation of the 20 m long, 3 m high and 5 m wide room was completed by using ten drilled and loaded blast roads carefully designed to minimize the zone affected by excavation damage. The disturbed zone in the wall of the room was determined by means of groups of radial boreholes. By using various techniques to determine changes in stress (gas permeability, cross-hole ultrasonic velocities, elastic modulus), the depth of disturbance in one particular zone was shown to be less than 1 m. However, a great deal of analysis remains to be done to determine the meaning of the individual results and the relation between them and the blasting method used.

The objective of the heated block test was to develop and evaluate a suitable test method for quantifying the mechanical and thermal behaviour of a jointed rock mass. A block, 2 m on a side, was line-drilled to a depth of 2 m and remained connected to the rock mass at the bottom. The block had three subvertical natural fractures, one of which was instrumented. The slots around the block were filled with hydraulic flat jacks to load the block in two directions. The orientation of the instrumented fracture was diagonal across the block so that normal and biaxial loadings were possible. Nine electric heaters were installed in a line across the centre of the block in one direction; two heaters were outside the block on each side and five were within the block. The test plan was developed to measure the stress–strain behaviour of the entire block and the fracture at ambient and elevated temperatures, and the thermal heating effects on the block and the fracture under various confining pressures and temperatures. The block was instrumented on the surface and in the interior, to measure deformation, strain, temperature, and fracture permeability. The block test demonstrated that the conduction of heat from heat sources in rock and the temperature can be simply predicted from laboratory observations, measurements and fundamental theories. This is not true of the thermomechanical or hydrogeologic properties, these being appreciably affected by the presence of joints and their direction with respect to the applied stress. Empirical relations can be established for a given block test and the range of most probable values specified for a given underground site. The block test is one of the few tests performed so far where the coupling of thermomechanical and hydrogeological properties was measured (Hardin *et al.* 1981).

The Basalt Waste Isolation Project is located within the Columbia River Basalts on the Hanford Reservation near Richland in Washington State. The detailed characterization of regional and local flow is difficult in these basalts, where only a few horizons have any appreciable potential for flow. For example, piezeometric maps have only been prepared with confidence for the surficial, water-table aquifer and for one of the interflow zones at the Hanford site. However, hydraulic head data from separated flow systems intersected by boreholes are sufficient to make deductions about the larger-scale regional flow pattern.

The geochemical and thermomechanical properties of basalt have been extensively investigated in the Near Surface Test Facility, which includes heater tests and a large block test. These are extensively instrumented and give a very comprehensive understanding of the behaviour of basalt when subjected to heat and applied stress. The conclusions from these tests are not too dissimilar from those made from research in other underground laboratories; namely that the temperatures and heat flow can be accurately modelled from basic principles and laboratory data. The block tests and the measured thermomechanical properties in general, demonstrate the value of *in-situ* measurements. For example, it has been shown that the rock-mass deformational response is strongly anisotropic and controlled by two major joint sets.

Other countries

Argentina has made a decision to dispose of highly active radioactive wastes at a depth of around 500 m in granite terrain. Four formations have been identified in the provinces of Chubut and Rio Negro in the south of Argentina (Palacios *et al.* 1984). Investigations have been undertaken in one of these formations at Sierra del Medio in Chubut where, after detailed surface surveys, ten sites were identified for borehole drilling to depths ranging from 200 to 280 m to examine the geology and structure of the area, including fractures and dykes. An area within the granite was then selected for more detailed study on the basis of its lower density of dykes and fractures and its less altered condition. Four boreholes have been drilled to 800 m within this area for detailed hydrogeological work, but results have not yet been published.

Both granite and dolerite are under investigation in Japan and, in 1981, preliminary *in-situ* heating and hydraulic conductivity tests were undertaken in dolerite within a disused mine in northern Japan.

In India four candidate sites within gneisses and granites have been selected for detailed investigation, and two abandoned underground chambers, located at 1000 and 1400 m depth respectively, in a mine within the Kolar Schist Belt are being developed as an underground research facility (Godse *et al.* 1984).

Granites, gneisses and metasediments of the Namaqualand Metamorphic Complex at Vaalputs in the arid northwestern part of Cape Province have been selected by the Republic of South Africa as the host for a repository. Currently the investigations involve the development of a low-level facility, but investigations directed towards the acceptance of high-level wastes are due to begin in 1988 (Hambleton-Jones *et al.* 1984).

Conclusions

It is generally recognized that measured rock properties depend on the volume tested. For a jointed rock mass, the overall behaviour of the composite will be significantly different from that of either the joints or the intact rock material between the joints. Thus the results obtained depend very much on the scale of the test and the volume of rock tested.

As indicated in the introductory sections of this paper, the only credible way by which radionuclides can reach the biosphere from an underground repository is through the action of circulating groundwater. Thus the accurate characterization of rock-mass permeability is perhaps the single most important parameter required for the successful siting of a repository.

A variety of permeability tests are available and have been used in field experiments on fractured crystalline rocks. Each of these tests has a different range of application. Some, such as slug and pulse tests, measure a wide range of permeabilities in small-diameter boreholes and others, such as ventilation tests, measure the permeability of a large volume of rock surrounding an underground room.

Permeability tests must be performed over a wide range of scales for adequate characterization of a site. Many small-scale tests on single fractures are needed to provide a statistical basis for assessing the true groundwater flow velocities needed for risk assessment. On the other hand, large-scale tests on multiple fractures involving 10^6 m^3 of rock are required for overall permeability characterization and development of a general groundwater flux model for the site (Wilson *et al.* 1979). Thus both large-scale and small-scale tests are necessary, and further work is still required to improve existing techniques and develop new methods. In particular there is a need to understand how the local flow fields in and around a repository will be connected to the regional flow system.

Among the most promising of the new developments are the cross-hole techniques, which are able to characterize larger volumes of rock than tests in a single borehole. One such hydrogeological testing method uses sinusoidal pressure fluctuations created in a packered-off section of a test borehole, which are monitored in surrounding observation boreholes (Black & Barker 1983). By making observations at discrete levels in the observation boreholes it is possible to obtain a three-dimensional picture of the hydrogeological properties of the crystalline rock mass.

Apart from the hydrogeological studies, the other main thrust of field experiments has been in the characterization of the thermomechanical properties of crystalline rocks. Attempts to predict their overall behaviour from basic principles have met with only limited success. The temperature distribution and heat conduction can be adequately modelled by using laboratory data and standard codes. However, the stress and displacements fields are much more difficult to predict, primarily as a result of the presence of fractures, which appear to allow some of the thermally induced displacements to be absorbed internally to the rock mass. Because of this effect, the significance of scale is a critical factor in thermomechanical experiments, and this leads to a need to investigate the effects of scale *in situ*. The flat jack tests in basalt at Hanford and in biotite gneiss at the Colorado School of Mines site have extended measurements to blocks with an edge length of up to 2 m. However, it is unlikely that tests of this type can be conducted on significantly larger scales. Experiments in granite drifts at the Nevada test site and similar experiments planned in other countries measure the change in rock properties on a larger scale. Similarly, the measurements of displacements in the shaft during construction of the Canadian URL are providing another source of information on the effects of scale. It is important to incorporate a hydrogeological dimension in future experiments, and the design of an effective hydrothermomechanical experiment is a challenge that still awaits the earth scientist.

However, although there is a need for continuing research, the extensive field studies made so far, including those with boreholes from the surface and those in underground rooms and shafts, have demonstrated that crystalline rocks have considerable potential as host rocks for a repository for high-level radioactive waste. What is needed is a continuing emphasis on field experiments, with the development of underground laboratories, to provide the data on which detailed risk assessment can be based. Generic site work is useful for the development of techniques and selection criteria but there is also a need for detailed site characterization of actual prospective disposal sites.

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