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TECHNICAL REPORT 90-35

STRIPA PROJECT

ANNUAL REPORT 1989

MAY 1990

Parkstrasse 23 5401 Baden/Schweiz Telephon 056/20 55 11

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Das Stripa-Projekt ist ein Projekt der Nuklearagentur der OECD. Unter internationaler Beteiligung werden im Rahmen einer 3. Phase dieses Projektes von 1986-1991 Forschungsarbeiten in einem unterirdischen Felslabor in Schweden durchgeführt. Unter Anwendung des in den vorhergehenden Phasen 1 und 2 Gelernten sollen folgende Arbeiten realisiert werden:

- Anwendung verschiedener Felduntersuchungs- und Berechnungsmethoden, um den Wasserfluss und Nuklidtransport in einem unbekannten Felsvolumen des Stripagranites vorherzusagen und anschliessend zu überprüfen
- Evaluation verschiedenster Materialien und Methoden zum Abdichten wasserführender Klüfte im Stripagranit

Seitens der Schweiz beteiligt sich die Nagra an diesen Untersuchungen. Die technischen Berichte aus dem Stripa-Projekt erscheinen gleichzeitig in der NTB-Serie der Nagra.

The Stripa Project is organised as an autonomous project of the Nuclear Energy Agency of the OECD. Over the time period 1986-1991 (Phase 3 of the Project), an international cooperative programme of investigations is being carried out in an underground rock laboratory in Sweden. Building on experience gained in Phases 1 and 2, the following research will be carried out:

- Application of various site characterisation techniques and analysis methods with a view to predicting and validating groundwater flow and nuclide transport in an unexplored volume of Stripa granite
- Verification of the use of different materials and techniques for sealing water-bearing fractures in the Stripa granite

Switzerland is represented in the Stripa Project by Nagra and the Stripa Project technical reports appear in the Nagra NTB series.

Le projet de Stripa est un projet de l'Agence de l'OCDE pour l'Energie Nucléaire. C'est dans le cadre d'une troisième phase de ce projet allant de 1986 à 1991, que des travaux de recherches sont réalisés avec une participation internationale, dans un laboratoire souterrain de Suède. Il s'agit d'effectuer les travaux ci-dessous, en mettant en application ce que l'on a appris au cours des précédentes phases 1 et 2:

- Application de diverses méthodes de recherches sur le terrain et de calcul, pour prévoir puis contrôler l'écoulement de l'eau et le transport des nucléides dans un volume rocheux inconnu du granite de Stripa
- Evaluation des méthodes et des matériaux les plus divers, en vue de colmater des fractures aquifères du granite de Stripa

La Cédra participe à ces recherches pour la Suisse. Les rapports techniques rédigés à propos du projet de Stripa paraissent en même temps dans la série des Rapports Techniques de la Cédra (NTB).

THE STRIPA PROJECT ANNUAL REPORT 1989

The Stripa Project is an international project being performed under the sponsorship of the OECD Nuclear Energy Agency (NEA). The Project concerns research related to the disposal of highly radioactive waste in crystalline rock. The Research and Development Division of the Swedish Nuclear Fuel and Waste Management Company (SKB) has been entrusted with the management of the project, under the direction of representatives from each participating country.

The aim of this report is to inform the OECD Nuclear Energy Agency and the participants in the project about the general progress of work during 1989.

Stockholm

May 1990

CONTENT

1 INTRODUCTION

An autonomous OECD/NEA Project relating to the final disposal of highly radioactive waste from nuclear power generation is currently under way in an abandoned iron ore mine at Stripa in central Sweden. Research is being performed in a granite formation 350 meters below the ground surface. The Stripa project was started in 1980, in co-operation with Canada, Finland, France, Japan, Sweden, Switzerland, and the United States. The first phase of the project, completed in 1985 at a total cost of approximately 47 MSEK, consisted essentially of three parts:

- o hydrogeological and hydrogeochemical investigations in boreholes down to a depth of 1230 metres below the ground surface,
- o tracer migration tests to study radionuclide transport mechanisms in the rock fractures, and
- o large-scale tests of the behaviour of backfill material in deposition holes and tunnels.

The second phase of the Stripa Project, which was joined by two additional countries, Spain and the United Kingdom, started in 1983. The second phase of the project was completed in 1988, at a total cost of approximately 65 MSEK. The investigations included in the second phase were:

- o the development of crosshole geophysical and hydraulic methods for the detection and characterization of fracture zones,
- o extended tracer experiments in fractured granite,
- o the sealing of boreholes, a shaft and a tunnel using highly compacted bentonite,
- o hydrogeological characterization of the Stripa site based on data from the Swedish-American co-operative (SAC) project, and
- o isotopic characterization of the origin and geochemical interactions of the Stripa groundwaters.

The formal agreement for an extension of the project into a third phase was signed in 1987. Participating countries in the Phase 3 of the Stripa Project is Canada, Finland, Japan, Sweden, Switzerland, United Kingdom and the United States. The research activities in this third phase of the Stripa Project are carried out under two headings,

- Fracture Flow and Nuclide Transport; and
- Groundwater Flow Path Sealing.

Under the heading Fracture Flow and Nuclide Transport the main objectives are:

- to predict groundwater flow and nuclide transport in a specific unexplored volume of the Stripa granite and make a comparison with data from field measurements. The comparison will be made by means of an integrated approach with existing site characterization tools and methods, particularly those developed under Phases 1 and 2, this programme is referred to as the "Site Characterization and Validation" programme,

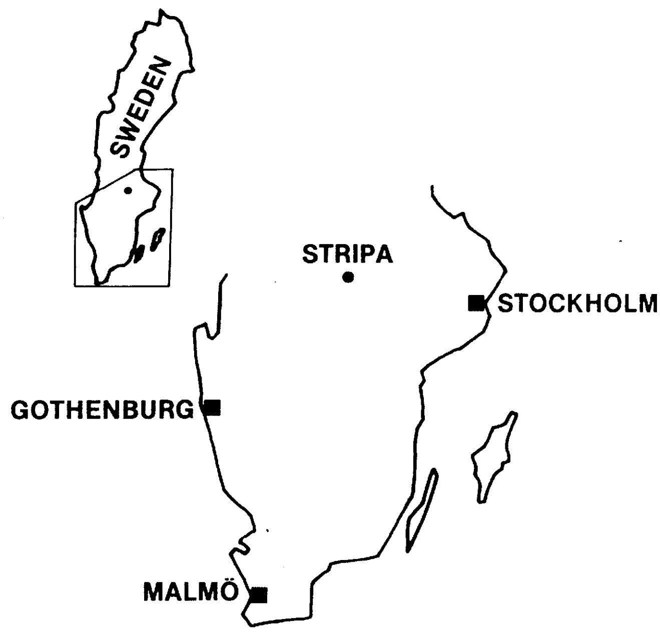


Figure 1-1. The Stripa mine is located approximately 250 km west of Stockholm.

– to continue the development of site assessment methods and strategies and, where found appropriate, apply them in later stages of the integrated site characterization exercise outlined above. This programme is referred to as "Improvement of Site Assessment Methods and Concepts".

Under the heading Groundwater Flow Path Sealing the principal objectives are:

– to identify, select and evaluate sealing substances which promise to possess long-term chemical and mechanical stability; and
– to demonstrate in field tests, by use of suitable methods and techniques, the effectiveness of such substances for the long-term sealing of groundwater flow paths in the Stripa granite. The total programme is referred to as "Sealing of Fractured Rock".

The conditions of participation in the Stripa Project are covered by separate agreements for Phase 1, Phase 2 and Phase 3, although all three phases share the same management structure. The project is jointly funded by the organizations listed below.

Responsibility for supervision of the research programme and for its finance resides with the Joint Technical Committee (JTC). This is composed of representatives from each of the national organizations. It also provides information on the general progress of work to the OECD Steering Committee for Nuclear Energy, through the NEA Committee on Radioactive Waste Management.

Each research activity is assigned to a principal investigator, a scientist with particular expertise in the research field in question. The conception of the experiments, and their realization, are periodically reviewed by a Technical Subgroup (TSG). The sub-group is composed of scientists from the participating countries. It deals with geology, geophysics, hydrogeology, numerical modelling of fracture flow, hydrogeochemistry, rock mechanics, chemical transport and engineered barriers.

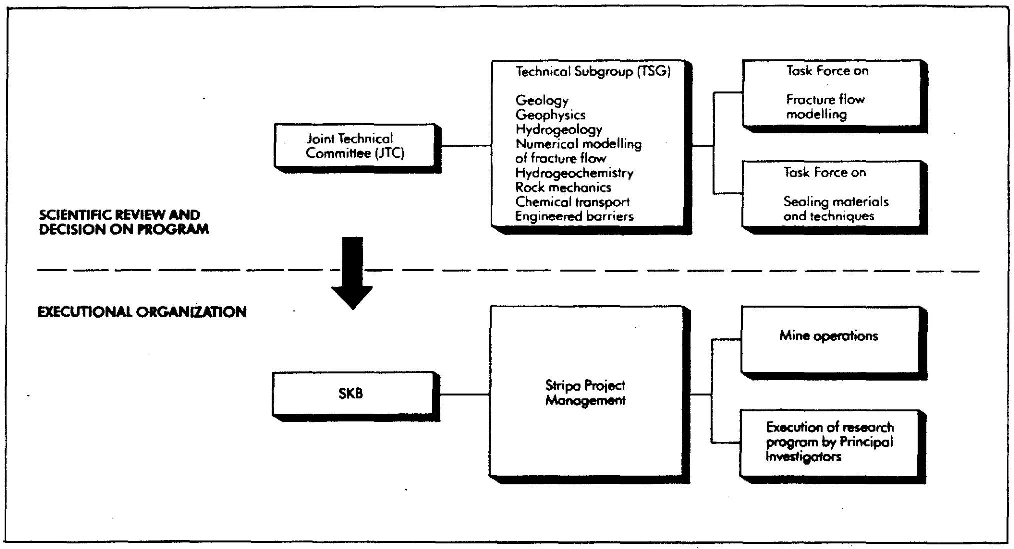


Figure 1-2. Organization of the Stripa Project.

Two "Task Force" groups one on Sealing Materials and Techniques and a second on Fracture Flow Modelling form ad hoc groups to the project. In each of the two groups the participating countries may assign a scientist with particular expertise in the research field considered. The ad hoc groups should report to the TSG on their activities.

As for the "Site Characterization and Validation" programme the project manager is supported by two Scientific Coordinators, John Black of Golders Associates and Olle Olsson of ABEM both with long experience in the Stripa Project. The "Site Characterization and Validation" programme will both in its phase of practical work in the Stripa mine and in the stages of data evaluation and reporting, call for extensive co-ordination between different groups of investigators. A detailed technical knowledge of the work within the programme is then necessary.

The Research and Development Division of the Swedish Nuclear Fuel and Waste Management Company (SKB) acts as the host organization, and provides management for the project. It is responsible for mine operations and for the procurement of equipment and material for experimental work. Meetings of the Joint Technical Committee, the Technical Sub-group, the two Task Force groups, the principal investigators and the project management are held on a regular basis to review the progress of the project.

A representative of the OECD Nuclear Energy Agency takes part in the meetings of the Joint Technical Committee in an advisory capacity. The Nuclear Energy Agency continues to foster the broadest possible participation in this and other projects by its member countries, and ensures co-ordination of the project with its other activities in the field of radioactive waste management.

The following organizations are participating in the Stripa Project:

Canada	Atomic Energy of Canada Ltd (AECL)
Finland	Industrial Power Company Limited (TVO); Ministry of Trade and Industry; Imatra Power Company (IVO)
France (Phase 2 only)	Commissariat á l'Energie Atomique (CEA); Agence Nationale pour la Gestion des Dàchets Radioactifs (ANDRA)
Japan	Power Reactor and Nuclear Fuel Development Corporation (PNC)
Spain (Phase 2 only)	Junta de Energia Nuclear (JEN)
Sweden	Swedish Nuclear Fuel and Waste Management Co
Switzerland	National Co-operative for the Storage of Radioactive Waste (NAGRA)
United Kingdom	Department of the Environment (UK DOE)
United States	Department of Energy (US DOE)

2 GENERAL

2.1 MEETINGS

The Twelfth meeting of the Joint Technical Committee was held in Örebro, Sweden on June 13-14 followed by a field trip to the Stripa mine on June 15. At the meeting presentations where given on the status of the different research activities of Phase 3.

The JTC made the following decisions based on recommendations made by TSG:

1. The JTC agreed to adopt the recommendations given by TSG on the Sealing program. These recommendations were;
   * Continue as planned with Sealing Tests 1, 2, 3 and 4 in the Stripa Mine.
   * Continue as planned with the oretical and laboratory studies of the longevity characteristics of bentonite based and cementbased grouts.
   * Establish more frequent interaction among PI's for the SCV and Sealing Programs.
2. The JTC agreed not to accept the recommendation from TSG on the clarification of the principal objective of the SCV program. The TSG recommended the following clarification of the Stripa Phase 3 objective;
   * To develop techniques and methods to predict and validate groundwater flow and transport in fractured rocks with specific data provided from application in the Stripa granite.
     This means that the principal objective of the SCV program stands as originally stated;
   * To integrate different tools and methods in order to predict and validate the groundwater flow and transport in a specific volume of the Stripa granite.
3. The JTC agreed to approve the revised and extended SCV program as recommended by the TSG, at an estimated cost of 2 700 000 SEK.

   The proposals approved were;

   1. SCV Site: Water and Tracer Collection System in Validation Drift.
   2. SCV Site: Tracer Test.
   3. SCV Site: Saline Injection with Radar monitoring before drift excavation.
   4. SCV Site: Saline Injection with Radar monitoring after drift excavation.
   5. SCV Site: Detailed Geological Characterization of zone H.
   6. SCV Site: Extension of Analysis of Borehole Seismic Data.

   The JTC noted that the proposal: "Characterization of Pore structure of the Fracture Planes using Resin Injection" will be reconsidered at the next TSG-meeting. The JTC decided that if the proposal is recommended by the TSG for funding, a per capsula decision will be taken by the JTC.
4. Since the proposals on "Extension of in-situ Channelling Experiments" and "Miniature Crosshole Seismic Tomography" were rejected by the TSG, it was agreed that JTC would also reject these items.

The JTC made the following decisions based on proposals made by Project Management, the Task Force on Fracture Flow Modelling, and SKB:

5. The JTC agreed upon the proposed support to Fracture Flow Modelling, at an estimated cost for one year of 325 000 SEK, because of the additional work since the establishment of the Task Force.

6. The JTC accepted the proposal on Modelling support to the crosshole, saline injection and tracer experiments at an estimated cost of 350 000 SEK.

The Third Symposium of the OECD/NEA Stripa Project was held in Stockholm on October 3-4, 1989. The symposium also included a fieldtrip to the Stripa mine on October the 5th. At the symposium approximately 200 participants gathered to listen to and discuss presentations on the results of Phase 2 and the on-going work of Phase 3. The symposium proceedings have been published by OECD/NEA. The OECD/NEA document will give an excellent overview of the results of Phase 2 and the progress made in the Phase 3 of the Stripa Project. The report will be available through the project management as well as directly from Dr. Daniel Galson at OECD/NEA in Paris.

The Task Force on Sealing Materials and Techniques and the Task Force on Fracture Flow Modelling both met twice to discuss and review the technical progress of the respective programme.

One workshop on Hydrologic testing in Stripa was conducted.

Notes from all meetings have been distributed separately.

3 PHASE 3

3.1 SITE CHARACTERIZATION AND VALIDATION

3.1.1 Introduction

The Site Characterization and Validation (SCV) Project focusses on the techniques and approaches used in site characterization. The central aim of the programme is to predict groundwater flow in a specific volume of rock and to compare these predictions with data from field measurements. The distribution of water flow into a drift (tunnel) will be predicted, the drift will be excavated, the inflows will be measured and compared with prediction. Above and beyond the central aim there are a number of subsidiary aims such as assessment of channelling, the small scale hydrogeological effects of drift excavation and tracer tests in the fractured rock mass.

The Site Characterization and Validation programme is based around the idea of cycles of data-gathering, prediction, and validation. Hence the programme has stages of work which can be described in these terms. In fact, the programme contains two cycles of this type where predictions are checked against observation. It is therefore divided into five stages as follows:

Stage	Title of stage	Period	Type of work	Cycle
I	Preliminary site characterization	86–88	data gathering	first
II	Preliminary prediction	87–88	prediction	first
III	Detailed characterization & preliminary validation	88–89	validation/ data gathering	first / second
IV	Detailed predictions	89–90	prediction	second
V	Detailed evaluation	90–91	validation	second

The programme of work contains a number of different techniques falling within the disciplines of structural geology, geology, geophysics, chemistry hydrogeology, and modelling. These have been combined so that predictions can be made and subsequently validated. The "cycles" of the programme envisage two modelling periods in which predictions would be made. These two periods are very different. In the first (Stage II), a conceptual model is made which is essentially geometrical with preliminary values of the important properties. Modelling at this stage will make primarily geometrical predictions. In the second (Stage IV), modelling will include the detailed properties and will include predictions of inflows to the test drift.

As can be seen Stage III fulfills two functions, that is the data gathered at this point in the programme will be compared against the preliminary predictions resulting from the Stage II work. They will also provide a basis for the detailed prediction in Stage IV. Stages I and II were completed during 1988 and Stage III data collection was completed during 1989 and analysis of that data is currently in progress.

3.1.2 Revision of Programme for the SCV Project

The knowledge about the geological and hydrological conditions at the SCV site learned from the Stage I and II investigations called for detailing the remaining parts of the investigation programme. A revision of the programme was also proposed taking into account the experience gained and development of new technology since the definition of the original programme in 1985. A revision of the SCV Project was discussed at the TSG meeting in March 1989 and the following additions and modifications were made to the original programme:

Detailed Geological Characterization of Zone GH

The objective of this programme is to determine the nature of the deformation (fracturing, shearing, etc.) within a large and well defined fracture zone, zone GH, and how this deformation varies over distances of 100 m or greater along the vertical and horizontal trends of zone GH. The geometry of the fractures making up the fracture zone will be determined in terms of orientation, trace length, spacing, and interconnectivity/termination characteristics and a description made of the surface characteristics in order to develop a generic model of the fracture zone.

Borehole Seismics – Extension of Analysis

The analysis of seismic data will be extended to provide detailed information on the rock volume surrounding the Validation drift with special emphasis on the properties and extent of fracture zone GH.

Monitoring of Saline Tracer Transport through Rock by Borehole Radar Measurements

The development of the borehole radar technique within the Stripa Project has provided the possibility of locating groundwater flow paths in rock during a flow test. The basic idea is to detect a saline tracer with radar attenuation tomography. If radar measurements are repeated at regular intervals the spreading of a tracer through rock can be monitored as a function of time.

The objective is to provide data on the geometry of flow paths from an injection point in a hydraulically conductive portion of zone GH. Two separate experiments will be conducted using the same injection point. The first experiment will be performed prior to the excavation of the Validation drift and the second after excavation of the drift. This will make it possible to see if the excavation of the drift causes any changes of the major flow paths.

Water and Tracer Collection System in the Validation Drift

The system for water and tracer collection has been expanded in order to obtain more accurate measurements of the spatial distribution of water and tracer inflows into the excavated Validation Drift.

Four different techniques will be used to measure water inflow and to collect the tracers:

- collection of wall and ceiling inflows through plastic sheets in a grid system (2x1 m grid),
- lower wall and floor inflow measurements through water collection in sumps located in a grid system,
- total drift measurement using a ventilation bulkhead,
- measurement of small scale inflow variation by the evaporation technique.

Tracer Test in the Validation Drift

The objective of the tracer test is to observe and evaluate the movement of tracers from different injection points towards the Validation drift. The original tracer test was due to last for a period of 18 months and occurred at the very end of the period of measurement. The inclusion of salt injection tests with radar detection into the overall proposal has resulted in a shortening of the original schedule from 18 months to 10 months.

Two boreholes will be drilled from the entrance area to the Validation Drift to intersect zone GH. Tracer injection points will be located in the fracture zone and in the "good rock" at distances between 10 to 30 m and 10 to 20 m from the drift, respectively. A different tracer will be used at every injection point. Tracers based on metal complexes will be used.

3.1.3 Detailed Characterization and Preliminary Validation (Stage III)

3.1.3.1 Drilling and Excavation

Three boreholes (C1, C2, and C3) were drilled for detailed characterization of the central parts of the SCV site. The boreholes were oriented to intersect two of the major features which had been identified during the Stage I investigations. Two of the boreholes were also given a steep dip in order to provide better sampling in the vertical direction compared to what was obtained with the Stage I boreholes. Later two boreholes (C4 and C5) were drilled as a part of the radar/saline tracer experiment.

An access drift has been excavated from the existing mine workings to the start of the Validation drift. From this location six boreholes (D1-D6) were drilled to outline the Validation Drift. There is a central hole (D1) surrounded by 5 boreholes symmetrically placed on a circle with a radius of 1.2 m.

The location of the new access drift and all boreholes drilled so far within the SCV Project is shown in Figure 3-1.

3.1.3.2 Geophysical Investigations

The Stage III borehole radar measurements comprised single hole reflection measurements in the three C-boreholes and the six D-boreholes (Sandberg, Olsson, and Falk, 1990). All boreholes were measured with the directional antenna developed within the Stripa Project. This considerably increased the reliability in interpretation of the radar reflection data as fracture zone orientations now could be determined based on data from one hole only. The directional antenna operates at a center frequency of about 60 MHz and the probing range at the

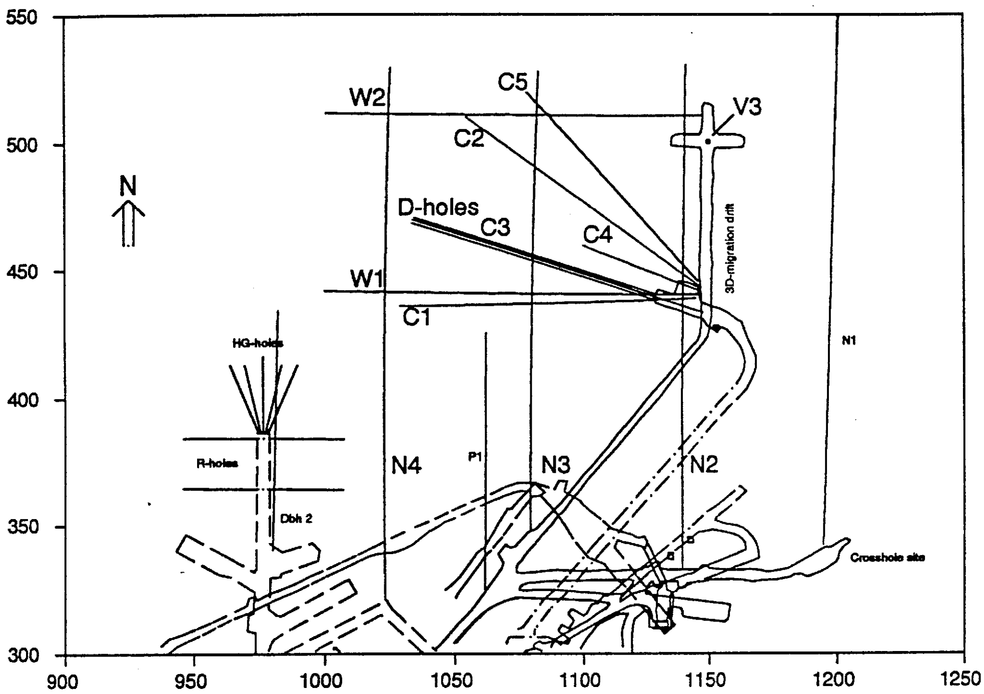


Figure 3-1. Location of boreholes and drifts at the SCV site.

SCV site has been 60–70 m. The boreholes were also measured with the 25 Mhz dipole antennas and in this case the probing range was about 100 m.

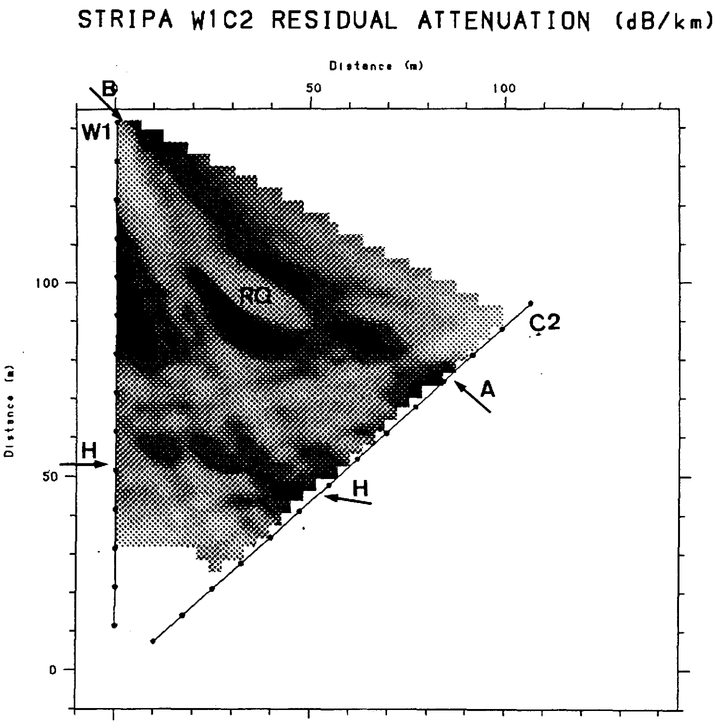
Crosshole tomography measurements were made of the borehole sections C1-C2, W1-C1, and W1-C2 using the 60 MHz antennas. The attenuation and slowness tomogram for the section W1-C2 is shown in Figure 3-2. It is interesting to note that the circular feature named 'RQ' in the N3-N4 attenuation tomogram obtained during Stage I also appears in the W1-C2 attenuation tomogram. The N3-N4 and W1-C2 planes intersect along a line which also intersects 'RQ'. The location of the highly attenuating parts of 'RQ' fall in the same place for both tomograms. This demonstrates that the feature 'RQ' is real and correctly represented in the tomograms. The feature is intersected by the D-boreholes and is characterized as a vuggy granite.

Seismic amplitude and velocity tomography has been made in the same borehole sections as was done with the radar. Crosshole seismic reflection measurements were made with receivers in Wl and C3 and the newly developed piezo source in C1 and C2. Reflection measurements were also made with the source in D1 and four receivers in D2–D5. New procedures for processing reflection data have been developed and an example of filtered data from a seismic crosshole reflection measurement is shown in Figure 3-3.

Preliminary conclusions from the geophysical investigations performed during Stage III indicate that the major features GH, GA, and GB predicted based on Stage I data exist in approximately the predicted positions. One of the predicted features (GC) is now considered insignificant.

3.1.3.3 Fracture Characterization

The basic objective of the SCV fracture mapping program is to provide a detailed data base that will permit a statistical characterization of the orientations, trace lengths and spacings of each fracture set making up the fracture system within the



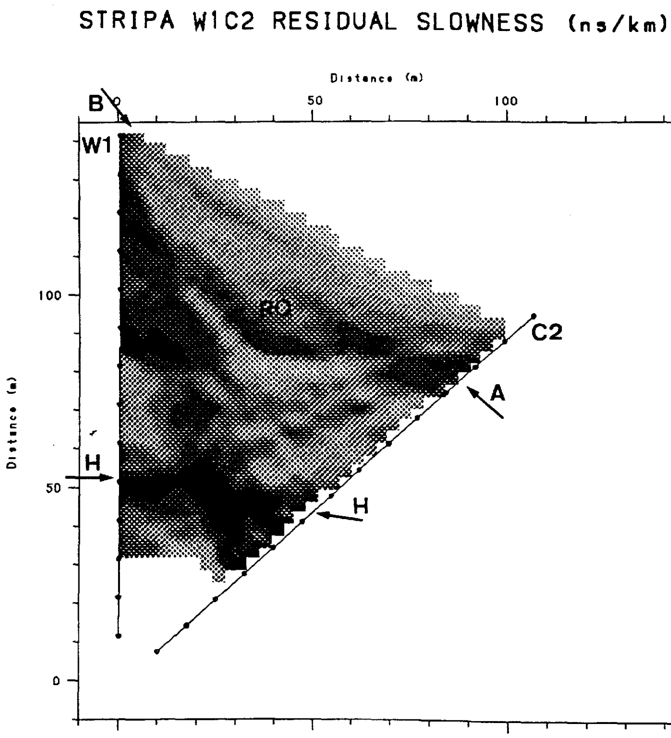


Figure 3-2. Radar slowness and attenuation tomograms for the borehole section W1-C2. The major features identified are labelled and indicated with arrows. The circular feature 'RQ' appears in the center of the tomograms.

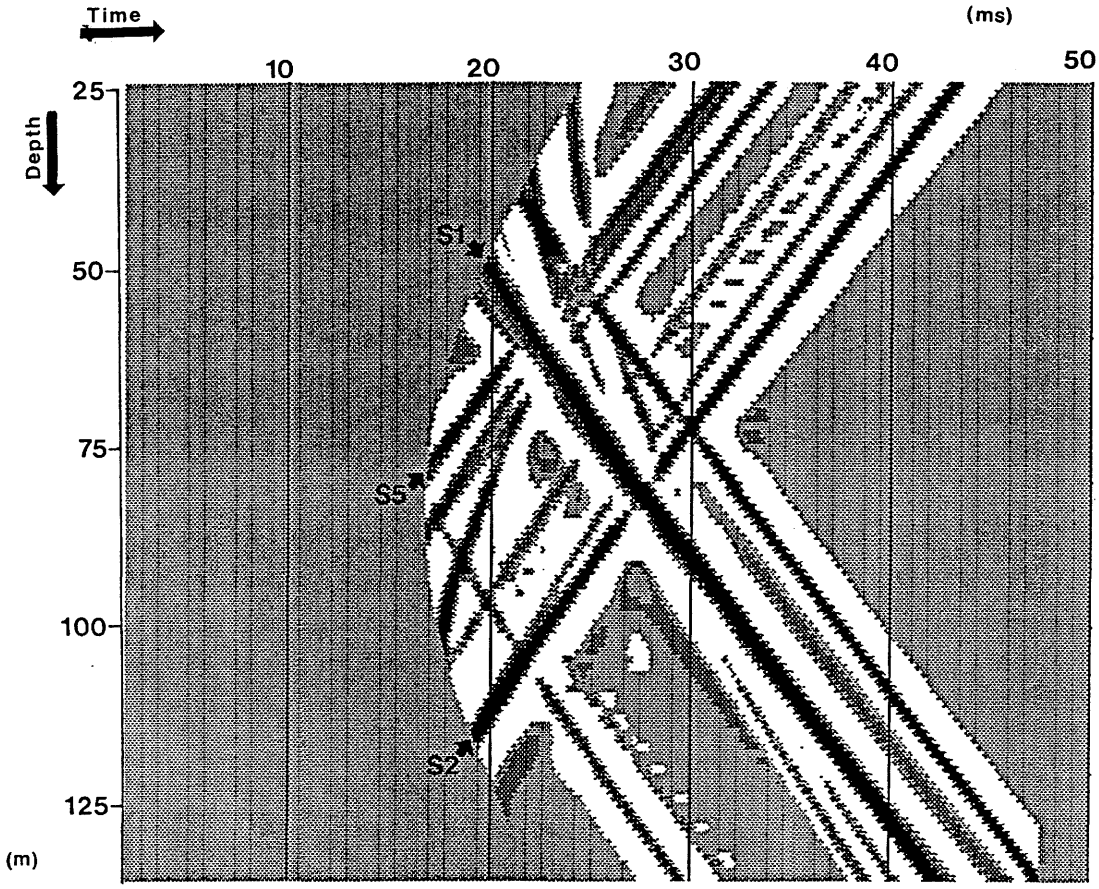


Figure 3-3. Results from crosshole seismic reflection measurements after filtering. The receiver was located at 100 m in W1 while the source was moved along C1. The reflector S1 corresponds to zone H.

SCV block. This characterization is designed to provide the basis for predicting and validating the fracture geometry of the test area, integrating the fracture and hydraulic data as well as provide the data needed to generate the fracture network in the test area for both flow and pathway predictions.

The walls of most of the drifts bounding the SCV block were photographed as they became available to the project. The photographs were enlarged and used as a mapping base. All fractures, with trace lengths greater than 0.5 m, intersecting seven individual scanlines, numbered 1 to 7, were systematically mapped as part of the Stage I Site Characterization program. Scanlines 8, 9 and 10 were mapped as part of the Stage III program and are located along the access drift from the 410 m level to the 385 m level. Scanline 11, also part of the Stage III program, is located along the vertical elevator shaft connecting the 360 m and 385 m levels. Basic data were collected on fracture orientation, trace length, termination mode, surface characteristics and fracture filling minerals.

In addition to the scanline data, fracture data were obtained from five cored holes in Stage I and eleven cored holes in Stage III. The cores from these boreholes were reconstructed and mapped to show lithology, fracture locations, fracture type, relative orientations, fracture minerals and fracture surface characteristics. In Stage III the fractures in the reconstructed core were oriented using a borehole TV camera.

The data from both the drift mapping and the drillcore logging have been analyzed. The combined scanline data (Figure 3-4) show a pattern of a strong sub-vertical, north-south trending set, a weaker, somewhat bi-modal (in terms of dip), west-northwest to east-southeast trending sub-vertical set and a poorly developed sub-horizontal set. The contour plot of the poles to the fracture planes for the combined Stage I and Stage III scanline and core data sets shows only one main fracture set. Cluster analysis of the combined Stage I and Stage III borehole and scanline data sets, using the minimum objective function approach, produced one large cluster, one intermediate size cluster and approximately ten small clusters. However, an analysis of the relationships between fracture orientation, fracture mineralogy and termination mode supports the conclusion from the scanline data that there are three to four main fracture sets present in the SCV block.

Figure 3-5 shows that fractures whose primary coating or filling mineral is epidote are associated with a steeply dipping, north-south trending set, fractures with calcite as the primary coating or filling mineral are associated with the steeply dipping, northwest-southeast trending set, whereas fractures with chlorite as the primary coating or filling mineral are associated with all orientations.

Fracture terminations (Figure 3-6) show that fractures with both ends free, termination mode of 0, form two well defined fracture sets, the north-south and the northwest-southeast trending sets, that have a mean intersection angle of approximately 60 degrees. The northwest-southeast trending set appears to form a conjugate set with the same strike but with mean dips about 45 degrees apart. The observation that these fracture traces terminate in the rock and not against other fractures, suggests that there were no pre-existing fractures to terminate against. For fractures with a termination mode of 1, T-junctions, there is an increase in the strength of the sub-horizontal fracture cluster, with a corresponding weakening of the two sub-vertical fracture sets. This suggests that the sub-horizontal fractures are younger. However, since a number of the T-junction fractures have the same orientation as the two sub-vertical sets one can interpret this as renewed fracturing of originally free-ended fractures to become T-junctions. The contour plot of the H-junction fractures, or termination mode 2, shows the increased strength of the sub-horizontal cluster which indicates that these were the last fractures to form.

The overall fracture pattern is one of progressive joint or fracture growth in response to changes in tectonic forces. Although both sub-vertical fracture sets are thought to have formed at the same time, the north-south trending set appears to have acted as the primary conduits for the relatively high temperature, epidote rich, hydrothermal fluids. Also, it is interesting to note that fractures in which calcite is the primary mineral are oriented sub-parallel to the existing major principal stress direction. Thus the orientation patterns associated with both the termination modes and the fracture minerals suggest that, while three or four fracture sets exists in the rock mass, the relationship between fracture orientation and principal stress directions may determine the relative contribution of each set to the rock mass permeability.

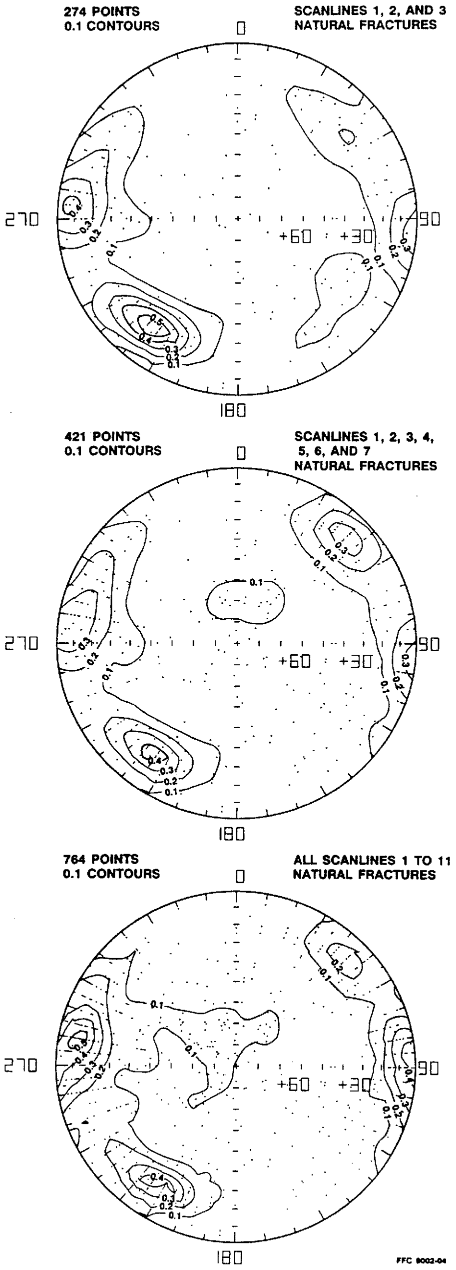


Figure 3-4. Contour diagrams of the normals to fracture planes intersecting scanlines 1, 2, and 3, scanlines 1, 2, 3, 4, 5, 6, and 7, and all scanlines, 1 to 11, in Stage I and III.

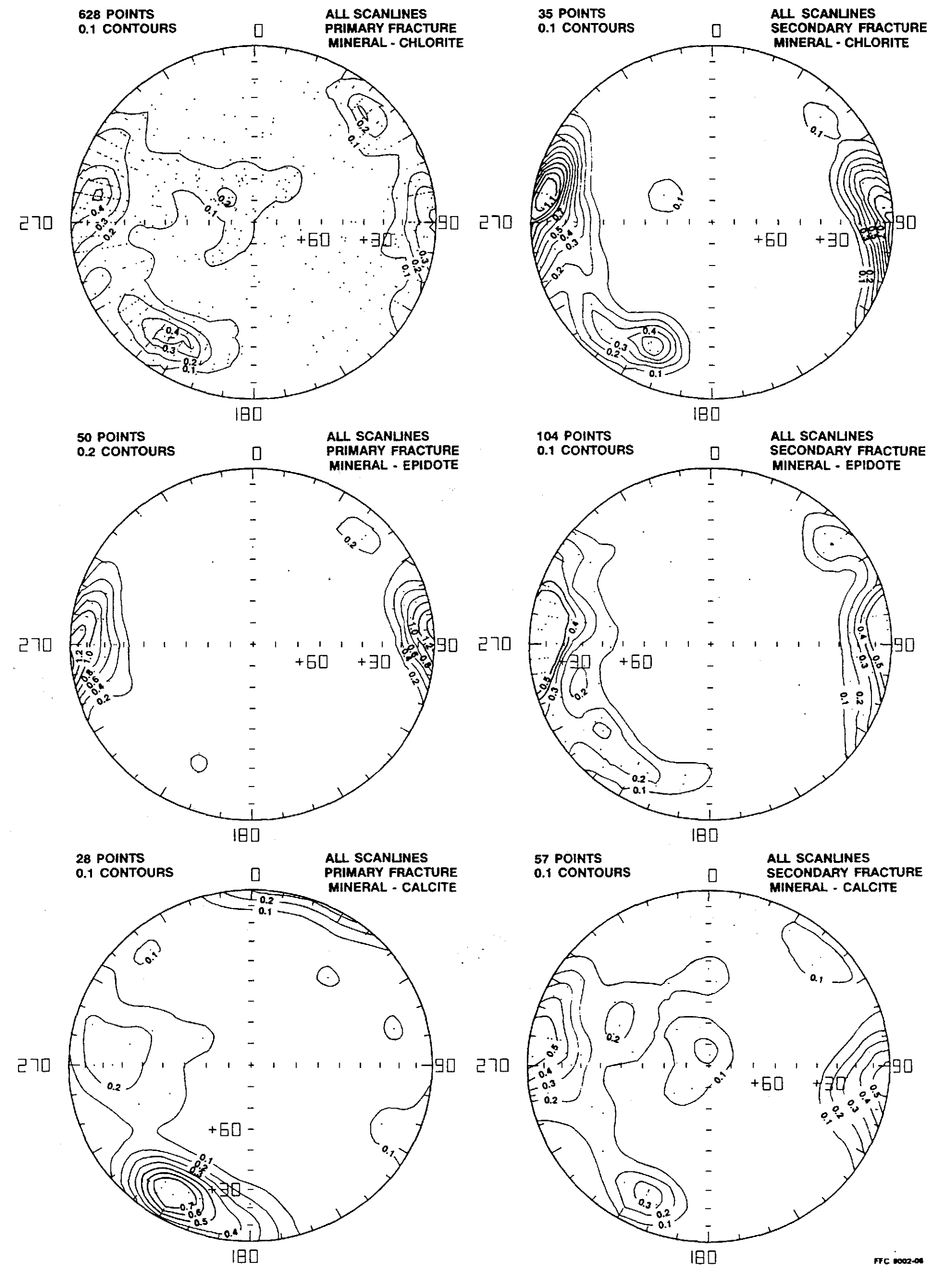


Figure 3-5. Orientation as a function of primary and secondary fracture minerals. Lower hemisphere pole stereoplots.

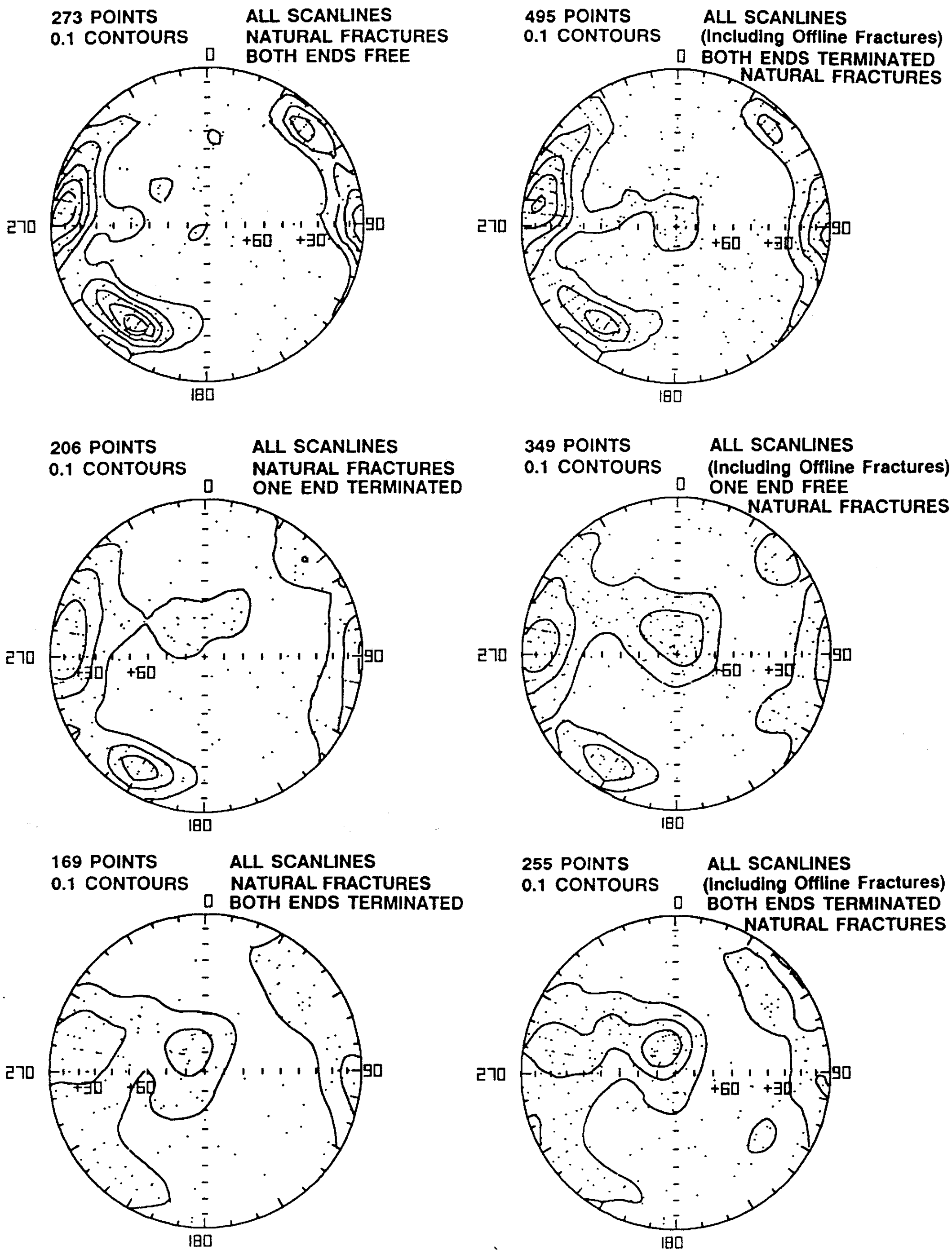


Figure 3-6. Orientation as a function of termination mode for fractures intersecting the scanlines and including off-scanline fractures.

3.1.3.4 Hydraulic Investigations

Major Activities in 1989

During 1989 the hydraulic investigations of the SCV project comprised four major data collection and interpretation exercises:

1. Focussed hydrogeological testing of boreholes C1, C2, and C3.
2. The Simulated Drift Experiment.
3. Small Scale Cross-hole hydrogeological testing.
4. Large Scale Cross-hole hydrogeological testing.

The focussed hydrogeological testing of boreholes C1, C2, and C3 was an extension of the preliminary site characterization to identify zones of enhanced hydraulic conductivity within the SCV site. The Simulated Drift Experiment measured the quantity and distribution of groundwater inflows into the D-boreholes and compared the measured values and the initial predictions of the various mathematical models of the SCV site. The small scale cross-hole testing consisted of a series of short-term constant head tests which aimed to determine the detailed hydraulic connections between the various D-boreholes in the B and H fracture zones. The large scale testing consisted of longer term constant rate, constant head, and sinusoidal tests which were performed in a number of boreholes around the mine to determine hydraulic connections across the SCV block.

Focussed Hydrogeological Testing of the C-boreholes

Single hole pulse, slug, and constant rate tests were performed using the equipment and methodology previously employed for the N and W boreholes and described by Holmes (1989). The aim of the testing was to identify zones of enhanced hydraulic conductivity and correlate these zones with the major fracture zones identified by geophysical techniques. Zones of enhanced hydraulic conductivity were identified at 35 m (zone C), 45–55 m (zone H) and 90–100 m (zone B) in borehole C1. The groundwater head was relatively uniform throughout the borehole at approximately 180 m. In borehole C2 zones of enhanced hydraulic conductivity were identified at 60 m (zone H), 80 m, and 95 m. The groundwater head rises gently from 160 m near the drift to 200 m at about 95 m depth and then falls rapidly to only 90 m at the end of the borehole. Although the rock is of low hydraulic conductivity the very low groundwater heads clearly indicate the nearby presence of a highly conductive zone with good hydraulic connections to the mined cavity. Borehole C2 is of low hydraulic conductivity throughout and has a relatively uniform groundwater head of approximately 180 m.

Simulated Drift Experiment

The D-boreholes were drilled sub-horizontally and parallel in a pattern of a central hole surrounded by five boreholes to simulate a drift of 100 m length. The aim of the experiment was to measure the quantity and distribution of inflows to the boreholes at a number of pressure steps and to compare these measurements with the predictions of the mathematical models.

Equipment and Methods

New equipment was designed and built to perform this experiment although the existing computers and data logger were utilized. One unit of the equipment enabled the pressure of the D-boreholes to be regulated and the total flow from each borehole to be measured. It employed a motor actuated gate valve, a pressure transmitter and a controller to regulate the pressure, and a system of solenoid valves to switch single borehole flows to a 20 litre/minute or a 1 litre/minute turbine flow meter depending on the flow rate. When the borehole flows reached steady state levels at each pressure step the individual flows in each borehole were identified and measured using a four packer probe. A special manifold, which uses "O" rings and internal mechanical packers to seal against the rods and service takes, was used to allow the probe to be moved while the borehole was pressurized. The outer two packers of the probe isolate a 1.5 m length of borehole and the inner two can be inflated to reduce the packered interval to 1 m and 0.5 m. A mass flow meter allowed the individual flows to be measured to an accuracy of 0.001 l/min.

Description of the Experiment

The first pressure step consisted of dropping the pressure from the environmental groundwater head of about 227 m to 148 m. After eight days the rate of change of total inflow was small and the probe was used to measure the individual flows. The second step lowered the head to 70 m and after a further nine days the probe was used to measure inflow locations which had given flows greater than 0.002 l/min during the first step. The head was lowered to 17 m during step 3 and the positive inflow locations were measured again.

Results of the Simulated Drift Experiment

The total flow from the D-boreholes for each step initially fell rapidly and then approached, but did not reach, an equilibrium value. However, the rate of change was small during the measurement of the individual inflows. Table 3-1 lists the flow rate and percentage contribution of each D borehole to the total flow at the end of each abstraction step. The percentage contributions for the 148 m and 70 m steps are broadly similar, however, the contributions at the end of the 17 m step are dramatically different. D3 ceased to flow and the contribution of D4 fell. Flows in D5 and D6 rose as the groundwater was re-directed into these boreholes.

Table 3-1. Flow rates from the D-boreholes during the Simulated Drift Experiment.

Borehole	148 m step		70 m step		17 m step	
	l/min	% of total	l/min	% of total	l/min	% of total
D1	0.008	1.1	0.029	2.2	0.096	5.6
D2	0.138	18.8	0.255	19.1	0.396	21.3
D3	0.097	13.2	0.184	12.7	0	0
D4	0.173	23.6	0.310	23.1	0.202	17.7
D5	0.131	17.8	0.212	15.8	0.369	21.3
D6	0.187	25.5	0.350	26.1	0.568	33.3
Total	**0.734**	**100.0**	**1.340**	**100.0**	**1.71**	**100.0**

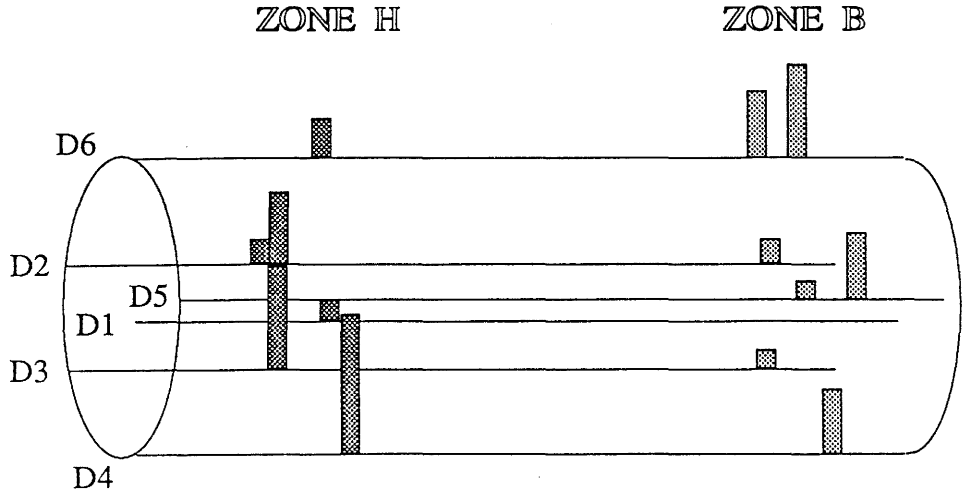


Figure 3-7. Inflows into the D boreholes measured during the Simulated Drift Experiment.

Two zones of individual inflows were identified in the boreholes, the H zone at about 25 m and the B zone at about 90 m, Figure 3-7. There were no measurable inflows elsewhere in the boreholes. The inflow zones were well defined, generally occurring within a 0.5 m interval. During the 148 m and 70 m Steps the two zones contributed approximately 80% of the total flow but during the 17 m step, after flow diversion, they contributed 100% of the total flow. The long-term drawdown of the D-boreholes generated hydraulic responses in almost all the borehole zones being monitored by the Piezomac head measurement system. This indicates a high degree of fracture zone connectivity over large distances.

Small Scale Cross-hole Testing

The aim of the small scale cross-hole hydraulic testing was to determine the variability of hydraulic connections between the D-boreholes in the B and H zones. Short duration constant head abstraction tests were performed in each borehole and each zone whilst monitoring heads in adjacent D-boreholes. In addition a 3 day constant rate abstraction test was performed in each zone. The tests were controlled using the focussed testing equipment. Table 3-2 lists the flow rates from the B and H zones in the D-boreholes 15 minutes after abstraction started. There are clearly very large differences in hydraulic properties over very short distances. The drawdowns measured during the tests indicate that boreholes D2 and D3 are not so well connected to zone B and that boreholes D1 and D5 are not so well connected to zone H.

Table 3-2. Flow measure during the small scale cross-hole testing.

Borehole	H zone flow (l/min)	B zone flow (l/min)
D1	0.051	0.080
D2	0.340	0.018
D3	0.280	0.008
D4	0.360	0.135
D5	0.075	0.230
D6	0.400	0.190

Large Scale Cross-hole Testing

Equipment and Testing

The large scale cross-hole testing aimed to determine the nature of the hydraulic connections across the entire SCV block. The tests consisted of long-term (70–220 hr duration) constant rate, constant head, and sinusoidal tests. Figure 3-8 shows an example of a 24 hour period sinusoidal test. The tests were performed using sections isolated for Piezomac head monitoring in order to minimize head disturbances due to opening and closing boreholes and used the single hole equipment to control flows and heads. The responses were monitored across the site by the Piezomac system and some zones were connected to transducers of the single hole equipment to allow rapid early time data collection. Table 3-3 summarizes the tests that were performed.

Table 3-3. Summary of tests performed during the large scale cross-hole testing.

Source borehole section	Depth interval (m)	Zone tested	Type of test	Flow rate (l/min)	Duration (hrs)
N4-3	77–108	?	Constant rate	2.3	72
C1-2	40–70	H	Constant rate	2.9	216
W2-1	110–150	A	Constant rate	5.3	95
N2-2	111–160	?	Constant rate	1.9	88
W2-3	66–75	H	Constant head	–	70
C1-2	40–70	H	Sinusoidal	15.15 m + 24 hr periods	
D6-B	All borehole except 22–28	B	Sinusoidal	15.15 m + 24 hr periods	

Results and Interpretation

All tests generated some responses within the SCV block. The tests in N4-3 and W2-2 generated only a few responses but the tests in C1-2, W2-1, W2-3, and D6-B generated a large number of responses. The constant rate and sinusoidal tests were corrected for background drift where appropriate. Initial calculations have been performed on the constant rate and sinusoidal tests interpreting them as extensions of the Theis methodology to non-integral dimensions (Barker, 1988). Skin, wellbore storage, and well radius have been set to zero for these initial calculations to allow the use of simpler models. The model used to get best fit estimates of the hydraulic parameters K_f and S_{sf} using a combination of parameter

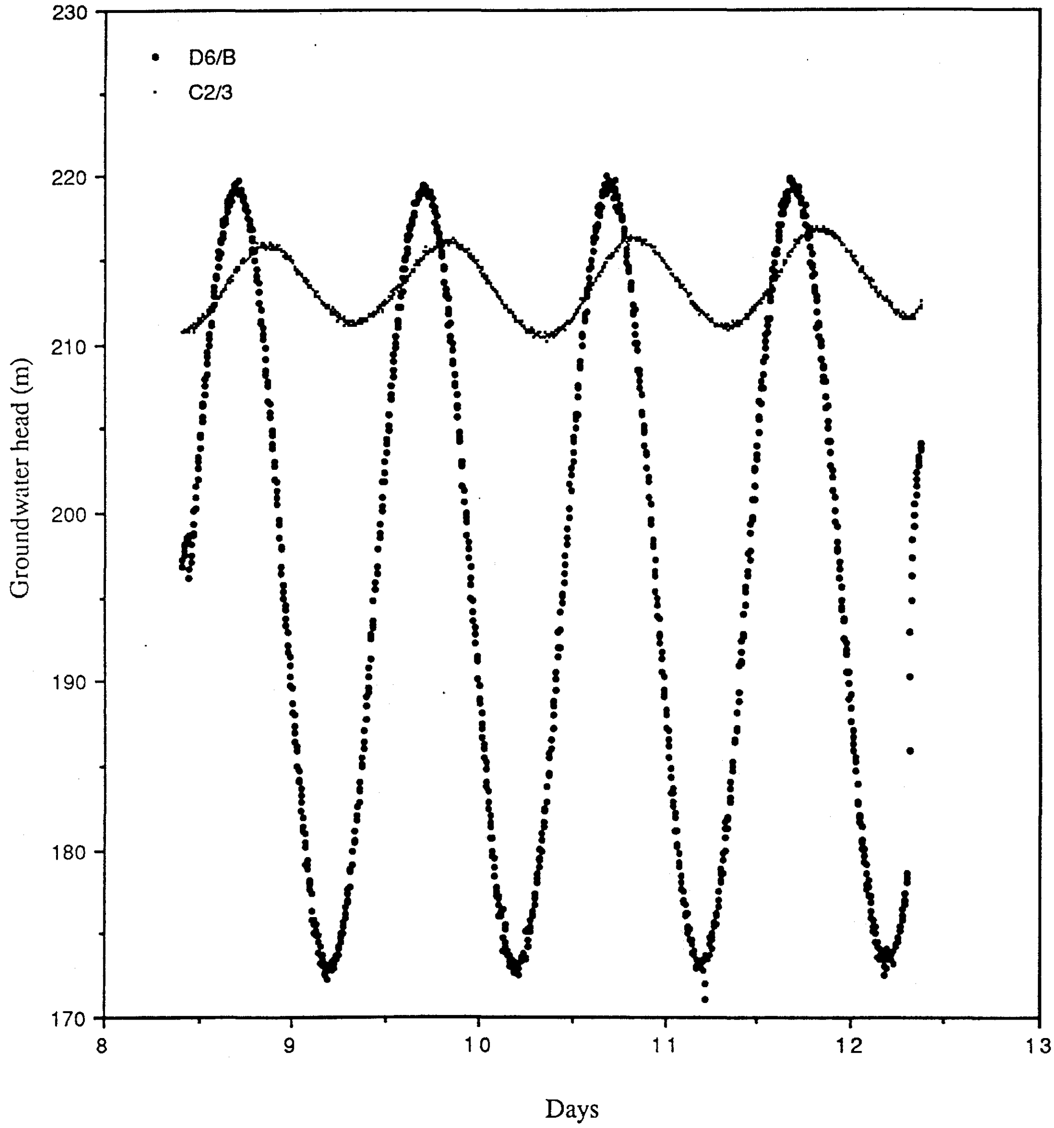


Figure 3-8. Sinusoidal test performed in D6-B and signal received in C2-3.

scanning and the Marquardt algorithm for different values of the dimension. These first interpretations are quite limited being based on the source zone being completely "through flowing" and using direct distances between source and receiver zones. The tests are currently being fully analyzed using realistic estimates of fracture flow area and likely flow paths.

3.1.3.5 Hydrochemical Characterization of the Stripa Groundwater

Background

The objective for the Stage III hydrochemical investigation was to classify groundwater and to determine the different flow paths within the investigated SCV-site by using water analysis from the C and D boreholes. The results from the investigation was compared with Stage I modelling and predictions.

Data from the C and D boreholes have been modelled by using multivariate analysis (MV-analysis). Several or all of the chemical variables in the data matrix are simultaneously examined with this statistical method. Data can be explored, minimized, structured, correlated and classified.

Results and Quality

The most conductive sections in the C and D boreholes, inflow 1 – 510 ml/min, were sampled in connection with the geohydrological and the radar measurements. The chemical components were analysed using ICP, ionchromatography, titrimetric and spectrophotometric methods. The chemical analysis include pH, Na, Ca, K, Mg, Si, Cl, Br, SO_4 and HCO_3. The results of the analysis are presented in Table 3-4.

Table 3-4. The results of the chemical analysis.

Bore-hole	Level m	Water Type	pH	Na (mg/l)	Ca (mg/l)	K (mg/l)	Mg (mg/l)	Si (mg/l)	F (mg/l)	Cl (mg/l)	Br (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	Ion bal %	Flow ml/min	Sampled Zone
D2:1	24.87	B	7.8	71.8	36.6	0.5	0.44	6.0	3.4	143	1.2	1.3	56	-1.70	42	GH
D2:2	25.82	B	7.6	66.7	35.7	0.5	0.53	6.0	3.6	126	1.2	1.3	55	0.53	25	GH
D3:1	26.00	B	7.9	54.8	26.0	0.4	0.27	6.0	3.8	84	0.7	1.4	68	-0.34	34	GH
D3:2	90.51	B	7.6	59.3	25.7	0.3	0.31	5.9	4.3	72	0.6	4.3	79	3.09	22	GB
D4:1	27.02	A	8.2	46.4	20.1	0.6	0.38	6.2	4.2	46	0.4	2.3	85	1.73	43	GH
D4:2	89.77	A	8.5	48.5	13.1	0.3	0.21	6.1	5.1	26	0.2	4.4	101	0.97	43	GB
D5:1	81.75	A	8.4	54.9	17.8	0.2	0.17	6.1	5.0	59	0.5	2.7	78	0.49	17	GB
D5:2*	87.13	A	8.7	47.8	14.4	0.3	0.19	6.2	4.9	30	0.3	3.5	97	24.56	45	GB
D6:1	25.98	B	8.0	66.6	32.7	0.6	0.36	6.1	3.4	118	1.0	1.3	60	0.37	31	GH
D6:2	81.04	A	8.5	55.4	18.1	0.4	0.16	6.2	4.7	59	0.6	2.6	77	1.60	40	GB
D6:3	86.59	A	8.4	49.3	15.5	0.4	0.26	6.2	5.7	38	0.4	4.0	92	-0.47	51	GB
C1:1*	1–39	A	7.8	53.8	5.0	0.3	0.13	0.4		29		17.4	36	19.09	1	GC
C1:2	40–70	A	8.2	51.5	21.4	0.4	0.34	6.0		67		2.7	80	1.27	510	GH
C1:3	71–105	C	7.1	70.3	37.6	0.4	0.22	2.3		168		6.8	17	-1.89	31	GB
C1:4	106–15	C	7.2	71.6	54.8	0.4	0.12	5.5		203		5.2	18	-2.13	11	GI
C2:1	1–70	A	8.1	44.7	17.8	0.3	0.23	5.4		48		1.7	83	2.14	348	GH
C2:2	71–86	C	7.3	74.0	36.5	0.3	0.29	3.5		173		5.0	24	-2.97	50	GB
C2:3	87–124	C	7.1	76.4	36.1	0.6	0.31	1.1		178		5.3	14	-1.84	5	GA
C2:4	125–14	C	6.1	74.4	40.8	0.3	0.27	5.1		188		31.6	29	-9.64	1	GA
C3:1	1–70	A	7.0	40.5	13.8	1.1	1.20	0.3		60		21.2	44	-4.90	39	GH
C3:2*	71–100	A	7.6	38.1	13.2	2.2	1.20	5.0		29		32.3	125	-17.80	13	GH
C4:1*	2–61	A	7.8	41.7	22.1	0.9	2.10	2.4		44		6.6	30	24.97	2	GH
C5:1	1–70	A	8.1	28.4	38.2	2.2	5.90	4.3		49		18.9	113	0.79	14	GH
C5:2	71–140	B	8.1	51.1	39.7	1.5	3.80	4.9		108		11.4	78	-0.23	47	GH

* = poor quality

As a quality criterion for chemical analysis we used the ion balance which should be within +/- 10% for acceptability. The ion balance calculations showed the ratio between anions and cations to be erroneous for the D5:2, C1:1, C3:2 and C4:1 samples. The results from the analysis of these samples should therefore not be used. Based on earlier water data from the area MV-analysis was used to find the reason for the deviation. The errors were found in the sulphate values.

Classification

The MV-analysis showed that C1 and HCO_3 are the only variables needed to classify the waters into three categories suggested by Wikberg et al. (1988). The probability is lower than 1% to classify the samples erroneously by using these two variables. The categories are; shallow (A), mixed (B) and deep groundwater (C). A-type waters have low Cl (<70 mg/L) concentration but a high HCO_3 (>50 mg/L) concentration. In C-type waters the situation is reversed; high Cl (>150 mg/L) concentrations but low HCO_3 (<30 mg/L) concentrations. The B-type (Cl 70–150 mg/L) water is a result from mixing between A and C-type waters.

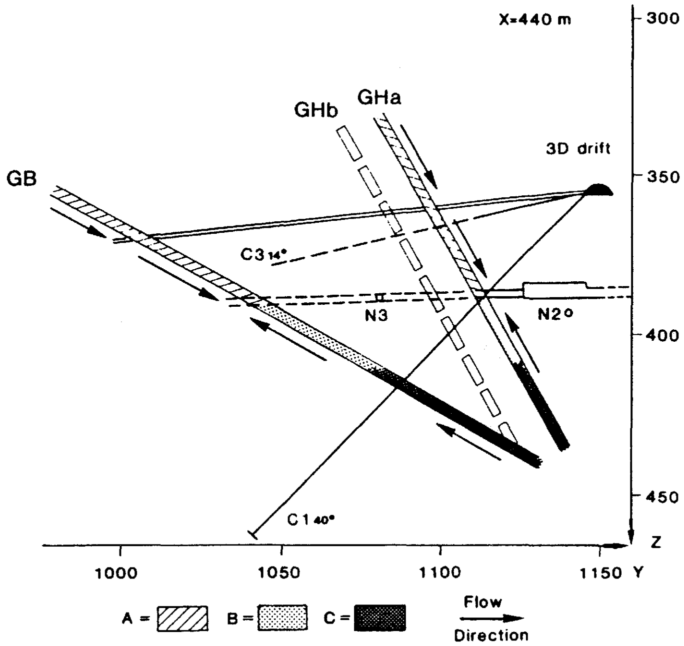


Figure 3-9. The local hydrochemical model of the site with the water types (A, B and C) and the flow directions.

Local Hydrochemical Model

The drainage of the mine results in disturbed hydrochemical conditions. The three water types were found in the important water conductors, the GB and the GH zones. Shallow water (A-type) is flowing downwards while deep groundwater (C-type) is flowing upwards because of the pumping. Where the two water types meet a 30 m thick zone with mixed (B-type) water is formed. The flow directions and water types are presented graphically in Figure 3-9.

Regional Hydrochemical Model

A regional hydrochemical model can be constructed based on the chemical and geohydrological investigations. Shallow water from the top and deep groundwater from below is drawn towards the mine by the pumping. Where these waters meet mixed water is formed. The regional groundwater situation is presented in Figure 3-10.

The models for the hydrochemistry in the SCV-site have been compared with Stage 1 predictions made by Wikberg et al. (1988). The same water types and flow directions were found. The old models were adjusted according to the new findings.

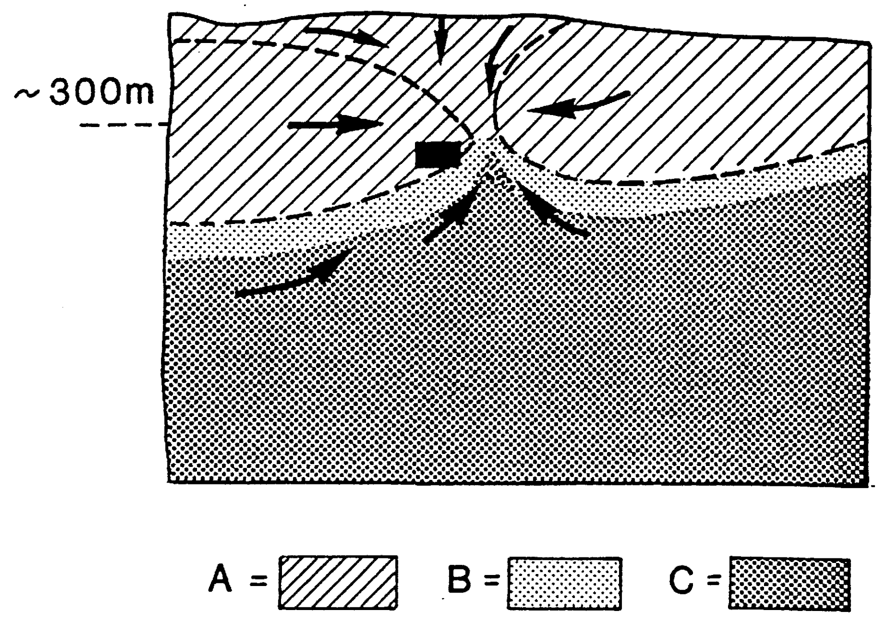


Figure 3-10. The regional model for the hydrochemical situation in the Stripa mine. Shallow water (A) and deep groundwater (C) is drawn to the mine because of the pumping. The mixed water (B) is formed.
(Based on picture 2.10 from Olsson et al., 1989).

3.1.3.6 Characterization of Joints

The joint characterization programme includes strength, roughness and friction characterization of 220 joint samples from the N3, W1 and W2 borehole cores and an in-situ coupled stress and flow "block" test by NGI on a 1 m by 1 m fracture plane at the end of the 3-D drift, and coupled stress and flow tests on fracture planes in 200 mm diameter cores, two by NGI and three by Memorial University of Nfld and three fracture replicas by the University of Luleå. Additional in-situ stress measurements have been performed in three boreholes close to the SCV block and 3-D numerical stress modelling has been conducted by JAA AB, Luleå.

Figure 3-11 (McKinnon, 1990) compares the stress measurements in the SCV programme with earlier measurements in the same area. These measurements indicate that the principal stresses measured in the area of the Validation Drift are reasonably consistent with the earlier measurements in V3 and SBH-4. These measured stresses have provided the boundary conditions for the 3-D numerical simulations of the stresses in the SCV block. The effects of the Validation Drift excavation on joint apertures will be investigated by two-dimensional discrete element (UDEC-88) modelling incorporating the A and C joints that strike sub-parallel to the drift. Elastic stress distribution from the 3-D modelling will be used to predict possible changes in aperture of the joints in set B which strike approximately perpendicular to the Validation Drift.

The coupled stress and flow in-situ and laboratory tests were designed to provide empirical data on the stress-aperture-permeability relationship for the joints in the SCV block. The fracture planes in all of the laboratory tests and in the in-situ "block" test represented planar, mineralized, joints. The fracture plane in the in-situ "block" test (Figure 3-12) was loaded by flatjacks to a peak normal stress of 10 MPa. With repeated loading cycles the fracture aperture was reduced below

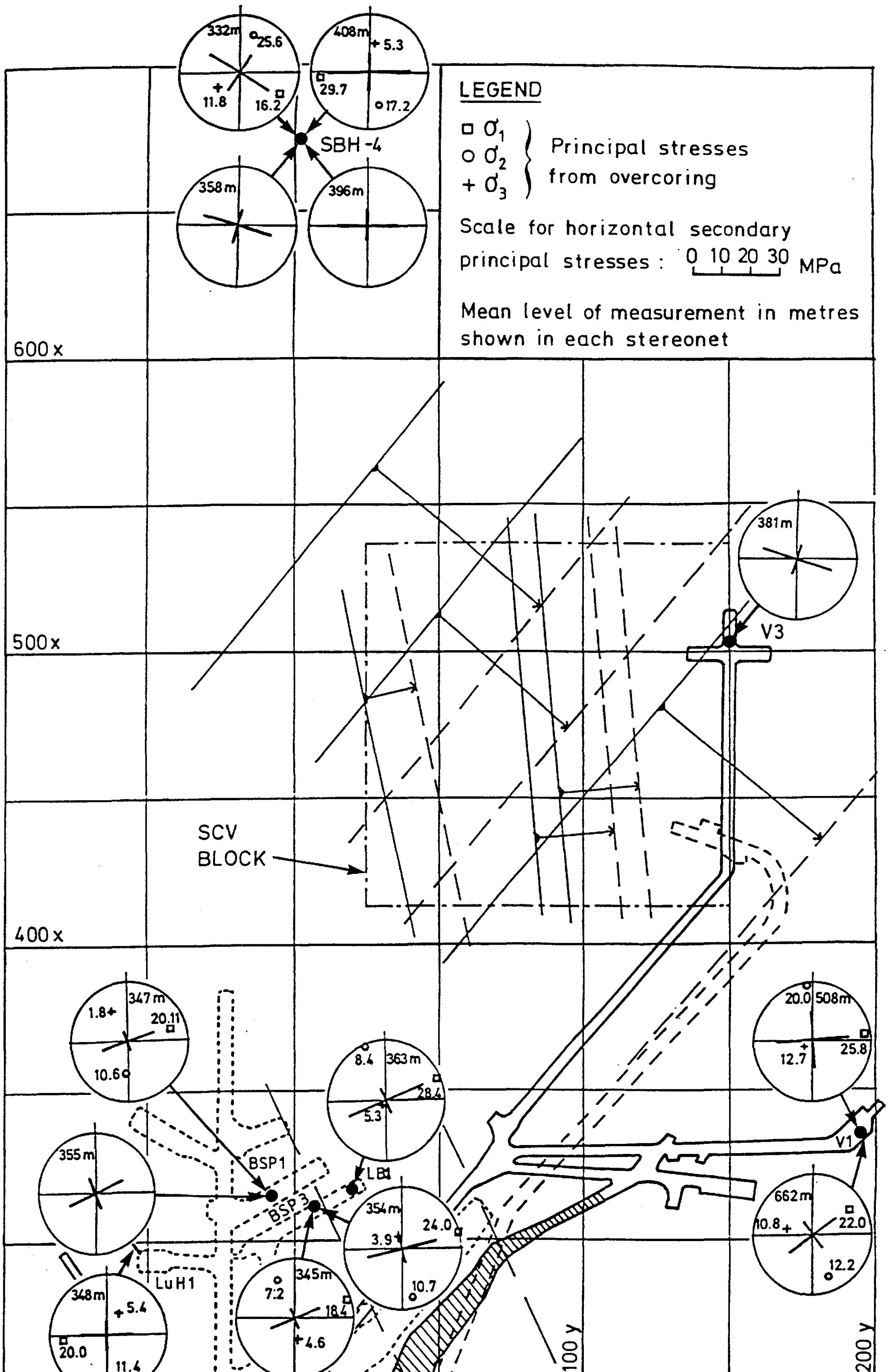


Figure 3-11. Summary of results from stress measurements performed at the Stripa Mine.

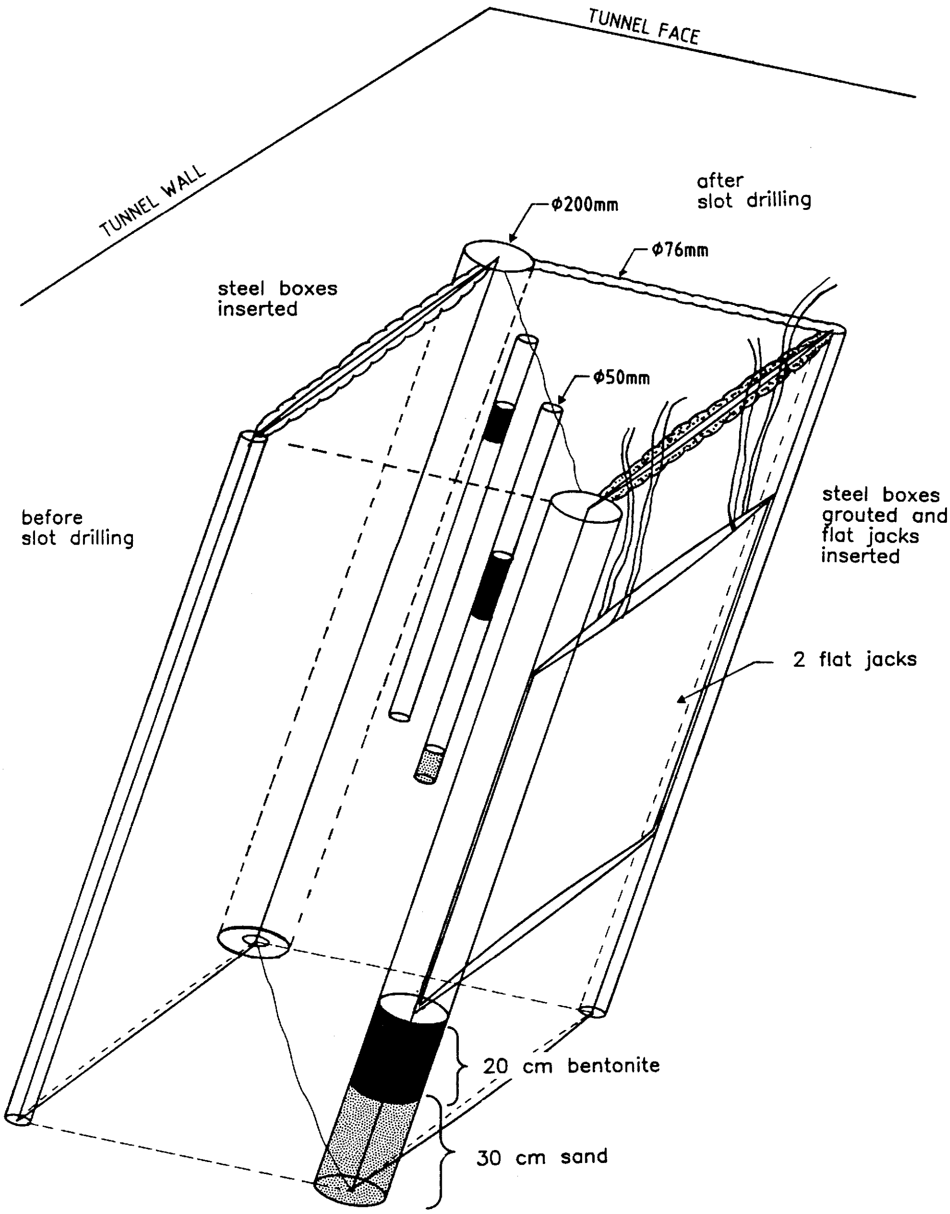


Figure 3-12. Schematic view of the in-situ block test performed in the Stripa Mine.

the flow detection limit and did not open even under shear displacement (Makurat et al., 1990).

The two core samples tested at NGI were subjected to three normal stress cycles to 25 MPa with simultaneous flow measurements in a biaxial shear apparatus. Each sample was sheared beyond peak shear strength on the fourth loading cycle and changes in flowrate and aperture were measured (Makurat et al., 1990). Both fractures showed significant reductions in permeability with increases in normal stress and increases in flowrate under initial shear displacement. Dilation during initial shearing increased with increase in joint roughness, but each sample showed joint closure with increase in shear displacement.

Two of the three 200 mm diameter core samples tested at Memorial University (Gale et al., 1990) were subjected to three normal stress cycles, to 8 MPa, and two shear stress cycles on a fourth normal loading cycle; at 4 MPa and 8 MPa normal

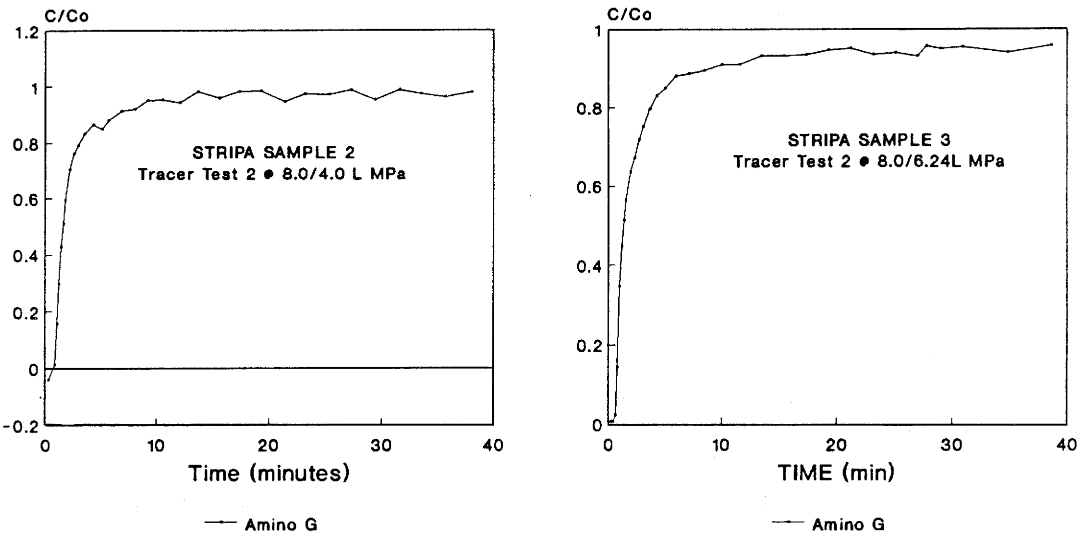


Figure 3-13. Breakthrough curves for tracer tests at peak shear stress.

stress, respectively, with the shearing forces directed along the length of the sample using a biaxial shear apparatus. Permeability tests, both parallel and perpendicular to the direction of shearing, with rectangular flow boundary conditions were conducted simultaneously with loading. Tracer tests (Figure 3-13) were completed at the maximum normal stress condition during the final shear cycle for both zero shear and peak shear stress conditions. Once the peak shear stress condition was reached for a given sample and the final tracer test completed, the fluid was removed from the fracture plane and while maintaining the shear and normal loads, a low viscosity, room temperature curing, resin was injected into the fracture plane. Once the resin solidified, the sample was sectioned perpendicular to the fracture plane and the resin filled fracture cross-section photographed and digitized.

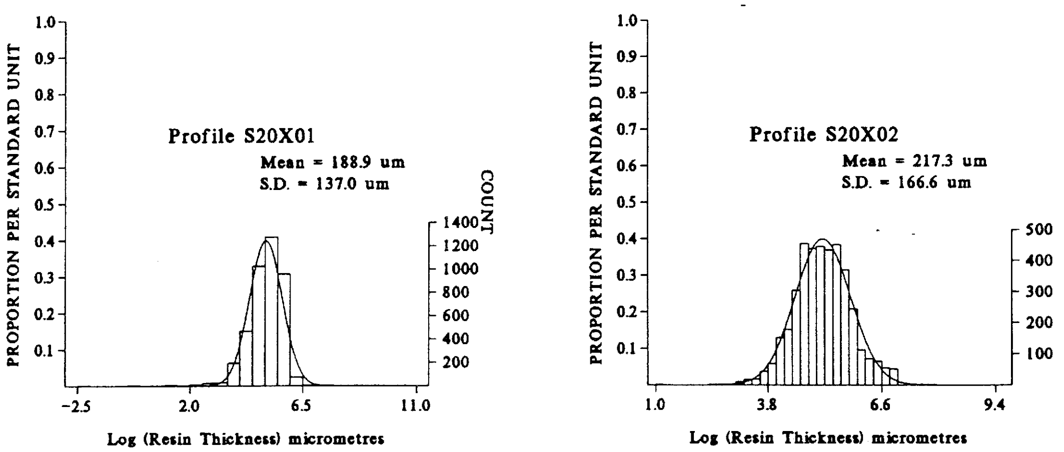


Figure 3-14. Frequency histograms of resin thickness for two profiles from sample number 2.

The natural log of the resin thickness for two typical profiles through one of the fracture planes (Figure 3-14) and a normal curve has been superimposed on each histogram. The degree of fit suggests that the resin thicknesses are well approximated by a log normal distribution or model. The mean resin thickness is approximately five to ten times the hydraulic aperture computed from the flow tests. In addition, the computed travel times are five to ten times the measured travel times as determined from the solute breakthrough curves. This aperture agrees very well with the aperture distribution model determined from the fracture replica study (Hakami, 1989).

3.1.3.7 Radar/saline Tracer Experiment

The objective of the radar/saline tracer test is to provide data on the geometry of flow paths from an injection point in fracture zone GH. The flow paths will be monitored through difference tomography.

The geometry of the radar/saline tracer experiment is illustrated in Figure 3-15. The saline tracer was injected in borehole C2 where it intersects zone GH. The D-holes were used as a hydraulic sink and the tracer concentration was moni-

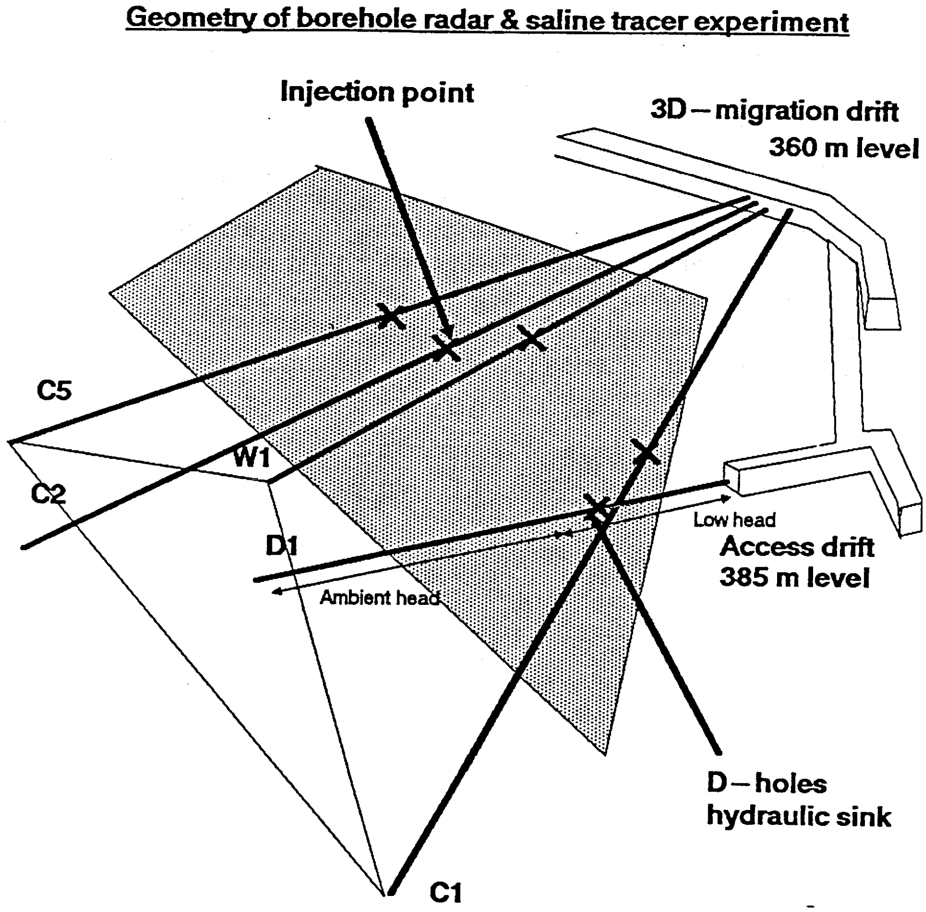


Figure 3-15. Geometry of the saline injection and radar monitoring experiment. Injection will be made in feature GH where it intersects borehole C2. Data on saline tracer distribution will be obtained in the C1-C5, W1-C1, and W1-C5 planes.

tored in the D-boreholes as a function of time. Radar measurements were made in the boreholes W1, C1, and C5. Measurements were made between these boreholes in pairs to produce tomograms for the three planes between the boreholes, i.e. the sections W1-C5, C1-C5, and W1-C1 indicated in the figure. The tomographic measurements were made at regular time intervals to get data on the spreading of the tracer with time. The radar data will show the distribution of tracer in the three measured planes.

The injection of saline tracer was performed as a continuous injection with constant flow rate. Potassium Bromide (KBr) with a concentration of 2% was injected into Zone H through borehole C2. The injection interval in C2 was 55–70 m borehole length.

The injection and recovery of tracer may be divided into three phases:

Phase 1: Injection in C2 with 165 m head in the D-holes. (0 – 362 h)
Phase 2: Injection in C2 with 0 m head in D-holes. (362 – 675 h)
Phase 3: Recovery in C2 and D-holes. (675 – 816 h)

The injection during phase 1 was made during 362 hours in order to be able to study the spreading of the saline tracer with time. The D-holes were then opened for 313 hours in order to simulate the presence of the open Validation drift and finally in phase 3 also the injection interval in C2 was opened in order to recover as much as possible of the saline tracer injected.

Tracer first arrival in the D-holes was observed after 8 hours of elapsed time. Then the concentration in the total flow from the D-holes increased to C/Co=0.34 until the head in the D-holes was set to 0 m at 362 hours of injection. The concentration then rapidly decreased to C/Co=0.20 and became almost constant between 500–675 hours of elapsed time (Figure 3-16). This indicates that

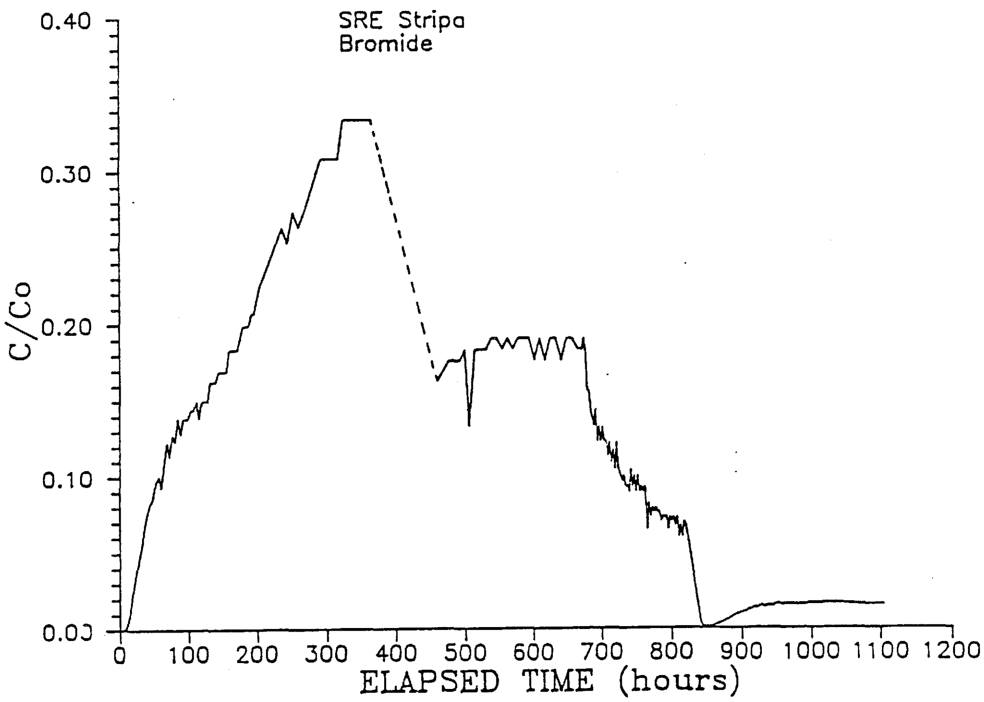


Figure 3-16. Bromide concentration as a function of time during the radar/saline tracer experiment. The head in the D-boreholes was kept at 165 m until 362 h when it was lowered to 0 m.

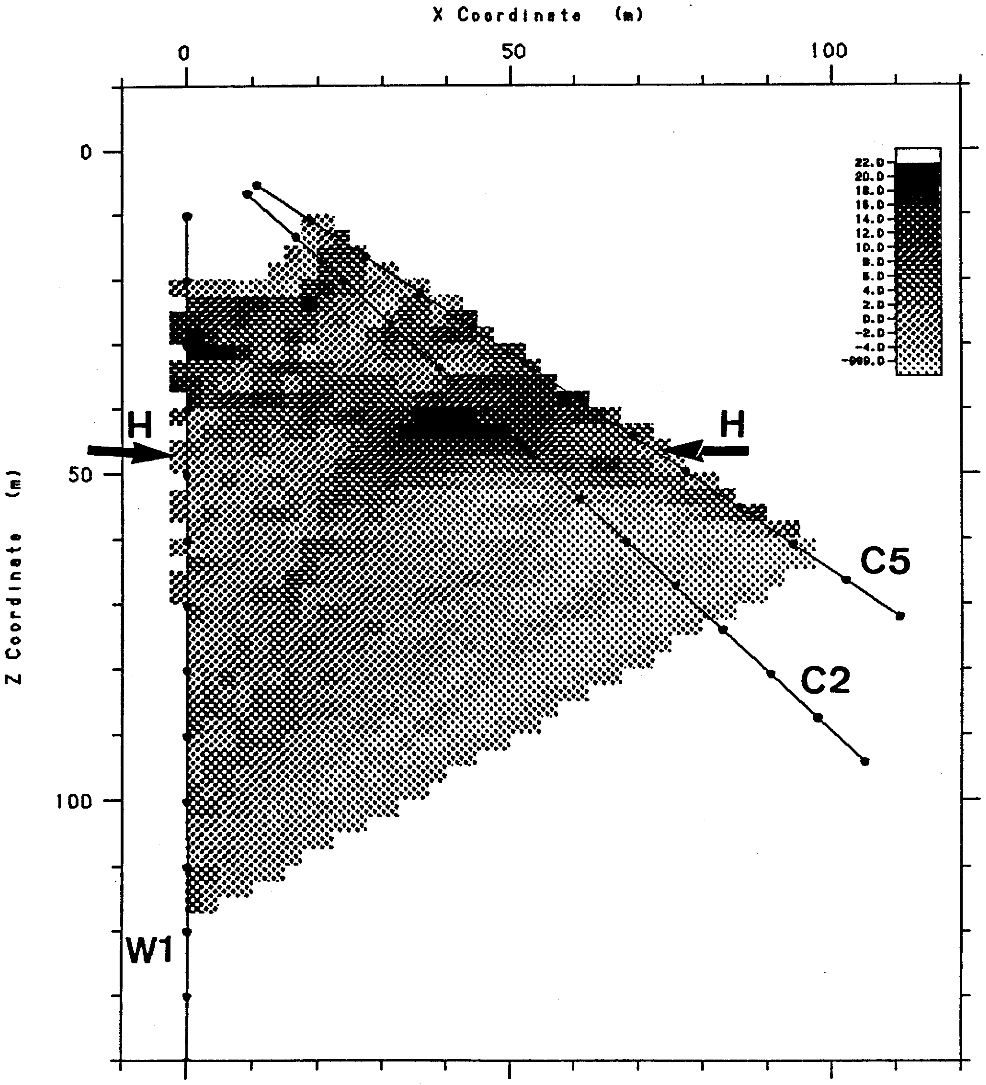


Figure 3-17. Differential attenuation tomogram for the section W1-C5 recorded 12 days after start of injection of saline tracer. Dark areas indicate presence of saline tracer.

steady state conditions regarding flow and head had been reached much faster than during phase 1 of the injection. The reason for this might be that the flow paths are much more narrow during phase 2 due to the large head difference between injection and detection boreholes. No tracer was registered in Zone B.

The radar measurements were made with 60 MHz antennas (wavelength approximately 2 m) to get good resolution. For most of the measurements the transmitter and receiver were moved in the depth interval 20 to 116 m of the boreholes with a separation of measurement points of 4 m. The time required to measure each section was approximately 6 hours. In the beginning of the experiment measurements were made with as short time intervals between sections as possible. The time between measurements was then successively increased.

In total 7 repeat measurements were made and analysis of the data is in progress.

A sample differential tomogram is shown from section W1-C5 which is closest to the injection point. The tomogram shown (Figure 3-17) is from the fifth repetition measurement made 12 days after the start of the saline tracer injection. The tion measurement made 12 days after the start of the saline tracer injection. The largest increase in radar attenuation, which indicates presence of saline tracer, can be observed close to the injection point. Borehole C2, from where the injection was made, is projected into the tomographic plane. Spreading of tracer from the injection point along zone GH can be observed. Minor amounts of tracer also appears to spread into fractures intersecting zone H.

3.1.4 References

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3.2 DEVELOPMENT OF HIGH RESOLUTION AND DIRECTIONAL RADAR

3.2.1 Previous Work

The RAMAC borehole radar was developed within the Stripa Project and has been used since 1985 to locate fracture zones in rock. Zones are clearly seen in the radar maps and can often be traced over large distances. During the work in Stripa several different measurement techniques have been tested (single borehole measurement, crosshole measurements, tomography) and they have been compared in detail with other methods such as borehole seismics, geophysical logging, etc.

Most methods agree concerning the position of fracture zones, but each method can also add some independent information about the site. This is particularly important since a measurement performed with dipole antennas in a single borehole can not determine the location of a fracture zone completely. The reason is that the antennas radiate and receive radar pulses symmetrically with respect to the borehole. There is thus no information about the azimuth of a reflector, though one can determine the range to a reflector accurately.

In order to orientate a reflector one must combine data from different measurements. This is often quite difficult since it must be shown that reflections seen in different radar maps are caused by the same reflector. The directional antenna has been designed to solve this problem, which is particularly troublesome at sites where there is only one borehole or where the boreholes are too far apart to allow crosshole measurements. Tests in Stripa have verified that the directional antenna can determine the position and the orientation of a reflector from measurements a single borehole. The directional antennas are also broadbrand in frequency and the pulses smooth with little ringing, which is essential for a correct interpretation of the data.

3.2.2 Processing of Directional Radar Data

Directional signals are synthesized from a set of antenna measurements and considerable effort has been devoted to the interpretation and calibration of the data, which can now be performed in the field.

A simple method used during the initial tests is to calculate a series of radar maps equivalent to different orientations of an ideal directional antenna placed in the borehole. When such pictures are printed in steps of 10° is fairly easy to determine the direction to a minimum of a reflector (the maxima provide a less accurate determination of the azimuth). The antenna resolution was determined in this way by comparing radar maps rotated in even smaller steps: for prominent fracture zones the accuracy is about $\pm 3°$ depending on the background.

It is a definite drawback that the greyscale of printed maps is fixed since much of the amplitude information will then remain hidden from the observer. For this reason the radar maps are also displayed on a computer screen where the plot levels can be changed easily. The viewer may rotate the antenna continuously and determine the direction to a minimum in real time.

Figure 3-18 shows the screen near the maximum of a steep reflector indicated by the arrow. By turning 90° one can extinguish this reflector almost completely as shown in Figure 3-19. The strong reflector now seen near the arrow is new fracture zone, which would seem very close in a dipole radar map, but is in fact almost 90° away from the first zone.

The methods described above rely heavily on the eye, which must identify reflectors in the clutter caused by other scatterers. Fortunately the human eye is an unsurpassed line indicator, but it was still decided to develop an automatic routine for determining the position to a reflector, because it can provide a quantitative measure of the strength of a reflector.

A reflector is a line consisting of a sequence of pulses. This line can be detected by computing the gradient of the amplitude, which is a vector at right angles to the line. The gradient is, however, only useful if the area contains **one** reflector. The observer is thus asked to define an area around the reflector shown by the black area in Figure 3-20. The program will then calculate the direction of the line as well as the contrast between the line and the background.

This type of analysis is useful for all radar maps, but it is particularly convenient for a directional antenna, since the computer has all the directional data available and one can thus locate the minimum automatically. As shown in Figure 3-20 the contrast is listed for arbitrary rotation angles. The minimum of this function agrees well with that obtained by eye in Figures 3-18 and 3-19.

Data from the SCV site was analyzed using both types of processing. Figure 3-21 shows the azimuth of zone H measured from different boreholes. The amount of intersection between the curves is typical for directional analysis: it is slightly

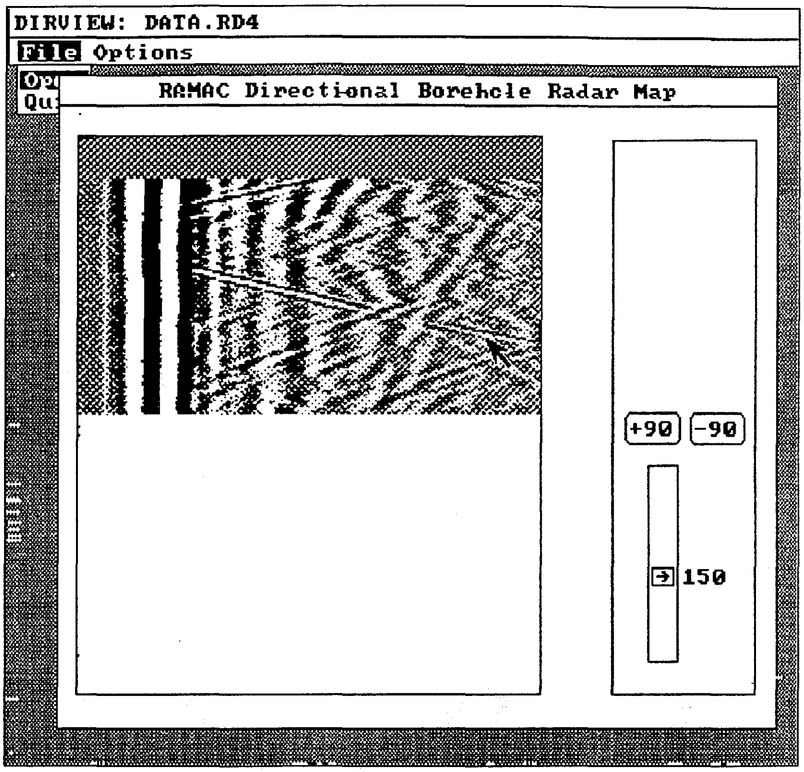


Figure 3-18. A reflection maximum from a fracture zone observed at azimuth 150° during analysis.

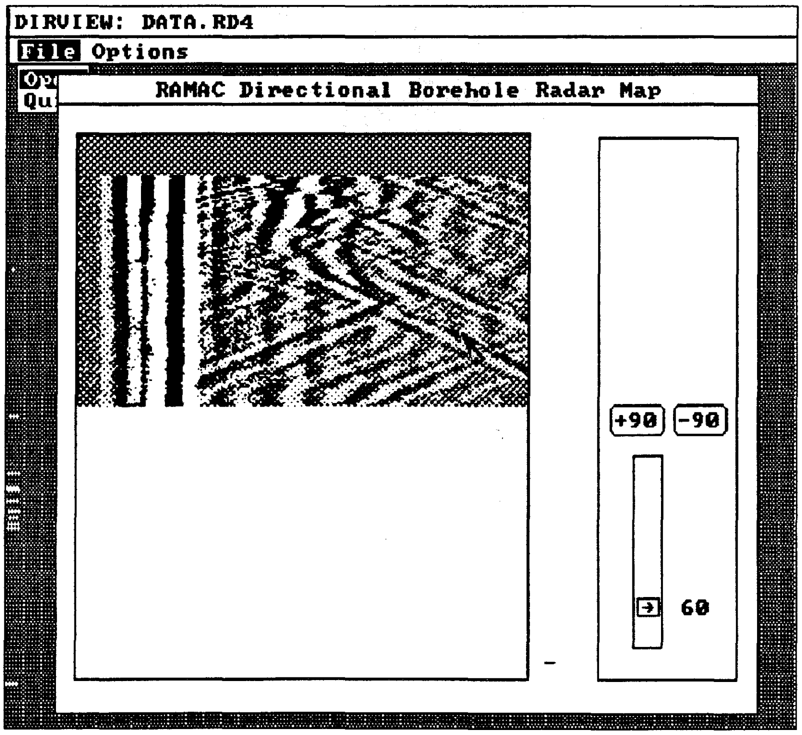
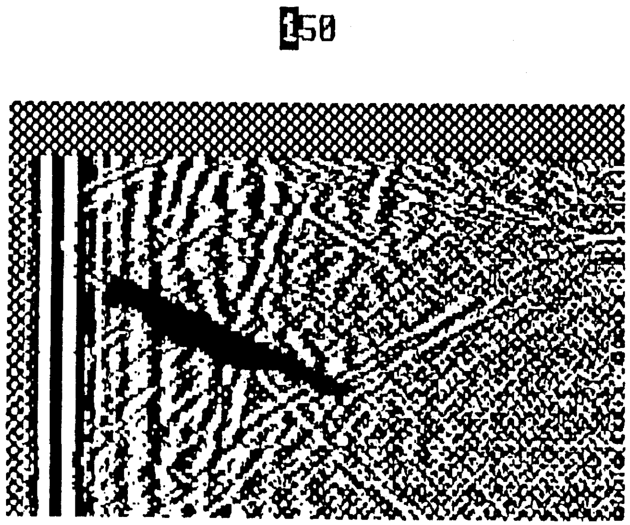
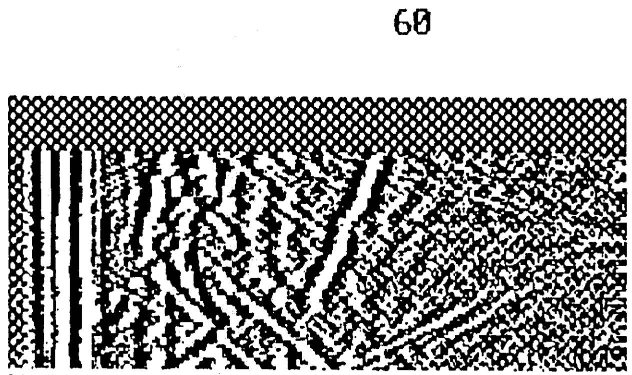


Figure 3-19. The minimum at 60°. A new zone is now seen close to the arrow.





ANGLE= 0	THETA=	68.404	CONTRAST=0.662
ANGLE= 15	THETA=	67.579	CONTRAST=0.620
ANGLE= 30	THETA=	65.648	CONTRAST=0.532
ANGLE= 45	THETA=	62.213	CONTRAST=0.417
ANGLE= 60	THETA=	62.942	CONTRAST=0.416
ANGLE= 75	THETA=	66.319	CONTRAST=0.516
ANGLE= 90	THETA=	67.925	CONTRAST=0.596
ANGLE= 105	THETA=	68.587	CONTRAST=0.641
ANGLE= 120	THETA=	68.869	CONTRAST=0.667
ANGLE= 135	THETA=	68.966	CONTRAST=0.680
ANGLE= 150	THETA=	68.937	CONTRAST=0.685
ANGLE= 165	THETA=	68.777	CONTRAST=0.680
ANGLE= 180	THETA=	68.405	CONTRAST=0.662

Figure 3-20. Automatic search for fracture zones in the selected (black) area. A maximum contrast is obtained near 150°.

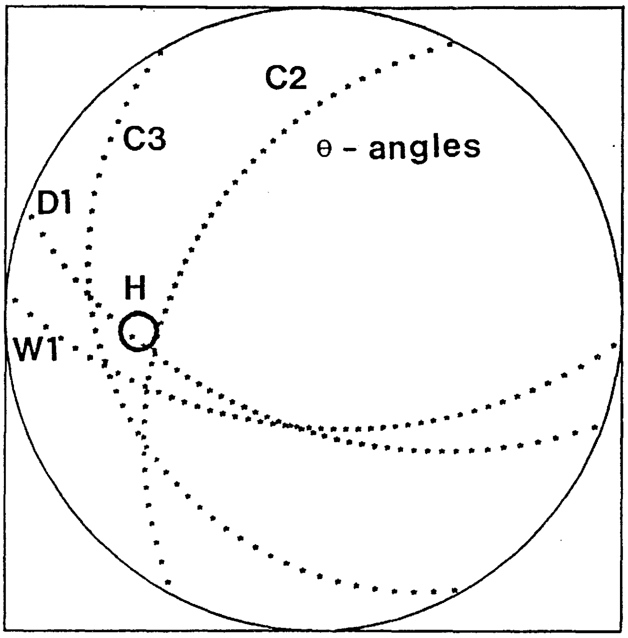


Figure 3-21. The azimuth of the H zone measured from four boreholes with the directional antenna at the SCV site in Stripa.

less accurate than the intersection angles but this does not matter much. The important point is that the antenna has delivered orientation data which was previously unavailable during the Stripa Project.

3.2.3 Theoretical Analysis of the Directional Antenna

The antenna has been analyzed and optimized using a simple transmission line model. A directional antenna is necessarily inefficient, but this turns out to be less important than thought because of the good quality of the pulse which is almost free from ringing. As a result the reflected pulses are simple to interpret and the directional radar pictures provide more information than expected considering the loss in range compared with standard dipole antennas. The antenna has also been analyzed to optimize the bandwidth and the shape of the radiation loobs.

The function of the antenna depends critically on its symmetry and the effect of deviations from cylindrical symmetry must be calculated. The antenna will in general be placed excentrically in a waterfilled borehole, but it can be shown that its performance will not be affected unless the water is very conductive. Similar calculations have been performed for the antenna structure as a whole. Calibration procedures were developed to check the antenna before measurements. Figure 3-22 shows how similar the antenna ports are: the directional signals measured by four ports are almost identical except for sign.

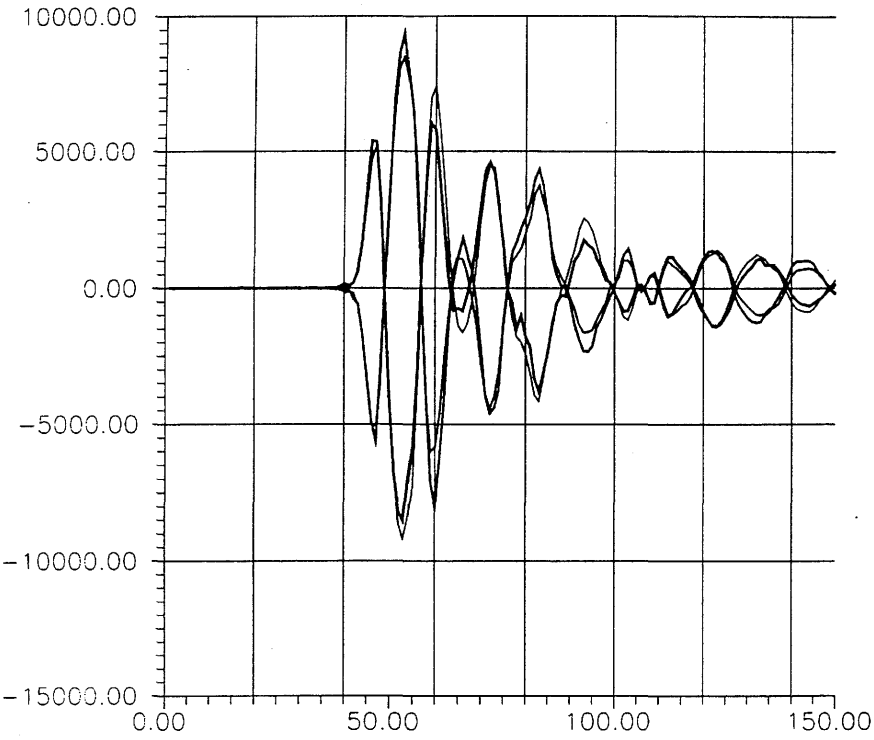


Figure 3-22. Directional signals from four antenna ports obtained during calibration.

3.3 IMPROVEMENT OF TECHNIQUES FOR HIGH RESOLUTION BOREHOLE SEISMICS

3.3.1 Scope of the Work

The role of seismics in the characterization of a repository site is to describe by remote sensing the pattern of discontinuities in the rockmass. However, the importance of the rock features which must be described is evaluated finally in terms of potential nuclide transport, outside the scope of seismics. Therefore, the seismic acquisition apparatus must be able to detect also rock features, possibly relevant for the site characterization in general, but with very low seismic response. The obvious missing component of such an acquisition system has been – at least at the beginning of this research programme – a specialized seismic source.

In parallel with the development of the acquisition apparatus, efforts have been put into enhancing the seismic response of the rock structure by computer processing. Here it must be kept in mind that the site has to be described as a three-dimensional volume.

During the year 1989, the different aspects of the work were merged into a complete technique. The SCV site provided the occasion for a full scale test where all the modules of the technique could be used in their logical sequence. A large number of measurements were performed with the new coherent source and the PC based acquisition system. The processing was done for both reflection analysis and tomography. The tomographic method has been described in earlier Stripa reports. The most significant development during the past year occured in the field of reflection analysis of crystalline rock data.

3.3.2 Techniques for 3-D Seismic Reflection Studies

The seismic acquisition apparatus has not been subject to major changes during the past year. It is worth reminding that the source emits coherent bursts of high frequency and the detectors are triaxial. Both the source and receiver probes are designed to operate in boreholes. The 6 kHz signals used for these tests have the very important advantage of practically annihilating the diffraction phenomena. A less desirable effect is that the wavelength of the tubewaves at this frequency is less than 0.25 m. To avoid aliasing in two-dimensional filtering procedures, a demodulation routine based on the Hilbert Transform has been applied. The envelopes thus obtained for each of the three components were combined in a total amplitude function and then only the slowly varying part of the phase was used to reconstruct low frequency signals. The effect of demodulation is exemplified in Figures 3-23 and 3-24. The result is that we can benefit from the original high frequency content of the signals to avoid diffraction phenomena and in the same time we can use a reasonable detector (or source point) spacing without inducing aliasing artifacts.

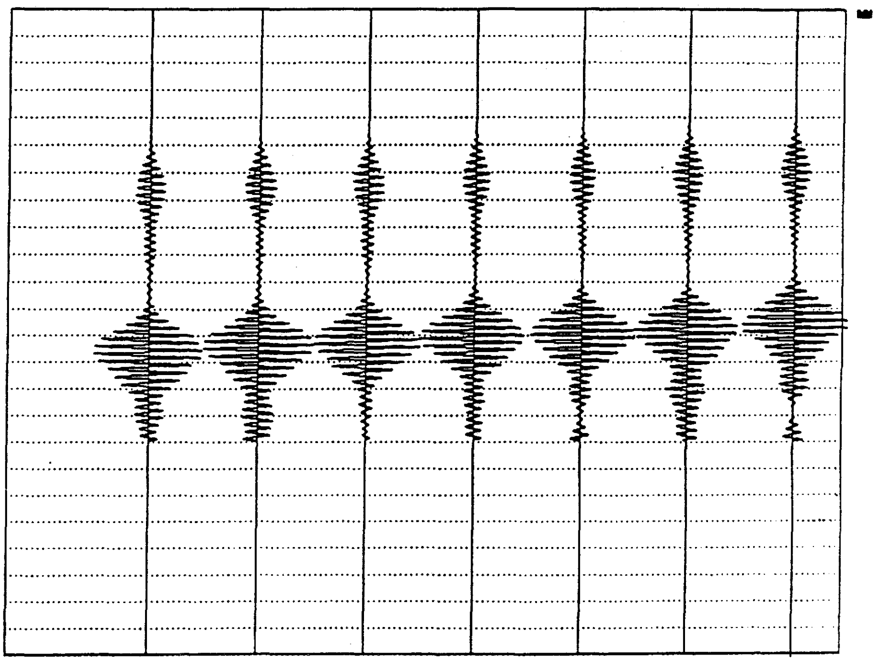


Figure 3-23. Sample of original high frequency data.

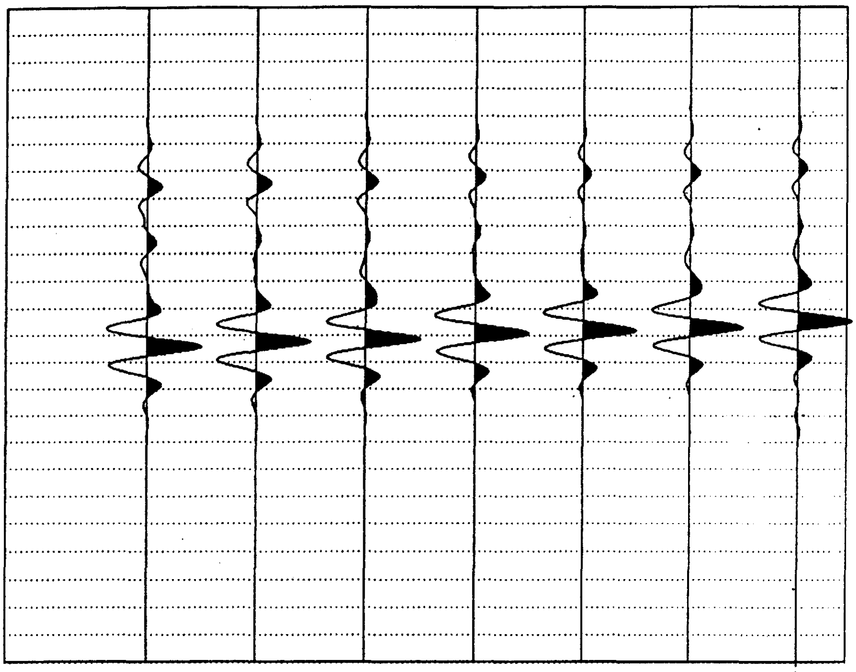


Figure 3-24. The effect of demodulation applied to Figure 3-23 is the decrease of the frequency.

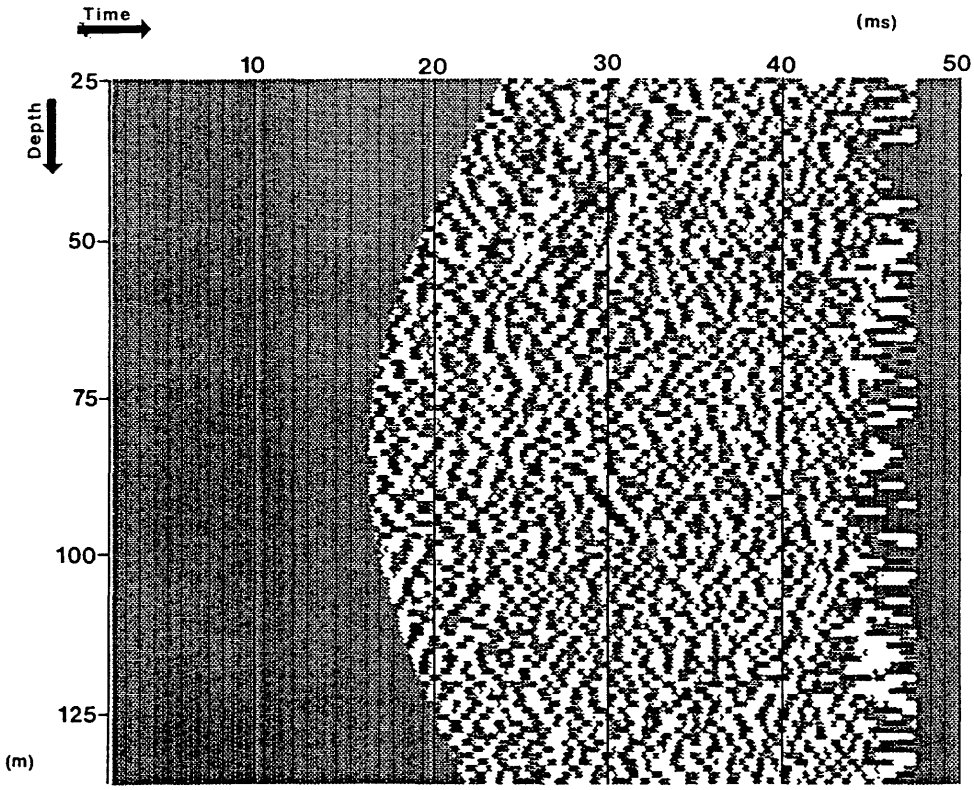


Figure 3-25. Reflection profile after removing tubewaves and direct arrivals by median techniques.

An efficient way to eliminate tubewaves is a procedure implying median filtering on the variable slant corresponding to their velocity. Because tubewaves are generated in and travel along the hole, their apparent and real velocity are the same giving straight patterns in the profile. The direct P- and S-waves can be removed in a similar way, with the exception that the trajectory along which median filtering is done is not straight, but follows the true travel time curve.

The data set after median filtering is seen in Figure 3-25. Because the following processing steps are applied to S-waves the signals are put to zero before the direct S-arrival.

A conclusion which can be drawn from examining Figure 3-25 is that reflection patterns cannot be readily identified by looking for larger signal amplitudes. The complicated reflection response of the crystalline rock demands further processing to extract the information contained in the phase of the signals. In other words, one has to look for the continuity of reflection patterns over several traces.

Image Space processing is a new technique, which we have developed for filtering and interpretation of reflection data. It is based on an integral transform from the timedepth domain, common for displaying seismic profiles, into a new domain called Image Space. Briefly said, the procedure consists of summing data in the original section along paths which may represent physically possible reflection events. The result of the sum is placed in the transformed section in the position corresponding to the image point of the reflector; the image point is the mirror image of the source with respect to the plane of the reflector. In the transformed profile reflected events are emphasized because during transformation only true P-wave reflections stack properly. The procedure has therefore a filtering effect.

Because the amplitudes will be high in those parts of Image Space which correspond to existing reflectors, the local maxima of the transformed section will tell us the positions of the probable reflectors. As seen in Figure 3-26, reflectors are much easier to identify in Image Space than in the original representation.

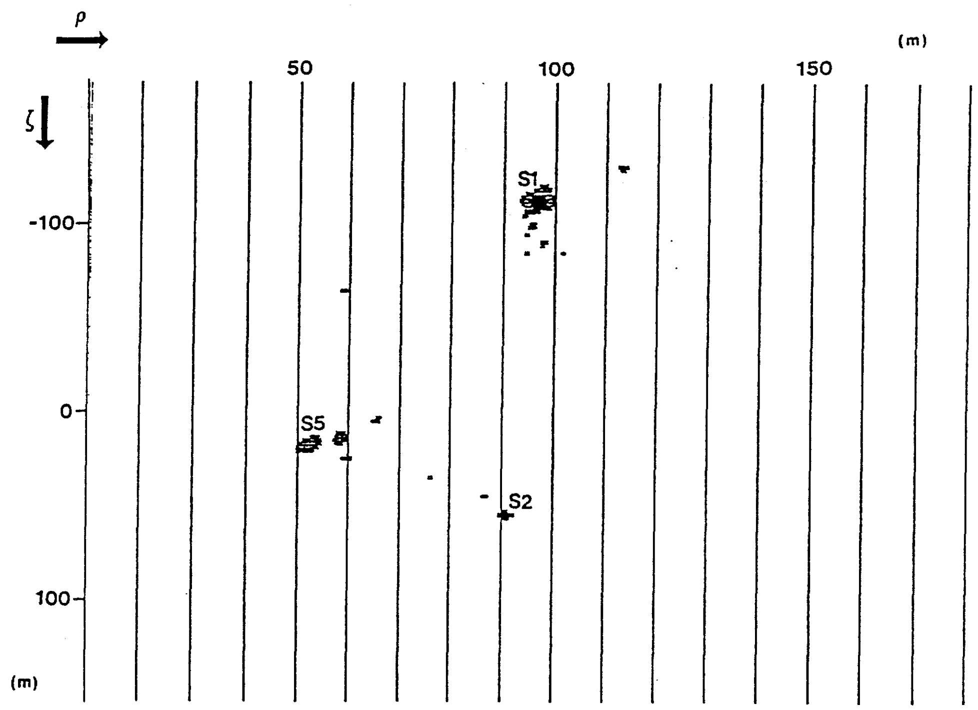


Figure 3-26. Image Space transform of the profile from Figure 3-25 after removing the noise.

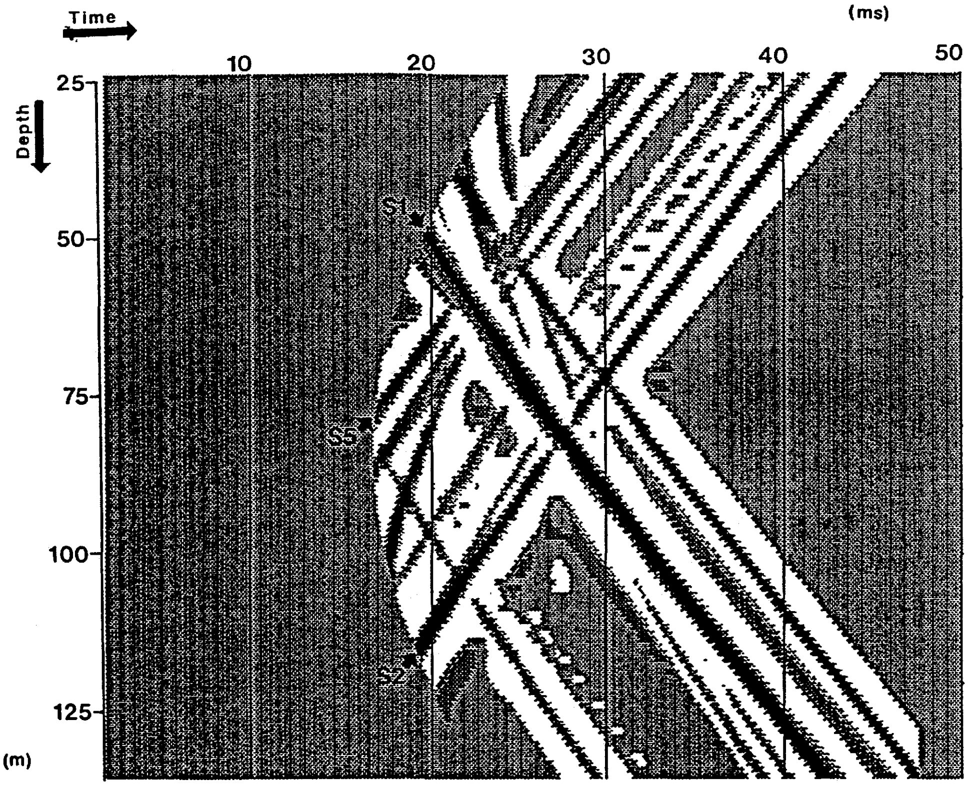


Figure 3-27. Retransformation in the original space of the profile from Figure 3-25 after noise filtering in Image Space. Only most prominent reflectors remain in the picture.

One can perform an inverse transform from Image Space back to Data Space by using a nonlinear algorithm which will emphasize the continuity of events with high amplitude in Image Space. The profile retransformed in this manner is shown in Figure 3-27.

The same reflector observed in sections with different source offsets will produce large amplitude values in the corresponding points of Image Space, but, due to the different view angle from each shotpoint, the images are situated in different parts of Image Space for different source positions. To create a global "map" of the reflector, we first have to modify the individual Image Space sections into such a form that the data from different shot points are comparable. By combining these modified Image Space transforms from all profiles, it is possible to calculate the 3-D orientation of the reflectors which are consistently appearing in several profiles.

3.4 FRACTURE NETWORK MODELLING

3.4.1 General

One of the objectives of Phase III of the Stripa Project is to develop an improved understanding of groundwater flow and radionuclide transport through hard fractured rock. In such rocks, groundwater flows primarily through a network of connected fractures, and it is not clear that these flows can be fully explained using models based on continuum approximations such as Darcy's law. In this project we are developing more direct models of such flow systems, numerically generating fracture networks which exhibit the same statistical properties as those measured in the rock. We are incorporating this approach in the NAPSAC computer code, and we aim to show that this approach is valid and feasible. It must improve our understanding of flow in the Phase III site at Stripa mine, and it must be generally applicable at other fractured rock sites.

In this report we outline the progress we have made towards these goals, and describe current developments of the NAPSAC computer code. Our major achievement has been the successful 'double-blind' prediction of inflows into the D-hole experiment at Stripa. This prediction was based on an integrated modelling approach using both fracture network models on a small scale, and equivalent porous medium models on larger scales. The successful prediction of fluxes is a first step in the demonstration of our understanding. We next describe how the NAPSAC code is being developed to enable us to predict groundwater velocities through the fracture network and eventually to simulate tracer transport.

We conclude this chapter by describing the complementary work being undertaken by modelling teams funded by the US DoE. At LBL, Jane Long is leading a team that is applying our approach and concentrating on modelling major flow paths associated with 'fracture zones'. Bill Dershowitz, at Golder Associates, uses a fracture network approach similar to that used by Harwell, but has been applying these models over a larger scale. His work aims to describe flows through the Phase III site entirely in terms of his fracture network model.

3.4.2 Modelling the D-hole Experiment

The D-hole experiment simulates the flow field due to an open drift through the centre of the Phase III site. This is achieved by drilling an array of six boreholes around on the circumference of the proposed drift. These are depressurized and the groundwater flux to short intervals of each borehole is measured. This experiment represents the simplest test of our approach; we predict only mass flux, not velocities; the flow field is relatively straightforward; and we do not have to account for the effect of a disturbed zone such as one would have near an excavated drift. Nevertheless, we are making a 'double-blind' direct prediction with no calibration of our model. It was a challenging first step towards validating the feasibility of our approach.

3.4.2.1 Network Permeability Models

We first generated representative networks exhibiting the fracture statistics observed in the S.C.V. site. This is not a trivial task since the raw data contains many biases. The data must be interpreted, and a number of simple models were used to infer probability distributions for three distinct fracture sets. In particular, John Gale used a sophisticated statistical package to identify clusters in the orientation data and thereby define the fracture sets; we developed a computer model to determine a maximum likelihood estimator for the parameters of a log-normal effective transmissivity distribution, and derived analytical tools to correct the biases and infer fracture-length distributions from trace-length measurements. The results of our fracture-network modelling showed a surprisingly small representative volume for flux predictions through the network. The predicted permeability for a typical cube of fractured rock was relatively insensitive to the scale of the model for cubes larger than 8 m. Smaller models resulted in conductivities that were strongly dependent upon details of each particular realisation of the network. We concluded that for flux predictions on a scale larger than about

10 m, at Stripa, the most appropriate model would be one using a continuum approximation; whereas for more detailed predictions a stochastic fracture network model should be used. This is a strong conclusion.

3.4.2.2 Regional Flow Modelling

When making predictions of the flux to the D-hole experiment, we need to apply boundary conditions to our model of the S.C.V. site and we know that the pressure field will be disturbed by the experiment over a region larger than this. John Gale has therefore developed three-dimensional finite-element, equivalent-porous-medium models of the Stripa mine region that account for all the major hydraulic features of the mine and nearby surface topography. The largest scale models extend over an area of 9 km by 12 km and account for the basic geology and flow boundaries of the Stripa mine region. A sub-model simulating a 4 km square region incorporates depth-dependent permeabilities calibrated from measurements in the surface boreholes, and also includes large fracture zones in the mine with enhanced permeabilities. This model gave an accurate representation of the head field within the mine region and predicted a total inflow of water to the mine of 500 litres/minute. This is in good agreement with the average mine discharge and this model provides the regional flow field used in models of flow through the mine.

To determine the boundary conditions for our predictive model of flow to the D-boreholes, we require more detail of the head distribution within the mine. Therefore John Gale constructed a further porous-medium model of the eastern half of the mine. This was based on the above regional sub-model, but with a more refined grid near the S.C.V. region, incorporating 14 layers vertically, and including four major fracture zones. The surface plan of this mine model is shown in Figure 3-28. Once again, head values on the boundary are interpolated from the next larger model: the regional sub-model. Mine workings and other mine openings are also incorporated as specified elevation-head boundary conditions. The properties of the sub-region model are used for the bulk rock, and measurements made during the characterization of the S.C.V. region are used to specify properties for the additional fracture zones. This procedure of using a hierarchy of models on different scales, and interpolating pressure boundary conditions between models, is not entirely straightforward, particularly as an increasing level of detail is incorporated in the more refined models. Fortunately, with an inflow directed towards our region of interest, the pressure field is not particularly sensitive to such inconsistencies in the permeability. By maintaining consistency in the fluxes across the planes formed by the boundaries of each model, using an iterative approach, a good physical understanding of the flow is built up and consistent boundary conditions for the models are established.

The mine model was run both with and without the D-boreholes being represented. The mine model with D-boreholes simulated was used to provide the regional flow field through the mine as a boundary condition for our detailed models of the D-borehole experiment discussed below. The mine model itself predicted an inflow of 0.242 litres/minute to the D-borehole experiment. We shall see that this is somewhat smaller than the predictions made by more detailed models, a difference that is most likely due to the approximations made in the description of the fracture zones in the S.C.V. region. A final porous-medium model of the S.C.V. region of the mine is planned, which will incorporate the fracture zones in more detail and integrate all the hydraulic information we have collected about this part of the Stripa site.

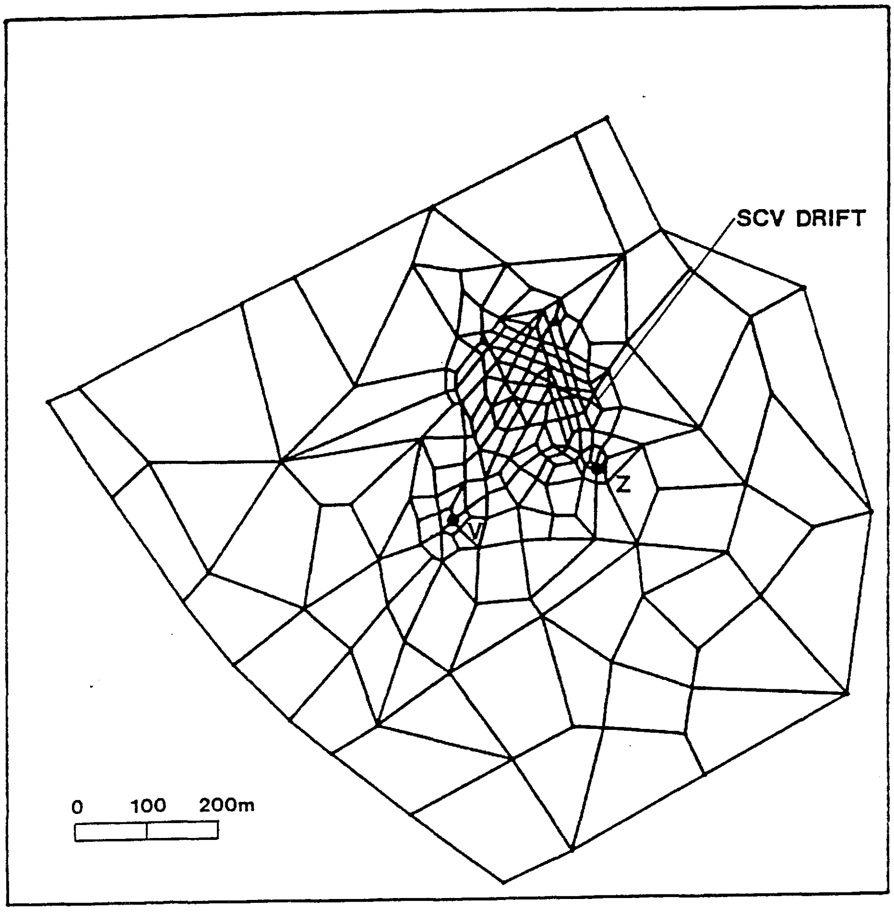


Figure 3-28. Plan view of the equivalent-porous-medium mine model used to derive boundary conditions for the S.C.V. site.

3.4.2.3 D-hole Predictions

As described in section 3.4.2.1, we determined that the most appropriate method of predicting bulk fluxes across the S.C.V. site was an equivalent-continuous-medium model. We used this approach to predict the total fluxes to the D-boreholes and the fluxes from the fracture zones identified by the geophysical studies. The permeability of the averagely fractured rock is taken directly from the predictions of our fracture network models described in section 3.4.2.1, and thus for our prediction is based directly on the interpretation of measurements of fracture properties.

For this predictive model, we account for the three-dimensional geometry of the known fracture zones explicitly. We generated the model using finite elements of a similar size to the network simulations described above. This is on a slightly more detailed level than a true R.E.V. and so we account for the variability of network conductivity by assigning the 'permeability' for each element independently, sampling the conductivity distribution predicted by our network models. Thus, we employ a stochastic continuum approach to simulate the flow through averagely fractured rock. There are only a small number of point measurements of the transmissivity of the fracture zones, and in the absence of any more detailed characterization, we simply assign to all elements representing a given fracture zone the corresponding measured mean transmissivity. Future experiments, and a detailed modelling study, should enable us to greatly improve the model in this respect. In particular, a study based on inverse modelling of cross-hole tests promises to provide an appropriate description of these zones.

The grid was generated so as to locate the fracture zones correctly, and thus, we have made approximations in locating the boreholes and the boundary of our model. To include all these features exactly would have involved an inappropriate level of effort. Boundary conditions were set on all surface nodes and the values were automatically interpolated from the regional flow model described above. We approximated the D-borehole array by a single line of nodes of specified atmospheric pressure, along the nearest element edges to the true line of the boreholes. We would generally aim to locate the line of the boreholes in our models exactly, but given the uncertainty, particularly in the characterization of the fracture zones, we regard this approximation as acceptable.

The results from this 'blind' prediction were very encouraging and are summarized in Table 3-5.

Table 3-5. Comparison of prediction and measurement.

	Prediction (l/min)	**Measurement (l/min)**
Total inflow to D-holes	1.45	1.71
Range	0.36–5.80	1.67–1.75
Total inflow from averagely fractured rock	0.09	0.2
Range	0.009–0.9	0.0–0.3

As well as predicting the bulk fluxes to the D-holes we wanted to predict the distribution of flow to 0.5 m lengths of the individual holes through the averagely fractured rock. This scale is smaller than our approximate R.E.V., and so we returned to direct fracture-network modelling. The D-borehole array was simulated in a 16 m x 8 m x 8 m fracture network and boundary conditions were interpolated from the equivalent-porous-medium model. The predicted distribution of inflows to a 90 m length of typical D-borehole is shown in Figure 3-29. Unfortunately, as predicted, the measurement limit was too high to resolve individual 0.5 m inflows. However, experiments at higher resolution aim to measure these small inflows and provide a better test of the model predictions.

In conclusion, we have used an integrated approach to simulate flow in the S.C.V. site. We use porous medium models, stochastic continuum models, and fracture network models; each where appropriate. Our flow predictions have been very successful and are not contradicted by any subsequent measurements.

3.4.3 Development of NAPSAC Code

As discussed in section 3.4.2, we have had to assume a uniform effective-transmissivity over each fracture plane for our predictive modelling and in our interpretation of characterization experiments. Whilst this seems adequate for flux prediction through averagely fractured rock, it does not explain the observations of channelling made by Ivar Neretniek's team. We will need to account for these observations when we consider velocities and transport processes. NAPSAC uses a

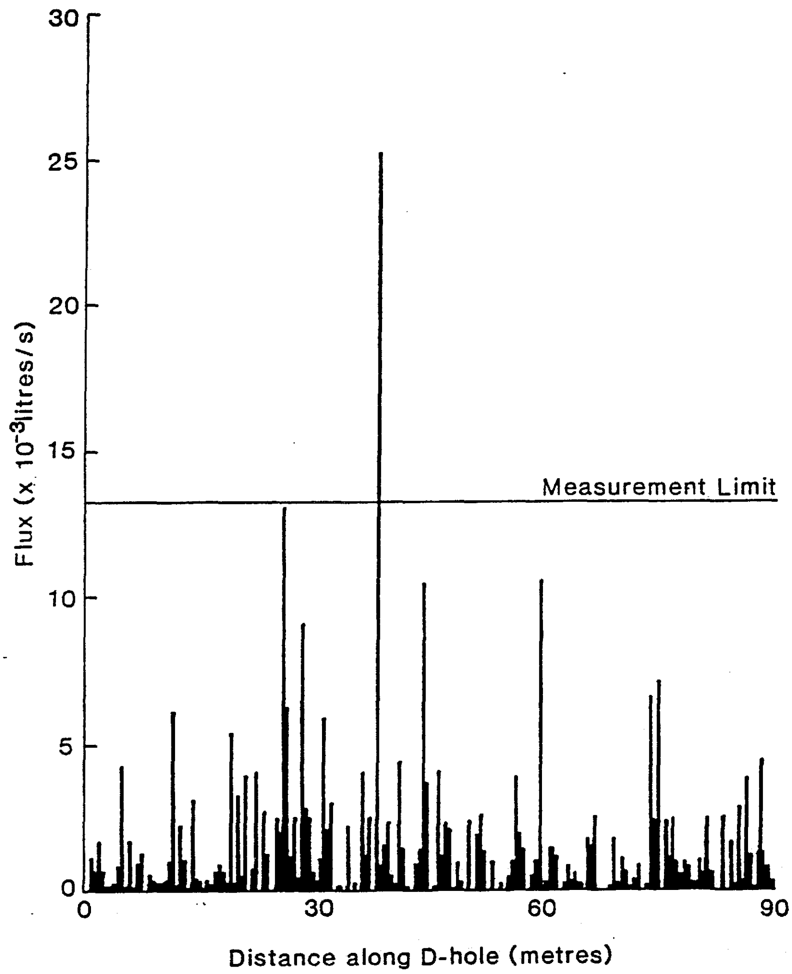


Figure 3-29. Distribution of fluxes predicted by Harwell for individual 0.5 m sections of a typical D-hole in averagely fractured rock.

fine finite-element mesh to calculate the hydraulic response of each fracture, and we have developed the code so that we can now assign different transmissivities to each finite element on this mesh. We can account for flow channelling by specifying a locally varying aperture over each fracture plane, and experimental measurements suggest that this local aperture variation is spatially correlated over the fracture plane. To simulate this numerically, we have developed a very efficient scheme that enables us to generate spatially correlated aperture fields for finely-discretized fracture planes within very large network models. On a 30x30-element fracture mesh, the cost of generating apertures with a correlation length of 8 elements is just over one second on the Cray-2 computer. An example of such a fracture showing the existence of channels is given in Figure 3-30. We are currently conducting a parameter study to investigate the effect of local aperture variation for both fracture hydraulic transmissivity, and borehole experiments. This aims to show likely biases arising in our interpretation of borehole tests, and also to help interpret channelling experiments.

We have also begun work on the development of a transport option for NAPSAC, based on a particle-tracking approach.

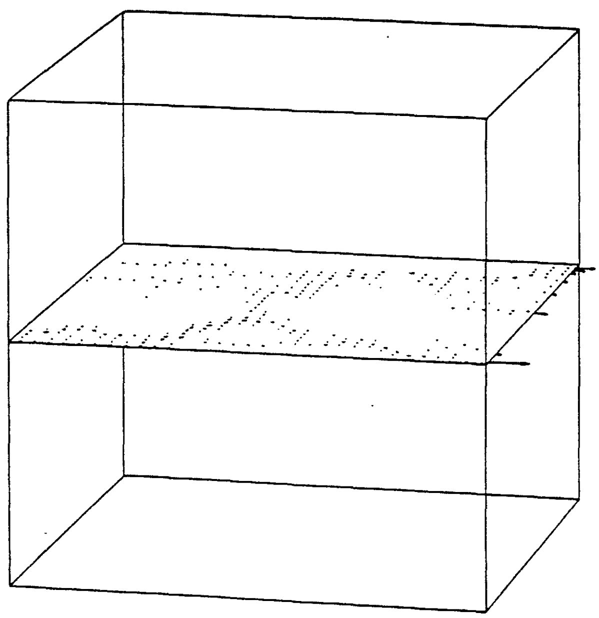


Figure 3-30. Flow channels on a typical Stripa fracture with an aperture correlation length of 1/4 the fracture size.

3.4.4 Fracture Flow Code Cross Verification

Preliminary results for simple flow test cases were produced by all three fracture flow modelling teams: AEA Technology Harwell and Intera-ECL using NAPSAC; Golder Associates using FRACMAN; and Lawrence Berkeley Laboratory using their FMG suite of computer codes. The results are in good agreement. There is also a more realistic test case that tests codes ability to simulate the geometry of, and flow through, a large network.

There were some difficulties in the interpretation of the test case specifications and the test cases are currently being re-specified to remove all possible ambiguities. This process of iteration in the definition of good benchmarking tests is inevitable when one designs verification tests to be applied to a range of independent codes. Dr Frank Schwartz has been appointed to coordinate this final definition of the verification test cases, and all three teams are now finalising their results.

A final report, confirming the accuracy of the algorithms used by the computer codes, will be produced by the middle of 1990.

3.4.5 Complementary Work by Lawrence Berkeley Laboratories

Lawrence Berkeley Laboratory have been principally involved over the past year in applying an alternative approach to the simulation of flow through the S.C.V. site to the D-borehole experiment. The Lawrence Berkeley Laboratory approach was to focus on flow through fracture zones, and thus the averagely fractured rock was taken to be impermeable in this study. This concentration of effort on the fracture zones allowed their properties to be considered in greater detail than in the Harwell or Golder Associates work. In particular, the number of zones has been re-examined and the heterogeneous substructure of zones has been modelled. This is achieved by discretizing the zones with a regular grid of

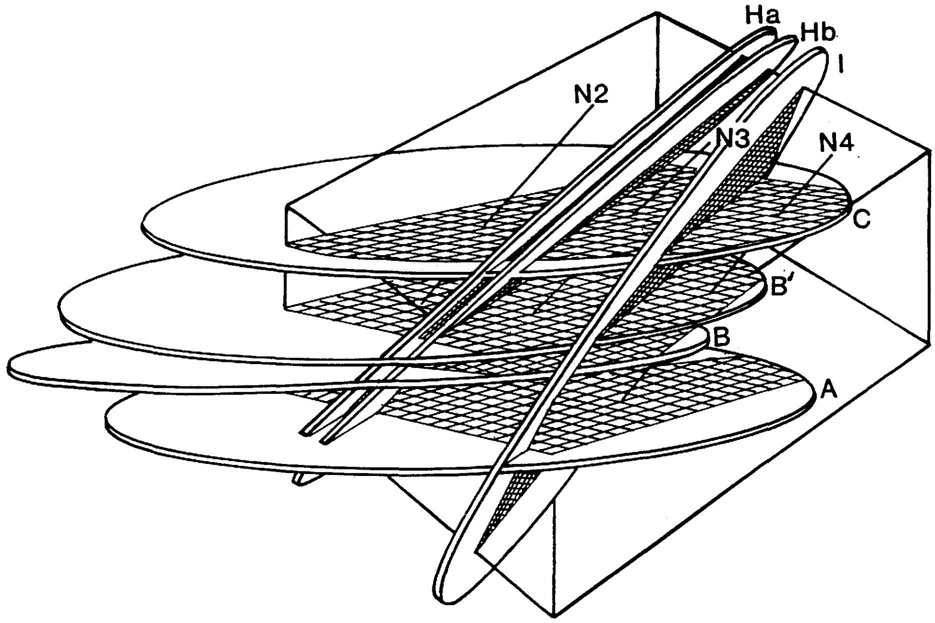


Figure 3-31. The LBL hydrological zone model shown in perspective from the North-West looking down: gridding on the planes represents the hydraulic conductors of the template used for annealing.

equally conductive channels with a fraction of missing links to provide an equivalent representation of the heterogeneity.

The hydrological and geophysical data was interpreted to assign all of the high transmissivity regions in the N and W boreholes to fracture zones. This was achieved by introducing a new zone, parallel to the existing B-zone. The new B'-zone is consistent with the geophysical measurements. In addition, the high transmissivity of a region in the W2 borehole between the H- and B-zones has been allocated to these two zones. In this way 98% of the observed transmissivity is accounted for by the zone model. The conductors used to model the hydraulic response of the zones are oriented along strike and dip lines because of geomechanical evidence that horizontal conductors are likely to be the most active.

Cross-hole hydraulic data is needed to calibrate the equivalent discontinuum zone model. Unfortunately, no controlled cross-hole tests were performed in advance of this exercise, although such information will be available for the Validation Drift predictions. As a learning exercise, synthetic results of a steady-state cross-hole test were constructed based on some ad hoc measurements performed by the British Geological Survey. The boundary condition used for the SDE exercise was that the head was maintained at 200 m in all directions far away from the block. This approximation is consistent with the other approximations and assumptions made in the analysis. Internal boundary conditions at known drifts were not included since the observe heads near the drifts in the S.C.V. block are close to 200 m. The model of flow in the S.C.V. block used in this work is shown schematically in Figure 3-31. An equivalent pattern of one-dimensional conductors representing the inhomogeneity of the zones has been determined using a simulated-annealing algorithm. The locations of the conductors were modified by the annealing algorithm until they gave a good representation of the inhomogeneities implied by the synthetic cross-holes tests. Several configurations of conductors were found to match the synthetic head data extremely well.

The predicted heads are independent of the conductance of the channels. The conductance was calibrated in order to give the observed flow from the W2 borehole. The calibrated model was then used to predict flow into the open D-hole array. The predicted inflow was 8.9 ± 0.1 litres/minute where the variability arises from using widely different network configurations. Thus with the present level of cross-hole information and assumption about overall heterogeneity, the annealing has rather little effect on flow prediction. Annealing was based on pressure head distribution, so the resulting patterns would be more useful for predicting heads. The above prediction is directly proportional to the measured flow in W2, which is somewhat anomalous since the transmissivity of W2 is much higher than the other holes. Consequently, the calibration has been repeated using ad hoc measurements of outflows from the other N and W holes. This results in five predictions with a mean of 3.1 litres/minute and a standard deviation of 3.1 litres/minute. The error associated with this prediction has been assessed by calibrating in turn to four out of the five measured inflows and calculating the root mean square of the differences between observed and calculated response for the fifth. This given an estimated prediction error of 4.6 litres/minute.

The above predictions are preliminary but have served to test out parts of the methodology in advance of the Validation Drift predictions. A final prediction is that the mean and standard deviation of the individual outer D-hole flows, assuming that the inner hole has a negligible inflow, are 0.63 and 0.55 litres/minute respectively. This large variability implies that one of the D-holes could easily account for at least half the total flow.

3.4.6 Complementary Work by Golder Associates

Golder Associates used a similar approach to AEA Technology, Harwell, to predict flows to the D-hole experiment. The main difference was that they used a different interpretation of the raw data and this led them to conclude that the fracture length scale was significantly larger than that inferred by the Harwell team. They were thus able to simulate the S.C.V. site using their fracture network models directly. Orientation data was analyzed utilizing ISIS in which clusters are defined by a maximum likelihood algorithm. The goodness of fit is calculated for several alternative distributional forms. Fracture tracelength data is analyzed by a forward modelling algorithm which corrects for sampling bias, censoring, and truncation processes to derive the best-fit fracture radius distribution. Fracture intensity and transmissivity data from fixed-interval-length packer tests are analyzed utilizing well-test type-curves, with a discrete fracture approach rather than the conventional continuum interpretation. Intensity and transmissivity are derived by forward modelling the flux into packer intervals as the sum of discrete fracture fluxes, and comparing the resulting distributions of type-curve transmissivity values to find the values for fracture statistics which best match observed response. These techniques were utilized to develop the statistics for the preliminary D-hole prediction, and for the preliminary S.C.V. drift inflow prediction.

The FracMAN discrete-fracture modelling package was utilized for a wide variety of applications. First, fluxes to the D-hole experiment and validation drift were predicted. Steady-state and transient simulations were carried out for the distribution of flux into the simulated drift experiment and S.C.V. drift. Discrete fracture simulations were carried out at the 200 m scale incorporating all drifts and boreholes explicitly. Due to computational limitations, it was necessary to utilize a sparse, calibrated network in most of the 200 m region, with the exception of a 20 m zone around the S.C.V. drift. This sparse region was calibrated to

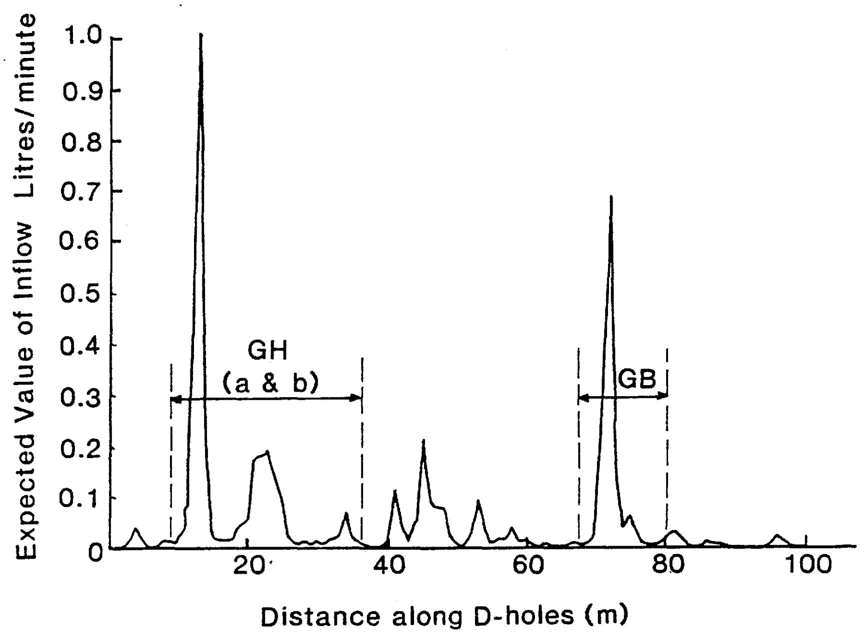


Figure 3-32. Distribution of flux into the D-holes from both fracture zones and good rock for the recalibrated Golder model.

fluxes into the 3D migration drift, resulting in a predicted D-hole influx an order of magnitude too low. The model was subsequently recalibrated against the N- and W-hole inflows and this resulted in a prediction of the correct order to magnitude, as shown in Figure 3-32. S.C.V. drift inflow predictions were carried out with the D-hole model with the coarse region calibrated against the N- and W-holes. These simulations did not include updated geological or hydrological parameters, stress effects, desaturation effects.

Additional modelling work considered the cross-hole response of the fracture networks at 5, 50 and 100 meter scales, using the MAFIC transient flow simulation feature with the re-calibrated SDE model. Simulations were carried out for transient response of the Piezomac monitoring system to head disturbances in the C- and D-holes. The response of the Piezomac system to construction of the S.C.V. drift was also simulated. Preliminary sensitivity studies were carried out for interpretation of the saline-injection radar experiment and for design of the solute transport experiments. These simulations utilized the MAFIC particle-tracking algorithm. Finally, analytical solutions and transient discrete-fracture flow simulations were carried out to assess the potential effect of backfill drift experiments upon pressures and fluxes in the S.C.V. block. Significant pressure transients were predicted within a timeframe of minutes to hours from constant-head injection within the Buffer Mass Test drift. Head changes of the order of 2 meters were observed in simulations.

In addition to their modelling activities, Golder Associates made substantial progress in the development of FracMAN and MAFIC codes. Developments include:

- FracMAN macro's for execution of Monte Carlo simulations and QA of interactive simulations;
- installation of a conjugate gradient solver in MAFIC;

- completion of sampling program simulation features in FracMAN, capable of simulating programs of multiple boreholes and traceplanes;
- preliminary verification of particle tracking solute transport in MAFIC;
- improved Mesh Generation in FracMAN, with improved file handling capabilities for transfer between FracMAN and MAFIC.

3.5 CHANNELLING EXPERIMENT

3.5.1 Introduction and Background

Lately it has been recognized that most of the water flows only in a small part of a fracture and that this may have a strong impact on the transport of escaping radionuclides. The water flowpaths in the fractures may connect to form a network of pathways, some of which may be faster than others. The surface area of the fractures which is in contact with the mobile water will determine how much surface area is available for sorption and retardation of the nuclides.

The channelling experiments were designed to study the transmissivity and aperture variations in fractures at depth in crystalline rock. Two types of experiments were designed. In the single hole experiments a hole was drilled more than 2 m into the plane of the fracture and the flowrates were measured in 5 cm sections using a specially designed injection packer. Photographs were also taken inside the hole along the fracture to determine the visible fracture aperture and to obtain other information. In the double hole experiment two parallel holes were drilled in the plane of a fracture at a center distance of 1.95 m. Hydraulic tests and tracer tests were made between the two holes to obtain information on connections in the plane of the fracture and to obtain information on residence time distributions in different paths (channels).

3.5.2 Experimental Design

The design was such that the channelling effects within a fracture plane should be tested along a line without missing any part along this line. It should also be possible to performed a tracer experiment with linear flow where up to five different tracers could be locally injected and monitored along a line "downstream". The conventional technique, penetrating the fracture with a hole perpendicular to the fracture plane, was discarded because this type of injection would give a radial outflow which would make it difficult to determine the exact location and size of the tracer source. Also these injection holes could not be drilled so close together that a line along the fracture plane could be completely covered. It was instead decided that holes, from which water and tracers could be injected, would be drilled along the fracture plane.

3.5.3 Experimental Equipment and Methods

The channelling experiments consist of three different types of tests: (1) the Single hole experiment, (2) the Double hole experiment and (3) the Tracer test.

3.5.3.1 Single Hole Experiments

To investigate the fracture characteristics along a fracture plane, a large diameter (∅200 mm) hole was drilled along the fracture plane to a depth of about 2.5 m. To facilitate the drilling, only planar fractures well seen in the drifts were selected for testing. A multi-pede packer, the Multipede, was inserted into the hole to seal off the hole from the drift. The packer was used to inject water all along the intersected fracture plane. Before the actual measurements with the Multipede, the holes were tested with a coarse injection method using a scanning packer. Only holes found suitable in these coarse tests were selected for further testing with the Multipede.

In the Multipede tests, the injection flowrates were monitored separately for the left and right side of the hole over 80 short sections of the fracture plane. The fracture intersection with the borehole was also photographed. These photographs were scrutinized to obtain data on fracture properties such as open fracture area, number of intersections, thickness of infilling. These tests are called "The Single Hole Experiments".

Photographs

After the drilling of the 200 mm holes, the boreholes were photographed using a system based on a 36 mm standard SLR camera equipped with a macro flash unit.

The following physical properties were measured from these photographs:

- opening area [mm^2/cm],
- total length of all fractures [mm/cm],
- total number of fractures [#/cm],
- average thickness of infilling [mm/cm],
- total number of intersections [#/cm].

The data was collected over small sections with an area of 10 x 50 mm, with the 10 mm going in the axial direction of the borehole.

Coarse Injection Tests

To determine if it was meaningful to do detailed water injection tests, implying movement of all measuring equipment, the hole was first scanned with a coarse method giving injection flowrates over 200 mm sections including both left and right side.

Detailed Injection Tests

The detailed injections were performed using the Multipede packer. Water was injected in twenty 50 mm x 50 mm sections at a time. These sections were located in a row, 50 mm apart. The parts between the sections were sealed off. To cover all parts of the fracture intersections, four sets of measurements had to be performed including one 50 mm movement of the Multipede packer. The injection tests were done with constant injection pressure during 5 to 10 hours. To eliminate the risk of spurious information on inflow from sections due to leakage passing the sealing back to the hole, the hole was kept at a slightly higher pressure than the injection sections. During these tests the face of the drift, close to the hole, was observed for emerging water. In some cases the areas surrounding the hole were covered with plastic sheets.

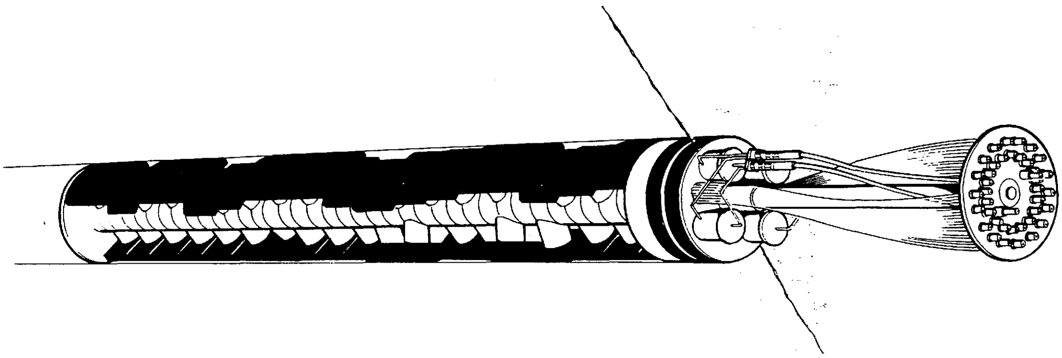


Figure 3-33. Final design of the Multipede packer.

As it was required to be able to seal off short (50 mm x 50 mm) sections along the fracture intersection separately on "left" and "right" side, no ordinary inflatable packer could be used. Instead it was decided to use small rubber cushions that were pressed to the wall of the bore hole by hydraulic pistons. As the fractures within the hole undulate, it was necessary to have the rubber cups individually adjustable. Figure 3-33 shows the final design of the so called Multipede packer.

3.5.3.2 Double Hole Experiment

The double hole experiment was performed in a fracture where earlier a single hole test had shown that channels exist. A second hole was drilled in the same fracture plane at a center to center distance of 1.95 m. This second hole was also subjected to a single hole test before suitable points for the cross hole pressure pulse tests could be selected.

A preliminary tracer test was performed prior to the pressure pulse tests using different salts as tracers to determine the suitability of the fracture for further investigations. One of the injected tracers occurred in the sampling hole, thereby indicating that this fracture plane was suitable for the double hole experiments.

A coarse test was performed to locate suitable sections in which to inject water for the detailed pressure pulse tests. In this test the entire hole was pressurized using the Scanning packer and the responses were monitored in the other hole, all along the fracture, using the Multipede packer. This coarse test was reversed, using the receiver hole as the injection hole. Sections which showed pressure responses and also had injection flowrates during the single hole tests were chosen for the detailed pressure pulse tests.

Detailed pressure pulse tests were performed from the selected points, in both directions, with injection at single sections, 50 mm x 50 mm, in one hole and monitoring in twenty sections along the fracture intersection in the second hole. Pressure pulse tests were performed in the double hole experiment using a single point source and a multi point receiver.

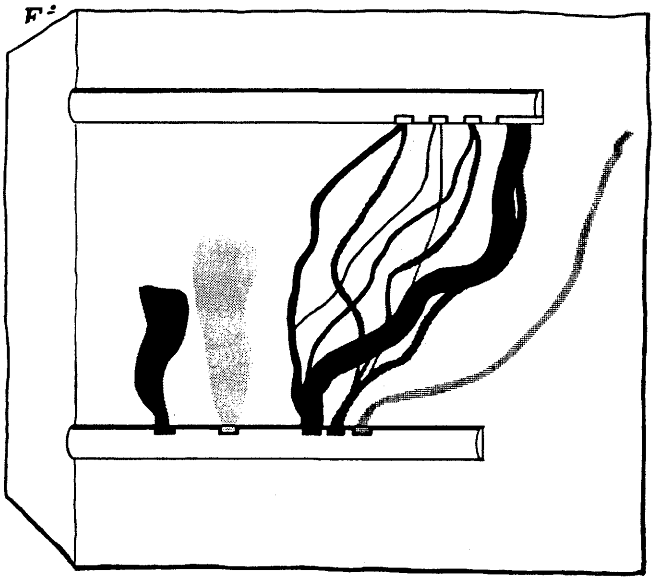


Figure 3-34. Artists's view of flow paths in the fracture. Width of the path correspond to mass flowrates.

3.5.4 Experimental Results

3.5.4.1 Tracer Test

The Multipede was used for injecting water into the fracture at 20 separate 50 mm sections, five of them containing different tracer solutions. Water was collected at 20 different locations in another hole in the same fracture plane. The injection pressure was the same as during the pressure pulse tests, 2 bar above atmospheric pressure. The tracers are non-sorbing dyes, earlier used in field experiments in Stripa.

The results of the tracer test are indicated in Figure 3-34. The largest amounts of tracers were found at the inner part of the collection hole, but there are differences in the pattern and amount with which they occur. These differences indicate that at least a part of the paths are different for the two tracers, injected only 10 cm apart. As can be seen in this figure, the two outer tracers as well as the innermost have not been found at detectable levels in any location in the collection hole.

In addition to the tracer occurrence in the collection hole, all five injected trácers have emerged in considerable amounts at the face of the drift well outside the sealed off fracture plane. At least 5 points with different proportion of tracers have been found.

3.5.5 Conclusions of the Tests

It is at first surprising that there is no obvious correlation between the observed aperture and the injected water flowrate. However, considering that the hydraulic aperture is a few micrometers on average and that the mechanical aperture is more than 10 times larger, obviously the visible local mechanical aperture is not what determines the pressure drop. It has been suggested that the pressure drop is determined by the smaller apertures along the flow path, which form the pinch points for flow. The larger apertures will determine the flow aperture because those are the regions where the water will acquire much of its residence time. This phenomenon will become more noticeable the tighter the fractures are.

The observations on the between hole pressure tests show that the investigated fracture is intersected by other fractures since the pressure responses are more similar to a porous medium with radial flow than flow in a single fracture.

The observations on the tracer movements lead us to conclude that there are dead end channels, that this single fracture has several intersecting fractures which divert the flow from the main fracture, and that the channel aperture can be on the order of several hundred μm. The flow apertures could not be determined with any accuracy but the values obtained lie in the same range as the visual apertures measured from the photographs.

How much of a fracture that is open to flow and the size of the flow wetted surface is essential information when calculating retardation of radionuclides. When trying to evaluate that number from the results from these experiments it is not possible to achieve an unambiguous result. To start with, one has to define what is meant with a channel. Either one can look at every individual flowpath and get very small channel widths or at a larger scale and identify more or less isolated clusters of small individual flowpaths. The cluster approach will give a more general view of flowpaths within fracture planes.

Based on photographs of totally 50 m of fracture intersections one can say that individual openings within fracture planes are in the range from millimeter to decimeter in length, in rare cases a few decimeters. These openings normally occur in clusters with widths of 0.05 to 1 m with typically 2 to 4 clusters over a length of 2.5 m. The open part in one of these clusters is at most half the cluster width and normally much less. The same results are obtained from the single hole injection tests. Looking at the infilling thickness, a footprint of longtime properties, the result is the same as for the methods mentioned above except for that it is in this case possible to find some distinct narrow channels (50 mm widths). One

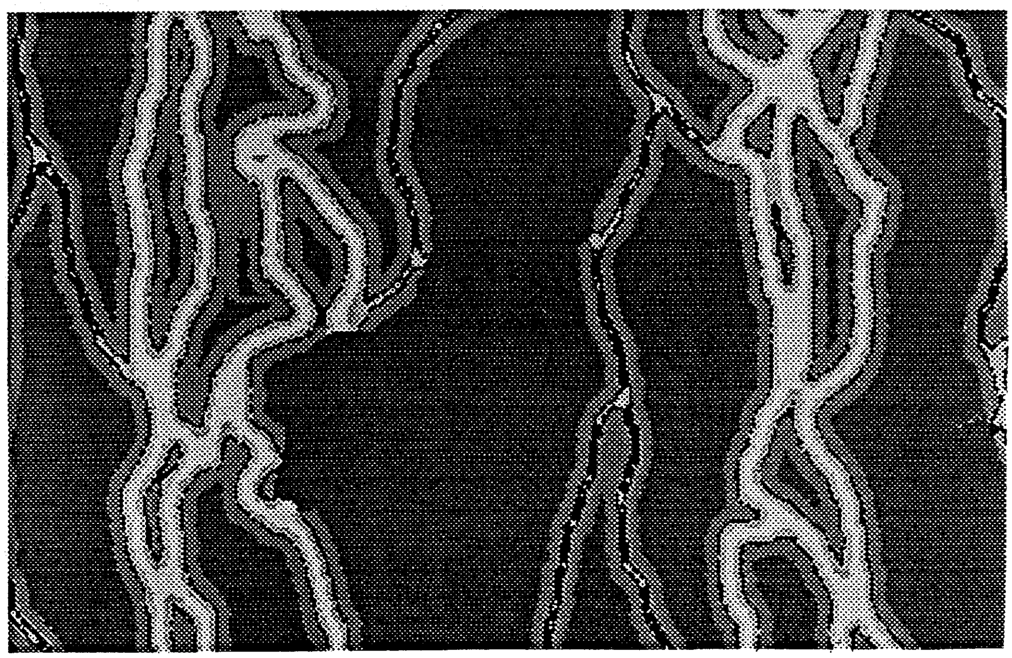


Figure 3-35. Artist's view of single channels and clusters within a fracture plane.

should, however, keep in mind that the channels now seen as infilling might not have been active at the same time period.

To sum up these observations, on the average 25 percent or less of the fracture plane is open to flow with individual channel widths from centimeter to decimeters. These channels normally occurs in clusters with cluster widths of decimeters. These clusters occur at half meter to meter apart. Individual fractures may, however, have properties that strongly deviate from the average.

These results are based on 12 well defined planar fractures selected from 1500 m mapped drifts. The results may not be applicable on all fractures found in a standard fracture mapping.

3.6 ROCK SEALING TEST

3.6.1 General

The general objective of the Rock Sealing Test is to identify suitable grouts and grouting techniques for sealing fine rock fractures in repositories. The grouts have to be sufficiently erosion-resistant and chemically stable to make them serve for long periods of time and part of the project is therefore focussed on the testing of candidate materials not only with respect to their initial sealing ability but also to their potential to survive in repository environment.

The requirement to seal fine fractures is met by use of "dynamic" injection technique, i.e. by applying vibrations of suitable amplitude and frequency to the grout in addition to the conventional static injection pressure. The project comprises development of suitable field-adapted equipment for such grouting, and application of the technique in the mine for determination of the sealing effect and for evaluation of the validity of a grout flow theory.

3.6.2 Major Activities in 1989

The work in 1989 consisted of three major parts: 1) Large-scale grouting experiment in former heater holes in the BMT area (Test 1), 2) Determination of water inflow and identification of water-bearing structures in the right 3D arm (Test 4), and 3) Laboratory study of the sealing and longevity properties of cement and clay grout candidates.

3.6.3 Grouting of Heater Holes

Two 76 cm diameter heater holes that are about 3 m deep have been grouted by use of bentonite clay, applying "dynamic" injection technique. For this purpose and for the preceding determination of the hydraulic conductivity a "megapacker" was built (Figure 3-36).

After the grouting, which was made according to somewhat different strategies in the two holes, the hydraulic conductivity was measured again and repeated once more after a heat pulse of about 1 year. The heating of the holes gave a temperature at the periphery of the holes of up to about 90°C while it was about 40°C at 1 m distance. The results of the measurements, which are compiled in Table 3-6 for the hole which was grouted in a way that appears most practical, show that the best sealing effect was achieved in the upper 2 meters of the hole, i.e. close to the tunnel floor. Here, the conductivity dropped to less than 1/1000 of the initial value after the grouting, while the subsequent heating increased the conductivity so that the net drop was about 1/20 to 1/30 of the original value.

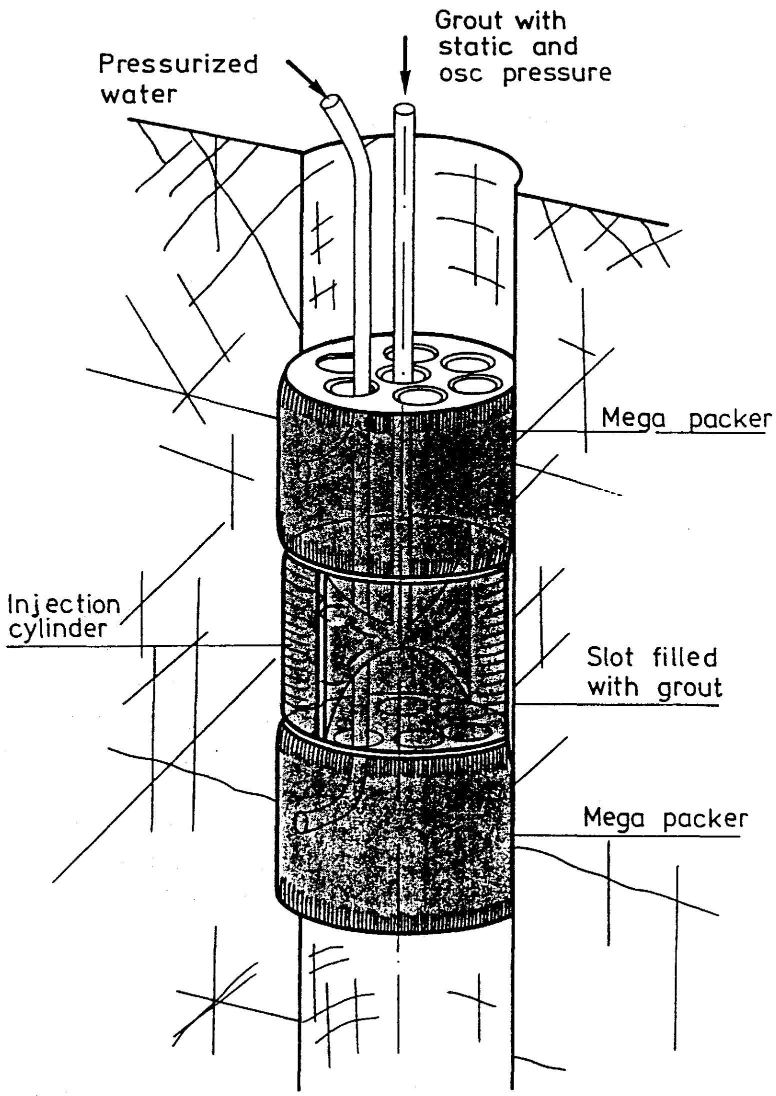


Figure 3-36. "Megapacker" developed for determination of the hydraulic conductivity and for grouting.

Table 3-6. Effect of grouting on the conductivity of granite around simulated canister hole (No. 2).

Depth Interval, m	Initial	Hydraulic conductivity, m/s After grouting	After heating
0.80 – 1.35	$k_1 = 3.7 \times 10^{-7}$	$k_1/1300$	$k_1/20$
1.30 – 1.85	$k_2 = 5.7 \times 10^{-8}$	$k_2/500$	$k_2/32$
1.80 – 2.35	$k_3 = 3.0 \times 10^{-10}$	$k_3/5$	$2\ k_3$
2.30 – 2.85	$k_4 = 3.1 \times 10^{-10}$	$k_4/2$	$1.7\ k_3$

Deeper down in the holes the sealing effect was smaller and it was concluded that rock with an initial hydraulic conductivity of less than 10^{-9} m/s cannot be effectively sealed. The fact that the heat treatment reduced the sealing effect of the grouting is ascribed to heat-induced movement of rock blocks, by which non-grouted fractures were widened locally.

3.6.4 Characterization of the Rock in the 3D Arm for Planning of Grouting

The eastern 3D arm will be used for a field test comprising grouting of a natural major water-bearing fracture zone. In 1989 a detailed hydrological survey has been made through which the rate and amount of water inflow into the drift have been determined. For this purpose, a ventilation experiment and comprehensive sampling of water have been made. In addition, detailed mapping of the distribution of water outflow from the wet northern wall has been made. The measurements show that the daily inflow has been almost constant and about 29 litres from midsummer, which is about three times the figure derived in the 3D experiment. The discrepancy indicates that drainage through the floor was considerable in the 3D experiment and that ventilation experiments must be evaluated with due respect to RH (Figure 3-37).

Pressure recordings show that the piezometric heads are 1.3 – 1.8 MPa 3–5 m from the walls of the drift, while they are only about 1 MPa 5–7 m above the roof and below the floor. This indicates rather effective lateral drainage westwards through the abundant sub-horizontal fractures. Except for an obvious pressure drop in early May 1989 there is no reaction to draining activities in the vicinity.

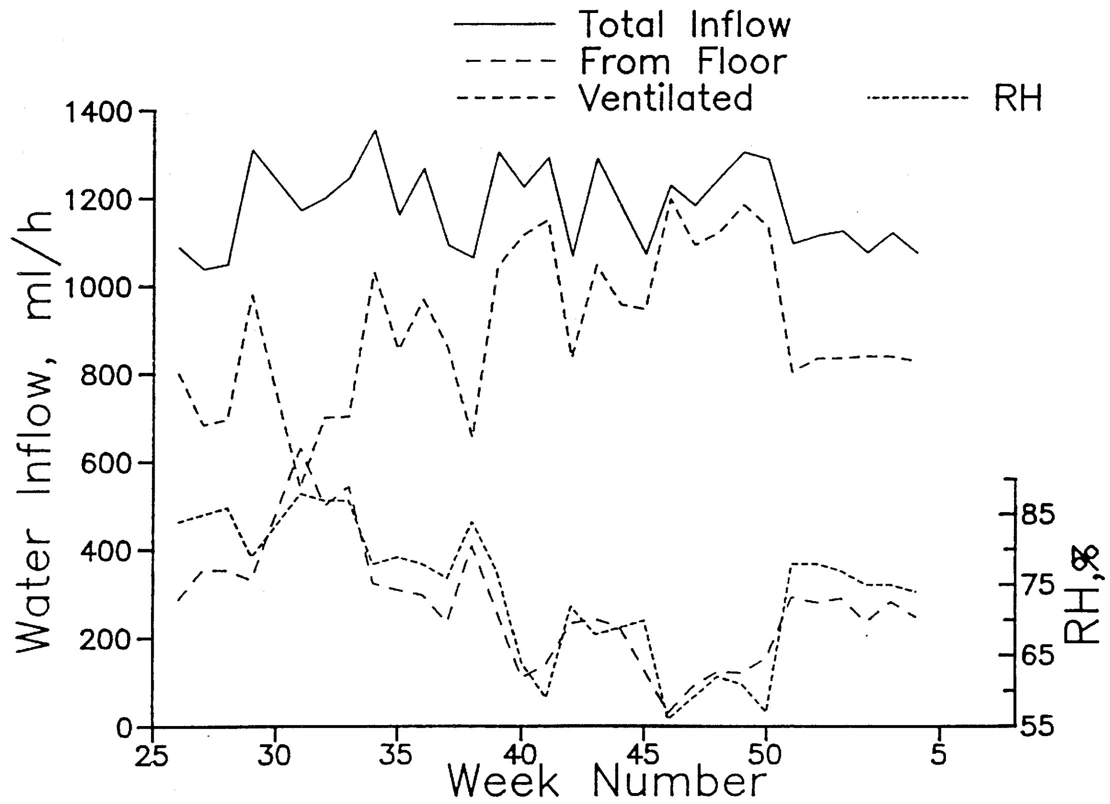


Figure 3-37. Flow diagram showing the contributions to the inflow and total inflow.

Tracer tests were started in the reporting period by injecting Elbenyl Brilliant Flavine in one of the BAT piezometers in the northern wall located about 4 m from the rock surface. Tracer appeared at the lower northeastern corner of the drift in about 1 day indicating the hydraulic importance of the steep fracture zone that strikes N/S.

3.6.5 Accessory Tests (Longevity Issue)

Clays

Two major types of lab experiments are being conducted:

1) Determination of the hydraulic conductivity of grouts in simulated rock fractures with heating and expansion/consolidation cycles, and

2) Determination of chemical changes in the form of dissolution and mineral alteration as indicated by XRD, chemical analysis, electron microscopy, and rheological testing.

The present state of the study can be summarized as follows:

* The groundwater composition is a key parameter for the sealing effect. Under fresh and weakly brackish water conditions Na montmorillonite clay prepared with NaCl to about 10 000 ppm concentration has optimum grouting and sealing properties. Addition of quartz powder improves the sealing effect but makes the grout more sensitive to piping.

  When the groundwater is strongly brackish with calcium as major cation, Ca bentonite prepared with fresh water, offers the best sealing properties.

* At heating to less than 60°C the microstructure and chemical constitution are entirely preserved. In the interval 60 – 90°C some microstructural changes are induced, giving a stiffer and slightly more permeable gel, while the montmorillonite is affected only by slight congruent dissolution. Stronger microstructural changes, yielding increased stiffening and some additional increase in conductivity, are produced by heating to 120°C, which also yields more rapid dissolution of the montmorillonite. Hydrous mica is neoformed in the presence of potassium.

  At higher temperatures non-congruent dissolution of montmorillonite takes place yielding beidellite, which forms hydrous mica by uptake and fixation of potassium. Neoformation of hydrous mica becomes a major process if potassium is available and some kaolinite may be formed as well. K-holding feldspars, occurring as accessory constituents, are dissolved.

Cement

Maria Onofrei and Malcolm Gray (AECL):

In the last 12 months, tests have been carried out to determine: the general leaching properties of pure cement phases and the hydraulic conductivity and porosity of reference grout.

General Leaching Properties of Reference Grout

Hardened samples of the reference grout mixed at 0.4 and 0.6 w/c and ALOFIX-MC (MC-500) mixed at 0.5 and 0.7 w/c were subjected to a series of static and dynamic leach tests. The leaching performance of grouts was determined by measuring the leach rates of Ca^{2+} and Si^{4+}.

For the reference grout the result from static tests show that the release of Ca^{2+} to solution is virtually constant tending to marginally increase with temperature and groundwater salinity. For MC-500 the release of Ca^{2+} exhibits a marked increase with increasing temperature. At the highest temperature (150°C) and with groundwater with high salinity the MC-500 grout releases Ca^{2+} at approximately six times the rate of the reference grout. The greater resistance of the reference grout to leaching can be attributed to the absence of large amounts of free $Ca(OH)_2$ in this material.

In the dynamic leach tests the effects of flow rate and temperature on the leaching properties of grouts were investigated. The leaching behaviour of the grouts mixed at low w/c (0.4) and high w/c (0.6) were found to be similar. Higher leach rates (10^{-8} kg/m² x s) were observed at higher w/c. This may reflect a higher proportion of capillary space in the reference grout mixed at high (0.6) w/c.

SEM/EDX examination of the leached samples showed that leaching is accompanied by precipitation and growth of an assemblage of secondary alteration phases. The precipitate layer consisted of two distinct phases; a Ca-phase and a Ca-Si phase. The precipitate layer likely has significant effects on the long-term leach rates of the grouts. It controls the leaching/dissolution behaviour of the cement grout under both static and dynamic conditions.

Leaching of Pure Cement Compounds

The leach tests have also been completed on mixtures of the following pure cement compounds: C_2S, C_3S, C_3A, and C_4AF ($C = CaO$, $A = Al_2O_3$, $F = Fe_2O_3$, $S = SiO_4$). Results confirm the findings of studies of dissolution and leaching processes in the industrial grade cements.

Hydraulic Conductivity and Porosity of Reference Grout

Static and dynamic leach tests have been carried out to determine the effect of groundwater chemical composition, temperature and time on the porosity of reference grout. Data show (Figure 3-38) that the effective porosity of the grout decreases with leaching time. The decrease in the effective porosity is assumed to be due to change in the volume of the solids by the continuous hydration, precipitation and associated reactions.

The intrinsic permeability and hydraulic conductivity, k_i, of cement-based grouts are being determined on bulk specimens of grouts and on thin films of grouts. The influence of stress, water content, superplasticizer content and silica fume content on permeability and hydraulic conductivity of grouts are being determined over a range of temperatures and hydraulic gradients. The first series of tests have confirmed the low intrinsic k_i of the reference grout ($<10^{-14}$ m/s) (Figure 3-39). Also, the data show that the hydraulic conductivity of the cement grouts decreases by adding silica fume to the mixture and by reducing the value of the water to cement ratio. The decrease in k_i reflects decreases in connected capillary pore space in grout.

Steve Alcorn, (RE/SPEC):

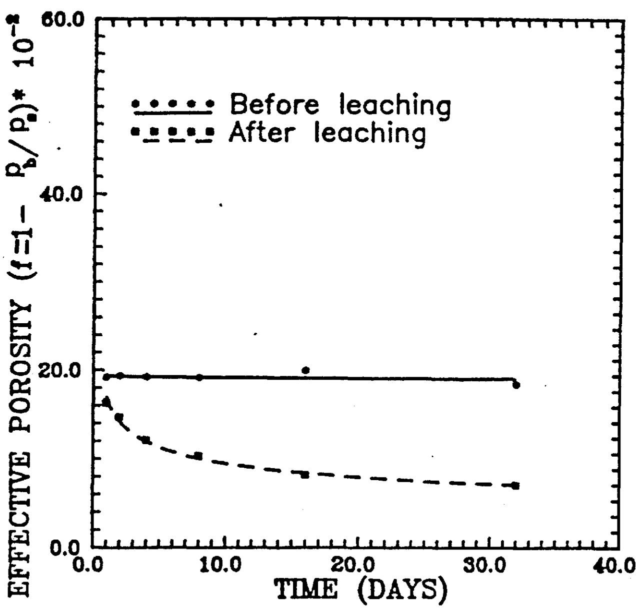


Figure 3-38. The effective porosity of reference grout mixed at 0.4 w/c with 1% superplasticizer and 10% silica fume before and after leaching in distilled deionized water.

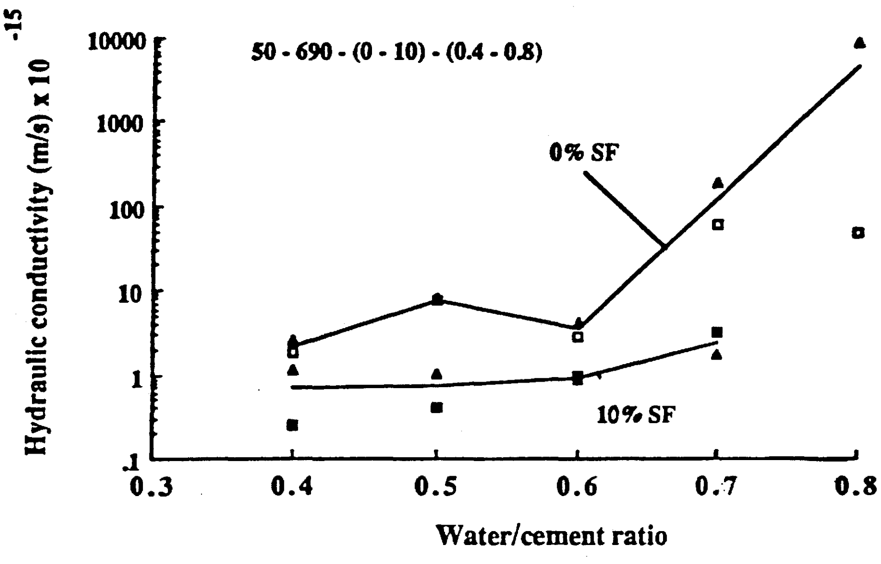


Figure 3-39. The effect of water/cement ratio and silica fume on the hydraulic conductivity of reference grout.

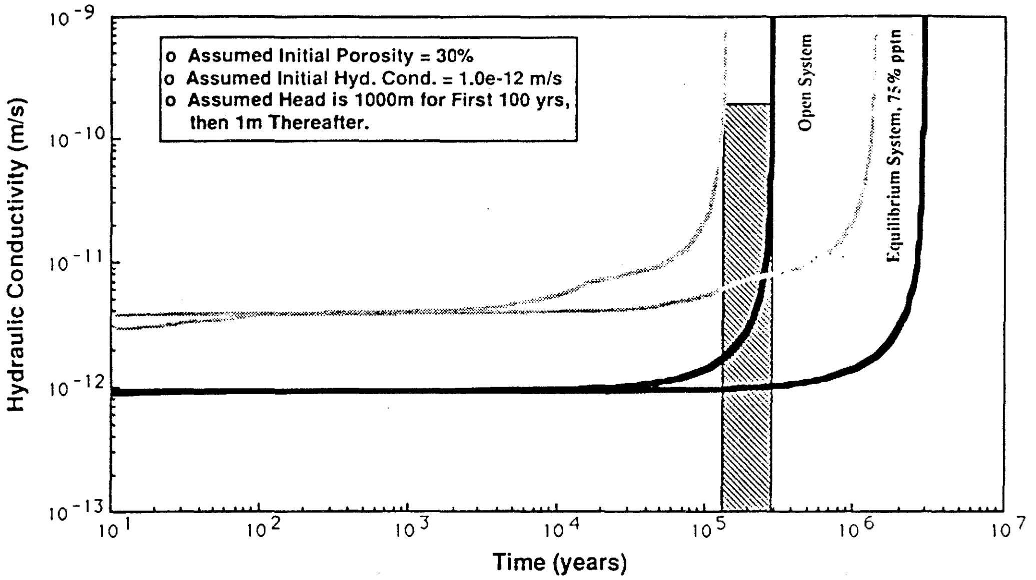


Figure 3-40. Diagram showing changes in hydraulic conductivity of a cement grout seal with time. The vertical bar indicates the minimum estimated useful life of a seal under the conditions analyzed, with uncertainties in the methodology considered.

Investigations into the longevity of cement grout seals focused during the year on analyzing increasingly realistic scenarios and incorporating experimentally derived data into the model input. The complexity of the geochemical and hydrologic models was developed in order to analyze realistic conditions anticipated in high-level waste repositories and provide information that may prove useful as input to conceptual seal designs.

The modelling of increasingly complex systems yielded results that continue to corroborate the approach being used to develop the longevity assessment methodology. Besides considering grout models of progressively detailed chemistry, realism was introduced by taking into account: (1) the metastability of grout phases, (2) the uncertainty of the equation relating changes in porosity to changes in hydraulic conductivity, and (3) the inclusion of a reasonable amount of portlandite in the grout model. Inclusion of portlandite is consistent with the observation that it is observed in cured grout, even in mixes with sufficient silica fume to preclude its formation on a stoichiometric basis. The results continue to suggest that properly engineered portland cement-based grouts, i.e., those with low initial hydraulic conductivities, can maintain acceptable performance for very long times, up to hundreds of thousands to millions of years (Figure 3-40).

It has also been found that long-term performance is likely to be influenced by site conditions. Theoretical and experimental studies indicate that cement dissolution is accompanied by the precipitation of calcium-silica-hydrate phases, carbonates, sulfates, clays and zeolites, as long as a relatively low hydraulic gradient at the site permits an approach to steady state conditions. Theoretical and experimental studies also indicate that cement grout degradation is somewhat sensitive to groundwater composition. The theoretical studies suggest that the rate of grout dissolution (and secondary mineral precipitation) is dependent upon the rate at which water flows through the grout, which depends ultimately upon the initial hydraulic conductivity of the grout. These are *the bases for the conclusion that, given the conductivity constraint, cement grout may be expected to persist for very long times.*

The development of a methodology for assessing the potential for fracture development in grout due to dissolution-induced stresses was initiated. The approach shows considerable promise for estimating the transition between a porous (Darcy or Darcy-like) flow-dominated regime and a fracture flow-dominated one. Very preliminary results from coupling chemical modelling data with fracture-potential analysis suggest that porous flow may predominate for long periods of time.

3.7 ECONOMY

The total cost of the Stripa Project Phase 3 as of December 31, 1989 is given in the Table 3-7 below.

Table 3-7. Stripa Project Phase 3 – Summary of costs as per December 31, 1988. All figures in SEK.

		Total program	
Program	**Original budget excl annual index esc. Jan 1990**	**Accumulated**	**Estimated Remaining**
Project Management	7 700 000	2 446 774	5 253 226
Stripa Generally	27 300 000	11 234 761	16 065 239
Site Char. and Validation	44 500 000	26 052 580	18 447 420
Dev. of Radar	5 500 000	4 792 217	707 783
Improv. of Bore-hole Seismics	3 700 000	2 779 095	920 905
Network Modelling	7 600 000	3 207 416	4 392 584
Channelling Experim.	7 400 000	6 901 926	498 074
Frac. length and Apert. f. Single	900 000	950 201	-50 201
Sealing of Frac-tured Rock	7 500 000	7 500 000	0
Large Scale Sealing	25 500 000	12 209 000	13 291 000
Total	**137 600 000**	**78 073 970**	**59 526 030**

Appendix

Stripa Project — Previously Published Reports, 1980–1989

1980

TR 81 – 01

"SUMMARY OF DEFINED PROGRAMS"

L Carlsson and T Olsson
Geological Survey of Sweden, Uppsala

I Neretnieks
Royal Institute of Technology, Stockholm

R Pusch
University of Luleå

Sweden, November 1980

1981

TR 81 – 02

"ANNUAL REPORT 1980"

Swedish Nuclear Fuel Supply Co./Division KBS, Stockholm

Sweden 1981

IR 81 – 03

"MIGRATION IN A SINGLE FRACTURE PRELIMINARY EXPERIMENTS IN STRIPA"

Harald Abelin, Ivars Neretnieks
Royal Institute of Technology, Stockholm

Sweden, April 1981

SUMMARY

A method of tracer injection and of water collection to be used in the main investigation of "Migration in a single fissure" has been tested and found to function well. With this injection equipment it is possible to introduce tracers into the fissure as a step or a pulse. The injection can be done either under natural pressure or with over pressure.

The collection of water sampled can be done under anoxic atmosphere. Injection of Rhodamine-WT and Na-Fluorescein with over pressure has been performed.

It has been found that Rhodamine-WT is influenced in some way along the flow path. Rhodamine-WT thus cannot be used to characterize the water residence time without a knowledge of the interaction mechanisms.

Based on the experiences from this investigation the equipment and operation will be somewhat modified for use in the main investigation.

1981 **IR 81 – 04**

"EQUIPMENT FOR HYDRAULIC TESTING"

Lars Jacobsson, Henrik Norlander
Ställbergs Grufve AB, Stripa

Sweden, July 1981

ABSTRACT

Hydraulic testing in boreholes is one major task of the hydrogeological program in the Stripa Project. A new testing equipment for this purpose was constructed. It consists of a downhole part and a surface part. The downhole part consists of two packers enclosing two test sections when inflated; one between the packers and one between the bottom packer and the bottom of the borehole. A probe for downhole electronics is also included in the downhole equipment together with electrical cable and nylon tubing. In order to perform shut-in and pulse tests with high accuracy a surface controlled downhole valve was constructed.

The surface equipment consists of the data acquisition system, transducer amplifier and surface gauges. In the report detailed descriptions of each component in the whole testing equipment are given.

IR 81 – 05

Part I "CORE-LOGS OF BOREHOLE VI DOWN TO 505 M"

L Carlsson, V Stejskal
Geological Survey of Sweden, Uppsala

T Olsson
K-Konsult, Stockholm

Part II "MEASUREMENT OF TRIAXIAL ROCK STRESSES IN BOREHOLE VI"

L Strindell, M Andersson
Swedish State Power Board, Stockholm

Sweden, July 1981

ABSTRACT

In the hydrogeological program of the Stripa project the vertical borehole V1 has been drilled 505.5 m. The drillcore has been logged with regard to rock characteristic, fracture frequency, dipping and filling. The results presented as cumulative fracture diagram have formed the base for subdivision of the borehole according to fracture frequency. The variation in the fracture dipping was also taken into account. Chlorite is the most common of the infilling material in the fractures. For the borehole 0 466 m the average fracture frequency is 1.46 fractures/m. Below 466 m the core is highly fractured and crushed indicating that the borehole has entered a crushed zone. Because of this the drilling is temporarily stopped.

1982 **TR 82 – 01**

"ANNUAL REPORT 1981"

Swedish Nuclear Fuel Supply Co./Division KBS, Stockholm

Sweden, February 1982

IR 82 – 02

"BUFFER MASS TEST – DATA ACQUISITION AND DATA PROCESSING SYSTEMS"

B Hagvall
University of Luleå, Sweden

August 1982

SUMMARY
This report describes data aquisition and data processing systems used for the Buffer Mass Test at Stripa. A data aquisition system, designed mainly to provide high reliability, in Stripa produces raw-data log tapes. Copies of these tapes are mailed to the computer center at the University of Luleå for processing of raw-data. The computer systems in Luleå offer a wide range of processing facilities: large mass storage units, several plotting facilities, programs for processing and monitoring of vast amounts of data, etc..

IR 82 – 03

"BUFFER MASS TEST – SOFTWARE FOR THE DATA ACQUISITION SYSTEM"

B Hagvall
University of Luleå

Sweden, August 1982

SUMMARY
This report describes the data aquisition software for the buffer mass test at Stripa. The software system handles input of information concerning the experiment design as well as measuring and storing of transducer signal values. It also provides a lot of service functions like measuring and printing of transducer signal values, printing of data stored on floppy disks, reporting transducers exceeding their alarm limits, etc.. The system also continuously checks the status of voltmeters, scanners, printers, etc. and reports failing devices. The software is written for a Hewlett Packard 9835A desktop computer.

1982 **IR 82 – 04**

"CORE-LOGS OF THE SUBHORIZONTAL BOREHOLES N1 AND E1"

L Carlsson, V Stejskal
Geological Survey of Sweden, Uppsala

T Olsson
K-Konsult, Engineers and Architects, Stockholm

Sweden, August 1982

ABSTRACT
The subhorizontal boreholes N1 and E1 were drilled in the monzogranite of the Stripa pluton for purposes of the hydrogeological investigations. This report presents the results of the megascopic petrographic investigation of the cores and fracture measurements compiled as fracture-logs, RQD-diagrams, cumulative fracture diagram and contour diagrams of oriented fracture measurements. It also describes geologic structures connected with the Stripa pluton.

IR 82 – 05

"CORE-LOGS OF THE VERTICAL BOREHOLE V2"

L Carlsson, T Eggert, B Westlund
Geological Survey of Sweden, Uppsala

T Olsson
K-Konsult, Engineers and Architects, Stockholm

Sweden, August 1982

ABSTRACT
In the hydrogeological programme of the Stripa Project, borehole V2 (previously termed Dbh V1) was prolonged to a final depth of 822 m. The previous core from 0–471.4 m was relogged, but the old log was partly used as seven core boxes have been sent to LBL. The drill core was logged with regard to rock characteristics, fracture frequency, dipping and filling. The results are presented as core-logs and fracture diagrams. Borehole V2 shows similar characteristics as found in other drillings in the Stripa Mine. It penetrates Stripa granite to its full depth. Recorded fractures show a clear predominance of medium-steep fractures, while flat-lying fractures are more sparsely occurring, a fact which is even more pronounced below 400 m depth. Due to the vertical direction of the borehole, steeply dipping fractures are underestimated in the core. The mean fracture frequency, related to the total length of the core, is 2.1 fractures/m. Chlorite, calcite and epidote are the dominating coating minerals in the fractures, each making up about 25–30 percent of all coated fractures.

1982 IR 82–06

"BUFFER MASS TEST – BUFFER MATERIALS"

R Pusch, L Börgesson
University of Luleå

J Nilsson
AB Jacobson & Widmark, Luleå

Sweden, August 1982

SUMMARY

Commercial Na bentonite (MX-80) is the clay component of the buffer material in the heater holes as well of the tunnel backfill. Important characteristics are the clay content, liquid limit, X-ray diffraction pattern, water content, and degree of granulation. The ballast material consists of quartz-rich sand and feldspar-rich filler.

The preparation of highly compacted bentonite for the near-field isolation of the canisters was made by using isolatatic compaction technique. The resulting dense bentonite core was cut into regularly shaped blocks which were arranged around each heater and lowered as one unit — heavily instrumented — in the respective deposition holes. For three of the six holes a narrow slot was left open between the bentonite stack and the rock; for the remaining ones a wider slot was chosen with a fill of soft bentonite powder. Both arrangements are expected to yield an ultimate bulk density which is sufficiently high to fulfill the requirement of a negligible permeability and a sufficient swelling pressure as well as heat conductivity, which are the essential parameters.

The tunnel backfill, which consists of a mixture of suitably graded ballast material and MX-80 powder, has a considerably lower swelling pressure and heat conductivity, and a higher permeability, all these parameters still within the requirements of the KBS-2 concept. The various zones with different bentonite/sand ratios and the technique to apply them are described in the final part of the report.

"BUFFER MASS TEST – ROCK DRILLING AND CIVIL ENGINEERING"

R Pusch
University of Luleå

J Nilsson
AB Jacobson & Widmark, Luleå

Sweden, September 1982

SUMMARY

The Buffer Mass Test (BMT) is being run in the former "ventilation drift" in which a number of rock investigations were previously conducted by the Lawrence Berkeley Laboratory (LBL). They have yielded valuable information on the rock properties, particularly the water pressure situation and the gross permeability, and a number of pressure gauges were still in operation when the BMT was prepared. A light wooden wall, anchored to the rock in a shallow slot, formed an outer boundary of the LBL test and the removal of this wall was the first step in the preparation of the BMT test. Next, a number of vertical pilot holes were drilled from the tunnel floor to get information of the water inflow in possible heater hole positions. The final decision of the location of the heater holes was then made, the main principle being that much water should be available in each hole with the possible exception of one of the holes. Thereafter, the Ø 0.76 m heater holes were drilled to a depth of 3–3.3 m. Additional holes were then drilled for rock anchoring of the lids of the four outer heater holes, for the rock mechanical investigation, as well as for a number of water pressure gauges. The complete drilling program will be specified in the text.

The inner, about 12 m long part of the tunnel, was separated from the outer by a bulwark. The purpose of this construction was to confine a backfill, the requirements of the bulwark being to withstand the swelling pressure as well as the water pressure. The design and performance of the construction is described in some detail.

Outside the bulwark an approximately 1.5–1.7 m thick concrete slab was cast on the tunnel floor, extending about 24.7 m from the bulwark. Boxing-outs with the same height as the slab and with the horizontal dimensions 1.8 x 1.8 m, were made and rock-anchored concrete lids were cast on top of them after backfilling, Fig. 1. This figure illustrates that a cross section through the boxing-outs and the heater holes represents an almost exact half-scale equivalent of a section through a true tunnel with a deposition hole as specified by the KBS 2 concept. The slab which thus represents "rock", also forms a basal support of the bulwark. The lids permit access to the backfill as well as to the underlying, highly compacted bentonite for rapid direct determination of the water distribution at the intended successive test stops. The construction of the slab and lids will be described in this report.

1982 **IR 82 – 08**

"BUFFER MASS TEST – PREDICTIONS OF THE BEHAVIOUR OF THE BENTONITE-BASED BUFFER MATERIALS"

L Börgesson
University of Luleå

Sweden, August 1982

SUMMARY

The predictions are based on laboratory-derived material parameters and assumed test conditions as they were at the start of the test.

The predictions show that the temperature of the bentonite will only slightly exceed 70° C if no drying takes place. The dried-out material may be as hot as 120° C.

The rate of the water uptake is highly dependent on the availability of water along the rock surface but not very much on the difference in the amount of water available in the six holes. The predicted time for water saturation (Sr95%) is about 2 years in the deposition holes and about 5 years in the tunnel if water is available from the entire rock surface. If water is available from only one or two fractures or narrow zones the highly compacted bentonite and the tunnel backfill will not be water saturated until after more than 100 years.

The ultimate heaving of the interface between the highly compacted bentonite and the tunnel backfill is estimated to be 6–12 cm, the maximum swelling pressure is 10–20 MPa.

"GEOCHEMICAL AND ISOTOPE CHARACTERIZATION OF THE STRIPA GROUNDWATERS – PROGRESS REPORT"

Leif Carlsson,
Swedish Geological, Göteborg

Tommy Olsson,
Geological Survey of Sweden, Uppsala

John Andrews,
University of Bath, UK

Jean-Charles Fontes,
Université, Paris-Sud, Paris, France

Jean L Michelot,
Université, Paris-Sud, Paris, France

Kirk Nordstrom,
United states Geological Survey, Menlo Park, California, USA

February 1983

ABSTRACT
This progress report contains the recent results of the hydrogeochemical program, a part of the hydrogeological investigations at the Stripa test site. A considerable number of groundwater samples have been collected and analyzed for major dissolved cations, anions, trace elements, stable isotopes, radioisotopes and dissolved gases to depths approaching 900 m. This report presents (1) the background geology and hydrogeology (2) major and trace element characteristics of the deep groundwaters (3) major radioelement characteristics and inert gases (4) stable isotopes of water and dissolved sulfate and (5) preliminary interpretations of the groundwater chemistry trends. As the studies at Stripa are still in progress, all interpretations are considered tentative and preliminary. Any conclusions drawn may be modified as a consequence of continued sampling and analysis.

1983 | **TR 83 – 02**

"ANNUAL REPORT 1982"

Swedish Nuclear Fuel Supply Co./Division KBS, Stockholm

Sweden, April 1983

IR 83 – 03

"BUFFER MASS TEST – THERMAL CALCULATIONS FOR THE HIGH TEMPERATURE TEST"

Sven Knutsson
University of Luleå

Sweden, May 1983

INTRODUCTION

The successive emptying of the heater holes in the running BMT in the Stripa mine, offers an opportunity of testing the properties of the highly compacted bentonite at higher temperatures than in the presently running tests. In the current study the temperatures in the bentonite do not exceed about 80° C, which is estimated to be a safe temperature with respect to chemical stability of the smectite. This temperature level is reached by a heater effect of 600 W. If this is increased to 1200 W the temperature at the surface of the heater is expected to yield a level of about 150°C. Thereby the water uptake and water redistribution will be largely influenced as well as the temperatures around the heater.

This report deals with some basic predictions of the temperature distribution in the vicinity of a heater producing an effect of 1200 W.

"BUFFER MASS TEST – SITE DOCUMENTATION"

Roland Pusch
University of Luleå and Swedish State Power Board

Jan Nilsson
AB Jacobsson & Widmark, Luleå

Sweden, October 1983

SUMMARY

The purpose of this report is to compile test site data that are assumed to be of importance for the interpretation of the Buffer Mass Test. Since this test mainly concerns water uptake and migration processes in the integrated rock/backfill system and the development of temperature fields in this system, the work has been focused on the constitution and hydrology of the rock.

The major constitutional rock feature of interest for the BMT is the frequency and distribution of joints and fractures. Earlier investigations by Lawrence Berkeley Laboratory offer comprehensive fracture data which are sufficiently detailed for BMT purposes with respect to the interaction between the rock and the tunnel backfill. However, the development of models for water uptake into the highly compacted bentonite in the heater holes requires a very detailed fracture survey. The present investigation shows that two of the holes (no. 1 and 2) are located in richly fractured rock, while the others are located in fracture-poor to moderately fractured rock.

The hydrologic conditions of the rock in the BMT area are characterized by water pressures of as much as 100 m water head at a few meters distance from the test site. The average hydraulic conductivity of the rock that confines the BMT tunnel has been estimated at about 10 m/s by Lawrence Berkeley Laboratory. The actual distribution of the water that enters the tunnel has been estimated by observing the successive moistening after having switched off the ventilation, and this has offered a basis of predicting the rate and uniformity of the water uptake in the tunnel backfill. As to the water inflow into the heater holes the detailed fracture patterns and various inflow measurements have yielded a similar basis.

The report also gives major data on the rock temperature, gas conditions, mineralogy, rock mechanics, and groundwater chemistry for BMT purposes.

1983 | **IR 83 – 05**

"BUFFER MASS TEST – IMPROVED MODELS FOR WATER UPTAKE AND REDISTRIBUTION IN THE HEATER HOLES AND TUNNEL BACKFILL"

R Pusch
Swedish State Power Board

L Börgesson, S Knutsson
University of Luleå

Sweden, October 1983

SUMMARY

In October 1983 the first heaters have been running for about two years and a number of observations show that the original physical model of the water uptake must be changed somewhat. The same goes for the tunnel backfill.

As to the highly compacted bentonite in the heater holes, the formulation of an improved model needs considering the following observations:

* Single water-bearing joints and fractures with apertures exceeding about 0.1 mm become sealed relatively soon by penetrating bentonite and do not serve as an effective water source.
* Fractured rock with a network of narrow joints and fractures serves as an effective water source.
* Rock with no visible joints or fractures serves as a stingy water source which, however, determines the water inflow into the larger part of the heater holes.
* Temperature gradients and absolute temperatures of the present magnitude drive water from the hot interior towards the periphery, where it accumulates. This is a rapid process with a rather well defined relationship between water content and temperature.
* The ultimate stage of water uptake is one characterized by slow flow driven by the hydraulic gradients in the rock.

The improved model for the water uptake in the tunnel is based on the well-founded assumption that the fairly small inflow in the tunnel that was observed before the backfilling has not changed. It is highly probable that the inflowing water is uniformly distributed over the tunnel periphery from where it is sucked by the backfill and transported towards the interior through a diffusion like process. This yields a fairly rapid moistening of the central parts of the backfill, and late saturation of the periphery, which is in good agreement with moisture sensor reactions and low water pressure recordings at the rock/backfill interface.

1983 IR 83 – 06

"CROSSHOLE INVESTIGATIONS – THE USE OF BOREHOLE RADAR FOR THE DETECTION OF FRACTURE ZONES IN CRYSTALLINE ROCK"

Olle Olsson, Erik Sandberg
Swedish Geological

Bruno Nilsson
Boliden Mineral AB

Sweden, October 1983

ABSTRACT

A borehole radar system has been developed by Boliden Mineral AB in Sweden. The system consists of a control unit and separate units for transmitter and receiver antennas. Thus the system may be used both for single hole and cross hole measurements. The communication of data and control signals between the control unit and transmitter and receiver is made on optical fibers. The system transmits energy in the frequency range 10–50 MHz.

Measurements have mainly been performed in the form of single hole measurements with a transmitter-receiver spacing of 13 m. Attenuation and delay of the direct wave between transmitter and receiver has been observed in connection with fracture zones which penetrate the borehole. Fracture zones also cause reflections which give information on the orientation of the fracture zone relative to the borehole. Reflections have also been observed from an air filled drift 30 m from the borehole. Reflections from a fracture zone has been observed for a two way travel distance of 88 m. The distance from the borehole to the drift and the orientation of the fracture zones relative the borehole has been found to agree well with other data available on the site.

In the present system resolution is limited by ringing on the antenna, however significant enhancement has been obtained of the radar data by deconvolution filtering.

The main part of this project has been funded by the Swedish Nuclear Fuel Supply Co. (SKBF/KBS) while some of the final evaluations have been performed within the OECD/NEA International Stripa Project.

1984 TR 84 – 01

"ANNUAL REPORT 1983"

Swedish Nuclear Fuel Supply Co./Division KBS, Stockholm

Sweden, May 1984

IR 84 – 02

"BUFFER MASS TEST – HEATER DESIGN AND OPERATION"

Jan Nilsson
Swedish Geological Co.

Gunnar Ramqvist
El-tekno AB

Roland Pusch
Swedish State Power Board

June 1984

The nuclear waste is assumed to be contained in cylindrical metal canisters which will be inserted in deposition holes. Heat is generated as a result of the continuing decay of the radioactive waste and in the Buffer Mass Test (BMT) the heat flux expected from such canisters was simulated by the use of six electric heaters. The heaters were constructed partly of aluminium and partly of stainless steel. They are 1520 mm in length and 380 mm in diameter, and give a maximum power output of 3000 W. The heater power can be monitored by panel meters coupled to a computer-based data acquisition system. Both the heater and the control system were manufactured with a high degree of redundancy in case of component failure. This report describes the design, construction, testing, installation and necessary tools for heater installation and dismantling operation.

1984 **IR 84–03**

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS – GEOPHYSICAL BOREHOLE MEASUREMENTS"

Olle Olsson, Ante Jämtlid
Swedish Geological Co.

August 1984

ABSTRACT

A standard geophysical logging program was performed in the boreholes N1, E1, V1 and V2 in the Stripa Mine. Several minor fracture zones were identified in the boreholes particularly with the aid of the resistivity logs. Information on the hydraulic properties of the fracture zones were mainly obtained from the temperature and the salinity logs. The borehole fluid in the boreholes V1 and V2 were found to be saline. The Stripa granite has a relatively high background radiation level of 70 R/h. Higher radiation levels, which were commonly observed, are mainly due to radon transported by groundwater from fractures into the boreholes.

The large fracture zone encountered at the bottom of V1 (466–505 m) gave a large resistivity anomaly, but no anomaly of comparable magnitude was found 1984 in any of the other holes. The single hole data from V2 indicated a fracture zone at 404–440 m, which to some extent had the same geophysical character as the zone in V1.

Mise a la masse or cross-hole electrical measurements were performed to find the orientation of the fracture zone in V1. The data were interpreted with a theoretical model where a trial and error procedure was used to find the best fit to the measured data. The fracture zone was interpreted to have the dip 60° SE and the strike N60° E. This zone intersects V2 at 409 m and N1 at 270 m. In the final interpretation consideration was also taken to the single hole data.

"CROSSHOLE INVESTIGATIONS – PRELIMINARY DESIGN OF A NEW BOREHOLE RADAR SYSTEM"

O Olsson, E Sandberg
Swedish Geological Co.

August 1984

ABSTRACT

If the resistivity of the bedrock is large enough electromagnetic waves will propagate through the bedrock for considerable distances. It is estimated that penetration ranges of several hundred meters are attainable in granitic rock for electromagnetic waves in the frequency range 20–200 MHz. The corresponding wavelengths will be in the range 0.5 m to 10 m. A resolution of objects with dimensions larger than a few parts of the wavelength is expected.

The new radar system designed as a part of the cross-hole program of the Stripa Project will be applicable both to cross-hole and single-hole measurements. The system will be a short pulse radar system to obtain a good resolution in the distance to reflectors. The radar system will consist of three units; a control unit, a borehole transmitter and a borehole receiver. All communication between these units will be made on optical fibers.

The control unit will be used to transmit trig-pulses to the transmitter and the receiver. The trig-pulses will determine when a radar pulse is transmitted and when a sample is taken of the received waveform. In principle the system will work as a sampling oscilloscope in recovering the high frequency pulses. The control unit will collect digital data from the borehole receiver. Stacking may also be done by the control unit. Sampling frequency, number of stacks, and sampling window position and length will be under software control. Data storage and display will be made on a micro-computer system with floppy discs.

The transmitter will generate a current pulse that is fed to the antenna. The pulse will be generated by a discharge of a transmission line, which will be controlled by an avalanche transistor. The transmission line will be charged by a DC voltage of 500 V. The pulse repetition frequency will be 40 kHz.

The receiver will consist of a high frequency amplifier, a sampler and an A/D converter. The A/D converter will have a resolution of 16 bits.

To obtain well defined radar pulses broadband antennas will be used. For borehole applications it is possible to construct broadband dipole antennas by increasing the characteristic impedance along the length of the antenna. Different antennas will be tested where the impedance increase is made either resistive, capacitive or inductive.

1984 **IR 84–05**

"CROSSHOLE INVESTIGATIONS – EQUIPMENT DESIGN CONSIDERATIONS FOR SINUSOIDAL PRESSURE TESTS"

David C. Holmes
British Geological Survey

September 1984

SUMMARY

This report is one of a series which describes work being undertaken by the British Geological Survey for the Stripa Project. The work forms part of the Crosshole Programme, which is a multidisciplinary approach to rock mass assessment around a potential repository, using radar, seismic and hydrogeological techniques.

Hydrogeological characterization will be attempted using the sinusoidal pressure test method, in addition to more standard methods, in six boreholes drilled from the 360 m level in the mine. Equipment has been designed to generate a hydraulic signal (source borehole) and monitor its progress through the rock mass (receiver borehole). Packers are used to isolate sections of rock.

The equipment design has been influenced by hydraulic conditions likely to be encountered in the local rock environment. Of major importance is the hydraulic pressure field caused by groundwater movement into mine cavities. This field varies considerably and has necessitated the design of a testing system which is extremely adaptable in generating and receiving hydraulic signals.

1984 IR 84–06

"BUFFER MASS TEST – INSTRUMENTATION"

Roland Pusch, Thomas Forsberg
University of Luleå, Sweden

Jan Nilsson
Swedish Geological, Luleå

Gunnar Ramqvist, Sven-Erik Tegelmark
Stripa Mine Service, Storå

September 1984

SUMMARY

The major objective of the Buffer Mass Test is to record the development of temperature fields, water uptake, and swelling and water pressures in the highly compacted bentonite in the heater holes, as well as in the tunnel backfill. In addition, internal displacements in the clay materials and change of rock joint apertures will be determined.

The temperature recording is made by use of more than 1200 copper-constant and thermal elements for detailed information of the temperatures, especially in the vicinity of the heaters. Swelling, or rather total pressures, are primarily measured by means of about 130 Gloetzl pressure cells, and this system is also applied for recording water pressures in heater holes, backfill and rock (28 gauges). 25 BAT-piezometers are used as a back-up of the Gloetzl system and for the recording of low water pressures.

Moistening of the clay materials is evaluated from moisture sensor signals which reflect the electric resistivity, or rather the capacitance, of these materials. The lack of suitable commercial gauges made it necessary to develop new equipment (560 gauges), which is useful for a rough estimation of moisture content changes, but less accurate for quantitative determination of the moisture content, particularly of the bentonite/sand backfill materials.

The water uptake and swelling of the highly compacted bentonite in the heater holes is expected to produce displacement of the interface between this bentonite and the overlying bentonite/sand backfill. This displacement, which is probably non-uniform, will be measured at the excavation of the heater holes by determining the z-coordinate of 40 copper "coins" located at the interface. Their original positions, expressed in terms of z=coordinates, were carefully determined at the application. Possible internal displacements in the overlying backfill are identified by measuring z-coordinate changes of long plastic tape stripes which were applied in connection with the backfilling operation.

The expansion of the highly compacted bentonite is also expected to affect the aperture of rock joints which intersect the heater holes. The possible changes in aperture will be determined by measuring axial displacements in four vertical boreholes. Kovari's technique is used for this purpose.

1984 IR 84–07

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL" INVESTIGATIONS IN BOREHOLES – FLUID INCLUSION STUDIES IN THE STRIPA GRANITE

Sten Lindblom
Stockholm University, Sweden

October 1984

ABSTRACT

Abundant fluid inclusions have been found in quartz in the Stripa granite. Inclusion occurrence reaches 1.74 x 10^8 inclusions per cm^3 with a mean size of 6 m in diameter.

These inclusions mainly contain an aqueous solution. Fractured rock sections contain inclusions with lower salinity than unfractured rock sections, 1.7 and 4 eq. wt% NaCl respectively. Comparison with measured salinities in the Stripa groundwater shows that only about 5–10% of the available fluid inclusions have to be leached in order to explain ground-water salinities.

Homogenization temperatures from the same inclusions indicate formation at over 130° C for the inclusions in unfractured rock sections. A later rehealing event at over 190° C is represented by inclusions in fractured rock sections. This later fluid has a lower salinity and indicates that the granite may have been flushed by deep circulating meteoric waters at a possible late date.

The aqueous inclusions are secondary but rare primary CO_2 inclusions occur which may indicate conditions of granite emplacement.

1984 IR 84–08

"CROSSHOLE INVESTIGATIONS – TOMOGRAPHY AND ITS APPLICATION TO CROSSHOLE SEISMIC MEASUREMENTS"

Sven Ivansson
National Defence Research Institute, Sweden

November 1984

ABSTRACT

The problem of seismic velocity estimation from first-arrival travel-times is discussed. mainly in a two dimensional crosshole geometry. Use is made of previously developed geophysical inverse theory and modern methods of computerized tomography. An overview of these foundations is included.

For typical crosshole cases the ray-path coverage will unfortunately be much less complete than what is generally achieved in medical applications of tomography. The implied uniqueness problems are discussed using the Radon transform.

Different ways of performing the tomographic inversion are tested on a number of synthetic examples. In general, the criterion of damped least-squares is used and solutions are computed by (for example) Gaussian elimination. SIRT-methods and the conjugate gradients (CG)method. The CG-method is found to converge very rapidly.

Because the risk of getting a distorted image will always be present, it is concluded that comparison with results from synthetic examples (forward modelling) is a valuable tool in the interpretation process.

Methods to include estimation of anisotropy and iterative procedures to take account of ray-bending are also discussed.

1985 **IR 85–01**

"BOREHOLE AND SHAFT SEALING – SITE DOCUMENTATION"

Roland Pusch, Jan Nilsson
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Gunnar Ramqvist
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Sweden, February 1985

ABSTRACT
Highly compacted bentonite as sealing substance is being tested in Stripa. The experiments comprise of borehole, shaft, and tunnel plugging tests which serve to illustrate clay application techniques, maturation rate of the clay plugs and sealing ability of such plugs. The latter is due to the very low hydraulic conductivity of dense smectite-rich clay, and of the swelling pressure, which it exerts on the confining rock. The swelling creates a tight contact with the rock and a tendency of closing joints and fractures in the rock adjacent to the clay plugs.

The sealing properties of bentonite plugs are known to be related to the structure and water bearing properties of the rock, which are the subjects of the present report.

IR 85–02

"MIGRATION IN A SINGLE FRACTURE – INSTRUMENTATION AND SITE DESCRIPTION"

Harald Abelin, Jard Gidlund
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Sweden, February 1985

ABSTRACT
The physical and chemical interaction between the bedrock and eventually leached radionuclides is considered to be one of the major retarding mechanisms in radionuclide migration. To test if it is possible to extend results obtained in the laboratory to a larger scale under real conditions an in situ migration experiment has been performed. A single fracture, in granitic rock, at the 360 m level in the Stripa mine, has been utilized. Both conservative (nonsorbing) and sorbing tracers have been injected. Equipment for automatic pressure pulse tests and tracer injection (pulse of step) have been developed. The injection equipment also allows small volume water sampling at the injection point. At the end of the injections part of the fracture has been excavated and the concentration of the injected sorbing tracers on the fracture surface as well as in the rock matrix have been determined. The rock samples have been prepared in an automatic grinding machine that uses a diamond-coated metal sheet as abrasive material.

1985 **TR 85 – 03**

"FINAL REPORT OF THE MIGRATION IN A SINGLE FRACTURE – EXPERIMENTAL RESULTS AND EVALUATION"

H Abelin, I Neretnieks, S Tunbrant, L Moreno
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Sweden, May 1985

ABSTRACT

Three fractures in granitic rock have been investigated by hydraulic testing and by migration tests with nonsorbing as well as with sorbing tracers. The sorbing tracers were Cs, Sr, Eu, Nd, Th and U.

The fractures are located in drifts at 360 m depth in the Stripa mine in mid Sweden. The fractures are clearly visible in the drifts. There is natural water flow in the fractures. Injection took place at 5–10 m distance from the roof of the drifts. The water was collected at 10–15 locations on every fracture as it intersects the drift. Injection and collection of water was done during more than 7 months in one of the fractures. The fracture where the sorbing tracers were injected was excavated after the test and the surface of the fracture was analysed for the tracers. The tracers were also analysed for, to a depth of up to 5 mm in the rock matrix.

The results show that there is distinct channelling in the plane of the fractures. The channels make up 5–20% of fracture. The fissure (or channel) widths are much (order(s) of magnitude) larger than what can be deduced from hydraulic testing assuming laminar flow in a smooth slit.

None of the sorbing tracers arrived at the collection points with the water. The sorbing tracer Sr migrated less than was originally expected. Cs, Eu, and U were found in highest concentrations very near the injection point. Nd and Th could not be found on the fracture surface because of the high natural background.

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS IN BOREHOLES – COMPILATION OF GEOLOGICAL DATA"

Seje Carlsten
Swedish Geological Co., Uppsala

Sweden, June 1985

ABSTRACT

Several reports on performed geological investigations in the Stripa granite have been published since 1977. The current one is in summary a compilation of these reports updated with additional data collected during the Stripa project, phase 1. The Stripa granite is a grey to reddish middle-grained granite with a rather high fracture frequency and it is considered to be about 1800 Ma, formed during the serorogenic phase of the Svecokarelian orogeny. The granite is composed of quartz, plagioclase, microcline, muscovite and chlorite. It also has a high uranium and thorium content. Breccias are a common feature in the granite. Associated to those are cavities containing idiomorphic crystals. Porous sections with up to 9% porosity occur in the granite, probably caused by dissolution of quartz. The granite is surrounded by leptite in which it has intruded. The contacts between leptite and granite is concordant with structures in the leptite. The ironore is located in the leptite. Numerous thermal and tectonic events since the original emplacement of the granite is indicated by fluid inclusions. The chloride content in the fluid inclusions is sufficiently enough to account for the salinity of the groundwater. Fracture orientation is mainly directed in NE–NNE with a secondary maximum in N 30 E, both with a steep dip. Microfractures occur both in association with tectonic zones and in the rock mass. Chlorite, sericite, quartz, epidote, calcite and fluorite are the most common fracture filling minerals in the granite.

1985 IR 85–05

"CROSSHOLE INVESTIGATIONS – DESCRIPTION OF THE SMALL SCALE SITE"

Seje Carlsten, Kurt-Åke Magnusson, Olle Olsson
Swedish Geological Co., Uppsala

Sweden, June 1985

ABSTRACT

At the Crosshole-site, located at the 360 m level in the Stripa mine, six boreholes have been drilled in a fanlike fashion. This borehole configuration was choosen in order to penetrate fracture zones in the test area with several boreholes.

To achieve a comprehensive knowledge of the geological and physical conditions, core mapping and a comprehensive program of geophysical borehole measurements has been carried out.

The specific geological and physical character of the major fractured zones distinguished in the boreholes can be recognized and correlated between several boreholes. The extension of six major zones and one minor zone have thus been correlated between the boreholes. The fractures within the zones and the rock mass have a dominating direction more or less subparallel with the zones. Parameter measurements on core samples show that the major zones have considerably higher porosity (up to 2%) than the rock mass (about 0.2%). The major zones are altered and tectonized and contain several deformed zones such as breccia, mylonites etc. Cavities partly filled with idiomorphic crystals, often occur in association with the deformed zones.

Key words: Granite, core logging, geophysical logging, fracture zones, tectonization, cross-hole.

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS IN BOREHOLES – FINAL REPORT OF THE PHASE I GEOCHEMICAL INVESTIGATIONS OF THE STRIPA GROUNDWATERS"

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July 1985

ABSTRACT

The hydrogeochemical investigations of Phase I of the Stripa Project (1980–84) have been completed, and the results are presented in this final report. All chemical and isotopic data on the groundwaters from the beginning of the Stripa Project to the present (1977–84) are tabulated and used in the final interpretations. The background geology and hydrology is summarized and updated along with new analyses of the Stripa granite. Water-rock interactions form a basic framework for the changes in major-element chemistry with depth, including carbonate geochemistry, the fluid-inclusion hypothesis, redox processes, and mineral precipitation. The irregular distribution of chloride suggests channelling is occurring and the effect of thermomechanical perturbations on the groundwater chemistry is documented. Stable and radioactive isotopes provide information on the origin and evolution of the groundwater itself and of several elements within the groundwater. Subsurface production of radionuclides is documented in these investigations, and a general picture of uranium transformations during weathering is presented. One of the primary conclusions reached in these studies is that different dissolved constituents will provide different residence times because they have different origins and different evolutionary histories that may or may not be related to the overall evolution of the groundwater itself.

1985 **TR 85 – 07**

"ANNUAL REPORT 1984"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

July 1985

IR 85 – 08

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS IN BOREHOLES – SHUT-IN TESTS"

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July 1985

ABSTRACT

This report present the results from the shut-in tests carried out within the program on hydrogeological investigations in boreholes. The groundwater system at the mine has successively been affected by the mining activities, and the mine acts as a sink, which gives a hydraulic system well suited for hydrogeological studies underground. The current shut-in tests utilize this condition, i.e. to use the natural drainage and to measure the build-up after shut-in. By this technique no foreign water is introduced in the water system which may disturb studies of the groundwater chemistry. In addition, the technique only causes a minor disturbance on the head around the mine which in turn gives only a minor interference to other activities in the project.

The report on the shut-in tests describes the testing techniques and illustrates different evaluation approaches to be used in order to obtain as much information as possible on the hydrogeological conditions of the target rock. Thus, evaluation was made with consideration to different flow regimes and to wellbore storage and skin; the latter effects were of great significance in the very low conductive rock mass found at the test site. In general the hydraulic conductivity is below 10^{-11} m/s, although some minor zones were found with a conductivity of about 10^{-8} m/s at the most. All of the tested zones were selected zones of expected higher conductivity and the remaining rock mass is therefore of even lower conductivity than the results reported.

The evaluation showed that the required testing time in order to overcome the secondary effects of wellbore storage and skin will be large in this kind of test, normally at least some days, which make an accurate testing in a low conductive formation very time consuming. Other techniques are also used and presented in a separate report.

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATONS IN BOREHOLES – INJECTION-RECOVERY TESTS AND INTERFERENCE TESTS"

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July 1985

ABSTRACT

The current report presents the results from hydraulic tests performed as water injection tests and interference tests. The water injection tests were conducted in 10 m sections in the three boreholes at the SGU-site in the Stripa mine. A major problem with these test was the significant formation pressure build-up which took place during testing. In several sections the injection stage was converted into a build-up stage, i.e. the formation pressure exceeded the applied injection pressure. The testing technique is fast and less time consuming than shut-in tests, and should therefore be considered for certain testing purposes. However, it is recommended to perform the tests when the natural formation pressure is in steady-state and to use specially designed equipment for this purpose.

The result of the water injection test gives results in the same orders of magnitude as other techniques used. As regards the different evaluation techniques, it is seen that no considerable difference exist between different techniques. However, the spreading is become more significant in the low conductive rock mass, i.e. below 10^{-11} m/s.

The interference tests were carried out by using the natural build-up or fall-off in the groundwater system around the mine. Thus, the natural drainage to the potential sink made up by the mine creates the disturbances. The disturbance was introduced in a specific section in one borehole and the resulting effect was recorded in other boreholes. The results from these tests give the hydraulic properties of the rock mass between the source and receiver holes. By this technique a hydraulic conductivity of the more fractured parts of the rock mass in the range 10^{-8} was obtained. A corresponding specific storage coefficient was also determined.

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS IN BOREHOLES – FINAL REPORT"

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July 1985

ABSTRACT

Underground investigations in boreholes are presumed to be an important investigation technique for the detailed design of a final repository for nuclear waste. The siting of the repository will be based on surface investigations, but for detailed investigations when the access shafts are sunk, investigations in underground boreholes from the initial shafts and tunnels will be of importance. The hydrogeological investigations in boreholes aimed at testing and developing of hydrogeological techniques and instruments for use in an underground environment in order to reflect actual working and testing conditions.

This report is the final report from the hydrogeological investigations in boreholes, and it summarizes the different activities carried out during the course of the program. Most of the included activities are reported in separate internal reports, and therefore only the most important results are included, together with the experiences and conclusions gained during the investigations.

The hydrogeochemical part of the program is in a separate final report, consequently no hydrogeochemical information is in the current report.

1985 **TR 85–11**

"FINAL REPORT OF THE BUFFER MASS TEST – Volume I: scope, preparative field work, and test arrangement"

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July 1985

ABSTRACT

The Buffer Mass Test was conducted in a 30 m long drift at 340 m depth in the Stripa mine, the main objective being to check the predicted functions of certain bentonite-based buffer materials in rock environment. These materials were blocks of highly compacted sodium bentonite placed in large boreholes simulating deposition holes for canisters, and on-site compacted sand/bentonite mixtures used as tunnel backfill. The blocks of bentonite embedded electrical heaters which served to produce heat so as to create conditions similar to those in a repository. The temperature in the initially non-saturated buffer materials was expected to be a function of the water uptake from the rock, which was also assumed to lead to rather high swelling pressures. The recording of these processes and of the moistening of the buffer materials, as well as of the associated build-up of piezometric heads at rock/buffer interfaces, was the major item of the field test. For this purpose the buffer materials and the rock were equipped with a large number of thermal elements, pressure and piezometric cells as well as moisture sensors. The choice of positions and properties of these gauges, which were connected to an effective data acquisition system, was based on predictions that required a careful site documentation with respect to the fracture characteristics and hydrological properties of the surrounding rock.

1985 TR 85–12

"FINAL REPORT OF THE BUFFER MASS TEST – Volume II: test results"

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August 1985

ABSTRACT

The evaluation of the Buffer Mass Test mainly concerned the heating of the bentonite/rock system that simulated hot canisters in deposition holes, the swelling and swelling pressures of the expanding bentonite in the heater holes, and the water uptake of the bentonite in the holes as well as in the tunnel backfill. These processes had been predicted on the basis of laboratory-derived data and FEM calculations with due consideration of the actual geometry.

The recorded temperatures of the bentonite and surrounding rock were found to be below the maximum temperature that had been set, but higher than the expected values in the initial period of testing. The heater surface temperatures dropped in the course of the tests due to the uptake of water from the rock even in the "driest" hole which was located in almost fracture-free rock.

The water uptake in the highly compacted bentonite in the heater holes was manifested by a successively increased swelling pressure at the bentonite/rock interface. It was rather uniformly distributed over this interface and reached a maximum value of about 10 MPa.

The water content determination confirmed that water had been absorbed by the bentonite from the rock even in the driest holes where the counteracting thermal gradient was rather high. In the wettest holes the saturation became almost complete and a high degree of saturation was also observed in the tunnel backfill. Both in the heater holes and the tunnel, the moistening was found to be very uniform along the periphery, which is at least partly explained by the self-sealing ability of bentonitic buffer materials.

A general conclusion is that the involved physical processes are well understood and that the ultimate physical state of the buffer materials under repository conditions can be safely predicted.

1985 **IR 85–13**

"CROSSHOLE INVESTIGATIONS – COMPILATION OF CORE LOG DATA FROM F1–F6"

S Carlsten, A Stråhle
Swedish Geological Co., Sweden

September 1985

TR 85–14

"FINAL REPORT OF THE BUFFER MASS TEST — Volume III: Chemical and physical stability of the buffer materials"

Roland Pusch
Swedish Geological Co., Sweden

November 1985

ABSTRACT

The Buffer Mass Test offered a possibility to investigate whether changes took place in the smectite component at heating to about one year. The alterations that could possibly take were a slight charge change in the crystal lattice with an associated precipitation of silica compounds, and a tendency of illite formation. The analysis showed that there were indications of both but to such a slight extent that the processes could not have affected the physical properties, which was also demonstrated by determining the swelling pressure and the hydraulic conductivity.

The BMT also showed that the erodibility of bentonite-based buffer materials is less than or about equal to what can be expected on theoretical grounds.

"CROSSHOLE INVESTIGATIONS – DESCRIPTION OF THE LARGE SCALE SITE"

Göran Nilsson, Olle Olsson
Swedish Geological Co., Sweden

February 1986

ABSTRACT

The Gideå site in Northern Sweden was selected as an experimental site for the large scale crosshole seismic field tests. The investigations made to characterize the site prior to the seismic tests cover an area of approximately 6 km^2 and extends to a depth of about 600 m. The Gideå site has a flat topography, insignificant soil depth and a high percentage of outcrops. The dominating rock type is veined gneiss of North-Easterly structural strike and small dip. In conformity with the structure of the gneiss there are strata of granite gneiss. The proportion of the granite gneiss in the boreholes is 6%.

Outside the Gideå site there are regional fracture zones towards the West-North-West and the North-West. Eleven local fracture zones have been identified within the site. The borehole investigations indicate that the fracture zones have an average width of 11 m and contain small portions of crushed and clay-altered rock. The fracture zones are steeply dipping with the exception of two subhorizontal zones in the northern and eastern parts of the site.

Existing strata of granite gneiss have a higher hydraulic conductivity compared to the surrounding veined gneiss. At a depth of 500 m the average hydraulic conductivity of the granite gneiss is 1.5×10^{-10} m/s and that of the veined gneiss 2×10^{-11} m/s. This implies anisotropic hydraulic properties in the rock mass with a higher hydraulic conductivity in the horizontal direction.

"HYDROGEOLOGICAL CHARACTERIZATION OF THE VENTILATION DRIFT (Buffer Mass Test) AREA, STRIPA, SWEDEN"

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February 1986

ABSTRACT

Fracture and hydrology data collected during the original KBS-LBL research program at Stripa, Sweden, have been reviewed, processed and analyzed in order to (1) describe the variation of permeability frequency and permeability with depth, (2) determine the relationship between fracture frequency and permeability, (3) calculate the parameters of the permeability and fracture aperture distributions, and (4) use the field data in a numerical simulation of the flow through the fracture network in the ventilation drift (Buffer Mars test) area at the Stripa site. These data include 766 injection and withdrawal tests that were completed in 3 surface and 15 subsurface boreholes. Detailed analysis of the hydrology and fracture data showed a general pattern of decreasing permeability with depth and no significant change in fracture frequency with depth in the surface boreholes. A weak correlation was found between fracture frequency and permeability in the subsurface boreholes. The large number of intervals with flowrates below the measurement limit of the packer test equipment produced truncation errors in the permeability and aperture data that were empirically corrected using cumulative probability plots.

The distribution parameters for fracture orientation, trace lengths, spacings and apertures for each of the four fracture sets, at the Stripa site, have been used as input for the generation of fracture networks for the ventilation drift (Buffer Mass Test) area. The total flowrates computed for these fracture networks, based on field defined hydraulic boundary conditions, agreed very closely with the flowrates measured during the macropermeability experiment when the mean fracture aperture used in the fracture network flow model was approximately equal to the mean aperture determined from the borehole packer injection tests.

1986 IR 86 – 03

"CROSSHOLE INVESTIGATIONS – THE METHOD, THEORY AND ANALYSIS OF CROSSHOLE SINUSOIDAL PRESSURE TESTS IN FISSURED ROCK"

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June 1986

ABSTRACT

This report describes the cross-hole hydrogeological testing technique known as sinusoidal pressure testing. The terms amplitude attenuation and phase lag which characterize a sinusoidal pressure test are defined and their measurement in the "Crosshole Programme" of the Stripa Project is described. The equipment to produce a sinusoidal variation is described in detail elsewhere but the computerized method of deriving the characteristic parameters, attenuation and phase lag, from the raw data is detailed. The small computer programme "SINEFIT" which performs this function is described in Appendix I.

Concepts of flow geometry are introduced in relation to sinusoidal tests and relationships between hydrogeological properties and measured characteristic parameters are derived. Mathematical solutions for a point source in a homogeneous porous medium, an isotropic fissured porous medium, an anisotropically fissured porous medium and a single fissure are given. The line source case in these configurations is introduced briefly as Appendix II. Additionally, for the fissured porous medium cases, the effect of differing shapes of matrix block is evaluated and a generalized solution applicable to fissured crystalline rock suggested. The possible option of mixing frequencies in a single test is considered unsuitable given the amount of background pressure fluctuation and the processing of the received signal. The inclusion of anisotropy produces large numbers of unknowns so a least squares interpretation procedure is introduced. This has been evaluated with a synthetic data set where it was found that fissure specific storage was effectively undefined. The accurate measurement of phase lag is crucial to test interpretation.

1986 **TR 86–04**

"EXECUTIVE SUMMARY OF PHASE 1"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

July 1986

SUMMARY OF CONCLUSIONS

The first phase of the Stripa Project concerned the development of methods and techniques for repository site investigations as well as verification of previously obtained laboratory results by in situ experiments.

The hydrogeological and hydrogeochemical investigations resulted in a recommendation on hydraulic testing at repository depth and the conclusion that detailed hydrogeochemical processes cannot be understood without the integrated use of several investigation techniques.

Increased knowledge on the detailed flow of water and migration of nuclides in single fractures have strengthened our confidence in predicted retardation. The diffusion of the radionuclides into the rock matrix and sorption onto fracture surfaces have proven to be active in situ processes.

The major conclusion from the investigation of bentonite as a buffer and backfilling material is that the main physical processes are understood and can be predicted for various repository geometries. The major process is water uptake from the rock since it governs the build-up of temperatures and swelling pressures. This uptake is primarily related to the water-bearing capacity of the surrounding rock and yields a fast maturation of the clay if the deposition holes are intersected by hydraulically active fractures. It was also concluded from the experiment that the techniques required for preparation and application of bentonite-based buffer materials are available.

TR 86–05

"ANNUAL REPORT 1985"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

August 1986

1987 **TR 87–01**

"FINAL REPORT OF THE BOREHOLE, SHAFT, AND TUNNEL SEALING TEST – Volume I: Borehole plugging"

R Pusch, L Börgesson
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January 1987

ABSTRACT
The Borehole Plugging Experiment comprised field tests of the sealing function and the practicality in handling and application of plugs consisting of segments of perforated metal casings filled with cylindrical blocks of highly compacted sodium bentonite. Preparative tests had shown that the clay swells out through the perforation and embeds the casings. The field tests demonstrated that even very long holes can be effectively sealed by such plugs and that the clay becomes very homogeneous and forms a tight contact with the rock in a relatively short time. By that the plugs become practically impervious and the flow along the clay/rock contact will be insignificant. The longevity of such plugs extends over several thousand years under the conditions that usually prevail in crystalline rock.

TR 87–02

"FINAL REPORT OF THE BOREHOLE, SHAFT, AND TUNNEL SEALING TEST – Volume II: Shaft plugging"

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G Ramqvist
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January 1987

ABSTRACT
Shaft sealing by use of highly compacted bentonite was investigated in a 14 m long shaft in which two plugs were constructed with a central sand-filled central space for injecting water. A first reference test with concrete plugs was followed by a main test in which the plug material consisted of blocks of highly compacted sodium bentonite powder. In the latter test, the outflow from the injection chamber was only a few percent of that with the concrete plugs, which demonstrates the excellent sealing properties of the clay. The main effect was that practically no water flow took place along the rock/clay interface. The longevity of smectite clay in crystalline rock is sufficient to make bentonite plugs operative for several thousand years.

1987 TR 87–03

"FINAL REPORT OF THE BOREHOLE, SHAFT, AND TUNNEL SEALING TEST – Volume III: Tunnel plugging"

R Pusch, L Börgesson
Swedish Geological Co., Sweden

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February 1987

ABSTRACT

Like the Borehole and Shaft plugging tests, the Tunnel test gave evidence of the very effective sealing power of Na bentonite. The test arrangement consisted of a 9 m long 1.5 m diameter steel tube surrounded by sand and cast in concrete plugs at each end. These plugs contained bentonite forming "O-ring" sealings at the concrete/rock interface. The test had the form of injecting water into the sand and measuring the leakage that took place through the adjacent rock and along the plug. It was concluded that the drop in leakage from more than 200 l/hour at 100 kPa water pressure early in the test to 75 l/hour at 3 MPa pressure at the end was due partly to the swelling pressure exerted by the bentonite on the rock and by penetration of bentonite into water-bearing rock fractures. The major sealing process appears to be the establishment of a very tight bentonite/rock interface.

1987 TR 87–04

"CROSSHOLE INVESTIGATIONS – DETAILS OF THE CONSTRUCTION AND OPERATION OF THE HYDRAULIC TESTING SYSTEM"

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May 1986

ABSTRACT

The Crosshole Programme, part of the international Stripa Project is designed to evaluate the effectiveness of various remote-sensing techniques in characterising a rock mass around a repository. A multidisciplinary approach has been adopted in which various geophysical, mapping and hydrogeological methods are used to determine the location and characteristics of significant features in the rock. The Programme utilises six boreholes drilled in a fan array from the 360 metre level in the Stripa Mine, Sweden.

The hydrogeological component of the work uses single and crosshole testing methods, including sinusoidal pressure testing, to locate fractures and characterise groundwater movement within them. Crosshole methods use packers to isolate portions of two boreholes which both intersect a significant feature in the rock mass. Hydraulic signals are generated in one isolated section and received in the other borehole. This report describes the design and operation of the computer-controlled system which automatically performs the hydrogeological tests.

Key words: Hydrogeological testing, equipment, mines, single hole testing, crosshole testing, sinusoidal testing.

1987 **IR 87–05**

"WORKSHOP ON SEALING TECHNIQUES, TESTED IN THE STRIPA PROJECT AND BEING OF GENERAL POTENTIAL USE FOR ROCK SEALING"

R Pusch
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February 1987

1 INTRODUCTION

While conventional rock sealing is normally made by use of cement grouts, clay has been applied in the very comprehensive rock sealing study that is part of the Stripa Project. This enterprise is an autonomous OECD project, financed and supervised by USA, Switzerland, Japan, Canada, Finland, Great Britain, France, Spain and Sweden. The major item has been to investigate the sealing power of sodium bentonite for the following purposes:

- To create a low-permeable envelope of metal canister with highly radioactive wastes.
- To plug boreholes and shafts so that the opening gets backfilled with a medium of lower hydraulic conductivity than the excavated rock.
- To seal off strongly water-bearing rock zones from intersecting tunnels while leaving a sufficiently large part of the plug open for vehicles etc.

The first-mentioned item was covered in the Buffer Mass Test (BMT), in which a setup was investigated that can be considered as an almost full-scaled version of the Swedish KBS 3 concept, while the other two served to investigate how the near-field isolation effect could be improved by sealing certain important structures which may indirectly affect the canister isolation. While the BMT involved application of thermal gradients to the clay, which largely affected the water uptake, the other tests were conducted at normal rock temperature, i.e. around 10°C.

The common feature of all the tests was that the sealing effect was obtained by the ability of Na bentonite to take up water and expand to fill up the space which was supposed to be sealed.

1987 TR 87–06

"CROSSHOLE INVESTIGATIONS – RESULTS FROM SEISMIC BOREHOLE TOMOGRAPHY"

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December 1986

ABSTRACT

A system for seismic crosshole measurements has been designed, built and tested. The system can be used both for small-scale (ie 10 – 200 m) and large-scale (ie 200 – 1000 m) operations.

The design includes both borehole receivers, amplifiers and recording system. The receivers can be used down to 700 m depth in slim boreholes.

Much work has gone into the development of analysis methods. Tomographic algorithms have been developed for the analysis of seismic data. The development includes basic theory as well as numerical methods.

Special care has been taken to minimize systematic errors. Many data quality checks have been made.

Field tests have been carried out at the large-scale test site at Gideå and at the small-scale test site at Stripa.

In the large-scale test some zones of fractured rock were found. In addition, there appears to be a relatively large area of rock without any major anomalous features.

It appears that problems asscociated with large-scale crosshole seismics are still substantial. Further work is needed to solve the problems with ray-bending and anisotropy.

In the small-scale test the measurements could be carried out with high precision. Several zones with different properties are visible in the tomograms.

It is our opinion that the technique for small-scale crosshole seismics is now developed to a level where it can be utilized as a useful tool for rock-quality assessment.

1987 **TR 87–07**

"REFLECTION AND TUBEWAVE ANALYSIS OF THE SEISMIC DATA FROM THE STRIPA CROSSHOLE SITE"

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December 1986

ABSTRACT

Reflection and tubewave analysis has been made using existing seismic crosshole data. The purpose of the work was to test if crosshole data are suitable for analysis by reflection and tubewave analysis methods.

The data from the crosshole research program (radar, seismics and hydraulics) in the Stripa Phase II Project resulted in the construction of a model. The results from the present study were compared to this model.

It was found that the existing data set used for tomographic analysis could only be used to a limited extent, as reflection analysis requires a more dense detector coverage. Nevertheless two reflectors were detected. The positions of the reflectors were compared to the existing crosshole model and proved to correlate well.

For the tubewave analysis almost all crosshole seismic data could be used. By comparing the results with previous hydraulic tests, it was found that tubewave sources and hydraulically conductive zones are in concordance. All previously defined zones but one could be detected.

1987 **TR 87–08**

"CROSSHOLE INVESTIGATIONS – SHORT AND MEDIUM RANGE SEISMIC TOMOGRAPHY"

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February 1987

ABSTRACT
Seismic tomographic tests were conducted as a part of the Crosshole Investigations program of the Stripa Project. The aim has been to study if it is possible to detect by seismic tomography major fracture zones and determine their dimensions and orientation. The analysis was based on both compressional (P) and transversal (S) waves. The Young's modulus has been also calculated for a sub-set of measurements as a cross check for the P and S wave velocities.

The experimental data was collected at the crosshole site in the Stripa mine during 1984–1985. A down-thehole impact source was used together with triaxial detectors and a digital seismograph. Five tomographic sections were obtained. The number of records per section was appr. 250. Measurements were done down to 200 m depth in all boreholes.

The main conclusion of this report is that it is possible to detect major fracture zones by seismic tomography. Their position and orientation can also be estimated.

TR 87–09

"PROGRAM FOR THE STRIPA PROJECT PHASE 3, 1986 – 1991"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

May 1987

1987 **TR 87–10**

"CROSSHOLE INVESTIGATIONS – PHYSICAL PROPERTIES OF CORE SAMPLES FROM BOREHOLES F1 AND F2"

K-Å Magnusson, S Carlsten, O Olsson
Swedish Geological Co., Sweden

June 1987

ABSTRACT
The geology and physical properties has been studied of roughly 100 core samples from the boreholes F1 and F2 drilled at the Crosshole site, located at the 360 m level in the Stripa mine. The granitic rock has been divided into two classes: fracture zones (also called major units) and a rock mass which is relatively undeformed. Samples from the major units have lower resistivity, higher porosity and dielectric constant than the samples from the less deformed rock mass.

The electrical properties of the core samples have been measured over a frequency interval ranging from 1 Hz to 70 MHz. The conductivity of the samples increases with frequency, approximately with the frequency raised to the power 0.38. The dielectric constant decreases with frequency but is essentially constant above 3 MHz. These results show that the Hanai-Bruggeman equation can be used to describe the electrical bulk properties of the Stripa granite.

The electrical conductivity of the samples is well correlated to the water content of the samples. The granite has a small contents of electrically conductive minerals which could influence the electrical bulk properties.

1987 TR 87–11

"CROSSHOLE INVESTIGATIONS – RESULTS FROM BOREHOLE RADAR INVESTIGATIONS"

O Olsson, L Falk, O Forslund, L Lundmark, E Sandberg
Swedish Geological Co., Sweden

May 1987

ABSTRACT

The borehole radar method has been developed and applied to the localization and characterization of fracture zones in crystalline rock. In a geological medium such as crystalline rock there is a significant attenuation of the radar waves, increasing with frequency. There is, however, a frequency window from a few MHz to a few hundred MHz where the wave aspect of the radar dominates and acceptable ranges can be achieved.

A new borehole radar system has been designed, built and tested. The system consists of borehole transmitter and receiver probes, a signal control unit for communication with the borehole probes, and a computer unit for storage and display of data. The system can be used both in singlehole and crosshole modes and probing ranges of 115 m and 300 m, respectively, have been obtained at Stripa. The borehole radar is a short pulse system which uses center frequencies in the range 20 to 60 MHz, corresponding to wavelengths of a few meters in the rock.

Single hole reflection measurements have been used to identify fracture zones and to determine their position and orientation. The zones often cause strong and well defined reflections originating from the resistivity change at the edges of the zones. The exact orientation of the zones can be determined by combining data from several boreholes.

Reflections are also observed in crosshole measurements. A new technique has been developed for the analysis of crosshole reflection data which in principle allows the orientation to be uniquely determined if the boreholes are not in the same plane.

The travel time and amplitude of the first arrival measured in a crosshole experiment can be used as input data in a tomographic analysis. Tomographic inversion has given detailed information about the extent of fracture zones in the plane spanned by the boreholes as well as a quantitative estimate of their electrical properties.

The radar method has been intensively tested at Stripa and has been shown to be an efficient instrument for locating and characterizing fracture zones. It is a unique instrument combining a resolution on the order of meters with probing ranges of about a hundred meters.

Keywords: Borehole radar, reflection, crosshole tomography, fracture zones, site investigations.

1987 **TR 87–12**

"STATE-OF-THE-ART REPORT ON POTENTIALLY USEFUL MATERIALS FOR SEALING NUCLEAR WASTE REPOSITORIES"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

June 1987

IR 87–13

"ROCK STRESS MEASUREMENTS IN BOREHOLE V3"

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July 1987

ABSTRACT
Hydrofracturing rock stress measurements have been conducted in a 50 m deep, vertical borehole at the end of the 3-D migration test drift in the Stripa Mine to determine the horizontal stress field in the test block of Phase 3 of the Stripa Project. The orientation of the maximum horizontal stress is found to be N71° W. The magnitude of the minimum horizontal stress is 11.1 MPa and the maximum stress is approximately twice as large. The vertical stress is found to be equal to the lithostatic stress from the weight of the overburden. The results are in excellent agreement with previous measurements in a deep surface borehole some 200 m to the NW of the test block but disagree to the stress data from the buffer mass test area located at similar distance but to the SW of the block. An attempt to measure the three-dimensional state of stress in the rock by injection tests on preexisting fractures in the borehole was not successful as the data set collected by the method was incomplete.

TR 87–14

"ANNUAL REPORT 1986"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

August 1987

1987 TR 87–15

"HYDROGEOLOGICAL CHARACTERIZATION OF THE STRIPA SITE"

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June 1987

ABSTRACT

This study was initiated in January, 1986, to determine a) if the permeability of the rock mass in the immediate mine area was anisotropic, b) the effective and total fracture porosity distributions based on field and laboratory data and c) the three dimensional configuration of the groundwater flow system at Stripa in order to properly interpret the hydrogeological, geochemical and isotopic data. The borehole packer test data show that on average SBH1 and SBH2 have lower permeabilities than SBH3. This is consistent with the pattern that one would expect for the orientation of the boreholes with respect to in-situ stresses. Laboratory studies showed a strong decrease in fracture permeability with increase in normal stress in core samples containing natural fractures suggesting that anisotropy to flow in the vertical direction must exist, since in-situ stresses increase with depth. The contribution of fracture geometry to the rock mass flow anisotropy was analyzed using a fracture network generator to simulate fracture networks in three orthogonal planes. In the horizontal plane the relative flowrates indicate an anisotropy factor of 1.5 with the principal direction oriented North-Northwest. Similar degrees on anisotropy were determined for the two vertical planes.

The total and flow porosities of single fractures from Stripa were determined in the laboratory using a resin impregnation technique. The equivalent uniform apertures for two samples, computed using the measured variation in fracture aperture and resin thickness, were consistent with apertures computed from the hydraulic data. The mean effective porosity contributed by the fractures in the rock mass calculated by combining the aperture data from the field packer tests with the fracture statistics for trace length and spacing was about an order of magnitude less than the porosity computed using the hydraulic data from the laboratory tests on single fractures in the core samples. More important, the porosity calculated using resin thickness data was almost a factor of 100 greater than that computed using the field data.

The three-dimensional numerical model gave mine inflows that were consistent with the measured mine inflows with perturbations extending to at least 3.000 m of depth. Transit times predicted from the flow tube calculations were much shorter than those predicted from the existing geochemical and isotopic data for porosities developed from field data. Corrections for the higher porosities determined from laboratory studies gave transit times that were more consistent with those inferred from isotope studies.

1987 **TR 87–16**

"CROSSHOLE INVESTIGATIONS – FINAL REPORT"

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Vibrometric OY, Finland

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National Defence Research Institute, Sweden

September 1987

The Crosshole programme has comprised the development of borehole radar, borehole seismic, and hydraulic testing methods. These methods provide data on the electric, elastic, and hydraulic properties of the rock. For each of these methods new equipment has been development, field tests have been performed, interpretation techniques developed and tested on the obtained data. Finally, a comparison of the results obtained with the different methods has been made.

During the course of the Crosshole project the radar and seismic methods have been taken from the prototype stage into being practical site characterization tools.

The analysis of the radar and seismic data has given a consistent description of the fracture zones at the Crosshole site in agreement with geological and other geophysical observations made in the boreholes. The geophysical methods have achieved a resolution of a few metres combined with a probing ranges of a few hundred metres.

The hydraulic investigations within the Crosshole project have yielded substantial progress in assessing the hydrogeology of fractured granitic rocks. The crosshole hydraulic testing concentrated on measuring the distribution of hydraulic properties within the extensive fractured zones identified by geophysics. An approach was adopted based on a sinusoidally varying pressure and flow rate to minimize testing time and to allow the signal to be observed against a changing background.

A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This is a versatile analysis well-suited to the sort of flow geometries likely to be found in crystalline rocks.

The combined analysis of the geophysical and the hydraulic data set has shown that groundwater flow is concentrated within a few major features which have been identified by the geophysical methods. The main features are considered to be broadly planar, containing patches of high and low hydraulic conductivity. The fracture zones are likely to be channelled, where the flow paths constitute a branching interconnecting network.

1987 IR 87–17

"SITE CHARACTERIZATION AND VALIDATION – GEOPHYSICAL SINGLE HOLE LOGGING"

B Fridh
Swedish Geological Co., Sweden

December 1987

ABSTRACT
Five "boundary boreholes" have been drilled for preliminary characterization of a previously unexplored site at the 360 m level in the Stripa mine. Three of these boreholes are directed towards the North in the mine coordinate system, while two are directed towards the West. Furthermore, a vertical hole has been drilled at the end of the 3D-migration drift.

To adequately describe the rock mass in the vicinity of these boreholes, a comprehensive program utilizing a large number of geophysical borehole methods has been carried out.

The specific geophysical character of the rock mass and the major deformed units distinguished in the boreholes are recognized, and in certain cases also correlated between the boreholes.

Key words: Granite, geophysical borehole logging, fracture zones.

1987 TR 87–18

"CROSSHOLE INVESTIGATIONS – HYDROGEOLOGICAL RESULTS AND INTERPRETATIONS"

J Black, D Holmes, M Brightman
British Geological Survey, United Kingdom

December 1987

ABSTRACT

The Crosshole Programme was an integrated geophysical and hydrogeophysical study of limited volume of rock (known as the Crosshole Site) within the Stripa Mine. Borehole radar, borehole seismic and hydraulic methods were developed for specific application to fractured crystalline rock.

The hydrogeological investigations contained both single borehole and crosshole test techniques. A novel technique, using a sinusoidal variation of pressure, formed the main method of crosshole testing and was assessed during the programme. The strategy of crosshole testing was strongly influenced by the results from the geophysical measurements.

The single borehole testing comprised roughly equal amounts of constant head and slug/pulse testing. Transmissivities varied between values around 1×10^{-12} $m^2 sec^{-1}$ and 5×10^{-7} $m^2 sec^{-1}$. For the most part high transmissivities were associated with geophysically identifiable fracture zones. Test zone lengths varied between 2 and 13 m and few tests were interpretable as single fissure responses.

The crosshole sinusoidal testing was carried out using computer-controlled test equipment to generate the sinusoidally varying head in a single zoner (the "source") isolated by packers. A second ("receiver") borehole contained a number of straddle intervals and was used to observe the propagation of the sinusoidal signal. The number of positive responses was limited and flow appeared to be concentrated within a few "channels". Analysis was attempted using single fissure, regularly fissured and porous medium models. None gave satisfactory fits to the measured data. A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This yields results involving "fractional dimensions" where flow may be assumed to occur within regions which do not fit within the existing 1, 2 and 3 dimensional models. This is a versatile analysis, well-suited to the sort of flow geometries likely to be found in crystalline rocks.

The long term, larger scale hydrogeological response of the region was assessed by examining the variation of heads over the region. These were responding to the presence of an old drift. A method of overall assessment involving minimising the divergence from a homogeneous response yielded credible values of hydraulic conductivity for the rock as a whole.

1987

TR 87–19

"3-D MIGRATION EXPERIMENT – REPORT 1 SITE PREPARATION AND DOCUMENTATION"

H Abelin, L Birgersson
Royal Institute of Technology, Sweden

November 1987

ABSTRACT
This report is one of the four reports describing the Stripa 3D experiment where water and tracer flow has been monitored in a specially excavated drift in the Stripa mine. The experiment was performed in a specially excavated drift at the 360 m level in granite. The whole ceiling and upper part of the walls were covered with more than 350 individual plastic sheets where the water flow into the drift could be collected. 11 different tracers were injected at distances between 11 and 50 m from the ceiling of the drift. The flowrate and tracer monitoring was kept up for more than two years. The tracer breakthrough curves and flowrate distributions were used to study the flow paths, velocities, hydraulic conductivities, dispersivities and channelling effects in the rock.

The present report describes how the site was prepared and what documentation is available.

TR 87–20

"3-D MIGRATION EXPERIMENT – REPORT 2 INSTRUMENTATION AND TRACERS"

H Abelin, L Birgersson, J Gidlund
Royal Institute of Technology, Sweden

November 1987

ABSTRACT
This report is one of the four reports describing the Stripa 3D experiment where water and tracer flow has been monitored in a specially excavated drift in the Stripa mine. The experiment was performed in a specially excavated drift at the 360 m level in granite. The whole ceiling and upper part of the walls were covered with more than 350 individual plastic sheets where the water flow into the drift could be collected. 11 different tracers were injected at distances between 11 and 50 m from the ceiling of the drift. The flowrate and tracer monitoring was kept up for more than two years. The tracer breakthrough curves and flowrate distributions were used to study the flow paths, velocities, hydraulic conductivities, dispersivities and channelling effects in the rock.

The present report describes the instrumentation developed and used as well as the tracers that were tested and used in the experiment.

Part I "3-D MIGRATION EXPERIMENT – REPORT 3 PERFORMED EXPERIMENTS, RESULTS AND EVALUATION"

H Abelin, L Birgersson, J Gidlund, L Moreno, I Neretnieks, H Widén, T Ågren
Royal Institute of Technology, Sweden

November 1987

Part II "3-D MIGRATION EXPERIMENT – REPORT 3 PERFORMED EXPERIMENTS, RESULTS AND EVALUATIONS, APPENDICES 15, 16 AND 17"

H Abelin, L Birgersson, J Gidlund, L Moreno, I Neretnieks, H Widén, T Ågren
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November 1987

ABSTRACT

This report is one of the four reports describing the Stripa 3D experiment where water and tracer flow has been monitored in a specially excavated drift in the Stripa mine. The experiment was performed in a specially excavated drift at the 360 m level in granite. The whole ceiling and upper part of the walls were covered with more than 350 individual plastic sheets where the water flow into the drift could be collected. 11 different tracers were injected at distances between 11 and 50 m from the ceiling of the drift. The flowrate and tracer monitoring was kept up for more than two years. The tracer breakthrough curves and flowrate distributions were used to study the flow paths, velocities, hydraulic conductivities, dispersivities and channelling effects in the rock.

The present report describes the structure of the observations, fracture mapping the flowrate measurements and how these were used to estimate the hydraulic conductivities. The main part of this report addresses the interpretation of the tracer movement in the rock outside the drift. The tracer movement as measured by the more than 160 individual tracer curves has been analyzed with the traditional advection-dispersion model, but also with more recent models which include the effects of channelling and the diffusion of tracers into stagnant waters in the rock matrix and in stagnant waters in the fractures themselves. The tracer experiments have permitted the flow porosity and dispersion to be studied.

1987 **TR 87—22**

"3-D MIGRATION EXPERIMENT — REPORT 4 FRACTURE NETWORK MODELLING OF THE STRIPA 3-D SITE"

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November 1987

ABSTRACT

This report is one of the four reports describing the Stripa 3D experiment where water and tracer flow has been monitored in a specially excavated drift in the Stripa mine. The experiment was performed in a specially excavated drift at the 360 m level in granite. The whole ceiling and upper part of the walls were covered with more than 350 individual plastic sheets where the water flow into the drift could be collected. 11 different tracers were injected at distances between 11 and 50 m from the ceiling of the drift. The flowrate and tracer monitoring was kept up for more than two years. The tracer breakthrough curves and flowrate distributions were used to study the flow paths, velocities, hydraulic conductivities, dispersivities and channelling effects in the rock.

The present report describes how fracture statistics and a fracture network model have been used to interpret the flow pattern in the 3D-drift.

"CROSSHOLE INVESTIGATIONS – IMPLEMENTATION AND FRACTIONAL DIMENSION INTERPRETATION OF SINUSOIDAL TESTS"

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British Geological Survey, United Kingdom

February 1988

ABSTRACT

The Crosshole Programme was an integrated geophysical and hydrogeological study of a limited volume of rock (known as the Crosshole Site) within the Stripa Mine. Borehole radar, borehole seismic and hydraulic methods were developed for specific application to fractured crystalline rock.

The hydrogeological investigations contained both single borehole and crosshole test techniques. A novel technique, using a sinusoidal variation of pressure, formed the main method of crosshole testing and was assessed during the programme. The strategy of crosshole testing was strongly influenced by the results from the geophysical measurements.

The crosshole sinusoidal testing was carried out using computer-controlled test equipment to generate the sinusoidally varying head in a single zone (the "source") isolated by packers. A second ("receiver") borehole contained a number of straddle intervals and was used to observe the propagation of the sinusoidal signal. The number of positive responses was limited and flow appeared to be concentrated within a few "channels". Analysis was attempted using single fissure, regularly fissured and porous medium models. None gave satisfactory fits to the measured data. A new analysis involving the "dimension" of the flow test has been developed to analyse the results of the crosshole sinusoidal testing. This analysis allows the dimension of the flow to assume non-integer values whereas conventionally the dimension is taken as either one, two or three, for example, radial flow in a uniform planar fissure would be two dimensional.

The new model is found to give a more consistent description of the test data than the conventional models and suggests a complex pattern of fracture properties within each fracture zone. However, the results presented must be considered as being preliminary since we still have much to learn about how to best apply this model and present the results. Also, it is not yet clear how the derived value of "dimension" can be related to the transport properties of the rock.

1988 **IR 88 – 02**

"SITE CHARACTERIZATION AND VALIDATION – MONITORING OF HEAD IN THE STRIPA MINE DURING 1987"

S Carlsten, O Olsson, O Persson, M Sehlstedt
Swedish Geological Co.

Sweden, April 1988

ABSTRACT
The groundwater head has been monitored in 26 borehole sections surrounding the site which is investigated as a part of the Site Characterization and Validation Project. This report contains basic data on the head monitoring system and graphical presentation of the results obtained during 1987.

Keywords: Piezometric head, monitoring system, crystalline rock.

TR 88 – 03

"SITE CHARACTERIZATION AND VALIDATION – BOREHOLE RADAR INVESTIGATIONS, STAGE I"

O Olsson, J Eriksson, L Falk, E Sandberg
Swedish Geological Co.

Sweden, April 1988

ABSTRACT
The borehole radar investigation program of the SCV site has comprised single hole reflection measurements with centre frequencies of 22, 45, and 60 MHz. Crosshole tomographic measurements have been made between the boreholes W1–W2, N2–N3, N3–N4, and N2–N4. Crosshole reflection measurements have also been made between the same boreholes. The radar range obtained in the single hole reflection measurements was approximately 100 m for the lower frequency (22 MHz) and about 60 m for the centre frequency 45 MHz. In the crosshole measurements transmitter-receiver separations from 60 to 200 m have been used.

The radar investigations have given a three dimensional description of the structure at the SCV site. A generalized model of the site has been produced which includes three major zones (RA, RB, and RH), four minor zones (RC, RD, RK, and RL), and a circular feature (RQ). These features are considered to be the most significant at the site. Smaller features than the ones included in the generalized model certainly exist but no additional features comparable to the three major zones are thought to exist. The results indicate that the zones are not homogeneous but rather that they are highly irregular containing parts of considerably increased fracturing and parts where their contrast to the background rock is quite small. The zones appear to be approximately planar at least at the scale of the site. At a smaller scale the zones can appear quite irregular.

Keywords: Borehole radar, fracture zones, granite

"ROCK SEALING – LARGE SCALE FIELD TEST AND ACCESSORY INVESTIGATIONS"

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March 1988

SUMMARY

The experience from the pilot field test and the basic knowledge extracted from the lab experiments have formed the basis of the planning of a Large Scale Field Test. The intention is to find out how the "instrument of rock sealing" can be applied to a number of practical cases, where cutting-off and redirection of groundwater flow in repositories are called for. Five field subtests, which are integrated mutually or with other Stripa projects (3D), are proposed. One of them concerns "near-field" sealing, i e sealing of tunnel floors hosting deposition holes, while two involve sealing of "disturbed" rock around tunnels. The fourth concerns sealing of a natural fracture zone in the 3D area, and this latter test has the expected spin-off effect of obtaining additional information on the general flow pattern around the norhteastern wing of the 3D cross. The fifth test in an option of sealing structures in the Validation Drift. The longevity of major grout types is focussed on as the most important part of the "Accessory Investigations", and detailed plans have been worked out for that purpose.

It is foreseen that the continuation of the project, as outlined in this report, will yield suitable methods and grouts for effective and long-lasting sealing of rock for use at strategic points in repositories.

TR 88–05

"HYDROGEOCHEMICAL ASSESSMENT OF CRYSTALLINE ROCK FOR RADIOACTIVE WASTE DISPOSAL THE STRIPA EXPERIENCE"

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August 1988

ABSTRACT

This report presents a programme for the hydro-geochemical assessment of a crystalline rock site for radioactive waste disposal. It is based upon experience gained during the international programme of hydrochemical work at the Stripa mine. The important results of this work are summarised in this report and fuller details may be found in the separate final reports of the Phase 1 and Phase 2 geochemical investigations of the Stripa groundwaters.

The present report summarises the general sampling requirements for a successful hydrochemical investigation; the isotopic and chemical parameters which should be determined and the geochemical characterization of the rock matrix necessary for the interpretation of hydrochemistry. A general strategy for site evaluation by geochemical methods is presented.

TR 88–06

"ANNUAL REPORT 1987"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

June 1988

"SITE CHARACTERIZATION AND VALIDATION – RESULTS FROM SEISMIC CROSSHOLE AND REFLECTION MEASUREMENTS, STAGE 1"

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Vibrometric OY, Finland

Monica Hammarström, Per Norén, Jörgen Pihl
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September 1988

ABSTRACT

The SCV site has been surveyed by seismic crosshole and reflection methods. The analysis shows a rather patchy structure, with features of three main orientations.

Three crosshole sections were measured. Tomographic analyses were made using both Direct Inversion and Conjugate Gradient methods. Six major features were found. Most of these seem to have a rather uneven structure.

Reflection measurements were made using a VSP geometry. Two zero offset and one 70 m offset sections were recorded. By means of an elaborate signal analysis many structures become visible. The correlation with the tomographic analysis is good. In addition to the major features several other ones can be found following one of the three main directions.

The borehole geometry of the SCV site is not the optimum for a survey of this type. A larger angle between the planes of the W and N sections would have made it possible to determine the dips of the features with higher accuracy.

1988 **IR 88 – 08**

“STAGE 1 JOINT CHARACTERIZATION AND STAGE 2 PRELIMINARY PREDICTION USING SMALL CORE SAMPLES”

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August 1988

ABSTRACT
This report describes the preliminary results from an investigation of joint surfaces from small diameter core samples from sections of the boreholes W1, N3 and W2. Fracture surface features such as roughness and compression strength have been measured for each individual joint, and the data has been grouped in the two major joint sets as described by John Gale (6).

The data are presented as histograms and frequency diagrams to define natural variation and mean values for each parameter.

Finally, the report gives a prediction of shear strength, vs shear deformation and change of joint aperture vs normal loading and conductivity change as result of this loading.

IR 88 – 09

“SITE CHARACTERIZATION AND VALIDATION – HYDROCHEMICAL INVESTIGATIONS IN STAGE 1”

P Wikberg, M Laaksoharju, J Bruno, A Sandino
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September 1988

ABSTRACT
The chemical composition of the groundwater in the SCV site has been determined. The samples have been taken from the boreholes N2, N3, N4, W1 and W2. A groundwater flow pattern has been established on the basis of the results. The redox conditions in the groundwater/rock system have been evaluated by analyses of the redox sensitive groundwater components iron, sulphide and uranium.

1988 **IR 88–10**

"SITE CHARACTERIZATION AND VALIDATION – DRIFT AND BOREHOLE FRACTURE DATA, STAGE I"

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September 1988

ABSTRACT

This report describes the procedures used in mapping fractures intersecting seven scanlines along the southern and eastern boundaries of the Site Characterization and Validation (SCV) site and the procedures used in logging and orienting the fractures intersecting the core from six "boundary boreholes" that were drilled as part of the site characterization program for the SCV site at the 360 m level in the Stripa mine. Scanline mapping along the mine drifts provided a detailed description of the fracture geometry on the boundaries of the SCV site. The cores from the boundary boreholes have been logged, reconstructed and oriented using a borehole Televiewer and a borehole TV camera and the true fracture orientations calculated. This has provide additional data on the fracture geometry within the SCV site.

The fracture data from both the scanlines and the core logging are presented in the Appendices. In addition, an initial analysis has been completed of the fracture orientations, trace lengths and spacings. Based on the variation in fracture orientations over the SCV site, there are two strong sub-vertical fracture sets or clusters and a poorly represented sub-horizontal fracture set. An empirical approach, based on the "blind zone" concept has been used to correct for orientation bias and to predict the orientations of the fracture system that will be intersected by the C and D boreholes in Stage III.

1988 **TR 88 – 11**

"ROCK SEALING – INTERIM REPORT ON THE ROCK SEALING PROJECT (STAGE I)"

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September 1988

ABSTRACT

The objective of the Sealing Project is to find ways of sealing finely fractured rock by grouting. This requires development of new injection technique as well as to identify materials which are sufficiently fluid to be groutable and acceptably low-pervious and physically and chemically stable. The present report describes the results of the first two years of investigation (Stage 1), which gave very positive results as concluded from a large field-scale test.

"EXECUTIVE SUMMARY OF PHASE 2"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

February 1989

SUMMARY OF CONCLUSIONS

The Second Phase of the Stripa Project included the continued development of methods and techniques for repository site investigations. The crosshole investigations demonstrated that it is possible to characterize fractures in crystalline rock with a reliability and realism not obtained before. At the investigated site at Stripa, it was shown that groundwater flow is concentrated within a few major fractures that were identified by geophysical methods. The main features were considered to be broadly planar, containing patches of high and low hydraulic conductivity.

Detailed investigations of the fracture hydrology at Stripa and of the migration of tracers in the groundwater, together with additional information of the groundwater composition, resulted in an improved knowledge of the groundwater flow in fractured crystalline rock. The work at Stripa has shown that it is possible to collect and analyze data that enable one to determine the type of distribution and its parameters for each of the essential geometrical and hydraulic properties of the fracture system, and hence compare one site with another as part of experience building in safety assessment studies. The migration experiment demonstrated that the groundwater flow could be very unevenly distributed in the rock. Together with the tritium measurements it also gave strong support to the notion that a non-negligible portion of the flow takes place in channels which have little contact with other main channels. A further research effort has to be devoted to development of appropriate numerical models for the description of flow in fractured crystalline rock. The hydrogeochemical investigations at Stripa also indicated that a new type of solute source must be considered – fluid inclusions in the host rock. The age of the solutes may be entirely different from the age of the groundwater. At Stripa, the age of the solutes is likely to be hundreds of millions of years older than the groundwaters. Furthermore, this source contributes the largest portion of the total porosity. Although fluid inclusions are considered to be a residual or non-flow porosity, it could become part of the flow porosity through microfracturing brought about by changing stress fields.

Sealing and redirection of the groundwater flow away from man made openings in the rock was tested at Stripa and found to be feasible as shown in the various plugging and sealing experiments. The use of Na bentonite in the form of suitably shaped blocks of highly compacted powder has been found to be very practical for sealing off boreholes, shafts and tunnels in repositories. The net hydraulic conductivity of the clay plugs formed when the initially partially unsaturated clay takes up water from the rock and expands, is significantly lower than the gross permeability of the surrounding rock. A very important function of the clay is that it forms a tight, integrated contact with the rock, so that water flow along the rock contact is hindered. The compressibility and expandability of the clay means that this tight contact is preserved even if slight rock displacements occur.

"FRACTURE FLOW CODE CROSS-VERIFICATION PLAN"

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March 1989

ABSTRACT

The hydrology of the SCV site will be modelled utilizing discrete fracture flow models. These models are complex, and can not be fully verified by comparison to analytical solutions. The best approach for verification of these codes is therefore cross-verification between different codes. This is complicated by the variation in assumptions and solution techniques utilized in different codes.

Cross-verification procedures are defined which allow comparison of the codes developed by Harwell Laboratory, Lawrence Berkeley Laboratory and Golder Associates Inc. Six cross-verification datasets are defined for deterministic and stochastic verification of geometric and flow features of the codes. Additional datasets for verification of transport features will be documented in a future report.

"SITE CHARACTERIZATION AND VALIDATION STAGE 2 – PRELIMINARY PREDICTIONS"

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J Gale
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May 1989

ABSTRACT

The Site Characterization and Validation (SCV) Project is designed to assess how well we can characterize a volume of rock prior to using it as a repository. The programme of work focuses on the validation of the techniques used in site characterization. The SCV Project contains 5 stages of work arranged in two "cycles" of data-gathering, prediction and validation. The first stage of work has included drilling of 6 boreholes (N2, N3, N4, W1, W2 and W3) and measurements of geology, fracture characteristics, stress, single borehole geophysical logging, radar, seismics and hydrogeology.

The rock at the SCV site is granite with small lithological variations. Based essentially on radar and seismic results 5 "fracture zones" have been identified, named GA, GB, GC, GH and GI. They all extend across the entire SCV site. They are basically in two groups (GA, GB, GC and GH, GI). The first group are aligned N40°E with a dip of 35° to the south. The second group are aligned approximately N10°W dipping 60°E.

From the stochastic analysis of the joint data it was possible to identify three main fracture orientation clusters. The orientation of two of these clusters agree roughly with the orientation of the main features. Cluster B has roughly the same orientation as GH and GI, while features GA, GB and GC have an orientation similar to the more loosely defined cluster C. The orientation of the third cluster (A) is northwest with a dip to northeast.

It is found that 94% of all measured hydraulic transmissivity is accounted for by 4% of the tested rock, not all of this "concentrated" transmissivity is within the major features defined by geophysics. When the hydraulic connections across the site are examined they show that there are several welldefined zones which permit rapid transmission of hydraulic signals. These are essentially from the northeast to the southwest.

1989 **IR 89 – 04**

"SITE CHARACTERIZATION AND VALIDATION – SINGLE BOREHOLE HYDRAULIC TESTING, STAGE 1"

D Holmes
British Geological Survey, United Kingdom

March 1989

ABSTRACT

This report describes the procedures used in measuring distributions of hydraulic conductivity and head of the six "boundary borehole" which form part of the Site Characterization and Validation (SCV) programme. A novel multipacker system, utilising total computer control and data analysis, has been used to measure the hydraulic parameters in test sections from 7 to 1 m in length. Generalised equipment descriptions and detailed results are included in this report.

The distribution of hydraulic conductivity has been correlated with measured fracture positions and orientations for each borehole. Values of hydraulic conductivity and hydraulic aperture have been assigned to each "coated" fracture which has been logged as being capable of transporting groundwater. Distribution statistics have been calculated for various fracture "sets". These distributions form part of the input required for fracture network modelling of the SCV site.

TR 89 – 05

"ANNUAL REPORT 1988"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

May 1989

1989 **IR 89 – 06**

"SITE CHARACTERIZATION AND VALIDATION – MONITORING OF HEAD IN THE STRIPA MINE DURING 1988"

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O Olsson
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M Sehlstedt
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April 1989

ABSTRACT

The groundwater head has been monitored in 47 borehole sections surrounding the site which is investigated as a part of the Site Characterization and Validation Project. This report contains basic data on the head monitoring system and graphical presentation of the results obtained during 1988.

IR 89 – 07

"SITE CHARACTERIZATION AND VALIDATION – GEOPHYSICAL SINGLE HOLE LOGGING, STAGE 3"

P Andersson
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May 1989

ABSTRACT

A total of 15 boreholes have been drilled for preliminary characterization of a previously unexplored site at the 360 and 385 m level in the Stripa mine.

To adequately describe the rock mass in the vicinity of these boreholes, a comprehensive program utilizing a large number of geophysical borehole methods has been carried out in 10 of these boreholes.

The specific geophysical character of the rock mass and the major deformed units distinguished in the vicinity of the boreholes are recognized, and in certain cases also correlated between the boreholes.

A general conclusion based on the geophysical logging results, made in this report, is that the preliminary predictions made in Stage 2, of the site characterization and validation project (Olsson et al., 1988) are adequate. The results from the geophysical logging can support the four predicted fracture/fracture zones GHa, GHb, GA and GB whereas the predicted zones GC and GI are hard to confirm from the logging results.

"WATER FLOW IN SINGLE ROCK JOINTS"

E Hakami
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May 1989

ABSTRACT

To study the hydromechanical properties of single rock joints a technique to make transparent replicas of natural joint surfaces has been developed. Five different joint samples were replicated and studied. The aperture distribution of the joints were obtained through a measurement method provided by the transparent replicas. The principle behind the method is that a water drop with a known volume, which is placed inside a joint, will cover a certain area of the surface depending on the average size of aperture at the actual point.

Flow tests were performed on the same joint replicas. The tortuosity of the flow and the velocity along single stream lines were measured using colour injections into the water flow through the joints. The equivalent hydraulic apertures determined from the flow tests were shown to be smaller than the average mechanical apertures. The velocity of the flow varies strongly between different paths over the joint depending on the spatial distribution of the apertures. The degree of matedness between the joint surfaces is an important factor influencing the channelling character of the joints.

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John H Black
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"Rock Sealing – Large Scale Field Test and Accessory Investigations"
R. Pusch
Clay Technology, Sweden
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J. Andrews
University of Bath, United Kingdom
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US Geological Survey, USA
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September 1988

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"Stage I Joint Characterization and Stage II Preliminary Prediction using Small Core Samples"
G. Vik
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Norwegian Geotechnical Institute, Norway
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P. Wikberg
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J. Gale
Fracflow Consultants Inc., Nfld., Canada
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Swedish Geological Co, Uppsala, Sweden
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"Rock Sealing – Interim Report on the Rock Sealing Project (Stage I)"
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A. Herbert
AERE Harwell Laboratory, U. K.
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"Site Characterization and Validation - Single Borehole Hydraulic Testing"
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"Site Characterization and Validation — Monitoring of Head in the Stripa Mine During 1988"
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Lawrence Berkeley Laboratory, Berkeley, USA
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A. Herbert
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