nagra
National Cooperative for
the Disposal of Radioactive Waste

TECHNICAL REPORT 91-29

STRIPA PROJECT

ANNUAL REPORT 1990

JULY 1991

Hardstrasse 73, CH-5430 Wettingen/Switzerland, Telephone + 41-56-37 11 11

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Der vorliegende Bericht betrifft eine Studie, die für das Stripa-Projekt ausgeführt wurde. Die Autoren haben ihre eigenen Ansichten und Schlussfolgerungen dargestellt. Diese müssen nicht unbedingt mit denjenigen des Auftraggebers übereinstimmen.

Le présent rapport a été préparé pour le projet de Stripa. Les opinions et conclusions présentées sont celles des auteurs et ne correspondent pas nécessairement à ceux du client.

This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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
1990

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 1990.

Stockholm

July 1991

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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,

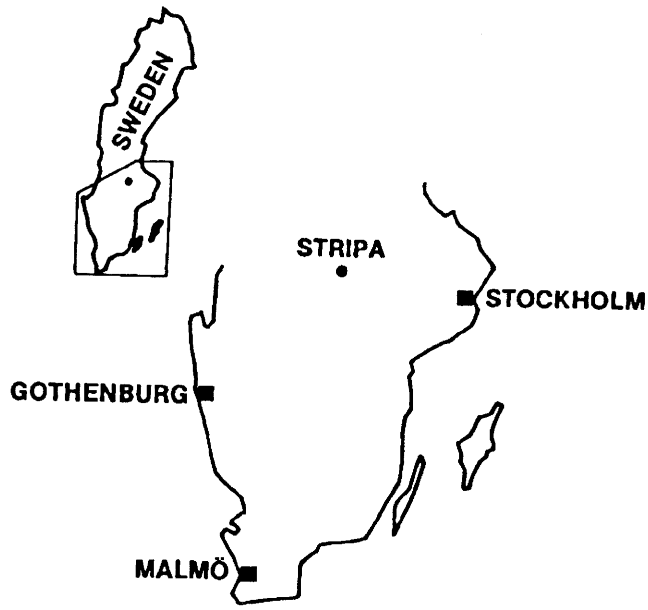

Figure 1-1. The Stripa Mine is located approximately 250 km west of Stockholm.

– 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 Sub-group (TSG). The sub-group is composed of scientists from the participating countries. It deals with geology, geophysics, hydrogeology, numerical modelling

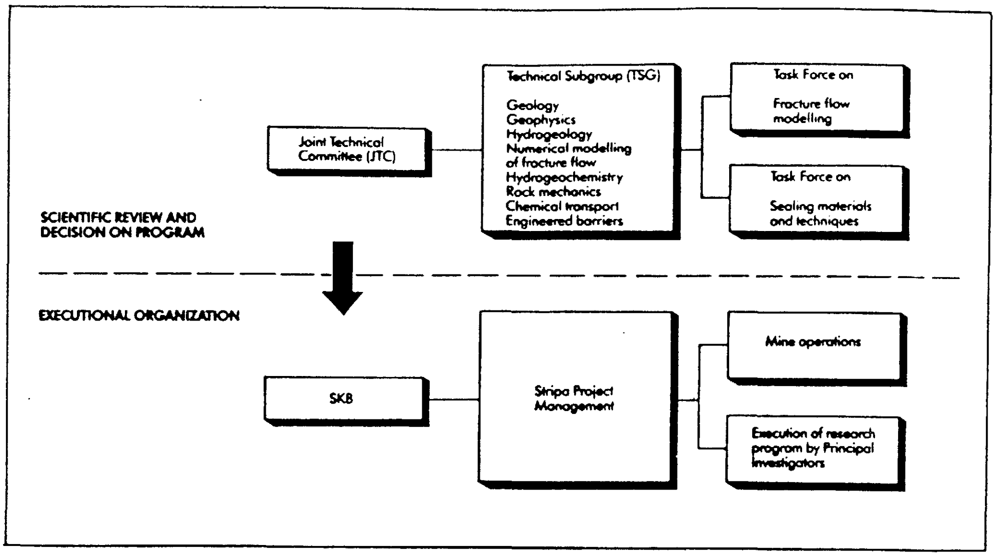

Figure 1-2. Organization of the Stripa Project.

of fracture flow, hydrogeochemistry, rock mechanics, chemical transport and engineered barriers.

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 Conterra AB 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 Thirteenth meeting of the Joint Technical Committee was held in Winnipeg, Canada in the third quarter of 1990. Among others the following decisions were made by the JTC:

1. As part of the final reporting of the International Stripa Project two overview reports will be made concerning;
   * The Site Characterization and Validation Program including the program for Improvements of Site Assessment Methods and Concepts.
   * The Program for Sealing Materials and Techniques.
2. A fourth Stripa Symposium will be arranged in 1992.
3. Founding will be reserved for a second Simulated Drift Experiment.

The Annual Meeting of the Technical Subgroup was held in Interlaken, Switzerland in the first quarter of 1990;

- The TSG discussed and approved the report "Process and Criteria of Validation of Groundwater Flow Models in the SCV Program" as prepared by the Fracture Flow Modelling Task Force.
- The TSG made the following principal proposals to the JTC on additional work within the Phase 3 program:
  * Re-Testing of the Remaining D-boreholes.
  * Continuation of the Work by John Gale in Support to the Harwell Modelling Work.
  * Laboratory investigations of the Durability of "Porous" Grout.
  * Second Phase of the Radar/Saline Tracer Experiment.

The four proposals were approved by the JTC soon after the TSG meeting.

The Task Force on Fracture Flow Modelling and the Task Force on Sealing Materials and Techniques held two separate meetings each.

3 PHASE 3

3.1 SITE CHARACTERIZATION AND VALIDATION

3.1.1 Introduction

The Site Characterization and Validation (SCV) Project is a five year program (1986-1991) which focusses on the problem of validating the correctness of the techniques and approaches used in site characterization. The central aims of the program are to:

– develop and apply an advanced site characterization methodology,
– develop and apply a methodology to validate that the models (both conceptual and numerical) are appropriate to the processes under examination.

The basic experiment of the SCV Project is to predict the distribution of water flow into a potential drift (tunnel), excavate the drift, measure the inflows and compare measurements with prediction. In support of the basic experiment there are a number of subsidiary experiments such as an assessment of channelling, the small scale hydrogeological effects of drift excavation, and tracer tests associated with fracture zones.

The concept underlying the SCV Project is that model-based predictions should be checked against experimental results on an iterative basis. Hence, the SCV Project reduces to a series of cycles of data-gathering, prediction, and validation. In fact, the project contains two cycles of this type where predictions are checked against observation 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	|
III	Detailed characterization and preliminary validation	88-89	validation/ data gathering	↓ ↑
IV	Detailed predictions	89-90	prediction	second
V	Detailed evaluation	90-91	validation	↓

The project aims at characterizing in detail a volume of rock which is about 125 m by 125 m in plan and about 50 m deep. The study site is situated around 380 m below ground to the north of the mined-out region of the Stripa Mine. The program 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.

Stage I comprised drilling of 5 boreholes and performing investigations in them. During Stage II the data were analyzed and a conceptual model of the site devised (Olsson, Black, Gale, and Holmes, 1989). This model was the basis for preliminary numerical predictions of the groundwater inflow to a set of boreholes (the D-boreholes) outlining the Validation Drift to be excavated during Stage V (Geier, J., Dershowitz, W., and Sharp, G., 1990; Herbert, A., and Splawski, B., 1990; Long, J., Karasaki, K., Davey, A., Peterson, J., Landsfeld, M., Kemeny, J., and Martel, S., 1990). During Stage III a number of boreholes were drilled in the central portion of the site and investigations made in them to provide data for detailed predictions of inflow to the drift and for validation of inflow predictions to the D-boreholes. Stage IV comprised an update of the conceptual model based on the additional data available and compilation of data needed for the numerical predictions of the inflow distribution into the Validation Drift.

3.1.2 Conceptual Model of the SCV-site (Stage IV)

3.1.2.1 Major Features

During the course of the SCV Project it has been assumed that a binary representation of the rock mass as "major features" (considered to be fracture zones) and "background rock" (or averagely fractured rock) is justified. The underlying assumption is that the "major features" should account for significant fractions of the flow across the site.

A binary representation of the rock mass has to be based on measured physical properties in specified locations. Hence, the data used for such a definition must be the measurements of the physical properties in the vicinity of the boreholes.

Based on principal component analysis of the results from sonic and resistivity logging, hydraulic conductivity, radar and open fracture measurements, we have constructed a "fracture zone index" (FZI). The frequency distribution of the "fracture zone index" (FZI) values for all boreholes shows a skewed distribution (see Figure 3-1). It is not bi-modal but can be considered to consist of two parts.

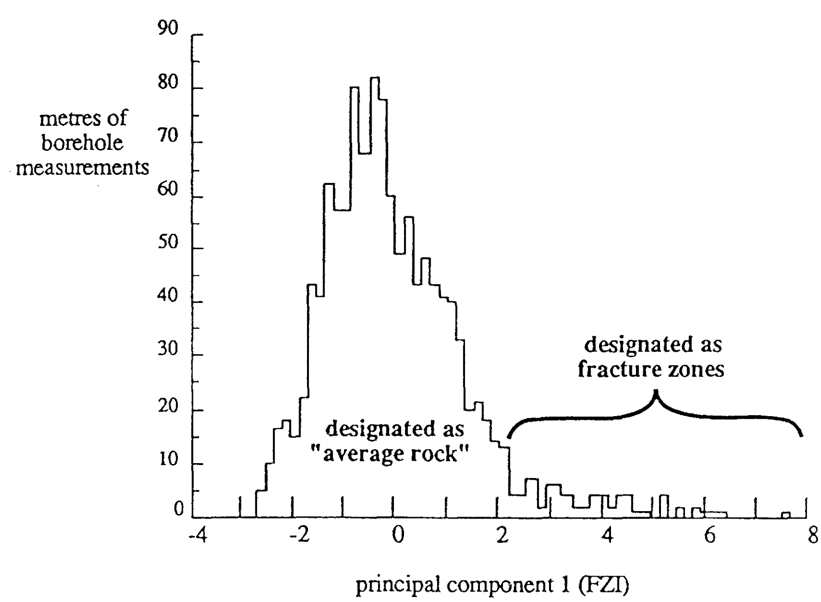

Figure 3-1. Frequency distribution of "fracture zone index" based on all boreholes at the SCV-site.

Based on the frequency distribution of the "fracture zone index" (FZI) we consider it justifiable to use a binary description by dividing the rock mass into "background rock" (FZI <2) and "major features" (FZI >2). Thus, using the index (i.e. the FZI), we can define the points in the boreholes which are considered to represent the occurrence of "major features" or "fracture zones".

The connection of features between boreholes, their extent and geometry are found through the use of remote sensing geophysics. The conceptual model of the SCV-site contains three major features or fracture zones named A, B, and H. These features are considered to extend beyond the limits of the SCV-site. Features A and B are thought to be parts of the major feature which can be observed as a 3 km long morphological lineament on the surface. H is also considered to extend to the surface where it has an extent of about 1 km. The connection between the SCV-site and the surface provided by these features is thought to cause the high heads observed at the SCV-site.

The properties and width of these major features are highly variable where they are observed intersecting the boreholes. The apparent width or thickness in the boreholes varies from 2 m to 21 m. Taking the relative orientation of the features to the boreholes into account, the maximum real width is approximately 15 m. At the borehole intersections the features generally exhibit anomalous properties compared to "background rock". This is demonstrated by the fracture zone index which has an average of approximately 2.5 for these zones. Fracture zone index anomalies are generally smaller in the southern part of the site and larger towards the north. The borehole with the largest anomalies is W2 which is probably caused by the proximity of W2 to the intersections of A, B, and H. These major features are important for the groundwater flow system across the SCV-site in that they account for 75% of the hydraulic transmissivity as measured by single hole hydraulic tests.

Three minor features named I, K, and M with an extent of 50 – 100 m have also been identified. These features are associated with fracture zone index anomalies close to or just below 2. Using the strict definition of major features (i.e. FZI >2), these features do not qualify as "major" since the fracture zone index is generally less than 2. However, these features are clearly observed in the remote sensing data (radar and seismics) and it has been possible to determine their orientation and extent. Another reason for including them in the conceptual model is that they provide hydraulic connections between the major features A, B, and H. These minor features account for 4% of the single hole hydraulic transmissivity measured in the boreholes.

The features identified at the SCV-site can also be divided into three sets based on orientation (see Figure 3-2):

- Features A and B strike N45E and dip 40-50S. They are considered to be part of the same regional structure. Their strike is approximately parallel to the Guldsmedshytte syncline and the fold axis of the synform making up the iron ore formation of the Stripa Mine.
- Features H and I strike approximately N5W and dip steeply (63 – 76°) to the east. The orientation of H and I coincides with the dominant fracture orientation observed in the cores and along scanlines. This orientation is also observed for faults in the mined out region.
- The minor features K and M strike N60W and dip steeply toward the NE (65-87°). They are only a few meters wide and their properties contrast only mildly with the background rock. However, they may still be important hydrogeologically as their orientation involves low normal stress on the fracture planes.

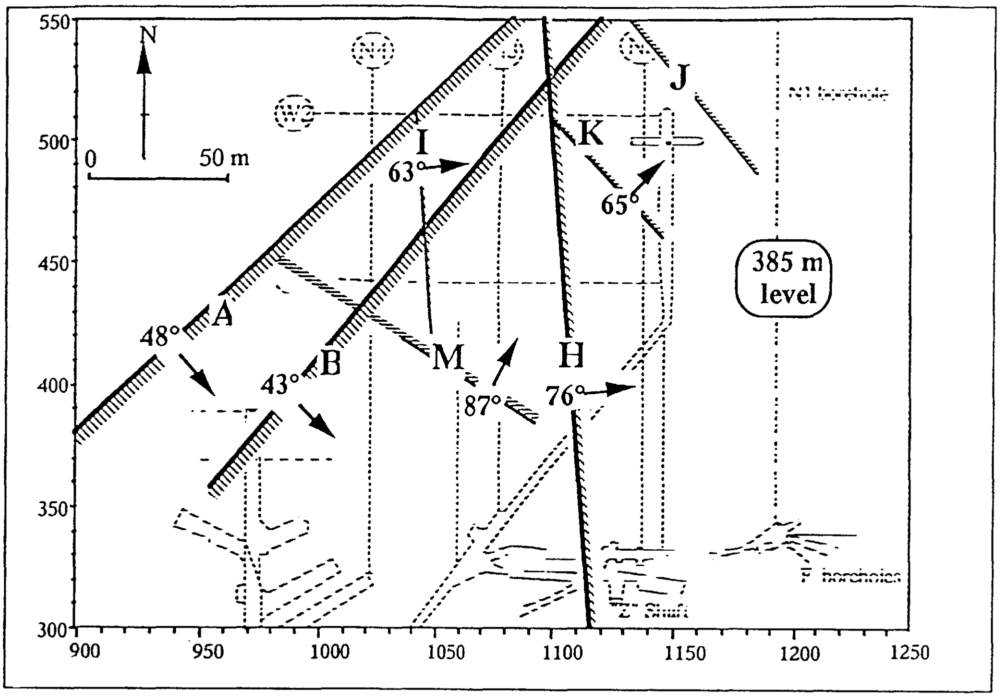

Figure 3-2. Plan view of the features contained in the revised conceptual model of the SCV-site. The map shows the location of the features at the 385 m level.

A plan view of the location of the identified features at the 385 m level of the mine is shown in Figure 3-2 and a perspective view of the features is shown in Figure 3-3. From the figures it is evident that A, B, and H intersect just north of W2. Feature I connects A and B with each other and borehole Wl. K connects borehole N2 with zone H.

The consistency of the model and its relevance for groundwater flow through the site have been tested by crosshole hydraulic tests. The general observations from the crosshole hydraulic tests can be summarized as follows:

- hydraulic responses are generally observed at expected locations consistent with the various positions of the source within the conceptual model,
- there are only a few locations (approximately 5 %) without responses where responses would have been expected. These locations normally correspond to fracture zone intersections where very low permeability was observed in single hole tests. It is assumed that the fracture zone is locally poorly permeable,
- a number of responses are observed outside the defined fracture zones. In particular Wl and W2 tend to respond as units, i.e. practically all test sections in these holes respond simultaneously and with similar magnitude. Responses in W2 are considered to be due to a well connected system in this region caused by the proximity of the intersections of fracture zones A, B, and H. Responses in Wl may be due to a feature observed in the radar/saline tracer tests with an approximate orientation of N60E/60SE. Other responses are thought to be caused by minor fractures connecting to the major zones. It has not been possible to positively determine the orientation of these features,

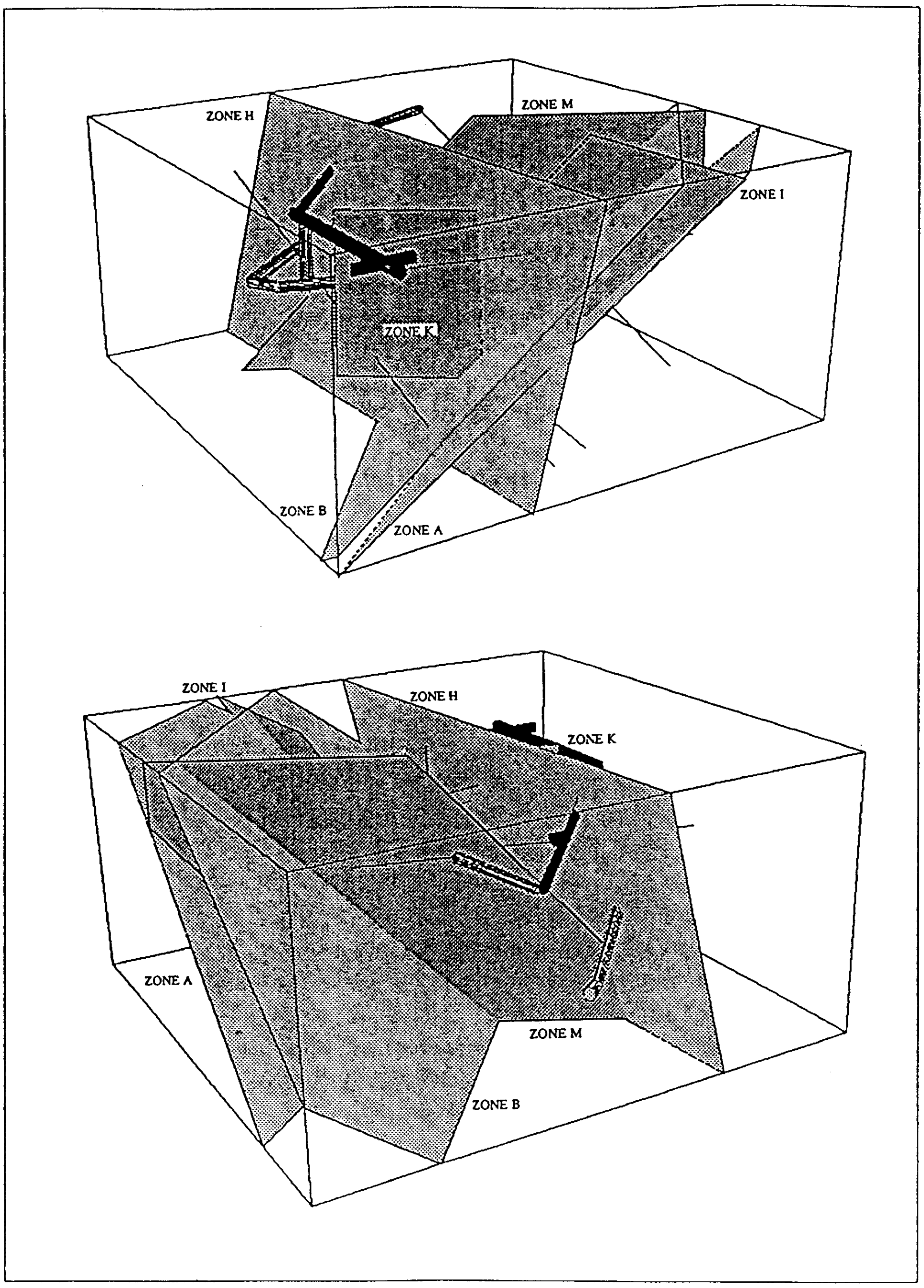

Figure 3-3. The location of all the features of the conceptual model in 3D space.

- hydraulic responses in the R-boreholes are observed in crosshole hydraulic tests where the source is located in zones A or B. Zones A and B are not predicted to intersect the R-boreholes but will pass close by. Responses in the R-boreholes are believed to be due to minor features which are connected to Zones A and B,
- hydraulic responses are observed in borehole I3 for tests where the source is in either A or B. Small responses are also observed for some source locations in H. The hydraulic connection between I3 and zone B is most likely provided by a minor fracture zone with an orientation similar to M and K, i.e. striking northwest with a steep dip towards north. This feature has been annotated J and its likely location is indicated in Figure 3-2. The existence of this feature is corroborated by the steeply dipping fractures striking northwest which are observed in the northern part of the 3D migration drift. No investigations to verify the existence of this zone has been made within the framework of the SCV Program.

In summary we conclude that the conceptual model gives a realistic representation of the flow system at the SCV-site. The features identified provide the major pathways for groundwater flow. These features act as "leaky aquifers" linked to the background rock by minor zones and joints.

3.1.2.2 Properties of Joints

The conceptual model of the SCV-site, in addition to the major features, also includes the description of orientation, spacing, trace lengths, and hydraulic properties of individual joints. This description is by virtue of the large number of fractures or joints stochastic.

From the combined Stage I and Stage III data set, we have identified two strong sub-vertical fracture clusters and a weaker sub-horizontal group or cluster. However, the horizontal bias in the scanline and borehole orientations produces an oversampling in the horizontal direction and the sub-horizontal fractures are lost in the tails of the sub-vertical fracture orientation distributions. Using classical contouring of poles to fracture planes and the more rigorous cluster analysis we were not able to determine if a strong sub-horizontal fracture system exists at the SCV-site or if it does exist that it was merely not well sampled. Hence, for numerical modelling purposes, we may have to accept a larger number of clusters than the three or four indicated by the scanline data. The fracture trace length and spacing statistics show that the fracture intensity increases towards the northwest corner of the SCV-site and that the North-South striking fracture set has a much higher density than the other sets or clusters.

The scanline fracture data were analyzed with respect to fracture mineralogy and termination mode. Fractures whose primary coating or filling material is epidote are associated with the 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 is associated with all orientations.

Analysis of fracture terminations shows that fractures with both ends free form two well defined fracture sets, the north-south and northwest-southeast trending sets, that have a mean intersection 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 suggest that they were the first fractures formed and that there were no preexisting fractures to terminate against.

For fractures which terminate in 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-junction fractures. The contour plot of the H-junction fractures shows increased strength of the sub-horizontal cluster which indicates that these were the last fractures to form.

The overall fracture characterization program in the Stripa Project also included five interrelated fracture testing programs. The first part of the fracture testing program consisted of index tests on 174 sections of fracture planes in core samples from the Stage I, 76 mm diameter, boreholes (Vik and Barton, 1988), that were carried out to provide data for predicting or calculating the stress-permeability relationships for the different fracture sets. The second stage of the program consisted of three programs of coupled stress-flow laboratory tests on a total of eight 200 mm diameter cores, each containing a single fracture parallel to the core axis (Hakami, 1989; Makurat et al., 1989, and Gale et al., 1990) to provide stress versus permeability relationships for calibration of empirical stress flow models. The final part of the fracture testing program consisted of a field experiment to determine the coupled stress-flow behavior of a 1.4 m long section of a fracture plane (Makurat et al., 1989) in order to determine its in situ behavior and assess the effects of sample size on the stress-permeability relationships.

The three laboratory studies plus the in-situ block test showed significant decreases of permeability with increase in stress. All of the fractures tested in this experimental program were representative of the more compliant fractures and were coated with chlorite. The experimental program showed a major difference between hydraulic and mechanical apertures, indicating that fracture porosities are much greater and fluid velocities are much slower than those predicted using flow and head measurements. The fracture planes tested also showed that the permeability tended to decrease slightly for small shear displacements, becoming dilatant at low normal stresses only after undergoing 0.1 mm or more of shear displacement.

3.1.2.3 Stress Boundary Conditions

Combining the in-situ stress measurements at Stripa that were made during the earlier phases of the project with those made during Stage I and Stage III of Phase 3 (McKinnon and Carr, 1990) determined the virgin stress tensor as shown in Table 3-1. This stress tensor was used to provide the boundary conditions for the 3D stress modelling of the SCV-site.

Table 3-1. Interpreted virgin stress tensor for SCV block.

Principal stress	Orientation (bearing/dip)	Magnitude by depth (MPa)
σ_1	105/00	7.5 + 0.044*D
σ_2	195/00	2.5 + 0.035*D
σ_3	Vertical	0.0 + 0.026*D

– D is depth below surface in meters,
– dip is positive down,
– bearing is positive clockwise from mine north.

The 3D numerical modelling was carried out by McKinnon and Carr (1990) in two stages in order to: a) determine the influence of the mine excavations on the stress field in the SCV block, and b) to examine in detail the state of stress around the Validation Drift, particularly at the locations of the fracture zones and in selected planes oriented perpendicular and parallel to the drift.

The program BEFE, a three dimensional hybrid boundary element/finite element program, was used in both stages of modelling (Lee et al., 1988). All of the locations of interest in and near the SCV block are in granite, and therefore, the entire rock mass in the model was taken to have granitic rock properties. Leptite surrounding the mine stopes was not explicitly modelled. The rock material was assumed to be homogeneous, isotropic, and linearly elastic. The fracture zones were not modelled explicitly but as artificial planes in a continuum.

The 3D stress modelling results suggested that the mine excavations have no effect on the stresses around the Validation Drift. Hence, only the drift itself was included in the model used to determine the effect of drift excavation on rock stresses near the Validation Drift. In addition to the generalized components of the stress tensor, the principal components of the stress tensor and their direction cosines were computed for six planes that were oriented perpendicular to the Validation Drift and for two orthogonal planes coaxial with the drift at the western end of the drift in order to examine stress concentrations near the end of the drift.

Because of the complexity of representing stress in three dimensions visually, contours of the stress difference ($\sigma_{max} - \sigma_{min}$) has been plotted for each plane. The contour intervals are in MPa. These plots show the important zone of stress concentration at the west end of the Validation Drift and the very high stresses at the top and bottom of the drift. The location of these zones of high stresses is controlled by the high horizontal stresses and high stress ratios. Figure 3-4 shows the general pattern of stress differences on a vertical plane, perpendicular to the drift, that is located approximately in the middle of the drift.

3.1.2.4 Disturbed Zone Effects

In addition to the 3D continuum stress modelling, 2D discrete fracture stress modelling was made using the UDEC (Universal Distinct Element Code) model. This model incorporates the discrete fracture network generated using the fracture geometry data, from the SCV block, in the discrete fracture code NAPSAC. Mechanical properties and constitutive relationships for each fracture plane were generated using the Barton-Bandis model index parameters measured on small sections of the fracture planes in the N and W borehole cores (Vik and Barton,

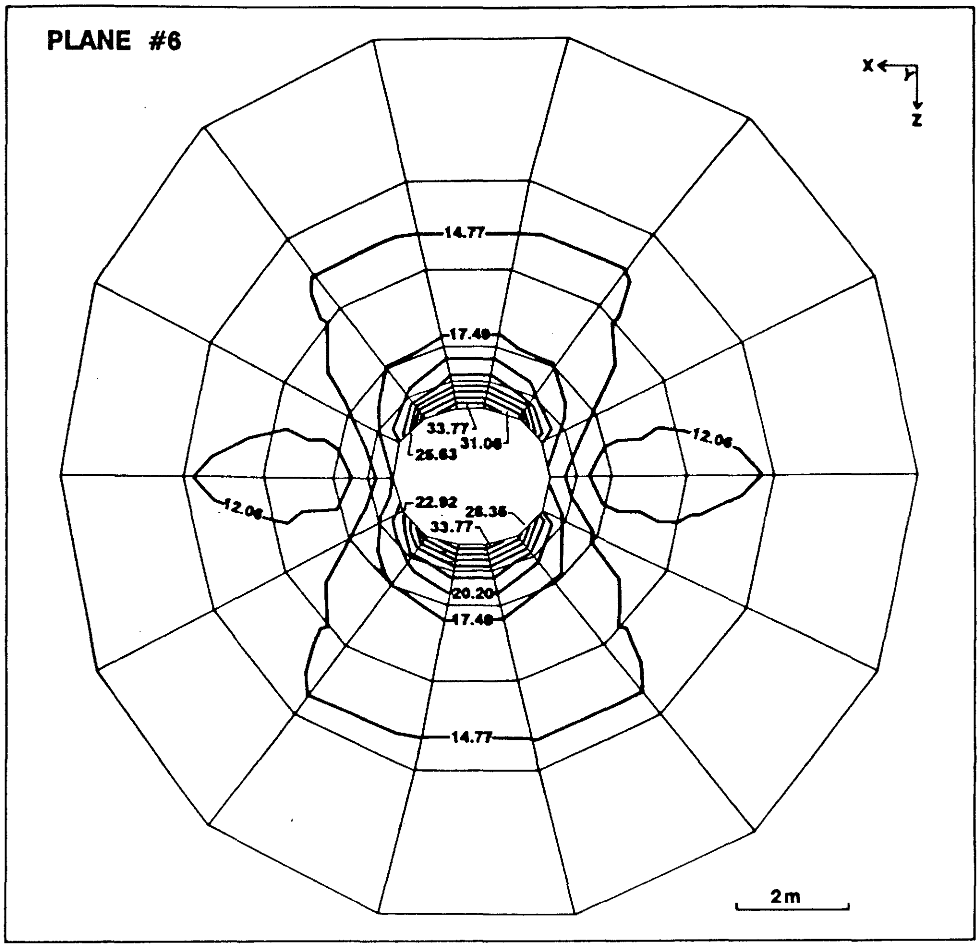

Figure 3-4. Stress difference contours in MPa for a plane perpendicular to the drift axis located approximately in the middle of the drift.

1988). The initial purpose of this 2D, discrete fracture, stress modelling was to determine if the rock-mass relaxation around the Validation Drift, produces a stress distribution that was significantly different from that generated using the 3D continuum stress model. The stress redistribution caused by excavation of the Validation Drift was expected to allow some joints to open due to reduced radial stresses, and others to close more due to increased tangential stresses.

Input data for the joint properties were obtained in the Stage I and Stage III joint index characterization briefly described above. Input data was organized in the form of histograms, so that the variability of the parameters JRC (Joint Roughness Coefficient), JCS (Joint wall Compressive Strength) and ϕ_r (residual friction angle) was accounted for.

Four of the eight UDEC-BB models run utilized mean values of these input parameters, while the other four models (with unchanged joint structures) utilized three sets of length-dependent values of the joint strength parameters. The longest joints were therefore given low values of JRC, JCS and ϕ_r to represent the frequently mineralized, smoother state of these features, while the shortest joints with less likelihood of interconnectivity, were given high values to represent rough, interlocked higher stiffness behavior. Joints of intermediate length were given intermediate properties.

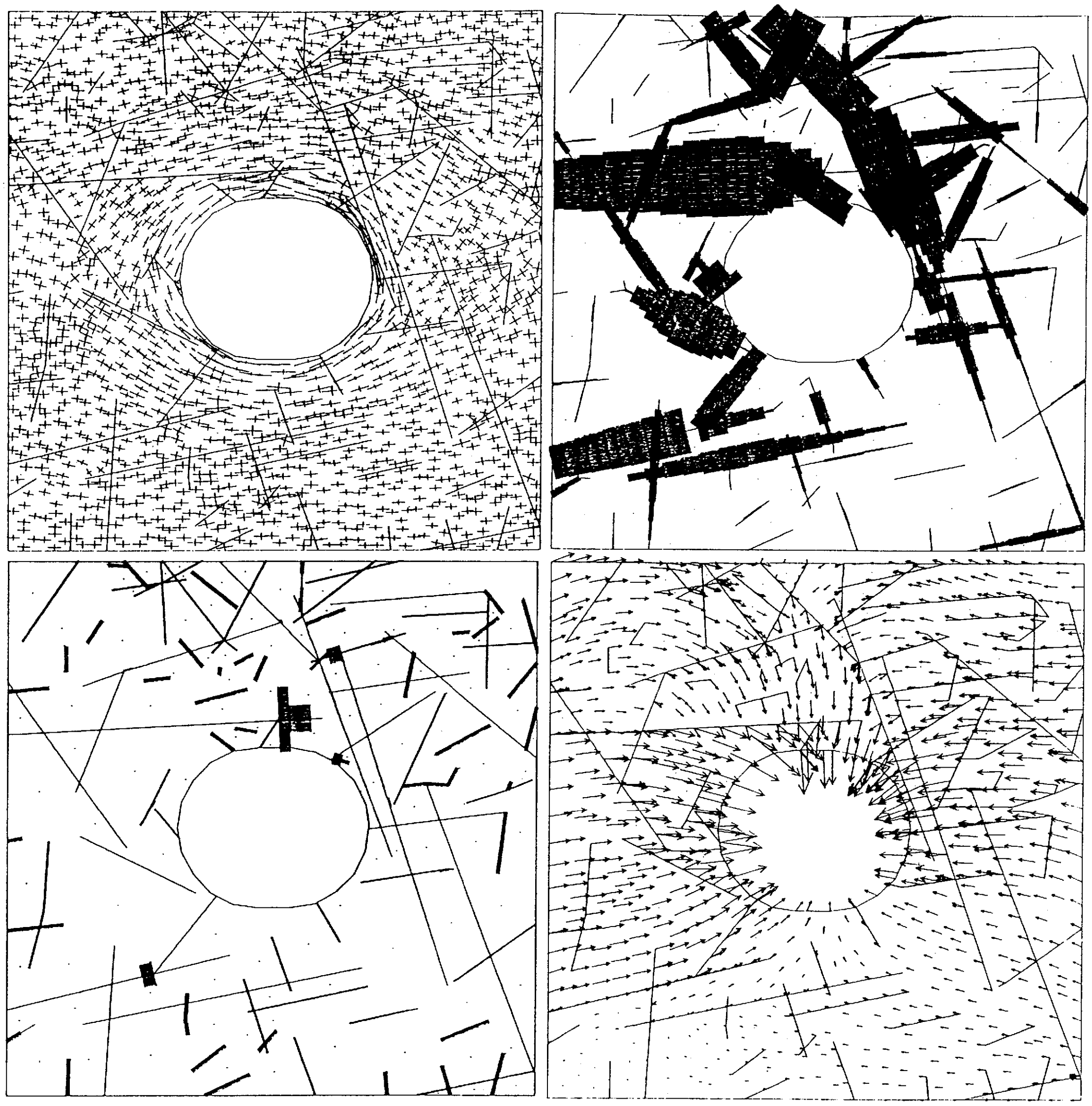

Figure 3-5. UDEC-BB model (no. 8) showing, in clockwise order; principal stresses (max. 61.9 MPa), joint shearing (max. 0.8 mm; 1 line = 10 μm), deformation (max. 1.32 mm), and major conducting apertures (max. 0.58 mm).

As a result of the numerical drift excavation, a variety of changes in the joint apertures occurred, some closing, others opening, some shearing and suffering dilation thereby potentially creating more openness. The stress redistribution, deformation, joint shearing and conducting apertures obtained from one of the models are shown in Figure 3-5.

In the models with length-dependent joint strength most aperture changes occurred in the 0.5 meter of rock nearest to the drift perimeter; an average of twelve joints per radial meter had changed aperture in this zone, while the next radial meter from 0.5 to 1.5 meters had 5 joints per meter with changed aperture, while from 1.5 to 3.0 meters only 3 joints per meter showed changed aperture. The most persistent joints had apertures of less than 1 μm prior to excavation, while joints of intermediate length were typically about 25 μm, and the roughest joints typically about 40 μm. Analysis of the post-excavation results shows that although the smoother persistent joints tended to shear most (generally between 0.3 and 0.9 mm), this was not enough to cause significant aperture changes since dilation was delayed and would have been weak anyway. In contrast, the shorter rougher joints were able to dilate slightly and increase their already higher initial aperture.

The shearing of joints in general, since limited to these moderate values of 0.3 to 0.9 mm, was more effective in generating channels at joint intersections than dilation related channels along a given joint plane. Examples of four joint intersection channels in one of the models are shown in Figure 3-5.

Channels that formed at joint intersections created local apertures of typically 150 to 350 μm and would provide potentially increased permeability parallel to the drift, generally at distances of 0.5 to 1.5 meters into the walls of the 2.8 m wide by 2.2 m high drift.

Detailed analysis were made of the excavation-induced tangential and radial stresses. These induced stress magnitudes were compared with those from an equivalent continuum model, which showed as expected, much more predictable stress gradients despite the anisotropy of stress and drift dimensions.

Peak tangential stresses of 55, 74, 64 and 62 MPa were registered in the four models with length-dependent joint parameters, while the continuum model registered a maximum tangential stress of 43 MPa (compared to virgin stresses of σ_v = 10 MPa and σ_h = 18 MPa). The continuum model registered a very small tensile stress (0.5 MPa) while the four jointed models registered maximum tensile stresses as high as 9 to 28 MPa, presumably due to block displacement.

Generally the level of tangential stress was lower in heavily jointed zones, and peak values tended to be reached about 0.5 to 1 meter from the periphery in these jointed models. High values of stress i.e. 25 to 40 MPa were registered as far as 2 to 3 meters from the drift walls in some cases.

Excavation induced deformations shown in Figure 3-6 showed maxima of 1.0 to 1.6 mm. Drift closures were therefore generally limited to 2 to 3 mm. The continuum result is, as expected, considerably different from the discontinuum results.

Excavation-induced joint shearing showed maximum values of 0.6 to 1.0 mm in both series of models. However, significantly larger magnitudes of joint shearing were seen in the three-joint-material models at some 2 to 3 meters from the drift, due to the reduced shear strength of the persistent mineralized joints. Their relative ease of shearing even at these distances from the periphery did not necessarily increase joint aperture or channel aperture, though potential for this is apparent in the case of a larger drift or in a more interconnected rock mass.

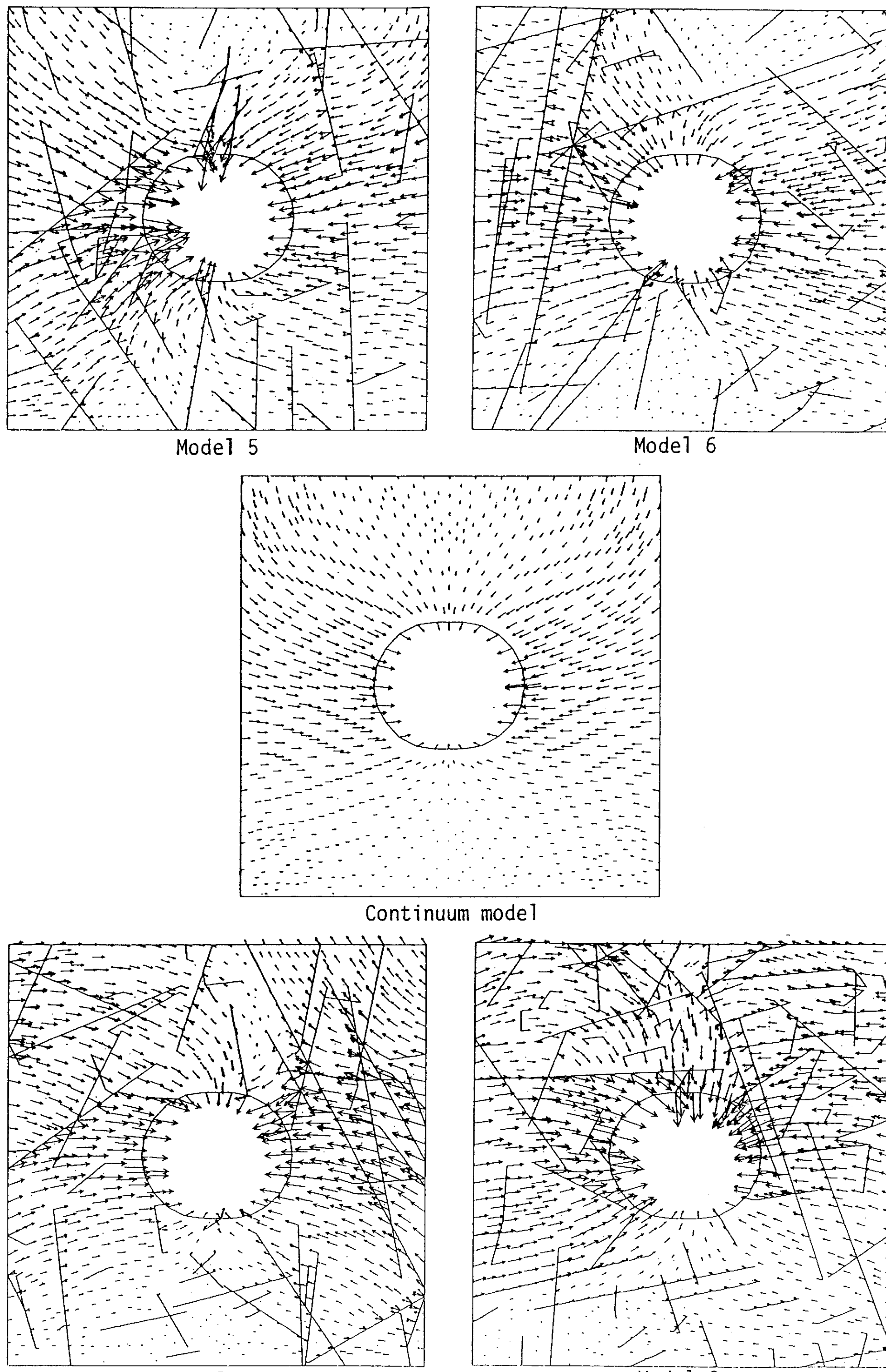

Figure 3-6. Deformation vectors in the four jointed models compared with the continuum model. Maxima were 1.55, 1.03, 0.75, 1.18, and 1.32 mm.

3.1.3 Detailed Evaluation (Stage V)

3.1.3.1 Excavation of the Validation Drift

The excavation of the Validation Drift started in November 1989 and was completed before the end of January 1990. The total length of the excavated drift is 50 m. The drift was made 3 m wide and 2.4 m high. To get a possibility to compare fracture data from the boreholes with data collected in the drift an attempt was made to make the drift profile intersect the D-boreholes. The elliptical shape of the drift made it only possible to retain boreholes D2, D3, and D6 on the drift perimeter.

A smooth blasting procedure was successfully used for excavation of the drift. The length of the blast holes which were drilled with hand held machines were approximately 2.2 m. The width of the drift is smallest at the start of each blast round and is approximately 20 cm wider at the end. The approximate shape of the drift perimeter and length profile is shown in Figure 3-7.

After cleaning of the drift a grid system was painted on the drift walls. Each grid cell has a size of approximately 1 m². The circumference of the drift is approximately 9 m varying somewhat due to the drill and blast procedure used. Hence, there are 9 grid cells around the periphery of the drift and about 50 cells along the extent of the drift, making a total of about 450 grid cells.

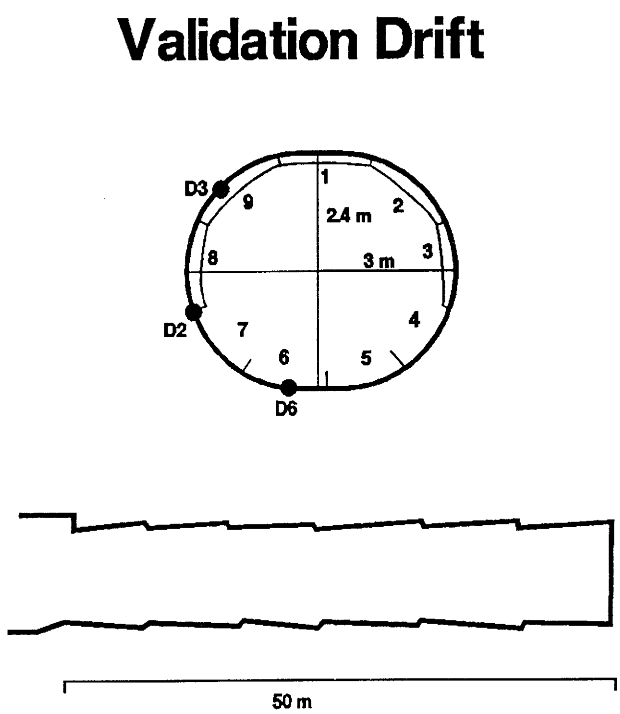

Figure 3-7. Approximate shape of the Validation Drift after excavation and division of perimeter into grid cells. Cells numbered 1, 2, 3, 8 and 9 are covered with plastic sheets.

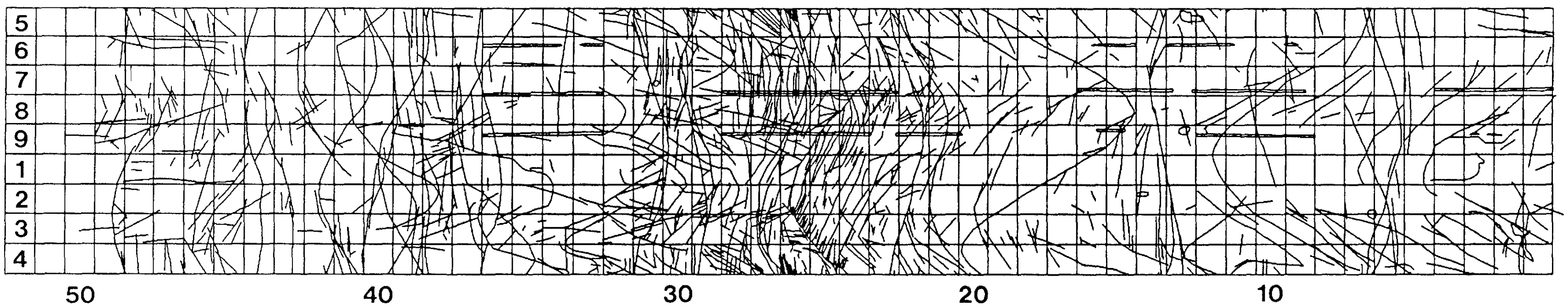

Figure 3-8. Plan view of the entire Validation Drift map. The map represents a surface that is approximately 9 meters in circumference and 50 meters long.

3.1.3.2 Fracture Characterization of the Validation Drift

The entire surface of the Validation Drift was mapped using the 1 m^2 reference grid painted on the drift surface described in the previous section. All of the fractures greater than 0.20 m in length were located on each grid cell, assigned a number and its orientation and other characteristics recorded. The field maps were digitized and cross-linked to the original field data files through a common numbering system.

Figure 3-8 shows the entire drift map and the mapping grid that were plotted using the digitized data. The top of the drift or the crown is located in the middle of grid square number one on the circumference and runs through this row of squares along the entire length of the drift (cf. Figure 3-7). In Figure 3-8, the fractures are shown from the inside of the drift looking at the walls. Since the excavation followed the outline of the D-boreholes, the discontinuous traces of three of the D-boreholes are also shown on the drift maps.

A total of 914 fractures were mapped in the Validation Drift. Figure 3-9, a lower hemisphere contour plot of poles to the fracture planes, shows four fracture sets. The most prominent fracture set is sub-vertical and strikes in a north-south direction. A weaker, subhorizontal set trends NNE-SSW. The two other groups are poorly developed, striking NE-SW and NW-SE with dips that are sub-horizontal and sub-vertical, respectively. Figure 3-10, consisting of contour plots for individual sections of the drift, shows that there is significant variation in fracture orientations along the drift. This variability was not discernable in the fracture data from the D-boreholes. Figure 3-11 shows the trace length histograms for all of the fractures in the Validation Drift, sub-divided in terms of termination mode, large-scale roughness, small-scale roughness, and censoring.

Comparison of the fracture data from the Validation Drift with the data from the Stage I and Stage III mapping efforts shows that similar groupings or sets of fractures can be found in all areas and each set or group has similar mean trace lengths and spacings in most areas. However, the orientation of a given set varies within the rock mass from area to area. Fracture orientations within the H fracture zone are similar to those mapped in the "good rock", but have different mean trace lengths and spacings. In general the orientation of large scale features tend to mimic mean orientations of the regular joint/fracture system. The converse is not necessarily true.

3.1.3.3 Water Inflow Measurements

The inflow of groundwater to the Validation Drift forms a focus for the Site Characterization and Validation Project. The inflows are due to be predicted by a series of numerical models based on measurements performed in Stages I and III and the conceptual model presented above.

A system for measurements of inflow to the Validation Drift was set up during 1990. The inflows are measured in a number of different ways based on location and inflow type. They are as follows:

1. Flows into the upper part of the drift.

The upper 55% of the drift (i.e. sections numbered 1, 2, 3, 8, and 9 in Figure 3-7) is covered in plastic sheets, very similar to those of the 3D migration experiment. These have an area of 1 m by 2 m except where they cover zone H where they have an area of 1 m by 1 m.

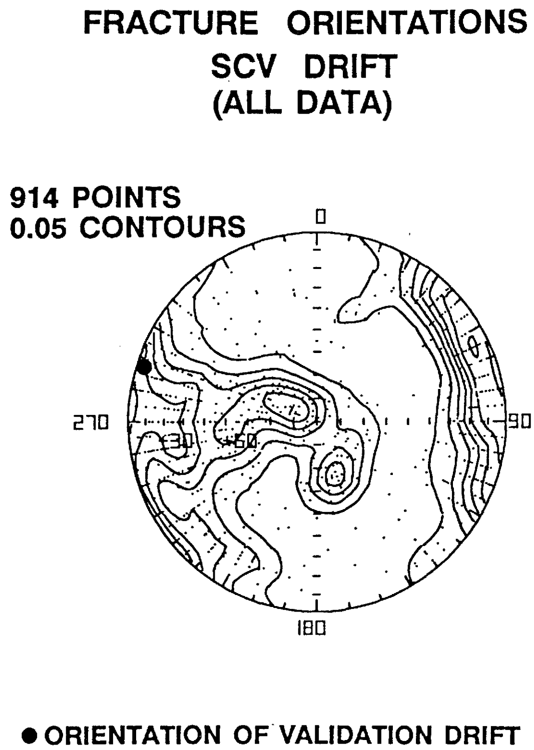

Figure 3-9. Contour plot of poles to fracture planes for all of the fractures mapped in the Validation Drift.

Where sheets cover flowing fractures, the edges of the sheets have been enhanced by metal plates cemented into 5-25 cm deep cut slots. This is to stop water flowing around the drift in the immediate vicinity of the drift wall.

2. **Flows into the lower part of the Validation Drift.**

   The flows into the lower part of the drift are collected in "sumps" which are drilled into the "wet" fractures where they cross the grid lines. Water removed from a sump is ascribed to the fracture (or part of it) which is situated topographically "above" the sump. The sumps are emptied each day and the inflows totalized up for each grid square per day. The lower measurement limit of this system is controlled by the evaporation rate.

3. **Evaporation from unsheeted areas.**

   This is measured by a bulkhead which seals the end of the drift. The inflow and outflow air volumes together with their humidity and temperature are measured.

4. **Specific evaporation studies.**

   Non-flowing areas of the Validation Drift will be measured twice by the "spot evaporation" technique devised by Professor Watanabe. The first measurement was made in April 1990 and the second will be performed just before termination of the experimental activities in the mine.

   The technique can be used over all open areas and will provide a check against the overall evaporation measured using the bulkhead.

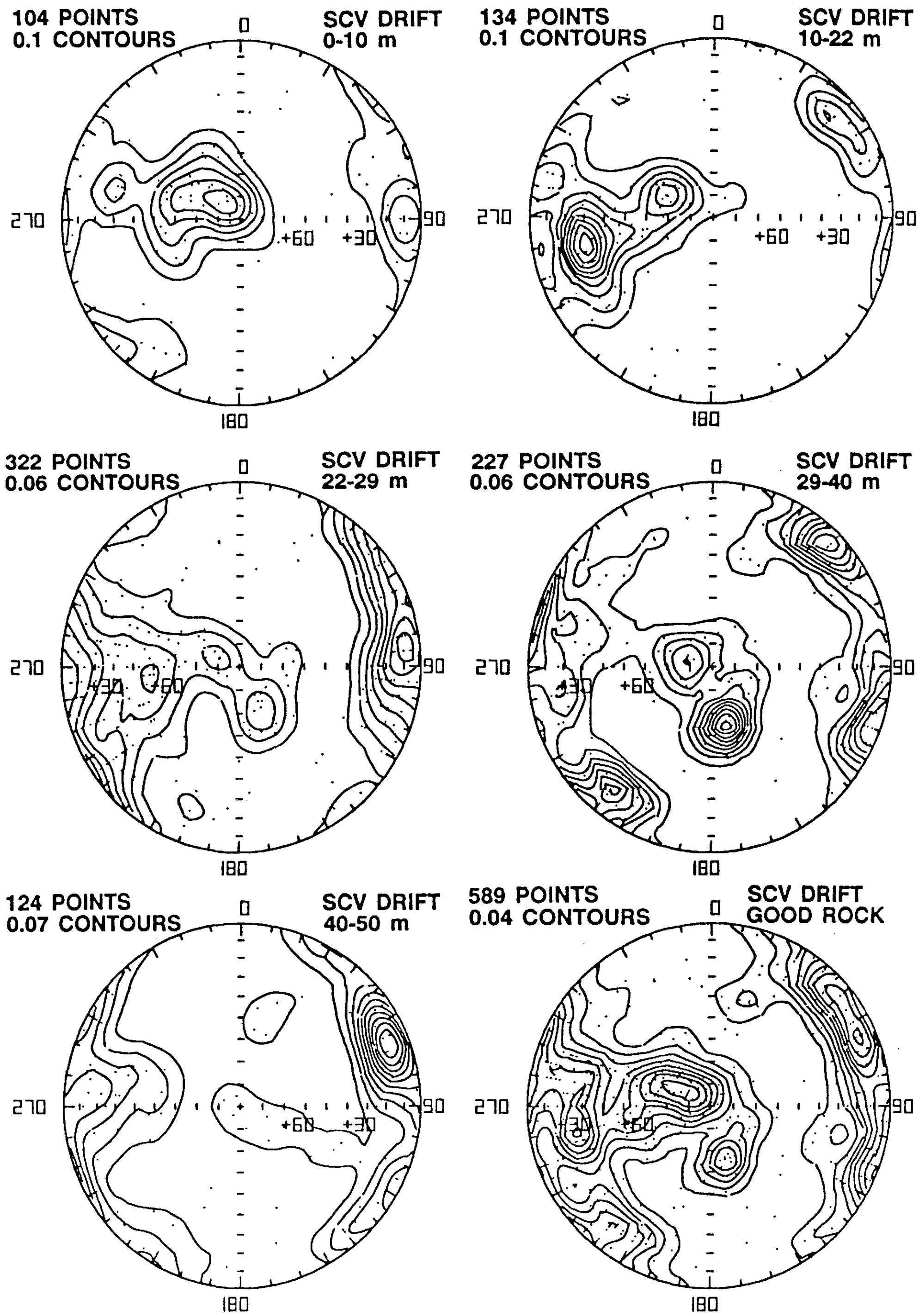

Figure 3-10. Contour plots of poles to fracture planes for individual sections of the Validation Drift.

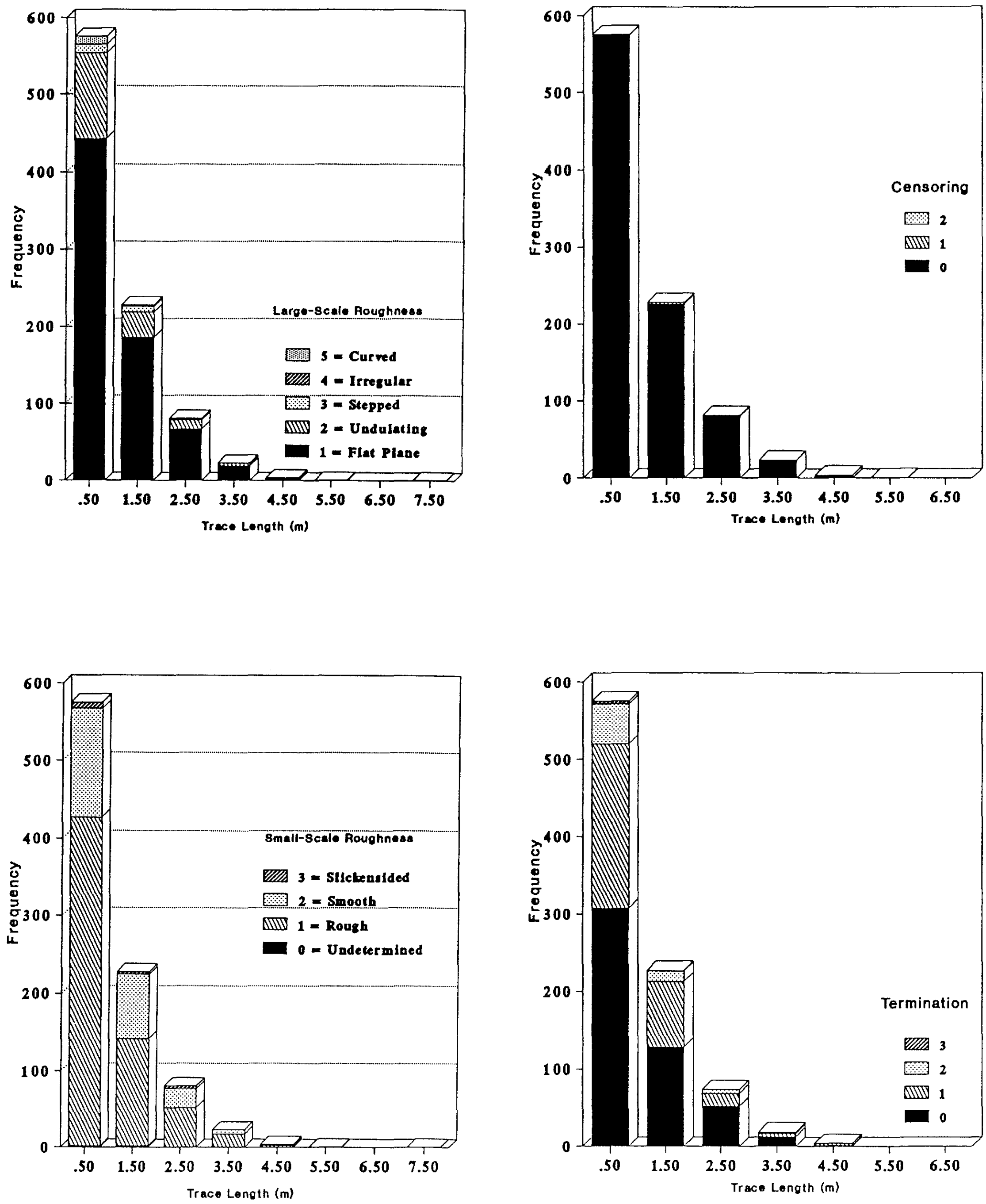

Figure 3-11. Distribution of trace lengths for all fractures in the Validation Drift as a function of large-scale roughness, small-scale roughness, censoring, and termination mode.

The distribution of flow into the plastic sheets and the sumps are summarized in Figure 3-12. The total flow into the sumps and plastic sheets is approximately 92.8 ml/min. This value has remained practically constant during the measurements. The amount of water transported by ventilation amounts to approximately 5 ml/min. This value is also fairly constant with time. The data are summarized in Table 3-2.

Table 3-2. Inflows to the Validation Drift (ml/min) based on data available 90-12-19.

Source	Validation Drift	SDE*-flow	Fraction drift/SDE
Sheets and sumps, zone H	92.8		
S and s, good rock	0.17		
Ventilation	5.0		
Total	98.0		
Zone H	92.8	650	14.3%
Good rock	5.2	190	2.6%
Total	98.0	830	11.8%

*Simulated Drift Experiment.

The numbers indicate a considerable reduction in the inflow to the drift compared to that of the boreholes. In this case the inflow to zone H is defined as the inflow to sheet rows 24 through 29. The reduction appears to be largest for the good rock. The reduction in the good rock has to be considered with some caution as the data on the "good rock" inflows from the Simulated Drift Experiment (SDE) are not very reliable. For example, the distribution of inflow was not obtained and it is not possible to strictly define the division between zone H and the "good rock".

The evaporation measurements gave an estimate of the total inflow from the "good rock" of approximately 9 ml/min. The evaporation rate was highest in the inner part of the drift, between zone H and 50 m. The average evaporation rate for the first part of the tunnel (0-22 m) was approximately 0.2 mg/m^{2}s while it was 0.47 mg/m^{2}s for the inner part (29-50 m).

The total evaporation of 9 ml/min compares favorably with the amount of water transported by ventilation which is approximately 5 ml/min. Approximately 5/9 of the rock surface has since the evaporation measurements were made been covered with plastic sheets and are now not contributing to the water transported by ventilation. Hence, it seems reasonable that ventilation transport should be about half the value obtained from the evaporation measurements.

The spatial distribution of the measured evaporation rates are shown in Figure 3-13. We can note large evaporation rates at zone H, the drift face, and the tunnel ceiling. There are also a few spots of high evaporation at the tunnel floor. The high evaporation rates at the tunnel ceiling could be caused by higher temperature and lower relative humidity at the ceiling compared to the floor of the tunnel. The evaporation measurements were made shortly after completion of excavation and steady state conditions had not yet developed. Hence, the high

Validation drift - Water inflow rates [ml/h]

1990-12-19

		23	24	25	26	27	28	29	30	31	32 33	34 35	36 37	38 39	40 41	42 43	44 45	46 47	48 49	50	
Sump holes			250		520	20		25													6
			10		3000																7
Top	Plastic sheets		60	50	700	0.4	0.6														8
			0.3	45	90	25		0.25				0.03	1.4								9
					14	70	2	0.8	0.4			0.8							0.03		1
				0.04	16	100	150		3		0.5	1.6	0.07					0.02	0.05		2
					35	30	80		1	0.4	0.1										3
Sump holes						2															4
			100		170																5

Figure 3-12. Inflow of groundwater to sumps and plastic sheets in the Validation Drift.

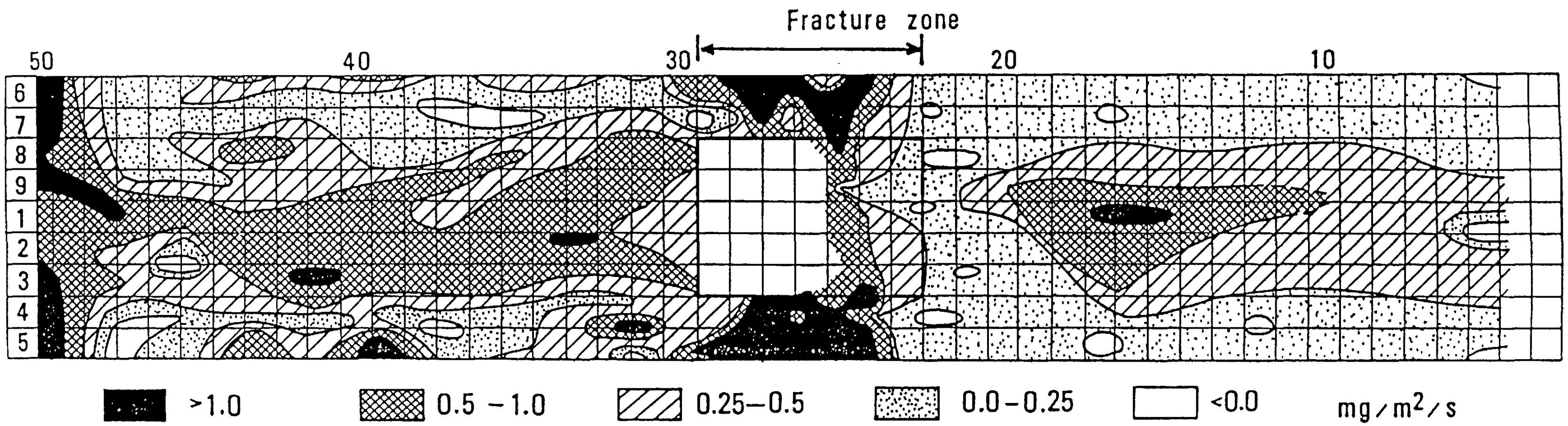

Figure 3-13. Evaporation rate distribution in the Validation Drift measured in April 1990 (from Watanabe, 1991).

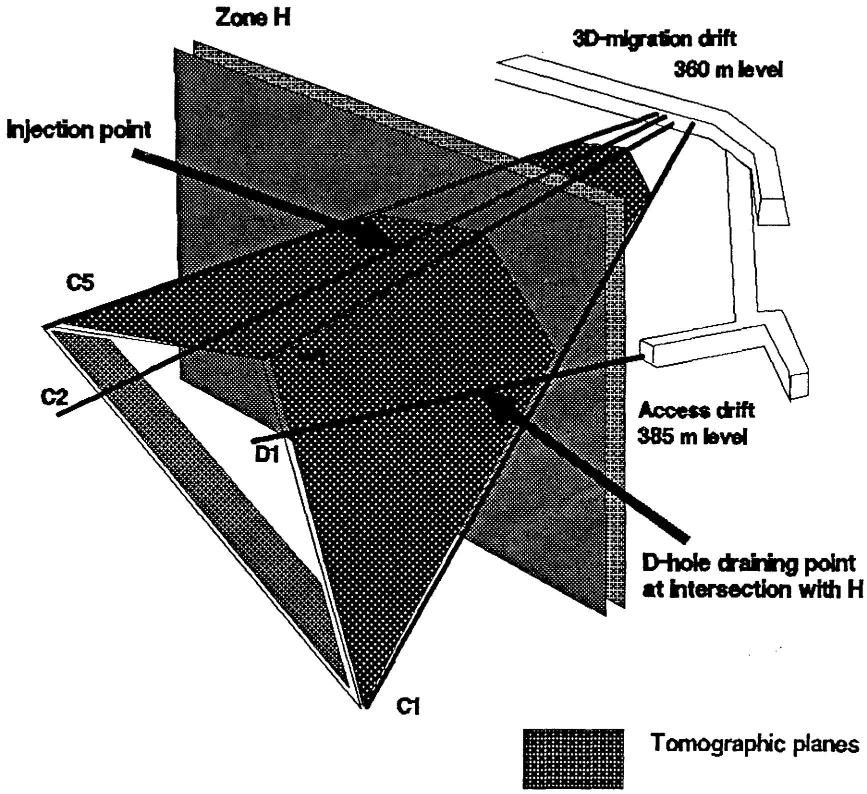

Figure 3-14. Generalized geometry of the Radar/Saline Tracer Experiment. Saline tracer was injected in borehole C2 where it intersects zone H. Radar tomography was made in the W1-C5, C5-C1, and W1-C1 planes.

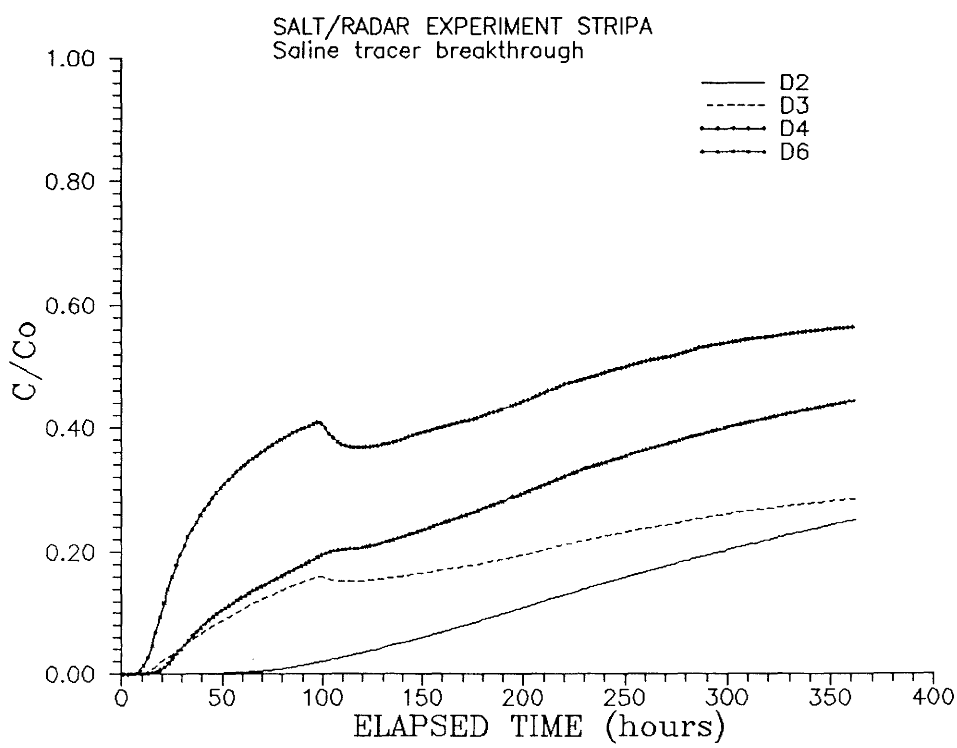

Figure 3-15. Saline tracer breakthrough in the D-boreholes during Phase 1.

evaporation rates might be due to differential drying of the rock. In steady state, the evaporation rate should equal inflow to the drift and be independent of relative humidity.

The evaporation rate along some fractures was also studied specifically. The fractures were found to contain a number of high evaporation spots, some of which coincide with fracture intersections.

3.1.3.4 Radar/Saline Tracer Experiment

The objective of the radar/saline tracer experiment is to provide data on the geometry of flow paths from an injection point in fracture zone H. The flow paths have been monitored through radar difference tomography. In the first experiment saline tracer was injected in borehole C2 where it intersects zone H and the D-boreholes were used as a drain (Figure 3-14). In the second experiment the excavated Validation Drift was used as a drain. The report on the first experiment is completed and analysis of data from the second experiment is in progress. Below follows a summary of the results from the first experiment.

Saline tracer with a concentration of 2% with a flow rate of 200 ml/min was injected to borehole C2. The concentration of tracer was monitored in each of the D-boreholes where they intersect zone H and zone B. No tracer was observed in monitoring points outside of zone H.

The first experiment was divided into two phases with different boundary conditions. During the first phase the head in the D-boreholes was kept at 165 m relative to the 385 m level of the mine. During the second phase the head in the D-boreholes was reduced to zero.

The first arrival in Phase 1 was observed in borehole D4 approximately 10 h after start of injection while the mean residence time was approximately 40 h. Arrivals in boreholes D3 and D6 occurred shortly thereafter (Figure 3-15). The first arrival of tracer in borehole D2 was significantly delayed and did not occur until after 60 h. It is likely that borehole D2 is connected to another flow system than the other boreholes. The distance between the injection point and the sampling points in the D-boreholes is approximately 25 m. The instantaneous recovery during Phase 1 was approximately 50%. A reduction of the head in the D-boreholes to zero (Phase 2) increased the instantaneous recovery to approximately 85%.

The injected tracer only caused minor increases in the radar attenuation. The maximum increase in attenuation due to saline tracer was 25 dB/km or approximately 5% of the normal attenuation of the Stripa granite. The small increase (5%) in attenuation observed is most likely due to that the injected tracer only occupies a fraction of the total pore space. Hence, the ratio of observed increase in attenuation to expected increase gives an estimate of the ratio of flow porosity to total porosity. These data give an estimate of the flow porosity approximately in the range 0.5–1 10^{-4}. This value is somewhat smaller than previous estimates based on values of flow porosity ($\approx 2\ 10^{-4}$) obtained by Andersson, Andersson, Gustafsson, and Olsson (1989) at the Crosshole Site in the Stripa Mine.

Figure 3-16 is an attempt to represent the evolution of the flow system with time. The figure is based on data on the increase of attenuation with time in zone H. The blocks on the lines represent increase of attenuation in excess of 10 dB/km. The time at which the tracer appears is indicated by the pattern in the boxes. The approximate time after start of injection for the measurements are M2 $\approx$ 65 h, M3 $\approx$ 110 h, M4 $\approx$ 170 h, M5 $\approx$ 290 h, and M7 $\approx$ 650 h. The width gives an estimate of where the attenuation has increased significantly for each

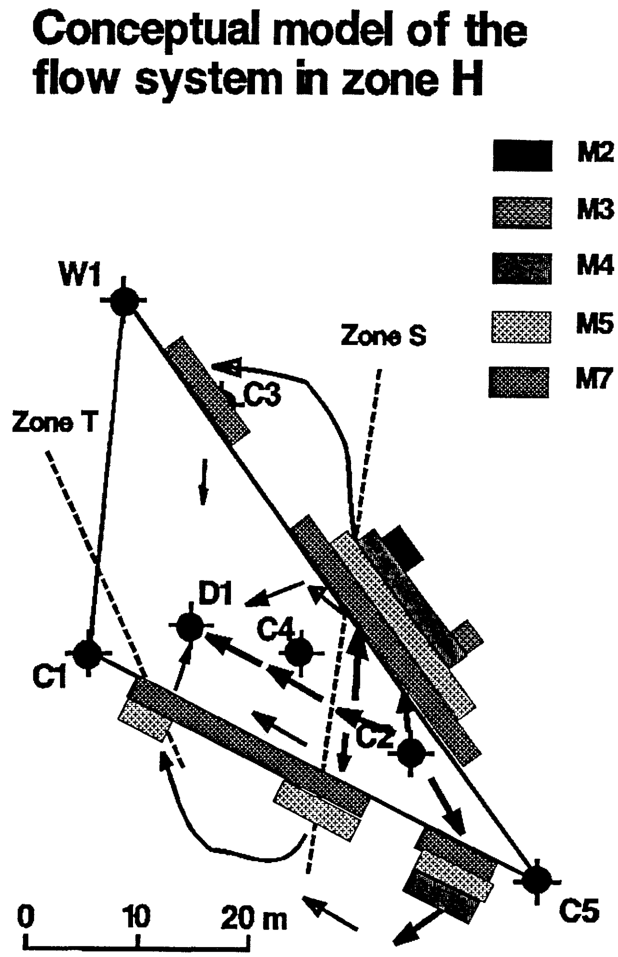

Figure 3-16. Conceptual model of saline tracer flow within zone H based on radar difference tomography. The boxes indicate when and where saline tracer is observed.

measurement. As the boxes are stacked on top of each other the height gives an estimate of the time of arrival. A large height indicates an early arrival.

Figure 3-16 shows a nonuniform spread of tracer with time. The injection in borehole C2 is made under an excess head and we would expect the flow to be radial close to the injection point (assuming homogeneous properties in zone H). The first tracer arrival actually observed occurs at the intersection of zone S with the Wl-C5 line in the plane of zone H. This occurs approximately 50 h after start of injection. At approximately 170 h (M4) tracer is also observed on the C1-C5 line close to C5. At approximately 290 h (M5) when near steady state conditions have developed tracer is also observed at the intersections of zones S and T with the C1-C5 line.

It should be noted that the radar difference tomography also indicates transport of tracer outside of zone H essentially concentrated to two zones annotated S and T. The lines of intersection between these zones and zone H are indicated in Figure 3-16. Both features have similar strike as the major features A and B identified at the SCV-site but the dip, particularly of zone T, is different.

Based on these data we can make a conceptual model of the flow pattern in zone H during Phase 1 (thick arrows in Figure 3-16). The fastest transport within zone H is to the D-boreholes where tracer is observed after 10 h. This flowpath, having a mean residence time of approximately 40 h, accounts for approximately 50% of the total flow. Part of the tracer flowing toward the D-boreholes is diverted by zone S both upward (to the Wl-C5 line) and downward (to the Cl-C5 line). Some other major flow paths pass through the W1-C5 and C1-C5 lines closer to borehole C5 as indicated by the arrows in Figure 3-16. Some of the tracer passing through the C1-C5 line close to C5 is flowing to the D-boreholes through a flow path passing the C1-C5 line at its intersection with zone T.

In Phase 2 the head in the D-boreholes was reduced to zero and the boreholes became a larger sink to the hydraulic system. This is reflected by the higher instant recovery (=85%). In the radar data from the end of Phase 2 (M7 at approximately 650 h) a change in the flow pattern is clearly indicated. Now, high values of increased attenuation is observed on the C1-C5 line between zones S and T and close to borehole C3 on the W1-C5 line. This is interpreted as flow is now diverted from zone S toward the D-boreholes and that there are preferential flow paths close to borehole C3 and at the intersection of zone T and zone H. The new flow paths believed to exist during Phase 2 are indicated by thin arrows in Figure 3-16.

In summary, based on this experiment we can conclude that the tracer appears to follow a few preferred flow paths where some of these paths are linked to the intersection of two minor features (fractures or fracture zones) with zone H. Tracer was also observed to be transported through these zones out of zone H. The radar data also indicated a change in flow pattern during Phase 2 as a consequence of the change of head in the D-boreholes.

3.1.3.5 Tracer Test in the Validation Drift

GENERAL

The objective of the tracer test is to make such measurements that a comparison can be made between the predictions of tracer movement in the rock around the Validation Drift and the actual tracer movement. Furthermore, the results will be used to further improve the understanding of water flow and tracer movement in fractured rock.

Tracers are injected in a fracture zone as well as in the "good" rock. The distance from the injection sections to the Validation Drift is between 10 and 25 m. A mixture of metal complexes and dyes are injected from each injection section. Both these types of tracers are conservative (non-sorbing). The tracers are collected in plastic sheets in the Validation Drift in the same manner as was used in the 3D experiment.

EXPERIMENTAL LAYOUT

The boreholes C2, C3, T1 and T2 have been sealed with bentonite except for 9 sections, 0.5 – 2 m in length, that can be used for tracer injection. 8 of these 9 sections are located in the H-zone and one is located in the "good" rock. All 9 sections are located between 10 and 25 m from the drift. The potential injection sections and sections used so far for tracer injection are shown in Figure 3-17.

Sections with "high" hydraulic conductivity have been chosen for tracer injection. Even though the four holes intersect the same fracture zone, H-zone, the hydraulic conductivities in these holes are very different. The C3 borehole, located between T1 and T2, is very tight. The largest inflow into C3, 1 ml/h, is located in one section in the H-zone. The T1 and T2 boreholes are as close as 5 m

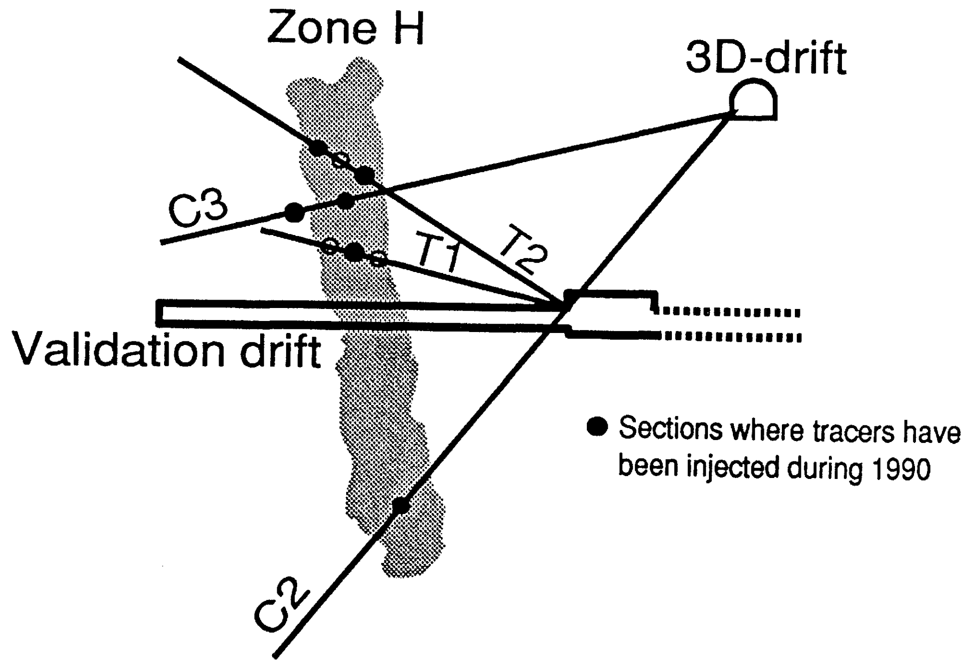

Figure 3-17. Location of the 9 potential injection sections and sections so far used for tracer injection.

from the C3 hole, but have sections with water inflow rates that are 50 and 200 times larger respectively.

Two tracers are injected simultaneously in each injection section, one metal-complex and one dye. The metal-complexes have not previously been tested in any experiment in Stripa and can not be visually detected. The advantage with metal-complexes compared with dyes is that the detection limit is significant lower and that there is no problem with the resolution in the analysis even if several metals occur in the same water sample. The dyes are well known from the 3D experiment, but have the limitation that the resolution in the analysis decreases if more than 4 dyes occur in the same water sample or if the concentration difference between the tracers is large.

The tracer injections are carried out with as little disturbance of the natural flow field as possible. This is achieved by using very low injection flowrates. The tracers are continuously injected during several months with injection flowrates less than 1% (in most cases) compared with the natural water inflow. The injection flowrates have been 2 ml/h for the tightest sections and up to 30 ml/h for the section with the highest hydraulic conductivity. These small disturbances have reduced the pressure build-up in the injection sections to one or a few meter of water head.

EQUIPMENT

A large part of the work during the first half of this year was to find an injection system that continuously can deliver a few ml/h up to 50 ml/h for long time periods. The system also had to work with pressures up to 3 MPa.

Since commercially available pumps could not fulfil the requirements, a new type of injection equipment had to be designed. The tracer injection system is

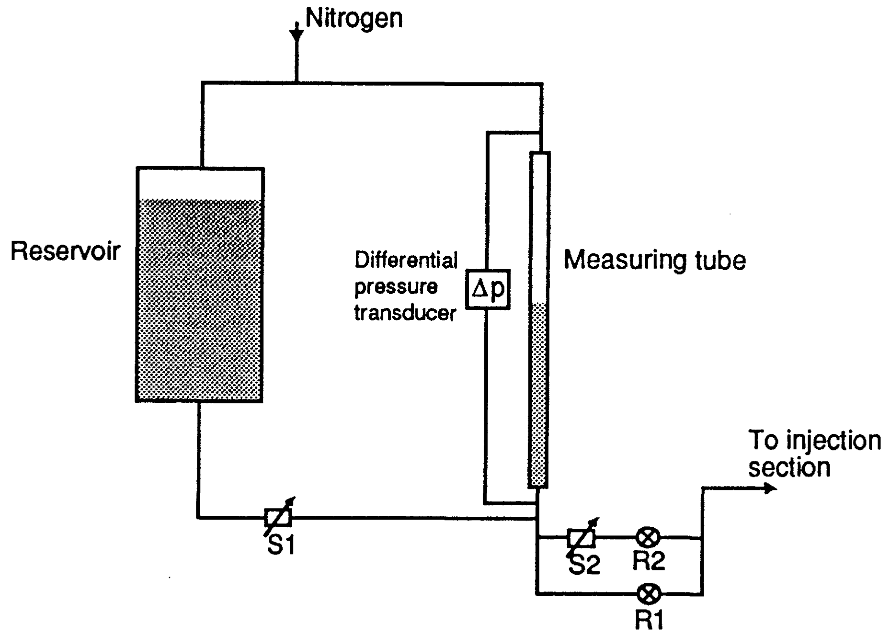

Figure 3-18. Tracer injection system.

based on emptying a vertical tube and measuring the injected amount with a differential pressure transducer, see Figure 3-18.

The tracer injection is controlled by a HP 9816 computer. The injected amount is the sum of the amount that continuously passes through control valve R1 and the small "pulses" that passes through valve R2 when solenoid valve S2 is opened. The continuous part of the injection flow, through valve R1, is adjusted to approximately half of the desired flowrate. To achieve the desired flowrate, the missing tracer amount is injected 10 times every hour as a pulse with a duration of a few seconds. The desired injection flowrate is therefore obtained over a 6 minute cycle. The injection cycle is :

Start of cycle
- Opening of solenoid valve S1 to adjust the level in the measuring tube to the same level as in the reservoir.
- Closure of valve S1.
- Measuring the start level in the measuring tube by the differential pressure transducer.

End of cycle
- Opening of valve S2 for a short time period in order to adjust the injected amount to achieve the desired injection flow rate.

One problem with this system is that the continuous part of the injection is very sensitive to clogging and other disturbances due to the extremely low flowrate. Therefore, this valve has to be adjusted on a more or less daily basis.

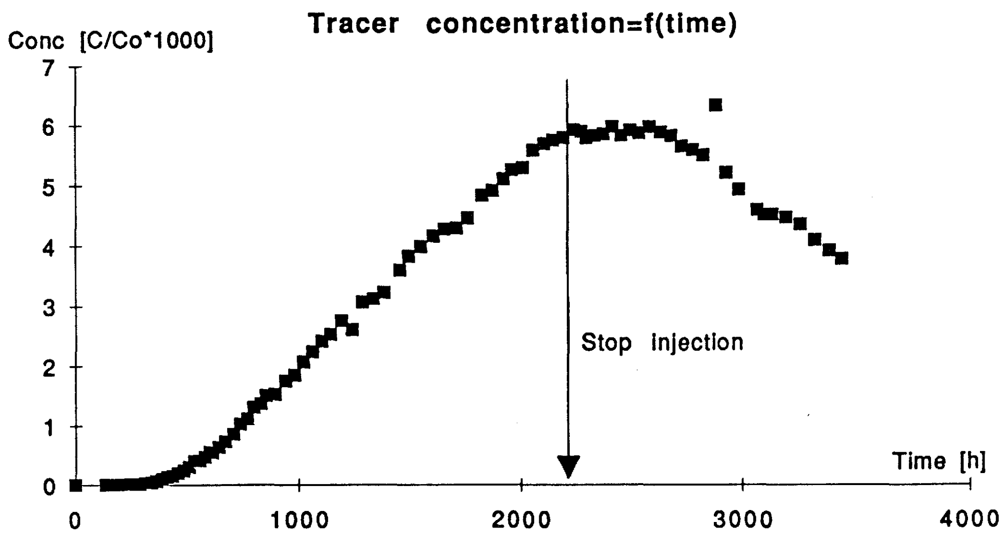

Figure 3-19. Tracer breakthrough curve for one of the tracers injected 20 m above the drift.

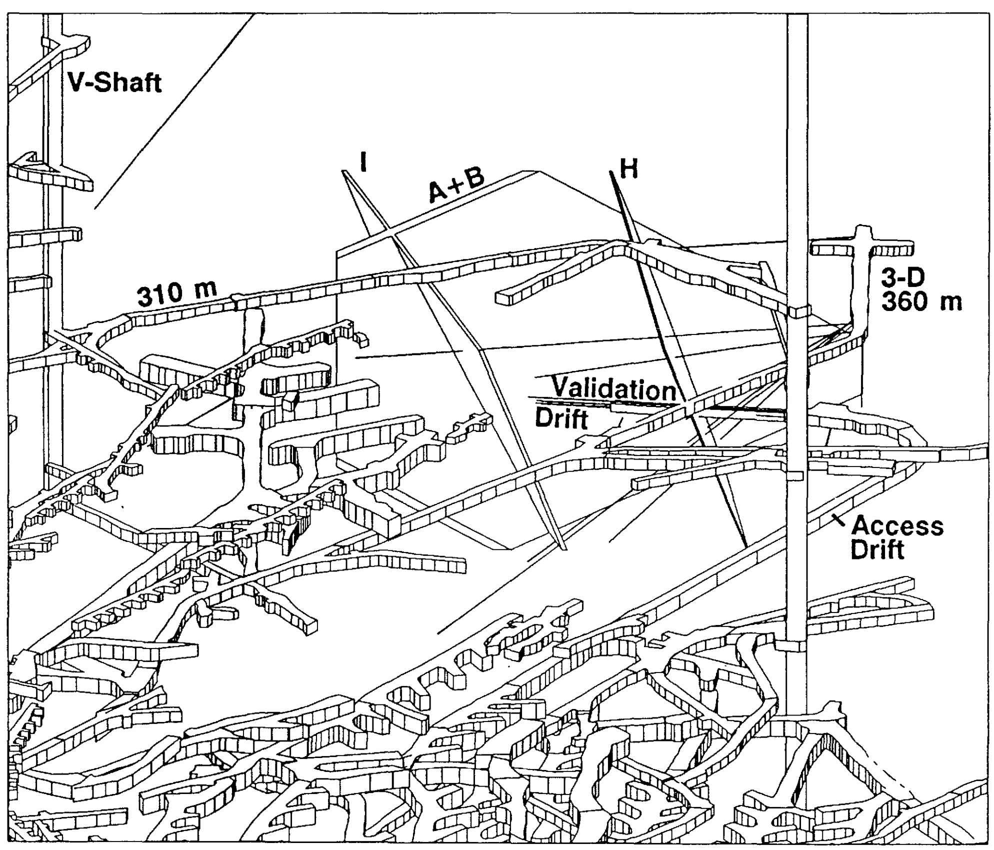

Figure 3-20. Perspective view of the SCV-site generated from the CADD-database developed within the Project.

MAIN ACTIVITIES DURING 1990

- Drilling of boreholes T1 and T2.
- Installation of bentonite packer systems in boreholes T1, T2, C2 and C3.
- Design of tracer injection system.
- Start of tracer injections, see Figure 3-19. Tracer injection started in 4 sections in early September. Two of these injections were terminated in early December while the other two are still running. Two other injections were started in mid December.
- Water collection and tracer analysis.

RESULTS

Tracer injection from four sections started in early September. Three of these tracers were found in the Validation Drift in detectable concentrations after about one week. The fourth tracer, injected in the good rock, has so far only been found in concentrations slightly above the detection limit. Two of these four tracers were found in high concentrations in the Validation Drift after a few months of injection. These injections were terminated in early December. The other two tracers are still being injected. Two other tracer injections were started in mid December and these tracers have already been found in low concentrations in the drift.

See Figure 3-19 for an example of a tracer breakthrough curve in one of the sampling areas in the Validation Drift. The figure shows the dye concentration from one of the injection sections in borehole T2, approximately 20 m above the drift.

3.1.3.6 CADD-modelling of the SCV-site

A CADD database has been produced of the Stripa Mine excavations, boreholes, and fracture zones. The objective has been to develop a database in an easily transferrable format to facilitate data exchange between research groups and in member countries. Another objective is to demonstrate how CADD systems can be used to present often very complex 3D geometries in a way perceptible to a larger audience.

An example of an output from the CADD database and the accompanying software is given in Figure 3-20. This figure shows a perspective view of the SCV-site including the location of fracture zones A, B, H, and I, and adjacent drifts and shafts.

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3.2 DEVELOPMENT OF HIGH RESOLUTION AND DIRECTIONAL RADAR

3.2.1 Previous Work

The directional radar antennas have been constructed as a direct continuation of the RAMAC radar system developed during Phase 2 of the Stripa Project. The dipole antennas used in that system have an omnidirectional radiation pattern, which makes it impossible to orientate fracture zones completely without measuring from several boreholes. By using directional antennas one can obtain all the required data from a single borehole. This was demonstrated during the first measurements at the SCV site: directional antennas were used to determine the position of several weak and irregular zones characteristic of this area (Sandberg et al., 1989). Such zones are difficult to orientate using other methods because radar reflections obtained from various boreholes may appear quite different.

The angular resolution in these measurements was on the order of 10°. This value can be improved to about 5° for prominent and clear reflectors. A detailed comparison of the different methods for orientating fracture zones has shown that the results obtained with the directional antenna are slightly less accurate than data based on the angle of intersection or the point of intersection with a borehole. On the other hand crosshole reflections are less precise than any of these methods (Sandberg et al., 1991).

3.2.2 Antenna Properties

Directional information can in principle be obtained by inducing a voltage in a loop formed by two wires extending along the borehole. The induced voltage will be small since the distance between the wires is on the order of the borehole diameter which is typically only 1/50 of the wavelength. The signal must be compared with noise and voltages induced in the coaxial lines of the feed, which produce nondirectional dipole modes. The antenna consists of four wires placed at in a square: the induced voltages are then measured in four symmetrical pairs. The four signals can be combined to calculate the dipole signal, two directional signals and a checksum, which ideally should be zero and is used to check the function of the system during measurements. The dipole voltage can be used advantageously to determine the phase of the directional components thus resolve the ambiguity between the two opposite maxima of the antenna radiation pattern. The dipole signal is troublesome if it becomes too large, but it has recently been considerably reduced by modifying the feeds.

The function of the directional antennas depends on the accuracy of each antenna component as well as on our ability to register the orientation of the antenna and to analyse the data properly. A set of calibrational procedures has consequently been developed to test the directional antennas. The calibration checks the function of the antenna directly in the laboratory without requiring a borehole, but it also involves all instruments registering the orientation of the antenna. Both gravitational and magnetic instruments have been tested and the algorithms required to calculate the antenna orientation have been derived in detail. A special program is used to calibrate the directional indicators. Figure 3-21 compares measured data with the calibration curves: the instruments are clearly very stable. The magnetometer is quite accurate but can be saturated if the magnetic field becomes too strong; the gravitational indicator, which uses an air bubble in coloured fluid or a small wheel with a weight, provides a result within 2°, which is quite sufficient in view of the precision of the antenna measurements.

3.2.3 Method of Analysis

Directional data was previously computed and printed on paper for different rotation angles and the minima of the reflections were then determined by inspection. The new program RADINTER for radar interpretation allows the user to perform this rotation directly on the screen as shown in Figure 3-22. Reflecting objects, such as planes or point reflectors, can be defined and the geometrical curves corresponding to the theoretical models appear directly on the screen. This model can be moved around with a mouse allowing the user to determine quickly which parameters best fit the measured data. RADINTER is so simple to use that in practice all radar measurements are now analyzed in this way, though automatic routines have also been tested. The complete orientation of a fracture zone is in this way obtained in a matter of seconds.

The program allows the user to switch between gravitational and magnetic directional indicators, which is useful when the borehole direction is well defined. Figure 3-23 demonstrates the most demanding test of a directional antenna: instead of letting it glide along the borehole as usually happens during a measurement the antenna is constantly being rotated to see how the forced rotation affects the results. The figure shows that the reflectors are unaffected by all rotations: the only phenomenon disturbing the picture is the direct wave propagating between the transmitter and the receiver in the borehole. This wave does not possess the azimuthal symmetry of the reflected wave and can not be described by

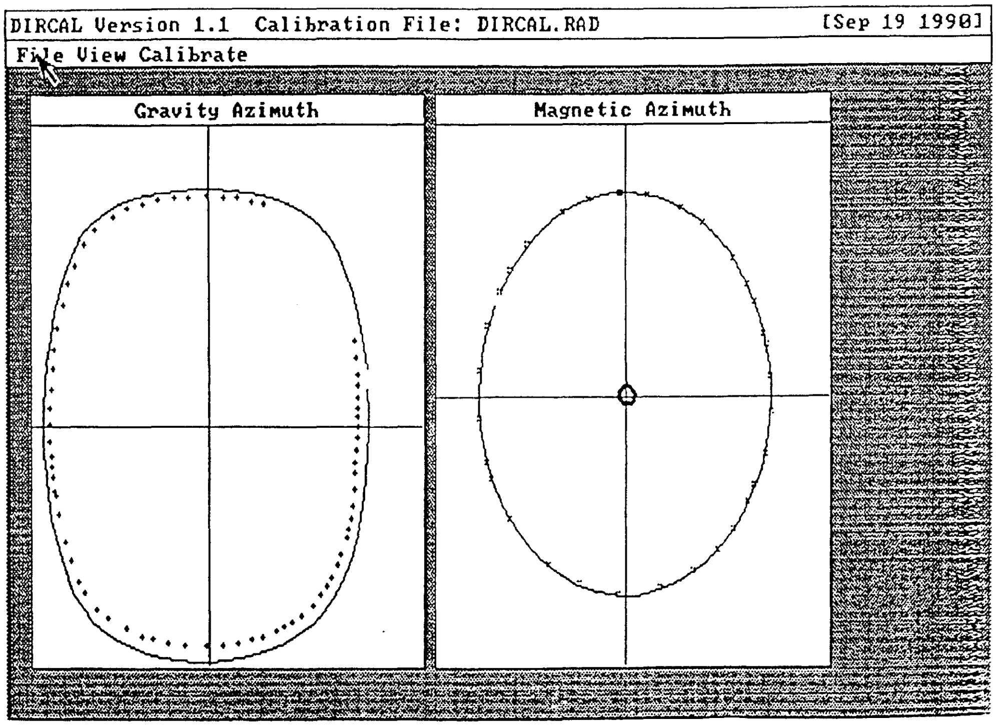

Figure 3-21. Comparison of measured directional data (gravitational and magnetic) with the calibration curves using the calibration program.

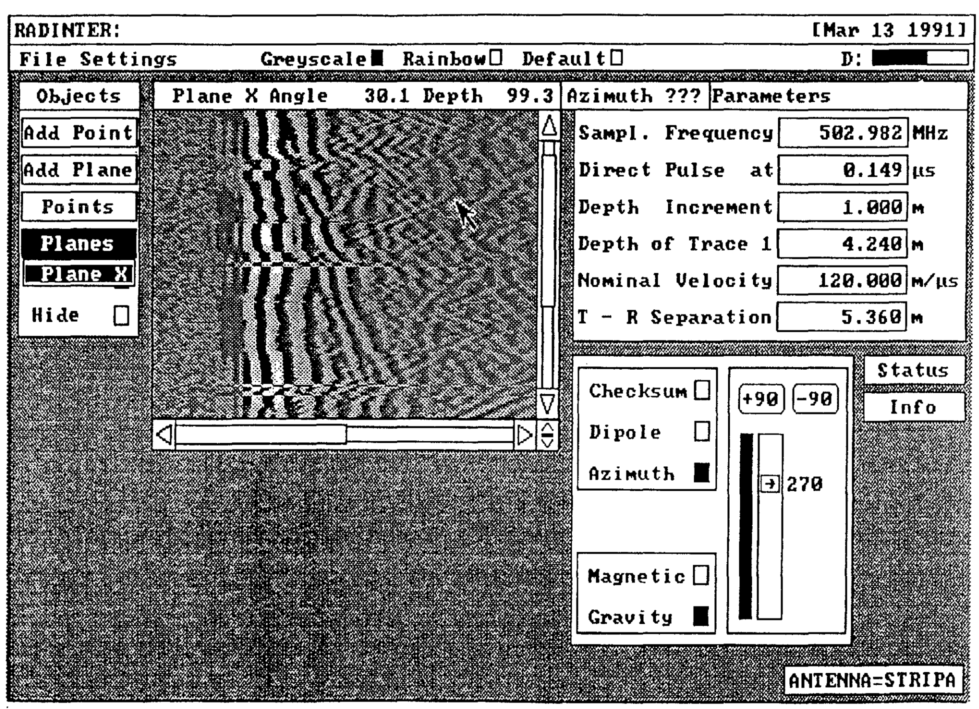

Figure 3-22. Interactive analysis of directional radar data using the program RADINTER.

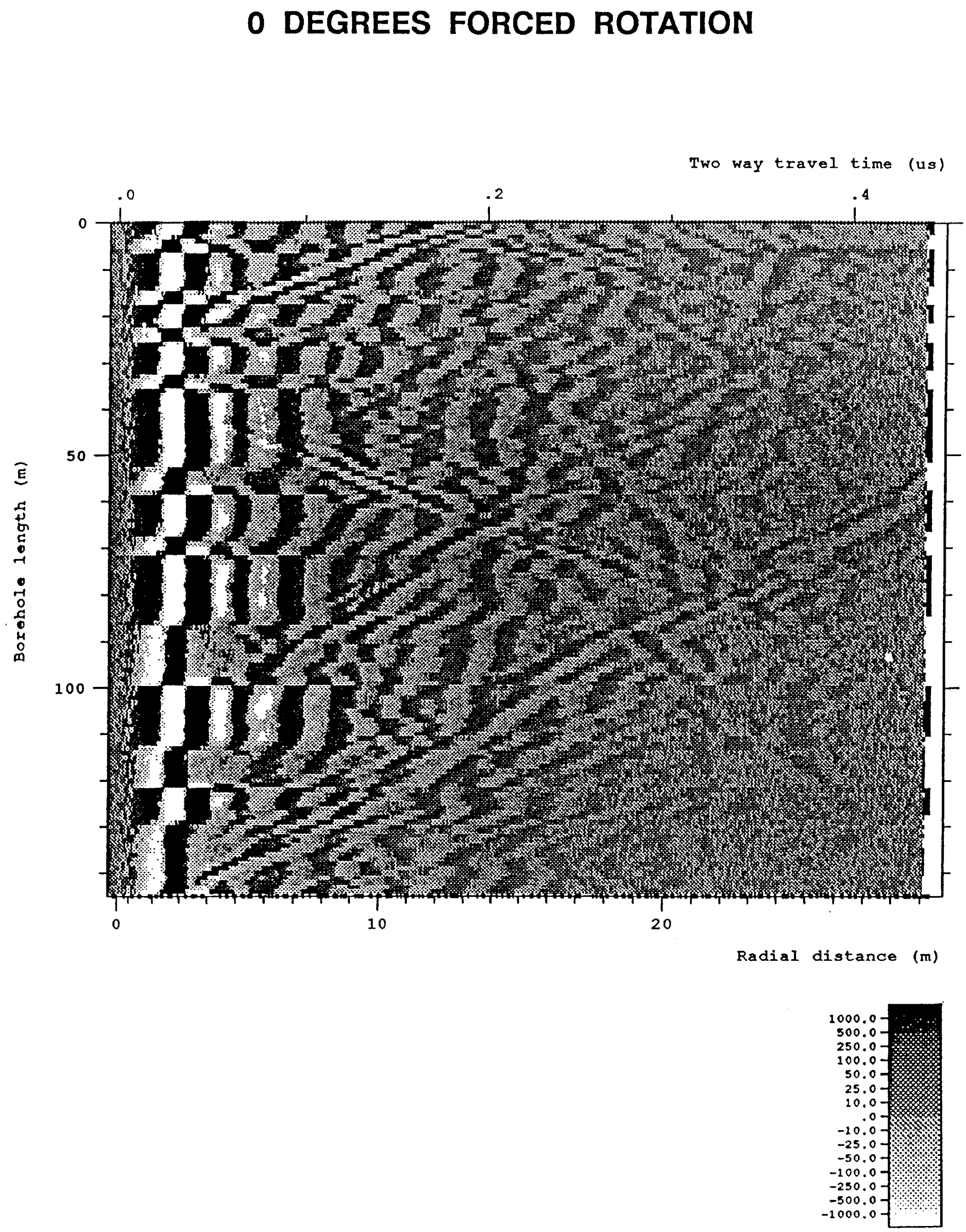

Figure 3-23. Directional radar data obtained during forced rotations in the Malå Laboratory borehole.

the corresponding formulas: the disturbance in Figure 3-23 extends some ten meters from the borehole. The distance is determined by the quality of the antennas but it is important to notice that the reflections from the fracture zones can still be clearly discerned.

3.2.4 High Frequency Measurements

A secondary goal of the radar project has been the development of a high frequency radar. The antennas can easily be scaled to higher frequencies, but there is a limit imposed by the electronics which must be placed between the antenna halves to make the coaxial connections sufficiently short. The commercially available samplers have improved recently, especially at higher frequencies, and some tests were performed with resistively loaded antennas but as expected these antennas show considerable ringing because proper loading can not be imposed near the feeds. The best antenna at high frequencies is in fact the directional antenna which is by construction very broadband. An interesting proof of this is Figure 3-24, which shows the results of directional radar measurements performed in an unusually wide borehole. The frequency spectrum contains an unexpected peak at 175 MHz demonstrating that the antenna and the

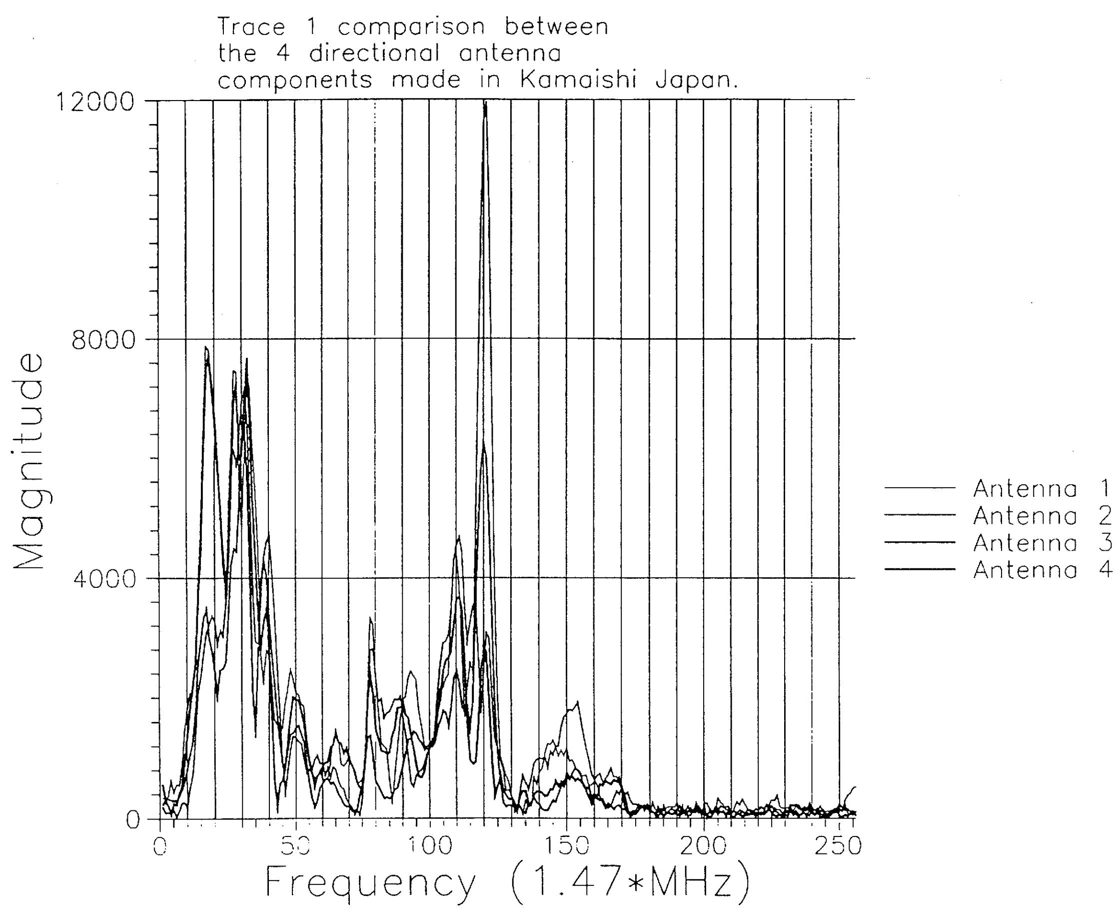

Figure 3-24. Signal spectrum of borehole measurement showing radar pulse at 45 MHz and TM-mode at 175 MHz.

sampler are effective even at these frequencies. The peak is caused by the excitation of a TM-mode propagating along the borehole; a simple analysis shows that for this borehole (diameter 15 cm) the cutoff frequency for the fundamental mode lies at 176 MHz in excellent agreement with observations.

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3.3 IMPROVEMENT OF TECHNIQUES FOR HIGH RESOLUTION BOREHOLE SEISMICS

3.3.1 Scope of the Work

As we are getting closer to the end of Phase 3, the efforts are directed more towards the finalizing of the work carried out earlier. The goals of the seismic development project have been:

- The design and construction of a seismic source complying with the requirements of repository site characterization programmes.
- The development of processing and interpretation techniques for mapping fractured zones.

During 1990, the main topics were:

A resonant seismic source working at lower frequency was constructed in order to extend the application range of the seismic method to softer rocks.

The program modules of the seismic reflection technique were organized in a processing sequence which, after testing many alternatives, was found to be the most suitable for data collected at Stripa. Reflection data was obtained also from other sites than Stripa, with various geological conditions, different site scales and collected with other acquisition systems. By applying the same procedures to various data sets we have improved the performance of the method and attempted to make it independent of the specific site conditions.

3.3.2 Extending the Spectrum of the Resonant Source

A high frequency piezoelectric resonant source has been developed for the project. Signals with a mean frequency of 6000 Hz could be transmitted for distances of over 200 m in the Stripa Mine. In this respect, the Stripa rock is exceptional by its low absorption of elastic energy. Much higher absorption has been noticed in tests performed at other sites. In order to widen the spectrum of applications of the techniques developed within the Stripa Project, a source based on the same principle but producing lower frequencies was constructed by modifying the previous model. Compared with the previous version, the new source provides a more efficient overall energy transfer to softer rocks, hence a larger operational range in media less competent than the Stripa granite. Signals produced by both versions are shown for comparison in Figure 3-25.

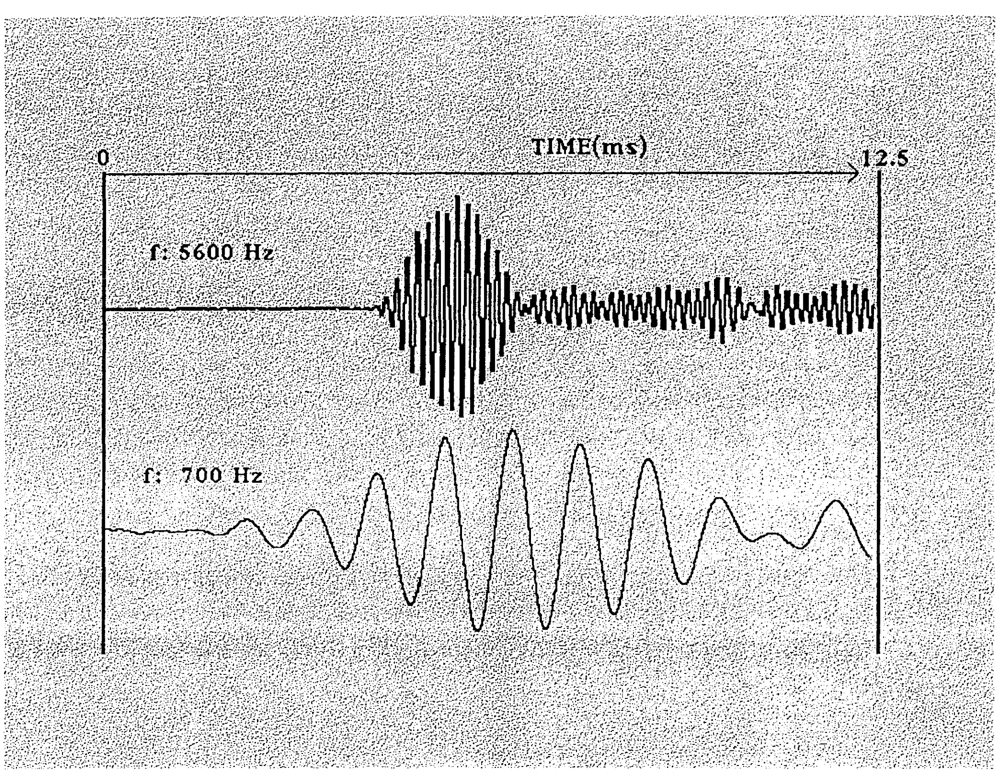


Figure 3-25. Comparison between signals recorded with the high (above) and low (below) frequency piezoelectric resonant sources.

3.3.3 Improving the Techniques for Spatial Orientation of Fractured Zones

The seismic reflection analysis starts with a number of filtering techniques forming a 'pre-conditioning' package. The aim of pre-conditioning is to suppress the coherent energy of the direct arrivals and tubewaves. The resulting profile contains therefore only coherent reflected energy and noise.

The extraction of the reflected events from noise presents a series of problems due to the low reflectivity of the fractured zones. We have been working on a comparative study of all the two-dimensional data filtering techniques used from the beginning of the project till today. These filtering techniques represent the main tools for identifying in the data the reflecting borders of fractured zones. We started with well known techniques like F-K and Tau-P filtering. Later in the project we have modified these techniques in a number of ways to increase their efficiency and reliability for repository site studies.

The two-dimensional transform which is currently applied now is a novel technique aimed at enhancing the coherent events, acting thus as a two-dimensional noise filter. An example is given in Figure 3-26 with a profile obtained in the borehole C1 from a source placed in the borehole C3. The picture is dominated by the two sides of zone H, which is considered as the primary zone of the SCV site. Zone A, with two subzones ranks second in strength, as it is also generally accepted by other investigators. The power of this approach is that it can select only the most prominent events. Reflector procedures applied earlier produced a large number of potential reflectors but could not set a reflector strength hierarchy, which led to confusion.

The technique was originally developed for VSP-like sections like the one described above. Lately, it has been applied also to single-hole type of measurements, as illustrated in Figure 3-27. The example is taken from the measurements performed in the D-holes.

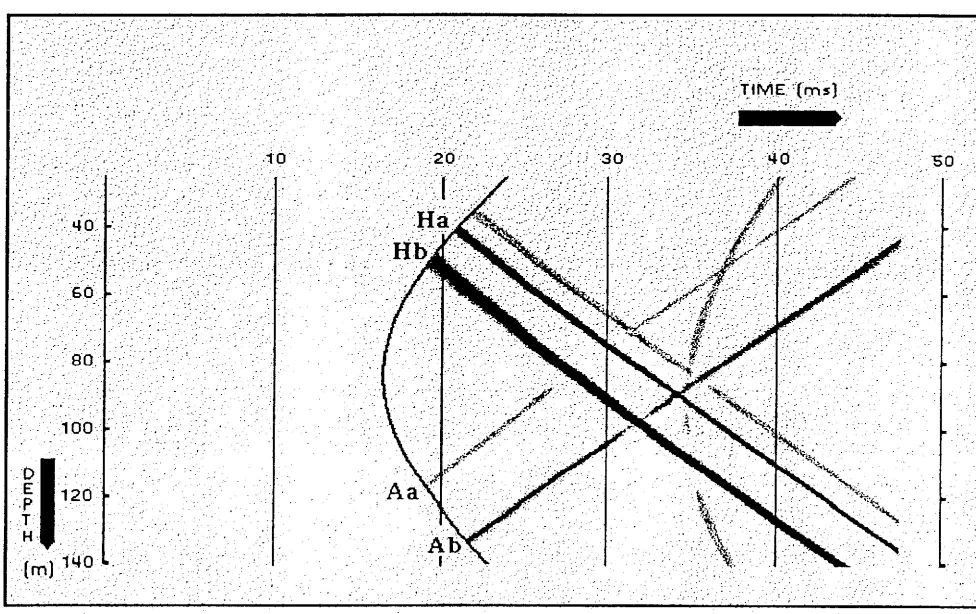


Figure 3-26. Reflection profile from borehole C1 using a VSP geometry (source in C3) after two-dimensional filtering. The less prominent reflectors are filtered out leaving in the plot only the major features.

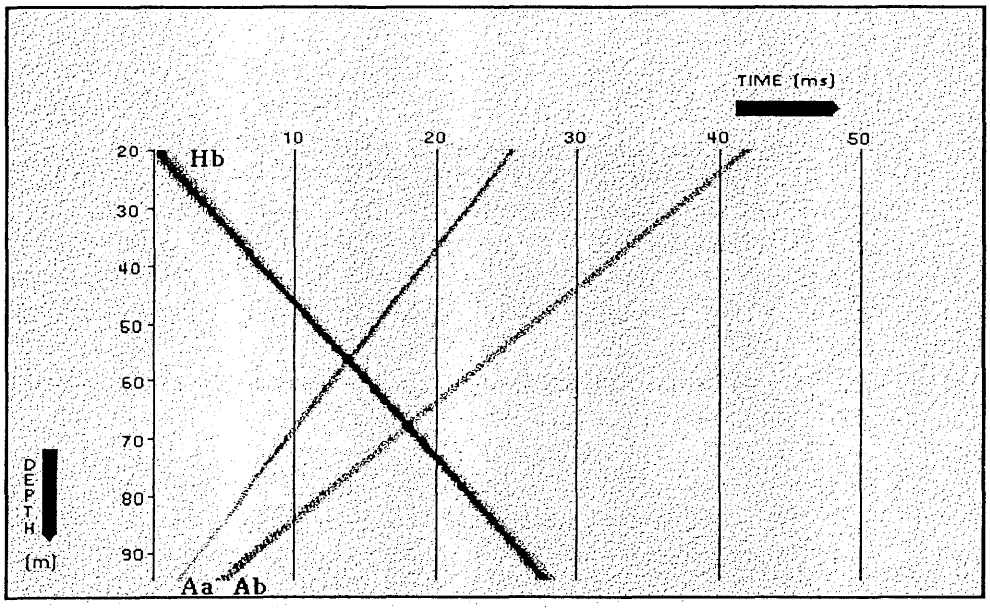


Figure 3-27. Two-dimensional filtering procedure applied to a single hole geometry. The profile was measured in the D-holes at level 410 in Stripa.

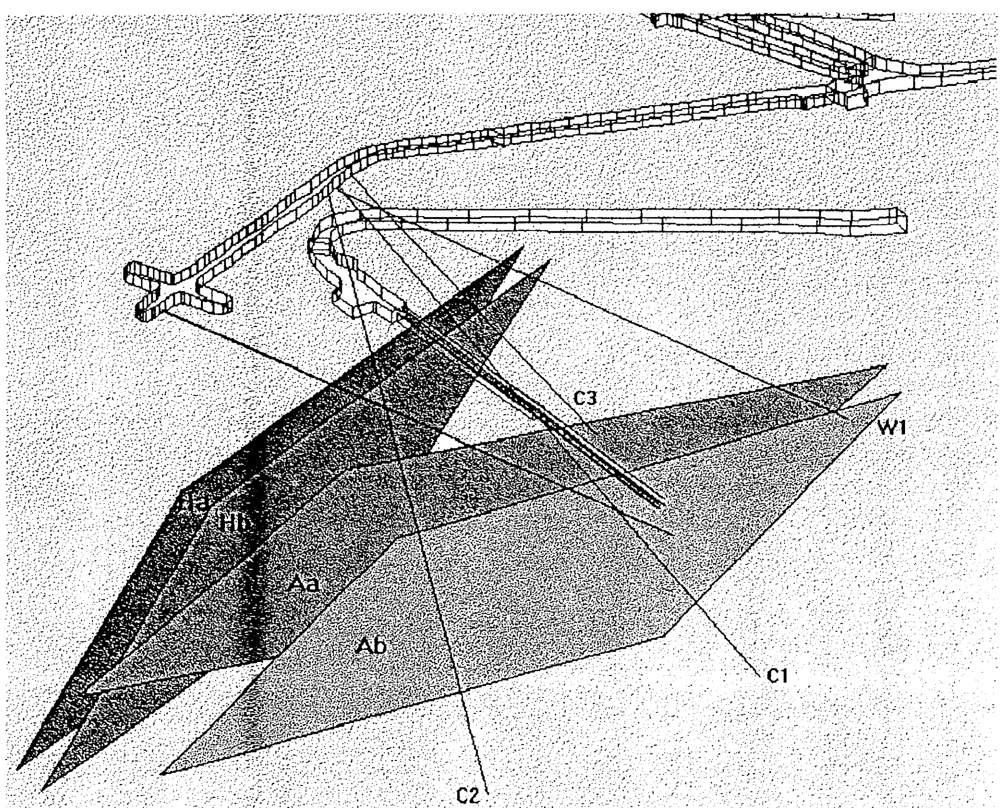


Figure 3-28. Predicted three-dimensional model of major fractured zones at the SCV-site viewed from 30 deg. above horizon.

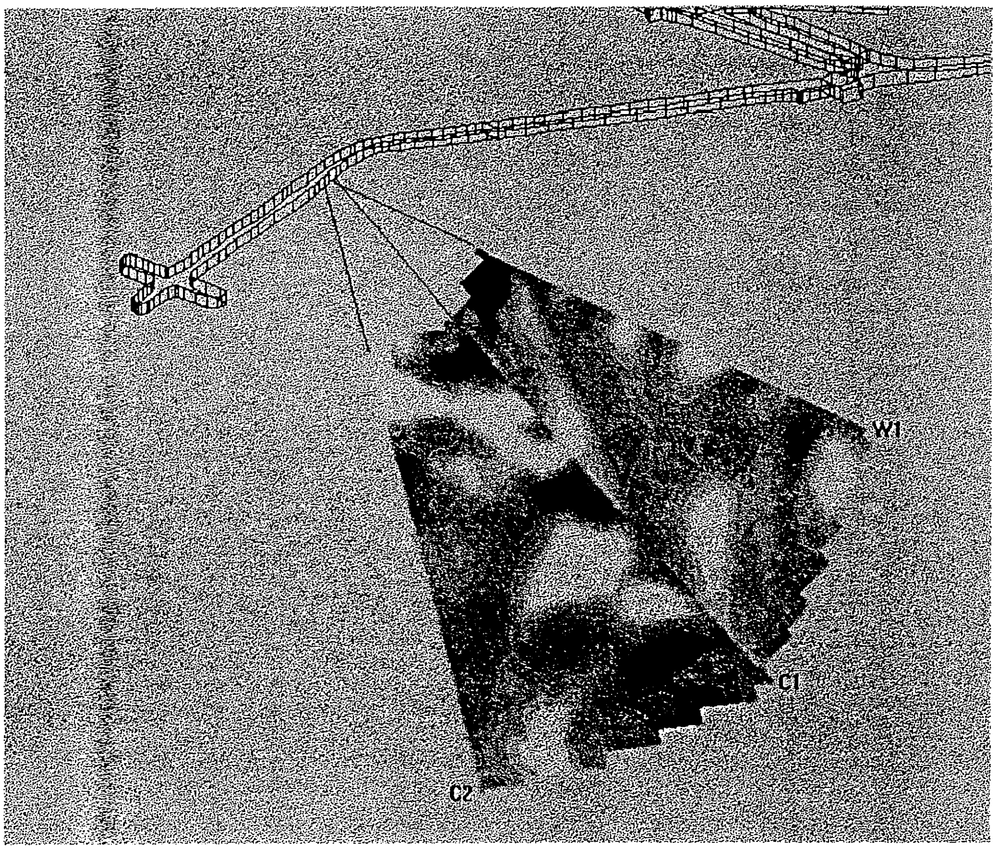


Figure 3-29. Crosshole tomograms of seismic velocities between holes C1-W1 and C2-C1 viewed from the same perspective as Figure 3-28.

By combining the information obtained from several profiles, the orientation of the reflectors in 3D is calculated. Figure 3-28 displays the orientation of the main fracture zones at the SCV-site, as found by seismic measurements. The CAD model of the mine was used as background.

The CAD model also prompted the idea of modifying the presentation of tomograms to allow perspective views. Figures 3-29 and 3-30 display the tomograms obtained between pairs of boreholes W1, C1 and C2. The tomograms depict mostly local features, which do not have large lateral extension and thus are not seen as reflectors.

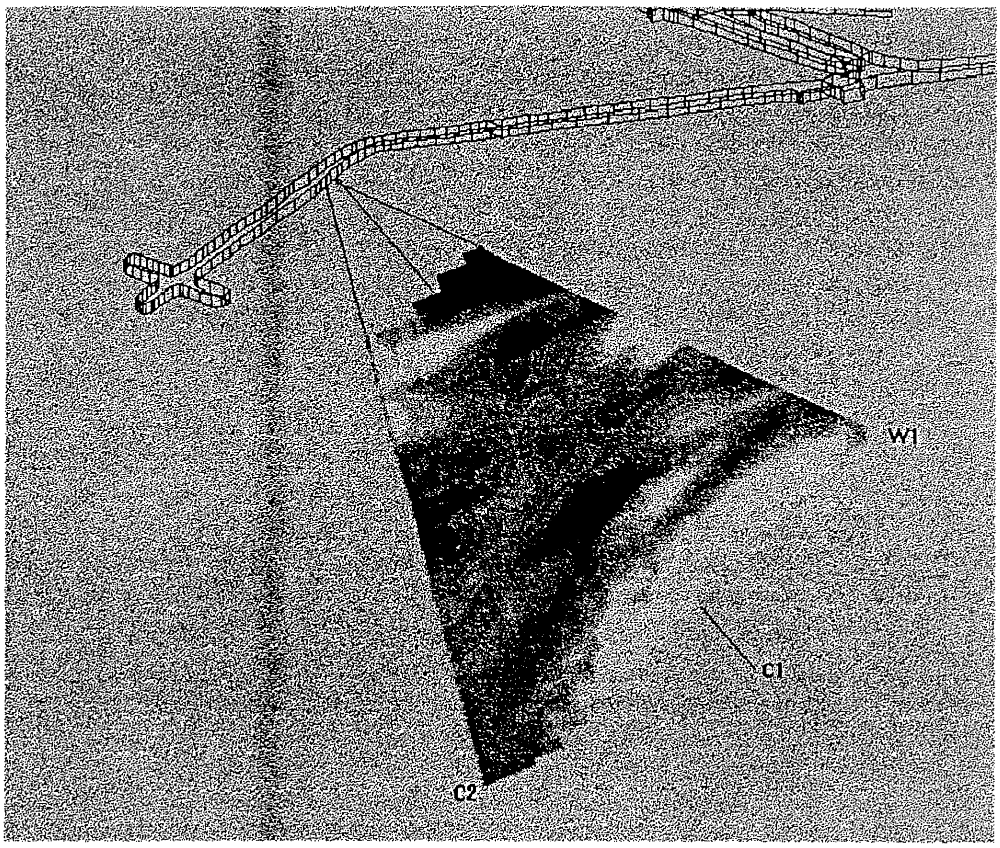


Figure 3-30. Crosshole tomogram of seismic velocities between holes C2-W1 viewed from the same perspective as Figures 3-28 and 3-29.

3.4 FRACTURE NETWORK MODELLING

3.4.1 Introduction

One of the objectives of Phase 3 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 approach is valid and feasible. It must improve our understanding of flow in Phase 3 at Stripa Mine, and it must be generally applicable at other fractured rock sites. In this chapter we outline the progress we have made towards these goals, and describe current developments of the NAPSAC computer code. The final two sections of this chapter describe the corresponding progress of the two research teams sponsored by the US DoE.

During the first part of 1990 we were able to complete our assessment of the results of the predictive modelling of the 'D-hole' experiment. The Stripa Project modelling the complementary studies by Golder Associates and Lawrence Berkeley Laboratory teams were reported and a summary report was prepared assessing the extent to which the models were validated. All three teams made good predictions and the Stripa Project has benefitted from the diversity of modelling approaches.

Whilst the three different modelling approaches predicted very similar bulk flows, the details of the inflow predictions were different. The original experiment did not resolve these details and therefore a new set of predictions and experiments is planned for the remaining sections of the D-holes early in 1991.

Following the success of the D-hole modelling, attention has been focussed on modelling of flow and tracer transport to the Validation Drift. These exercise involve considerable conceptual uncertainty. In particular, the properties of the fracture network will be distributed by the drift excavation, and the transport properties of fractures depend upon fracture storage as well as transmissivity. Neither of these two effects have been fully characterized experimentally, but must nevertheless be incorporated in our numerical models. During 1990 we developed facilities within NAPSAC to represent property changes near the drift due to the altered stress field. We also completed the development of the tracer transport model incorporated within NAPSAC.

There are many uncertainties involved in characterizing a model of tracer transport into the drift. In order to distinguish between different sources of uncertainty, the modelling program for tracer transport has been considerably expanded to incorporate three separate phases. The experiments are conducted within the H-zone feature rather than the averagely fractured rock since timescales for transport in the averagely fractured rock are too long. We therefore spent considerable effort during the second half of 1990 in developing and characterizing separate fracture network models of the H-zone feature and the averagely fracture rock. Preliminary results in early 1991 suggest that we have been successful in this ambitious extension of our modelling programme.

Finally, towards the end of 1990, plans were made to construct a detailed porous-medium model of the SCV-site to incorporate our best understanding of the hydrology of the site. In addition to consolidating our hydrogeological understanding of the site, this model will provide a very useful contrast between the best conventional modelling of the SCV-site and the fracture network approaches developed during Phase 3 of the Stripa Project.

3.4.2 Continuing Development of the NAPSAC Fracture Network

The NAPSAC steady-state flow model is essentially complete, and is being applied to simulate flow experiments at Stripa. Development of the NAPSAC code has therefore focussed on providing the capability to predict the outcome of the tracer transport experiments taking place at Stripa.

During the first part of the year we completed the development of the NAPSAC tracer transport option based on particle swarm tracking. The particle tracking algorithm is now integrated into the NAPSAC code. When the option is used to simulate transport across realistic, stochastically generated networks, there are many pathological cases that need to be accounted for reliably. In particular, there may be very short intersections between highly conductive fracture planes. Special code has been developed to evaluate the finite-element consistent flux from such point-like intersections. We have also started development of a num-

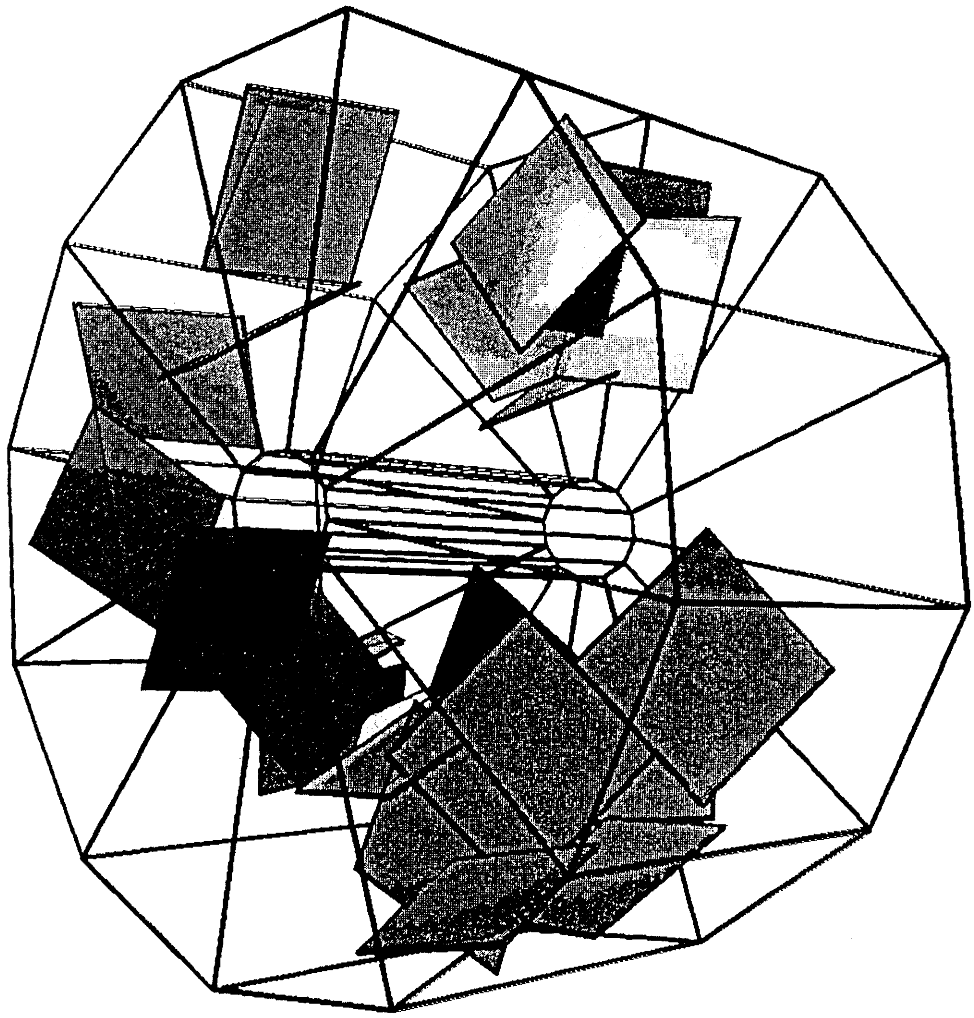


Figure 3-31. Local aperture variation over NAPSAC fracture-planes near the Validation Drift. Dark regions of fractures will be compressed, light regions will open, whilst neutral regions will be unchanged. The local apertures are calculated using a compliance model to the normal-stress on the plane, which is in turn calculated from elastic-continuum solutions to the problem of stress around a tunnel. The fractures are oriented with the mean orientation of fracture sets in the average rock at Stripa.

ber of output options. These will help identify the transport properties of the fracture networks characterized at Stripa, and identify the principal transport pathways through the numerical networks we generate to represent them.

The second area of development has been to enable fractures to be generated with locally varying apertures. The finely discretized finite-element meshes used to calculate the flow field across each fracture plane means that we can specify or calculate apertures for each element separately. We have used this capability to study two specific problems. First, we have used a compliance model to investigate the influence of the stress changes around the excavated Validation Drift. This model modifies the apertures for each element of fractures near the drift boundary. For fractures larger than a meter, there can be considerable structure to the aperture changes on the plane: the aperture variation for fractures typical of the averagely fractured rock in the SCV-site is illustrated in Figure 3-31. The compliance model, and the conclusions we draw from its application are described in the next section. The second problem where we need to consider the detailed flow structure over fracture planes is to explain channelling experiments and the discrepancy between measurements of effective 'flow apertures' and of 'transport apertures'. We carried out a parameter study considering the importance of parameters used to characterize local aperture variation in terms of the resulting effective cross-fracture transmissivity and borehole-test transmissivity. The base case parameters were taken from the channelling experiments at Stripa. Whilst the data collected in Stripa channelling experiments was insufficient to form the basis for our inflow predictions, we shall be using them to generate a 'local aperture variation' case as part of the uncertainty studies associated with our predictions.

The final area of NAPSAC development concerns the progress of NAPSAC verification and documentation. In both these areas we are working closely with Intera Sciences. We have made progress towards flow verification with good agreement between all the codes used at Stripa for all but the large, stochastic, flow test-case. Here there is a significant difference between NAPSAC and FRACMAN results. There is no exact solution for this test-case and we are investigating the details of our solutions in order to resolve the discrepancy. We have also begun transport verification with two test cases specified and good agreement for preliminary calculations. A documentation plan has been created for NAPSAC and a first draft of the NAPSAC technical description is now available.

3.4.3 Application of NAPSAC to Simulation of Flows in Stripa Mine

For the modelling of the Validation Drift Inflow Experiment, the Harwell group has built upon the success of the models used to simulate the inflows to the D-holes (the Simulated Drift Experiment). Our models are direct forward models predicting large-scale properties and fluxes from measurements of individual fracture properties. The fracture network flow field is modelled directly in a cylinder of radius 12.5 m around the Validation Drift axis, which we have shown to be of a representative volume, with boundary conditions inferred from porous-media models of the SCV-site as discussed in the next section. A typical realization of these networks is illustrated in Figure 3-32. We have used the full coated-fracture-density as measured at Stripa and have relied upon the experimental Principal Investigators for their interpretation of the raw data. By restricting our models to simple concepts with measurable parameters, much of this data can be incorporated directly. Where further interpretation is required or additional physics is incorporated to our basic model, we can clearly identify its importance and consequences.

In addition to updating the input data, the models have been improved in two main respects. First we have modelled the fracture system of the H-zone directly as a fracture network. Separate, comprehensive datasets have been measured for the H-zone and the averagely fractured rock. Thus, we no longer have to artificially modify our networks to compensate for 'double-counting' of fracture zones: previously fracture zones both contributed to fracture statistics and were explicitly incorporated in the equivalent-porous-media models of the SCV-site. Secondly, we have concentrated on demonstrating the consistency of our interpretations. Numerically generated trace maps and scan lines have been used to check our interpretation of fracture lengths. Full network calculations on representative scales have been used to justify the extent to which the network can be truncated by ignoring the least transmissive fractures. Finally we have used a

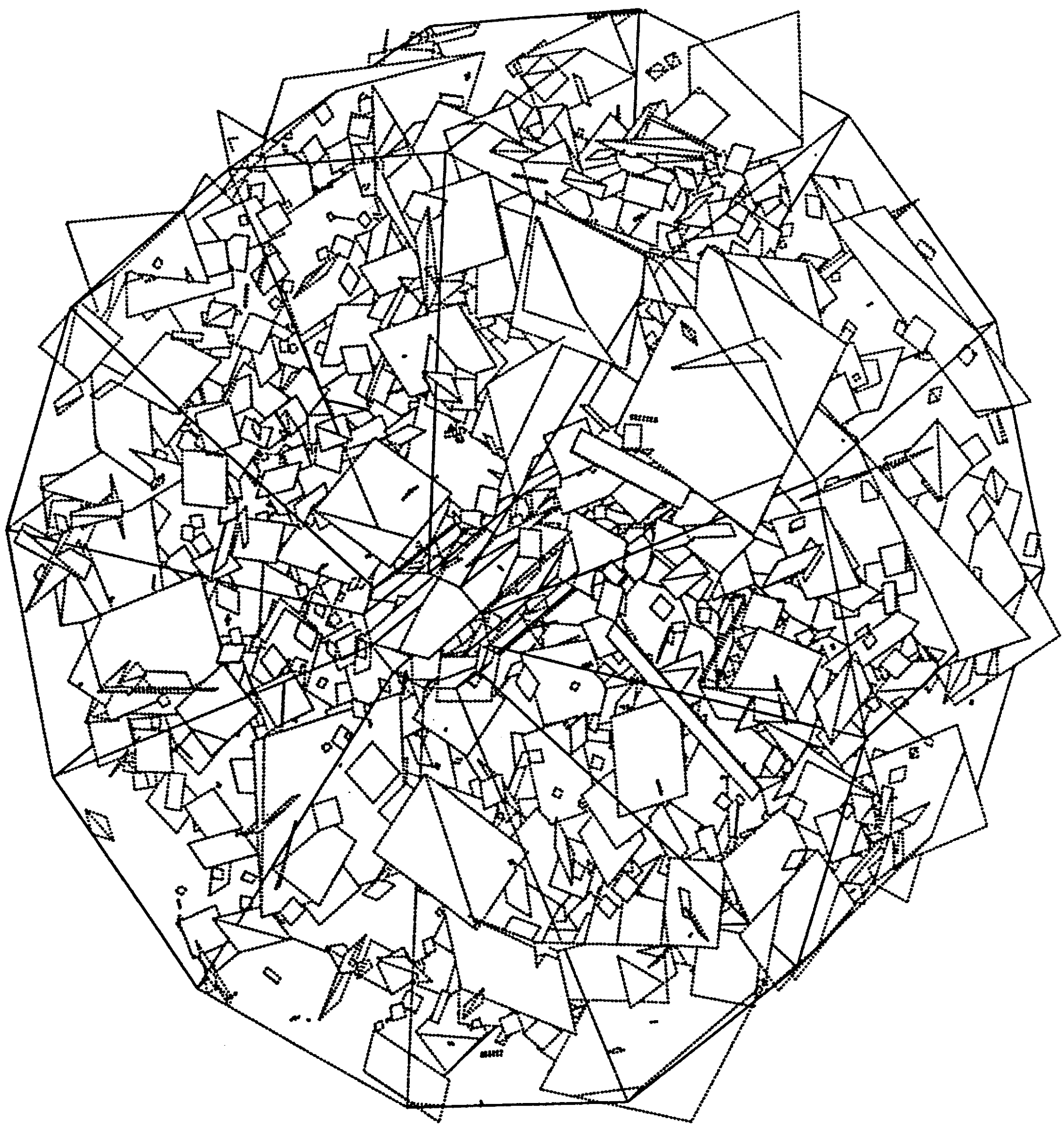


Figure 3-32. NAPSAC fracture network model used to calculate inflow to the Validation Drift. Only 10% of the modelled fractures are plotted to clarify the illustration.

range of extreme cases to assess the uncertainty in our maximum-likelihood interpretation of transmissivities. For averagely fractured rock we show good consistency and predict D-hole flows to within 50% of the measured values. The H-zone is less well characterized, and involves a very dense network with a wide range of length-scales. For the D-hole experiment our inflow prediction for the H-zone is low by a factor of about 5. This would probably be best improved by using single-fracture transmissivities directly: our log-normal fitting procedure for H-zone transmissivities showed poor convergence.

The important difference between the D-hole flows and the drift inflows is the effect of the disturbed zone. We believe our D-hole inflow predictions are acceptable and the different geometry of the experiments has only a small effect on the flow-rate per meter. We therefore consider the percentage change in inflow resulting from disturbed zone effects. The only effect for which we have any information is that of the stress-field and even that is not well characterized. The hydraulic tests did not resolve individual fractures and so no stress-aperture correlation was measurable. We therefore adopted a normal-stress compliance model, basing our parameters on a few large core laboratory tests. In these tests, the change in transmissivity was related to the change in normal stress by a simple power law. This gives

$$T/T_0 = (\sigma / \sigma_o)^{-0.2},$$

where T is transmissivity, σ is normal-stress and the subscript (o) represents properties prior to excavation. The stress-field around the excavated drift was approximated by an elastic continuum finite-element model, and this continuous stress-field was used to calculate the normal-stress field over each fracture in our numerical models. When the transmissivities of fractures near the drift were modified in our model, the predicted inflow to the drift was 10% to 20% higher than that predicted by models which did not represent the effect of the changed stress-field. This is in contrast with the experimental results, where flow measured in the Validation Drift is smaller by a factor of 8 than that measured in the D-hole experiment. The increase is due to the predominance in both H-zone and average-rock fracture networks of fractures intersecting the drift perpendicular to the drift axis. These fractures experience a reduction of stress due to a Poisson's ratio effect, and therefore an increase in transmissivity. Indeed, we can see that it is very difficult to obtain reductions of flow comparable to those observed by using this sort of compliance model. To reduce permeability near the drift by a factor of 8, the normal stress on all fractures would have to be increased by the same factor, that is, to unrealistic levels of between 80 MPa and 160 MPa. By using the continuum stress field and assuming no transmissivity increase on reduction of normal stress (i.e. all fracture closures being permanent deformations) the reduction in predicted inflow was no more than 5%.

We conclude that whilst our underlying fracture network model gives good flow predictions, the stress compliance model is not a valid description of the disturbed zone. We consider a number of neglected physical processes to be potentially important. Two-phase flow effects may reduce fluxes to the drift and be important in a very narrow skin, but these are unlikely to reduce flows by a factor as large as 8. Disturbance of fracture infill may be more important, but is not quantifiable. Finally, dynamic stress effects, such as permanent deformation during the high stresses experienced during blasting, may be significant. This last hypothesis is supported by the fact that the formation of the skin can be seen in the pressure monitoring of nearby holes: the skin reduced the influence of the D-hole sink immediately and progressively as the drift excavation proceeded.

3.4.4 Porous Modelling of Required Flows in the Stripa Mine

Three-dimensional equivalent-porous-media modelling of the SCV-site was completed using the CFEST code. This current modelling follows earlier regional (9 km by 12 km) and sub-regional (3 km by 4 km) modelling to 3000 m depth. This larger scale modelling provided the boundary conditions for the current model (MINE2) that is approximately 1.5 km by 1.5 km in surface area to 600 m of depth. The mesh for the finite-element model used to simulate the hydraulic heads in the immediate region of the SCV block is similar to that used in the SCV-2 report. Small changes to the surface expression of the 3D mesh were made to incorporate the changes in the geometry of the fracture zones determined from the Stage III field program. Significant changes in the thickness of the layers were made to accommodate the geophysical and hydraulic features inferred from the Stage II field program. The model consisted of 14 layers, with layer thicknesses selected to correspond as closely as possible to the main mine levels.

Four fracture zones have been included in the model. They included an east-west fracture zone located in the southwest corner of the model, the H-zone, I-zone and the combined A-B-zone. The main focus of this current modelling has been to determine the impact of the extensive nature of these fracture zones on the distribution of hydraulic heads within the SCV block and the flux into the D-holes and Validation Drift. This modelling showed that extending the fracture zones to the surface increased the pressure heads at the 385 level.

Comparison of computed heads in the form of contour plots with contour plots of field measurements suggest that fracture zones I and A-B may have been extended too far to the southwest in the numerical model. In addition, the steeper hydraulic gradients measured in the field probably reflect the effects of stress concentrations around the drifts and the pinching and swelling of the fracture zones along strike, and hence a strong variation in hydraulic properties that has not been reproduced in the model. However, the overall agreement between the measured and computed hydraulic heads suggest that additional refinement in the distribution of hydraulic properties within the 3D model may enable one to complete a first order calibration of the 3D model against the measured hydraulic heads.

The importance of building stress concentration effects into the elements surrounding the simulated SCV drift, and other drifts, is apparent when we compare the effects of opening the SCV drift on the hydraulic head distribution (Figure 3-33). The measured head changes are much more localized than the computed head changes, suggesting a low-permeability zone around the SCV drift.

3.4.5 Complementary Work by Golder Associates

Golder Associates based their modelling of the Validation Drift inflows on a similar approach to the Harwell team. Their interpretation of the data was different, and this led to much larger regions being modelled using the fracture-network approach directly. Their interpretation of the data from the SCV Stage IV measurements was based on a 'bootstrapping' approach as compared with Harwell's use of statistical estimators.

Fracture orientation was evaluated based upon assumptions of 1 to 5 sets for fracture zone and non-fracture zone data from both core logs and trace maps in mine drifts. The ISIS interactive set identification procedure did not distinguish statistically significant sets. As a result, the fracture conceptual model implements fracture orientation using 'bootstrap' resampling from measured orientations. Fracture size distributions were fit to fracture zone and non-fracture zone data

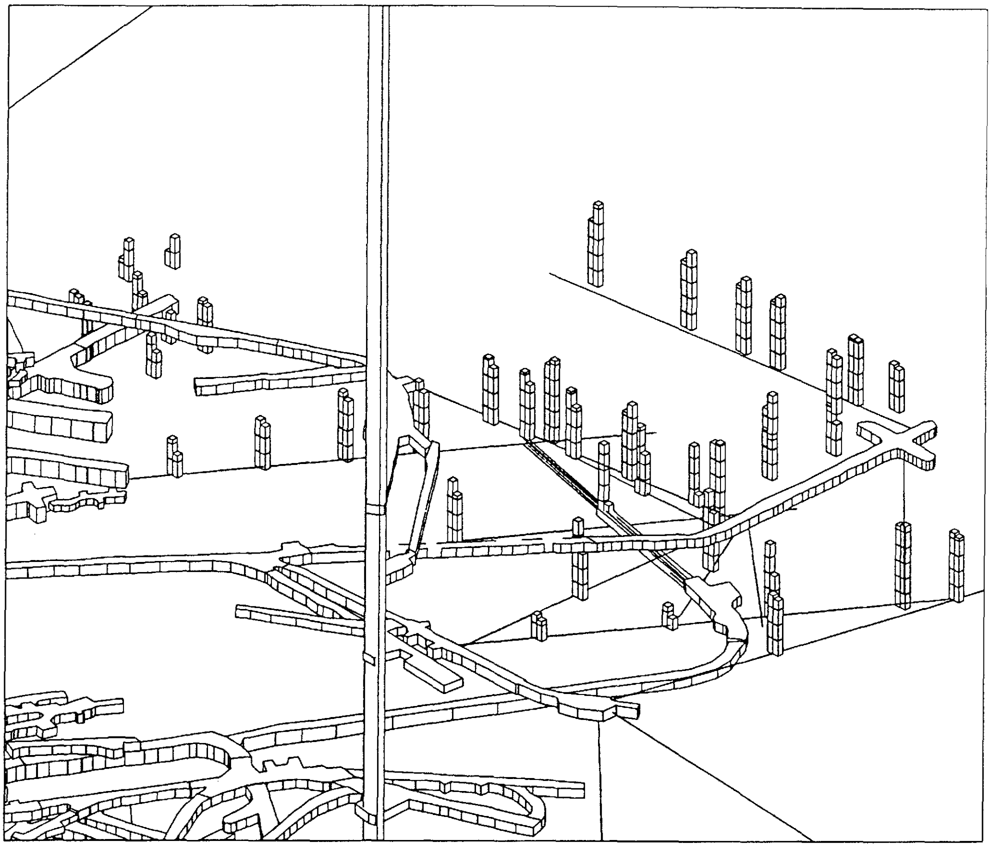
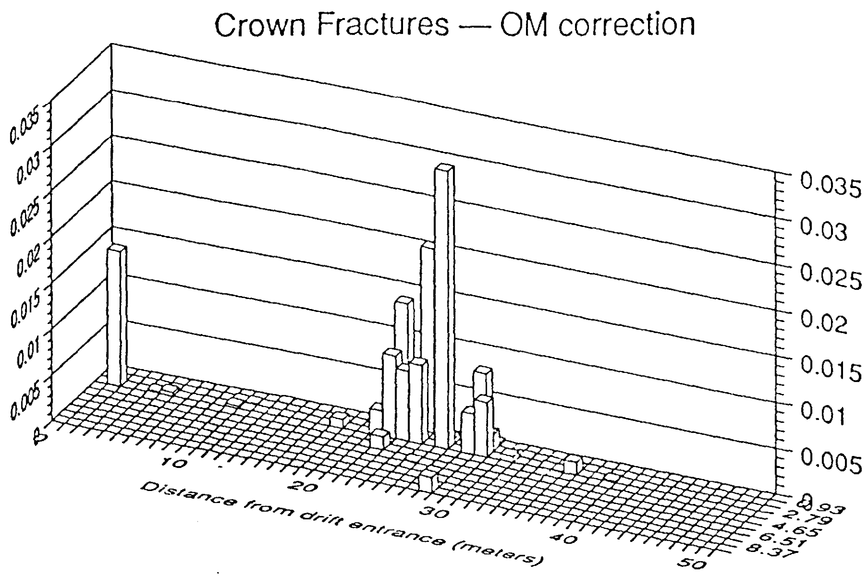


Figure 3-33. CADD diagram showing comparison of measured versus computed pressure heads for selected monitoring points around and in the SCV block. The pressure heads are shown as columns with 50 m sections. The measured pressure heads are given by the left column and the computed pressure heads are shown as the right hand column.

from traceplanes using the FracSize procedure. FracSize simulates the process used for collection of fracture trace date, postulating alternative distributions for fracture size until a statistically significant match is found between observed and simulated trace length distributions. FracSize obtains fits for log-normal, exponential, and power law distributions for fracture radius. Simulated-annealing optimized search was used to obtain fits for fracture radius distribution. In the current approach, the transmissivity of the packer interval is assumed to be given by the sum of borehole transmissivities of the conductive fractures intersecting that interval. The borehole-transmissivity is, in this case, related to the cross-fracture transmissivity by a scaling factor derived from single-fracture flow modelling. The cross-fracture transmissivity distribution and conductive-fracture frequency can then be evaluated using maximum likelihood approach. Finally, fracture zone properties were calibrated from the distance drawdown curves for large scale (cross-site) response to pressure changes in the D-holes. Fracture zone locations were based on the interpretations of the experimental Principal Investigators, given in the SCV Stage IV report.

Using the above interpretation, three scales of flow modelling were carried out: modelling of flow in single fractures to calibrate the relationship between at-borehole and cross-fracture transmissivity; transient modelling of cross-hole experiments to calibrate transmissivity and storativity properties of fractures and fracture zones; and predictive flow modelling of the D-hole and Validation Drift



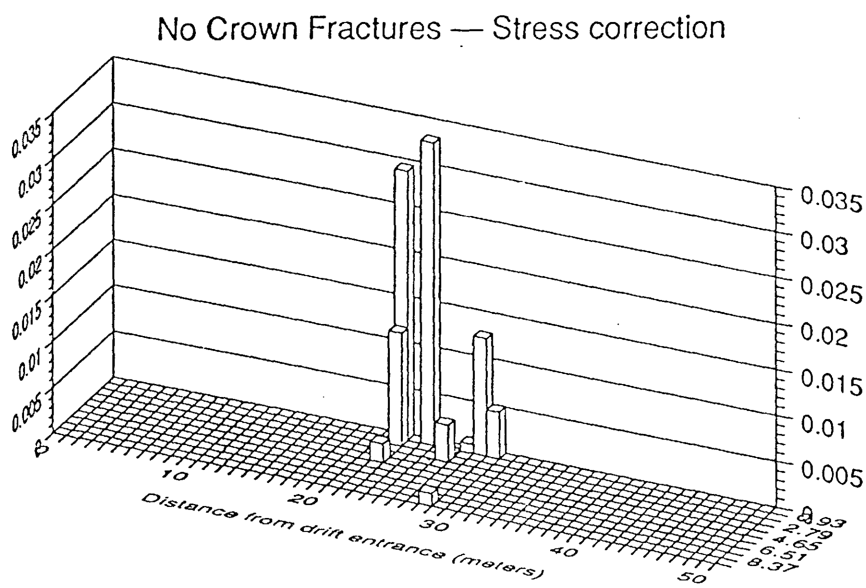


Figure 3-34. Distribution of predicted inflow to the Validation Drift from the Golder Associates model, using two different disturbed zone conceptual models:

a) 'Crown fractures' stress relief fracturing model;

b) Compliance model of transmissivity – normal-stress relationship.

inflow experiments. The conceptual model utilized in the model studies was based upon a "strong zone" concept of hydraulic response at the SCV-site. In this concept, major hydraulic response at the site is controlled by fracturing within fracture zones. As a result, only those fractures within zones need to be modelled at the 200 m SCV block scale. Discrete fractures outside of zones are only modelled within a 10–20 m radius cylinder or block around boreholes and drifts of interest, to represent the local pathways defined by individual fractures and fracture networks. In this model, only conductive fractures (as defined by the packer interval transmissivity analysis) are included in either coarse or fine models.

Flow modelling of the Validation Drift was first carried out under assumptions of no stress effect on fracture transmissivity. The effect of the disturbed zone around the drift was again investigated using a compliance law of the form

$$T/T_0 = (\sigma / \sigma_o)^{-\beta}.$$

Stress-transmissivity coefficients β between 0.2 and 2.5 were evaluated. In addition, the possible formation of "onion-skin" stress-relief fracturing parallel to the axis of the drift was evaluated by introducing an artificial fracture set parallel to the axis of the drift in the drift crown. The distributions of inflow resulting from these disturbed zone models are illustrated in Figure 3-34.

Flow modelling was also undertaken to evaluate the effect of pressure disturbances due to fracture sealing experiments in the Buffer Mass Test (BMT) area on pressures and inflows in the SCV drift region.

The other significant area of modelling was to carry out solute transport simulations in support of the design of tracer experiments. These simulations utilized the discrete fracture model developed for flow simulations. Solute transport simulations require three parameters in addition to those derived for flow modelling: fracture storativity, transport porosity, and transverse and longitudinal dispersivity. Storativity was derived by calibration of fracture zone fractures using large scale cross-hole simulations results. As a first approximation, transport porosity was derived based upon a cubic relationship to fracture transmissivity, transverse and longitudinal dispersivity were calibrated from results seen in saline injection experiments. The calibrated solute transport model was used to evaluate the range of travel times and recoveries for alternative tracer injection locations, and to produce simulated tomograms of tracer concentration. In addition to this detailed transport modelling, solute transport was evaluated using FRACMAN pathways analysis, which carries out a dynamic programming search through possible fracture network connections between injection and monitoring points to determine the possible transport pathways.

Finally, Golder Associates completed simulation of geometric flow and solute transport cross-verification cases by the end of 1990. Additional flow and solute transport cross-verification cases will be defined during 1991, and additional runs of existing cross-verification cases will be carried out to explain observed results.

3.4.6 Complementary Work by Lawrence Berkeley Laboratory

The objective of the LBL modelling work is to develop a suite of models to explain and predict the hydraulic behavior of the rock in the SCV-site. The class of models being developed are equivalent discontinuum models and the general strategy behind these modelling efforts is to use a limited set of data to make a series of predictions that are consequently checked by access to further data.

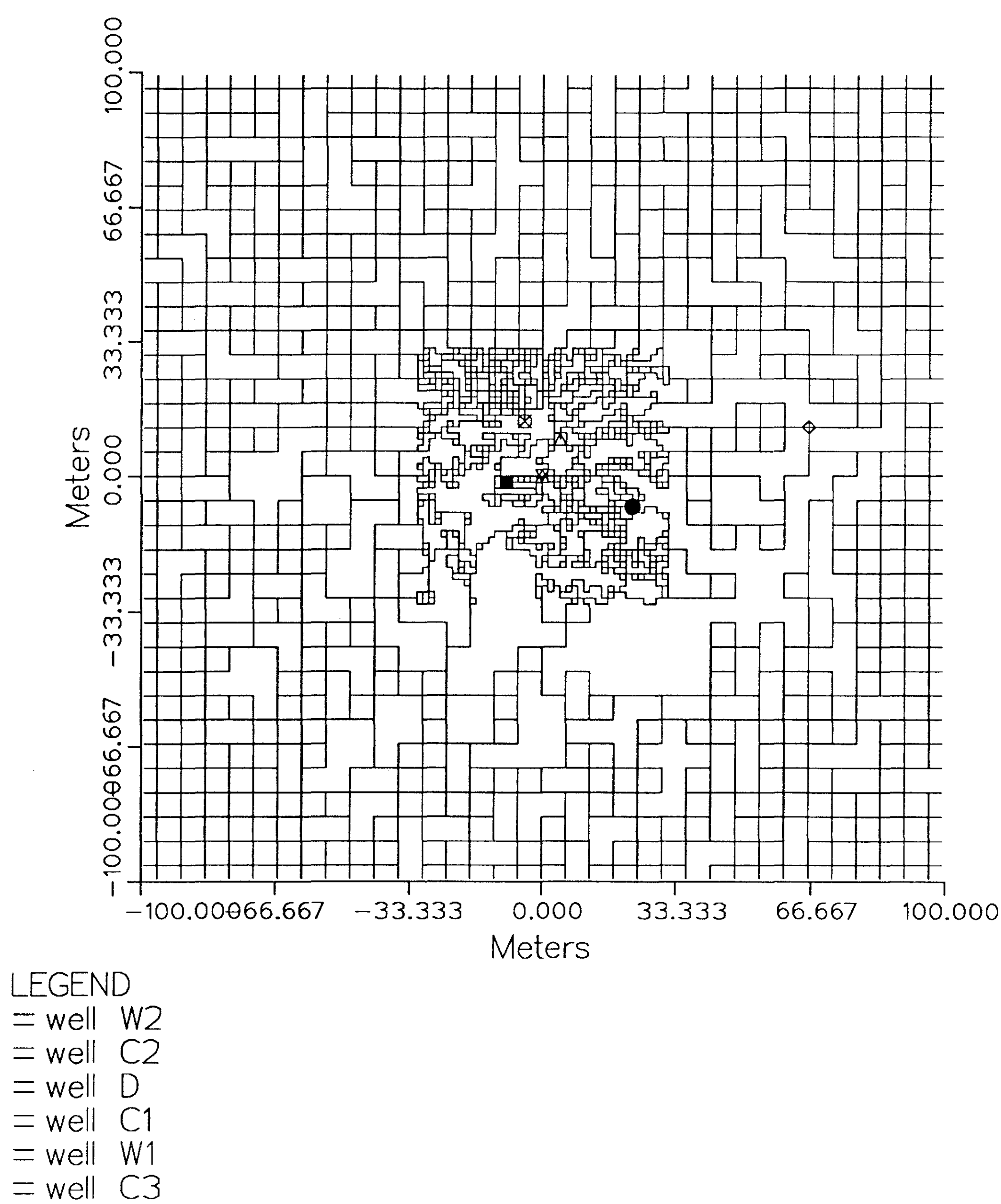


Figure 3-35. Typical realization of the two-dimensional equivalent-discontinuum model of the H-zone generated by LBL, using 'simulated-annealing' to solve the inverse hydrologic problem.

Equivalent discontinuum models for fracture networks are based on the premise that it is not important to know every detail about the location of each fracture conductor in the rock. It is important to have a model that reproduces the hydraulic behavior of the rock. This modelling approach is similar to using an equivalent continuum to model flow in homogeneous porous media. In our case, we construct a lattice model which approximates the location of equivalent hydraulic conductors in the rock. The location of these conductors can be determined in a variety of ways through the geophysical analysis, well testing and fracture data. Then, we use an inverse technique to parameterize the lattice such that it behaves like the hydrologic tests that have been performed. For Stripa, we have been applying an inverse technique called "Simulated annealing" which looks for arrangements of lattice elements which minimize the difference between observed and predicted behavior.

Three sequences of models are being produced. The first set of models are two-dimensional models of the H-zone. In these models we are making the assumption that flow into the Validation Drift is controlled by the H-zone which can be modelled as a two-dimensional feature. A square lattice is used as the template for conductors in this zone. Simulated annealing is applied to the steady-state values of drawdown observed in the H-zone during the D-hole experiment. As is common in hydrologic inverse problems, the data is not sufficient to determine a unique solution, and for this two-dimensional case, many realizations can be easily generated. An example is shown in Figure 3-35. Using this model we can examine the effect of discretization and look at the distribution of possible results given the data we have.

For this model, we can look at the effects of excavation on inflow to the drift. The first effect is that of changing hydraulic boundary conditions from that of six boreholes to a single large "borehole" circumscribing the original six. For the scale of our model, this change is insignificant. Further, it can be shown analytically that the change in flow rate due to this circumscribing "borehole" is negligible. Secondly, there will be effects of the change in stress state due to the opening. The net effect of this change will depend on the orientation and location of the major conductors with respect to locations where the stress increases or decreases. A prediction could be made by using a series of stochastic realizations of the fracture patterns near the drift. Each of these patterns would specify a combination of fracture orientation, location and conductivity with respect to the drift. Then the change in normal and shear stress on these planes can be estimated using a continuum model for stress; and laboratory data can be used to estimate the consequent change in fracture conductivity and inflow. This approach models a significant number of estimates based on estimates and the technique is not conducive to our model because we do not include actual fracture orientations and locations: we have equivalent conductors. Thirdly, there will be effects due to the interface with air in the drift. These in turn are of at least three types. One, is that the actual ventilation process can create a further gradient essentially sucking water out of the rock. Two, is that there can be two-phase flow effects if gas has entered the fracture network near the drift wall. This could happen for example if blasting drives air back into the rock or if gas comes out of solution in the groundwater as it is lowered to atmospheric pressure near the drift. Three, is that there could be surface tension effects at the interface which retard the flow of water especially through small aperture fractures.

In sum, we expect that the net effect will be essentially a "skin effect", either positive or negative which will change the flow into the drift. Although there is some data available to analyse all these effects, it is our judgement that the number of assumptions required to make such an analysis is large. Consequently, we have looked at the data available from the Macropermeability experiment which was performed about ten years ago located nearby the west. With this data, it is possible to plot the head versus log of radius to the drift and see that there is a skin effect of approximately 25% of the background permeability averaged over a five meter distance from the drift. This decrease in permeability is observed without understanding the cause. Given this observation, we plan to decrease the permeability of the conductors in our model within five meters of the drift by a factor of four and calculate the reduction in flow to the validation.

The second model being developed at LBL is an orthogonal grid model. John Gale's analysis of the fracture orientation data has concluded that there are clusters of sub-vertical and sub-horizontal fractures. Without looking at these distributions in detail, the gross distributions suggest that the rock might be modelled on an equivalent orthogonal grid in three dimensions. Such a model has been created and is being "annealed" on the steady state values of head observed in the D-hole experiment. The annealed model can then be calibrated in much the same way as the 2D model described above. After the calibration, the model can be used to predict the flow into the Validation Drift, flow into the remaining D-holes, and the distribution of head changes due to the excavation of the drift.

The result of the grid model can be compared to the conceptual model developed based primarily on geophysics. Probably this would be most effective if the grid model were annealed with the transient cross-hole test results. In this way we can have a check on whether the hydrology alone supports the concept of fracture zones dominating the behavior. Finally, we can develop a grid model by conditioning the annealing process with the geophysics. In this way we would encourage the inversion to find solutions which match the geophysics. This may turn out to be a very good way to model both the "good rock" and the fracture zones.

The final model being pursued is a zone model. In this model we place a grid of conductors on each of the planes identified as fracture zones by geophysics and the Fracture Zone Index. Then annealing is used to find the pattern of grid elements which can reproduce the well test data. This is the chief model we have been developing for the Stripa Project.

The strategy for using this model is as follows. First we will use all the hydrologic information except any data associated with the D-holes or the Validation Drift. This primarily includes the Large Scale Cross-hole data. After annealing to this series of transient tests, we will predict the results of the D-hole experiment. Although this process is the reverse of the order the data was collected, we believe that this approach is a much better test of our modelling approach than predicting flow into a drift that is dominated by excavation effects we cannot easily quantify. Once this prediction is made, we will include the results of the D-hole experiment results in the annealing process and calibrate the model to the skin observed in the Macropermeability experiment as above. This model will be used to predict flow into the drift, flow into the remaining D-holes and distribution of head due to excavation. Finally the zone model will be adjusted to predict the actual flow into the Validation Drift. This will be done by adjusting the skin as above until the correct flow rate is obtained. This model will be the base model for predicting tracer transport to the drift.

3.5 ROCK SEALING TEST

3.5.1 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.

3.5.2 Major Activities in 1990

The work in 1990 consisted of three major parts:

1) Field work concerning the evaluation of the hydraulic conductivity of the "disturbed zone" of the BMT Drift (Test 2).
2) Field work concerning the characterization of the natural fracture zone in the eastern arm of the 3D cross (Test 4).
3) Laboratory work comprising hydrothermal tests of clay in different chemical environment, and theoretical and experimental investigations of cement-based grouts.

3.5.3 Evaluation of the Hydraulic Conductivity of the Disturbed Zone of the BMT Drift

Figure 3-36 shows the general test arrangement of Test 2, which is conducted in two steps, i.e. a first one in which the inner slot and borehole curtain were pressurized while recording the inflow into the rock and the flow from the outer borehole curtain, and a second one of identical form after "hedgehog grouting".

The flow measurements, which were made at water injection pressures of 0.25, 0.45, 0.75 and 0.95 MPa, showed that the rock next to the periphery of the blasted drift has a hydraulic conductivity of around 10^{-8} m/s, assuming the disturbed zone to extend 1 m from the periphery. The conductivity of the rock next to this zone, reaching 6 m further into the rock, is concluded to have become about five times as high as the conductivity of the virgin rock, which is taken as 10^{-10} m/s.

The walls of the drift had to be tight for carrying out the test and it turned out that even a carefully made rubber-based liner was not good enough. The preparation of the drift for the experiment therefore required filling the drift with a bentonite slurry that could be pressurized by use of a central rubber bladder.

In the fall the drift was emptied as a preparation of the "hedgehog" grouting, i.e. injection of cement grout into densely spaced, short holes. The grouting was completed at the end of the year.

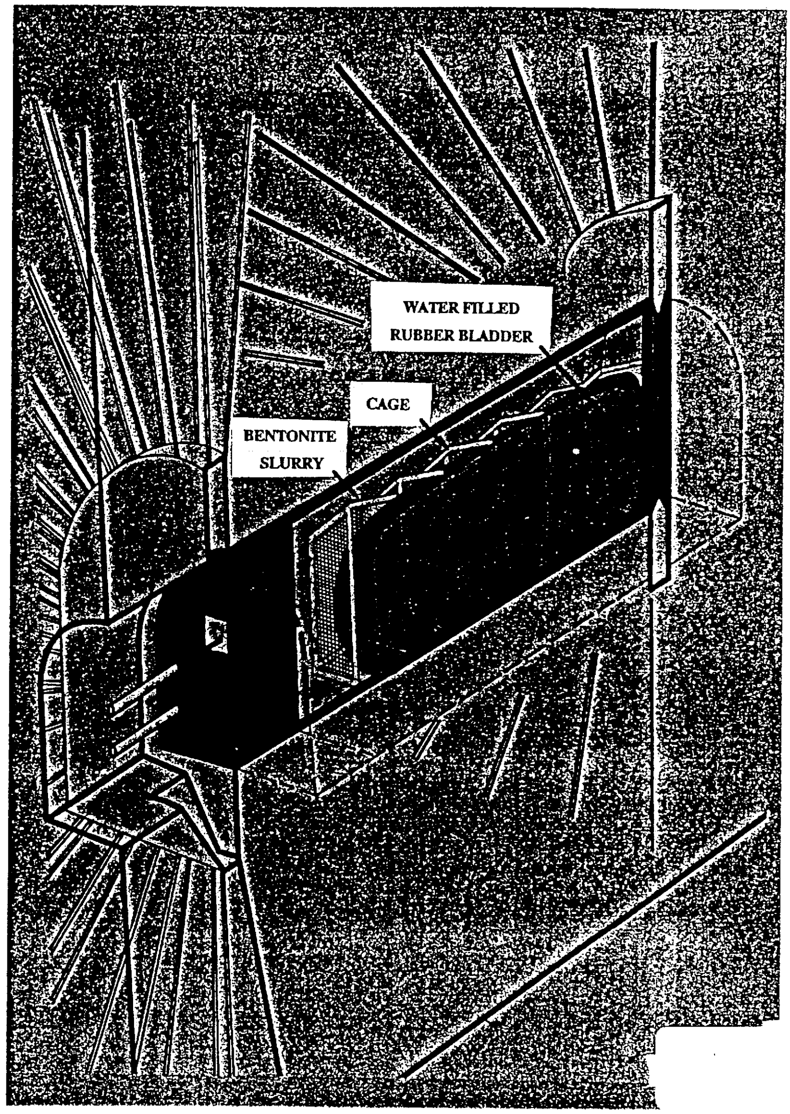


Figure 3-36. General arrangement of Test 2. K represent water-pressurized boreholes extending radially from 0.75 m deep slots cut around the inner and outer ends.

3.5.4 Characterization of the Natural Fracture Zone in the Eastern Arm of the 3D Cross

Comprehensive drilling and hydraulic characterization of the rock in the right arm of the 3D cross has been made and a first grouting phase completed.

Water inflow measurements and tracer tests revealed the major water-bearing structure that controls the inflow and it was characterized by core drilling, "Lugeon testing" and tracer experiments. Generally speaking the structure has the form of one, locally bifurcating, major fracture that is a member of one of the dominating fracture sets in the area, striking almost NW/SE and dipping slightly more than 80° (Figure 3-37).

FEM calculations, in which the rock is modelled as porous zones with specific hydraulic conductivities, have been conducted. Assuming that the fracture can be sealed so that its conductivity drops to 10^{-10} m/s, the inflow pattern will be very significantly altered and the inflow capacity reduced to 50–60% of the initial value.

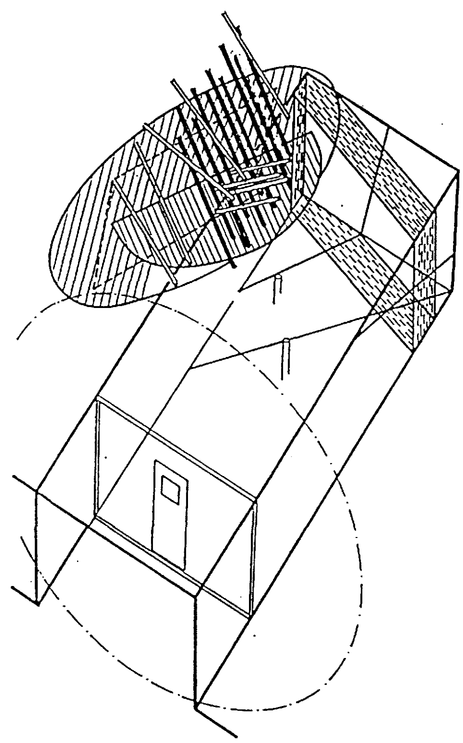


Figure 3-37. Identified dominant water-bearing structures that supply the eastern arm of the 3D cross with water. The ellipsoidal structure represents a long-extending fracture zone that is of major importance. The boreholes indicated in the figure were drilled for hydraulic characterization. They will be grouted, except for one hole that will be used for tracer experiments.

3.5.5 Hydrothermal Tests of Clay in Different Chemical Environment

A comprehensive set of hydrothermal tests of smectite clay was started and certain test series were stopped after 10 and 30 days, respectively in order to get a first picture of the kinetics. A major conclusion is that a temperature of around 130°C represents a critical level with respect to the dissolution of smectite. Transformation to yield mixed layer and hydrous mica seems to require access to magnesium or iron and 120 – 130°C temperature, while neoformation takes place at any temperature exceeding about 70°C, the process being entirely dependent on the access to potassium.

3.5.6 Experimental and Theoretical Investigations of the Long-term Performance of Cement-based Grouts

The cement study has been pursued by considering chemical degradation, of which leaching/dissolution of more soluble constituents like $Ca(OH)_2$ or reaction with aggressive species like sulphate and chlorite are the major ones. The independent and combined effects of these processes have been investigated experimentally and seem to indicate that high performance cement grouts are virtually impermeable. Surface leaching is likely to be the major degrading process, meaning that fracture widening may be the controlling factor of cement longevity. The parallel thermodynamic modelling has concerned flow and diffusion through the cement matrix and in the later part of the year the work has been focussed on successive changes in diffusivity of the grout due to chemical reaction with the grouts. Preliminary results suggest that cement grout seals should provide acceptable performance for very long times.

3.5.6.1 Experimental Investigations

The laboratory studies are scoped to determine the ability of the cement-based grout to maintain its design performance through time under the range of temperatures, pressure and geochemical conditions encountered in a disposal vault.

The investigation into the longevity of performance of cement-based grouts continued during the past year. Specifically, laboratory studies were assessing; the general leaching properties of the reference grout; the permeability and the hydraulic conductivity of grouts; changes in porosity distribution and size due to changes in grout volume that accompany dissolution plus precipitation and the effects of these changes on grout permeability.

GENERAL LEACHING PROPERTIES OF REFERENCE GROUT

An important factor influencing the longevity of cement-based grouts is interaction with the groundwater and various components of the disposal vault system.

Leaching by water involves the penetration of the grout by water or aqueous solutions, the dissolution of soluble constituents of the hydrated grout and transport of the dissolved species through the pore structure to the surrounding water. The depth of penetration of the water or aqueous solution into the grout will largely be controlled by the permeability of the grout and potentials in the free and pore water.

Hardened samples of reference grout mixed at 0.4 and 0.6 w/cm and ALOFIX-MC (MC-500) mixed at 0.7 w/cm were subject to static leach tests in WN-1 synthetic groundwater. Tests were carried out to determine the effect of temperature and time on the leaching behavior of grouts. Leach tests were conducted at 10°C, 25°C, 50°C and 85°C. Leaching performance of grouts was determined by measuring the leach rates of Ca^{2+} and Si^{4+}.

The results from the static tests show that over the investigated range of water cement ratio (w/cm) for the reference grout mixed at 0.4 and MC-500 grout the release of Ca^{2+} to solution exhibits a marked decrease with the increase in leaching time. Additionally, Ca^{2+} concentration exhibits a minimum in most cases and then increases to a constant value, as shown in Figures 3-38 and 3-39. The time to achieve the constant value increases as the temperature increases. For the reference grout mixed at 0.6 w/cm the release of Ca^{2+} increases with leaching time up to ~14 days of leaching (Figure 3-40) at which point the release approaches steady-state. Preliminary results indicate that the leaching mechanisms and the structure of the leached surface strongly depend not only on the composition of the leachant and the contact time between the leachant and grout but also on the grout microstructure. Leaching was found to be accompanied by precipitation and grouth of an assemblage of secondary alteration phases. SEM/EDX analysis showed that the precipitate to consist of phases such as $Mg(OH)_2$, $CaCO_3$ and $Ca(OH)_2$. The composition of the precipitate layer may reflect the chemical transformation in cement as well as the changes in the groundwater which is in contact.

The performance of grouts will depend (strongly) on those alteration, precipitation solids formed subsequent to initial grout dissolution. The precipitates or al-

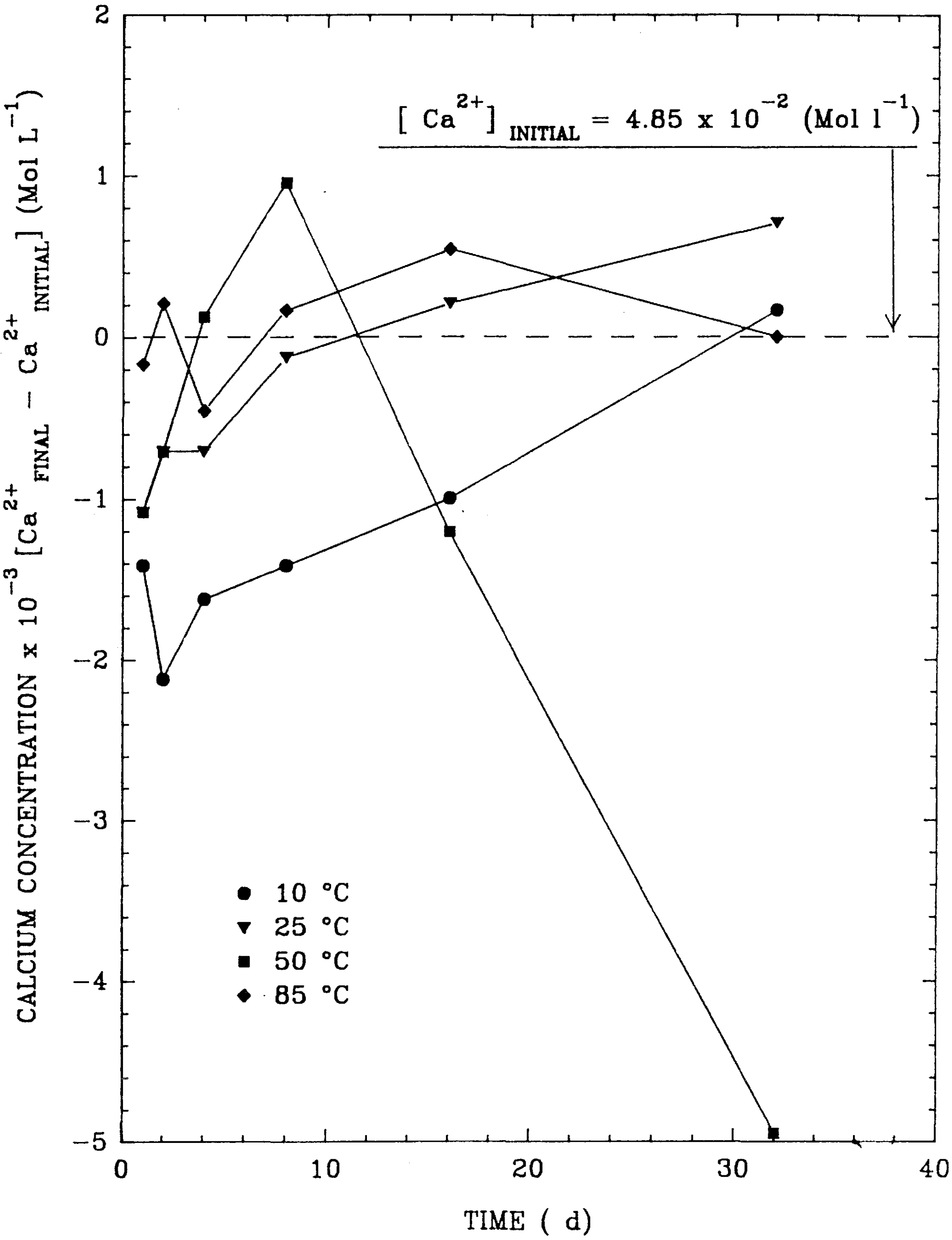


Figure 3-38. Calcium concentration vs. time for Type-50 cement 0.4/1/10 grout reacted with WN-1 groundwater at different temperatures.

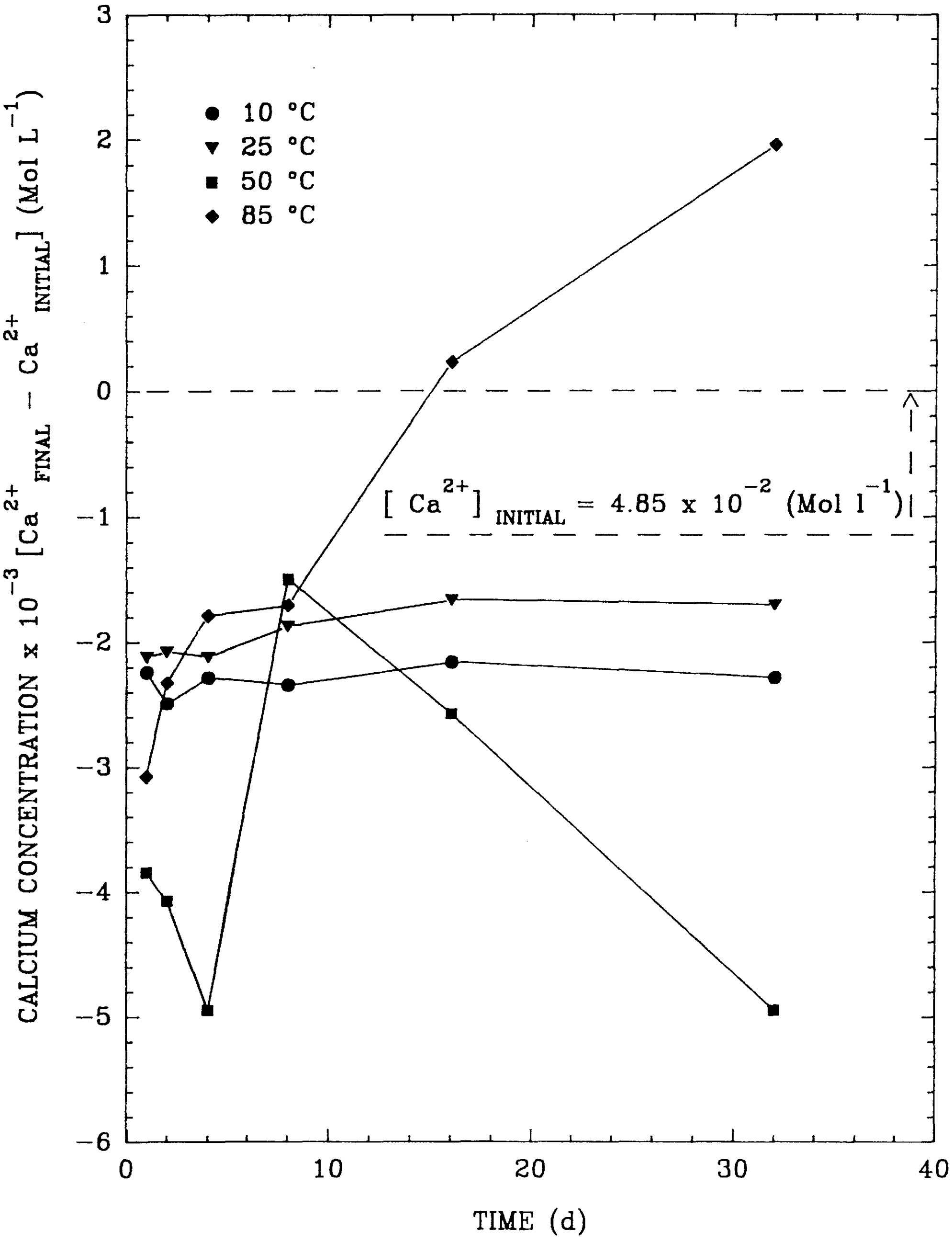


Figure 3-39. Calcium concentration vs. time for ALOFIX-MC [MC-500] 0.7/1/10 grout reacted with WN-1 groundwater at different temperatures.

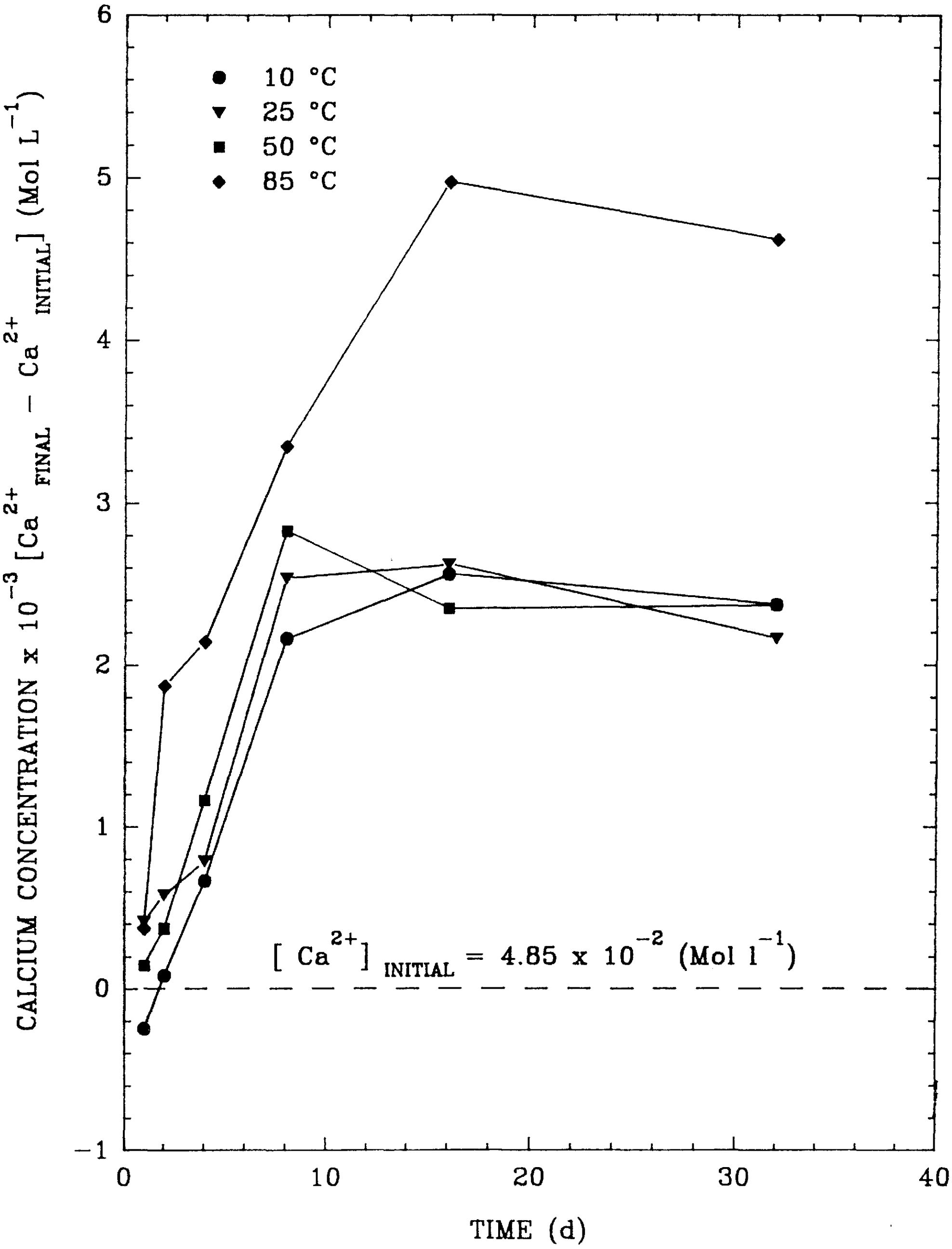


Figure 3-40. Calcium concentration vs. time for Type-50 cement 0.6/1/10 grout reacted with WN-1 groundwater at different temperatures.

teration products that formed on the cement surface can arise from a number of sources. The groundwater is already supersaturated with respect to many possible alteration phases. Moreover, the dissolution/leaching of grout may lead also to supersaturation of groundwater with respect to alteration phases (e.g. $Ca(OH)_2$, $CaCO_3$, $Mg(OH)_2$). In addition, pH increase may also initiate precipitation. It is possible that alteration solids of intermediate stability (metastable) may form rather than the most stable ones. This type of behavior is commonly recognized in the alteration of natural minerals and glasses under both static and dynamic system conditions as described Ostwald step-rule, or the "rule of stages" based on kinetics of nucleation and crystal growth. *"The Ostwald step-rule state that the transition of chemical system from an unstable state to a stable state typically occurs via a series of irreversible metastable state".* The stability of the alteration/precipitate phases may influence the long-term performance of the cement grout.

HYDRAULIC CONDUCTIVITY AND POROSITY OF REFERENCE HIGH PERFORMANCE GROUTS

Ongoing investigations on the permeability of the reference high performance grout have shown that the grout is practically impermeable under hydraulic gradients ($i < 36\,000$) higher than those expected in a disposal vault where "i" may be as low as 10^{-2}. Also, the data show that the hydraulic conductivity is decreased by adding silica fume and by reducing the water-to-cementitious materials ratio. The reference grouts containing silica fume have very low hydraulic conductivity (i.e. $<10^{-14}$ m/s). Moreover, studies on the effect of leaching on the pore structure of the reference high performance grouts revealed that the material's porosity does change during leaching, but only within the limits that depend on the grout's composition and its initial porosity. The observed decrease in the pore radius during leaching was found to depend on the total porosity of the grout and, more importantly, on the activity of the cement and the volume and the type of hydration products developed in the grout during leaching. Changes in porosity during leaching (Figure 3-41) were related mainly to changes in the volume of solids caused by the formation of new hydration products as a result of the increase in the degree of hydration. It is commonly assumed in the durability models developed to estimate the long-term performance of cement grouts that the grout will degrade through pore water exchange and associated leaching processes. A decrease in the performance of cement grouts was considered to be the result of increased porosity. Our studies on the porosity and permeability of grouts tend to suggest that pore size distribution rather than total porosity provides the measure through which longevity can be assessed. The small pores do not make a significant contribution to permeability.

The very low hydraulic conductivity as well as the presence of finer pore size distribution do not allow for pore water exchange and cement dissolution effects on the grout performance to be observed. These observation are needed for adequate development and qualification of the grout durability models. Thus, a study has been initiated to assess the permeability and hydraulic conductivity of grouts with high capillary porosity. The hydraulic conductivity and permeability of the "porous" grouts are being determined using specially developed hydraulic conductivity cells. Nine permeameters capable of measuring the hydraulic conductivity of "porous" grouts at pressures up to 5 MPa have been build and installed. The laboratory work involves samples of granulated hardened reference grout mixed at 0.4 and 0.6 w/cm and MC-500 mixed at 0.7 w/cm and samples of hardened grout mixed at high water to cement ratio (>0.8). The experimental responses assessed include examination of water permeating through the cell, thermal analysis

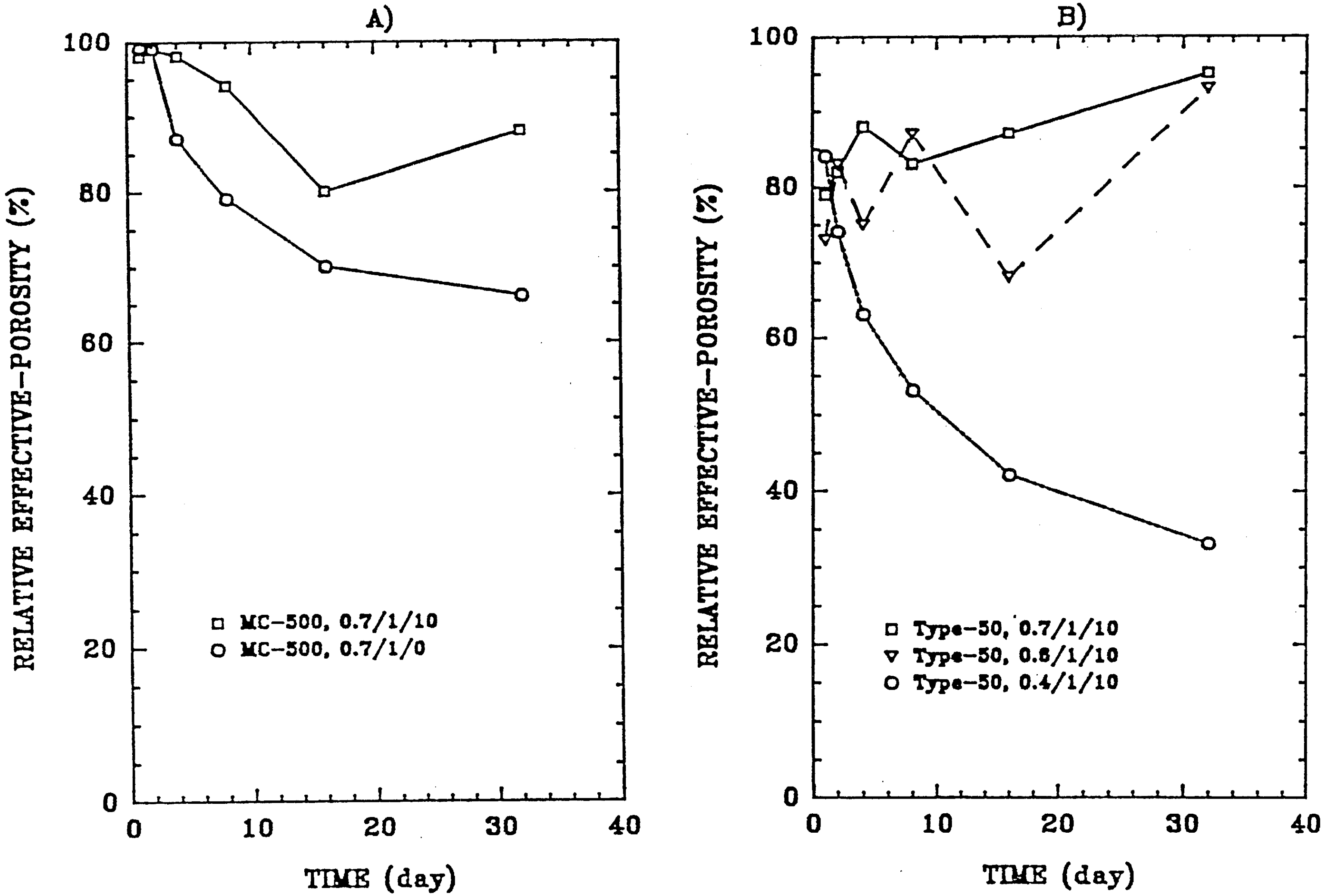


Figure 3-41. The effect of leaching time on the relative effective-porosity (REP = ρ_A/ρ_B x 100), for A) ALOFIX – MC (MC-500) grout, B) Reference grout (Type-50).

(DTA, DTG), surface analysis (SEM/EDXA and XRD), porosity measurements of the grout specimen before and after the tests. Preliminary results show that the k decreased with time. In some cases the k decreased from 10^{-7} m/s to 10^{-9} m/s. This is likely associated with the formation of alteration/precipitate phases in the grout as noted in the leaching studies.

3.5.6.2 Theoretical Investigations

The modelling analyses performed through the end of 1989 as part of the theoretical investigations of the long-term performance of Portland cement grout-based seal materials have dealt primarily with the hypothetical interactions between grout and groundwater. The grout model has gone from simple to relatively complex, several actual groundwater compositions have been incorporated into the analyses, and uncertainties arising from the weak crystallinity of cement phases have been evaluated. Results derived from the modelling have consistently suggested that cement grout seals will maintain an acceptable level of performance for a long time (perhaps tens of thousands to millions of years), provided the repository is sited where groundwater chemistry is compatible with the grout and hydrologic gradients are low (see Figure 3-42).

In preparation for the March 1990 meeting of the Task Force on Sealing Materials and Techniques in Örebro, focus was placed for the first time on the effects on grout chemical stability of including host rock minerals in the modelled grout-groundwater interactions. The geochemical code EQ3/6 was used to analyze chemical reactions involving the six-phase grout, granitic rock (quartz, albite/anorthite, and microcline), and groundwater. Common secondary fracture-filling minerals (clay, calcite) were incorporated into some of the analyses. The analytical results show that secondary phases resulting from interactions involving rock, water, and cement include zeolites, clays, carbonate, sulfate, and probably CSH/CAH phases (see Figure 3-43). These results are similar (although not identical) to those of the water/cement systems analyzed, and the predicted reaction products fundamentally mirror the secondary minerals found in natural systems. This suggests that the introduction of cement in amounts that are small relative to the available volume of groundwater does not greatly perturb the natural system over the long term. In addition, the interactions result in a net volume *increase*, i.e. the volume of secondary minerals produced exceeds the volume of cement phases dissolved, by several volume percent. This suggests that fractures will tend to seal up with time, just as they do in nature.

Porous (Darcy) flow has been the transport mechanism analyzed so far by which groundwater enters the seal and dissolved grout constituents leave the seal. The time taken for groundwater to flow through a seal is calculated based on Darcy's Law, assuming a hydraulic gradient for the site and an initial hydraulic conductivity for the grout. As the grout reacts with the groundwater, the groundwater travel time through the seal changes dynamically in response to changes in the hydraulic conductivity, which in turn are related to changes in the grout porosity cause by the chemical/mineralogical changes.

The question of the role of matrix diffusion in the degradation of cement grout was thoughtfully addressed by Dr. Ivars Neretnieks in a note distributed to the Sealing Task Force. A response to the note was developed by the U.S. Representative and Principal Investigator and presented to the Task Force. It was acknowledged by the Task Force that matrix diffusion could be potentially significant as a mechanism for grout degradation in hydrologic regimes where flow is very low or non-existent, although preliminary calculations incorporating realistic assumptions indicate that cement grout will perform acceptably for a very long time. The

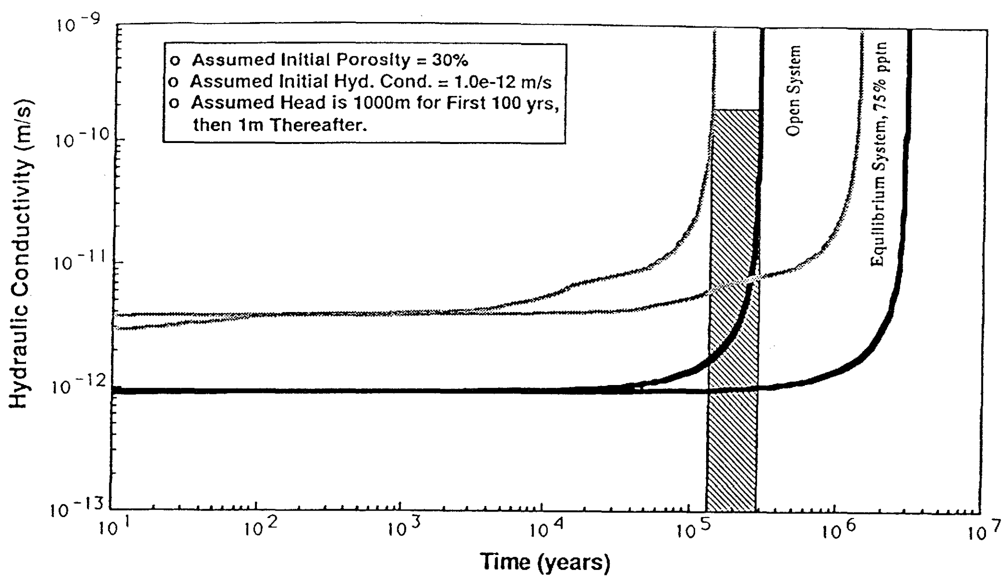


Figure 3-42. Results of geochemical-hydrological modelling analysis showing changes in hydraulic conductivity with time. The vertical bar indicates the possible minimum estimated useful life of a seal under the conditions analyzed, with uncertainties in the assumptions incorporated.

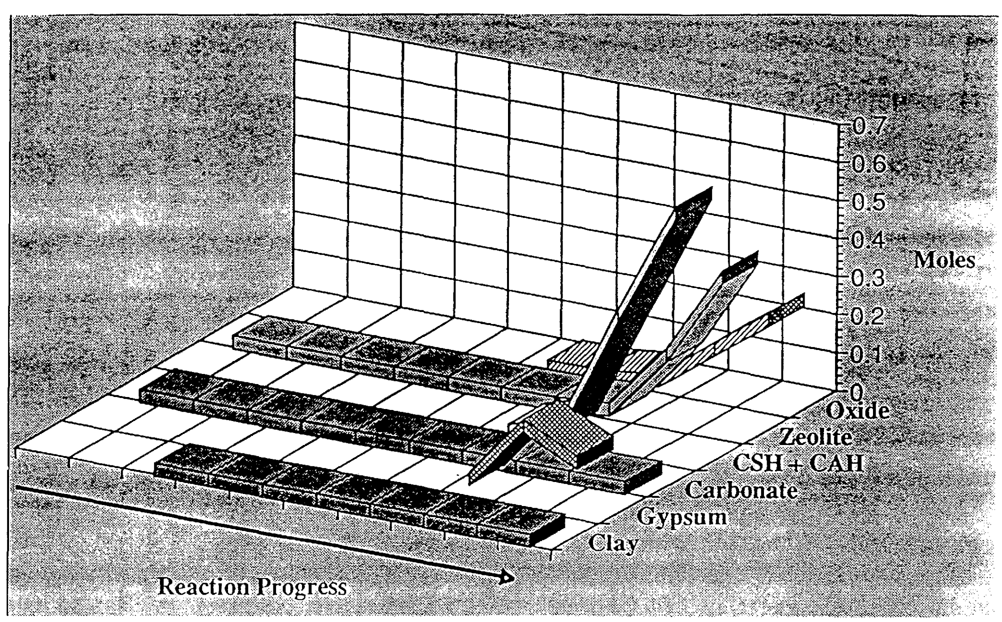


Figure 3-43. Development of secondary minerals with EQ6 reaction progress in the system six-phase-grout + saline groundwater + granitic host rock.

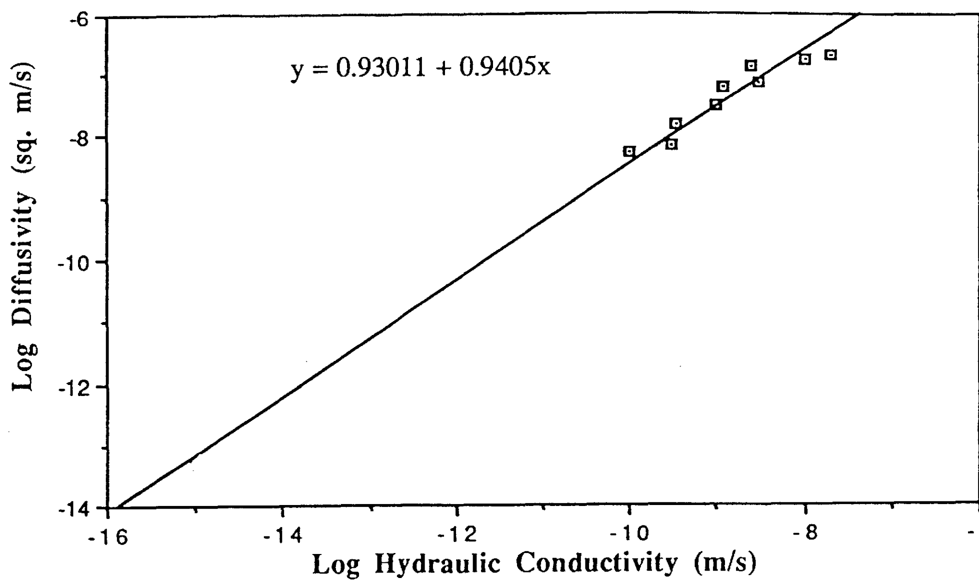


Figure 3-44. Plot of derived diffusivity-hydraulic conductivity relationship, based on correlation of O_2 diffusivity in concrete with hydraulic conductivity (modified from Grube, 1985).

Task Force therefore recommended that a diffusion term is incorporated into the long-term performance model, which heretofore has analyzed solely flow scenarios.

As a result of the Task Force recommendation the modelling effort has been redirected toward developing a methodology to estimate grout degradation due to diffusion processes, a methodology that is compatible with the one developed for analysis of porous flow processes. A preliminary relationship between diffusivity and hydraulic conductivity was developed to relate porosity changes (calculated from the geochemical modelling calculations) and hydraulic conductivity changes (calculated from the previously derived porosity-hydraulic conductivity relationship) with changes in diffusivity (see Figure 3-44). This relationship was applied to the grout and groundwater compositions used in previous porous flow-based calculations. A FORTRAN code was written to compute: (1) successive changes in diffusivity of the grout due to chemical reaction with the groundwater, (2) times for diffusion of water and ions into and out of the grout for each new diffusivity, and (3) cumulative change in diffusivity with time.

The results of this exercise were presented at the October Task Force meeting in Sherbrooke, Quebec, Canada. From this analysis the following preliminary conclusions may be drawn. Diffusion processes may play a significant role in degradation of grout performance (see Figure 3-45), given rather conservative simplifying assumptions regarding the diffusion of ions out of the seal. Accordingly, with regard to diffusion processes cement grout seals should provide acceptable performance for very long times, on the same order as the performance anticipated for flow processes, given the compatible-chemistry/low-flow siting conditions prescribed above.

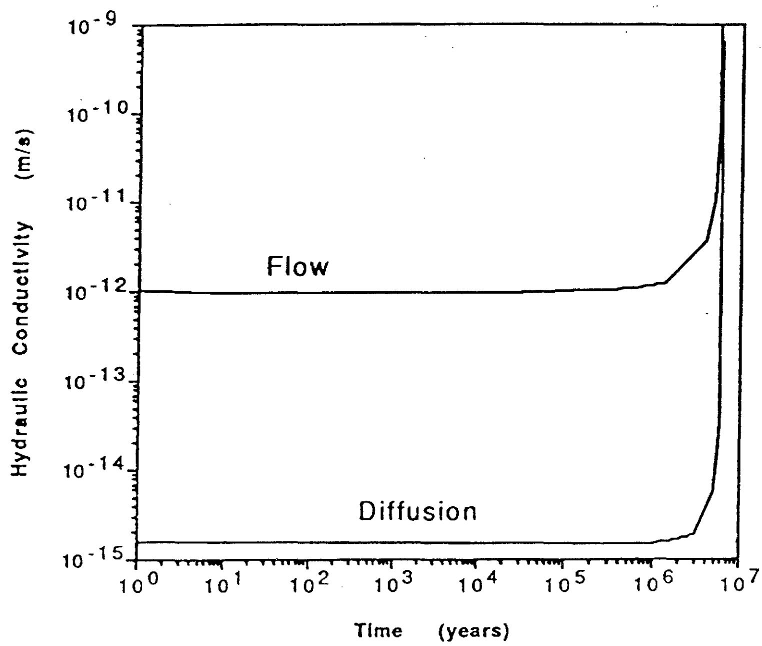


Figure 3-45. Comparison of change in seal performance (change in hydraulic conductivity) with time for flow and diffusion processes for the system six-phase-grout + saline groundwater.

3.6 ECONOMY

The total cost of the Stripa Project Phase 3 as of December 31, 1990 is given in the Table 3-3 below.

Table 3-3. Stripa Project Phase 3 – Summary of costs as per December 31, 1990. All figures in SEK.

	TOTAL PROGRAM		
Program	**Original budget incl. annual index esc. Jan 1990**	**Accumulated**	**Estimated Remaining**
Project Management	8,200,000	4,002,193	3,697,807
Stripa Generally	29,900,000	15,376,565	11,923,435
Site Char. and Validation	45,400,000	38,109,891	6,390,109
Dev. of Radar	5,500,000	5,289,302	210,698
Improv. of Borehole Seismics	3,800,000	3,152,360	547,640
Network Modelling	8,000,000	5,130,118	2,469,882
Channelling Experim.	7,400,000	7,372,782	27,218
Frac. Length and Apert. f. Single	900,000	997,512	-97,512
Sealing of Fractured Rock	7,500,000	7,500,000	0
Large Scale Sealing	26,200,000	20,636,936	4,863,064
Total	**142,800,000**	**107,567,659**	**30,032,341**

Appendix

Stripa Project — Previously Published Reports, 1980–1990

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.

1982 IR 82–07

"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.

"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.

1983 **IR 83 – 01**

"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.

1983 IR 83–04

"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.

"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.

"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
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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
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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"

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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
Swedish Geological Co.

Gunnar Ramqvist
El-tekno AB

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
Royal Institute of Technology, Stockholm

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
Royal Institute of Technology, Stockholm

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.

1985 **IR 85–04**

"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.

1985 TR 85–06

"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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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.

1985 **IR 85 – 09**

"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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Swedish Geological Co., Sweden

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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.

1986 **IR 86 – 01**

"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 $1.5x10^{-10}$ m/s and that of the veined gneiss $2x10^{-11}$ m/s. This implies anisotropic hydraulic properties in the rock mass with a higher hydraulic conductivity in the horizontal direction.

1986 **IR 86–02**

"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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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
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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.

"CROSSHOLE INVESTIGATIONS – RESULTS FROM SEISMIC BOREHOLE TOMOGRAPHY"

J Pihl, M Hammarström, S Ivansson, P Morén
National Defence Research Institute, Sweden

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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S Bähler, M Hammarström, J Pihl
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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"

C Cosma
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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"

B Bjarnason, G Raillard
University of Luleå, Sweden

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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British Geological Survey, United Kingdom

C Cosma
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J Phil
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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 $1x10^{-12}$ m^2 sec^{-1} and $5x10^{-7}$ 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.

1987 **TR 87–21**

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
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 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"

J Andersson, B Dverstorp
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 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"

D Noy, J Barker, J Black, D Holmes
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

1988 TR 88 – 04

"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.

1988 **TR 88–05**

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

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P Fritz
University of Waterloo, Canada

K Nordstrom
US Geological Survey, USA

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

1988 **IR 88 – 07**

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

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Monica Hammarström, Per Norén, Jörgen Pihl
National Defence Research Institute, Sweden

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
Royal Institute of Technology, Sweden

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.

"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)"

R Pusch, L Börgesson, A Fredrikson
Clay Technology, Sweden

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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.

1989 **TR 89 – 02**

"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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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, Wl, 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"

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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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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"

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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.

1989 TR 89 – 08

"WATER FLOW IN SINGLE ROCK JOINTS"

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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.

1990 TR 90–01

"SITE CHARACTERIZATION AND VALIDATION – BOREHOLE RADAR INVESTIGATIONS, STAGE 3"

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November 1989

ABSTRACT

The borehole radar investigation program Stage III of the SCV-site has comprised single hole reflection measurements with centre frequencies of 22 and 60 MHz. Single hole reflection measurement with both omni-directional and directional antennas have been performed in the boreholes C1, C2, C3 and the D-holes (D1-D6). Crosshole tomographic measurements as well as crosshole reflection measurements have been made between the boreholes C1-C2, W1-C1 and W1-C2. The range obtained in the single hole reflection measurements was approximately 100 m for the lower frequency (22 MHz) and about 60-70 m for the centre frequency 60 MHz. In the crosshole measurements transmitter-receiver separations from 20 to 120 m have been used.

The Stage III radar investigations have essentially confirmed the three dimensional description of the structures at the SCV-site. The conceptual model of the site which was produced based on the Stage I data included three major zones (GA, GB, and GH), two minor zones (GC and G1) and a circular feature (RQ). The major features are considered to be the most significant at the site and are all observed in the Stage III boreholes close to their predicted locations. The circular feature RQ has also been found in two of the additional tomograms at the predicted location. RQ is seen as a ringshaped feature in the attenuation tomograms and as a single spot anomaly in the slowness tomogram.

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, directional antenna, fracture zones, granite.

1990 **IR 90 – 02**

"SITE CHARACTERIZATION AND VALIDATION – DRIFT AND BOREHOLE FRACTURE DATA, STAGE 3"

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February 1990

ABSTRACT
This report describes the procedures used in mapping fractures intersecting three scanlines along the access drift from the 410 m level to the Site Characterization and Validation (SCV) site, one scanline along the elevator shaft connecting the 360 m and 385 m levels, and the procedures used in logging and orienting the fractures intersecting the core from nine boreholes that were drilled as part of the Stage III detailed site characterization program for the SCV site in the Stripa mine.

The relationships between fracture orientation, trace length, termination mode and fracture mineralogy have been examined. This analysis suggests that there are three main fracture sets present in the SCV site. However, the over-sampling in the horizontal direction makes it difficult to identify these three sets using classical contouring or cluster analysis approaches.

IR 90 – 03

"HIGH VOLTAGE MICROSCOPY OF THE HYDRATION OF CEMENT WITH SPECIAL RESPECT TO THE INFLUENCE OF SUPERPLASTICIZERS"

R Pusch, A Fredrikson
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February 1990

ABSTRACT
This report describes a study of cement hydration, using high voltage "humid cell" electron microscopy. Samples with and without superplasticizer were inserted in the humid cell, thus allowing the superplasticizer to affect the hydration process while observing it in the microscope.

It is concluded that after an initial period of rather rapid hydration, further hydration is retarded by the superplasticizer. It probably forms a Helmholtz-type cloud of organic molecules around cement grains.

1990 **IR 90–04**

"PRELIMINARY PREDICTION OF INFLOW INTO THE D-HOLES AT THE STRIPA MINE"

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February 1990

ABSTRACT

Lawrence Berkeley Laboratory is contracted by the U.S. Department of Energy to provide an auxiliary modeling effort for the Stripa Project. Within this effort, we are making calculations of inflow to the Simulated Drift Experiment (SDE), i.e. inflow to six parallel, closely spaced D-holes, using a preliminary set of data collected in five other holes, the N- and W-holes during Stages 1 and 2 of the Site Characterization and Validation (SCV) project. Our approach has been to focus on the fracture zones rather than the general set of ubiquitous fractures. Approximately 90% of all the water flowing in the rock is flowing in fracture zones (Olsson et al., 1989) which are neither uniformly conductive nor are they infinitely extensive. Our approach has been to adopt the fracture zone locations as they have been identified with geophysics. We use geologic sense and the original geophysical data to add one zone where significant water inflow has been observed that can not be explained with the other geophysical zones.

We superimpose a regular grid of conductors on the fracture zones. These could be considered "channels", but mathematically, the grid is simply a discretization of the plane. The grid elements are each assigned an equal conductance. Then we use cross-hole hydrologic tests to condition the model with a technique called "simulated annealing". In simulated annealing, we simulate well tests using the model and compare the calculated results to the measured well test behavior. We then adjust the model by removing or replacing grid elements until the predicted heads are as close as possible to the observed ones. From annealing we get a series of models which all fit the hydrologic data to approximately the same degree of agreement. Annealing theory allows us to rank these according to their relative likelihood.

At the time this work was done, there were no systematic cross-hole well test data available for the SCV site. In order to test our approach, we have synthesized data for a cross-hole test from some informal cross-hole tests performed by the British Geologic Survey (BGS). In these tests, W2 was opened and responses were observed in the other holes. From this data, as well as the head and flow records in the holes, we have made a synthetic steady state well test record due to the opening of W2. We have annealed to this data to develop a preliminary estimate of a hydrologic model of the SCV site.

We then scale the conductance of the elements such that the model makes the best possible prediction of inflow rates which were observed in the W- and N-holes. Finally, we close off the wells used to calibrate the model, open the D-holes and calculate inflow to the D-holes. Using this technique we predict a mean total flow of approximately 3.1 (*l/min*) into the six D-holes with a coefficient of variation nearly unity. We estimated the flow to the D-holes five times, sequentially leaving one inflow measurement out of each calculation. The remaining tests would then be used to predict the flow into the hole left out. By then com-

paring the prediction to the measured result, a prediction error of about 4.6 l/min was calculated. This is an estimate of the error to be expected in the prediction of inflow. Based on preliminary analysis of the SDE experiment, the actual inflow is close to 2 l/min.

In our calculation of flow into the D-holes, we have not differentiated flow between the D-holes. This is because the diameter of the ring of D-holes is about 3 m whereas the grid elements are about 10 m apart. By using the distribution of flows into the N- and W-holes, we followed a bootstrapping technique to estimate that the coefficient of variation for flows among the D-holes would be almost unity. This implies that one of the six holes could carry more than half the total flow.

1990 **TR 90–05**

"HYDROGEOCHEMICAL INVESTIGATIONS WITHIN THE STRIPA PROJECT"

Reprint from

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ABSTRACT

The International Stripa Project (1980–1990) has sponsored hydrogeochemical investigations at several subsurface drillholes in the granitic portion of an abandoned iron ore mine, central Sweden. The purpose has been to advance our understanding of geochemical processes in crystalline bedrock that may affect the safety assessment of high-level radioactive waste repositories. More than a dozen investigators have collected close to a thousand water and gas samples for chemical and isotopic analyses to develop concepts for the behavior of solutes in a granitic repository environment. The Stripa granite is highly radioactive and has provided an exceptional opportunity to study the behavior of natural radionuclides, especially subsurface production. Extensive microfracturing, low permeability with isolated fracture zones of high permeability, unusual water chemistry, and a typical granitic mineral assemblage with thin veins and fracture coatings of calcite, chlorite, sericite, epidote and quartz characterize the site. Preliminary groundwater flow modeling indicates that the mine has perturbed the flow environment to a depth of about 3 km and may have induced deep groundwaters to flow into the mine.

1990 **TR 90–06**

"PREDICTION OF INFLOW INTO THE D-HOLES AT THE STRIPA MINE"

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Golder Associates Inc. Redmond, Wash., USA

April 1990

ABSTRACT
Groundwater flow through three-dimensional networks of discrete fractures was modeled to predict the flux into a set of parallel boreholes, as part of the Site Characterization and Validation Project conducted during Phase 3 of the Stripa Project. Influx was predicted from fracture statistics derived from geological, geophysical, and hydrological site characterization data. Individual fractures were treated as probabilistic (random) features, whereas the major fracture zones inferred from geophysics were treated as deterministically located zones of relatively high fracture intensity. The flow predictions were produced by generating multiple, Monte Carlo realizations of the fracture population, and by solving the flow equation for each population using the finite element method. The predictions thus produced are presented in the form of probability distributions for flux. The most likely value for total influx to the boreholes was predicted to be 90 liters/hour, with a 90% confidence interval extending from 30 to 5700 liters/hour.

Keywords: Site characterization, fracture flow modeling, joint statistics.

TR 90–07

"SITE CHARACTERIZATION AND VALIDATION – COUPLED STRESS-FLOW TESTING OF MINERALIZED JOINTS OF 200 MM AND 1400 MM LENGTH IN THE LABORATORY AND IN SITU, STAGE 3"

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February 1990

ABSTRACT
Coupled stress-flow tests (CSFT) have been performed on nearly planar, mineralized joints in Stripa granite. Sample lengths have been 200 mm (laboratory CSFT) and 1400 mm (in situ block test). The loading sequences followed in each case have involved three normal stress cycles (to 25 MPa and 10 MPa respectively) followed by shear of up to at least 2 mm. The tested surfaces have been relatively non-dilatant and limited changes in aperture were observed during shear. However, normal stress cycles caused significant reductions in aperture, and at the largest 1400 mm scale threshold stress levels were reached beyond which the joint was essentially sealed.

1990 TR 90–08

"SITE CHARACTERIZATION AND VALIDATION – HYDROCHEMICAL INVESTIGATIONS STAGE 3"

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February 1990

ABSTRACT

The objective for the Stage III hydrochemical investigations was to classify groundwater and to determine the different flow paths within the investigated SCV-site by using water analyses from the C and D boreholes. The models for the hydrochemistry in the SCV-site have been compared with Stage 1 predictions framed by Wikberg et al. (1988).

The water was divided into three classes shallow (A), mixed (B) and deep groundwater (C). This division was based on Cl and HCO_3 concentration.

The local geohydrological situation in the SCV-site can be divided into a disturbed situation and an undisturbed situation. The disturbed situation refers to the occasion when the boreholes are open for sampling. The undisturbed situation is the flow situation when the boreholes are sealed. This affects the flow paths and changes the flow direction.

Opening of the boreholes and sampling causes a disturbance of hydrochemical conditions. 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 driven by the pumping of the mine. Where the two water types meet a zone of approximately 30 m thickness with mixed (B-type) water is formed. The flow situation is revealed by the geohydrological measurements.

At undisturbed conditions shallow water (A-type) is flowing down in the investigated zones. The B and C water types are then found at a deeper level than during disturbed conditions.

A regional model can be constructed based on the described chemical and geohydrological investigations. Shallow water from the top and deep groundwater from below are drawn towards the mine by the pumping. Where these waters meet mixed water is formed.

Keywords: Crystalline bedrock, deep groundwater, mixed groundwater, shallow groundwater, multivariate analysis, flow paths, pressure head.

1990 TR 90–09

"SITE CHARACTERIZATION AND VALIDATION – STRESS FIELD IN THE SCV BLOCK AND AROUND THE VALIDATION DRIFT, STAGE 3"

Stephen McKinnon, Peter Carr
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April 1990

ABSTRACT

The results of previous stress measurement and stress modelling programmes carried out in the vicinity of the SCV block have been reviewed. Collectively, the results show that the stress field is influenced by the presence of the old mine excavations, and the measurements can be divided into near-field and far-field locations. The near-field measurements denote the extent and magnitude of the mining induced stresses while the far-field measurements reflect virgin conditions.

Because of large scatter in the previous data, additional stress measurements were carried out using the CSIRO hollow inclusion cell. Combining all measurements, an estimate of the virgin stress tensor was made.

Three-dimensional stress modelling was carried out using the program BEFE to determine the state of stress in the SCV block, and around the Validation Drift. This modelling showed that most of the SCV block is in a virgin stress field. Stresses acting on the fracture zones in the SCV block will be due only to the virgin stress field and induced stresses from the Validation Drift.

1990 TR 90–10

"SITE CHARACTERIZATION AND VALIDATION – SINGLE BOREHOLE HYDRAULIC TESTING OF 'C' BOREHOLES, SIMULATED DRIFT EXPERIMENT AND SMALL SCALE HYDRAULIC TESTING, STAGE 3"

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April 1990

ABSTRACT
This report describes the hydraulic testing programme performed during Stage 3 of the Site Characterization and Validation Programme. It involved three separate components. Firstly, single borehole testing techniques (focused testing using equipment developed specifically for the Stripa Project) were used to determine the distribution of hydraulic conductivity and head in the C boreholes. Secondly, water was abstracted from boreholes which had been drilled to simulate a tunnel (Simulated Drift Experiment – SDE). Locations and flow rates were measured together with pressure responses of points scattered throughout the SCV rock mass. Thirdly, the Small Scale Crosshole (SSC) involved detailed hydraulic interference testing between the D boreholes and in the B and H zones to measure how hydraulic parameters such as transmissivity and storativity varied.

1990 **TR 90–11**

"SITE CHARACTERIZATION AND VALIDATION – MEASUREMENT OF FLOWRATE, SOLUTE VELOCITIES AND APERTURE VARIATION IN NATURAL FRACTURES AS A FUNCTION OF NORMAL AND SHEAR STRESS, STAGE 3"

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April 1990

ABSTRACT

Laboratory tests have been completed on natural fracture planes in three, 200 mm diameter, cores, to determine the effect of changes in normal and shear stress on fracture permeability and porosity. In each core, a single fracture plane was oriented parallel to the core axis and the flow and tracer tests were completed under linear flow boundary conditions. At the completion of the full stress-flow test cycle, the fracture plane was impregnated with resin and, after the resin had hardened, the fracture plane was sectioned and the structure of the pore space characterized.

The test data showed that there is linear relationship between the logarithm of flowrate and the logarithm of normal stress. For shear tests on the two main samples, which were conducted at shear stresses less than the peak shear strength, the flowrates decreased slightly with increase in shear displacement. The porosities determined from the resin data and the fluid velocities determined from the tracer tests show that the volume of fluid in the fracture plane is much greater than that predicted using equivalent smooth parallel plate model.

1990 **TR 90 – 12**

"THE CHANNELING EXPERIMENT – INSTRUMENTATION AND SITE PREPARATION"

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Chemflow AB, Stockholm, Sweden

January 1990

ABSTRACT
The presented report describes the instrument developed and used in the channelling experiments as well as site preparation and considerations.

TR 90 – 13

"CHANNELING EXPERIMENT"

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July 1990

ABSTRACT
Channeling of water flow and tracer transport in real fractures in a granite body at Stripa have been investigated experimentally. The experimental site was located 360 m below the ground level. Two kinds of experiments were performed. In the single hole experiments, 20 cm diameter holes were drilled about 2.5 m into the rock in the plane of the fracture. Specially designed packers were used to inject water into the fracture in 5 cm intervals all along the fracture trace in the hole. The variation of the injection flowrates along the fracture were used to determine the transmissivity variations in the fracture plane. Detailed photographs were taken from inside the hole and the visual fracture aperture was compared with the injection flowrates in the same locations. Geostatistical methods were used to evaluate the results. Five holes were measured in great detail. In addition 7 holes were drilled and scanned by simpler packer systems.

A double hole experiment was performed where two parallel holes were drilled in the same fracture plane at nearly 2 m distance. Pressure pulse tests were made between the holes in both directions. Tracers were injected in 5 locations in one hole and monitored for in many locations in the other hole.

The single hole experiments and the double hole experiment show that most the fracture planes are tight but that there are open sections which form connected channels over distances of at least 2 meters. It was also found in the double hole experiment that the investigated fracture was intersected by at least one fracture between the two holes which diverted a large amount of the injected tracers to several distant locations at the tunnel wall.

1990 **TR 90 – 14**

"PREDICTION OF INFLOW INTO THE D-HOLES AT THE STRIPA MINE"

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August 1990

ABSTRACT
We present, in detail, the model used to predict the outcome of the D-hole experiment in the Stripa mine. The D-hole experiment measures details of inflow to an array of boreholes through a previously undisturbed volume of heavily fractured granite. The interpretive techniques used to infer fracture network properties from experimental measurements are described, and the corresponding uncertainties are discussed. Stochastic network models are then used to predict the scale at which continuum approximations are appropriate, and to predict details of flow distribution, whilst effective-continuum models predict bulk behaviour. The uncertainties in the model are discussed and we conclude by identifying how the models should be improved.

IR 90 – 15

"ANALYSIS OF HYDRAULIC CONNECTIONS BETWEEN BMT AND SCV AREAS"

T Doe, J Geier, W Dershowitz
Golder Associates Inc. Redmond, Wash., USA

July 1990

ABSTRACT
This report presents the results of a study to determine the possible effects of the large-scale rock sealing project on other experimental activities in the Stripa Site Characterization and Validation area. The large scale sealing project involves injections into a ring of holes around the Buffer Mass Test drift to investigate the flow of water in the excavation-damaged and stress-affected zones surrounding a drift.

The study uses head change as the primary measure of the influence of the injections. Two models were employed. We first used an analytical model of flow from a disk in an infinite porous continuum. Assuming an infinite flow field, the maximum head changes in the vicinity of the validation drift are about four percent of the injection at the ring.

A discrete fracture model used a dense fracture network around the Buffer Mass Drift which in turn fed the major fracture zones. This model showed a rapid falloff in head with distance along the fracture paths. The maximum head changes should be less than one percent of the injection heads in the sealing experiment.

1990 **TR 90 – 16**

"ANNUAL REPORT 1989"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

May 1990