nagra National Cooperative for the Disposal of Radioactive Waste

TECHNICAL REPORT 92-10

STRIPA PROJECT

ANNUAL REPORT 1991

MAY 1992

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

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

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

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

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

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

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

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

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

THE STRIPA PROJECT
ANNUAL REPORT
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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 1991.

Stockholm

May 1992

CONTENT

1 INTRODUCTION

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

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

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

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

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

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

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

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

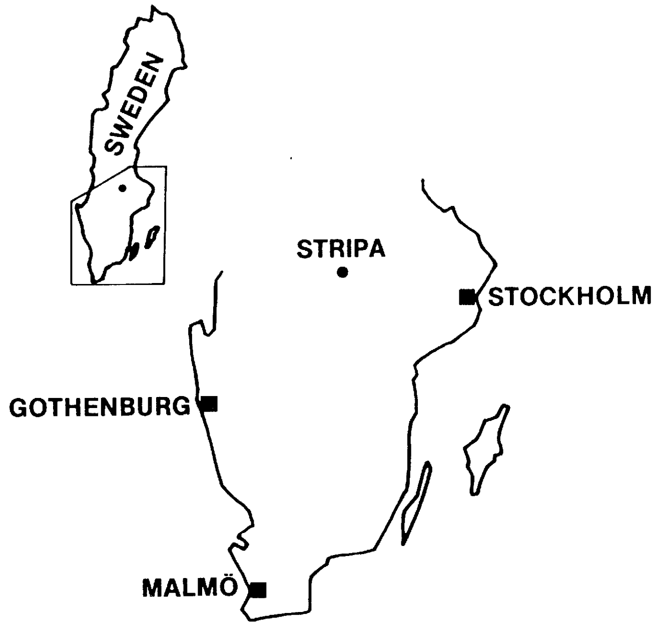

Figure 1-1. The Stripa Mine is located approximately 250 km west of Stockholm.

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

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

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

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

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

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

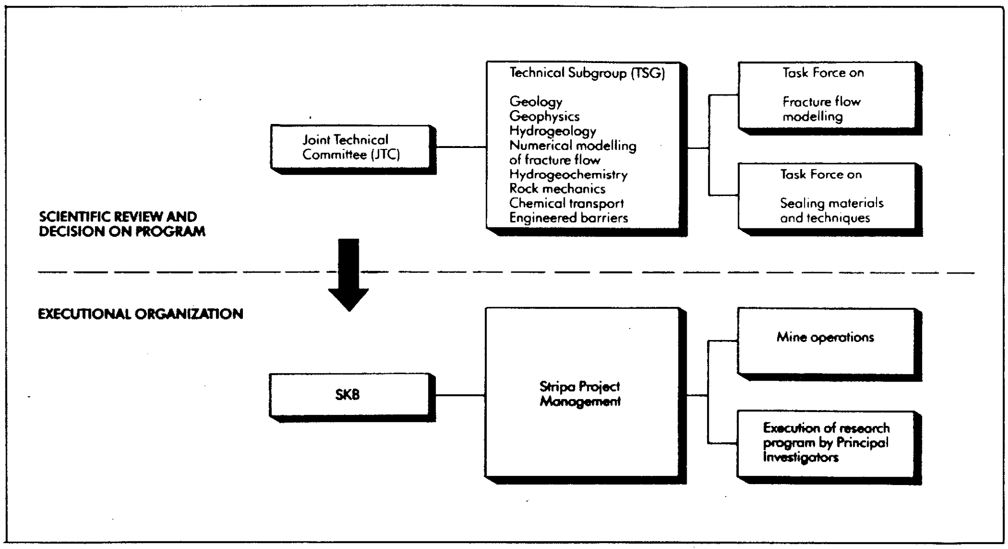

Figure 1-2. Organization of the Stripa Project.

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

As for the "Site Characterization and Validation" programme the project manager is supported by two Scientific Coordinators, John Black of Golders Associates and Olle Olsson of 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 Fourteenth meeting of the Joint Technical Committee was held in Forsmark, Sweden in the second quarter of 1991.

Apart from a number of decisions made on the basis of recommendations from the TSG, the Project Manager also reported from a meeting with the Overview Reporting Group (ORG), held in Key Biscane, Florida on March 1, 1991. Participants were Prof. Charles Fairhurst, Drs. Ferrucio Gera, Paul Gnirk, Malcolm Gray and Bengt Stillborg.

The work of the ORG must fit a time frame bound by the following dates:

- June 30, 1991; experimental work in the Stripa facility finished and principal investigators started finalizing the final reports.
- August 3, 1992; overview reports, in camera ready form, must be delivered to the printer.
- October 14-16, 1992; final symposium of the Stripa Project. The overview reports must be ready for distribution at the symposium.

The tasks for the ORG members are as follows:

- Dr. Paul Gnirk will write the overview for activities dealing with site characterization and assessment; in other words the report should cover work aimed at determining the characteristics and clarifying the behaviour of the natural isolation barriers.
- Dr. Malcolm Gray will write the overview for activities dealing with backfilling and sealing of openings and penetrations; in other words this report should address the work on engineered barriers.
- Prof. Charles Fairhurst and Dr. Ferruccio Gera will act as peer reviewers and will contribute to the writing of the executive report: that is a relatively concise summary of the overview reports.
- The Project Manager will manage the overview reporting activity; among other activities he will provide liaison between the ORG and The Joint Technical Committee of the Stripa Project.

The ORG proposed that the overview report should be composed of various parts with the following structure:

- two relatively comprehensive overview reports on natural and engineered barriers respectively (about 200 pages each),
- an executive report (summary of 40-50 pages),
- optical diskettes containing the text of all technical reports will be produced by the Stripa Project.

This structure would allow the various products to be addressed to different audiences; thus the overview reports could be aimed at the scientific community at large, the executive report would be addressed to decision makers and the diskettes would provide the information needed by technical people directly involved in waste disposal programs.

The overview reports will describe work carried out during the entire Stripa Project, but the emphasis will be placed on activities performed during Phase 3 of the Project.

Preliminary outlines of the overview reports were made at the ORG meeting. In September, 1991 complete drafts of the first three chapters will be written. Next ORG meeting will be held in September 12-13, 1991.

In February, 1992 Drs. Paul Gnirk, Malcolm Gray and Bengt Stillborg plan to travel to all participating countries, to discuss the reports, aiming at each country shall contribute from the perspective of their own waste program. JTC endorsed this part of the preparation of the report, and the chairman asked the JTC members to help and cooperate in timing the visits to the participating organizations.

It is of most importance that the overview reports, in special the conclusions which will be drawn, will be reviewed by the JTC. It was therefore decided that draft of the overview reports and the executive report will be sent out to the JTC members, not later than June 1, 1992 for two weeks reviewing. The Project Manager shall one month in forehand inform the JTC members about the time schedule of the reviewing process.

It was also decided that the overview reports shall be printed as Stripa Reports, however, with a special type of cover. The most practical way of distributing the optical diskettes will be decided by the Project Manager.

A decision was also made at the meeting to extend the Stripa Project Phase 3 from August 1 to December 31, 1992 with no affect in any way on the total budget of the project.

The last Annual Meeting of the Technical Subgroup was held in Västerås, Sweden in March. The Task Force on Fracture Flow Modelling and the Task Force on Sealing Materials and Techniques held two separate meetings each.

Sunday, the thirtieth of June, 1991 was the last day of the Stripa Mine. All activities at the mine site, on surface as well as underground were terminated. The owner of the mine has decided to cease all pumping of the mine which means that the mine eventually will be water filled and die. It looks like June 30, 1991 was the last day of an operation that started in 1448. For those of you that would like to obtain a documentation of the history of the Stripa Mine is welcome to contact Project Management.

3 PHASE 3

3.1 SITE CHARACTERIZATION AND VALIDATION

3.1.1 Introduction

The main objective of the SCV Project is to determine how well the techniques and approaches used in site characterization can be used to predict groundwater flow and radionuclide transport in a fractured medium. The central aims of the project are:

- to develop and apply an advanced site characterization methodology which integrates different tools and methods,
- to predict distribution of groundwater flow and solute transport pathways in a specific volume of the fractured Stripa granite,
- to develop and apply a methodology to validate that the models (both conceptual and numerical) are appropriate to the processes under examination in a fractured rock mass.

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 includes two cycles of data-gathering, prediction, and validation 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 & preliminary validation	88–89	validation/ data gathering	↓ ↑
IV	Detailed predictions	89–90	prediction	second
V	Detailed evaluation	90–91	validation	↓

The basic experiment within the SCV Project is to predict the distribution of water flow and tracer transport through a volume of rock, before and after excavation of a sub-horizontal drift, and to compare these predictions to the actual field measurements.

Stage I comprised the drilling and investigation of 5 boreholes for preliminary characterization. Three 200 m long semi-horizontal boreholes were drilled 60 m apart towards north (N2-N4). Two 150 m long boreholes were drilled towards west 70 m apart (W1 and W2). The volume of rock investigated was situated in a granitic pluton around 380 m below ground to the north of the mined-out region in the Stripa Mine (Figure 3-1).

During **Stage II** the data were analyzed and a conceptual model of the site devised. This model was the basis for preliminary numerical predictions of the groundwater inflow to six 100 m long parallel boreholes (the D-boreholes) that outline a cylinder (diameter 2.4 m) centrally located within the SCV site. Four different types of numerical groundwater flow models were used for the inflow predictions.

In **Stage III** five boreholes (the C-boreholes) were drilled from essentially the same point at the 360 m level towards the central portion of the site and investigations made in them to provide data for detailed predictions of inflow to the Validation Drift (to be

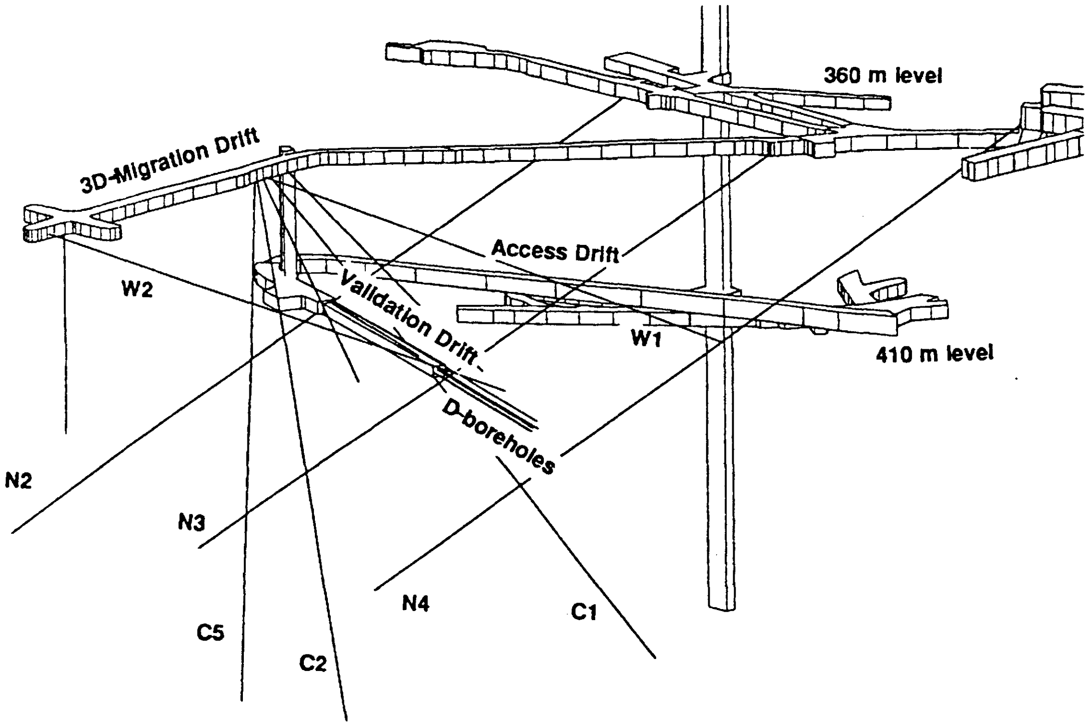

Figure 3-1. The SCV site is located north of existing mine workings. The site was investigated from boreholes drilled from the 360 m level. The Validation Drift and the D-boreholes at the 385 m level were used to check the predictions.

excavated in Stage V, Figure 3-1) and for a check on the first conceptual model. An access drift was excavated from the 410 m level to the 385 m level. The six 100 m long D-boreholes were drilled from the end of the Access Drift, the inflow measured, and compared to predictions. This constituted the first attempt of validating the models.

In **Stage IV** the conceptual model was updated based on the additional data available from Stage III. This model was used as input to the upgraded numerical models which were used to make predictions on fracture occurrences, distribution of groundwater inflows, and tracer transport to the Validation Drift.

At the beginning of **Stage V** the Validation Drift was excavated in place of the first 50 m of the cylinder outlined by the D-boreholes. This was followed by fracture mapping, measurements of groundwater inflow, and tracer transport to the drift.

The experimental activities within the SCV Project were completed in June 1991 when the Stripa mine was closed. In addition to the experimental work much effort has been devoted during 1991 to analysis and reporting of obtained results. The activities and results of the SCV Project will be summarized in a final report which will be published in 1992.

Reported below is the second Radar/Saline Tracer Experiment which was performed in 1990 but where data were analyzed and reported during 1991. The main experimental activity during 1991 was the Tracer Migration Experiments to the Validation Drift which had started in September 1990. In June, 1991 detailed characterization of inflow distribution to the Validation Drift was made through evaporation measurements. Similar measurements had been performed a year earlier and these measurements were made to check on changes in flow through the averagely fractured rock with time.

3.1.2 The second Radar/Saline Tracer Experiment

Introduction

The objective of this experiment was to describe tracer transport within zone H and possible transport of tracer into the rock surrounding zone H before and after excavation of the Validation Drift. The first experiment was performed prior to excavation and the second experiment after excavation of the Validation Drift. In order to meet the objectives, two sets of data were gathered; tracer breakthrough data from different locations within and outside the Validation Drift and radar difference tomograms from three planes intersecting zone H.

Outline of the experiment

Figure 3-2 shows the geometry of the experiment in a generalized manner. Fracture zone H extends north-south in a direction nearly parallel to the 3D-Migration Drift. Boreholes W1, C1, and C5 all start from approximately the same location but extend in different directions so they outline the sides of a tilted pyramid. Zone H cuts the pyramid approximately 50 m from the top of the pyramid which is located at the 3D-Migration Drift.

In both experiments tracer was injected in borehole C2 where it intersects zone H. In the first experiment the D-boreholes and in the second experiment the Validation Drift were used as sinks. The distance between the injection point and the D-boreholes/Validation Drift sink was approximately 30 m. The injection flow rate and

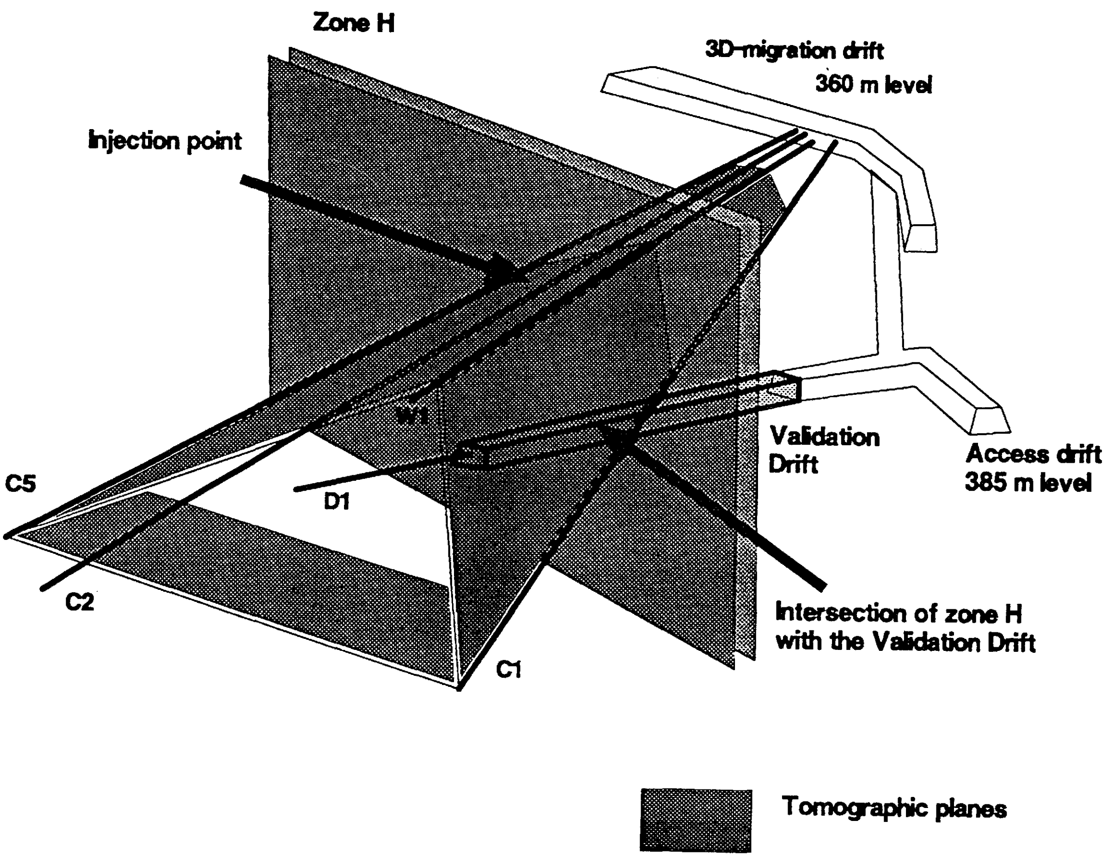

Figure 3-2. Generalized geometry of the Radar/Saline Tracer Experiment. Saline tracer was injected in borehole C2 where it intersects zone H. Radar tomography has been made in the W1-C5, C5-C1, and W1-C1 planes.

salinity of the injected fluid was the same in both experiments, i.e. 200 ml/min and 2%, respectively. In the first experiment the head in the D-boreholes was kept at 165 m, relative to the 385 m level, for the first 362 hours after start of tracer injection, then it was reduced to atmospheric (Olsson, Andersson, Gustafsson, 1991a).

In the second experiment the Validation Drift acted as a sink at atmospheric pressure. The injection flow rate was reduced in two steps, after 315 and 596 hours, due to a high pressure buildup in the injection interval (Olsson, Andersson, Gustafsson, 1991b). Tracer breakthrough was continuously monitored in the plastic sheets in the roof and in the "sumps" drilled in the floor of the drift. In addition, saline tracer concentration was monitored in two boreholes above the Validation Drift penetrating zone H; T1, and T2.

Radar tomography measurements were made of borehole sections C1-C5, W1-C1, and W1-C5 prior to the commencement of tracer injection to serve as a set of reference data. Radar tomography (difference tomography) of the same sections was repeated to map the presence of tracer in the three planes as a function of time.

Results of the second experiment

The tracer breakthrough in the Validation Drift was concentrated to the section 24-29 m with a concentration around two semi-parallel fractures in zone H. The tracer breakthrough data showed a variety of mean travel times and dispersivities. The fastest tracer arrival, 18 hours, occurred in the roof. In general, the tracer first arrivals varied between 20-100 hours for most of the grid elements and the tracer arrived somewhat faster and less diluted in the roof. Only the grid elements some distance away from the two dominant fractures, 29-35 m along the drift, had slower first arrivals, 200-500 hours. The breakthrough curves also showed that steady state was not reached more than in a few of the faster flow paths to the roof. Especially the tracer concentration in the sump holes seemed to be in a slowly rising stage when injection was stopped after 630 hours.

The highest tracer concentrations were observed in the roof of the drift, while lower concentrations were observed in the high flow grid elements in the floor. The distribution of C/Co maximum is shown in Figure 3-3. The tracer arrivals observed in the roof

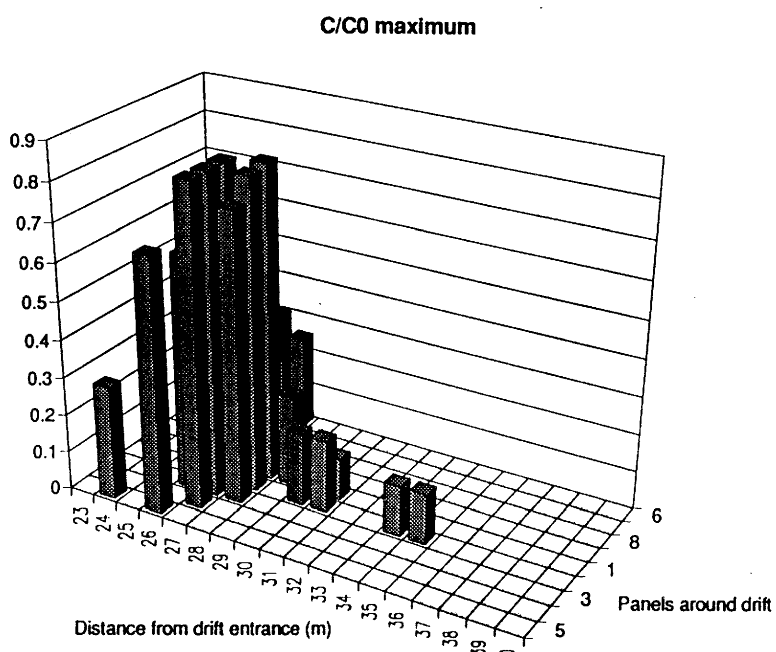

Figure 3-3. Distribution of tracer concentration in the Validation Drift. The maximum concentration (C/Co) is given for each grid element.

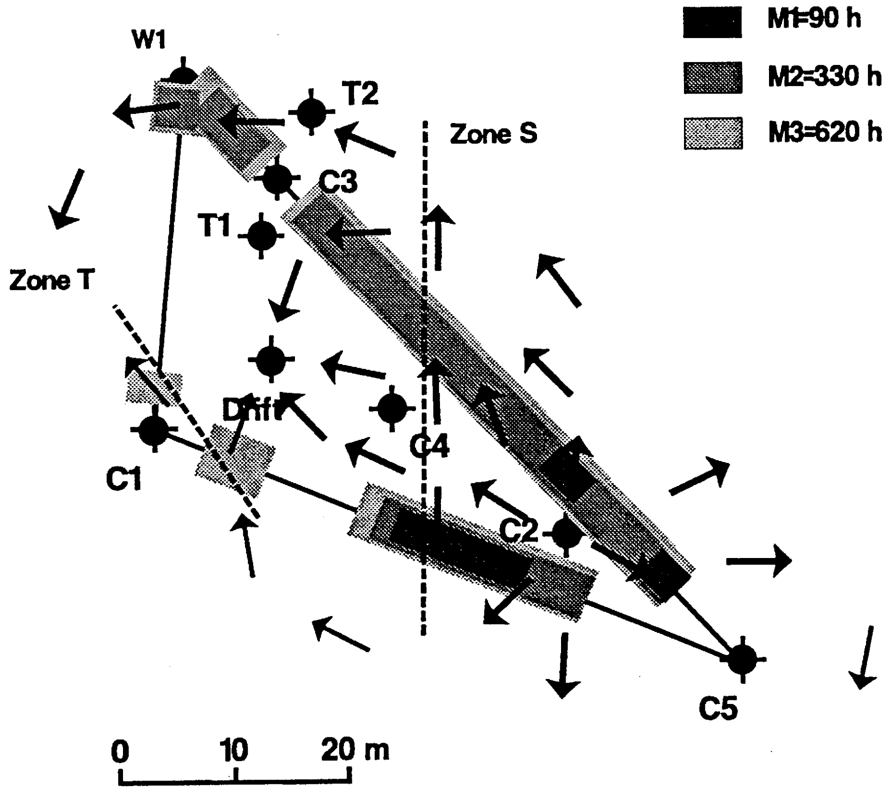

Figure 3-4. Conceptual model of saline tracer transport within zone H based on radar difference tomography and breakthrough data. The boxes indicate where tracer is observed and the grey shades indicate when it is first observed.

30-35 m from the drift entrance are due to transport through a sub-horizontal fracture intersecting zone H a few meters above the drift. Tracer breakthrough was also observed in boreholes T1 and T2 after 180 and 400 hours, respectively.

The amount of tracer recovered in the Validation Drift, expressed as instantaneous recovery rate was 21%. Nearly 70% of the total recovered mass of tracer was found in three grid elements (266, 267, and 268) which correspond to the location of the old boreholes D2 and D3. Another way to express the recovery is to simply study the increase of the inflow to the Validation Drift due to injection in C2. In this case the inflow increased with 40 ml/min based on the mean inflow rates. Using the weighted mean of the injection rate, 174 ml/min, the flow recovery was about 23% which is consistent with the instantaneous recovery.

The presence of tracer in significant amounts along the lines of intersection between zone H and the tomographic planes made during the second experiment is shown in Figure 3-4. Naturally, the largest and most rapid increases in attenuation were observed close to the injection point along the W1-C5 and C1-C5 lines. After approximately 330 hours significant amounts of tracer was observed essentially all along the W1-C5 line. The observation of tracer in the radar tomograms close to borehole W1 is consistent with the observed tracer breakthroughs in T1 after 180 hours and in T2 after 400 hours.

The radar difference tomograms also indicated transport outside of zone H. The largest values of increased attenuation were observed at the points where a small fracture zone, S, intersects the W1-C5 and C1-C5 lines. This is an indication of that the intersection of two zones can provide a preferred flow path. Zone S also provided a transport path for tracer out of zone H. Based on the data available a conceptual model of the flow system during the second Radar/Saline Tracer Experiment was constructed. The conceptual model of the flow paths is presented graphically in Figure 3-4.

Changes in flow regime due to excavation of the Validation Drift

The tracer breakthrough showed a significant difference between the two experiments. In the first experiment a large portion of the mass travelled through a relatively fast transport path with a mean travel time of 33 hours, as given by 1D-modelling of the total breakthrough curve. The shape of the curve also showed that there was a second major flow path with a mean travel time of about 220 hours. The fast flow path was dominating in the two "upper" boreholes, D3 and D4, while the slower flow path dominated in "lower" boreholes, D2 and D6. In borehole D2 only the slower flow path was represented.

The breakthrough in the second experiment was much slower, the mean travel time from the total breakthrough curve was about 430 hours, and there was only a very small portion of the fast flow path with a mean travel time of 65 hours, i.e. delayed with a factor of 2 compared to the first experiment. The two total breakthrough curves are shown in the same graph in Figure 3-5 below.

The fast breakthrough originating from grid elements 282 and 283 in the roof occurred in a location corresponding to borehole D4, where the fast breakthrough was found also during the first experiment. In the second experiment the first arrival was delayed by a factor of 2 to 3 and there seemed to be almost no dilution. The slow flow path monitored in sump hole 267 corresponds well to the slow breakthrough monitored in borehole D2.

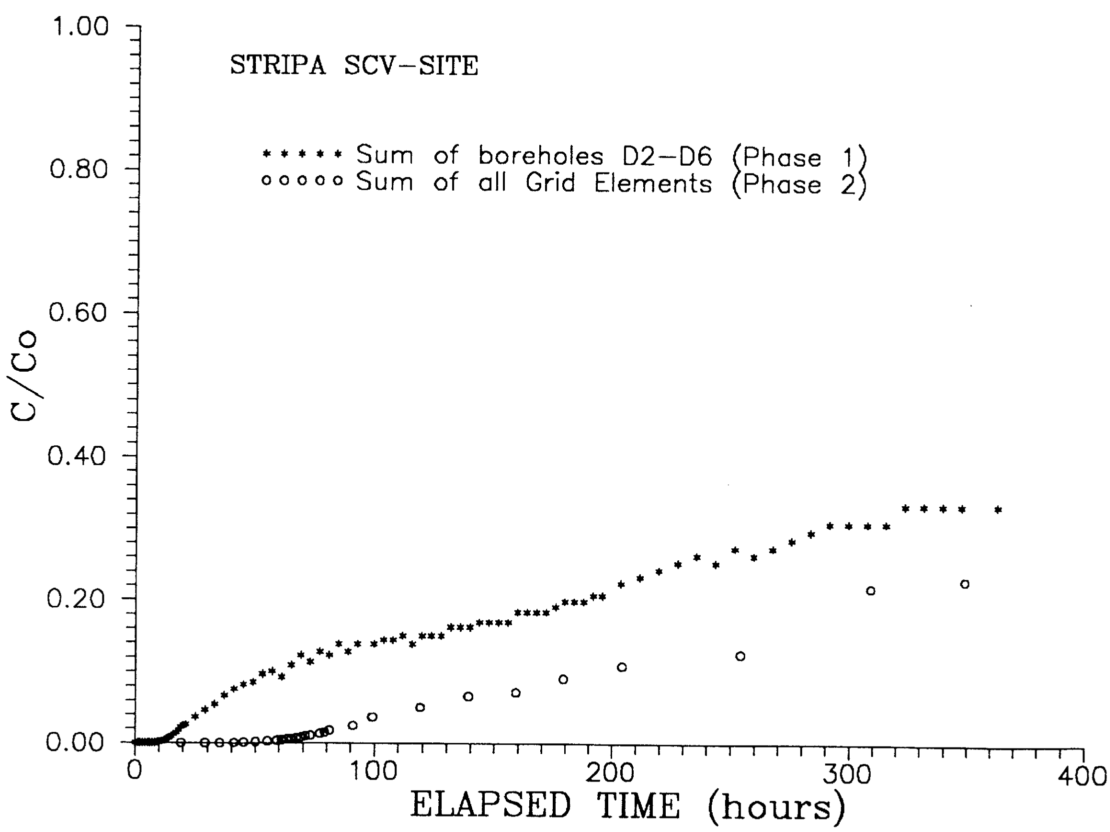

Figure 3-5. Comparison of the total breakthrough curves for the two experiments.

The radar data, the breakthrough curves, and the flow data to the D-boreholes and the Validation Drift are consistent. The radar data show that during the first experiment a larger portion of the tracer was confined within the triangle outlined by the three tomographic planes. This is in line with the relatively large tracer recovery observed in the first experiment where the instantaneous recovery with partly closed D-boreholes was about 50% (86% with open D-boreholes).

During the second experiment a lower tracer recovery was obtained (instantaneous recovery 21%). The radar data showed larger amounts of tracer along the tomographic lines. This implies that a larger amount of tracer was being transported out of the triangle. In both experiments the highest increases in radar attenuation were observed on the W1-C5 line. This implies that tracer was preferentially transported in this direction (i.e. upwards and in a direction opposite to the natural gradient). Hence, the transmissivity of Zone H in this direction must be larger than in other directions.

The breakthrough data from both the first and the second experiment indicate that there are two major transport paths from borehole C2 to the D-boreholes/Validation Drift. One to the bottom of the drift which carries the bulk of the mass and one to the crown of the drift. The transport path to the roof of the drift is fastest and high concentrations are observed ($C/C_0 \approx 0.85$ in the second experiment) while the path to the bottom is slower and significantly diluted ($C/C_0 \approx 0.25$). The same general geometric distribution of tracer concentration and arrival times was observed in the D-boreholes during the first experiment. However, in the first experiment a larger portion of the tracer mass was transported through the faster path.

The differences in transport parameters between the experiments is basically due to the different relative strengths of the sources and sinks. The source strength was the same in both experiments while the sink was stronger in the first experiment than in the second. The strength of the sink is represented by the flow rate to the D-boreholes and Validation Drift which were 340 ml/min and 100 ml/min, respectively. A simplified representation of the flow system for both experiments is shown in Figure 3-6. This is based on two-dimensional flow model of the H-zone where the hydraulic properties within the zone have been assumed to be homogeneous and the actual flow

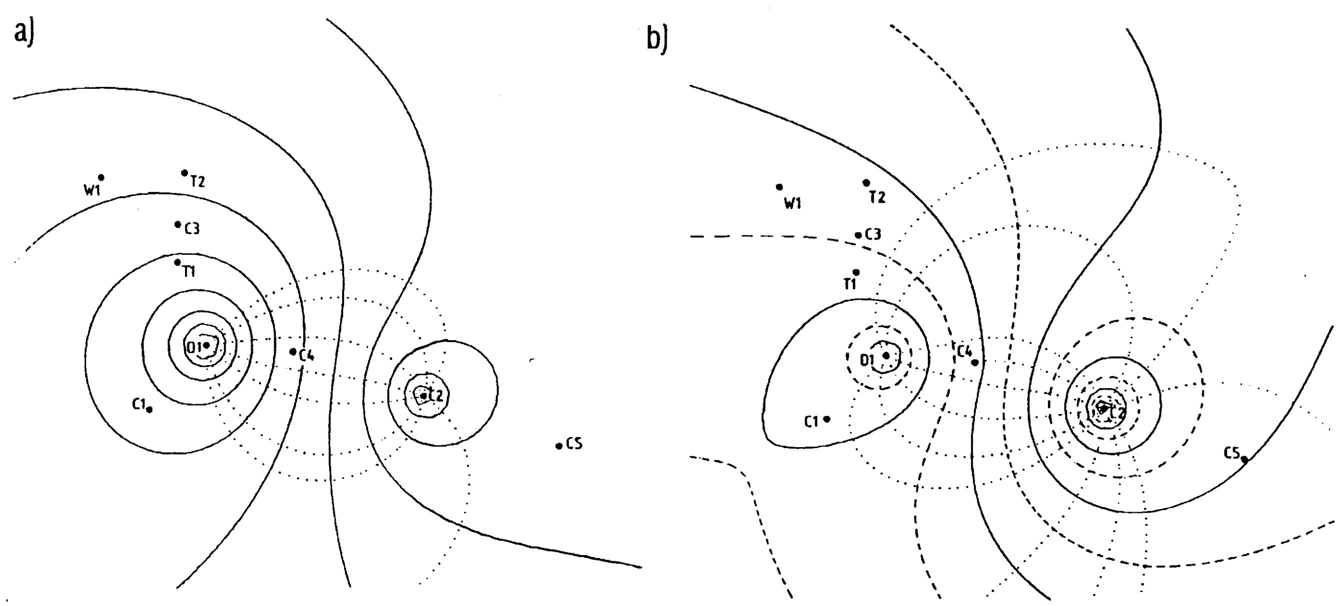

Figure 3-6. Two-dimensional model simulation of head and flow lines in zone H for the first (a) and second (b) Radar/Saline Tracer Experiments. Solid line; 10 m isopotentials, Dashed line; 5 m isopotentials.

rates at the source and sink used as boundary conditions (Olsson, Andersson, Gustafsson, 1991b). This simple model shows a larger spread of tracer in the second experiment similar to what was observed in the radar data. The average gradient between source and sink given by the model is approximately a factor 2 larger in the first experiment than in the second which is in rough agreement with the observed difference in travel times.

The breakthrough data and the radar difference tomograms have also been used to estimate flow porosity. The estimates obtained are of the same order, approximately 10^{-4}.

3.1.3 The Tracer Migration Experiment to the Validation Drift

Introduction and background

The objective of the Tracer Migration Experiment was to measure water inflow and tracer breakthrough to the Validation Drift. The measurements performed during the experiment gave information on properties governing the transport of water and solutes in fractured rock. The fact that the Validation Drift was intersected by a fracture zone made it possible to examine the transport properties of both the averagely fractured rock and a fracture zone.

Advection-Dispersion and Advection-Dispersion-Diffusion models were fitted to breakthrough curves to obtain values of mean residence times, dilution, Peclet numbers, and interaction with the rock matrix. The water inflow distribution and patterns of tracer breakthrough were examined and interpreted. The results from the measurements have also been compared with predictions from the fracture network modelling performed by Fracflow, AEA, Golder Associates and Lawrence Berkeley Laboratory.

Performed experiments and layout

Field experiments

Tracers were injected with constant injection flowrates from sealed off borehole sections and collected in the Validation Drift using plastic sheets and sumpholes. The injected tracers were six dyes, previously used in the Stripa Mine, and six metal complexes never before used in field experiments. Two tracers, one dye and one metal complex, were simultaneously injected from each injection section. The tracer mixtures were injected from borehole sections located between 10 and 25 m from the Validation Drift. Six of the injection sections used for tracer injection were situated within the H-zone and one within the averagely fractured rock. In order to minimize the disturbance on the natural flow field at the injection section, tracer injections were performed using injection flowrates as low as a few ml/h.

The injections in sections T2:1, C2:1, and C3:1 were started during the autumn of 1990 and continued until February-March of 1991. The injections in T1:2 and C3:2 started in September 1990 and were also terminated in the spring of 1991. Water inflow measurements and tracer concentration monitoring in the Validation Drift continued until June, 1991.

Experiments performed before and after excavation of the Validation Drift showed that the disturbed zone around the drift had great influence on water inflow rates and tracer migration. It was therefore decided to inject tracers in borehole T2 and to monitor tracer breakthrough in T1. This would provide information from breakthrough curves which were not affected by the disturbed zone. This was done during the last one and a half months of the Tracer Migration Experiment. The injection flowrates used during these repeated injections in borehole sections T2:1 and T2:3 were identical to the previous injections.

Laboratory experiments

The dyes arrived to the Validation Drift in lower concentrations compared to the metal complexes. One possible explanation would be if the dyes are slightly sorbing and not, as earlier believed, nonsorbing. Differences in effective diffusivity could also be a potential explanation for the differences in recoveries between dyes and metal complexes.

The effective diffusivity of the dyes and the metal complexes were evaluated in a series of diffusion experiments using pieces of rock from the H-zone. The values for the dyes and the metal tracers were found to be almost identical. This can be explained by the fact that both types of tracers are rather large molecules with molecular weights of approximately 600 g/mol.

A series of experiments were started to examine sorption properties of both dyes and metal tracers. The experiments continued for 10 months and indicated that some of the dyes might be slightly sorbing. Although the ratio between rock and tracer solution was increased to enhance the effects of sorption, the changes were too small to be detected using the UV/Visible spectrophotometer. Sorption that hardly might be detected in these laboratory experiments could, however, drastically change the breakthrough curves in a field experiment. Instead other types of experiments, e.g. column experiments, have to be performed if one wishes to calculate values of K_d for weakly sorbing species.

Results

Water inflow

The total water inflow rate to all sampling areas in the Validation Drift was about 6 000 ml/h. Altogether 51 sampling areas had measurable inflow rates ranging from 0.01 ml/h to 3 000 ml/h. These "wet" areas covered 67 m^2 out of a total area of 441 m^2 in the drift. More than 99% of the water emerged into the 6 m long intersection with the H-zone located at 24-29 m into the drift, see Figure 3-7. In addition to the inflow rates given above about 300 ml/h entered the lower part of the drift and was "lost" through ventilation.

Approximately 50% of the total water inflow was located to one single sampling area situated in the lower part of the drift wall. The remaining 50% of the water inflow was equally distributed between the upper and lower sections of the drift, i.e. between plastic sheets and sumpholes. Three of the sampling areas had almost 80% of the total water inflow to the drift. The water inflow was not only unevenly distributed in the drift but also uneven along single fracture planes.

Among the many hundreds of fractures seen in the Validation Drift, there are two major fractures in the H-zone that dominate the water inflow. Sampling areas with high water inflow rates, accounting for more than 90% of the total water inflow, are all intersected by at least one of these fractures.

Tracer breakthrough

Tracers were found in 41 out of the 51 sampling areas where water was obtained. All sampling areas at the intersection with the H-zone carrying water also had measurable amounts of tracers. It was only a few sampling areas in the averagely fractured rock that did not have any measurable tracer concentrations.

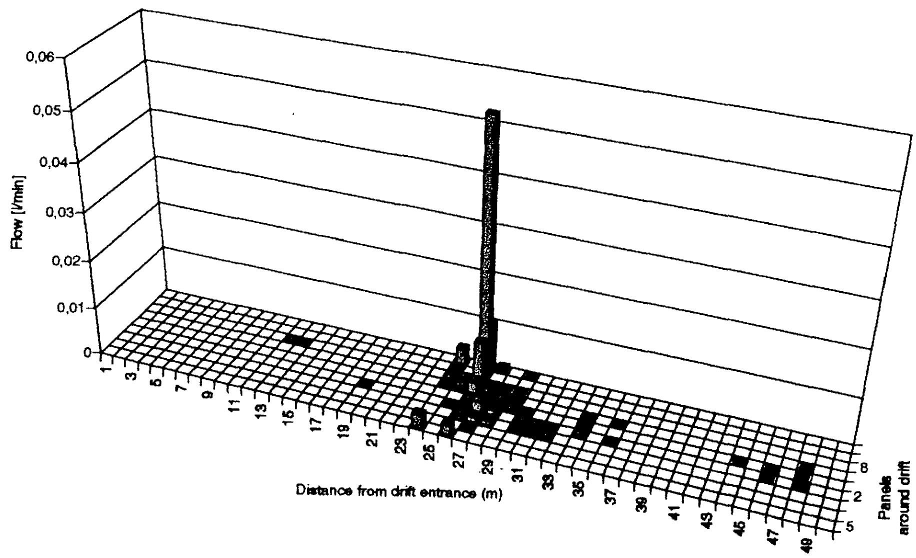

Figure 3-7. Flowrate distribution in the Validation Drift.

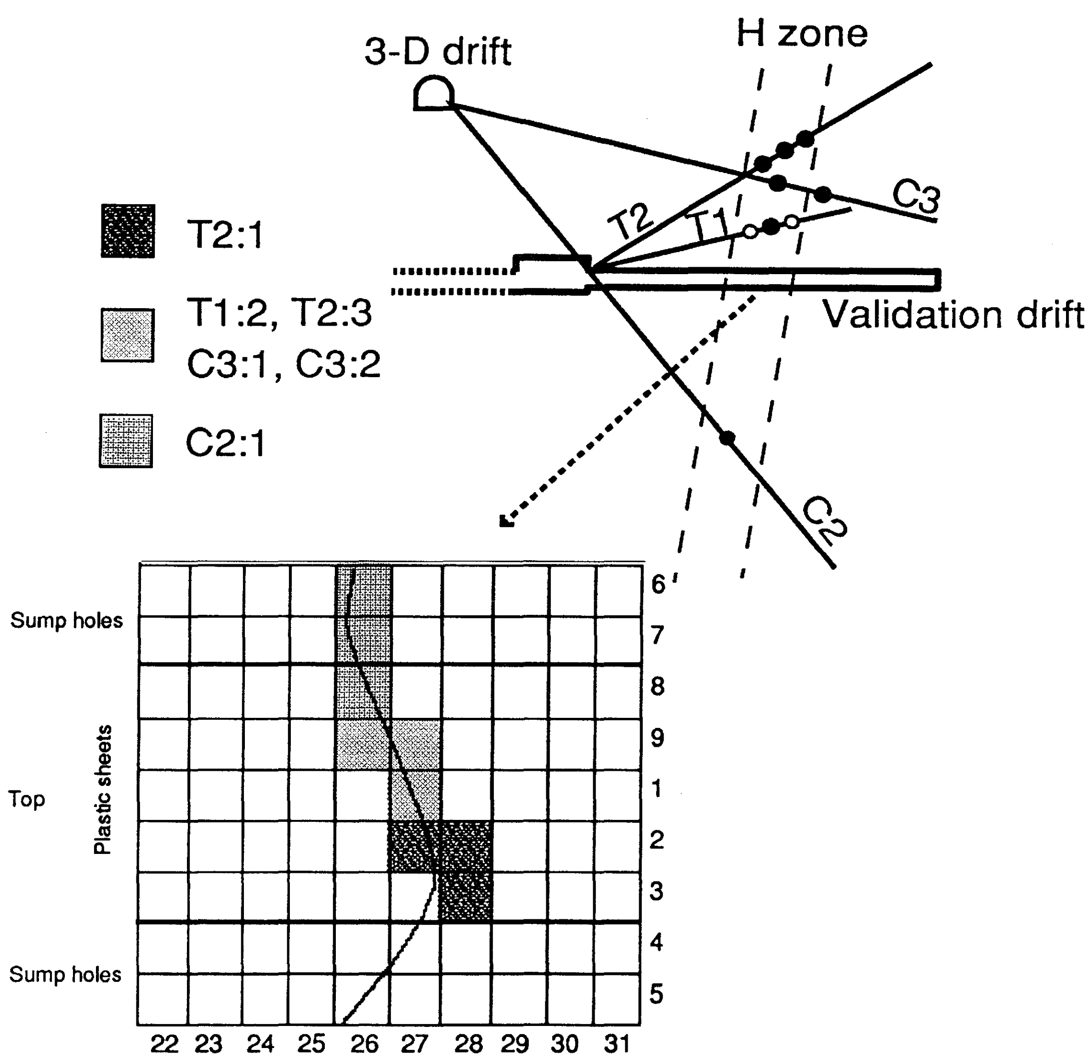

Figure 3-8. Sampling areas where the highest mass flow rates for tracers were found.

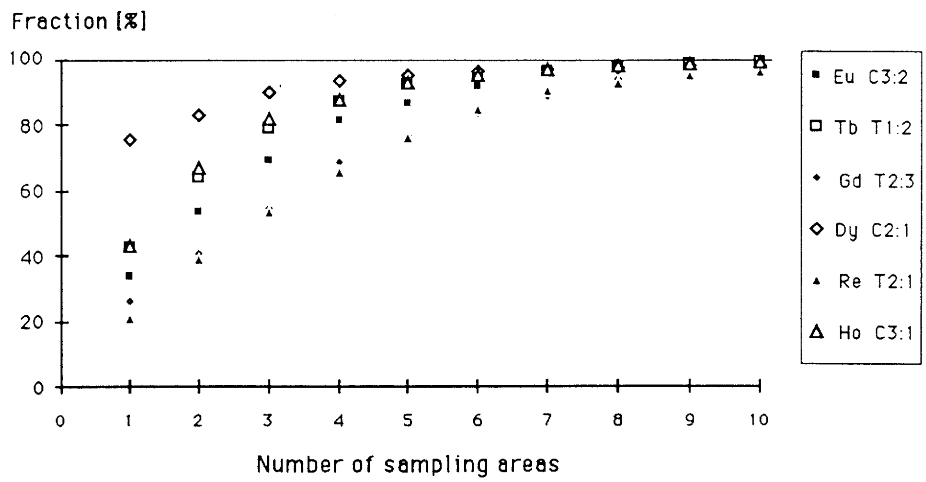

Figure 3-9. Fraction of total recovery as a function of the number of sampling areas.

The largest mass flowrates of the tracers are, in the same way as the water inflow rates, limited to a few sampling areas. The six tracer injections show different concentration patterns in the drift and may be grouped into three different groups according to their patterns, see Figure 3-8. All three groups have their largest mass flow rates limited to different sections along the fracture with the largest water inflow. This fracture is shown in the figure.

Figure 3-9 shows the total recovery as a function of the number of sampling areas. Between 20 and 75% of the total mass found in the drift of a tracer is found in one sampling area. Roughly 75% of the total recovery of a tracer is found if three sampling areas are considered, as in Figure 3-8. Almost 100% of the total recovery is found in 10 sampling areas even though detectable concentrations of the tracers were found in 38 sampling areas. The recoveries of the dyes are lower compared to the metal complexes.

Model fitting

The Advection-Dispersion (AD) model and the Advection-Dispersion-Diffusion (ADD) model were fitted to the breakthrough curves. Not all obtained breakthrough curves could be used. Some were rejected because they never reached a plateau, others because of concentration values close to noise level. Approximately 150 curves were fitted with the AD model. 47 of these were later selected to be fitted with the ADD model. Breakthrough curves representing the total inflow of tracer to the drift were also used for model fitting. These curves represent the concentration response if all water emerging into the drift would have been collected in one vessel. Table 3-1 gives Peclet numbers (Pe), mean residence times (t_w) and dilution factors (DF) from AD model fitting of breakthrough curves obtained for metal complexes in the Validation Drift.

Table 3-1. Representative values for the parameters obtained from the Advection-Dispersion model fitting.

Section	Pe [-]	t_w [h]	DF [-]	Inj. distance [m]
T1:2	3–8	1200–2000	50– 200	(10)
T2:1	1.5–3	2000–4000	50– 100	(20)
T2:3	2–6	3000–5000	50–4000	(20)
C2:1	2.5–5	1300–2200	400–1200	(25)
C3:1	2–7	1500–2500	100–1000	(15)

The mean travel times were considerably smaller in the experiment where tracers were injected in borehole T2 and collected in T1 than when collected in the Validation Drift. The distance between these holes is 9.5–12 m, which is comparable to the distances between some of the injection sections and the Validation Drift. A compilation of typical values obtained from these breakthrough curves with the AD model is given in Table 3-2. There is a high uncertainty in the obtained parameters due to high background concentrations caused by earlier injections.

Table 3-2. Me-DTPA complexes in the between hole experiment. Typical values obtained with AD model fitting.

Section	Pe [-]	t_w [h]	DF [-]	Distance to T1 hole, [m]
T2:1	8	500	200	(9.5)
T2:2	2–10	700	60	(10.0)
T2:3	15	300	50	(12.0)

The ADD model requires determination of four parameters; Pe, t_W, DF and an A-parameter. The A-parameter depends on the fracture aperture, the flow wetted surface and the properties of the rock matrix (porosity and pore diffusivity) as well as the sorption properties of the tracers. The results from the model fitting gave variations in the A-parameter by several orders of magnitude. This can hardly be explained by variations in the rock and channel properties. More likely it is explained by the fact that the effects of matrix diffusion and hydrodynamic dispersion are not well distinguished in the fitting procedure. Together with noise in the breakthrough curves, this will obstruct the fitting procedure. Differences in the A-parameter between the two groups of tracers, dyes and metal complexes could, however, explain differences in recovery and also explain the non-recovery of tracers and thus enhance the understanding of the experiment.

Several observations were needed to pinpoint the factors, which could explain the differences in the A-parameter. Results from diffusion experiments showed identical values of effective diffusivity for metal complexes and dyes which eliminated the effective diffusivity as a reason for the differences in A-parameter. The breakthrough curves for dyes and metal complexes injected simultaneously from one injection section, see Figure 3-10, show that the peak concentrations are found at approximately the same time for the two tracers, while the concentrations are significantly lower for the dye. These observations eliminate fracture aperture, matrix porosity

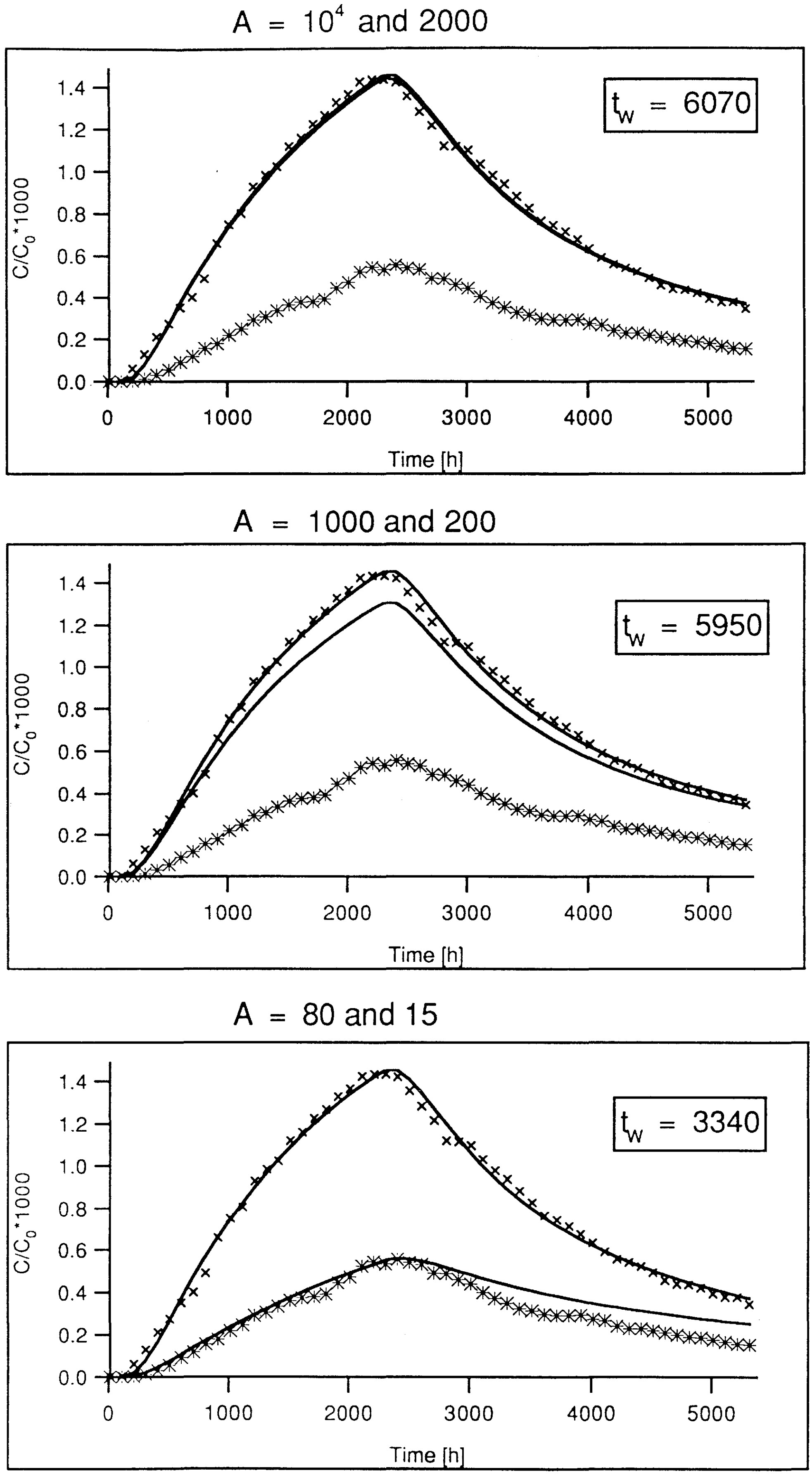

Figure 3-10. Theoretical breakthrough curves with a factor 5 in difference between the A-parameters and the total breakthrough curves obtained for the tracers injected in section T2:1.

(both tracers used the same flow paths) and surface retardation (peak concentrations had no time delay) leaving only the matrix retardation as the cause for the difference in A-parameter.

Considering the noise in the concentration measurements, the results from the sorption experiment maximized the differences in A-parameters between dyes and metal complexes to a factor 5. Evaluating breakthrough curves, like those in Figure 3-10, using different values on the A-parameter resulted in A-parameters for the metal complexes and the dyes of approximately 100 $h^{1/2}$ and 20 $h^{1/2}$, respectively. All this indicates that interaction with the rock matrix can explain the observed differences in recoveries between metal complexes and dyes.

The obtained maximum value on the A-parameter can be used to calculate a maximum fracture aperture. Using the obtained effective diffusivity of $2 \cdot 10^{-13}$ m^2/s and assuming that the metal complexes are nonsorbing and that the rock matrix has a porosity of 0.3%, the fracture aperture becomes 0.3 mm.

Discussion and conclusions

Pressure measurements performed in the injection sections of boreholes T1, T2, and C3, which all are located above the Validation Drift, do not show any evident pressure gradient towards the drift. These seven injection sections situated 10 to 20 m above the drift in the H-zone have almost the same pressure head. The low water inflow rate to the Validation Drift compared to the inflow to the D-boreholes before drift excavation and a situation where the pressure drop is limited to a narrow section reaching only a few meters outside the drift indicate the existence of a disturbed zone around the drift.

Considerably lower values on the mean residence times were obtained for breakthrough in borehole T1 compared to the Validation Drift. The values obtained in the between hole test are almost one order of magnitude lower than those obtained in the Validation Drift. Although the flowpaths are not identical, the differences in mean residence times are remarkable.

The mass flow rates of tracers are, in the same way as the water inflow rates, dominated by a few sampling areas. The six tracer injections show different concentration patterns in the drift and may be divided into three different groups according to their patterns. All groups have their highest mass flowrates limited to different sections along the fracture with the largest water inflow. For some of these patterns, most of the tracer can be found in sampling areas with rather low water inflow rates compared with adjacent sampling areas. These observations show that channels important for transport do not necessarily have to be those carrying the largest amounts of water.

The observation that the largest tracer mass flowrates for four out of the six injection sections were found in the same sampling areas in the Validation Drift indicates that the number of channels important for tracer transport and connected to the Validation Drift is very limited. Tracers injected at different locations find the same way to the sampling areas in the drift. Five of the six injection sections were, however, located in a narrow section above the Validation Drift. The large variation in mean residence time between the tracers must therefore be an effect of the initial migration of the tracer from the injection section to the flowpath, channel, that is connected to the Validation Drift. The uniform mean travel time for a tracer independent of sampling area also indicates that the transport from the injection section towards the drift most likely occurs in one or a few major channels. However, close to the Validation Drift the tracer seems to spread out over a large area. This phenomena can be an effect of the disturbed zone due to the excavation.

3.1.4 Evaporation measurements

Measurements of evaporation were made to study the small scale variations in inflow of the averagely fractured rock. These measurements provided data with a better resolution than the 1x2 m plastic sheets put up in the "averagely fractured rock" parts of the Validation Drift. Hence, it was possible to study small scale variations in inflow through the rock matrix and along fracture traces in the drift wall.

These measurements assume that for low rates of groundwater inflow the rate of water evaporation from the rock surface is equal to the inflow. The absolute humidity is measured at two points within the layer of laminar air flow close to the drift wall. The evaporation rate can then be derived by assuming that the humidity increases linearly towards the rock surface. Laboratory experiments have demonstrated the accuracy of the technique (Watanabe, 1991).

Measurements of evaporation rate were made on two occasions; approximately 1 month and 14 months after the excavation of the Validation Drift was completed. This was to study if there were transient changes in the evaporation rate. Figure 3-11 shows the frequency distribution of the evaporation rates from the matrix rock obtained from the first and second measurements. This shows that the average inflow rate due to

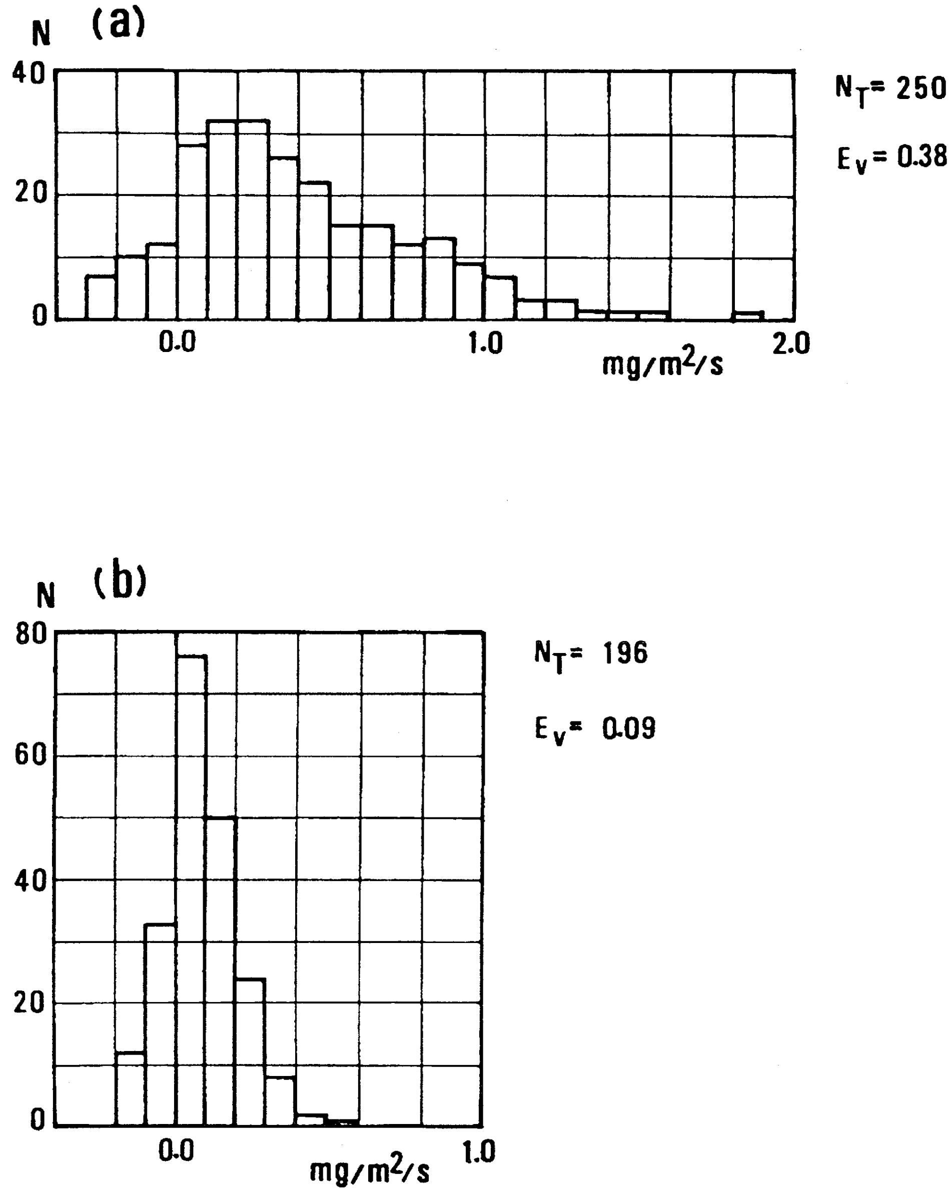

Figure 3-11. Frequency distribution of the evaporation rates from the rock matrix; a) one month and b) 14 months after excavation of the Validation Drift.

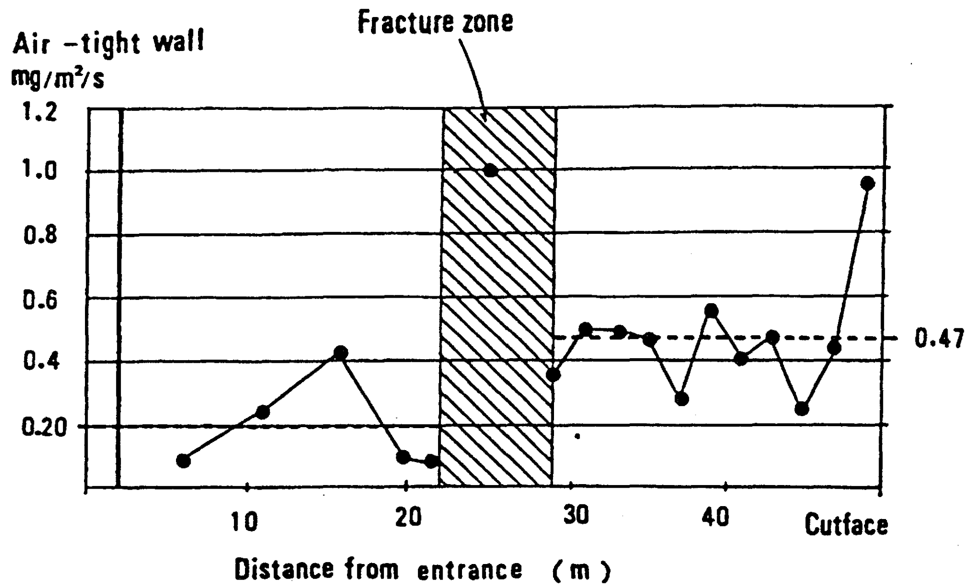

Figure 3-12. Variation in average evaporation rate along the Validation Drift.

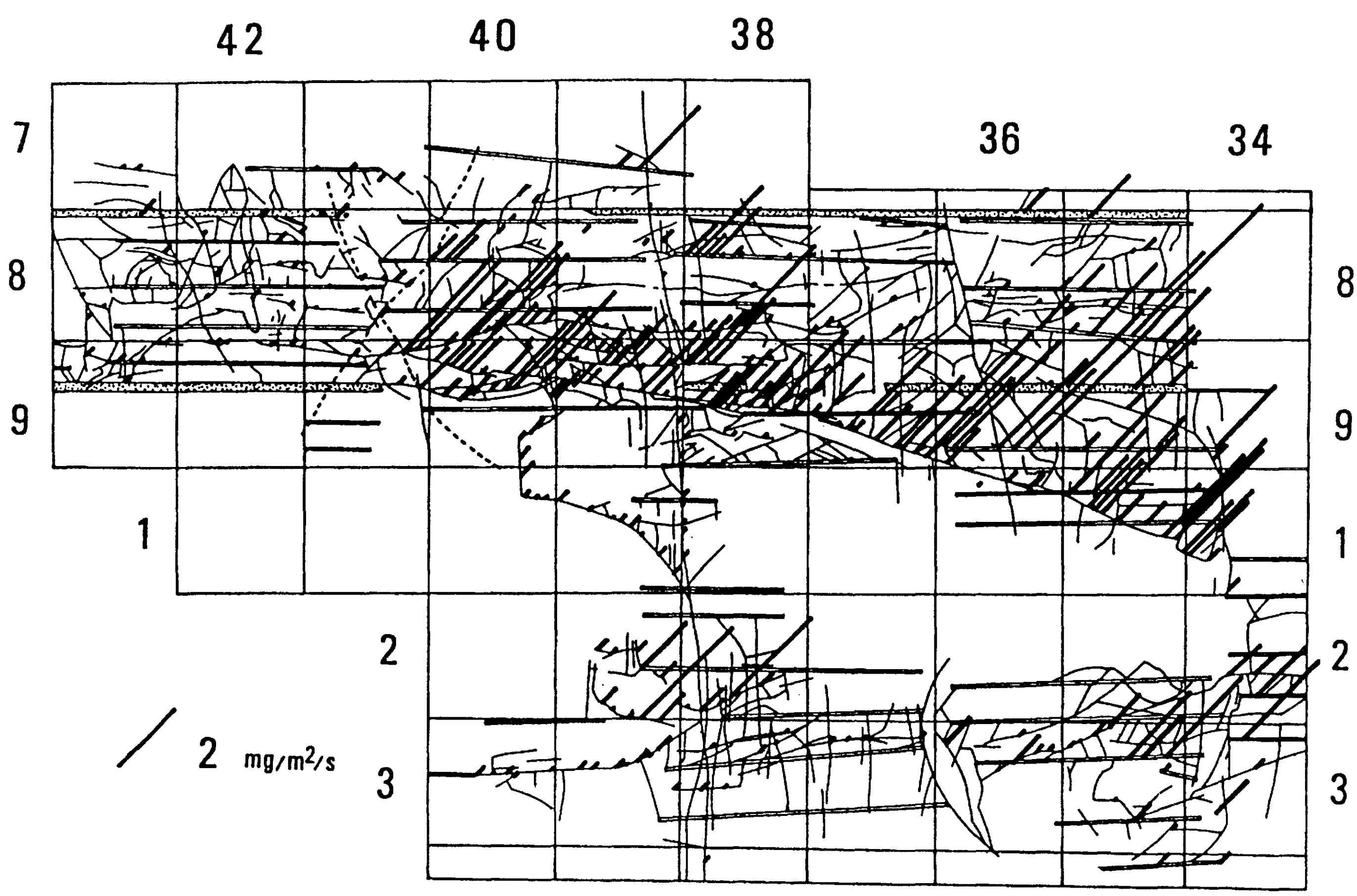

Figure 3-13. Details of the evaporation rate distribution along a semi-horizontal fracture intersecting the roof of the Validation Drift.

evaporation was 0.38 $mg/m^2/s$ one month after excavation compared to 0.09 $mg/m^2/s$ about 13 months later.

To some extent this difference can be attributed to the difference in air temperature during the two measurements. In the first measurement the air temperature was approximately 18°C near the roof and about 12°C at the floor which was approximately equal to the rock temperature. In the second measurement the temperature was almost identical to the rock temperature and homogeneous within the drift volume. During the first measurement high evaporation rates were observed in the crown where the air temperature was high. In the second experiment similar evaporation rates were observed all around the drift perimeter. Hence, the high evaporation rates observed in the first measurement may partly be due to a forced drying of the rock.

Figure 3-12 shows the average wall evaporation rates measured along the length of the Validation Drift during the first measurement. This indicates that the evaporation rate from the rock between the entrance to the Validation Drift and the H-zone was lower than that between the H-zone and the end of the drift. This is in agreement with inflows to the plastic sheets where only a few sheets between the entrance and the H-zone produced measurable inflows (cf. Figure 3-7).

The details of the evaporation distribution was also studied along some fractures to get an idea of the channeling within fractures (Watanabe and Osada, 1991). From Figure 3-13 it is evident that measurable inflow occurs along most of the fracture trace of the sub-horizontal fracture that intersects the roof of the drift. However, there are large variations in the magnitude of the inflows and the high inflows often occur in places where fractures intersect. It is also interesting to note that high inflows occur rather frequently along the blast holes (thin parallel lines in the figure). This must be due to fractures radial relative to the blast holes generated during blasting which connect to permeable fractures in the rock mass. Such fractures could cause increased axial conductivity along a blasted drift.

For measurement points along specific water bearing fractures there was a decrease in the average evaporation rate of 20% between the two measurements, from 1.21 $mg/m^2/s$ to 0.91 $mg/m^2/s$. The reduction in evaporation rate for the fractures is thus much smaller than the reduction observed for the rock matrix. A possible reason for a larger reduction in evaporation rate for the matrix could be the development of an unsaturated zone close to the drift wall.

3.1.5 References

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3.2 FRACTURE NETWORK MODELLING

3.2.1 Introduction

1991 was the final year of the Stripa project and saw the culmination of our modelling work. The data from stage three investigations and stage four interpretations of the SCV programme was available and the four modelling teams were able to demonstrate the progress made over the course of the project by predictive modelling for a series of large scale experiments.

The first of these was the Validation Drift inflow experiment. The predictions for this exercise were presented in February 1991 to the fracture flow modelling task force, along with the experimental results. The final interpretation of the results from this exercise have been prepared by the task force at the other two meetings in June and December 1991. Briefly, the various flow modelling approaches all performed well, and made good predictions of the inflow, but failed to explain the disturbed zone around the drift excavation. Whilst experience enabled us to predict that there should be a reduction of flow into the drift as compared with D-boreholes, attempts to explain this in terms of physical models were not successful. In general, predictions of inflow to the Simulated Drift Experiment (SDE) were better, and the best representation of the disturbed zone was a simple reduction of transmissivity for conduits near the tunnel. The inflow experiment together with the SDE has provided for the first time a precise quantification of the importance of the disturbed zone, and highlighted conceptual uncertainty concerning the mechanisms involved.

During the second half of the year, our effort were concentrated on the development of our approaches for predicting transport experiments. Given our uncertainty in the flow properties of the disturbed zone and the transport properties of the site, the programme was arranged in a series of three modelling exercises. First Radar Saline 1, a strong injection of a highly concentrated saline solution with recovery in the D-holes. The results of this experiment were available to us in 1990, and we used this experiment to calibrate transport models. Second, a repeat of this experiment with recovery in the Validation Drift provided a 'training exercise' for predictive modelling. Finally, a series of tracer transport experiments, with low injections of a series of metal-complex and dye tracers in boreholes around the Validation Drift, with recovery in the drift. These tracers were injected into the natural flow field of the drift inflow. Two cross-hole tracer tests were also carried out at the end of the project. In general the models made good predictions of these experiments, particularly when the flow fields were accurately represented. The models illustrated the importance of the fracture network geometry as a (predictable) source of tracer dispersion.

The Stripa project modelling teams at AEA D&R and Fracflow developed and demonstrated an integrated approach to modelling in fractured rock, using discrete modelling codes on the small scale, below representative volumes, and using continuum approximations in conventional porous medium modelling on the scale of the mine or the SCV site as a whole. This approach could be used as an integrated part of a site investigation programme. In contrast, the two collaborative modelling teams from LBL and Golder Associates demonstrated quite distinct approaches, illustrating the use of discrete models on the large scales. These approaches were based on equivalent discontinuum and fracture network methods respectively. Their conclusions are sometimes quite different.

As this is the final annual report, the following sections describe the modelling approach, results and conclusions of each team in turn. The experimental results and code predictions did not identify one single approach as 'correct', rather we conclude that each of these approaches has value and helps in our understanding of flow and transport through fractured rock. The approach chosen at any given site will also depend on the data available at that site and the purpose of the modelling.

In conclusion, we have successfully developed the techniques required for modelling flow and transport at fractured sites. We have applied these techniques to make genuine, 'blind' predictions of field experiments (as opposed to the more usual modelling exercises for which the answers are known in advance). Finally, this structure programme of experimental site characterization and modelling prediction, with close interaction between modellers and experimental groups, has made a significant step forward in our understanding of flow and transport through fractured rock.

3.2.2 AEA D&R Fracture Network Modelling

3.2.2.1 Fracture network modelling approach

The aim of our fracture network modelling is to improve our understanding of flow and transport through fractured rock systems. In fractured hard rocks such as Stripa granite the water flows through a discrete network of individual fractures. Conventional approaches to modelling such flow systems are based on averaging the flow and transport properties of the system over representative elementary volumes (REVs). The scale of these volumes must be large enough to be representative of the fracture network, and this can mean that the REV is difficult to characterise directly. Such approaches have been successful for flow predictions, but it is not clear that they always will be, nor is it clear at what scale such an approximation is valid for a given fracture network. Finally, effective-porous-media models have not succeeded in explaining nuclide transport in fractured rocks, where scale dependent dispersion length is observed experimentally. To improve our understanding and to support the use of such models on large scales, our fracture network approach represents the geometry of the flow system more directly. As described below, we show how the scale of a REV can be predicted, above which continuum approximations are justified. We make predictions of bulk properties of the rock, from direct measurements of the properties of individual fractures, and we make predictions of the distribution of flow and tracer recovery on more local scales. Thus our approach can explain all the qualitative features of flow and transport as seen in mines and borehole, and provide the parameters and justification required to use conventional models on larger scales.

In order to provide understanding of the flow system, we have adopted a 'forward modelling' approach. We make simple assumptions when constructing representations of the site and investigate the consequences of these straightforward models. In principle, fracture network models have many millions of adjustable parameters: the difficulty is not in representing physical complexity in the models, rather it is in characterising our models with the sometimes limited data. This was particularly the case with the disturbed zone around the Validation Drift, which we do not understand (although empirical changes to network properties near the drift can give good matches to the observed flows). Throughout, we have endeavoured to incorporate directly in our models as much as possible of the experimental data gathered at Stripa.

Our approach is embodied in the NAPSAC computer code developed on behalf of the Stripa project. This is a flexible fracture network code specifically designed for the Stripa project to investigate realistically large networks. It is restricted to fracture flow and currently to steady-state flow systems. The aim is to understand the effect of the geometry of the network on flow and transport: more complex physical processes can be better investigated with other tools. It can represent the detailed flow through networks of over 50 000 fractures, involving up to 200 000 000 finite elements when implemented on a Cray supercomputer.

The conceptual model of the site divides the rock into two distinct categories: averagely fractured rock, and discrete features or 'fracture zones'. Three distinct zones of importance cross the SCV site: in order of significance these are the H-zone, B-zone and I-zone. Of these only the H-zone intersects the drift, and this feature dominates the flow through the site. Fracture data gathered at the site was split into separate datasets for each of these types of rock. However, there was insufficient data to characterise the networks comprising the B- or I-zones, and so we had to represent these as simple planar features with a typical transmissivity. Fortunately, these did not intersect the Validation Drift. It does mean that in the prediction of D-hole fluxes, the flux from the end of the D-holes, where B- and I-zones intersect, is not predicted using the fracture network approach.

We have chosen to take the fracture frequency from the density of hydraulically active fractures in the core logs, resulting in a very dense network. The network for the H-zone network in particular posed a difficult numerical problem for flow calculations.

The first stage of our modelling is to establish the flow properties of the fracture networks, in particular the permeability of the fracture flow system, and the scale of the REV. We determine the REV to be the smallest scale for which the permeability of cubes of rock is insensitive to the realization or details of individual fractures of the network. For scales larger than this REV, the use of continuum models is justified. Here we consider either the network in average rock (i.e. excluding the fracture zones), or that within the H-zone: had the fracture zones been incorporated in our stochastic model, they would have provided heterogeneity on a very much larger scale and averaging over these features at small scales would not have been valid. We need to represent the major features explicitly in order to justify REVs on small scales. If we accept an uncertainty of about 50% then for average rock the REV size is 12 m, and in the H-zone it is 7 m. The corresponding permeability tensors are:

$$k_{ij} = \begin{pmatrix} 2.1 & -0.1 & 0.2 \\ -0.1 & 2.6 & -0.2 \\ 0.2 & -0.2 & 2.8 \end{pmatrix} \times 10^{-17}\ \mathrm{m}^2$$

for the average rock, and

$$k_{ij} = \begin{pmatrix} 1.7 & 0.2 & -0.2 \\ 0.2 & 2.7 & 0.3 \\ -0.2 & 0.3 & 2.2 \end{pmatrix} \times 10^{-16}\ \mathrm{m}^2$$

for the H-zone. The networks for the H-zone are less well characterised, since we have fewer measurements of H-zone fractures, and there is an order of magnitude uncertainty in this tensor (mainly due to uncertainty in the interpretation of fracture hydraulic properties). These permeability tensors were used in the porous medium modelling as described in section 3.2.3.

Having established the permeability of the fracture networks, we are now able to investigate the extent to which relatively untransmissive fractures can be ignored. We showed that 30% of the least transmissive fractures could be removed with only a 10% reduction in the permeability of the networks. We regarded this as an acceptable approximation and subsequent network calculations were made on this truncated network.

The network models are very computationally intensive and the scale of the models with our interpretation of the fracture system is limited to a few tens of meters. The scale of the flow system associated with the SDE is much larger: of the scale of the SCV site. However, we have demonstrated the validity of continuum approximations on these scales, and so to model the bulk fluxes in the SDE, we adopted porous medium models of section 3.2.3. Note that for these models, the finite-element size is larger than our predicted REV, and the finite-element properties are given by the predicted values from fracture network models. Our modelling remains based on the discrete fracture network approach and we have not had to calibrate the models.

Once we have the continuum approximation to the pressure field of the SDE experiment, we can return to using fracture network models directly. These network models will predict the distribution of flux to the experiment, as well as the bulk fluxes. We note that the pressure field is cylindrically symmetric about the D-hole array on a scale of 10-20 m and we can therefore generate separate network models of disks of rock centred on D1. These models extend to a radius of 12 m, and these fracture network flow predictions are summarized in Table 3-3.

Note that in these models, the boundary conditions to the models were approximately interpolated and a better boundary condition would increase flux by a factor of 2.5. The flux from the H-zone network is a factor of 2-3 lower than that given by the SCV stage 3 single plane representation. This is not surprising given the uncertainty in the H-zone network characterization.

Table 3-3. Summary of inflow predictions to the D-holes.

	D1	D2	D3	D4	D5	D6	Total
Average rock (average of 8 realizations) (ml/m/min)	0.09	0.23	0.22	0.24	0.14	0.23	1.20
H-zone (average of 4 realizations) (ml/m/min)	1.67	4.65	2.88	1.69	2.25	3.48	15.75
B-zone	not modelled in SCV stage 5 (no data collected)						

3.2.2.2 Modelling inflow to the Validation Drift

The differences between modelling the SDE experiment and the Validation Drift inflows are the presence of the disturbed zone, and the increased resolution of flow measurements. We again aimed to explain the flow field by using forward modelling of physical processes to predict flows. We could at this point have calibrated the SDE model to the measured SDE flows, and then incorporated a model of the disturbed zone. We decided that there was no value in doing this, since the calibration could be performed in several ways, which might interact with our representation of the disturbed zone. Calibrating would simply increase the inflows from the H-zone by a factor of 2-3 and consequently increase its importance relative to average rock. We therefore present our results in terms of a change in flux, as compared with models that did not represent the disturbed zone; that is as a change from SDE results.

There was no direct experimental characterization of the disturbed zone. We therefore chose to investigate the conventional model of disturbed zone effects: changes in hydraulic properties due to stress changes. There were no direct measurements of these stress changes, and so the Stripa project commissioned a modelling study of the SCV stress field. This used a continuum elastic approximation, and provided input to our fracture network models. The stress field predicted was in good agreement with simple analytical models of stress around tunnels, and reasonable agreement with two-dimensional discrete model of the plastic deformation around the tunnel. Using this modelled stress field, we can calculate the normal and shear stress on each fracture plane in our network model, and also the change in stress due to tunnel excavation. We applied a simple normal compliance model of transmissivity change due to changes in normal stress. This is the simplest model, and one that has been suggested as a cause of skin around tunnels:

$$\frac{T}{T_0} = \left(\frac{\sigma}{\sigma_0}\right)^{-\beta}$$

where T is the fracture transmissivity, σ is the normal stress on the fracture and subscript 0 refers to the undisturbed values. The stiffness parameter β was measured for a few large core samples with a typical value of 0.2 for Stripa fractures. The result of applying this model to our predictive network models,was to increase the inflow by less than 2%. This is explained by the dominant fracture set intersecting the tunnel perpendicularly and experiencing a slight decrease in normal stress due to a Poissons ratio effect in the stress models. Clearly this model of normal stress effects does not represent the disturbed zone around the Validation Drift where flow rates were a factor of eight lower than those measured for the SDE More detailed parameter studies investigating the influence of stress changes are given in Herbert et al. (1992).

The other aspect of the inflow prediction to the Validation Drift in the detailed prediction in inflow distribution. We did not understand the disturbed zone, and this might significantly affect the pattern of inflow: our results, neglecting the disturbed zone, are shown in Figure 3-14. Note also that the relative importance of the H-zone is underestimated here since we have not calibrated against the known SDE inflows.

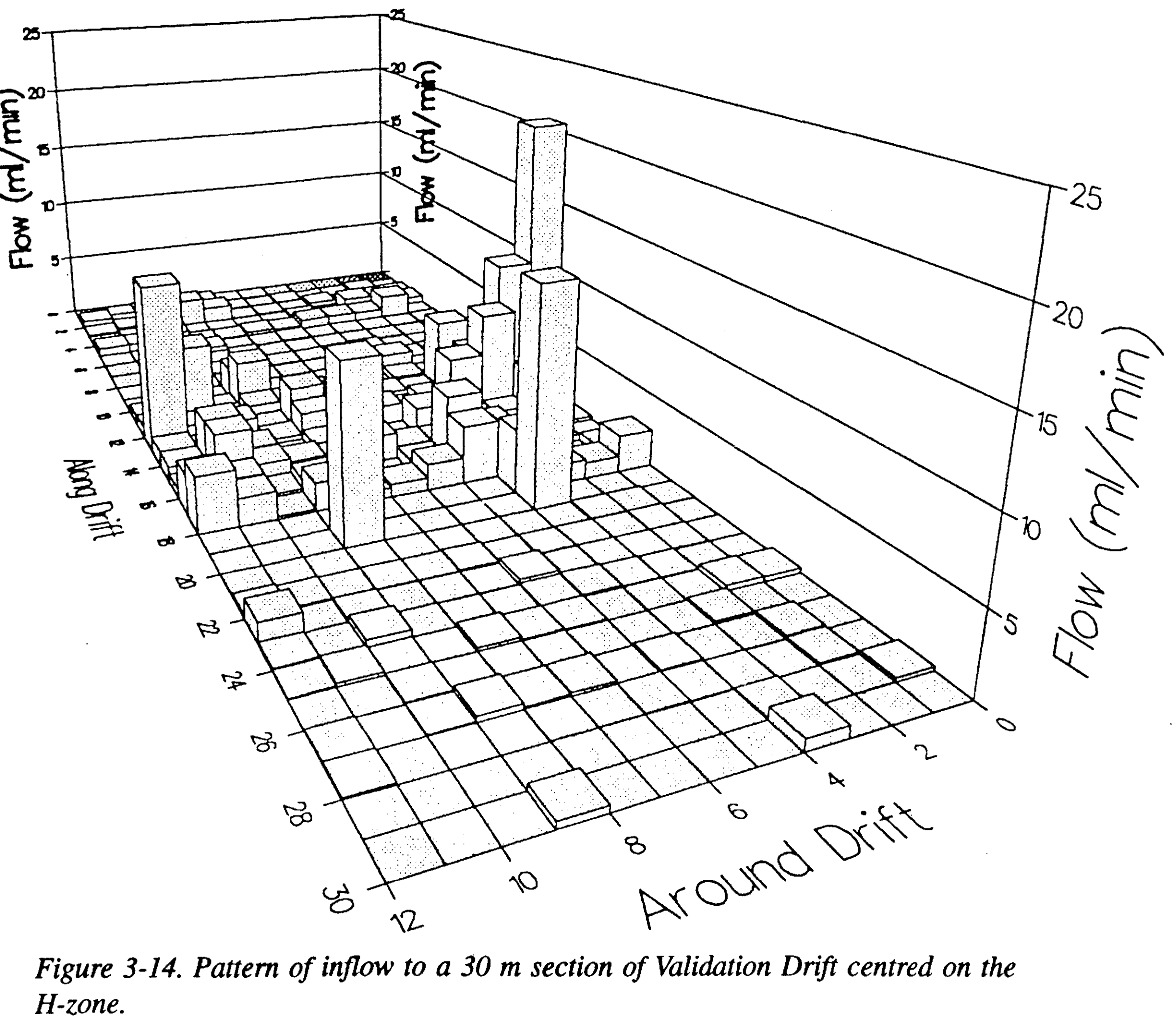


Figure 3-14. Pattern of inflow to a 30 m section of Validation Drift centred on the H-zone.

3.2.2.3 Tracer transport modelling

The final stage of our work was to model the tracer transport experiments performed in the SCV site: the Radar Saline experiment 1 with the D-hole sink (RS1); the Radar Saline experiment 2 to the Validation Drift (RS2); and the Tracer injection experiments with recovery in the Validation Drift and borehole T1 (TR). These experiments took place within the H-zone, and the results of the flow experiments mean that we can neglect the average rock for the purposes of these models.

The objective of our transport modelling is to try and build understanding of fracture network transport, by directly modelling tracer transport in a discrete model. This is the only approach able to quantify the dispersive effect of the fracture network geometry. The models are, however, computationally intensive, which means they have difficulty representing complex physical effects such as rock-matrix diffusion, two-phase flow and density driven flows. All of these mechanisms may be present for the Stripa experiments, but the parameters of these processes were not measured. We chose to use NAPSAC to investigate the effect of the network geometry, and to neglect the other processes.

There are two main problems to be addressed before we can use NAPSAC to model the Stripa tracer experiments. First, there is considerable uncertainty in the flow-field, and in particular in the influence of the disturbed zone. This was not understood in the flow modelling. We wish to investigate tracer transport in this stage of our modelling. Therefore, to avoid confusing flow approximations with the uncertainties of our transport model, we chose to calibrate the flow solutions to the tracer experiments and to fit as good a match to experimentally measured inflows as was reasonable in our stochastic model.

Secondly, there is the problem of scale. The flow systems of the transport experiments is typically 30-40 m: an order of magnitude larger than the simulations of the flow experiments. Here, in contrast to the flow modelling, we are not necessarily justified in using porous-medium approximations, since there are well known scale dependencies in the transport properties of heterogeneous rock. We therefore increased the scale of our models to represent network of more than 60 000 fractures, 180 000 intersections and more than 200 000 000 finite elements. We also further truncated the fracture network distributions, showing that if we accept a 30% loss of transmissivity, then 70% of the smallest and least transmissive fractures could be deleted. This is a significant reduction but nevertheless our results will still adequately reflect the influence of the fracture network geometry on tracer transport.

Since we are calibrating the flow field, the most straightforward approach to supplying regional flow boundaries within the H-zone was to set up a simple two-dimensional planar model of H-zone in the SCV site and impose the observed regional pressure head gradient over the boundaries. This scoping model had a scale of 200 m and included all the major sinks in the SCV site. From this model we were able to match the observed fluxes in the experiments by fitting an H-zone transmissivity, together with skins of reduced transmissivity around the Validation Drift (for RS2 and TR experiments), 360 m Drift, and increasing the transmissivity of the specially chosen C2 injection interval. This was used to predict the flow fields of the RS1, RS2 and TR experiments. Pathlines in this models enabled flow divides to be located and appropriate boundaries for the network models to be identified. The requirement on the boundaries of local model regions was for them to be about 10 m away from sources and sinks, and to include almost all the tracer transport pathways. In fact for RS1 we had to use a symmetry argument and model a half-region.

The additional characterization required for our network models are transport apertures for the fractures, which were again represented using an equivalent-parallel-plate model, the width of the H-zone and a prescription for the disturbed zone representation. We expect the transport aperture to be smaller than the hydraulic aperture by a factor resulting in residence times being 2-10 times longer (Gale et al., 1990).

The results of the RS1 experiment were known when we carried out this work, but we approached the task as a predictive modelling exercise. With the calibrated flow field and a 5 m wide H-zone, our results are illustrated in Figure 3-15. The best match to the first breakthrough uses a transport aperture equal to the hydraulic aperture, although there were difficulties in comparing results at later times due to changes in the experimental conditions after 100 hours and to our use of a symmetry boundary condition along an approximate flow divide.

To model RS2, we followed a similar procedure, using a regional model to derive boundary conditions for a 40 m scale network model. We used the H-zone model calibrated to SDE flows, and introduced a disturbed zone, calibrated to match the observed flow field. We chose to do this by modifying the transmissivity of the regional model within 4 m of the drift boundary (approximately three drift radii). Similarly in the network model we modified the aperture of all fractures within 4 m of the drift. The transmissivity was reduced by a factor of 30 in the scoping calculation and by 60 in the network model (the difference being due to the use of a coarse discretization near the drift in scoping calculations). This choice of disturbed zone influence is not unique, and different fractures are likely to experience different disturbances. This calibration gives a good match to RS2, but if there is any anisotropy to the disturbed zone, we will not represent it. The calibration will be less good for experiments that involve flows crossing other parts of the disturbed zone.

The results are shown most clearly for a pulse test, and Figure 3-16 shows a comparison of our prediction with the measured recovery from a pre-test pulse injection of Amino-G tracer. The results from the saline injection that followed are fully consistent with this tracer pulse test. It can be seen that a better match is obtained by scaling the transport aperture to increase residence times by a factor of three, and we then have an excellent agreement. We therefore used this calibrated scaling factor to make our 'blind' predictions for the tracer experiments.

The final set of simulations concerned the tracer tests from boreholes around the drift held at near ambient pressure. We modelled 5 separate injections to the drift and 3 interhole experiments in the H-zone. The other experiments, involving tracer injection outside the H-zone and the use of a sorbed tracer were not simulated. The results of these injections are influenced by the transmissivity of the specific injection interval (in contrast to RS2 where a large flux was imposed on a transmissive interval). We simulated a large number of injections in several realizations, with particles injected in several intervals in each of the four boreholes. Thus we do not calibrate our models to match the selection procedure used to identify injection intervals, but instead predict the range of results for typical intervals within the injection boreholes. The flow disturbance due to the injection fluxes was minimal and so many transport simulations could be performed within the same flow realization. We had shown in the verification work that 50 000 particles were needed to converge the breakthrough distribution, and some of these simulations tracked swarms of 450 000 particles comprising 9 different tracers from 9 injection intervals. All the particles were recovered at the drift or the model boundaries.

This results in a very large number of results to compile. This task is addressed in Herbert and Lanyon (1992), here we present a few typical results. As expected, the best results were for injections in C2, where the experiment took place in the same part of the H-zone as had been used for our calibration. Figure 3-17 illustrates a representative swarm of particle paths for an injection of 10.8 ml/min in an interval of C2. Figure 3-18 summarizes the corresponding breakthrough to the drift, for all our simulations of the tracer experiment in C2. These figures show very smooth results, and our continuum approximation of the flow field is very consistent. The range of

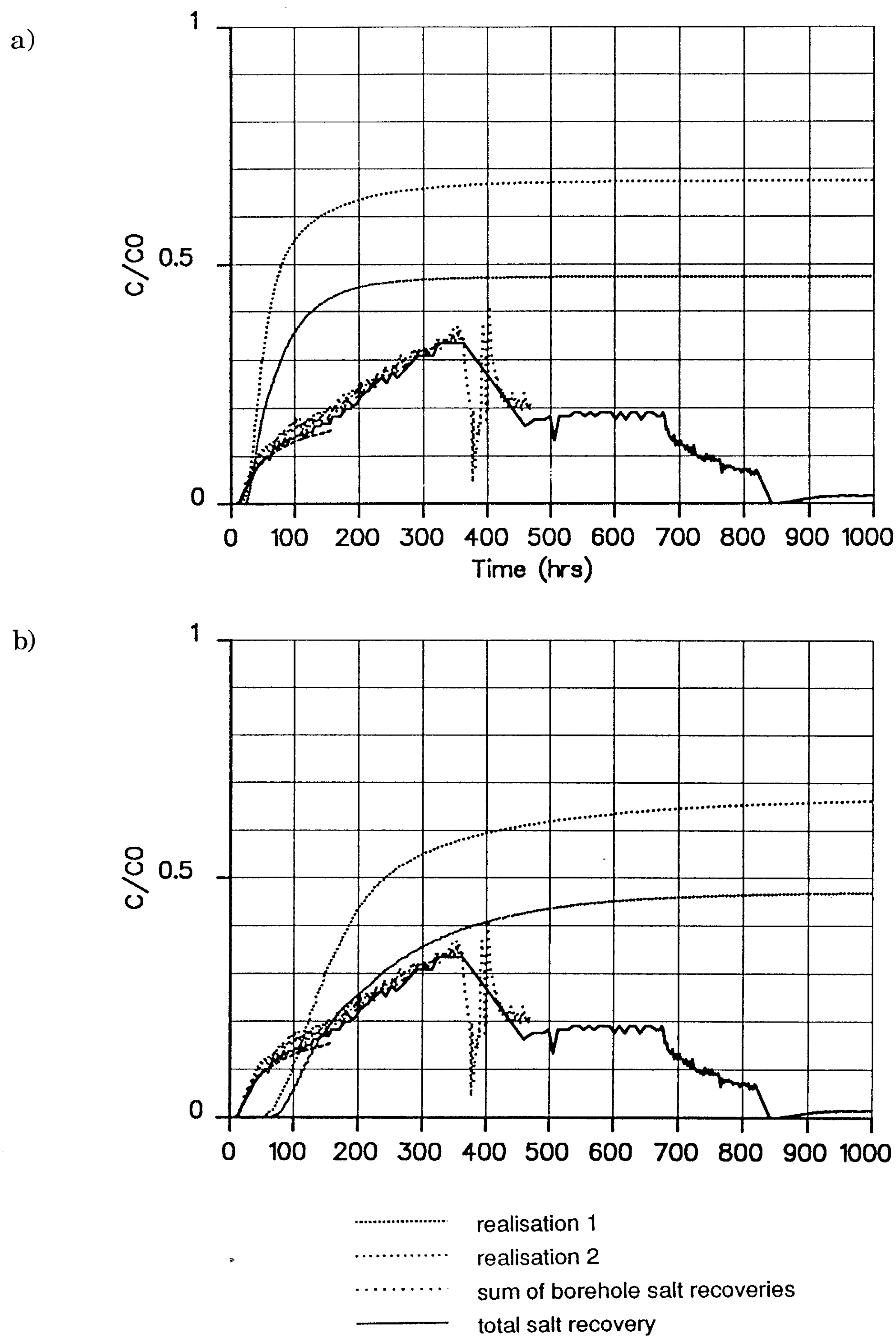


Figure 3-15. Comparison of model and experimental cumulative breakthrough of saline tracer to the D-holes for Radar Saline 1 experiment phase 1; a) transport velocity equal to parallel-plate flow velocity, and b) transport velocity a factor of three less than parallel-plate flow velocity.

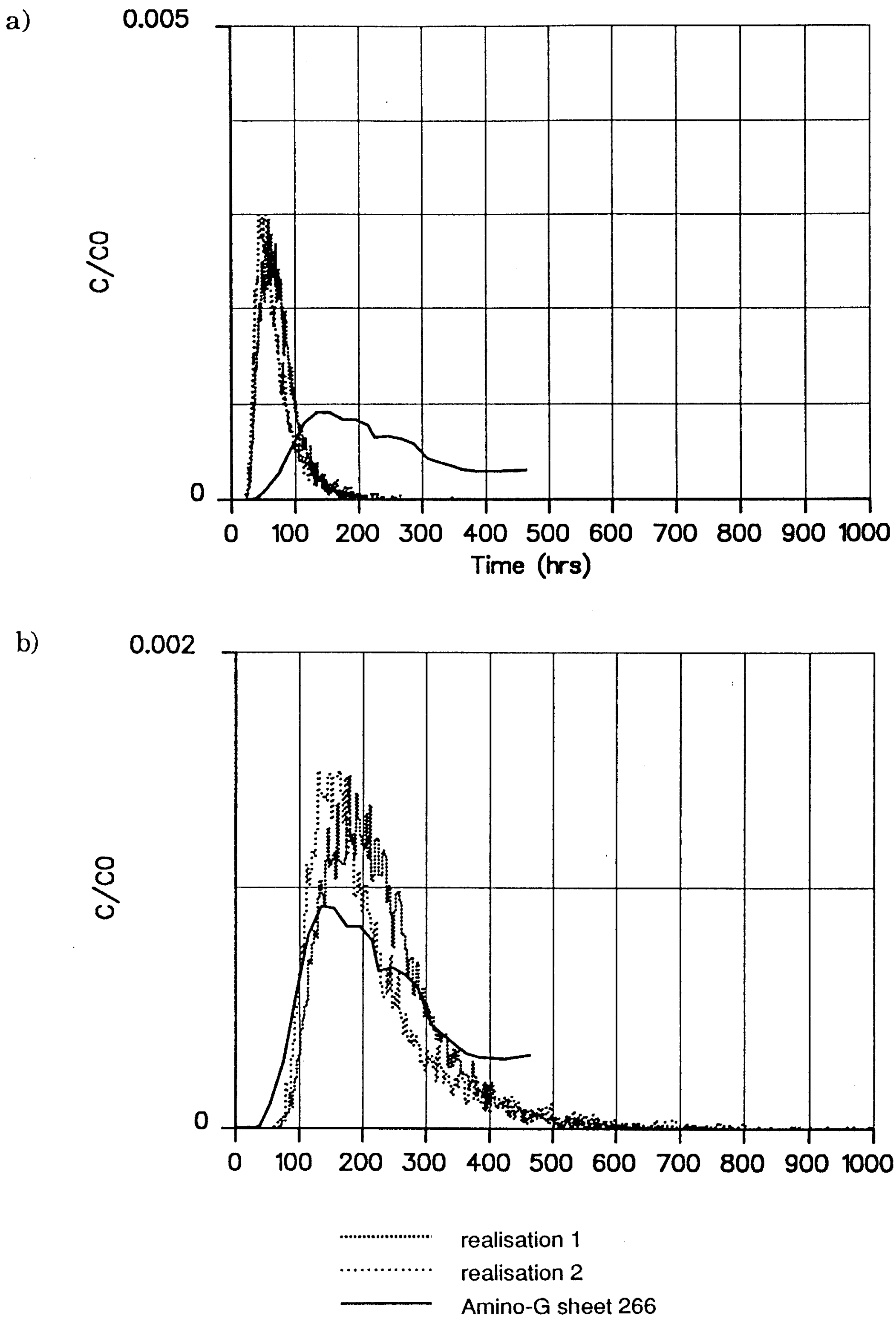


Figure 3-16. Comparison of model and experimental cumulative breakthrough of saline tracer to the Validation Drift for Radar Saline 2 experiment Amino-G pulse test; a) transport velocity equal to parallel-plate flow velocity, and b) transport velocity a factor of three less than parallel-plate flow velocity.

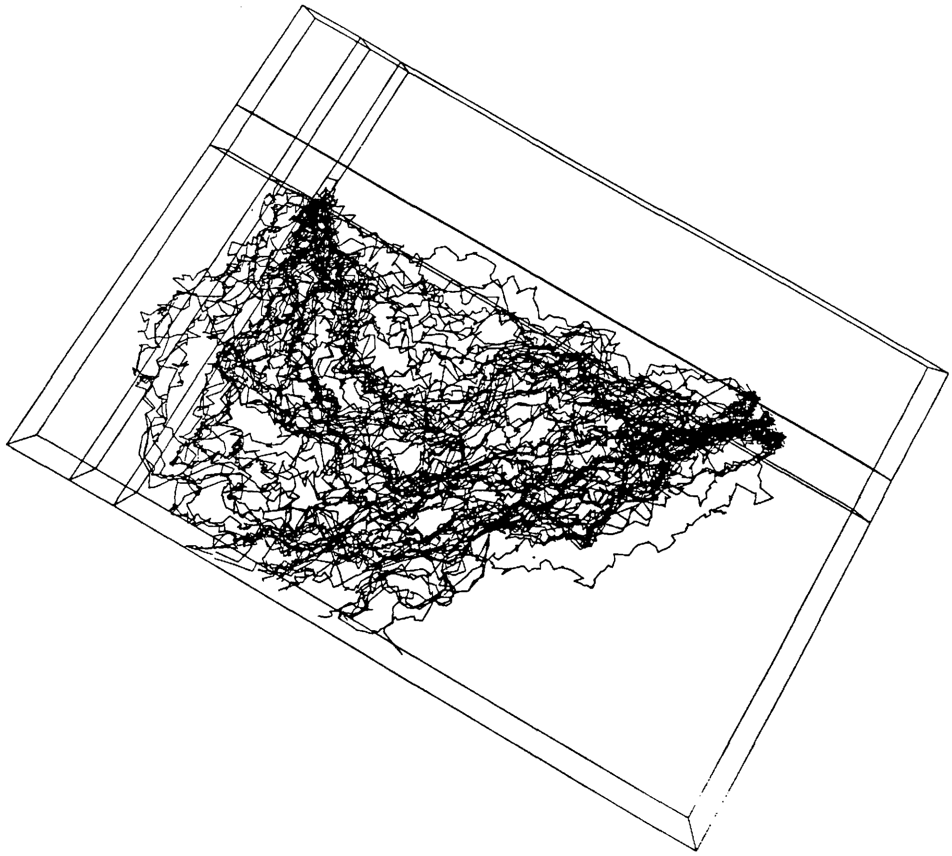


Figure 3-17. Pathlines follows by 100 representative particles in the network simulations with recovery in the Validation Drift from injection in borehole interval C2-1.

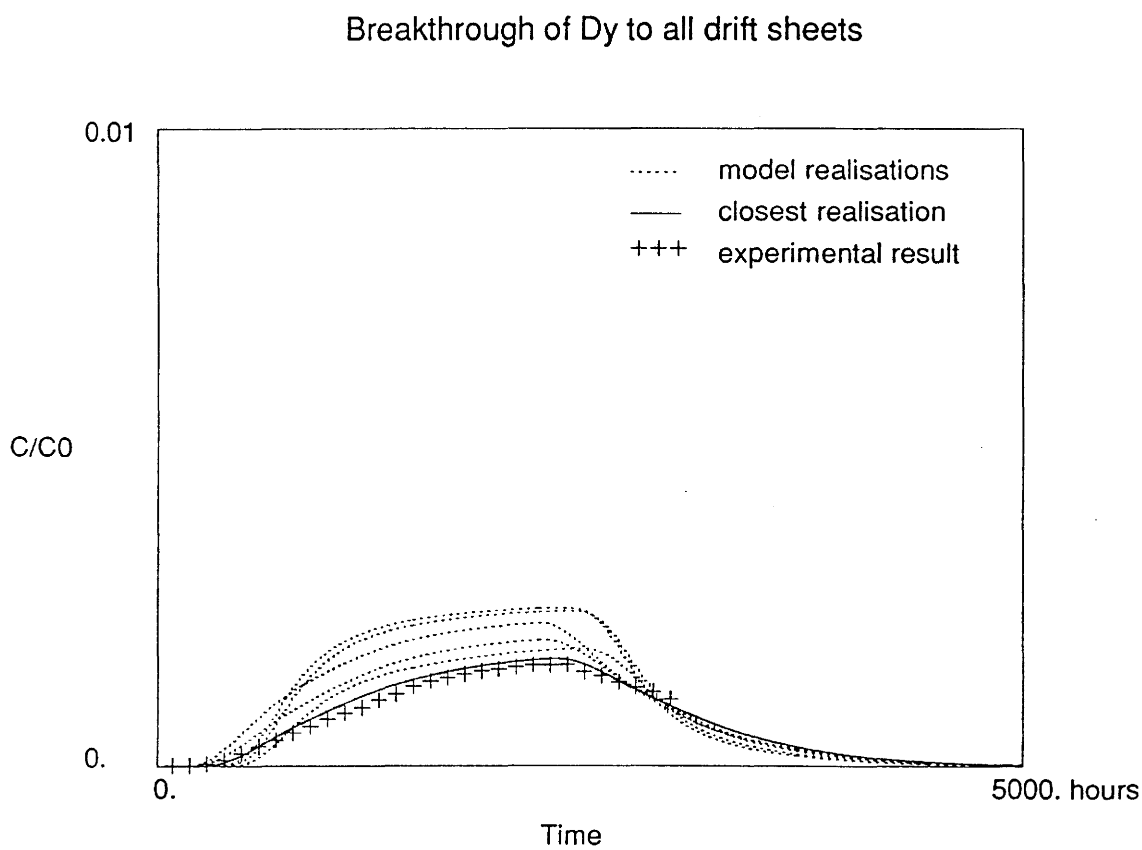


Figure 3-18. Comparison of predicted and experimental breakthrough for Dy tracer experiment: injection in borehole interval C2-1 and recovery in the Validation Drift. All model realizations shown.

breakthrough curves for the different realizations is very small, and in this 'double-blind' exercise, they predict the experimental recovery correctly. Indeed, one of the realizations matches the experiment almost exactly.

Away from the calibration region, above the drift, the results are less impressive, and pressure field for drift inflow is in error by a factor of four. Our prediction of drift breakthroughs from these experiments are correspondingly a factor of four fast. The other experiments were the cross hole tracer tests. These took place in a flow-field that was not strongly influenced by the disturbed zone, and our flow model was quite accurate. Here again, once we have a good flow representation, our transport predictions were accurate.

3.2.2.4 Summary

Our work for the Stripa project has developed a very powerful computational tool, the NAPSAC computer code. It has proven possible to infer fracture network statistics from the experimental investigations, and to incorporate these statistics in NAPSAC models without having to recourse to unjustified simplifications. There is a clear path from data collection to numerical model to prediction. This exercise was successfully carried out for the SDE experiment. The success of this exercise has lead to a clear justification for the use of equivalent porous medium models on sufficiently large scales, and a quantification in the inherent uncertainty associated with such a conventional approach. It provides strong support to safety assessment programmes.

When predicting the inflow to the Validation Drift, the use of NAPSAC highlighted our lack of understanding of this region. Previous studies incorporating such a disturbed zone accounted for it empirically, with inadequate justification. The modelling has also provided a useful integration of geomechanical modelling expertise with hydrogeologic modelling. We have demonstrated a valuable tool to aid future studies that address the experimental characterization of such disturbed zones.

Finally the modelling of tracer transport has proven feasible, even in the highly fractured H-zone. Our modelling is on scales beyond that at which continuum behaviour is shown for flux calculations: our preliminary analysis of these experiments indicates that we can accurately predict the dispersive effect of the network geometry. Future work will enable us to investigate the importance of other dispersive mechanisms, and the validity of continuum approximations.

We have succeeded in our objective of demonstrating the validity of the fracture network approach as a useful tool for understanding flow and transport in field experiments in hard fractured rocks.

3.2.3 Fracflow Porous Media Modelling

Three finite-element meshes, MINE, MINE2, and SCV, were used for the equivalent porous medium modelling of flow and transport to the D-boreholes (SDE) and the Validation Drift (Herbert et al., 1992). The MINE2 mesh was developed from the MINE mesh to accommodate changes in the location and orientation of the major fracture zones as the SCV project progressed. The SCV model was developed:

1) to allow a more correct approximation of the inclined nature and horizontal and vertical interconnection of the major fracture zones in the SCV block for tracer transport modelling;

2) to provide finite elements that were on a scale consistent with the size of the simulation volume that could be used by NAPSAC to generate equivalent porous media properties.

In addition, the detail provided by the small finite elements in the SCV model were required for flowpath and tracer simulations (MacLeod et al., 1992). The relevant details of the boundary conditions and the input parameters for the MINE2 and SCV models are summarized below, and the details of these and the MINE model simulations are presented in Herbert et al. (1992) or MacLeod et al. (1991).

The MINE2 model, approximately one square kilometer in surface area, is centred over the eastern half of the Stripa mine. This model consists of fourteen layers of varying thickness and extends to a depth of 600 m below ground surface. Four fracture zones have been included in the MINE2 model. These include an east-west fracture zone located in the southwest corner of the model, the H-zone, the I-zone and the combined A-B-zone. All of the H, I, and part of the A-B fracture zones are represented by narrow vertical elements, with a width of 5 meters. The hydraulic conductivity of the fracture zones were adjusted to reflect the measured transmissibility for the assumed thickness of the zone.

The held head conditions for the nodes on the vertical sides as well as the bottom of the model at 600 m depth were extracted from the hydraulic heads computed for the Sub-Region model (Gale et al., 1987), that simulated the effects of the Stripa mine. Internal nodes located on mine openings were assigned hydraulic head values equal to the elevation head at each node. Hydraulic conductivities were assigned to each layer using the depth versus permeability relationship given in Gale et al. (1987).

The mesh for the SCV model covers a surface area of 0.36 km^2. This model included the vertical section that lies between the 310 m mine level and 490 m of depth. This vertical section was divided into twelve layers within and ten layers outside the immediate Validation Drift area. The four middle layers within the immediate Validation Drift area were assigned a thickness of 2.5 m. The hydraulic head boundary conditions for the SCV model were extracted from the MINE2 model. The SCV model flux simulations were conducted to show the effects of the smaller element size in the SCV model on the flux into nodes representing the D-boreholes and the Validation Drift.

The initial input parameters assigned to the MINE model were those developed from the pre-1986 dataset for the entire mine area and used in the earlier regional flow modelling work (Gale et al., 1987). The MINE models were used to estimate or predict the flux for the SDE using very little site specific data. Actual predictions for the SDE and the Validation Drift were made using the MINE2 model. Input parameters for the MINE2 and SCV models reflect the additional measurements made during the SCV project. The MINE2 model mesh incorporated the most recent hydraulic and geometry data for the fracture zones in the SCV site, and the best estimates from the field measurements of the hydraulic properties for the average rock. In addition, a number of MINE2 model simulations were conducted to examine the different ideas on distribution and interconnection of high permeability zones within and adjacent to the SCV block.

3.2.3.1 Comparison of measured and computed heads

The initial head distribution (Figure 3-19) before the opening of the D-boreholes was computed using the MINE2 model and input parameters based on the permeability tensor data from NAPSAC (Herbert et al., 1992). The heads computed by this MINE2 model are higher than the measured heads, with the difference having a mean of 20.67 m and a standard deviation of 51.02 m, assuming a normal distribution. We should note, however, that the measured heads are not steady-state values whilst the computed heads are steady-state values; and also, the computed heads have not all been corrected for drift excavation effects, or for the difference produced by comparing point values computed by the model against the average heads for the packed off

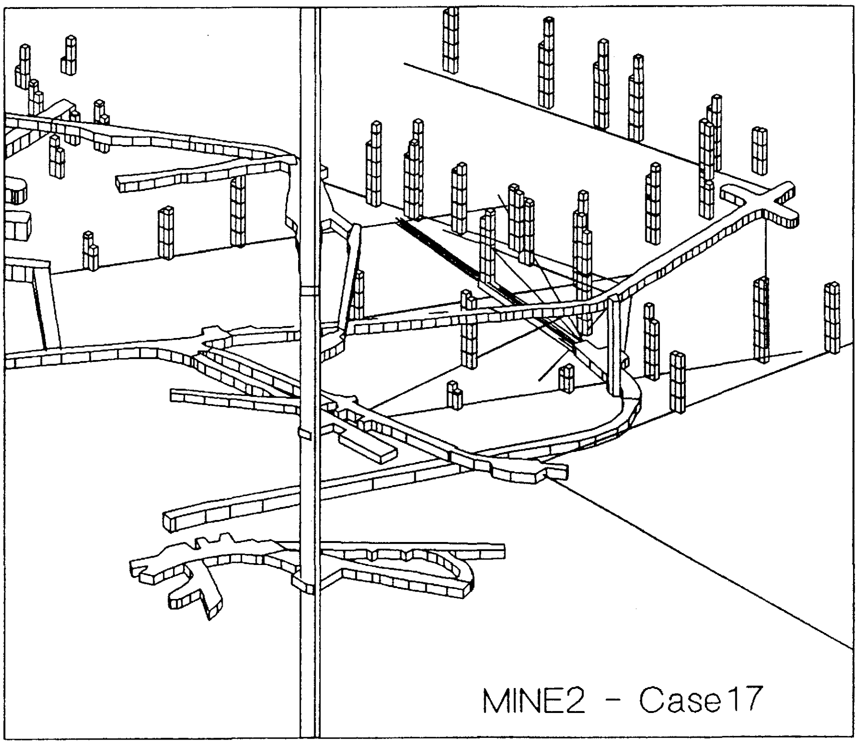


Figure 3-19. Comparison of measured (left column) versus computed (right column) pressure heads (MINE2 – Case 17 Model) in the SCV block.

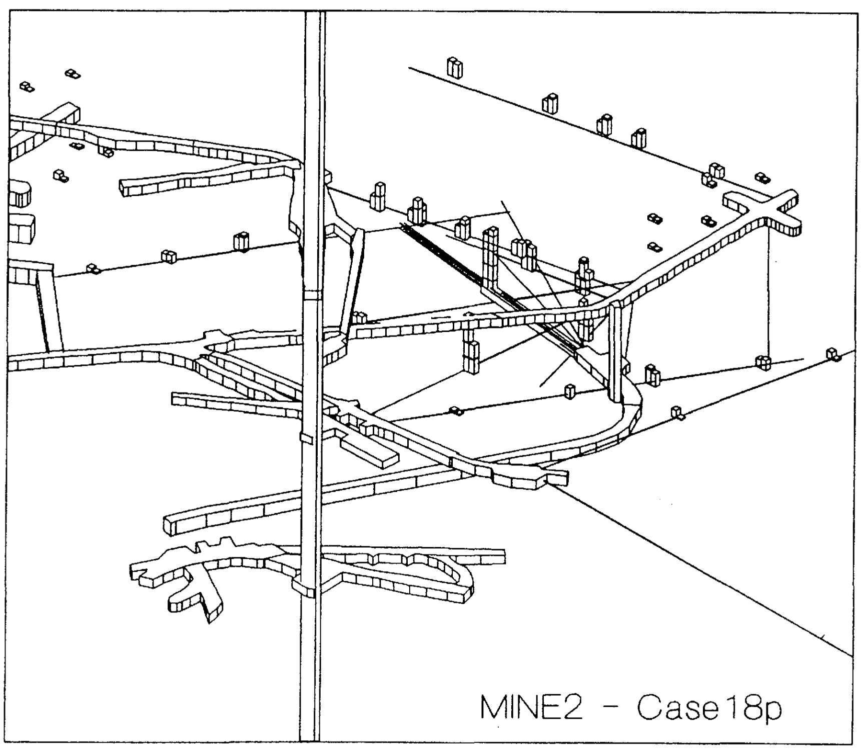


Figure 3-20. Comparison of measured (left column) versus computed (right column) drawdowns (MINE2 – Case 18p Model) in the SCV block.

interval lengths in the boreholes. One would expect the computed heads to be higher than the measured heads, and this is indeed the case in this model. It should be noted that using the raw field values for the hydraulic properties, but with the same distribution of large fracture zones, gave a much better fit between the measured and computed heads (Herbert et al., 1992).

The predicted drawdowns (Figure 3-20) for the SDE are those computed using the MINE2 model and the same input properties used to determine the initial heads. This model also incorporates the correct pressure head boundary conditions on the SDE nodes during the actual outflow tests. The difference between the measured and predicted heads have a mean of 3.63 m and a standard deviation of 23.76 m. Similarly good agreement between the measured and computed drawdowns (mean 1.00 m and a standard deviation of 24.45 m) was obtained using the same model with the heads on the nodes, representing the D-boreholes, equal to elevation heads.

The drawdowns predicted for the Validation Drift model agreed very well with the heads measured during the SDE. The set of head data, measured after the Validation Drift was excavated, are in reasonably good agreement with the model results, except near the drift itself.

3.2.3.2 Predicted flow rates for the SDE and Validation Drift

A flux of 2.44 l/min (CASE18P) was predicted for the full 100 m of the D-boreholes that were open during the SDE. The flux predicted for the first 50 m of the D-boreholes in the SDE is 0.562 l/min. The flux predicted for the same 50 m of excavated drift, the Validation Drift, is 0.779 l/min when the permeability of the elements bounding the drift nodes were corrected for the depth-stress effects (Herbert et al., 1992) using results from the stress modelling and the field measurements reported in Gale et al. (1987). Similar values for the flux to the D-boreholes were calculated using the SCV model (Herbert et al., 1992).

In addition to the final models used to predict the flux to both the SDE and the Validation Drift, it is worth noting the results (Herbert et al., 1992) obtained from the models used to make the initial estimates of flux to the D-boreholes and to assess the effects of different degrees of interconnection between the fracture zones and major sinks within the mine. The initial simulations using the MINE mesh models gave reasonable estimates of the measured flux to the D-boreholes. The MINE model, which was based on stage 1 hydraulic data predicted a flux of 3.169 l/min for the SDE. When this flux is corrected for the difference between the drift size and the effective node (well) size, the flux predicted for the SDE is 2.619 l/min, less than a factor of 2 more than the measured flux.

In summary, the MINE2 and SCV models have produced close agreement between the measured and computed initial pressure heads and close agreement between the measured and computed SDE drawdowns. However, the best agreement between measured and computed pressure heads and drawdowns were found for models in which the fracture zones were limited in vertical extent. Since this conflicts with the groundwater geochemistry, that suggests relatively rapid movement of surface waters to the SCV site, we must assume that the hydraulic properties of the fracture zones are variable in the vertical direction as observed during hydraulic testing in the SCV site (Holmes, 1990).

Also, close agreement was found between the measured and computed flux for the first 50 m of the SDE-boreholes. However, the corrections for stress concentration effects around the Validation Drift produced an increase in flux to the drift rather than the expected decrease in flux and poor agreement between the measured and predicted flux to the drift. The lack of agreement between the measured and computed fluxes for flow to the full 100 m of the D-boreholes indicates that the I and A-B fracture zones were not properly characterized and represented in the MINE2 and SCV models.

3.2.3.3 Tracer simulations

The SCV model was calibrated (MacLeod et al., 1992) to give the correct flux to the SDE, to the D-boreholes plus Validation Drift, and to provide a reasonable match between the distribution of flux between the 'average rock' and individual fracture zones. The SCV-SDE model was then calibrated against the tracer data for the Radar Saline 1 experiment (Figure 3-21) and the D-boreholes plus Validation Drift model was calibrated against Radar Saline 2 experiment (Figure 3-22). The initial porosity values used for calibrating the numerical model of the SCV site were those computed from field data (Gale et al., 1987). The porosity values were subsequently adjusted by multiplying the original estimate by factors that ranged from 1 to 4.75 in order to calibrate the model using the first and second Radar Saline tracer experiments. The values of the longitudinal (D_L) and transverse (D_T) dispersion that were assigned in the transport simulations were obtained from the literature (Domenico and Schwartz, 1990; and Herbert et al., 1992).

The first arrival of tracer in the D-boreholes predicted by the model, using the initial porosity and dispersivities, was earlier than that measured during Radar Saline 1. However, the peak concentration C/C_0 agreed very well with the measured value. The best match between the model results and the measured data for the Radar Saline 1 experiment was provided by dispersivities of $D_L = 5$ m and $D_T = 0.5$ m and porosities ranging from 0.00021 to 0.00038 for the 'average rock' and from 0.00059 to 0.00074 for the fracture zones.

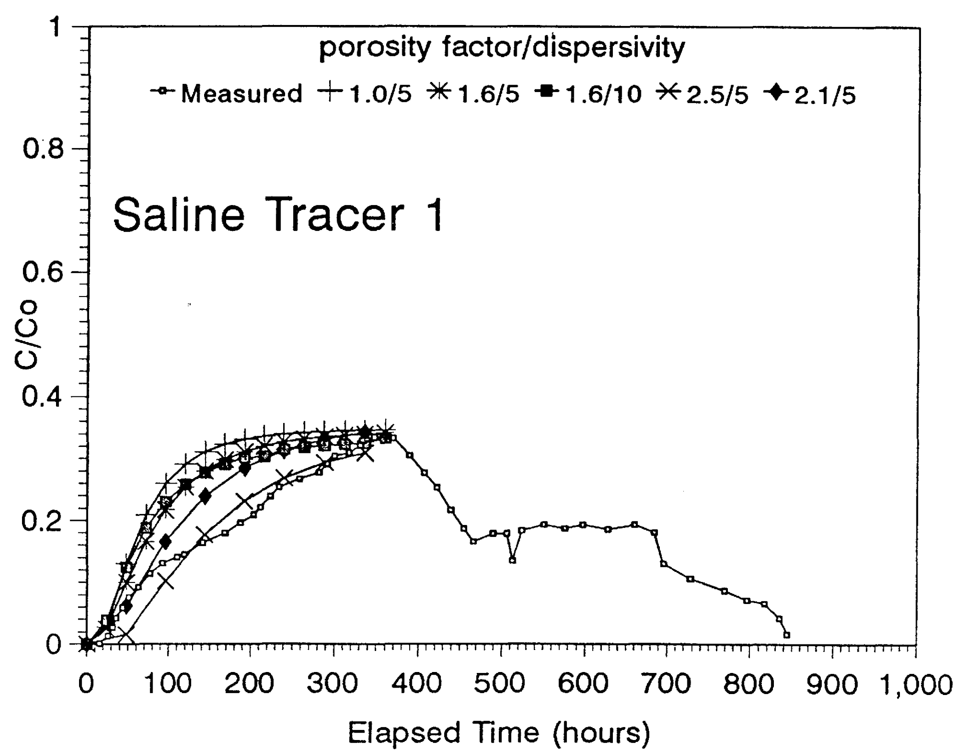


Figure 3-21. Tracer breakthrough curves for Radar Saline 1 experiment calibration simulations.

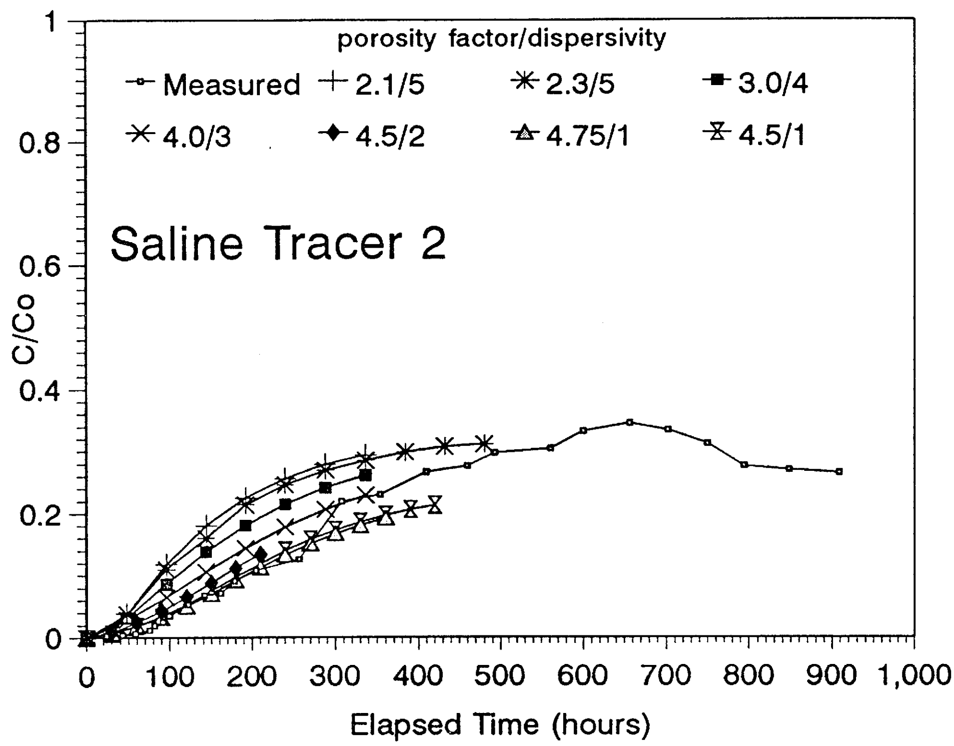


Figure 3-22. Summarized tracer breakthrough curves for Radar Saline 2 experiment calibraiton simulations.

The Radar Saline 2 experiment was modelled by the SCV-Drift model using the final porosity and dispersivity values from the SCV-SDE Radar Saline 1 model. It was found that these input properties predicted that tracer would arrive in the drift much earlier than was observed. This observation plus the steeper slope on the breakthrough curve suggested that the dispersivities and/or porosities assigned were too small. It was determined that the simulation with the best overall match to the measured data (Figure 3-22) was the simulation which used a dispersivity of D_L = 1 m and D_T = 0.1 m and porosity of 4.75 times the originally assigned porosity ranging from 0.00048 to 0.00087 for the 'average rock' and from 0.00130 to 0.00160 for the fracture zones. The small dispersivity length versus element size did not appear to produce any numerical problems in the simulation.

The validation phase of the porous media modelling exercise was to predict tracer movement towards the Validation Drift from tracer injected into a series of packed off sections of individual boreholes. Constant concentrations of tracer were injected at low injection heads and low flow rates in each interval. The model node which most closely matched the coordinates of the injection interval was designated to represent the tracer injection point. Due to the scale of the SCV model and the close proximity of many of the injection intervals (<5 m), some injection points (e.g. T2-1 and T2-3) had to be represented by the same model node. The concentration of tracer and the injection flow rate were fixed at the node for a particular tracer test. However, using this approach, a much larger mass of tracer was introduced into the rock mass due to the volume represented by the node compared to the actual injection point. Therefore the measured concentration at the nodes had to be corrected by a dilution factor to account for the ratio of the volume flux through the node to the injection flux (MacLeod et al., 1992).

Figure 3-23a shows typical tracer breakthrough curves for the Validation Drift experiments with injections into the C3-1 borehole. The earliest arrivals and largest peak recovery were predicted for tracers injected in the T1-borehole. This is probably due to the fact that borehole T1 is the closest borehole to the drift. Predictions for tracers injected in boreholes T1 and T2 and interval C3-1 all show early arrival of tracer and approach a peak 'steady-state' concentration within 400 to 500 hours. Tracer injected in interval C2-1 is slower to arrive at the drift, within the first 100 hours, and are present in low concentrations with the concentrations slowly approaching steady-state concentrations after 4 500 hours. Very little tracer from the C3-2 interval which is in the 'average rock' is predicted to reach the drift until 300 to 400 hours after injection and steady-state concentrations are not predicted until after 4 000 hours. Predictions of t_5 and t_{50}, time to reach 5% and 50% of the 'steady-state' breakthrough, and C_{ss}/C_0 the normalized steady-state breakthrough concentrations for each test were within an order of magnitude of the measured values.

Most of the tracer from tests T1-1, T2-1, T2-3, and C3-1 was recovered from the H-zone. However, for the test with injection in C2-1, the tracer is only recovered in the three nodes representing the first 20 meters of the drift and very little tracer is predicted to arrive in the H-zone. The same is true for the modelled injection in interval C3-2, shown in Figure 3-23b, where the injection is in the 'average rock'. The bulk of the tracer is predicted to arrive in the last 20 m of the drift with very little arriving in the H-zone.

3.2.4 LBL Equivalent Discontinuum Modelling

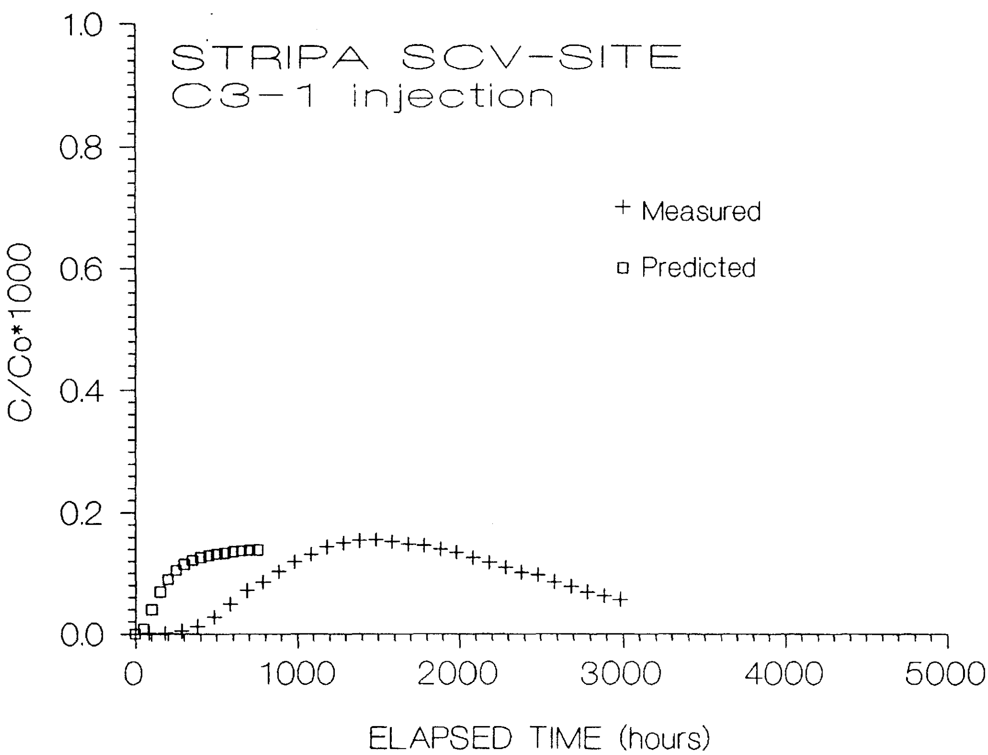
3.2.4.1 Modelling approach

An equivalent discontinuum model is a model which uses a partially filled lattice of one-dimensional conductors to represent equivalent fracture flow paths. The model is designed to represent the discontinuous nature of fracture flow in a simple manner under two principles: (1) That all partially connected systems have universal properties described by percolation theory, and therefore (2) it is reasonable to represent the real, complex system by a simpler lattice. In other words, fractures or fracture clusters can be represented by some average equivalent conductor and the flow of fluid through the rock can be modelled on a partially filled lattice of such conductors.

Equivalent discontinuum models are derived starting from a specified lattice or "template". An inverse analysis is performed on the template to find a pattern of lattice elements (a configuration) which can reproduce hydrologic data as observed in the field. In general, interference test data is used. The inversion finds arrangements of conductors in space that behave like the observed head and flow responses. Once the inversion has been accomplished the model can be used to predict behaviour in the fracture system under different flow conditions.

The lattice template is in effect a conceptual model for a fracture system chosen based on as much a priori data as is available. The hydrologic conceptual model used by LBL for the SCV predictions was patterned directly after the seven-zone structural model (A,B, H, I, M, K and J). Based on the evidence collected, only about 10% of the flow occurs outside of fracture zones and so the template was constructed only in the planes of the zones. However, the transmissivity within the fracture zones is not uniform. Within them there are a myriad of fractures, some of which are important for flow and most of which are not. This was evidenced in the Validation Drift where nearly all the water came in through the H-zone and 80% from one fracture in the H-zone. Therefore the location of the conducting elements within a zone was treated stochastically.

a)



b)

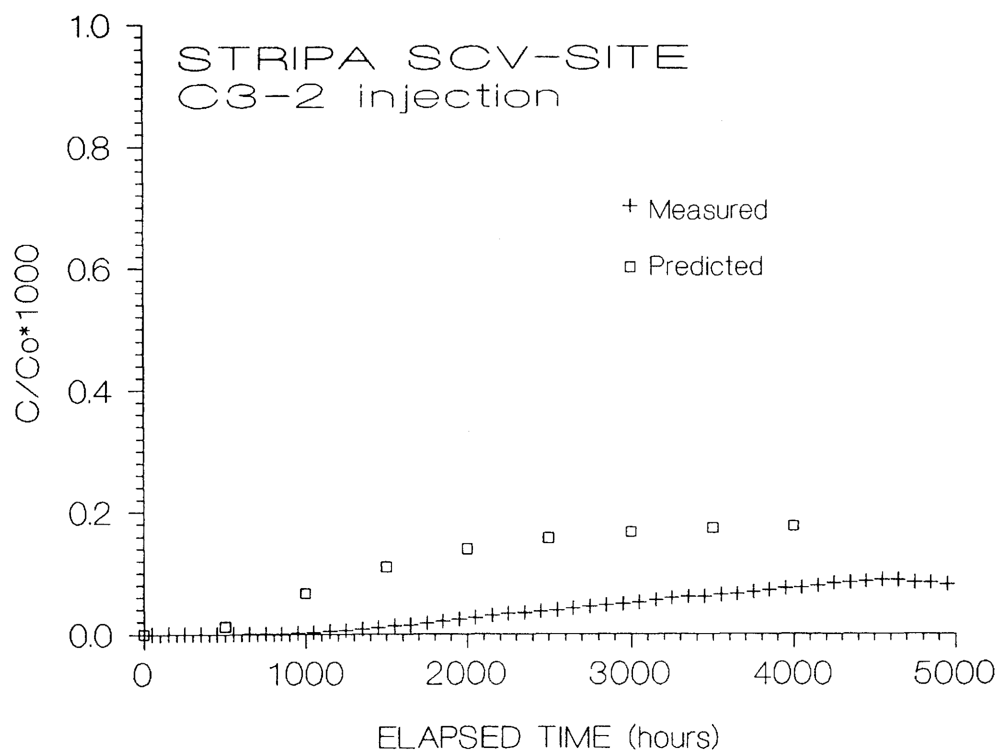


Figure 3-23. Comparison of the predicted versus measured breakthrough curves to the Validation Drift for tracer injected into borehole intervals a) C3-1 (H-zone) and b) C3-2 (average rock).

Once the template is decided on, "Simulated Annealing" (Davey et al., 1989) is used to conduct a random search through the elements of the lattice to find a configuration that matches the hydraulic test data. At each iteration, the configuration is used to calculate the response to an in situ test, such as an interference test. The calculated response is compared to the real response and the "energy" a term expressing the difference between the measured responses and the calculated responses, is computed. Then a lattice element is chosen. If the element is present, or "on", then it is turned "off" or visa versa. If the energy is decreased, the change in the configuration is kept. If the energy is increased by the change, the choice of whether or not to keep the new configuration is made randomly based on a probability proportional to the amount of energy increase. This allows the algorithm to "wiggle" out of local minima and find a more global solution.

Simulated Annealing results in a non-unique solution. This is considered to be an advantage because: (1) there is never enough data to truly determine a unique model and (2) Simulated Annealing obtains a series of models which can be used to make a series of predictions. Thus, the approach is stochastic.

In summary, the approach short circuits the process of inferring flow paths through detailed geometric analysis of individual fractures. The individual fracture statistics are used qualitatively in the construction of the lattice and annealing is used to find lattice configurations that make sense for hydraulic behaviour. This leads to a model that behaves like the system observed.

3.2.4.2 Two-dimensional models of Validation Drift inflow

The H-zone was the only major zone to intersect the drift. Consequently, much of the analysis can be reduce to two dimensions by only considering the flow in the H-zone. A major advantage of developing the two-dimensional models was that they are very appropriate for predicting tracer transport in the H-zone.

A two-dimensional template was designed to get as much detail as possible in the vicinity of the D-holes, to be large enough mesh to prevent the transients from reaching the boundary too soon, and to keep the number of elements and bandwidth as small as possible for efficient annealing.

Annealing to C1-2 has provided enough information to predict the SDE flow rate and one of the observed drawdowns within the estimated experimental error. The other drawdown in H-zone was too small by at least 17 m. To some extent this is not surprising because the SDE caused draw downs both in zones H and B while the C1-2 tests only affected zone H. Hence, the C1-2 results are most appropriate for the two-dimensional model.

In order to predict the effects of excavating the Validation Drift, the mesh was annealed simultaneously to both the C1-2 and the SDE (co-annealing). Once the model that predicts the SDE was defined, a skin was applied in order to predict the inflow and drawdown due to excavation.

Permeability near the drift was expected to change due to blasting, degassing, drying, stress changes etc. The physics associated with each of these is poorly understood. However, a low-permeability skin can be inferred from the head data recorded in the boreholes emanating from the Macro-permeability Drift just to the west of the SCV block (Wilson et al., 1981). According to this data, the best estimate of the average permeability in the first 5 meters should be 0.25 the average permeability elsewhere, that is $K_s/K = 0.25$. A low estimate of $K_s/K = 0.05$ and a high estimate of $K_s/K = 0.41$ can also be justified based on data from individual boreholes in the drift. The decreased permeability was applied in the elements within 5 m of the drift wall.

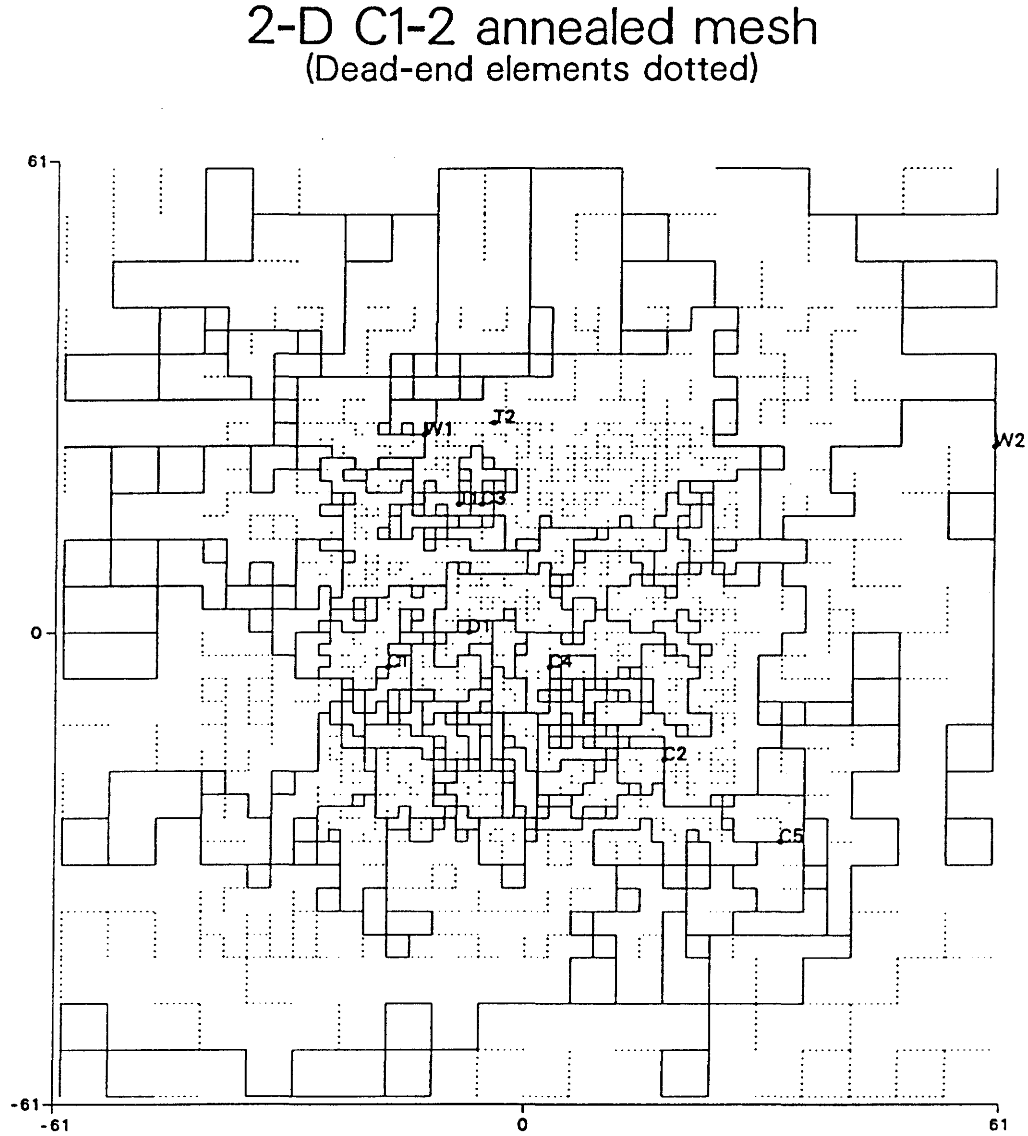


Figure 3-24. The two-dimensional model annealed to C1-2.

The best prediction (K_s/K=0.25) of flow into the Validation Drift was 0.54 l/min: about a factor of 5 too high. Even the lowest prediction (K_s/K = 0.41) was almost twice the measurement. However, it was possible to predict the drawdown at W1-5 quite well with the best estimate, and as before the estimate of drawdown at W2-4 was not very good. The best estimate of skin was K_s/K = 0.25. A model with K_s/K = 0.025 was required to make the flow equal to 0.1 l/min.

3.2.4.3 Three-dimensional models of Validation Drift inflow

The three-dimensional model, called the zone model, used the conceptual model developed by Black et al., (1991) explicitly. The zone model only included the fracture zones. This model reflects what can be learned from a combination of geophysical data and hydraulic data. The H-zone was more finely discretized than the other zones. Each zone was represented by a disc, but conductive channels are assigned to the discs only within the block. It does not show the 200 m long "fin" elements that connect nodes on the boundary of the block to the constant head hydraulic boundaries. The north side of the block was a "no flow" boundary as in the two-dimensional case.

The model annealed to Cl-2 estimates the H-zone flow into the D-boreholes during the SDE well. However, it overestimates the flow through the B-zone by about a factor of two. The drawdowns are on average about right. The annealed model was calibrated by decreasing the conductance of all the elements by 25%. This improves the model prediction of flow into the D-boreholes but does not affect the drawdowns.

Using the estimates of the ratio of skin permeability to average permeability (K_s/K) described above, the conductivity of the elements within 5 meters of the drift wall was decreased by a factor of 0.41, 0.25 and 0.05. To actually match the observed flows the permeability around the H-zone must be reduced by a factor of 67 and in the B-zone by a factor of 11. The best estimate of drift inflow was high by a factor of 5 and inflow to the B-zone is by a factor of 2.

3.2.4.4 Conclusions on flow modelling

The prediction of the SDE experiment with this technique was extremely accurate and very encouraging. However, very little can be learned about annealing from the comparison of prediction with data for the Validation Drift inflow. All the estimates are too high by a factor of between 5 and 8. The reason for this is not known but there is strong evidence for two phase flow around the drift caused by degassing of nitrogen as water reaches the atmospheric boundary of the drift. This complex flow condition is not yet well understood.

3.2.4.5 Simulation of tracer transport

Tracer simulations for transport in the H-zone were based on the two two-dimensional flow models. The first annealing to a test from the C1-hole and called "Cl-2"; the second based on simultaneous inversion of both the Cl-2 test and the SDE is called the "co-annealed" configuration. The C1-2 and the co-annealed configurations are derived in Long et al. (1992). The first Radar Saline experiment (RS1) case simulated transport from one borehole to the D-holes. A subsequent set of tests consisted of transport from points in the H-zone to the Validation Drift.

The following approach was followed to simulate the tracer tests. To begin with, the first Radar Saline 1 tracer experiment was simulated and used to find appropriate values of porosity and element dispersion coefficient. These values were then used to simulate the second Radar Saline tracer experiment. Then the series of T-borehole tracer tests were simulated with these values. In all cases, breakthrough curves were generated. For the Radar/Saline cases, snapshots of concentration in the lattice elements are given for selected times. These can be compared to the radar tomography results at similar times.

There are two mechanisms for dispersion within a fracture system. One is dispersion due to the network geometry itself. The other is dispersion and diffusion within the fractures. TRINET, an advection dispersion code for general networks of one-dimensional conductors, models both effects by treating the geometry of the network explicitly and allowing for dispersion and diffusion within the fracture elements.

3.2.4.6 Parameters needed to model transport

The models created for flow predictions do not contain all the parameters necessary to simulated these tracer transport experiments. Simulated Annealing is used to match interference tests and these can be matched with lattice elements that all have the same conductance. The pattern of elements accounts for the observed distribution of head, and the magnitude of the conductance of the elements accounts for the magnitude of the flow and drawdowns. Additional parameters must be specified in each element in order to simulate the change in concentration of an injected tracer in space and time. At a minimum, the ratio of flow to velocity (q/V) must be specified in each element, i.e. an equivalent cross-sectional area (Ae). If the transport is advection dominated, then this q/V is all that is needed. However, if there is a significant amount of dispersion within the individual fracture flow elements, then an equivalent element dispersion coefficient must be specified as well. Flow tests do not provide any information for determining these parameters.

The tracer transport calculations were made under the assumption of a steady-state flow system in spite of the fact that flow rate changes occurred during the experiments. However, a larger number of unknown parameters are needed to model transport under transient conditions. Hence, it was decided to assume steady conditions based on the best estimate of average flow.

In each case, constant head or no-flow boundaries are applied to the outer edges of the models as explained in Long et al. (1992). For the inner boundaries (the D-boreholes or later the drift) constant flow boundaries are used, and are set to the value that was measured.

3.2.4.7 Modelling the first Radar Saline tracer experiment

The first Radar Saline experiment was simulated on both the C1-2 annealed network and the co-annealed network. An injection flow rate of 0.22 l/min was applied at the C2 node. A flow rate of 0.34 l/min was applied at the D-holes. Only one breakthrough was obtained to simulate the average breakthrough for all the D-holes.

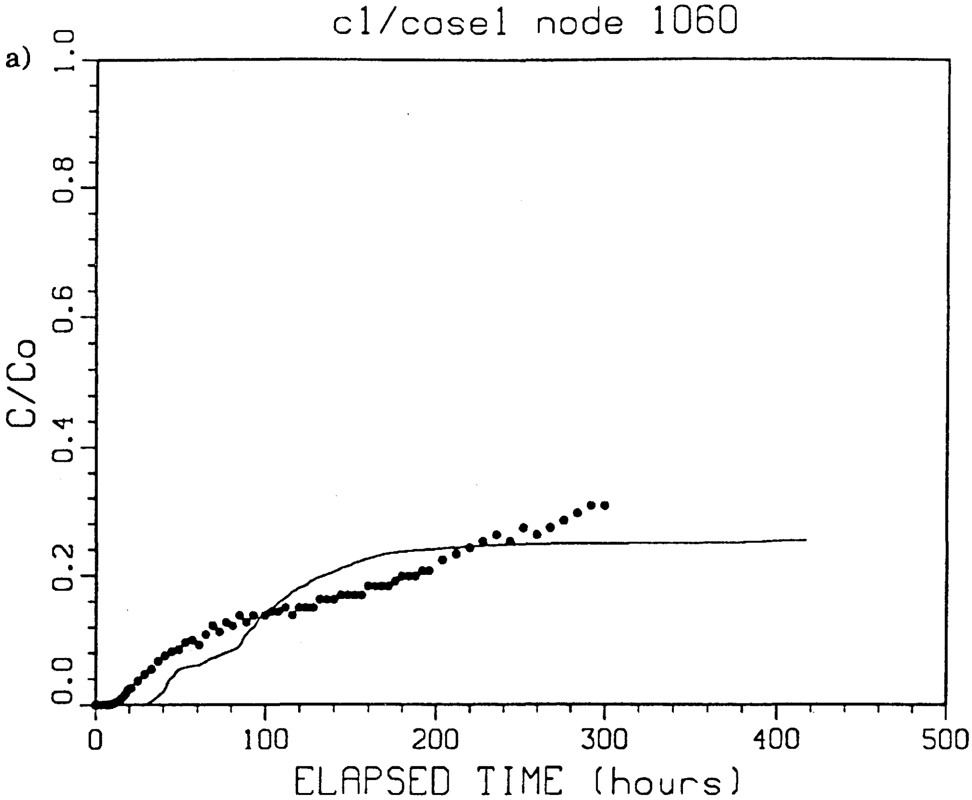
The breakthrough of saline tracer to the D-holes for the C1-2 annealed network is shown in Figure 3-25 where the value of Ae has been adjusted such that the breakthrough curve gives the best fit (by eye) to the data and dispersivity is zero. The curve shows that C/C_0 levels are below the values observed. The reason for this can be seen in the figure which also shows a snapshot of tracer concentration in the configuration at approximately 277 h. C/C_0 is too low because there are too many pathways; too much advective dispersion and too much flow to Z shaft.

For the co-annealed network the value of Ae was adjusted such that the breakthrough curve gave a good estimate of the first arrival. The C/C_0 levels obtained were far above the values observed due to the sparse network. There were too few pathways to get the experimentally observed dilution (Figure 3-25).

To some extent it is encouraging that these two simulations bracket the actual behaviour because it may indicate that a sufficient number of configurations could provide a good estimate of tracer behaviour.

The effects of adding non-zero dispersivity to the simulations was not in agreement with radar results and all the predictions were made considering the dispersion to be due to the network geometry alone.

a)



b)

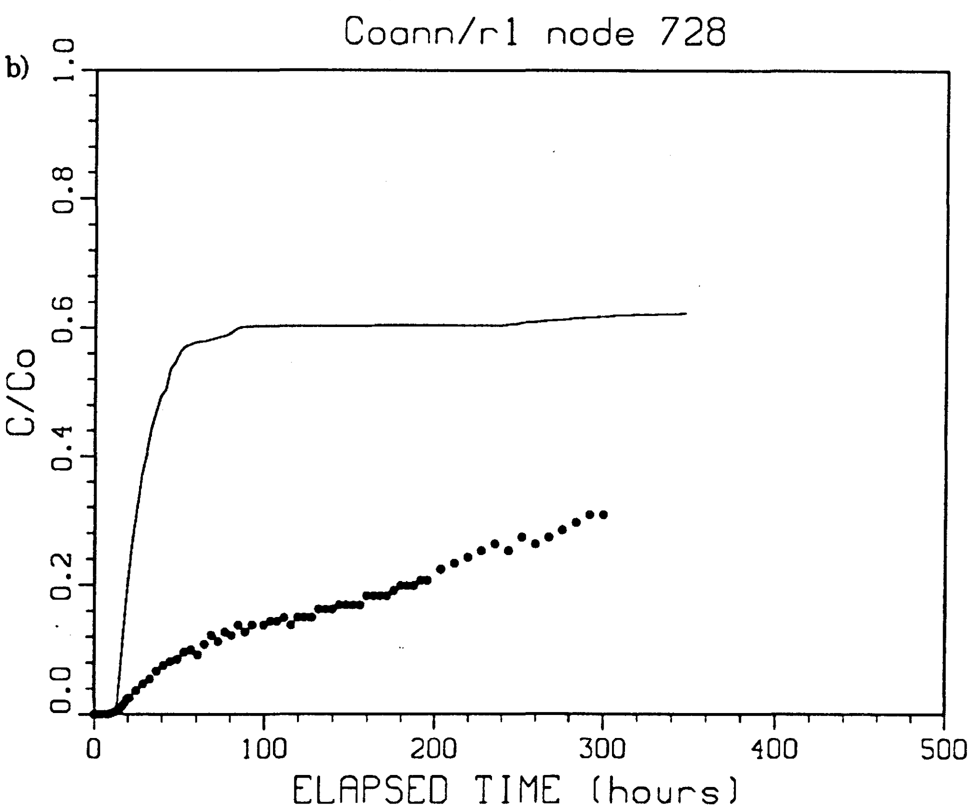


Figure 3-25. Simulated tracer breakthrough at the D-holes for Radar Saline experiment 1 plotted against the data using a) the C1-2 annealed configuration, and b) the co-annealed configuration.

3.2.4.8 Modelling the second Radar Saline tracer experiment

The second Radar Saline experiment was simulated on both the C1-2 annealed network and the co-annealed network. An injection flow rate of 0.2 l/min was applied at the C2 node. A flow rate of 0.13 l/min was applied at the Validation Drift. Thus the drift was a much weaker sink than the D-boreholes were in the first Radar Saline test. Only one breakthrough was obtained to simulate the average breakthrough for all parts of the drift. The breakthrough of saline tracer to the Validation Drift based on the C1-2 annealed network is shown in Figure 3-26 where the value of Ae is the same as in Figure 3-25.

This simulation does a good job of matching the first arrival, but the curve shows that C/C_0 now levels out well above the values observed. In the first Radar Saline experiment the reverse was true: the predicted C/C_0 was lower than the final observed value. This change in the relative positions of the data and the simulated values between the first and second Radar/Saline tests is surprising. Contrary to the model results, the data indicates that there is not much change in C/C_0.

The co-annealed network predicted a first arrival time that was in reasonable agreement with the measured first arrival time. C/C_0 again levels out far above the values for the simulation of the first Radar Saline experiment using the C1-2 configuration. The simulations show the proportion of tracer to water increasing as the total flow to the drift decreases. The data shows that this proportion is relatively unaffected by the change in conditions induced by the drift. Apparently the modelled results for C/C_0 are controlled by boundary conditions that may be somewhat unrealistic.

3.2.4.9 Predictions of tracer transport from the T-boreholes

Four tracer test predictions were made. Cases 1 to 3 simulate tracer transport from various sources to the drift, and Case 4 simulates transport from T2 when T1 is open to atmospheric pressure. Each of these predictions were simulated twice: once with the C1-2 configuration and once with the co-annealed configuration as described above. No dispersion coefficient was used.

There was very little difference between the estimates for the C1-2 and the co-annealed configurations for Case 4 probably because our models do not have very much resolution on the scale of the distance between these two boreholes. Thus, this estimate is probably more dependent on the level of discretization than the others.

Figure 3-27 shows an example breakthrough curve generated with the co-annealed configuration compared with the actual data. This predicted curve for the breakthrough from T2-1 is much steeper than that observed. The reason for this is the flow pattern generated by the hydraulic conditions of the tracer tests was confined to a few channels within the configurations. Flow from the injection points to the drift was consequently equivalent to plug flow. In contrast, the flow conditions imposed by the stronger source of the Radar Saline experiment 2 conditions incorporated more channels and the breakthroughs were not as steep.

The models do reasonably well in predicting the breakthrough times. The exception is breakthrough to the drift from the T2-T1 test. However, in this case, the flow to T1 was significantly over-estimated and this made the sink at T1 overwhelm the sink at the drift. In general, C/C_{0max} is under-estimated. The reason for this is that much of the tracer in the models does not reach the drift whereas nearly all the tracer was recovered in reality. Poor knowledge of boundary conditions is probably the cause of this problem.

In conclusion, it seems as if these hydraulically based models do reasonably well in predicting arrival times. However, more physical effects, such as more channel conductance variability, may be needed to capture more of the transport behaviour.

a)
b)

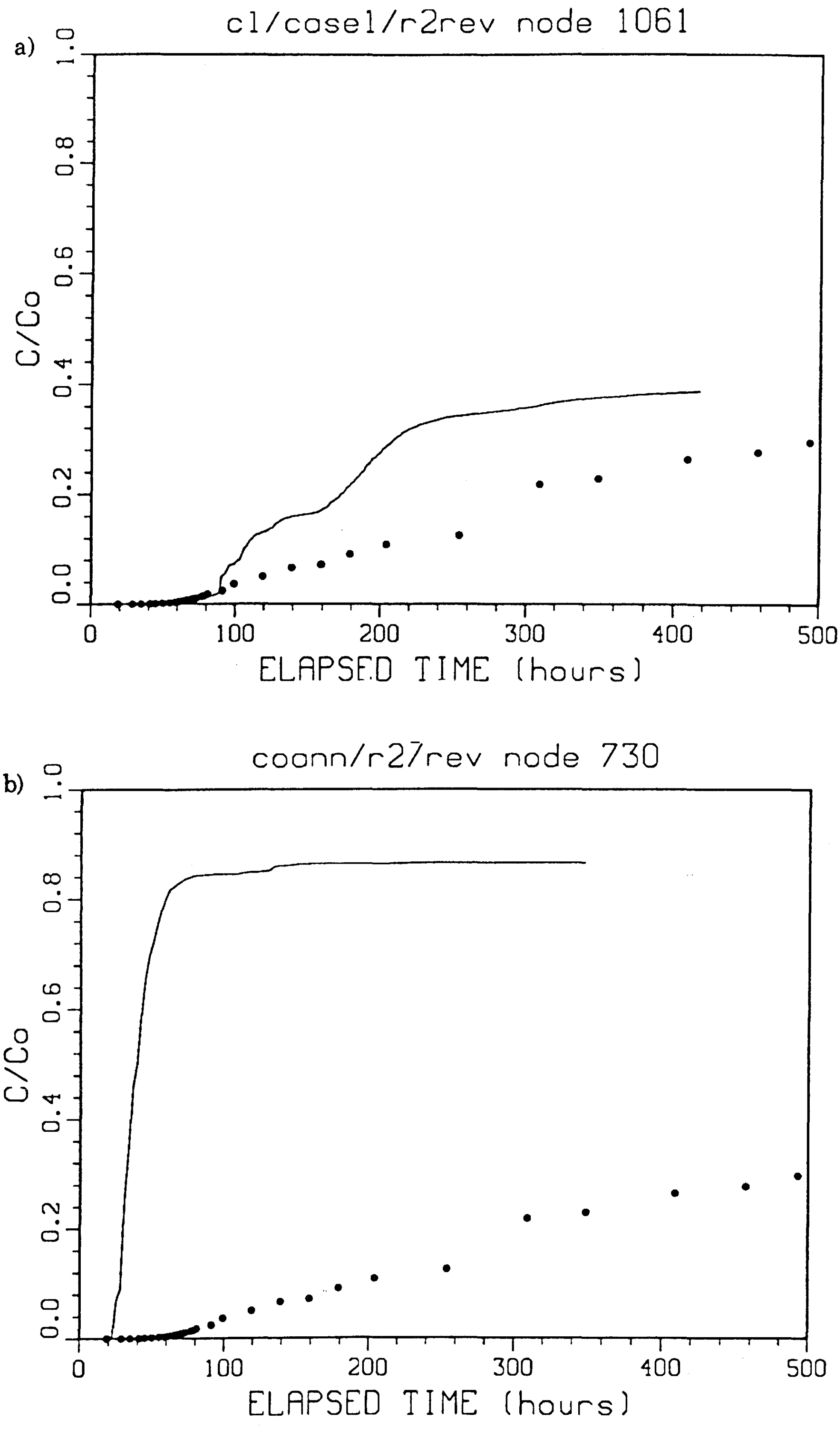


Figure 3-26. Simulated tracer breakthrough at the Validation Drift for Radar Saline experiment 2 plotted against the data using a) the C1-2 annealed configuration, and b) the co-annealed configuration.

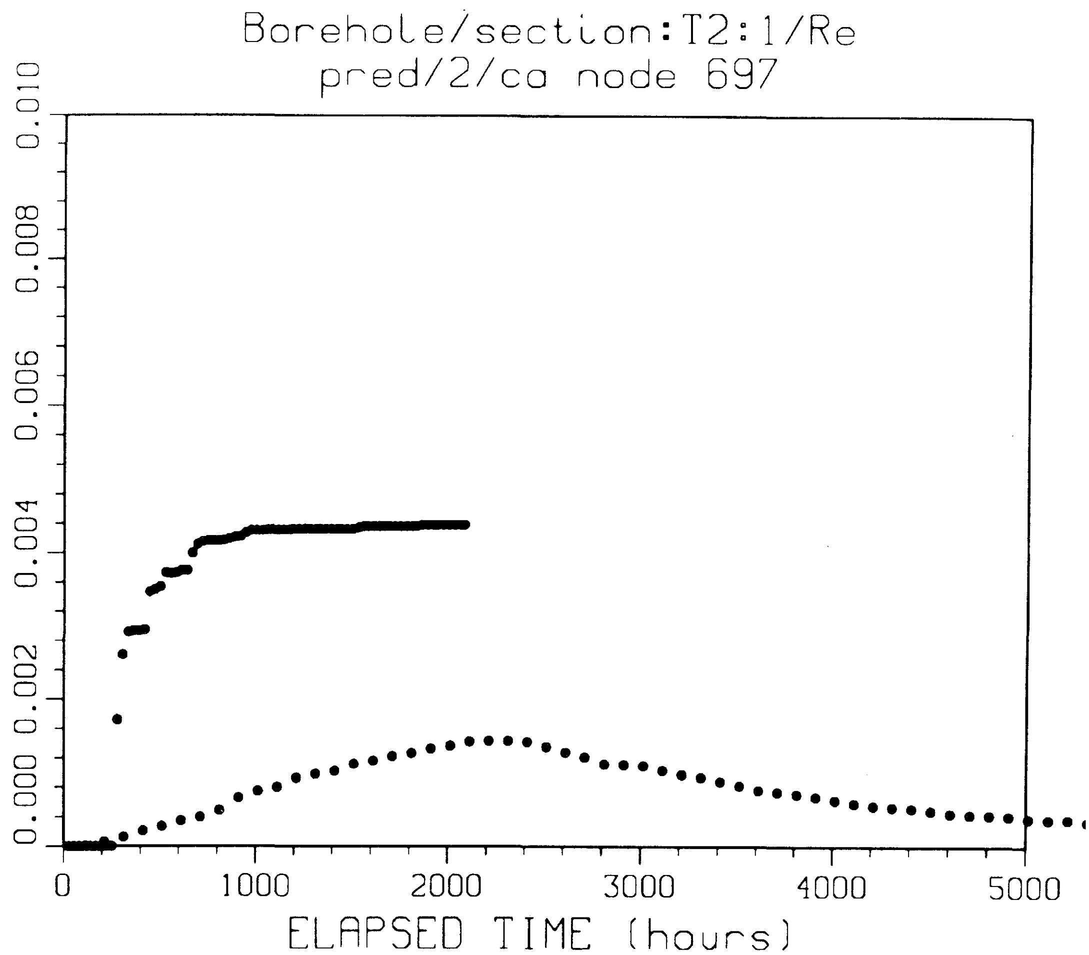


Figure 3-27. Predicted breakthrough into the Validation Drift from T2 for the co-annealed configuration.

Knowledge of boundary conditions is critical to predicting tracer transport, whereas flow models are much less sensitive.

3.2.5 Golder Associates modelling

3.2.5.1 Modelling objectives

The purpose of discrete fracture modelling carried out by Golder Associates Inc. (GAI) during 1991 was to demonstrate the validity of discrete fracture approaches for transport modelling through the Saline Radar 2 and Tracer Validation experiment procedures. Major activities carried out were as follows: data analysis for the development of an updated hydrogeologic discrete fracture conceptual model; flow and transport modelling for the Radar Saline experiment 2 prediction; flow and transport modelling for the Tracer transport experiment predictions.

Data analysis was carried out on the data collected within the Validation Drift as part of the drift inflow prediction, and updated discrete fracture conceptual models were developed.

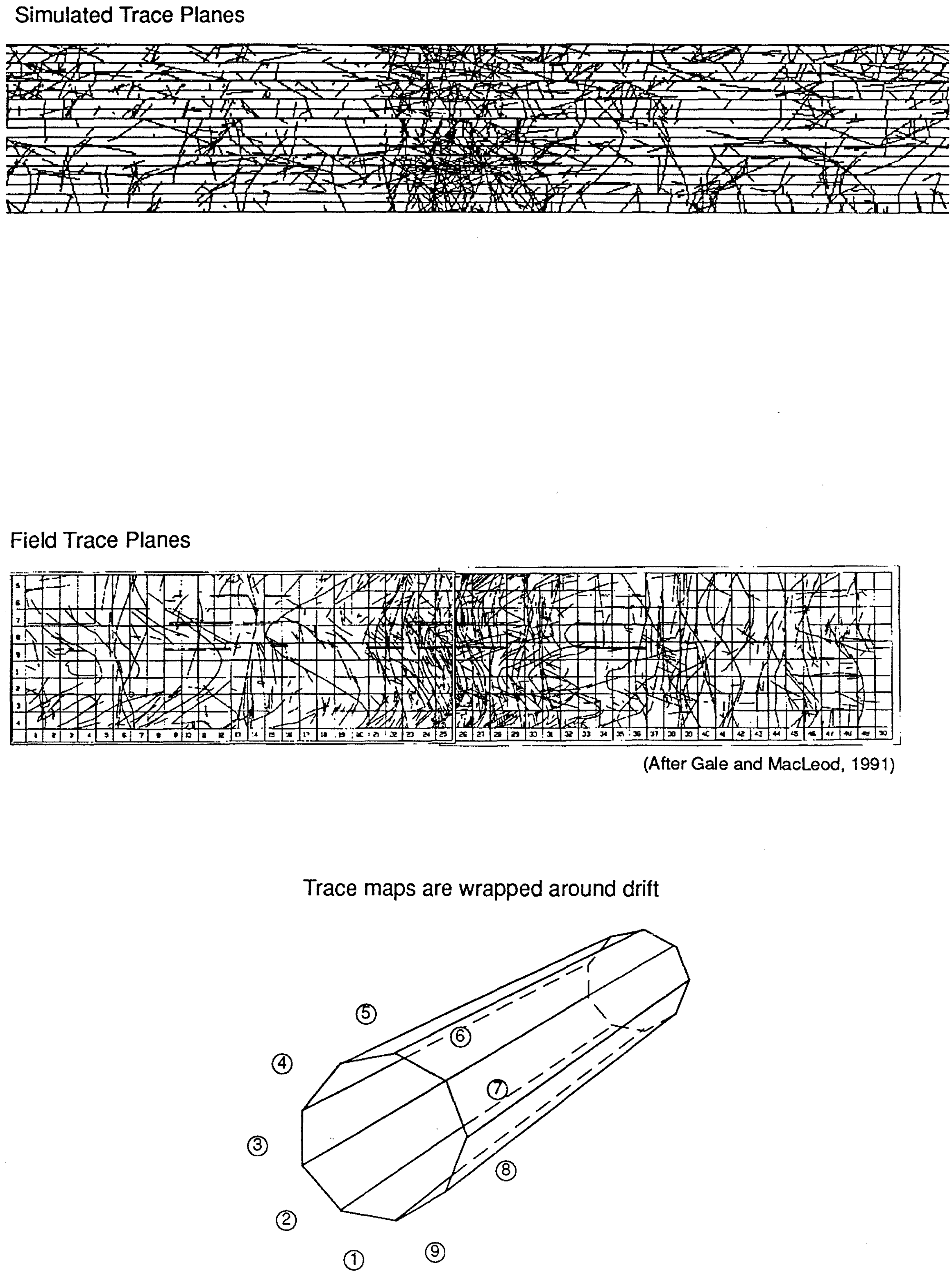


Figure 3-28. Simulated fracture trace map using the increased fracture termination percentage.

3.2.5.2 Data analysis

Data analysis was carried out on the data collected within the Validation Drift as part of the drift inflow prediction, to develop an updated discrete fracture conceptual model. All analyses were carried out within the FracSys data analysis portion of the FracMan model. Particular emphasis was placed upon development of a refined model for the spatial distribution of fractures.

Fracture size and orientation were derived for updated geological conceptual models using the FracSize simulations of the processes of field data collection. This provided a better model for the difference in fracture characteristics within and outside of fracture zones than was available previous to drift excavation. A conditioned fracture simulator, FracBase was developed to allow simulation of three dimensional discrete fracture patterns, conditioned to match the observed fracture traces in the drift. Unfortunately there was not sufficient time to allow the use of this feature in transport simulations.

The major result of data analysis during 1991 was revision of the percentage of fractures terminating at intersections from 30% to 60%. This produced a more well-connected discrete fracture model (Figure 3-28).

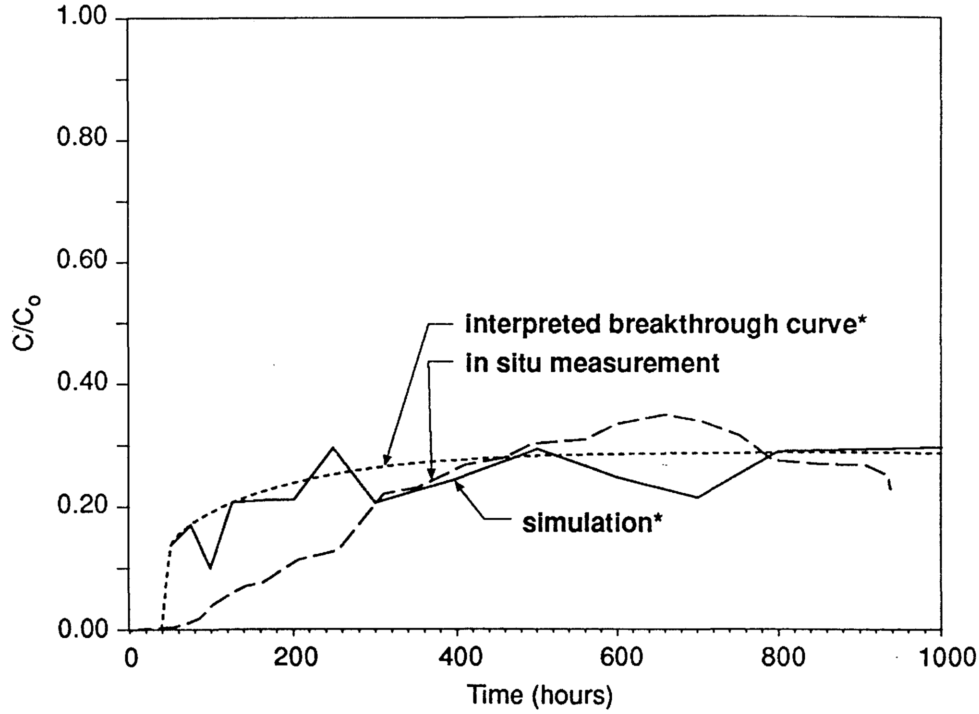
3.2.5.3 Radar Saline experiment 2 simulations

Following the completion of the Validation Drift inflow prediction, the Validation Drift geologic conceptual model was used to predict breakthrough to the drift from the Radar Saline 2 experiment. These simulations were run using the same meshes generated for the Validation Drift inflow prediction, using transport properties of transport aperture and lateral/transverse dispersivity found by calibration against the Radar Saline 1 experiment. Validation Drift meshes used in these predictions were conditioned by selecting those meshes which matched observed fluxes well. No attempt was made to improve the representation of fracture geometry or boundary conditions used in the Validation Drift model.

Figure 3-29 shows the total breakthrough to the Validation Drift from one realization of the Validation Drift conceptual model, using transport aperture equal to 0.25 of the cubic law apertures, and lateral and transverse dispersivities of 0.3 m and 0.1 m. The breakthrough curve matches the in situ measurement quite well. Figure 3-30 shows the normalized "steady state" breakthrough to the drift panels from the same realization. Approximately twice as many panels collect tracer in situ as predicted by this simulation, but the distributions of concentrations are similar. Figure 3-31 compares simulated and measured tomograms for saline location in the W1-C5 tomographic plane. The predictions are summarized in Table 3-4.

Table 3-4. Summary of the prediction of Radar Saline experiment 2.

Measure		Drift recovery	Drift sheets	T1 recovery	T2 recovery
C_{ss}/C_0	predicted	0.3–0.4	0.01–1.00	0–0.3	0–0.03
	measured	0.38	0.13–0.84	0.07, 0.05	0.01
t_5 (hrs)	predicted	30–150	20–550	100–1000	100–1000
	measured	70	50–500	200, 300	450
t_{50}(hrs)	predicted	100–150	200–500	>1000	>1000
	measured	280	96–800	>300, >500	>1000



*Simulation results are coarse due to the limited number of particles used.

Figure 3-29. Total breakthrough to the drift predicted for Radar Saline experiment 2.

3.2.5.4 Tracer Experiment simulations

The geohydrologic conceptual model developed for prediction of the results of tracer experiments was based upon the Validation Drift conceptual model. The diameter of the detailed model region was increased from 40 to 62 meters to encompass the C-1 injection location. In order to avoid increasing the number of fractures simulated beyond the capabilities of our computer, the length of the detailed model region was decreased from 140 to 60 m, eliminating the region surrounding the D-boreholes (Figure 3-32). This was deemed acceptable based upon the lack of recovery of saline tracer in the D-boreholes during the Radar Saline 2 experiment.

Fracture geometric statistics within the detailed model region were replaced by values derived from data collected within the Validation Drift (Bursey et al., 1991). Boundary conditions, fracture zone and mine geometry, and fracture properties in the coarse model region were not changed from the values used in the Validation Drift model.

Fracture transport properties were derived by calibration of the model against breakthrough curves from the Radar Saline experiment 2.

Solute transport simulations were carried out for five injection experiment configurations. Of the 50 meshes generated, 4-8 realizations were selected for use in developing tracer predictions. These realizations were selected by comparing model and measured drift flux and Saline 2 experiment breakthroughs.

Predictions were produced for each of the five "performance measures" specified by the Fracture Flow Task Force, for each of the injection experiments. The results of these predictions are summarized in Figures 3-33 and 3-34. Figure 3-33 shows examples of t_5, the 5% breakthrough time predicted for panels on the drift from the injection interval C2-1. Figure 3-34 shows a summary of total breakthrough curves for recovery to the drift.

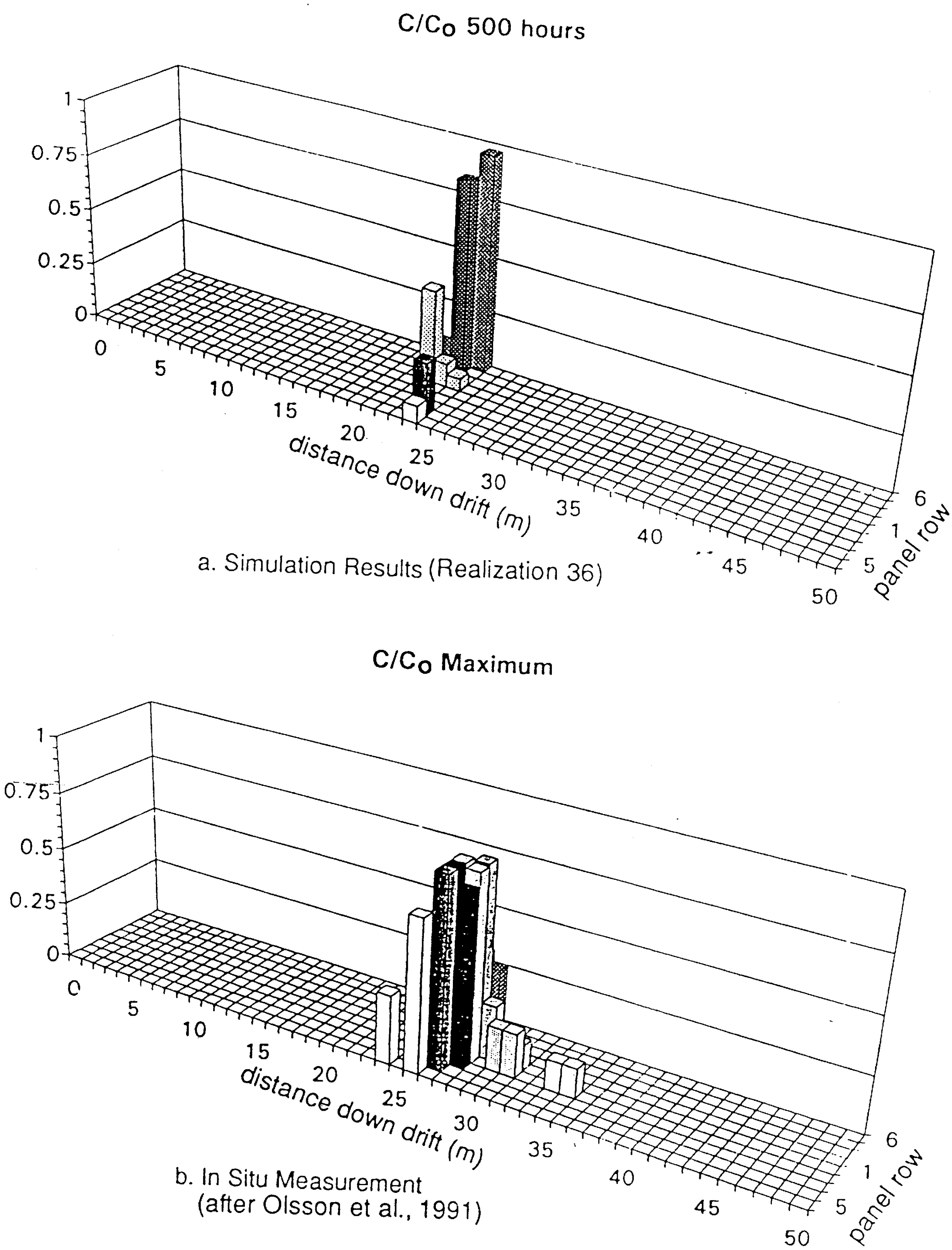
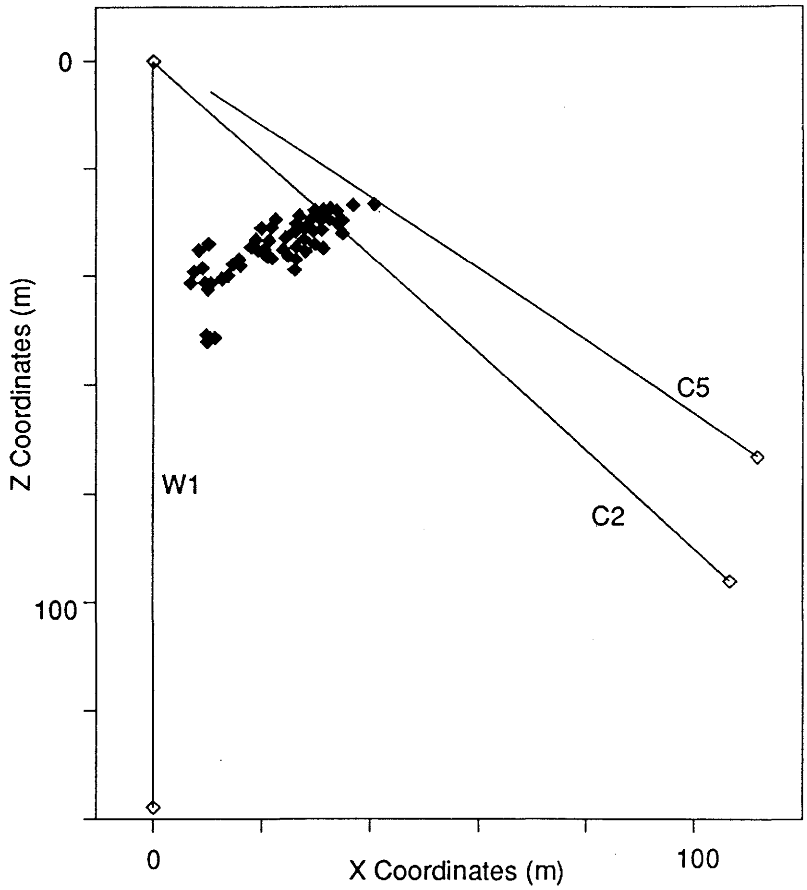
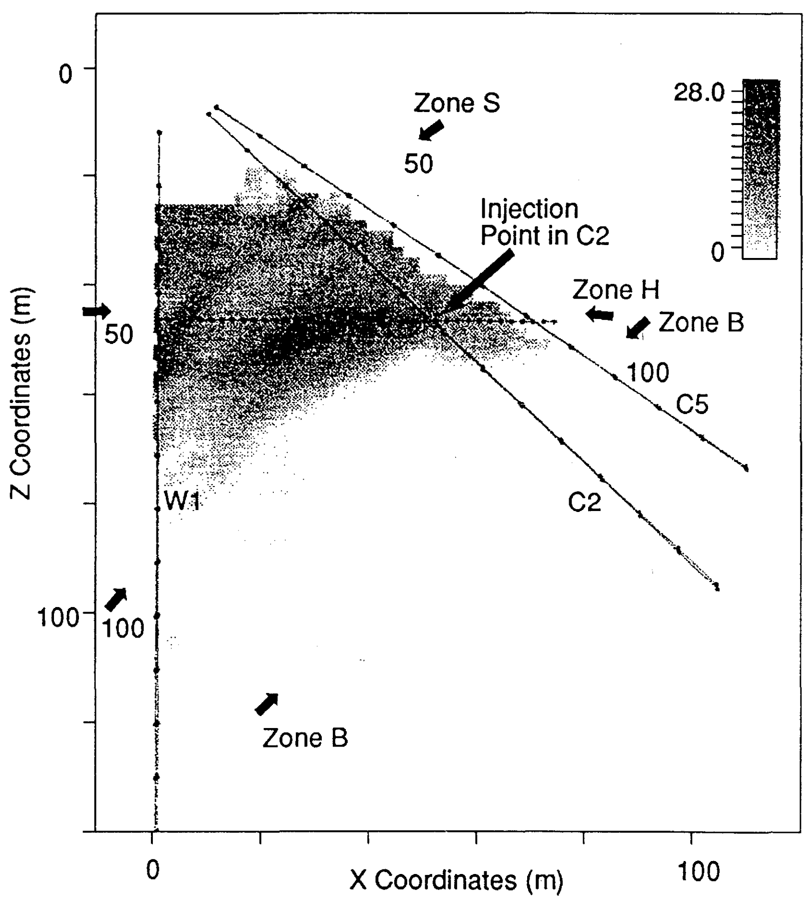


Figure 3-30. Predicted C/Co in individual sheets at 500 hours in Radar Saline experiment 2.

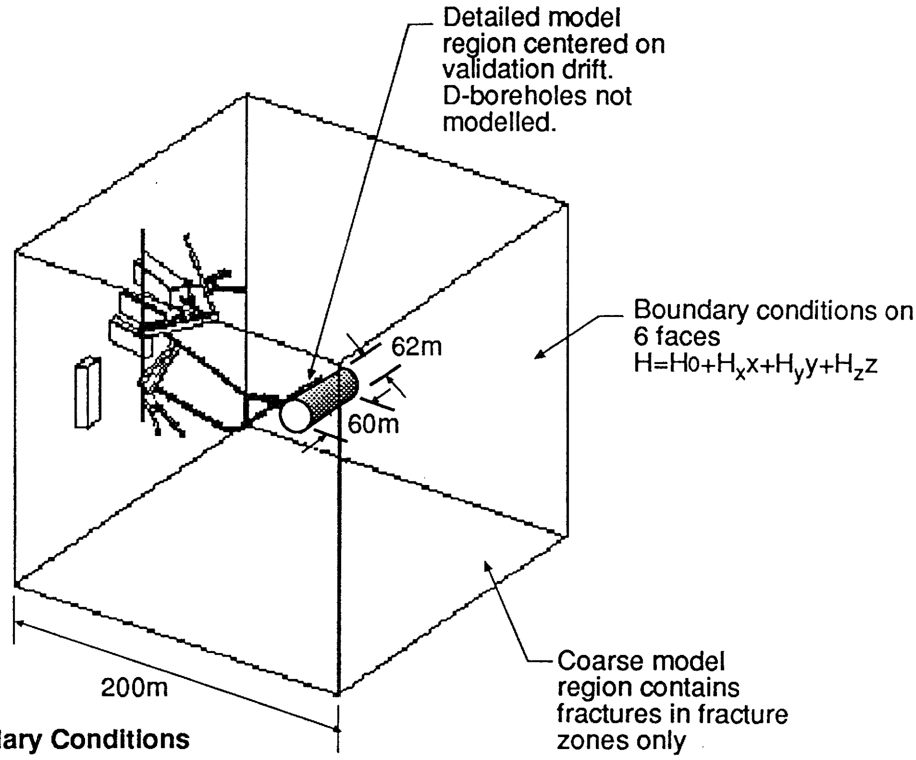


a. Simulation - One Realization

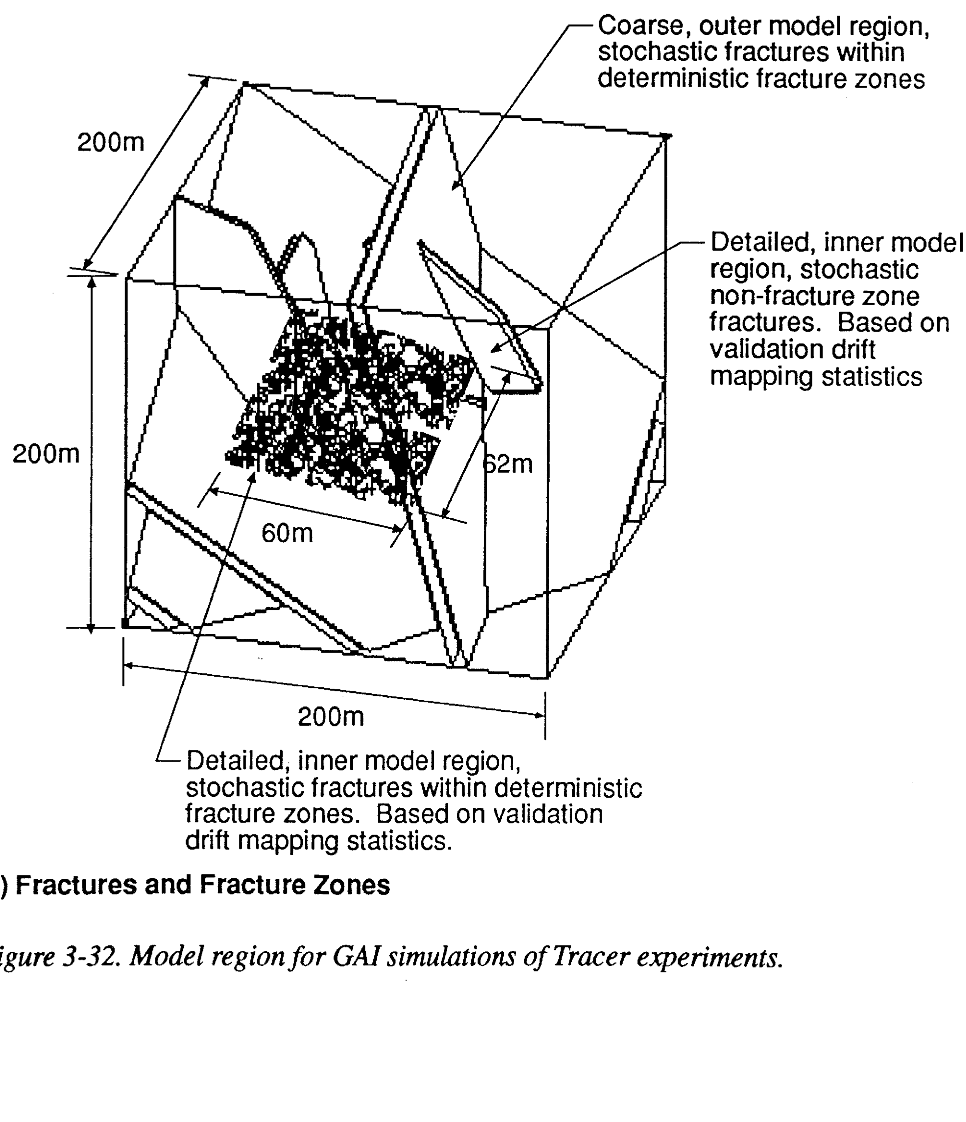


b. Radar Tomogram (Olsson et al., 1991)

Figure 3-31. Simulated and measured tomograms in the plane of W1 and C5 boreholes during Radar Saline experiment 2.

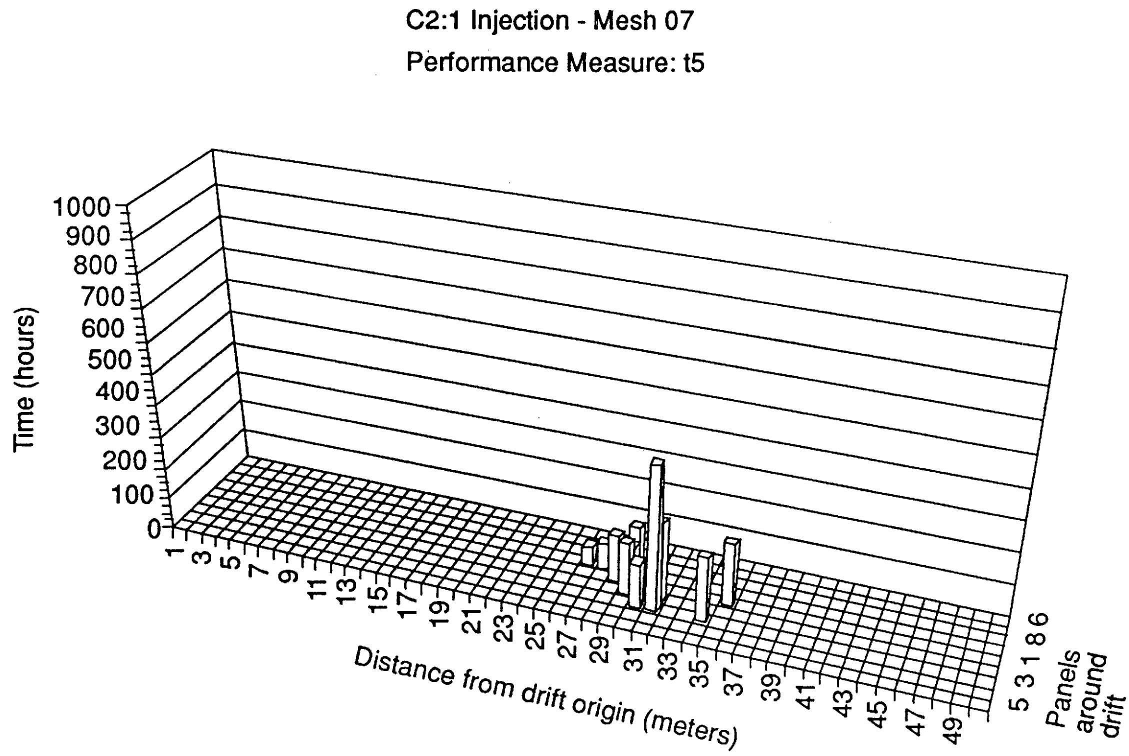


a) Boundary Conditions



b) Fractures and Fracture Zones

Figure 3-32. Model region for GAI simulations of Tracer experiments.



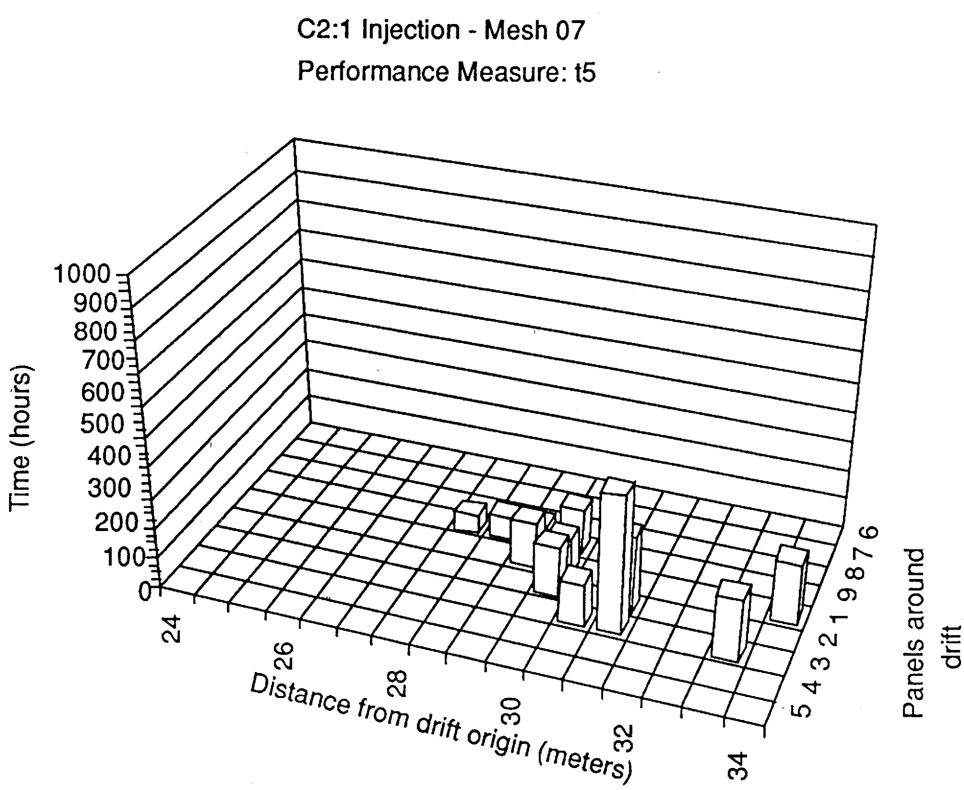


Figure 3-33 . Prediction of the 5% breakthrough times to individual sheets for the tracer injection in borehole interval C2-1.

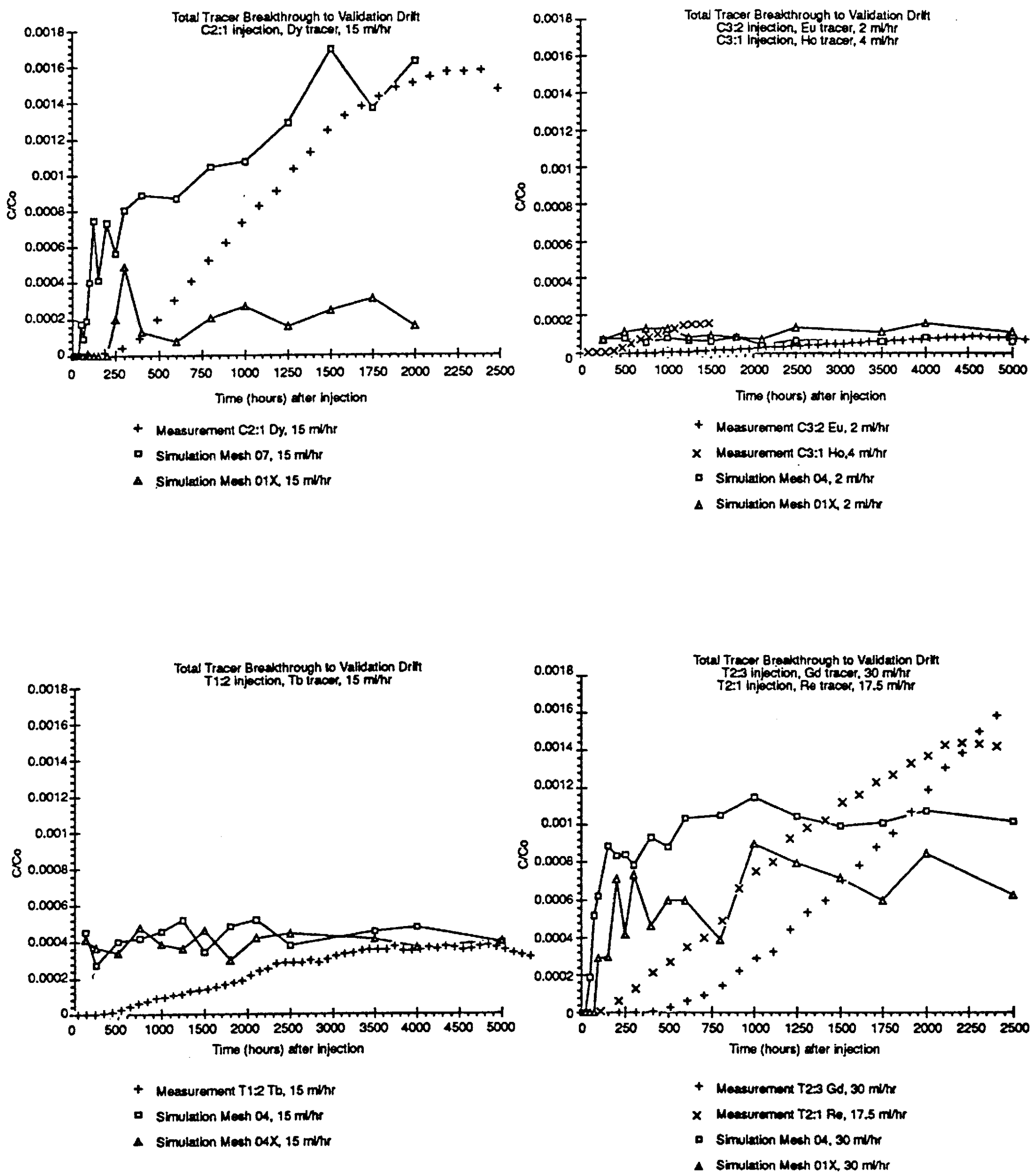


Figure 3-34. Predicted breakthrough curves for tracer experiments.

Following the Fracture Flow Task Force meeting in December 1991, calibration runs were carried out to determine what changes would be required in the transport parameters used to match to results of the tracer experiments. These simulations indicate that, using the same hydrogeologic discrete fracture conceptual model, an increase in transport apertures by a factor of 4 and an increase in longitudinal and transverse dispersivity by a factor of 10 will match observed drift breakthrough curves.

Refined simulations were carried out using superposition of slug tests rather than pulse tests. This produced a much smoother breakthrough curve (Figure 3-35), providing a more presentable result, with approximately the same statistical characteristics and computational requirements.

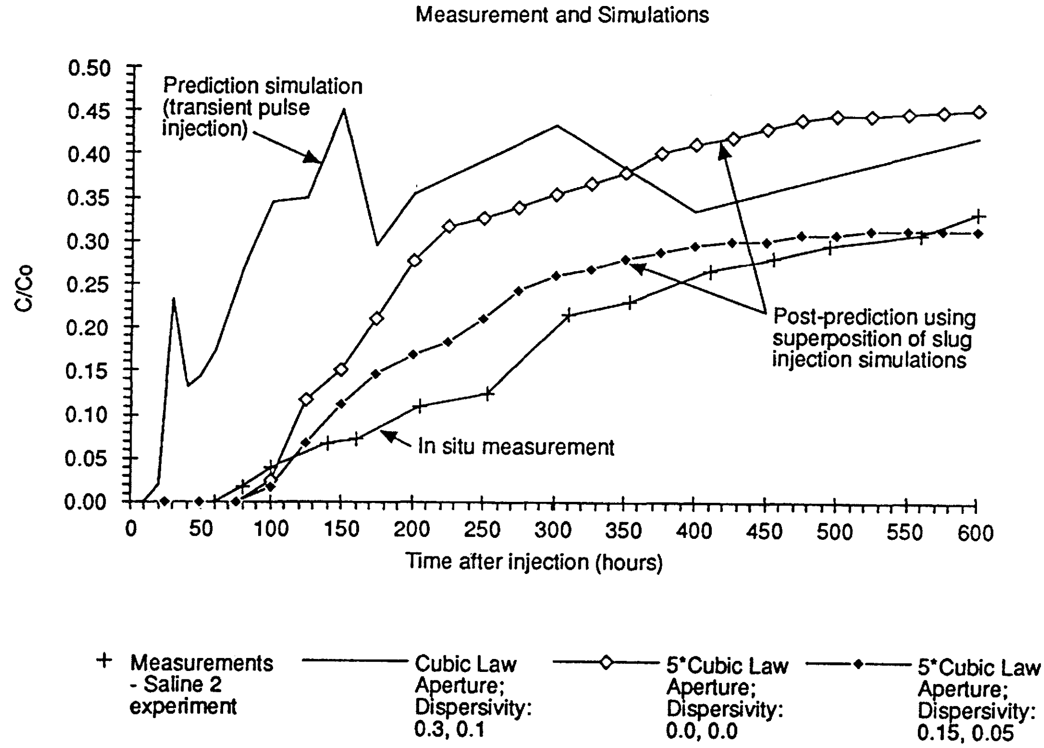


Figure 3-35. Recalibration of Radar Saline experiment 2, fitting modified transport aperture and dispersivity.

3.2.6 References

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3.3 ROCK SEALING TEST

3.3.1 General

The study aimed at investigating whether relatively fine-fractured rock can be sealed by use of clay or cement grouts and what the longevity will be in repositories for highly radioactive waste, where heat is produced.

Three large-scale experiments and comprehensive laboratory work and flow modelling were conducted in the 5 year Stripa Rock Sealing project. "Dynamic" injection was applied for sealing fine-fractured rock using clay or cement.

3.3.2 Major activities in 1991

The investigation of the extension and properties of disturbed zones around blasted tunnels and of the possibility to seal them by "hedgehog" grouting (Test 2), was completed in 1991, and so was Test 4, which was an investigation of whether a fine-fractured, natural water-bearing discontinuity can be sealed by cement grouting.

The comprehensive study of the longevity of clay and cement grouts has been completed.

3.3.3 Tests 2 and 3, "Disturbed zones"

3.3.3.1 Test arrangement

Preceding experiments in the drift where the large-hole grouting took place, had given strong indications of a significantly increased axial hydraulic conductivity of the rock close to the periphery. This was further investigated in a large-scale test where the 12 m long inner part of the drift was exposed to a hydraulic gradient by pressurizing an inner gallery of radially drilled and closely spaced boreholes, and collecting water in a corresponding gallery at the outer end as indicated in Figure 3-36. The holes formed a continuous slot to 0.7 m distance from the periphery in each of the galleries. The hydraulic conductivity was evaluated from tests at various pressure levels in the inner gallery with the drift completely filled bentonite slurry that prevented water from flowing into and through the drift. The measurements were repeated after shallow grouting of the entire section.

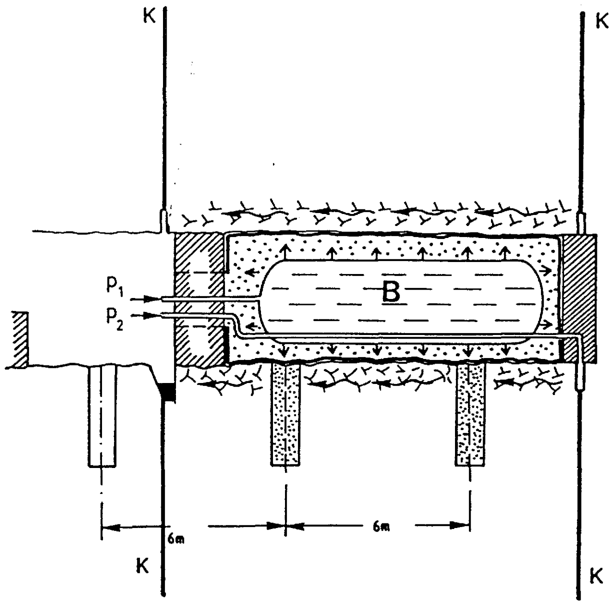


Figure 3-36. Field determination of nearfield conductivity. B is water-filled bladder surrounded by bentonite slurry. Inner (right) K-hole curtain pressurized for flow testing.

3.3.3.2 Hydraulic conductivity

The evaluation of the comprehensive flow data showed that the outer half of the drift was located in rock with an initial conductivity of 3×10^{-11} m/s while the corresponding conductivity was 10^{-10} m/s of the rock in which the inner half was located, the higher value being due to the presence of more conductive, intersecting zones. The average hydraulic conductivity of the rock to 0.7 m distance from the periphery was found to be 1.2×10^{-8} m/s, while that of the surrounding stress-influenced 0.7–3 m zone was 10 times higher in the axial direction and 5 times lower in the radial direction than the respective conductivity of the two virgin rock masses. Variation of the effective pressure on the rock from 0.1 to 1 MPa by changing the slurry pressure did not affect the hydraulic conductivity of the rock.

The flow and piezometric patterns at all stages of slot-drilling and testing could be accurately described by FEM modelling, modelling both the virgin rock and the disturbed zones as porous media.

Comprehensive 2D-modelling using UDEC and some 3DEC studies were performed for estimating the effect of stress release on the conductivity of the nearfield rock.

3.3.3.3 Grouting and evaluation of sealing effects

Cement grouting of 0.8 – 1.1 m long percussion-drilled holes with a spacing of 0.7 – 0.9 m by both static and dynamic techniques was made using Alofix cement with w/c 0.45 and 1.4% SP for the dynamic injections, and w/c 0.5 – 0.7 and 1.5 – 3.0% SP for the static ones. The total number of holes was 345, 80 of them being packer-tested with respect to the conductivity before the grouting operations. These measurements gave conductivity values between 10^{-10} and 10^{-8} m/s, i.e. somewhat lower than that of the macroscopic tests, which is explained by the small chance of hitting fracture channels and by the fact that the inner end of the packers was 15 to 20 cm down in the holes, leaving the most conductive shallow rock untested.

The sealing effect was determined by repeating the macroscopic flow tests and it could be shown that the obtained flow data agreed very well with the FEM-derived average conductivities of the disturbed rock zones before the grouting operations with a reduction by no more than 50%. The reason for the insignificant sealing effect is concluded to be

1) hindrance of grout to enter fracture channels by blocking of chlorite debris produced in conjunction with the blasting operation;
2) too deep packer positions;
3) displacement of shallow blocks;
4) too small fracture apertures; and
5) small chance of hitting channels.

3.3.4 Test 4, "Natural fracture zone"

Comprehensive drilling and flow measurements were made for characterizing a natural fracture zone at 360 m depth, which did not intersect the test drift but was located very close to it as shown in Figure 3-37. A small part of it was grouted from the drift as illustrated by the right figure, in which the location is shown of 10 core-drilled holes used for characterizating the zone and for cement grouting. The primary horizontal rock stress perpendicular to the drift is estimated at around 20 MPa and the vertical at around 9 MPa. The evaluation of the hydraulic properties led to the assumption that the effectively water-bearing part of the zone could be defined as 2 interconnected, parallel fractures with 1 cm wide channels with an aperture of 100 μm and a spacing of 0.2 m. The hydraulic conductivity would be isotropic and about 10^{-8} m/s. Japanese Alofix cement with w/c 0.45 and 1.4% superplasticizer was used for the grouting, which was made with two packer positions except for two holes, the static pressure being 1 MPa, a frequency of 40 Hz, and injection times of 30-45 s.

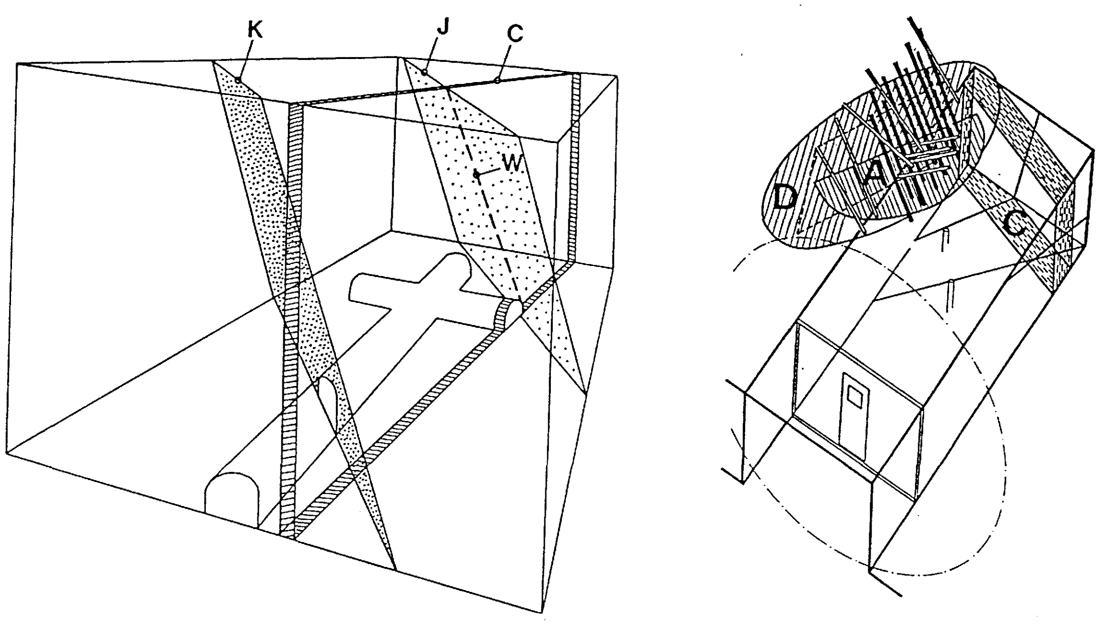
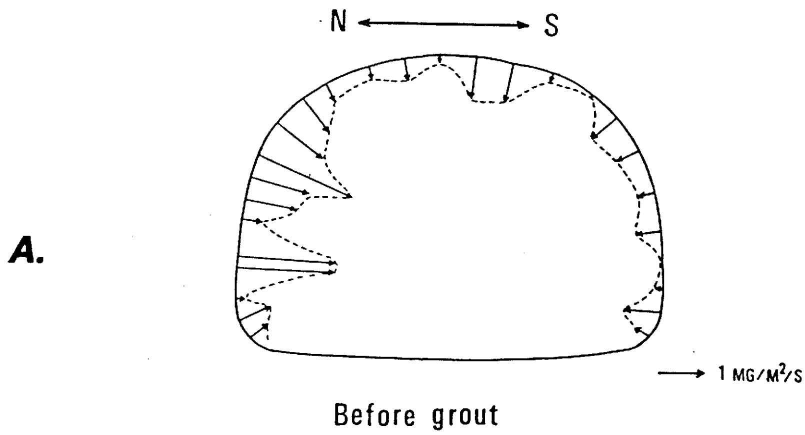


Figure 3-37. Left: The natural fracture zone "J" ("D"), a member of a set of steep zones with 75 m spacing. Right: Close-up of the structure with grouting holes.



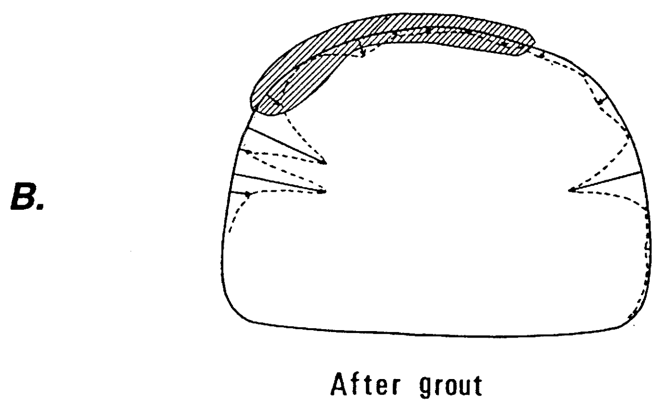


Figure 3-38. Evaporation tests, hatched areas mark good sealing.

The rock mechanical FLAC code was used for predicting piezometric pressure changes and water flow into the test drift, generalizing the drift with the closely located zone to be 2-dimensional. The outcome of the calculations was that the total inflow into the drift would drop by 5–10% by reducing the average hydraulic conductivity of the zone from 10^{-8} m/s before grouting, to 10^{-9} m/s after grouting. Also, the piezometric head should be increased by around 50-100 kPa at the upper end of the grouted zone, and decreased by about 200 kPa in the center of the grouted zone.

The measurements showed that these effects actually occurred, i.e. that the total inflow was reduced by about 5% and that the expected pressure changes took place.

A good, visual impression and quantitative measure of the sealing effect was offered by evaporation measurements before and after grouting. Figure 3-38 shows the changed inflow over the two scanned profiles A and B in the drift.

The various measurements indicated that the average hydraulic conductivity of the grouted part of the zone had dropped from about 10^{-8} to around 10^{-9} m/s. For identifying the nature of the injected cement, core-drilling was made in the grouted zone and careful inspection showed that cement had entered fractures with an aperture of down to 10-20 μm to 2-3 dm distance from the injection hole. The relatively moderate sealing effect was due to the fact that the cement could not reach deeper into fine fractures and that the spacing 0.7 m of the injection holes was not sufficient to hit the majority of the channels forming the groutable parts of the fractures. It was concluded that cement had moved at least 1.5 m in one or a few channels with an estimated average aperture of around 100 μm.

3.3.5 General conclusions concerning groutability

All injection tests comprised prediction of grout penetration by applying the grout flow model, and both the systematic slot injection tests and the field tests showed that the penetration depth, which should be a few decimeters for fracture apertures of 20 μm and a couple of meters for apertures of 50-100 μm for montmorillonite clay with a water content of 1.3–1.6 times the liquid limit, or cement with w/c 0.47 and 1.4% superplasticizer, agreed reasonably well with recorded data.

A comprehensive study of the nature of injected cement led to the conclusion that channels can be modelled to have a more or less rhomboidal cross section of which the parts with smaller aperture than 10-30 μm can not be filled with grout. At less than 50 μm maximum aperture the cement appears to be heterogeneous. An important conclusion from this study and the evaluation of the large-hole testing is that the unfilled parts of the channels control the net hydraulic conductivity of grouted rock and makes it difficult to reduce it to less than about 10^{-10} m/s.

Very shallow rock, like the blasting-disturbed zones around a drift, cannot be effectively sealed because of the fracture debris, the shallow packer positions and the easy displacement of rock blocks. The latter was investigated by applying the FLAC code for studying possible expansion of fractures by high grout pressures, and this study showed that even very high injection pressures have an insignificant effect on channels apertures in rock as well confined as the "J"-zone in Test 4. However, shallow blocks supported by lower confining pressures and with grout expelled to 75 cm distance into the fracture should yield considerably more expansion.

3.3.6 Longevity of grouts

Cement with a low content of portlandite or with silica fume additive has a very significant operative lifetime as tentatively indicated by comprehensive laboratory work by AECL, Canada, and theoretical investigations by RE/SPEC, USA.

Na and Ca bentonite grouts with densities that make them easily injected into fine fractures have the advantage of being flexible enough to sustain significant rock strain but are sensitive to high hydraulic gradients which can produce piping and erosion. Exposure of such grouts to salt groundwater increases the conductivity of the grout from very low values to around 10^{-5} m/s, which is on the same order of magnitude as the value at complete conversion from montmorillonite to hydrous mica, i.e. the ultimate reaction product. Still, even this "worst scenario" case, which will take several hundreds or thousands of years to develop, will not lead to a higher bulk conductivity than around 10^{-10} m/s of rock with a conductivity of 10^{-8} m/s before qrouting.

Laboratory studies

Laboratory studies into longevity of performance of cement based grouts indicated that a large number of processes and mechanisms are involved in the interaction between cement-based grouts and aqueous solutions. They include matrix dissolution, saturation, diffusion across a protective layer, alteration and precipitation. The controlling mechanism depends on many factors, including the composition of the grout, chemical composition of the leachant and the contact time between the grout and water. The results indicate that grouts will leach through dissolution of its more soluble phases (i.e., $Ca(OH)_2$ unreacted silica fume). The leaching processes were found to decrease with time and to be accompanied by precipitation and grout of an assemblage of secondary alteration phases (i.e., $CaCO_3$, $Mg(OH)_2$).

The investigations on the permeability of the developed reference high performance grout have shown that the grout is practically impermeable under hydraulic gradients (i <3 6000) higher than those expected in a disposal vault where i may be as low as 10^{-2}. The reference grout containing silica fume and superplasticizer have very low hydraulic conductivity (i.e., $<10^{-14}$ m/s).

Laboratory studies have shown that the hydraulic conductivity/porosity relationships for high performance grout are more complex than those established for normal cements. Studies on the effect of leaching on the pore structure of the reference high performance grout indicated that the material's porosity does change with time, but only within the limits that depend on grout composition and it's initial porosity. The observed decrease in the pore radius during leaching was found to depend on the total porosity of the grout, 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 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. Both studies on porosity and permeability of the developed grouts indicate that pore size distribution rather than the total porosity provides the measure through which longevity can be assessed. The small pores (<1 μm) do not make a significant contribution to permeability.

Theoretical investigations

Theoretical investigations into the longevity of repository seals have dealt primarily with the development of a methodology to evaluate interactions between portland cement-based grout and groundwater. Evaluation of chemical thermodynamic equilibria between grout and groundwater, and among grout, groundwater, and granitic host rock phases using the geochemical codes EQ3NR/EQ6 suggests that a fracture filled with grout and saturated with groundwater will tend to fill and "tighten" with time. The grout-groundwater calculations predict that some grout phases will react with groundwater, and that there will be precipitation of secondary phases which collectively have a larger overall volume than that of the material dissolved. Results of these investigations suggest that cement grout seals will maintain an acceptable level of performance for tens of thousands to millions of years, provided the repository is sited where groundwater chemistry is compatible with the seals and hydrologic gradients are low.

The results of the grout-groundwater-rock calculations suggest that buffering of the fracture seal's chemical system by the granitic rock may be an important influence on the long-term fate of grout seals and the formation of certain phases in the resulting phase assemblage in the fracture. The similarity of the modeled reaction products to those observed in naturally filled fractures suggests that with time equilibrium will be approached and grouted fractures subject to low hydrologic gradients will continue to seal. If grout injected into fractures materially reduces groundwater flux, the approach to chemical equilibrium will likely be accelerated. In light of this, even very thin or imperfectly grouted fractures would tighten in suitable hydrogeologic environments.

Overall, we conclude that portland cement grout will tend to promote the attainment of geochemical equilibrium in fractures. This is reasonable in view of the similarities in suites of secondary minerals produced in the grout-groundwater and grout-rock-groundwater systems simulations. The grout is more chemically reactive than the rock; therefore, its presence in a fracture may be viewed as the introduction of a more kinetically favoured reactant within the same chemical system. The chemical presence of the grout will accelerate the move toward steady-state chemical conditions and will promote the permanent closing of fractures. To be effective, however, upon curing the grout must have a low enough hydraulic conductivity that flow through the system is retarded to the point where precipitation kinetics is no longer outpaced by dissolution kinetics. Once this condition is achieved, then the effectiveness of the grout seal will be essentially permanent. Modelling (and preparing design specifications for) such a grout awaits obtaining dissolution and precipitation kinetic data for grout and secondary mineral phases.

3.4 ECONOMY

The total cost of the Stripa Project Phase 3 as of December 31, 1991 is given in the Table 3-4 below.

Table 3-4. Stripa Project Phase 3 – Summary of costs as per December 31, 1991. All figures in SEK.

	TOTAL PROGRAM		
Program	**Original budget incl. annual index esc. Jan 1991**	**Accumulated**	**Estimated remaining**
Project Management	8,200,000	7,575,430	624,570
Stripa Generally	29,900,000	18,473,488	11,426,512
Site Char. and Validation	45,400,000	46,203,061	-803,061
Dev. of Radar	5,500,000	5,510,395	-10,395
Improv. of Bore-hole Seismics	3,800,000	3,392,179	407,821
Network Modelling	8,000,000	9,441,787	-1,441,787
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	26,068,874	131,126
Total	**142,800,000**	**132,535,508**	**10,264,492**

Appendix

Stripa Project — Previously Published Reports, 1980–1991

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.

"BUFFER MASS TEST — BUFFER MATERIALS"

R Pusch, L Börgesson
University of Luleå

J Nilsson
AB Jacobson & Widmark, Luleå

Sweden, August 1982

SUMMARY

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

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

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

"BUFFER MASS TEST — ROCK DRILLING AND CIVIL ENGINEERING"

R Pusch
University of Luleå

J Nilsson
AB Jacobson & Widmark, Luleå

Sweden, September 1982

SUMMARY

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

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

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

1982 IR 82–08

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

L Börgesson
University of Luleå

Sweden, August 1982

SUMMARY

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

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

The rate of the water uptake is highly dependent on the availability of water along the rock surface but not very much on the difference in the amount of water available in the six holes. The predicted time for water saturation (Sr 95%) 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,
Universitê, Paris-Sud, Paris, France

Jean L Michelot,
Universitê, 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"

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June 1984

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

1984 | IR 84–03

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS — GEOPHYSICAL BOREHOLE MEASUREMENTS"

Olle Olsson, Ante Jämtlid
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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"

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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
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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"

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September 1984

SUMMARY

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

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

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

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

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

1984 IR 84–07

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

Sten Lindblom
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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 ground-water 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"

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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

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Swedish Nuclear Fuel and Waste Management Co., Stockholm

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IR 85–08

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

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July 1985

ABSTRACT

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

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

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

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.

1985 **TR 85–10**

"HYDROGEOLOGICAL AND HYDROGEOCHEMICAL INVESTIGATIONS IN BOREHOLES — FINAL REPORT"

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July 1985

ABSTRACT

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

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

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

1985 **TR 85-11**

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

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July 1985

ABSTRACT

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

1985 TR 85–12

“FINAL REPORT OF THE BUFFER MASS TEST — Volume II: test results”

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August 1985

ABSTRACT

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

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

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

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

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

1985 **IR 85–13**

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

S Carlsten, A Stråhle
Swedish Geological Co., Sweden

September 1985

TR 85–14

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

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

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
Swedish Geological Co., Sweden

G Ramqvist
El-Tekno Co., Sweden

January 1987

ABSTRACT

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

TR 87–02

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

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G Ramqvist
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January 1987

ABSTRACT

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

1987 **TR 87-03**

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

R Pusch, L Börgesson
Swedish Geological Co., Sweden

G Ramqvist
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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"

D Holmes
British Geological Survey, United Kingdom

M Sehlstedt
Swedish Geological Co., Sweden

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
Swedish Geological Co., Sweden

February 1987

1 INTRODUCTION

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

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

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

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

1987 **TR 87–06**

"CROSSHOLE INVESTIGATIONS — RESULTS FROM SEISMIC BOREHOLE TOMOGRAPHY"

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"

C Cosma
Vibrometric OY, Finland

S Bähler, M Hammarström, J Pihl
National Defence Research Institute, Sweden

December 1986

ABSTRACT

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

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

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

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

1987 **TR 87–08**

"CROSSHOLE INVESTIGATIONS — SHORT AND MEDIUM RANGE SEISMIC TOMOGRAPHY"

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February 1987

ABSTRACT

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

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

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

TR 87–09

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

Swedish Nuclear Fuel and Waste Management Co., Stockholm

May 1987

1987 TR 87–10

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

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

June 1987

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

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

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

1987 TR 87–11

"CROSSHOLE INVESTIGATIONS — RESULTS FROM BOREHOLE RADAR INVESTIGATIONS"

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

May 1987

ABSTRACT

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

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

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

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

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

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

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

1987 **TR 87-12**

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

Swedish Nuclear Fuel and Waste Management Co., Stockholm

June 1987

IR 87-13

"ROCK STRESS MEASUREMENTS IN BOREHOLE V3"

B Bjarnason, G Raillard
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July 1987

ABSTRACT

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

TR 87-14

"ANNUAL REPORT 1986"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

August 1987

1987 TR 87–15

"HYDROGEOLOGICAL CHARACTERIZATION OF THE STRIPA SITE"

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C Cole, L Vail
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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.

"CROSSHOLE INVESTIGATIONS — FINAL REPORT"

O Olsson
Swedish Geological Co., Sweden

J Black
British Geological Survey, United Kingdom

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Vibrometric OY, Finland

J Phil
National Defence Research Institute, Sweden

September 1987

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

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

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

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

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

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

1987 IR 87–17

"SITE CHARACTERIZATION AND VALIDATION — GEOPHYSICAL SINGLE HOLE LOGGING"

B Fridh
Swedish Geological Co., Sweden

December 1987

ABSTRACT

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

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

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

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

1987 **TR 87-18**

"CROSSHOLE INVESTIGATIONS — HYDROGEOLOGICAL RESULTS AND INTERPRETATIONS"

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

December 1987

ABSTRACT

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

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

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

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

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

1987 **TR 87–19**

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

H Abelin, L Birgersson
Royal Institute of Technology, Sweden

November 1987

ABSTRACT

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

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

TR 87–20

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

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

November 1987

ABSTRACT

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

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

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.

1988 **TR 88-01**

"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

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

R Pusch
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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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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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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"

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September 1988

ABSTRACT

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

1988 **IR 88–10**

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

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September 1988

ABSTRACT

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

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

1988 **TR 88–11**

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

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September 1988

ABSTRACT

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

1989 TR 89–01

"EXECUTIVE SUMMARY OF PHASE 2"

Swedish Nuclear Fuel and Waste Management Co., Stockholm

February 1989

SUMMARY OF CONCLUSIONS

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

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

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

"FRACTURE FLOW CODE CROSS-VERIFICATION PLAN"

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March 1989

ABSTRACT

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

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

1989 **TR 89-03**

"SITE CHARACTERIZATION AND VALIDATION STAGE 2 — PRELIMINARY PREDICTIONS"

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J Gale
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May 1989

ABSTRACT

The Site Characterization and Validation (SCV) Project is designed to assess how well we can characterize a volume of rock prior to using it as a repository. The programme of work focuses on the validation of the techniques used in site characterization. The SCV Project contains 5 stages of work arranged in two "cycles" of data-gathering, prediction and validation. The first stage of work has included drilling of 6 boreholes (N2, N3, N4, 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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O Olsson
ABEM AB, Uppsala, Sweden

M Sehlstedt
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April 1989

ABSTRACT

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

IR 89–07

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

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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.

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

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ABEM AB, Uppsala, Sweden

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
Clay Technology, Sweden

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 comparing the prediction to the measured result, a prediction error of about 4.6 l/min was calculated. This is an

1990 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.

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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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.

"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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P LeMessurier
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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"

H Abelin, L Birgersson, T Ågren
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"

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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

1991 | **TR 91–01**

"DISTINCT ELEMENT METHOD MODELING OF FRACTURE BEHAVIOR IN NEAR FIELD ROCK"

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December 1990

ABSTRACT

This report concerns the numerical calculations of the behavior of the near field of a nuclear waste repository, carried out during the first stages of an intended three year program. The calculations were performed using the two-dimensional distinct element code UDEC. The distinct element method accounts specifically for discontinuities, e.g. fractures that intersect the model region.

It is shown that, if an appropriate joint constitutive relation is applied, the calculated joint behavior can be brought in close agreement with empirically derived stress-strain relations.

Three basic geometries, related to the KBS-3 concept, are studied, namely a vertical tunnel section, a horizontal borehole section and a combination, i.e. a vertical section of tunnel and deposition hole.

The effects of different processes and activities are investigated, e.g. effects of excavations, of thermal loads, of internal tunnel pressures and of pore pressures and fracture flow resulting from the hydraulic ground water pressure.

The interpretation of the results concerns in particular joint behavior, especially joint openings, in the nearest surroundings of excavations and of thermally affected regions. The calculations show that joint shear and joint normal displacements induced by excavation and by thermal processes may be considerable, and that thermal cycles may result in residual joint aperture changes, especially in systems with loosely bound rock blocks.

It is concluded that the UDEC code, when applied to problems that have a two-dimensional character, gives results that are probably qualitatively correct. The results appear to be strongly dependant on the detailed joint structure close to free boundaries such as tunnel walls, which indicates that the 3-D situation regarding joint orientation might have to be considered.

It is recommended that 3-D calculations should be performed to verify and quantitatively interpret the 2-D results and to analyze situations that are actually three-dimensional. It is further recommended that the work done so far on simulation of grout injection should be continued. Finally it is recommended that the results presented in this report should be closer analyzed with respect to changes in rock permeability.

1991 **IR 91-02**

"SITE CHARACTERIZATION AND VALIDATION - MONITORING OF HEAD IN THE STRIPA MINE DURING 1989"

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Mikael Sehlstedt
Swedish Geological Co., Malå

Olle Olsson
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November 1990

ABSTRACT

The groundwater head has been monitored in some 50 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 1989.

1991 **TR 91–03**

"INTERPRETATION OF FRACTURE SYSTEM GEOMETRY USING WELL TEST DATA"

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November 1990

ABSTRACT

This report presents three methods of determining fracture geometry and interconnection from well test information. Method 1 uses evidence for boundary effects in the well test to determine the distance to and type of fracture boundary. Method 2 uses the spatial dimension of the well test to infer the geometry of the fracture-conduit system. Method 3 obtains information on the spacing and transmissivity distribution of individual conductive fractures from fixed-interval-length (FIL) well tests. The three methods are applied to data from the Site Characterization and Validation (SCV) at the 360 m level of the Stripa Mine. The focus of the technology development is the constant-pressure welltest, although the general approaches apply to constant-rate well tests, and to a much lesser extent slug or pulse tests, which are relatively insensitive to boundaries and spatial dimension.

Application of the techniques to the N and W holes in the SCV area shows that there is little evidence for boundary effects in the well test results. There is, on the other hand, considerable variation in the spatial dimension of the well test data ranging from sub-linear (fractures which decrease in conductivity with distance from the hole) to spherical, for three-dimensional fracture systems. In some cases flow changes dimension over the course of the test. The absence of boundary effects suggests that the rock mass in the SCV area contains a well-connected fracture system.

Major uncertainties in the analysis of well test data limit the use of single borehole measurements. Without assuming the value of specific storage, one can reliably determine only the spatial dimension, and, for two dimensional flow only, the transmissivity. Among the uncertainties are the effective well radius, the degree to which the fracture conduits fill the n-dimensional space in which flow occurs, and the cross-sectional area of the conduits at the wellbore.

This report presents a complete development of constant-pressure well test methods for cylindrical flow and flow of arbitrary dimension. Computer code listings for generation of type curves are provided.

1991 **TR 91-04**

"APPLICATION OF COMPUTER AIDED DESIGN (CADD) IN DATA DISPLAY AND INTEGRATION OF NUMERICAL AND FIELD RESULTS - STRIPA - PHASE 3"

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December 1990

ABSTRACT

Existing CAD/CADD systems have been reviewed and the micro-computer compatible solids modelling CADD software SilverScreen was selected for use in constructing a CADD model of the Stripa site. Maps of the Stripa mine drifts, shafts, raises and stopes were digitized and used to create three-dimensional images of the north-eastern part of the mine and the SCV site. In addition, the use of CADD sub-programs to display variation in fracture geometry and hydraulic heads have been demonstrated. The database developed in this study is available as either raw digitized files, processed data files, SilverScreen script files or in DXF or IGES formats; all of which are described in this report.

1991 **TR 91–05**

"DISTURBED ZONE MODELLING OF SVC VALIDATION DRIFT USING UDEC-BB, MODELS 1 TO 8 – STRIPA PHASE 3"

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January 1991

ABSTRACT

Several rock mechanics studies were performed within the site characterization and validation (SCV) project at Stripa. Joints represented in Harwell's stocastically generated 8 m x 8 m x 8 m cubes were used to select four possible joint geometries for two-dimensional rock mechanics simulations of the 2.8 x 2.2 m validation drift, and the rock mass response to its excavation. The joints intersecting the four end faces of these cubes were set up in distinct element UDEC-BB models, and loaded with boundary stresses of 10 MPa vertically and 14 to 18 MPa horizontally. In numerical models 1, 2, 3 and 4 average values of the Barton Bandis joint parameters JRC, JCS and ϕ_r were utilized for all joints, irrespective of length. These values were obtained from NGI's index characterization of 220 joints in 100 mm core and from 200 mm diameter and 1 x 1 2 m block testing where coupled closure-shear-flow testing (CSFT) was also performed. In numerical models 5, 6, 7, 8 the same joint geometries were utilized with length-dependent values of JRC, JCS and ϕ_r. The longest joints were given low values representing mineralized persistent discontinuities, while the shortest joints were given high values.

As a result of numerical drift excavation, changes in joint apertures occurred, some closing, others opening. Most aperture changes; 12 per meter per model, occurred in the first 0.5 m from the drift. Some block movements allowed channel development at joint intersections. Most persistent joints had pre-excavation apertures in the range 1 m to 25 m. Channels that formed at joint intersections had local apertures typically of 150 to 350 m, and would provide for potentially increased permeability parallel with the drift. The smoother persistent joints did not dilate with shear, only the rougher non-persistent joints.

Detailed analyses were made of the tangential and radial stress magnitudes that were obtained in the four UDEC-BB discontinuum models 5, 6, 7 and 8. Results were presented for all sectors of the models as a function of radius from the drift walls. These stress magnitudes were compared with those from an equivalent continuum model which showed, as expected, much more predictable stress gradients. Modelled drift closures ranged from 2 to 3 mm in the jointed models and from 1 to 1.5 mm in the continuum model. Local tensile stress development, maximum 28 MPa, and local shearing of individual joints, maximum 1.0 mm, were a feature of the jointed models. Peak tangential stresses locally reached 54 to 74 MPa in the jointed models, compared to 43 MPa in the continuum model.

1991 **TR 91–06**

"EVAPORATION MEASUREMENT IN THE VALIDATION DRIFT – PART 1"

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January 1991

ABSTRACT

Evaporation rate distribution over the wall surface of the Validation Drift was detaily mapped by using an equipment newly developed. The evaporation measurement was carried out to make clear the spatial variability of the inflow rate of groundwater seeping toward the tunnel. Air in the tunnel was warmed by an electric heater during the measurement period for reducing the relative humidity of air and for drying up the wall surface. Evaporation rates from rock matrix as well as from some major fractures were measured at about 500 points.

Spatial distributions of evaporation rates over the tunnel wall were obtained under two different ventilation conditions. The average evaporation rates from the rock matrix of the wall were 0.29–0.35 $mg/m^2/s$ under these ventilation conditions. The average evaporation rate measured on some major fractures was about 1.3 $mg/m^2/s$. The maximum evaporation rate measured was 12.8 $mg/m^2/s$. Some spots of high evaporation rate were clearly found along some major fractures and these spots seemed to be the special seepage ways (channels) developed in those fractures. The fracture flow is relatively small compared with the matrix flow in the inner part of the drift.

This measurement was performed about 1 month after the excavation of the Validation Drift. Groundwater flow around the tunnel might not be in a steady state because the period between tunnel excavation and the measurement was not so long. The evaporation rate distribution under the steady state of groundwater flow will be studied in 1991.

1991 TR 91-07

"SITE CHARACTERIZATION AND VALIDATION - RESULTS FROM SEISMIC CROSSHOLE AND REFLECTION MEASUREMENTS - STAGE 3"

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January 1991

ABSTRACT

The purpose of the Site Characterization and Validation (SCV) Project is to predict groundwater flow and nuclide transport in a previously unexplored volume of the Stripa granite. The project comprises five stages. This report concerns the borehole seismic investigations carried out during Stage III.

The objective has been to review the localization and characterization of fractured and altered rock zones performed in Stage I. The seismic acquisition apparatus and the data processing techniques have been the subject of major changes with respect to Stage I and their features are outlined. The use of boreholes is important, as surveys performed from drifts and surface permit only a limited probing angle of the site volume.

The approach consists of applying in parallel two methods: two-dimensional cross-hole tomography and a new three-dimensional reflection imaging technique. The reflection method detects changes in acoustic impedance, which is an accurate way of finding the boundaries of rock features. The tomographic method maps variations of the rock properties, like wave velocity and attenuation. The fractured zones from the SCV site produce a faint seismic response. Extensive processing was used to achieve a unambiguous interpretation of the reflection data. The tomographic analysis of velocities reveals an extremely flat variation of 1-3 %.

1991 TR 91–08

"SITE CHARACTERIZATION AND VALIDATION – STAGE 4 – PRELIMINARY ASSESSMENT AND DETAIL PREDICTIONS"

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December 1990

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 included drilling 6 boreholes and measurements of geology, fracture characteristics, stress, single borehole geophysical logging, radar, seismics, and hydrogeology.

This work was then evaluated and an initial conceptual model proposed (see Olsson and others, 1989). This included 5 "fracture zones" within otherwise "average background rock". This "average rock" was characterized based on clusters of fracture orientations which were similar to the fracture zones.

In this report, a more rigorous definition of fracture zones based on principal component analysis is developed. In this approach, all the single-borehole, measured parameters (eg sonic velocity, hydraulic conductivity, etc) which indicate hydrogeologically conductive features are included using a set of weighting functions are then listed across the site using geophysics. A revised conceptual model is proposed which includes three large scale features, Zone A, Zone B and Zone H all of which extend to the surface. Three smaller features Zones I, Zone K and Zone M are observed to form important connections within the SCV Block.

1991 TR 91–09

"SITE CHARACTERIZATION AND VALIDATION – MONITORING OF SALINE TRACER TRANSPORT BY BOREHOLE RADAR MEASUREMENTS – PHASE 1"

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February 1991

ABSTRACT

The objective of the radar/saline tracer experiment was to provide data for a description on the geometry of the flow paths in the vicinity of the planned Validation drift. Saline tracer was injected into zone H through borehole C2 where it intersects the zone. Radar tomography was made in three borehole sections surrounding the injection borehole (W1-C5, C1-C5, and W1-C1). Reference radar tomography measurements were made prior to injection of saline tracer and were repeated 7 times after start of injection.

Saline tracer with a concentration of 2 % was injected with a flow rate of 200 ml/min. The first arrival was observed in borehole D4 approximately 10 h after start of injection and the mean residence time was approximately 40 h. The distance between the injection point and the sampling point in the D-boreholes is approximately 25 m.

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. In spite of the small changes in amplitude the difference tomograms displayed consistent anomalies both with respect to location and evolution with time.

The difference tomograms showed a nonuniform spread of tracer with time. 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) intersecting zone H. Tracer was also observed to be transported through these zones out of zone H.

Radar difference tomography together with saline tracer injection has proven to be a useful tool for characterizing the groundwater flow system through fractured rocks.

1991 **TR 91–10**

"A COMPARISON OF PREDICTIONS AND MEASUREMENTS FOR THE STRIPA SIMULATED DRIFT EXPERIMENT"

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February 1991

ABSTRACT

This paper presents a comparison of measurements and predictions for the Simulated Drift Experiment based on groundwater flow to the D-holes at the SCV site. The comparison was carried out on behalf of the Stripa Task Force on Fracture Flow Modelling, as a learning exercise for the validation exercise to be based on flow to the Validation Drift.

The paper summarises the characterisation data and their preliminary interpretation, and reviews the fracture flow modelling predictions made by teams from AEA Harwell, Golder Associates and Lawrence Berkeley Laboratory. The predictions are compared with each other and with the D-hole inflow measurements, and this experience is used to provide detailed feedback to future experimental and modelling work.

TR 91–11

"Annual Report 1990"

Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden

July 1991

IR 91–12

"SITE CHARACTERIZATION AND VALIDATION – MONITORING OF HEAD IN THE STRIPA MINE DURING 1990"

Seje Carlsten, Göran Nyberg, Pirrka-Tapio Tammela
Swedish Geological Co., Uppsala

Olle Olsson
CONTERRA AB, Uppsala

April 1991

ABSTRACT

The groundwater head has been monitored in 45 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 1990.

1991 TR 91–13

"IMPROVEMENT OF HIGH RESOLUTION BOREHOLE SEISMICS. PART I: DEVELOPMENT OF PROCESSING METHODS FOR VSP SURVEYS. PART II: PIEZOELECTRIC SIGNAL TRANSMITTER FOR SEISMIC MEASUREMENTS"

Calin Cosma, Pekka Heikkinen, Seppo Pekonen
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May 1991

ABSTRACT

The purpose of the High Resolution Borehole Seismics Project has been to improve the reliability and resolution of seismic methods in the particular environment of nuclear waste repository sites. The results obtained, especially the data processing and interpretation methods developed, are applicable also to other geophysical methods (e.g. Georadar).

The goals of the seismic development project have been:

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

Because these two aspects of the work are very different in nature, we have structured the report as two self contained parts.

Part I describes the development of interpretive techniques. We have used for demonstrating the effect of different methods a VSP data set collected at the SCV site during Stage I of the project. Five techniques have been studied: FK-filtering, three versions of Tau-p filtering and a new technique that we have developed lately, Image Space filtering.

Part II refers to the construction of the piezoelectric source. Earlier results obtained over short distances with low energy piezoelectric transmitters let us believe that the same principle could be applied for seismic signal transmitters, if solutions for higher energy and lower frequency output were found. The instrument which we have constructed is a cylindrical unit which can be placed in a borehole and is able to produce a radial strain when excited axially. The minimum borehole diameter is 56 mm.

1991 TR 91-14

"TRACER TRANSPORT IN FRACTURES: ANALYSIS ON FIELD DATA BASED ON A VARIABLE-APERTURE CHANNEL MODEL"

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June 1991

ABSTRACT

A variable-aperture channel model is used as the basis to interpret data from a three-year tracer transport experiment in fractured rocks. The data come from the so-called Stripa-3D experiment performed by Neretnieks and coworkers. Within the framework of the variable-aperture channel conceptual model, tracers are envisioned as travelling along a number of variable-aperture flow channels, whose properties are related to the mean $\bar{b}$ and standard deviation σ_b of the fracture aperture distribution.

Two methods are developed to address the presence of strong time variation of the tracer injection flow rate in this experiment. The first approximates the early part of the injection history by an exponential decay function and is applicable to the early time tracer breakthrough data. The second is a deconvolution method involving the use of Toeplitz matrices and is applicable over the complete period of variable injection of the tracers. Both methods give consistent results. These results include not only estimates of $\bar{b}$ and σ, but also ranges of Peclet numbers, dispersivity and an estimate of the number of channels involved in the tracer transport. An interesting and surprising observation is that the data indicate that the Peclet number increases with the mean travel time; i.e., dispersivity decreasing with mean travel time. This trend is consistent with calculated results of tracer transport in multiple variable-aperture fractures in series. The meaning of this trend is discussed in terms of the strong heterogeneity of the flow system.

1991 **IR 91–15**

"INFLOW MEASUREMENTS IN THE D-HOLES AT THE STRIPA MINE"

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June 1991

ABSTRACT

Flow measurements in 0.5 m-sections in the D-boreholes at Stripa were performed by Swedish Geological Company during February to April 1991. The purpose of the measurements was to determine in detail the inflow to an array of boreholes through an undisturbed volume of fractured granite.

A lower measurement limit of $1 \cdot 10^{-4}$ l/min was stipulated for the measurements in 0.5 m-sections. However, in practice the inflow measurements were initially performed in 4.5 m-sections, which made it possible to reach an even lower measurement limit. Furthermore, by this method the tests were speeded up, because in all 4.5 m-sections where the flow fell below $1 \cdot 10^{-4}$ l/min, no detailed measurements in 0.5 m-sections were necessary.

The accuracy of the measurements was 5 % for flow in the interval $1 \cdot 10^{-3}$ l/min and 100 % for flow below that value.

The boreholes D5 and D6 have relatively high inflows to the entire boreholes, about $450 \cdot 10^{-3}$ l/min respectively $90 \cdot 10^{-3}$ l/min. The inflow values to the remaining boreholes are much lower: between about $3 \cdot 10^{-3}$ and $13 \cdot 10^{-3}$ l/min.

The flow distribution along the boreholes is rather similar in boreholes D1, D3 and D6, with flow maxima at about 80-90 m borehole length. At this level peaks are found also in boreholes D2, D4 and D5, but in the latter boreholes increased flow values occur also closer to the borehole outlets.

Indications of hydraulic connections between different boreholes were observed. Inflation of the packers at certain locations in one borehole caused in some cases flow changes in neighbouring boreholes.

1991 TR 91-16

"DISCRETE FRACTURE MODELLING FOR THE STRIPA SITE CHARACTERIZATION AND VALIDATION DRIFT INFLOW PREDICTIONS"

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June 1991

ABSTRACT

Groundwater flow through three-dimensional networks of discrete fractures was modeled to predict the flux into a fifty meter long drift, as part of the Site Characterization and Validation Project conducted during Phase 3 of the Stripa Project. Predictions were made on the basis of a site scale discrete fracture conceptual model developed by synthesis of geological, geophysical, and hydrological site characterization data. Individual fractures were treated as stochastic features, described by probability distributions of geometric and hydrologic properties. Fractures were divided into three populations: Fractures within fracture zones near the drift, non-fracture zone fractures near the drift, and fractures in fracture zones over 20 meters from the drift. Fractures outside fracture zones are not modelled beyond 20 meters from the drift.

Both data analysis and flow predictions were produced using the FracMan discrete fracture modelling package. Probabilistic flow predictions were produced in seven formats specified by the Stripa Task Force on Fracture Flow Modelling.

1991 **TR 91-17**

"LARGE SCALE CROSS HOLE TESTING"

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T Doe
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May 1991 (Revised January 1992)

ABSTRACT

As part of the Site Characterisation and Validation programme the results of the Large Scale Cross Hole Testing have been used to document hydraulic connections across the SCV block, to test conceptual models of fracture zones and obtain hydrogeological properties of the major hydrogeological features.

The SCV block is highly heterogeneous. This heterogeneity is not smoothed out even over scales of hundreds of meters.

Results of the interpretation validate the hypothesis of the major fracture zones A, B and H; not much evidence of minor fracture zones is found.

The uncertainty in the flow path, through the fractured rock, causes severe problems in interpretation. Derived values of hydraulic conductivity were found to be in a narrow range of two to three orders of magnitude.

Test design did not allow fracture zones to be tested individually. This could be improved by testing the high hydraulic conductivity regions specifically.

The Piezomac and single hole equipment worked well.

Few, if any, of the tests ran long enough to approach equilibrium. Many observation boreholes showed no response. This could either be because there is no hydraulic connection, or there is a connection but a response is not seen within the time scale of the pumping test.

The fractional dimension analysis yielded credible results, and the sinusoidal testing procedure provided an effective means of identifying the dominant hydraulic connections.

1991 **TR 91-18**

"SITE CHARACTERIZATION AND VALIDATION - MONITORING OF SALINE TRACER TRANSPORT BY BOREHOLE RADAR MEASUREMENTS, FINAL REPORT"

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August 1991

ABSTRACT

The objective of this experiment was to map tracer transport in fractured crystalline rock through a combination of radar difference tomography and measurements of tracer concentration in boreholes and the Validation Drift. The radar tomography measurements were repeated a number of times to get data on tracer distribution as a function of time. The experiment was performed twice, first the D-boreholes were used as a sink and then they were replaced by the Validation Drift and the experiment repeated. In both experiments saline tracer (200 ml/min, 2% salinity) was injected into fracture zone H about 25 m from the Validation Drift.

The inflow to the Validation Drift was approximately 1/8 of the inflow to the corresponding part of the D-boreholes. The flow system is basically controlled by the relative strength of sources and sinks within the experimental volume. The observed travel times to the Validation Drift are roughly 3 times longer than the corresponding travel times to the D-boreholes during phase 1 of the first experiment (D-holes held at pressure of 165 m). The corresponding inflow rates were 335 ml/min and 98 ml/min during the first and second experiments, respectively.

The experiment revealed an inhomogeneous transmissivity distribution in Zone H. A significant portion of the tracer is transported upwards along Zone H and towards boreholes T1, T2, and W1. The breakthrough data from both experiments indicate that there are two major transport paths from borehole C2 to the D-boreholes/Validation Drift. One slow and diluted path to the bottom of the drift which carries the bulk of the mass and one fast path to the crown of the drift with high tracer concentration. The radar difference tomograms show that some tracer is lost through Zone S which intersects Zone H and is nearly perpendicular to it. The intersection between the two zones seems to constitute a preferred flow path.

The combined analysis radar and tracer breakthroughs have clearly given a better understanding of the flow system than would have been possible otherwise.

The breakthrough data and the radar difference tomograms have also been used to estimate flow porosity. The estimates obtained are of the same order, approximately 1E-4.

1991 TR 91-19

"SITE CHARACTERIZATION AND VALIDATION - VALIDATION DRIFT FRACTURE DATA, STAGE IV"

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August 1991

ABSTRACT

This report describes the mapping procedures and the data collected during fracture mapping in the Validation drift. Fracture characteristics examined include orientation, trace length, termination mode, and fracture minerals. These data have been compared and analyzed together with fracture data from the D-boreholes to determine the adequacy of the borehole mapping procedures and to assess the nature and degree of orientation bias in the borehole data. The analysis of the Validation drift nature and degree of orientation bias in the borehole data. The analysis of the Validation drift data also includes a series of corrections to account for orientation, truncation, and censoring biases.

This analysis has identified at least 4 geologically significant fracture sets in the rock mass defined by the Validation drift. An analysis of the fracture orientations in both the good rock and the H-zone has defined groups of 7 clusters and 4 clusters, respectively. Subsequent analysis of the fracture patterns in five consecutive sections along the Validation drift further identified heterogeneity through the rock mass, with respect to fracture orientations. These results are in stark contrast to the results from the D-borehole analysis, where a strong orientation bias resulted in a consistent pattern of measured fracture orientations through the rock. In the Validation drift, fractures in the good rock also display a greater mean variance in length than those in the H-zone. These results provide strong support for a distinction being made between fractures in the good rock and the H-zone, and possibly between different areas of the good rock itself, for discrete modelling purposes.

1991 **TR 91-20**

"SITE CHARACTERIZATION AND VALIDATION - EXCAVATION STRESS EFFECTS AROUND THE VALIDATION DRIFT"

John P Tinucci, Jan Israelsson
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August 1991

ABSTRACT

The results of previous numerical modeling studies to investigate excavation stress effects around the Site Characterization Validation (SCV) Drift at the Stripa Mine have been reviewed. Though three-dimensional fractures were not directly simulated in previous studies, estimates of stresses on fracture planes were made. This study examines the direct effect of fractures on excavation stresses around the Site Validation Drift for the purpose of understanding how excavation-induced stress changes might influence fluid flow in fractures.

Three-dimensional stress modelling was carried out using the discontinuum code 3DEC to determine the state of stress around the drift. Fractures were assumed to have linear elastic normal behavior and elastic perfectly-plastic shear behavior. Results suggest that fracture shear displacements are small enough to be elastic – that is, no significant slip was evident. Fractures from the major fracture sets generally tend to close immediately around the drift, while further in the wall rock they tend to slightly open as a result of the excavation. The presence of fractures produce stress distributions that differ little from continuum models and analytic solutions. The most important difference between the continuum and discontinuum models is that the fracture behavior results in a nonuniform distribution of stresses around the excavation. The effect of fractures on displacements is most pronounced in the highly fractured H- zone, which strikes nearly perpendicular to the drift.

1991 TR 91–21

"SUPERPLASTICIZER FUNCTION AND SORPTION IN HIGH PERFORMANCE CEMENT BASED GROUTS"

Maria Onofrei, Malcolm N Gray, H Leyton
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August 1991

ABSTRACT

This report describes laboratory studies undertaken to determine interactions between the main components of high-performance cement-based grout (i.e. organic superplasticizers, cement and silica fume). These interactions were studied with the grouts in both their unset and hardened states with the specific intention of determining the following: the mechanistic function of superplasticizer; the phase of residence of the superplasticizer in hardened materials; and the permanence of the superplasticizer in hardened grouts. In unset pastes attempts were made to extract superplasticizer by mechanical processes. In hardened grout the superplasticizer was leached from the grouts. A microautoradiographic method was developed to investigate the phases of residence of superplasticizer in hardened grouts and confirm the inferences from the leaching studies.

In hardened grout the superplasticizer was located on the hydrated phases formed during the early stages of cement hydration. These include tricalcium aluminate hydrates and tricalcium silicate phases. There is some tendency for the superplasticizer to sorb on ettringite. The presence of superplasticizer did not coincide with the locations of unreacted silica fume and high silica content phases such as C_2S-H. The observations explain the findings of the studies of unset pastes which also showed that the sorption of superplasticizer is likely to be enhanced with increased mixing water content and, hence, distribution in and exposure to the hydration reaction surfaces in the grout. Superplasticizer can be leached in very small quantities from the hardened grouts. Rapid release takes place from the unsorbed superplasticizer contained in the accessible pore space. Subsequent release likely occurs with dissolution of the cement phases and the exposure of isolated pores to groundwater. These latter processes are considered in other reports and are shown to be so slow that organic superplasticizers should not significantly add to the organic contents of groundwaters in the vicinity of a fuel-waste repository.

"DISTINCT ELEMENT MODELLING OF JOINT BEHAVIOR IN NEARFIELD ROCK. RELEVANCE OF TWO-DIMENSIONAL SIMULATIONS CONSIDERING 3-D EFFECTS OF THE FRACTURE SYSTEM"

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September 1991

ABSTRACT

The investigation reported here concerns numerical simulations of the behavior of the jointed rock mass in the nearest surroundings of a portion of a KBS-3 type tunnel, including one deposition hole. Results from three-dimensional models are presented and compared to results obtained from previous investigations of two-dimensional models. The three-dimensional models and the previous two-dimensional models relate to conditions prevailing in and around the BMT drift in Stripa mine.

In particular are the importance of conditions, implicitly assumed in two-dimensional models, regarding joint orientation and joint persistence, investigated.

The evaluation of the results is focused on effects on joint apertures. The implications regarding rock permeability is discussed for a couple of cases.

It is found that the real three-dimensional geometry is of great importance, and that the two-dimensional models in some cases tend to overestimate the magnitudes of inelastic joint displacements and associated aperture changes considerably, i.e. the real three-dimensional situation implies locking effects, that generally stabilizes the block assembly.

It is recommended that further three-dimensional simulations should be performed to determine relevant ranges of alteration of fracture apertures, caused by excavations and thermal processes, and that fracture geometries, that are typical to virgin granitic rock, should be defined and used as input for these simulations.

1991 **TR 91-23**

"PRELIMINARY – DISCRETE FRACTURE NETWORK MODELLING OF TRACER MIGRATION EXPERIMENTS AT THE SCV SITE"

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September 1991

ABSTRACT

This report describes a numerical modeling study of solute transport within the Site Characterization and Validation (SCV) block at the Stripa site. The study was carried out with the FracMan/MAFIC package, utilizing statistics from Stages 3 and 4 of the Stripa Phase 3 Site Characterization and Validation project. Simulations were carried out to calibrate fracture solute transport properties against observations in the first stage of saline injection radar experiments. These results were then used to predict the performance of planned tracer experiments, using both particle tracking network solute transport, and pathways analysis approaches. Simulations were also carried out to predict results of the second stage of saline injection radar experiments.

TR 91-24

"THEORETICAL INVESTIGATIONS OF GROUT SEAL LONGEVITY. I. GEOCHEMICAL MODELING OF GROUT-GROUNDWATER INTERACTIONSFLOW AND DIFFUSION MODELS"

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September 1991

ABSTRACT

Theoretical investigations into the longevity of repository seals have dealt primarily with the development of a methodology to evaluate interactions between portland cement- based grout and groundwater. Groundwater travel times through a seal have been calculated based on Darcy's Law, with an assumed hydraulic gradient for the site and initial hydraulic conductivity for the grout. Chemical interactions between a model grout and actual groundwater compositions have been evaluated by means of geochemical modeling codes. Changes in grout porosity derived from the geochemical modeling have been extended to yield estimates of hydraulic conductivity, based on published experimental results. Also, a preliminary approach to the evaluation of the role of diffusion processes in grout alteration has begun. Results of these investigations suggest that cement grout seals will maintain an acceptable level of performance for tens of thousands to millions of years, provided the repository is sited where groundwater chemistry is compatible with the seals and hydrologic gradients are low.

1991

TR 91-25

"SITE CHARACTERIZATION AND VALIDATION – EQUIPMENT DESIGN AND TECHNIQUES USED IN SINGLE BOREHOLE HYDRAULIC TESTING, SIMULATED DRIFT EXPERIMENT AND CROSSHOLE TESTING"

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October 1991

ABSTRACT

This report describes the equipment and techniques used to investigate the variation of hydrogeological parameters within a fractured crystalline rock mass. The testing program was performed during Stage 3 of the Site Characterization and Validation Programme at the Stripa Mine in Sweden. This programme used a multidisciplinary approach, combining geophysical, geological and hydrogeological methods, to determine how groundwater moved through the rock mass. The hydrogeological work package involved three components. Firstly, novel single borehole techniques (focused packer testing) were used to determine the distribution of hydraulic conductivity and head along individual boreholes. Secondly, water was abstracted from boreholes which were drilled to simulate a tunnel. (Simulated Drift Experiment). Locations and magnitudes of flows were measured together with pressure responses at various points in the SCV rock mass. Thirdly, Small Scale Crosshole tests, involving detailed interference testing, were used to determine the variability of hydrogeological parameters within previously identified, significant flow zones.

TR 91-26

"FINAL REPORT ON TEST 4 – SEALING OF NATURAL FINE-FRACTURE ZONE"

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October 1991

ABSTRACT

Test 4 involved characterization and grouting of a rather richly water-bearing natural fracture zone. Available rock structure data suggested that most inflowing water originated from a fracture set oriented NW/SE or from a N/S oriented zone perpendicular to the test drift, both intersecting it, but comprehensive drilling and a first grouting attempt showed that the actually most important zone was steep, NW/SE-striking and not intersecting the drift. Part of this zone was grouted in a second phase, and a number of tests indicated that the grouting had been relatively effective, yielding a drop in conductivity by approximately one order of magnitude. Analysis of drillings through the grouted rock showed that Alofix cement grout had entered fractures with an aperture of down to 10-20 m to several decimeters depth.

"EVAPORATION MEASUREMENT IN THE VALIDATION DRIFT – PART 2"

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November 1991

ABSTRACT

The second evaporation measurement was carried out from May 27 to June 13, 1991 in the Validation Drift. The evaporation rate distribution over the wall surface of the drift was successfully measured. The drift was excavated in March, 1990 so that the distribution at about 14 months after the excavation became clear by this second measurement. The first evaporation measurement was performed approximately one month after excavation.

Temperature and humidity in the drift were almost the same over the entire wall surface during the measurement. Evaporation measurements were performed at 240 points on the matrix part of the wall surface and at about 550 points on some major fractures and traces of blast holes. The ceiling and side walls of the drift were covered with plastic sheets before the measurement. The measurement was carried out after the removal of plastic sheets. Transient evaporation changes after the removal of plastic sheets were measured at 30 points.

The times for the evaporation rate to reach steady state after the removal of plastic sheets were in the range between about 5 hours to 60 hours. This transient time seems to be influenced not only by the geologic features of the wall but also the air humidity above the wall.

The average evaporation rates on matrix part, fractures and traces of blast hole were 0.09, 0.58 and 1.02 $mg/m^2/s$, respectively. Many high evaporation spots that might be the exits of seepage ways (channels) were found along some fractures. High evaporation spots were also found on some traces of blast holes. This implies that some fractures were newly created around the blast holes and ground water might flow through these fractures.

1991 **TR 91–28**

"ANALYSIS OF SPATIAL CORRELATION OF HYDRAULIC CONDUCTIVITY DATA FROM THE STRIPA MINE"

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November 1991

ABSTRACT

Hydraulic conductivity data from the Stripa mine were analysed to establish the characteristics of spatial variability. In addition the univariate statistics were calculated. Data on different supports were analysed; 10 m data, variable section length data (1-7 m), and the latter variable section data deregularised to 1 m data. The analyses of data from boreholes with orthogonal orientations indicated an apparent anisotropy in the geometric mean hydraulic conductivity, with a one to two order higher mean conductivity in the east-west direction than that of north-south. The analysis of spatial variability on a 10 m support revealed weak spatial correlation, whereas that based on the data deregularised to 1 m data showed finite, well developed spatial correlation with practical ranges of c. 10 m. The covariance structure of hydraulic conductivity, as opposed to that of the calculated geometric mean hydraulic conductivities, showed an isotropic structure. The established variograms constitute a starting point for further data expansion and estimation by eg. stochastic continuum simulations of groundwater flow and mass transport within the SCV block at Stripa.

"CROSS-VERIFICATION TESTING OF FRACTURE FLOW AND MASS TRANSPORT CODES"

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November 1991

ABSTRACT

This report discusses the results of a set of crossverification tests involving codes from AERE Harwell Laboratory, Lawrence Berkeley Laboratory and Golder Associates Inc. The cross-verification exercises involved testing the ability to simulate the geometry of a complex network as well as flow and mass transport through three different types of deterministic fracture networks. The codes were able to generate virtually identical representations of a complex fracture network. For simple cases of flow, all three codes accurately predicted rates of flow. The accuracy of the calculations of hydraulic heads was generally acceptable but appeared to deteriorate in situations where there were extreme contrasts in fracture apertures. Flow test 3 involved Harwell and Golder codes simulating flow through a large 1000 fracture network for cases with two different drifts. The initial results were characterized by relatively large and consistent discrepancies in estimates of flow rates. This problem developed as a consequence of the mismatch in the scale of discretization of the fractures. Subsequent reruns of flow test 3b produced excellent agreement in the results. In terms of exercises to test the transport capabilities, all three modeling packages produced the correct solution for the simplest problem involving four fracture planes. The FracMan/MAFIC and NAPSAC codes were successfully cross-verified with transport tests 2 and 3. Thus, overall, the major objective of the modeling exercise to assure the validity of the primary calculational codes has been met.

1991 **TR 91–30**

"FINAL REPORT OF THE ROCK SEALING PROJECT – SEALING PROPERTIES AND LONGEVITY OF SMECTITIC CLAY GROUTS"

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December 1991

ABSTRACT

Na and Ca bentonite clay grouts with densities that make them easily injected into fine fractures have been hydrothermally treated and investigated with respect to the hydraulic conductivity and shear strength.

Exposure of the grouts to salt groundwater increased the hydraulic conductivity up to around 1E-5 m/s, which is on the same order of magnitude as the value at complete conversion of soft montmorillonite clay to hydrous mica, i.e. the major ultimate reaction product. Still, even this "worst scenario" case will not lead to a higher bulk conductivity of the grouted rock than around 1E-10 m/s of rock with a conductivity of 1E-8 m/s before grouting. The rate of such conversion, which is entirely dependent on the potassium content of the groundwater, can be anything from a few hundred years to several thousand years depending primarily on the magnitude of prevailing hydraulic gradients.

The shear strength of the grouts, which determines the resistance to piping and erosion, increases with time and temperature. The most critical situation is immediately after injection into the rock, when hydraulic gradients exceeding about 30 may produce piping.

TR 91–31

"NAPSAC Technical Document"

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December 1991

ABSTRACT

NAPSAC is a numerical model of the flow of groundwater through fractured rock, and the associated transport of dissolved chemicals. The program can generate a very large three-dimensional network of random plane rectangular fractures, using probability distributions set by the user. It will find the steady-state (incompressible) flow and pressure fields in the network, using a finite element algorithm. A particle-tracking method is used to compute the transport of chemicals.

This document, one of a series describing all aspects of NAPSAC relevant to the Stripa project, deals with the scientific background to the model.

1991 **IR 91-32**

"SITE CHARACTERIZATION AND VALIDATION – MONITORING OF HEAD IN THE STRIPA MINE DURING 1991"

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December 1991

ABSTRACT
The groundwater head has been monitored in a total of 60 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 the period from January to June 1991.

TR 91-33

"CEMENT BASED GROUTS – LONGEVITY LABORATORY STUDIES: LEACHING BEHAVIOUR"

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December 1991

ABSTRACT
This report describes a series of laboratory tests carried out to determine the possible leaching behaviour of cement-based grouts in repository environments. A reference high-performance cement-based grout, comprised of Canadian Type 50 (U.S. Type V) Sulphate Resisting Portland Cement, silica fume, potable water and superplasticizer, and a commercially available cement grout were subjected to leaching in distilled water and three simulated groundwaters of different ionic strength. Hardened, monolithic specimens of the grout were leached in static, pulsed-flow and continuous flow conditions at temperatures from 10°C to 150°C for periods of up to 56 days. The changes in concentration of ions in the leachants with time were determined and the changes in the morphology of the surfaces of the grout specimens were examined using electron microscopy. After a review of possible mechanisms of degradation of cement-based materials, the data from these experiments are presented.

The data show that the grouts will leach when in contact with water through dissolution of more soluble phases. Comparison of the leaching performance of the two grouts indicates that, while there are some minor differences, they behaved quite similarly. The rate of the leaching processes were found to tend to decrease with time and to be accompanied by precipitation and/or growth of an assemblage of secondary alteration phases (i.e., $CaCO_3$, $Mg(OH)_2$). The mechanisms of leaching depended on the environmental conditions of temperature, groundwater composition and water flow rate. Matrix dissolution occurred. However, in many of the tests leaching was shown to be limited by the precipitated/reaction layers which acted as protective surface coatings.

1991 **TR 91-34**

"FINAL REPORT OF THE ROCK SEALING PROJECT - SEALING OF THE NEAR-FIELD ROCK AROUND DEPOSITION HOLES BY USE OF BENTONITE GROUTS"

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December 1991

ABSTRACT

Test 1 of the rock sealing project comprised determination of the hydraulic properties of the rock around large-diameter holes like canister deposition holes or TBM tunnels and attempts were made to seal the fractures intersecting such holes with bentonite slurry.

The heater holes from the Buffer Mass Test which are 76 cm in diameter, were used and injection made from inside the holes with a specially designed device using dynamic injection technique. The hydraulic properties of the surrounding rock were tested by use of the same device before and after the injections, as well as after a 3 months heat pulse.

The results were interpreted by applying a special derived grout flow model and by analyzing the rock response through different calculation techniques, as well as by localizing the injected grout by rock excavation.

The experiments showed that grouting of fractured rock by using the applied technique can give very significant sealing.

1991 TR 91–35

"MODELLING FOR THE STRIPA SITE CHARACTERIZATION AND VALIDATION DRIFT INFLOW: PREDICTION OF FLOW THROUGH FRACTURED ROCK"

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December 1991

ABSTRACT

We present our approach to predicting flow through a fractured rock site; the Site Characterisation and Validation region in the Stripa mine. Our approach is based on discrete fracture network modelling using the NAPSAC computer code. We describe the conceptual models and assumptions that we have used to interpret the geometry and flow properties of the fracture networks, from measurements at the site. These are used to investigate larger scale properties of the network and we show that for flows on scales larger than about 10 m, a porous medium approximation should be used. The porous medium groundwater flow code CFEST is used to predict the large scale flows through the mine and the SCV region. This, in turn, is used to provide boundary conditions for more detailed models, which predict the details of flow, using a discrete fracture network model, on scales of less than 10 m. We conclude that a fracture network approach is feasible and that it provides a better understanding of details of flow than conventional porous medium approaches and a quantification of the uncertainty associated with predictive flow modelling characterised from field measurements in fractured rock.

"EVAPORATION MEASUREMENT IN THE VALIDATION DRIFT – PART 3. COMPARISON BETWEEN THE FIRST AND SECOND SET OF MEASUREMENT RESULTS"

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December 1991

ABSTRACT

Two evaporation measurement series were carried out during April 3 – April 18, 1990 and May 27 – June 13, 1991 respectively in the Validation Drift (Watanabe, 1991a and Watanabe and Osada, 1991b). The first and the second measurement series were performed about one month and 14 months after the excavation, respectively. The results obtained by these measurement series are compared to each other with the aim to know the evaporation rate change during the period between these series.

The evaporation rate from the matrix part of the rock mass decreased from the first measurement to the second. The average evaporation rate obtained from the second measurement series was about 1/4 of the first measurement. The frequency distribution of the evaporation rate measured in the second measurement series was more concentrated compared to the distribution of the first measurement series. The frequency distribution obtained by the second measurement seems to be approximated with a normal distribution curve. The evaporation rate from some major fractures did not decrease so much compared to the rate on the matrix part. The average rate obtained in the second measurement series on some fractures was about 80% of that of the first measurement series.

The reduction of the evaporation rate may be due to the creation of an unsaturated zone around the drift. As the permeability decreases significantly when the saturation of the rock mass decreases, the evaporation rate or in the other word, the inflow rate must become smaller.

An attempt was made to estimate the ratio between the matrix flow and the fracture flow. However, a detailed study is needed on unsaturated flow in rock mass for precise estimation.

1991 TR 91-37

"CHARACTERIZATION OF THE STRUCTURE AND GEOMETRY OF THE H FRACTURE ZONE AT THE SCV SITE"

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December 1991

ABSTRACT

A steeply dipping fracture zone (H zone), averaging 3.62 m in width, located in homogeneous, medium grained, granite adjacent to the Stripa mine was mapped in detail along eleven drift walls over vertical and horizontal distances of approximately 100 m. This mapping provided data on the variation in fracture geometry and consisted of scanlines that extended from the regularly fractured granite adjacent to the fracture zone, across the zone and to a similar distance on the other side of the fracture zone as well as one metre high areal maps across the entire width of the fracture zone. Several combinations of the scanline and areal map data sets with the fracture data from earlier borehole drilling through the H zone have been used to evaluate the fracture geometry within the H zone. The fracture data have been analyzed and the orientation, trace lengths and spacings of the individual clusters or groups within the fracture zone have been compared to both the geometry of the fracture system adjacent to the H zone, and the fracture geometry in the average rock.

The fracture intensity within the H zone is clearly much greater than that in the average rock and there is considerable variability in the characteristics of the H zone. The general impression is one of decreasing fracture strength and trace length with increasing depth. Two strong sub-vertical fracture sets, a northeast-southwest and a weaker northwest-southeast set, are present in the H zone. Comparison of the mean orientations of the fracture sets in the H zone with the average rock in the Validation drift, shows that the main differences are in the mean orientations of the clusters and the presence of the stronger subhorizontal fracture sets.

The H zone is characterized by mylonites and breccias as well as anastomosing structures, duplexes and splays. In addition, a significant number of fractures within the H zone show evidence of shear displacement and close examination of the orientation of these striations suggest an oblique dip-slip shear structure. Fractures within the fracture zone form a set of Reidel shears and P shears that extend into the adjacent rock.

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"Geologic Characterization of Fractures as an Aid to Hydrologic Modeling of the SCV Block at the Stripa Mine"
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April 1992

TR 92-25
"Tracer Migration Experiments in the Stripa Mine 1980–1991"
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