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Äspö Hard Rock Laboratory

First True Stage

Pilot Resin Experiment

Summary Report

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March 2000

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Foreword

This report describes the Pilot Resin Experiment. The experiment has been carried out in order to develop and test techniques for characterization of the connected pore space of a selected target volume using resin injection and subsequent excavation, sample preparation and analysis.

The Pilot Resin Experiment is one component of the First TRUE Stage.

Abstract

One part of the First TRUE Stage is characterisation of the pore space of the target volume using resin injection and subsequent excavation. The overall aim with the resin programme is to incorporate the measured pore space data into the evaluation of the hydro- and tracer tests that will be carried out in TRUE. This report is part of the resin study and includes the main results from the Pilot Resin Experiment. The background information and detailed results from the aperture measurements are found in individual reports which are referenced and summarized in this report.

The Pilot Resin Experiment involves the test of epoxy resin penetration and behavior in fracture planes that are located within a few metres of the drift wall. The pilot experiment has been carried out in order to develop and test techniques for characterization of the connected fracture pore space within a small volume of a fractured rock mass using resin injection techniques, followed by recovery of sections of the target fracture planes. The resin injection, sample recovery, methods developed in the Pilot Resin Experiment, or a modified method will be used at a later stage to characterize the pore space of the main fracture planes that form the flowpaths at the TRUE-1 site.

The site that was used for the pilot experiment was initially penetrated by 9 small diameter boreholes that were used for site characterization. The site characterization included core logging, borehole TV inspection, hydraulic tests (flow logging, pressure monitoring in packed-off sections and interference tests) and tracer tests.

Resin was successfully injected from 3 borehole sections at the Pilot Resin site. Despite the relatively short curing times (about one hour) for the resin, the inline mixing of the resin and the hardener made it possible to inject the resin for several, 5-10 hrs, hours before the resin started to cure and develop high back-pressures at the injection sections. Resin breakthrough in adjacent boreholes indicated that it was possible to inject resin for at least one or more metres into the fracture planes.

The resin spreading was mapped by drilling 12 small diameter boreholes and investigating the cores for resin occurrence. This information was incorporated in a 3-D CAD model that was used to guide the drilling of the large diameter (200 mm and 146 mm) sampling core boreholes.

Resin was found at several locations in these large diameter cores. Two of these fractures were selected for aperture analysis. The analysis was carried out using two different techniques, an image analysis approach (KTH, Stockholm) and a photo-microscope-digitizing approach (FracFlow, Canada). Both methods showed the same magnitude of aperture, and similar standard deviations. The results show mean apertures of the analysed fracture planes in the order of 266 and 239 microns, respectively. The coefficients of variation were found to be 37 % and 39 % of the mean aperture, respectively. One sample had only about 1 % contact area and practically zero voids while the second sample had 22 % contact area and about 20 % void area.

It should however be pointed out that a consequence of the near-drift location of the site is that the fractures that were the subject of this experiment may have been mechanically disturbed to a certain degree and the measured pore space information may therefore not be representative for an undisturbed structure further away from the drift. However, the main goal of the Pilot Resin Experiment was to develop the techniques for the resin injection and subsequent sampling.

Sammanfattning

Karakterisering av porvolymen i den bergvolym som kommer att studeras i den första TRUE-etappen kommer att utföras med hjälp av injektering av epoxyharts och efterföljande utbrytning och analys. Det övergripande målet med epoxyinjekteringen är att inkludera erhållen information angående porvolymen i utvärderingen av de hydro- och spårämnesförsök som genomförts inom ramen för TRUE-1. Denna rapport är en del av epoxyprogrammet och behandlar de huvudsakliga resultaten från ett genomfört pilotförsök. Bakgrundsinformation och detaljerade resultat redovisas i separata rapporter vilka refereras och summeras i denna rapport.

Pilotförsöket har inkluderat testning av epoxys egenskaper i ett ortnära spricksystem. Syftet med pilotförsöket var att utveckla och testa teknik för karakterisering av porvolymen i en mindre bergvolym med hjälp av injektering av epoxy och efterföljande utbrytning och analys. Den utvecklade tekniken avses att användas för att karakterisera porvolymen i den bergvolym som undersökts inom ramen för TRUE-1 experimentet.

Strukturen där pilotförsöket utfördes har karakteriserats från 9 st 56 mm kärnborrhål. Borrhålen penetrerar strukturen ca 2-3 m från orten. Karakteriseringen inkluderade kärnkartering, borrhåls-TV, hydrotester (flödesloggning, tryckregistrering i avmanschetterade sektioner och interferenstester) och ett spårämnesförsök.

Lyckade injiceringar av epoxy utfördes från 3 st borrhål. Trots epoxys relativt korta härdningstid (ca 1 timme) möjliggjorde den utvecklade kontinuerliga "in-line" blandningen av epoxy och härdare injiceringstider av flera timmar, 5-10 timmar, innan epoxyn härdat så mycket att injiceringstrycket byggdes upp alltför mycket. Genombrott av epoxy i angränsande borrhål indikerar att epoxyn injicerades åtminstone en eller några meter i de skärande strukturerna.

Epoxys utbredning kartlades genom att borra 12 st 56 mm kärnborrhål och inspektera kärnorna med avseende på förekomst av epoxy. Informationen från dessa karteringar inkluderades i en 3-D CAD modell vilken användes för att planera borrningen av grövre kärnborrhål (diameter 200 mm och 146 mm) för provtagning av de epoxyimpregnerade strukturerna.

Epoxy återfanns i ett flertal av de strukturer som genomskärs av provtagningshålen. Två av dessa valdes ut för mätning av epoxyns (sprickans) vidd. Mätningarna genomfördes med två olika tekniker; bildanalys (KTH, Stockholm) och foto-mikroskop-digitalisering (FracFlow, Canada). Båda dessa tekniker gav liknande vidd på epoxyn och även liknande standardavvikelse. Medelvidden av epoxyharts var 239 respektive 266 µm. Variationskoefficienten var 37 respektive 39 % av medelvidden. En av de analyserade strukturerna befanns ha ca 1 % kontaktyta och praktiskt taget inga volymer som inte var epoxyfyllda. Den andra analyserade strukturen hade ca 22 % kontaktyta och ca 20 % av volymen var inte fylld med epoxy.

Det skall noteras att pilotförsöket har inkluderat testning av epoxyns egenskaper i en ortnära spricka. Detta innebär att strukturerna kan vara mekaniskt störda vilket medför att den erhållna porvolymsinformationen antagligen inte är representativ för en ostörd struktur längre in i berget. Pilotförsöket syftar emellertid till att utveckla teknik för epoxyinjektering och efterföljande provtagning av strukturen och analys.

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1 Introduction

This is one in a series of reports concerning the Pilot Resin Experiment, which is a part of the Tracer Retention Understanding Experiment (TRUE).

The main results from the resin injections and the pore space compilations are found in this report. Background information and detailed results from hydraulic tests, tracer tests, coreloggings and aperture measurements are found in a separate report *[Birgersson et al, 2000]*.

The choice of resin and resin injection technique are based on the findings that have been reported in the literature survey *[Birgersson and Lindbom, 1995]*. The test plan for the resin injection programme have been published in *[Birgersson et al, 1996]*.

The techniques for resin thickness measurements, detailed results and discussions regarding the aperture measurements are found in *[Gale and Hakami, 1999]*.

The procedure and results from the supporting bonding experiments are presented in a separate report *[Gale and MacLeod, 1998]* as well as the detailed results from the tracer experiment *[Andersson, 1998]*.

The Pilot Resin site has also been used for a two–phase flow experiment. The findings from this experiment are found in *[Jarsjö, 1997]* and *[Jarsjö, 1998]*.

1.1 Background

1.1.1 Justification of experimental work

One planned component of the First TRUE Stage is characterisation of the connected pore space of the investigated target volume using epoxy resin injection, subsequent excavation and analysis. The purpose of the characterisation using resin is both qualitative and quantitative. On the one hand, resin may reveal the geometry of the flow pattern, thereby improving our understanding of the flow path geometry. On the other hand, resin may be used for estimation of physical fracture aperture, which could possibly be related in a quantitative manner to tracer advection and mass transfer. The detailed pore space data may also be used to provide insight into the validity of the assumptions made in the evaluation and modelling of tracer tests conducted in the same fracture plane and in fracture planes in general.

A performed literature survey *[Birgersson and Lindbom, 1995]* revealed that resin injection and subsequent excavation have so far not been conducted *in-situ* in a structure that resembles the TRUE-1 target structure *[Winberg, 1996]*. The experiments that have been performed have been carried out mainly in the laboratory over considerably smaller length scales than the scale of the planned TRUE experiments. The *in-situ* test that was carried out in the Grimsel laboratory was carried out in a structure that has a significantly higher transmissivity and a different structure compared to the TRUE-1 structure (Feature A) *[Dollinger et al. 1995, Möri et al. 1996]*. In addition, the resin was injected under fully dewatered conditions. However, available methods and techniques ought to be applicable for the conditions that prevail for the TRUE-1 target structure. The inclusion of resin injection and subsequent sampling/data processing seems to be the most ambitious attempt to date to incorporate pore space information into the interpretation of hydraulic- and tracer experiments.

1.1.2 Output from the literature survey

This section summarises the major findings from the literature survey *[Birgersson and Lindbom, 1995]* regarding the resin injection and subsequent sampling.

Several different methods have been used in order to obtain pore space data from a fracture. The methods that have been applied or considered are:

- Fracture surface topography.
- Injection of curing component(s).
- Casting.
- Freezing.

These techniques are discussed in *[Birgersson and Lindbom, 1995]*.

All these methods have their pros and cons, but the injection method seems to be the most relevant for our purpose since it will give connected pore space data for the ambient *in-situ* stress and hydraulic boundary conditions under which both flow and tracer tests have been conducted.

Injection can be carried out using a metal (Wood´s metal), cement based grouts or resins. Injection of a melted metal is unfortunately not applicable in a fairly large scale *in-situ* experiment. The excavation of the drifts in Äspö was preceded by an injection of grout in order to reduce the amount of water inflow into the drifts. Some fractures intersecting the drifts have been analysed with regard to the grout thickness *[Hakami, 1994]*. However, the use of a grout seems to be restricted to fractures that have considerably larger aperture than the target structures for the TRUE-1 experiment. Injection of a resin followed by excavation and sampling is considered the best alternative for the type of fractures that will be investigated in the TRUE experiments.

Several types of resins such as polyester-, polyurethane-, acrylic- and epoxy-based are available. Epoxy resins seem best suited for our purpose due to a fairly low viscosity and the fact that epoxy resins do not shrink significantly during the curing process. Some of the other types of resins have drawbacks like gas generation, shrinking and chemical reactions with water.

The discussion above indicates that injection of an epoxy resin seems to be the best choice for determination of the connected pore space. However, the water in the fracture plane has to be removed prior to the resin injection in order to make it possible for the resin to penetrate the pore space and bond to the fracture walls. The literature survey revealed that this has been accomplished in the laboratory in several ways, including allowing the fracture to dry, flushing of nitrogen and carbon dioxide gas through the fracture plane, or by replacing the water with acetone or iso-propanol. The use of iso-propanol is probably the best choice for the Pilot Resin Experiment since this method has been carefully developed and tested *in-situ* by the group at Grimsel and on laboratory specimens.

The viscosity of the epoxy resin mixtures used by NAGRA *[Frieg et al.,1995]* and by FracFlow *[Gale, 1995]* will increase with time as the resin cures. However, the resin can be injected for a few hours before the increase in viscosity requires injection pressures that are too large. The distance the resin will penetrate into the target structure during this time will depend on the injection pressure and the properties of the target structure. The resin used by FracFlow *[Gale, 1995]*, EPO-TEK 301, is commercially available in a number of countries, including Sweden, and this availability resulted in it being recommended for use in the laboratory and pilot experiments carried out in this study. The properties of EPO-TEK 301 are provided in *[Birgersson et al, 2000]*.

1.2 Outline of the resin injection programme

The resin injection in a selected target structure could be preceded by a tracer test using a dye which will allow a direct comparison between the characteristics of the connected pore space inferred from measurement of the resin distribution with that seen by the dye. This comparison will have to take into account the scale of the fracture plane impregnated with resin and the subsequent resin/fracture plane sampling scale, relative to the scale on which the tracer tests are conducted.

The following activities are planned subsequent to resin injection in a typical target structure;

- Excavation and/or drilling.
- Analysis of pore space (resin thickness, etc) and flow paths.
- Sampling and analysis for matrix diffusion.
- Updating and conditioning of numerical models using pore space data.

Prior to application of the resin impregnation technology in the target structure, it has to be further developed and tested in a pilot scale experiment in an easy accessible (near-drift) fracture. The objective of the Pilot Resin Experiment is to develop a proper resin injection technique, determine the rheologic properties of the selected resin under the field conditions that prevail at Äspö and to assess that acceptable penetration of resin into the fracture plane(-s) can be obtained.

The technology development and full field application of the pore space characterization technology using resin employed during the First TRUE Stage is designed to generate techniques that can be applied during subsequent experimental phases of TRUE.

1.3 The Pilot Resin programme

1.3.1 Objectives

The First TRUE Stage is partly devoted to the development of a methodology for determination of the connected pore space distribution in the investigated target structure. The objectives of the Pilot Resin Injection experiment are:

- "to develop and test a technology for injection of epoxy resin on a detailed scale and to develop and test techniques for excavation (drilling) of injected volumes and subsequent analysis" *[Winberg, 1994]*.

Furthermore, the resin and the structure to be selected for use in the Pilot Resin Experiments should fulfil the following requirements:

- The fracture plane that will be used in the pilot experiment should have properties that resemble those of a potential target fracture.
- The pilot resin injection and subsequent data collection/compilation/evaluation should be carried out in a way that is as close as possible to the procedure that will be applied for the target fracture.
- The pilot experiment should give data that could be applied in existing models or modified versions of these models in order to develop conceptual understanding of resin behaviour during injection into a fracture plane.
- It should be possible to inject the resin for hour(s).
- It should be possible to inject resins, labelled with different dyes, from several holes.
- It should be possible to inject the resin over an area of the fracture plane(-s) that is on the order of square metres.
- The applied injection pressure should not exceed the *in-situ* fluid pressures in the pilot fracture by more than about five bars, after corrections for the differences in viscosity and density between the groundwater and the resin. Actual resin injection pressures in the borehole section during resin injection may have to be as high as 20 to 25 bars above existing hydraulic pressures to ensure resin penetration of the fracture plane. However, the resin injection pressures will be relaxed to five bars or less above existing hydraulic pressures before the resin sets or cures substantially.

Finally, it would be advantageous to inject a slightly sorbing dye (“ink”) in order to carry out a visual correlation between the flow paths “seen” by the water and the fracture pore space occupied by resin.

1.3.2 Expected outcome from the experiment – defined prior to the experiment

For the Pilot Resin Experiment, a set of expectations in key areas for both the performance and the outcome of the experiment were given in the Test Plan *[Birgersson et al, 1996]* that was written prior to the resin injection. These expectations are outlined below. The actual outcome from the Pilot Resin Experiment is discussed in Chapter 8.

Injection distance/area

It was expected that the resin would be injected at least about 0.5 m to 0.75 m (1.0 to 1.5 m in diameter) or more into the fracture plane from each borehole if the fracture has an average hydraulic aperture of at least 0.050 to 0.100 mm. If there is a series of well connected pores, one can expect that the resin will be injected for several metres along well-defined pathways. However, much depends on how the first resin that is injected into each borehole, or the leading edge of the resin, cures and whether it cures and plugs the larger pores first and thus forces the following resin to redistribute, invade and fill the smaller or more poorly connected pore space. Overall, it should be possible to inject the resin into an area of the fracture plane on the order of m^2 when all of the available exploration boreholes are used to inject the resin.

Injection pressures

While it is very important not to "hydrofrac” the fracture plane by using too high injection pressures, the injection pressure has to be high enough to compensate for the more viscous nature of the resin. It was projected that the maximum resin injection pressure should be about 15 to 20 bars above the ambient hydraulic pressure in each borehole during resin injection, but these pressures will be reduced to about 5 bars after about an hour of resin injection (i.e. when the resin starts to cure) and will be maintained at this pressure while the remainder of resin is curing.

Injection time

For most resins, the time available before the resin begins to cure, and increase its viscosity, is about one hour. It was estimated that about one hour was needed before considerable curing starts in order to get reasonable resin impregnation. An absolute minimum is in the order of about half an hour. However, the developed piston-pump and mixing head system, and the reduced resin volumes in the packed off intervals, that were developed for the Pilot Resin Experiment, were expected to increase injection times, before curing at the borehole, to several hours. The piston-pump and mixing head system are described by *[Birgersson et al, 2000]*.

Time lag between injection and excavation

Based on existing experience in the laboratory, it should be possible to start the sampling of the resin impregnated structures about 48 hours after completing the resin injection. Previous experience also suggests that the longevity of the resin will make it possible to collect additional samples several months after the resin has been injected into the fracture plane.

Boundary conditions

One of the main differences between this Pilot Resin Experiment and experiments in the laboratory, as well as the field experiment at Grimsel, is the difference in the boundary conditions. In the laboratory, it is possible to control the boundary conditions, remove the water from the fracture plane by placing the fracture plane under a vacuum, flush the remaining water from the pore space with alcohol, apply a second vacuum to remove or reduce the amount of alcohol in the fracture pore space and then inject the resin under an initial vacuum followed by an increasing injection pressure. A similar approach was used at Grimsel *[Dollinger et al, 1995]*.

The technique used for the resin injection in the Pilot Resin Experiment is based on selectively injecting in one or more boreholes and withdrawing from other holes in order to seal parts of the fracture plane from the *in-situ* water.

2 Experimental concept

2.1 Experimental procedure

The objectives of the pilot study are related to technology development, to the determination of the rheologic properties of the selected resin under field conditions, and to assess that acceptable penetration of the resin into the fracture plane(-s) is obtained.

The Pilot Resin Injection experiment has included the following main steps:

- Identification and characterization of the test site.
- Instrumentation with packer systems.
- Resin injection.
- Exploratory drilling (Ø 56 mm).
- Quantitative drilling (Ø 200 mm and Ø 146 mm).
- Sample preparation.
- Analysis of pore space.
- Conceptual modelling.

These main items are described in this report. Detailed information is found in Appendix, the report "Background Information" *[Birgersson et al, 2000]* and stand alone reports, see Chapter 1.

2.2 Selection of the experimental site

Before the site for the Pilot Experiment was selected, a list of requirements were established to determine the suitability of the site/fracture for the Pilot Resin Experiment. These requirements are outlined below and have been included in this report to reflect the discussions that preceded the site selection. It should also be pointed out that it was not possible to chose the optimal site at the Äspö laboratory for the Pilot Experiment, since the choice had to take distance to other structures, distance to other experiments, logistics (not blocking transportation tunnels etc) and other considerations into account. The choice of site was therefore in practice restricted to a few locations rather far from ongoing experiments and main transportation tunnels.

2.2.1 Requirements on the selected site

Transmissivity

The Pilot Resin Experiment fracture (PEF) should have a transmissivity that is close, within one order of magnitude, to that of a typical target fracture (TF) at the TRUE-1 site ($T=5\cdot10^{-8} - 5\cdot10^{-7}$ m^2/s). It was expected that it is harder to inject resin in a less conductive fracture. This implies that the transmissivity of the PEF needed to be equal to, or lower than that of a typical TF.

Geometry

The geometry (strike/dip) for the PEF should resemble that of a typical TF which are preferentially oriented north-west. The impression is that the geometry of a typical TF may be quite complex. Such a complex geometry may induce problems in the evaluation of the pore volume characterisation. The site selection was therefore focused on finding a structure with a geometry that was similar or simpler than that of a typical TF.

Strike/dip and rock stresses

A general impression from Äspö and Stripa is that fractures with different orientations can have significantly different hydraulic properties. This can be due to variations in rock stresses, fracture type, fracture mineralogy and infilling materials, fracture stiffness, etc. Thus, it was considered that a PEF with the same orientation as a typical TF should be preferred. However, a typical PEF is located close to the drift and will therefore be subjected to rock stresses that are not representative for a TF in a rock volume which is not affected by an underground opening. Therefore, it was decided not to make the orientation of the PEF a controlling factor.

Drilling of boreholes

It was decided that the angle between the boreholes used for resin injections and the PEF should not be 90 degrees since this might allow the cores to rotate during drilling and damage the fracture planes in the core. Angles of at least 15 to 20 degrees from perpendicular were preferred. The large diameter boreholes for sampling after resin injection could be perpendicular as well as parallel to the fracture plane.

Distance from drift

For ease of both resin injection as well as sampling, it was decided that it should be possible to intersect the PEF with several boreholes 1-3 m in length and intersecting the PEF at least 1 m from the drift wall. Furthermore, the distance between the boreholes should be no more than 1-2 m in the plane of the fracture.

Orientation relative to the drift

It was first assumed that the PEF should be almost parallel to the drift. However, after considering that this would probably induce very unfavourable stress conditions, it was decided that the angle between the drift and the PEF should be somewhere between 45 and 90 degrees. It was decided that 45 degrees would be the optimum angle since this angle would allow the subsequent sampling of the fracture plane (large diameter drillcores) to be carried out perpendicular as well as parallel to the fracture plane.

Intersection with the drift

Given the lack of information on whether a fracture is a conduit or not, it was felt that the fracture plane should be visible over some (2 or more) metres in the drift to ensure that the trace of the fracture could be properly mapped and described. This would allow comparison of the structure of the fracture plane with the flow rate, tracer and pore volume characterisation.

The structure selected for the TRUE-1 experiments *[Winberg, 1996]* has been penetrated by five boreholes. These boreholes intersect the structure about 10-15 m from the drift. It is not possible to identify the structure in the drift even though the structure is near perpendicular to the drift. It should however be noted that a mylonite structure can be seen in the drift. This structure could be a splay of the TRUE-1 target feature, but it has a smaller inclination than the TRUE-1 target feature and is not associated with any water seepage. The hydrostatic pressures measure in the range of 3-4 MPa (30-40 bar) and the water inflow rates 0.1-4.12 l/min (at atmospheric pressure).

2.2.2 Structure selected for the Pilot Resin Experiment

The structure that was selected for the pilot experiments is the fracture labelled "13" in the centre of Figure 2-1. The structure is located in the F-tunnel at the 450 m level, parallel to the main access tunnel, see Figure 2-2.

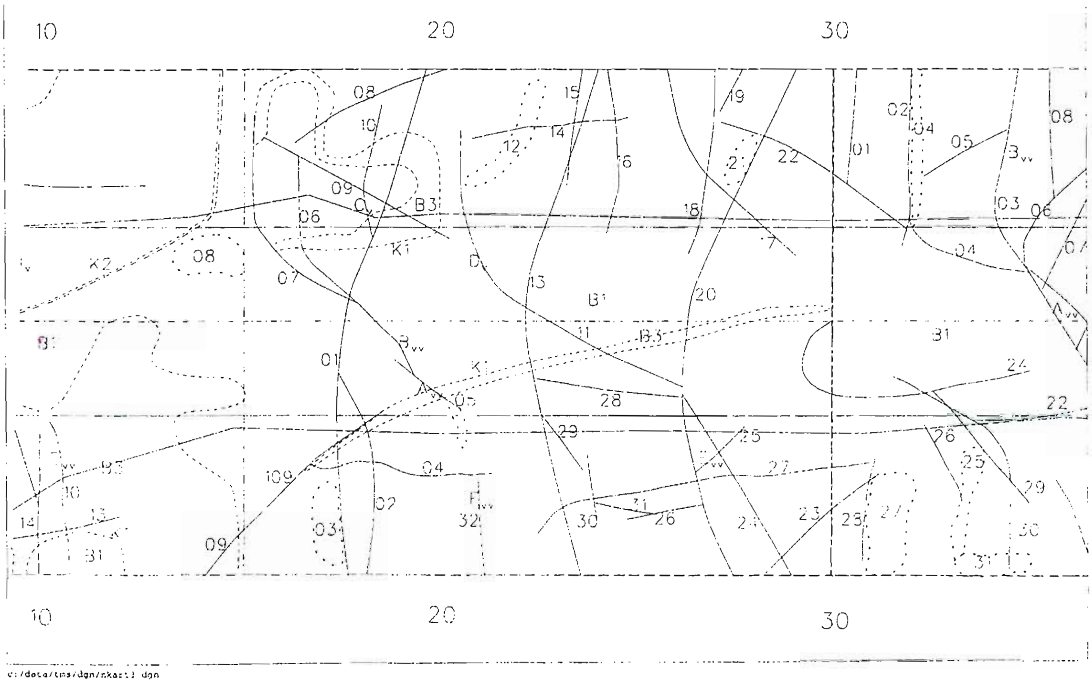


Figure 2-1 Fracture mapping of a 25 m section in the F-tunnel. The target fracture for the Pilot Resin Experiment is located in the central part of the figure and has been labelled "13". "Fold-out" with ceiling forming the centre part with the walls above and below.

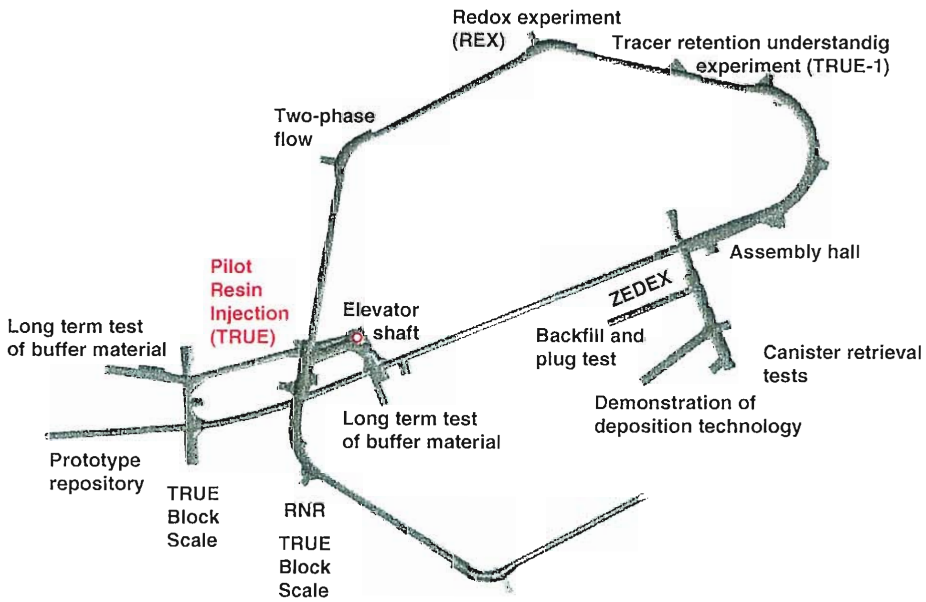


Figure 2-2 Experimental sites at the Äspö laboratory.

The identified structure seems to be fairly simple and does not appear to have any major cross-cutting structures in the immediate vicinity.

A total of nine 56 mm boreholes (the KXTP boreholes) were drilled into the structure, see Figure 2-3. This is quite a large number of boreholes considering that all of the holes are located within a few metres. The reason for the large number of boreholes was that the drill rig was only available for a short time period and all drillings at the site therefore had to be carried out in a single drilling campaign. The advantage with the large number of boreholes was that the site could be well characterized. The drawback was that the dense borehole array created significant hydraulic interference and disturbances between the holes.

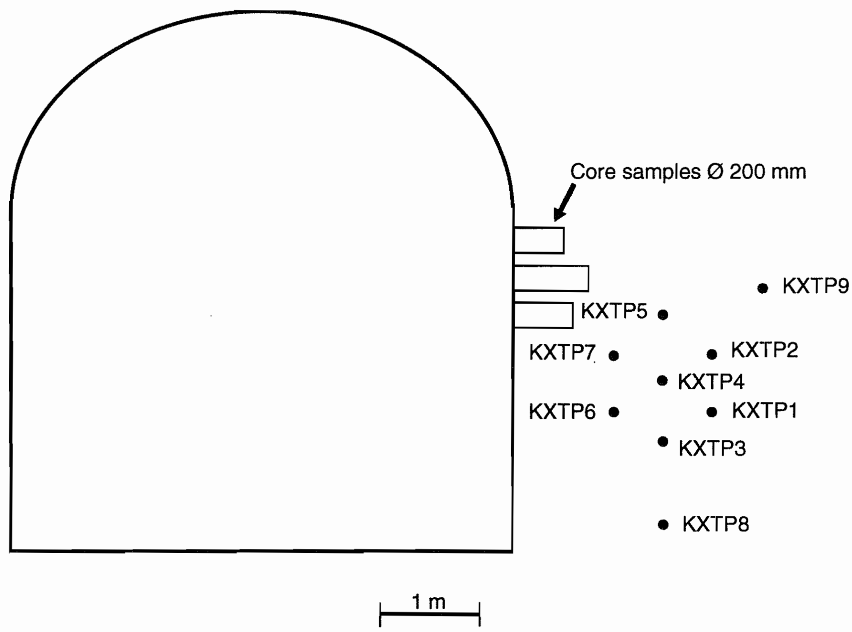


Figure 2-3 Schematic illustration of the borehole pattern at the intersection with the target structure. View along Tunnel F seen from the East.

3 Site characterization

3.1 Overview of performed characterisation

The chosen main structure for experimentation is a well defined, more or less isolated, structure that can be followed over several metres on the drift wall, see Figure 2-1. The site was characterized using 9 cored boreholes, Ø 56 mm, each about 3-4 m in length, see Figure 2-3. The characterization programme included:

- **Surveying:**
  - Collar coordinates.
  - Deviation.
- **Geology**:
  - Core logging.
  - Borehole TV (PearPoint).
- **Hydrology**:
  - Flow logging (resolution 0.05 m).
  - Measurement of hydraulic pressure.
  - Interference tests.
  - Tracer tests.

The core logging and borehole TV inspection were carried out to characterise the fractures intersecting the boreholes with regards to fracture filling, fracture location (x, y, z) and absolute orientation (dip, strike). This information was combined for the nine cores to get a description of the structures at the site. The main results from these tests are described in this chapter.

The core logging, together with the hydraulic testing and the tracer tests, formed the principal basis for the descriptive model of the structures at the site.

3.2 Summary of performed drillings and core loggings

All holes drilled at the site have been core drilled. All cores have been logged. A compilation of the boreholes is given in Table 3-1. Geometric information about the boreholes is given by *[Birgersson et al, 2000]*.

Table 3-1 Boreholes drilled at the Pilot Resin site. F-tunnel L=0/025 m.

Borehole	Number of boreholes	Diameter [mm]	Pilot hole [mm]	Comment
KXTP	9	56	-	Used to characterise the site
KXTRI	10 + 2	56	-	Used to characterise the resin spread
KXTE	3 + 3	200 / 146	36	Sampled the structures for resin

The KXTP1 through KXTP9 boreholes were drilled in order to characterize the site. The remaining boreholes were drilled after the resin injection. The KXTP boreholes are intersecting the target structure about 1-2 m from the drift wall.

The KXTRI1 through KXTRI10 boreholes were drilled in order to characterize the resin spread. The information from these boreholes was incorporated in a 3-D CAD-model in order to guide the drilling of the large diameter coreholes. Ten boreholes were drilled according to the plans, each about 4 m in length. The drilling of another two boreholes was terminated after a short distance, 1-2 m, due to technical problems.

The KXTE1 through KXTE6 boreholes were drilled in order to sample the structures for quantitative analysis of resin thickness.

3.2.1 Core logging of the KXTP cores

The logging of the KXTP boreholes was primarily focused on structural geological characteristics and primarily on the following items:

- Tentative geological description of the host rock.
- Description of fracture surfaces (roughness, slicken lines, minerals).
- Angle of intersection between borehole and fracture.

The KXTP boreholes are quite short, about 3 m, and are located within a rock volume of a few cubic metres. All cores therefore have more or less the same geological character. Apart from providing the basis for the structural description, the core logging showed that:

- The dominating rock type is Äspö diorite, which is found in about 90-95 % of the core length. The remaining 5-10 % consists of red fine-grained granite.

- The fracture frequency is about 3-4 fractures per meter. The fractures are rather evenly distributed along the core length. However, in some cores there is a slight tendency that the fractures are clustered to a certain part of the core. This tendency is however not strong.

- The dominating fracture coating mineral is chlorite, followed by calcite. Both these coating minerals are found in a large number of fractures. Epidote and quartz is found in a few fractures.

The cores were not oriented, but the angle between the core (borehole) and the fracture was mapped, i.e. the α-angle. Fractures with α-angles varying from 0 degrees (parallel) to 90 degrees (perpendicular) are found in the cores. However, most of the fractures, including the target fracture illustrated in Figure 2-1, have a large α-angle (45-90 deg). It should however be noted that fractures that were included in the descriptive model of the site were oriented based on the TV-logging and borehole deviation information.

3.2.2 Core logging of the KXTRI cores

The logging of the KXTRI boreholes was primarily focused on compiling resin and/or dye observations. These observations were incorporated in a 3-D CAD-model in order to guide the drilling of the subsequent large diameter boreholes.

A brief examination showed that about 90-95 % of the cores consist of Äspö diorite and the remaining 5-10 % of red fine-grained granite. This was also observed in the KXTP cores, see above.

The cores were oriented and both the α- and the β-angles were monitored for the fractures where dye and/or resin was found. The orientation was however lost in some cores due to rotation of the core.

3.2.3 Core logging of the KXTE cores

The KXTE holes were drilled in order to sample the structures at the site for resin, see Section 5.3. The logging of these cores was restricted to observations of dye and/or resin.

The KXTE boreholes were drilled into the same small rock volume that had been characterized geologically based on information from the KXTP boreholes and studied by the KXTRI boreholes.

All cores, except KXTE6, were oriented using visual inspection and the α- and the β-angles were measured for the fractures where dye and/or resin was found. The core from KXTE6 was broken in a large number of pieces due to technical problems during the drilling. Absolute orientation is therefore missing or uncertain for this core.

3.3 Summary of hydraulic testing

Hydraulic testing was carried out in the KXTP boreholes in order to identify sections in the boreholes with high water inflows. The hydraulic testing programme of the boreholes included:

- High resolution flow logging (0.05 m increments).
- Measurement of hydraulic pressure (in packed off borehole sections).
- Interference tests.

3.3.1 Flow logging

Prior to the tests, all holes were sealed off using a single mechanical packer located fairly close to the start of the borehole. The flow logging tests were carried out by opening one packed-off hole to atmospheric pressure one at the time and monitor the water inflow rate. Subsequently the packer was moved and the measurement repeated.

The flow logging was carried out using a single packer in such a way that it was possible to differentiate the water inflow into 0.05 m sections. Flow logging was not carried out in boreholes KXTP5, 6 and 7 due to very low water inflow rates into these boreholes.

The main results from the flow logging are summarized in Table 3-2. Detailed information regarding the measurement procedure and results is found in *[Birgersson et al, 2000]*.

Table 3-2 Main results from the flow logging.

Borehole	Total flow rate [ml/min]	Relative inflow into the 5 cm section with **largest** inflow. Percent of the total water inflow.	Relative inflow into the 5 cm section with the **second largest** inflow. Percent of the total water inflow.
KXTP1	62	37[a]	27[b]
KXTP2	73.5	44	12
KXTP3	18	39	17
KXTP4	16	95	-
KXTP8	9.5	58	11
KXTP9	70	~ 100	-

[a]Section length 6 cm.
[b]Section length 18 cm.

It can be seen from Table 3-2 that a significant part (37 % to about 100 %) of the total inflow into the entire borehole is found in a single 5 cm section. The water inflow into the two sections with largest inflow is for all boreholes well above 50 % of the total inflow.

One important finding from the flow logging is that the water inflow into the boreholes can be associated with one or a few intersecting structures.

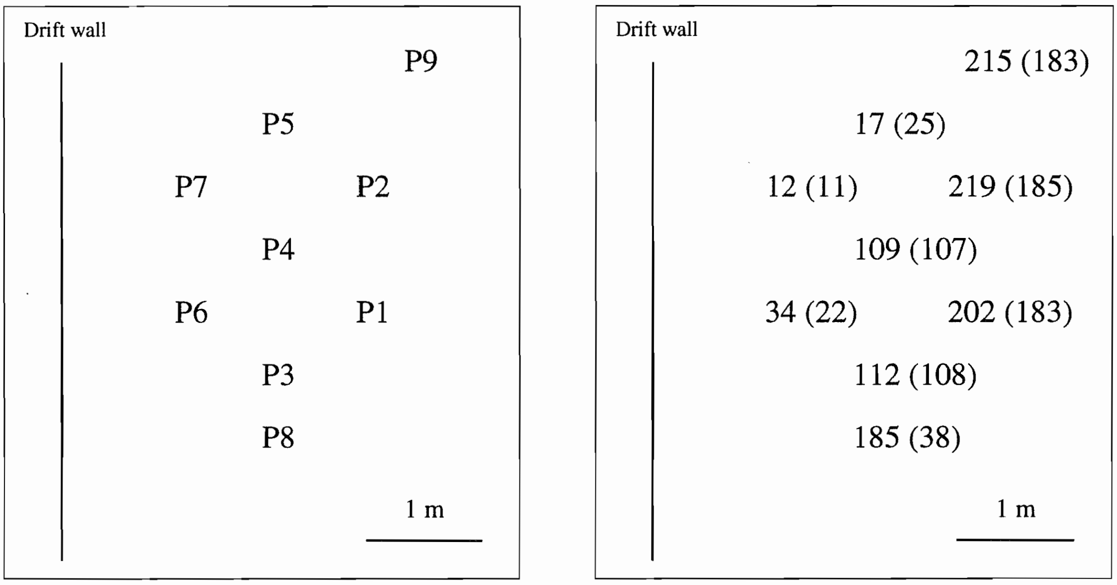
3.3.2 Measurement of hydraulic pressure

The boreholes were equipped with mechanical packers packing off the interior of the borehole. The length of the sections varied between 0.6 and 2.9 m. Dummies were installed in the packed off borehole sections in order to reduce the volume, see section 4.5. The pressure in the sections were logged using individual pressure transducers and portable data loggers. The hydraulic pressure has been monitored in boreholes KXTP1-9 at several occasions.

A schematic illustration of the borehole configuration at the intersection with the target structure and pressures monitored shortly after that the drilling of the holes was completed is found in Figure 3-1. The water pressures were measured using low resolution manometers. The monitored water pressures should therefore be regarded as uncertain.

Values on the water pressure that was observed several months later, at time 960410 12.00 (i.e. 1.5 hours after injection of Uranine in KXTP2), are shown in Table 3-3 and in Figure 3-1. These pressures were measured using high resolution pressure transducers.

The pressures in boreholes KXTP5, -6 and -7 are in all measurements very uncertain due to very low water inflow rates.



Borehole configuration *Elevation head*

Figure 3-1 Sketch showing intersections of the drilled boreholes with the identified target structure #13 and rough estimates of the elevation heads (m) above the datum of the tunnel floor. The heads were monitored using low resolution manometers. Data from September 1995. Data from April 1996 using high-resolution pressure transducers, see Table 3-3, within brackets.

Table 3-3 Pressures registered during the Pilot Resin Tracer test (960410, 12.00). Pressures monitored using high resolution pressure transducers.

Borehole	Borehole section (m)	Elevation head (m)	Distance from drift to intersection with target structure (m)
KXTP1	0.76 - 3.645 (end of bh)	183	~ 2
KXTP2	0.73 - 3.595 (end of bh)	185	~ 2
KXTP3	1.15 - 3.165 (end of bh)	108	~ 1.5
KXTP4	2.30 - 2.90 (end of bh)	107	~ 1.5
KXTP5	1.18 - 2.805 (end of bh)	25	~ 1.5
KXTP6	0.95 - 1.75 (end of bh)	22	~ 1
KXTP7	1.12 - 2.025 (end of bh)	11	~ 1
KXTP8	0.85 - 2.17 (end of bh)	38	~ 1.5
KXTP9	0.95 - 2.915 (end of bh)	183	~ 2.5

When comparing the pressure readings from September 1995 and April 1996, see Figure 3-1, it can be seen that the pressures are generally somewhat lower in September 1995. This is not surprising since the measurements are based on two different monitoring systems with large difference in accuracy and resolution but above all the data reflect seasonal changes in pressure.

The only major difference in pressure between the two pressure readings is found in borehole KXTP8. The low value from April 1996 (38 m) is a result of a small leakage. The larger value on the pressure from September 1995 (185 m) is a more representative pressure for KXTP8.

Even though there are some differences between the pressure readings from September 1995 and April 1996, the relative magnitudes and pattern are the same. It can be seen that the pressure generally increase with increasing distance from the drift. The gradient is in the order of 100 m/m over the array. Furthermore, the pressure difference is in some cases in the order of 100 m between boreholes separated by less than 1 m. This gives a gradient that is locally larger than 100 m/m.

Furthermore, it was observed that the pressures at the site were very sensitive to small changes in the packer positions and any leakage due to the short distance between the boreholes as well as between the boreholes and the drift.

Boreholes KXTP1, KXTP2 and KXTP9 (and possibly also KXTP8) were found to have about the same hydraulic pressure, 20 bars. The hydraulic pressure in boreholes KXTP3 and 4 was about 10 bars. No reliable pressure data could be obtained from boreholes KXTP5, KXTP6 and KXTP7 due to very low water inflow rates into these borehole sections.

3.3.3 Interference tests

One important type of hydraulic test in order to determine the connection between the different boreholes are crosshole pressure interference tests. In these tests, one borehole was opened to atmospheric pressure and the pressure response was monitored in the remaining eight borehole sections. A change in pressure indicate a hydraulic connection between the boreholes. The test sections during the interference tests are found in Table 3-3.

The activities and the manual readings of the pressure gauges during the interference tests are compiled in Appendix 1. The main activities are found in Table 3-4. The pressure responses during the interference tests are found in Figures 3-2 and 3-3.

Table 3-4 Main activities during the interference tests. Time given in relative time in hours from 960401 00:00.

Borehole	Opened [h]	Closed [h]
KXTP1	~ 46	~ 47
KXTP2	~ 62	~ 63
KXTP3	~ 56.5	~ 57.5
KXTP4	~ 59.5	~ 60.5
KXTP8	~ 43.5	~ 44.5
KXTP9	~ 41	~ 42

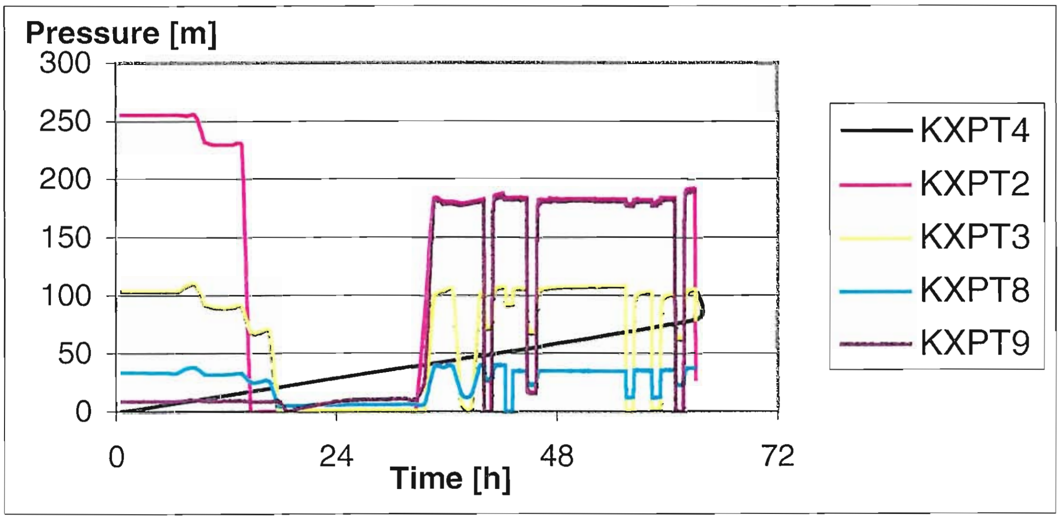


Figure 3-2 Interference tests. Pressure responses in boreholes KXTP2, KXTP3, KXTP4, KXTP8 and KXTP9. Time given from 960401 00:00. See Table 3-4 for main activities during the tests.

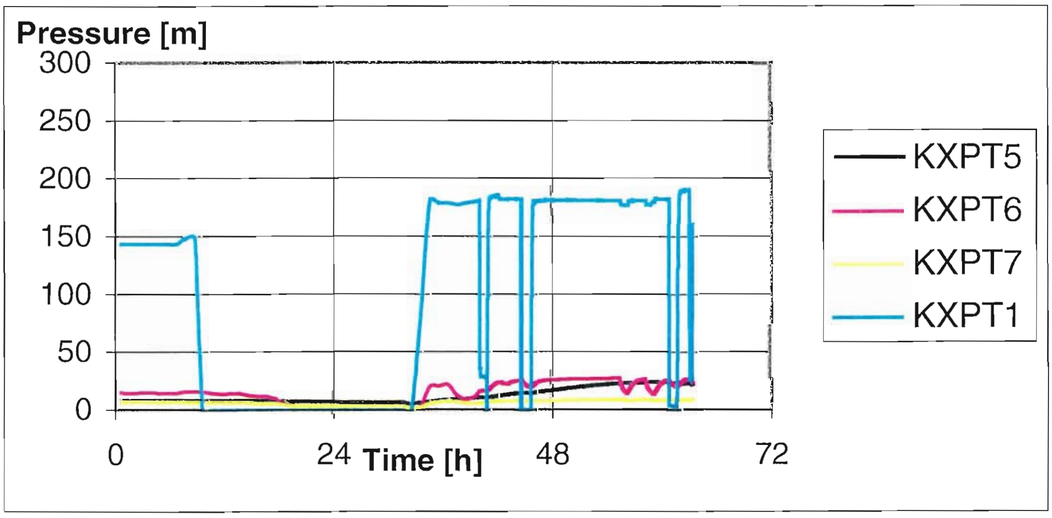


Figure 3-3 Interference tests. Pressure responses in boreholes KXTP1, KXTP5, KXTP6 and KXTP7. Time given from 960401 00:00. See Table 3-4 for main activities during the tests.

The low pressures during between ~ 15 h to ~ 35 h were caused by a reinstallation of packers in some of the boreholes.

The pressure responses in the different boreholes have been compared in terms of normalized drawdown dH/Q, where dH is the head decrease (m) in the observation sections and Q is the water inflow rate into the open borehole section (l/h), see Table 3-5. A blue label indicate a large response and a red label a small pressure response.

Table 3-5 Pressure response in the different boreholes.

Borehole kept open	Pressure response, dH/Q [m/(l/h)]								
	KXTP1	**KXTP2**	**KXTP3**	**KXTP4**	KXTP5	KXTP6	KXTP7	**KXTP8**	**KXTP9**
KXTP1	-	37.4	35.2	39.6	0	?	0	19.3	38.2
KXTP2	50	-	37.0	41.7	0	?	0	24.6	44.2
KXTP3	0.81	0.68	-	114	0	?	0	38.6	0.69
KXTP4	0.81	0.68	95.4	-	0	?	0	38.6	0.69
KXTP5	NA	NA	NA	NA	-	NA	NA	NA	NA
KXTP6	NA	NA	NA	NA	NA	-	NA	NA	NA
KXTP7	NA	NA	NA	NA	NA	NA	-	NA	NA
KXTP8	0.81 ?	0.68 ?	14.4	16.1	0	?	0	-	0.69 ?
KXTP9	41.7	35.4	31.9	35.9	0	?	0	21.1	-

Blue Large pressure response compared to the other boreholes.
Red Small pressure response compared to the other boreholes.
The pressure decreases are taken from the Interference tests presented in Figures 3-2 and 3-3.
The water inflow rates are based on the results from the water inflow measurements, see section 3 in *[Birgersson et al, 2000]*. The following water inflow rates have been used in the calculations. KXTP1: 3.72 l/h, KXTP2: 4.41 l/h, KXTP3: 1.08 l/h, KXTP4: 0.96 l/h, KXTP8: 0.57 l/h and KXTP9: 4.32 l/h.

It can be seen in Table 3-5 that the pressure response, dH/Q, is almost the same (within a factor 2) for all boreholes when KXTP1, -2 or -9 are opened. These boreholes have the largest flowrates and therefore control the flow situation at the site.

When opening borehole KXTP3 or -4, there is a large difference (2 orders of magnitude) between the responses in the different boreholes. The response in boreholes KXTP1, -2 and -9 is very small (red colour) compared to the response in KXTP3 and -4 (blue colour).

The difference in response when opening borehole KXTP8 is quite large between the holes. KXTP3 and -4 show the largest response, while the response in KXTP1, -2 and -9 is considerably lower. Some of the pressure responses when opening KXTP8 are somewhat uncertain, see Table 3-5.

Boreholes KXTP5, -6 and -7 all have very low water inflow rates. No pressure decrease was observed in KXTP5 or -7 during the interference tests. A small pressure decrease was observed in KXTP6. However, the response, dH/Q, is not meaningful to calculate due to the low and uncertain value on the water inflow.

3.3.4 Evaluated specific capacities

The flow logging was carried out using a single packer in such a way that it was possible to differentiate the water inflow into 0.05 m sections. The total inflow rates and calculated specific capacities are given in Table 3-6. On the average, about 50 % of the total inflow into the entire borehole was found in a single 0.05 m section, see Table 3-2.

Table 3-6 Water inflow rates and calculated specific capacities.

Borehole(s)	Inflow rate Q [ml/min]	Pressure drop (dH) [m]	Specific capacity [m^2/s]
KXTP 1, 2 and 9	≈ 70	≈ 210	$6 \cdot 10^{-9}$
KXTP 3 and 4	≈ 20	≈ 110	$3 \cdot 10^{-9}$
KXTP 8	≈ 10	185	$9 \cdot 10^{-10}$

3.3.5 Main findings from the hydraulic testing

It is quite obvious from the results of the flow logging, the measurement of hydraulic pressure and the interference tests that there are at least two important flow systems at the site. The flow situation is in many ways similar in boreholes KXTP1, -2 and -9. The boreholes KXTP3 and -4 also have a similar flow situation. Borehole KXTP8 is quite odd. It has about the same hydrostatic pressure as boreholes KXTP1, -2 and -9, see Figure 3-1, but the pressure response, see Table 3-5, resembles that seen for boreholes KXTP3 and -4.

3.4 Summary of the tracer tests

The purpose of the tracer test carried out at the site was to obtain estimates of transport properties. A summary of the results is given in the following sections. Breakthrough curves are found in Appendix 3.

3.4.1 Tracer injection and sampling

The tracer test was performed in a converging flow geometry by using the tunnel as a sink. Two tracer injections were made in the packed off sections in KXTP2 and KXTP3, respectively. The injections were made as decaying pulse injections without applying any excess pressure. The tracers used were Uranine (Sodium Flourescein) and Rhodamine WT.

Samples for tracer breakthrough were taken in boreholes KXTP1, KXTP3, KXTP4 and KXTP9. Occasional samples were also taken in the tunnel. After finishing the test a sample was taken in KXTP8.

In order to calculate the actual mass flux of tracer to a borehole section, the flow rate through the borehole section had to be estimated. This was done by tracer dilution tests in the above selected borehole sections. The dilution tests were made in the same way as the tracer injections by injecting a short pulse of tracer (Rhodamine WT or Uranine) and measuring the decay of the pulse.

3.4.2 Main conclusions from the tracer tests

Tracer injection in borehole KXTP2 gave a fast breakthrough in KXTP1 (<0.5 h) and a relatively high recovery (37%). The noted recovery is partly an effect of the very small pumping (5 ml/h) performed in KXTP1 which increase the zone of influence around the borehole. However, the recorded mass recovery and fast travel time indicates a major flow path between the two boreholes.

The breakthrough in KXTP9 is much slower (first arrival after 5.5 h) and show a low mass recovery (0.1%) indicating a minor flow path.

The injection of Rhodamine WT in KXTP3 gave no breakthrough other than in the tunnel.

3.5 Descriptive model of the site

The objectives of the model building were to develop a geometrical model showing the boreholes and fractures in 3-D as well as identifying the fractures that are associated with most of the observed water inflow.

The descriptive structural hydraulic model in 3-D of the Pilot Resin site has mainly been constructed from the following data/observations:

1. Geological and fracture information from the nine KXTP-cores; rock type, mineral, striation, form, type, surface structure and angle of intersection between borehole axis and fracture (α).

2. Strike and dip of the fractures, determined from the TV-logging with the Pier Point P 220 Borehole TV system and borehole deviation data.

3. Geological and structural data from the tunnel adjacent to the experimental volume.

4. Results from the hydraulic and tracer tests in the boreholes.

Flow logging using a mechanical packer has been performed in all nine boreholes with the objective to identify the hydraulically active sections, see Section 3.3. The information from the flow logging has been combined with the information from the core logging and the TV-survey to identify the location, strike and dip of the hydraulically active structures, see Table 3-7. Boreholes KXTP5, -6 and -7 have very low flowrates and have therefore not been included in further hydraulic investigations.

Table 3-7 Identification of hydraulic active structures in KXTP1-9.

Borehole	Hydraulic active section (m)	Inflow (l/min)	Drill core (m)	α	Fracture mineral	TV-logging (m)	Cad-model (m)	Strike (local north)	Dip	Comment
KXTP1	2.065-2.125	0.023	1.92-2.10	15	Ka, Kl, (Su)	1.9-2.1	1.92-2.10	122	88	
	2.175-2.355	0.016	1.98-2.16	15	Ka, Kl, (Su)	1.95-2.15	1.98-2.16	122	88	
KXTP2	2.775-2.825	0.033	2.67-2.90	15	Ka, Kl	not visible	2.67-2.90	122	86	
KXTP3	2.215-2.265	0.007	2.12-2.28	20	Ka	2.12-2.28	2.12-2.28	172	84	
KXTP4	2.520-2.570	0.015	2.25-2.42	15	Ka	2.25-2.40	2.25-2.42	172	84	no fracture in the hydraulic active section
KXTP5										low water inflow to borehole
KXTP6										low water inflow to borehole
KXTP7										low water inflow to borehole
KXTP8	0.950-1.000	0.006	0.90-0.94	40	Kl, Ep	not visible				
			0.96-0.99	40	Ka, (Su)	not visible	0.96-0.99	115	43	
KXTP9	1.875-1.925	0.070	1.81-1.87	45	Ka, Kl, (Su)	1.81-1.87	1.81-1.88	122	86	

The structures have been extrapolated to the surrounding boreholes and have also been given labels in Roman numerals, see Table 3-8.

Table 3-8 Description of identified structures in the Pilot Resin site.

Fracture plane id	Borehole	Location (m)	Strike (local north)	Dip	Mineral[1]	Striation
I'	KXTP2	2.67-2.90	122	86	Ca, Ch	no
	KXTP9	1.81-1.87	122	86	Ca, Ch, (Su)	no
I"	KXTP1	1.98-2.16	122	88	Ca, Ch, (Su)	no
	KXTP2	1.10-1.28	122	88	Ca, Ch, (Su)	no
III	KXTP3	2.12-2.28	172	84	Ca	no
	KXTP4	2.25-2.42	172	84	Ca	no
IV	KXTP8	0.96-0.99	115	43	Ca, (Su)	no
	KXTP3	2.04-2.06	115	43	Ep, Ch, Ca	no
XIII	KXTP1	2.67-2.69	14	78	Ch, (Su)	yes
	KXTP2	2.40-2.42	14	78	Ep, Ca	yes
	KXTP3	1.94-1.96	14	78	Ch, Ca	yes
	KXTP4	2.01-2.03	14	78	Ch, Ca	yes
	KXTP5	2.04-2.06	14	78	Ch, Ca, Ep	yes
	KXTP6	1.41-1.43	14	78	Ch, Ca	yes
	KXTP7	1.47-1.49	14	78	Ch, KA, (Su)	yes
	KXTP8	1.07-1.11	14	78	Ch, Ca	yes
	KXTP9	2.29-2.33	14	78	Ch, Ca	yes

[1] Ca=Calcite, Ch=Chlorite, Ep=Epidote

Blue: Hydraulic active section, see Table 3-7 and *[Birgersson et al, 2000]*.

Green: Possible hydraulic section. Minor mismatch between intersection of identified structure and water inflow.

Red: No match between intersection of identified structure and water inflow.

Grey: No reliable water inflow information.

It can be seen in Table 3-8 that there seems to be four main structures within the site. The first structures (I' and I") are found in boreholes KXTP1, -2 and -9. It can also be seen in the table that structures I' and I" were found to be hydraulic active.

Another structure (III) is found in KXTP3 and KXTP4. This structure was as well found to be hydraulically active.

Boreholes KXTP3 and -8 are connected by structure IV. A hydraulic active section of KXTP8 is found at the intersection of this structure. KXTP3 is not hydraulically active at the intersection with this structure.

The target structure for the drilling campaign of the KXTP-boreholes (XIII) can be found in all boreholes. The characterisation programme was initially focused on this structure, but none of the boreholes, except for KXTP8, show any significant water inflow at the intersection with this structure. This structure was as a consequence found not suitable as the main target for the Pilot Resin Experiment.

The findings illustrated in Table 3-8 are supported by the results from the interference tests and the tracer tests, which indicated two fairly separated systems within the site. These two systems were found to be sampled mainly by boreholes KXTP1, KXTP2 and KXTP9 and boreholes KXTP3 and KXTP4. The resin injection was focused on investigating these structures. The interpretation of the relative geometry of the structures that are included in the 3-D CAD are given in Figure 3-4.

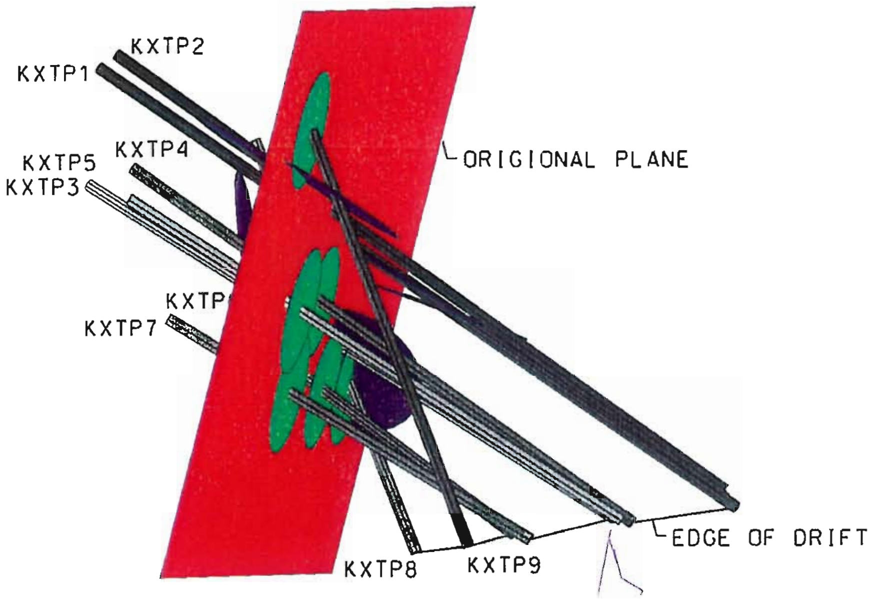


Figure 3-4 Plan view of the Pilot Resin site showing the KXTP-boreholes, fracture planes of main hydraulic importance (blue) and the initial target structure (green discs and red plane).

4 Dye and resin injections

4.1 Introduction

Laboratory experiments have shown that water in a fracture has to be removed or exchanged with another liquid, using i.e. alcohol, before resin is injected in order to obtain a good resin impregnation without any "fingering" effects. This was achieved in the field using injection of iso-propanol. Apart from being tested in the laboratory, this procedure has been tested during *in situ* epoxy resin tests at the Grimsel test site in Switzerland *[Dollinger et al., 1995]*.

It is important to ensure that water and resin flow in the same flow paths. Therefore, all fluid injections prior to the actual resin injection were labelled with a slightly sorbing dye (Rhodamine B) which should not be washed away during subsequent excavation drilling activities.

These considerations resulted in the following injection sequence:

1. Dye-labelled water.

2. Dye-labelled iso-propanol.

3. Dye-labelled epoxy resin.

The resin injection sequence started with injection of water labelled with a slightly sorbing dye, Rhodamine B. Subsequently iso-propanol was injected, also labelled with Rhodamine B. Finally, epoxy resin labelled with uranine and a dye was injected. The resin injection was carried out using a specially designed injection pump. The two resin components (resin + hardener) were continuously mixed in line in proper proportions (4:1).

4.2 Injection of dye-labelled water

Dye-labelled water was injected in KXTP1, KXTP2 and KXTP3. The resin injections into holes KXTP1, KXTP3 and KXTP7 were preceded by injection of dye-labelled water. The injections were carried out using the piston pump described in Chapter 4.5. Details about the injection of dye-labelled water are given by *[Birgersson et al, 2000]*.

4.3 Injection of dye-labelled iso-propanol

Dye-labelled iso-propanol was injected in KXTP1, KXTP2, KXTP3 and KXTP7. The injections were carried out using the piston pump described in Section 4.5. Details about the injections of dye-labelled iso-propanol are given by *[Birgersson et al, 2000]*.

4.4 Injection of dye-labelled resin

4.4.1 Resin injection strategy

Once the two resin components are mixed, the curing process starts and the viscosity will increase with time. It will take a few hours before the resin have cured so much that it no longer is possible, using moderate injection pressures, to inject it further into the fractures.

The strategy of the resin injection was to:

1. Get the resin "far" into the target structure intersecting the injection section.
2. Create a boundary "far" away from the injection hole as the resin cures, against which the pressure could build up.
3. Continue to inject against this boundary "as long as possible" in order to get a good resin impregnation of the structure(s).

At the time for the resin injections, a total of nine boreholes (the KXTP-holes) were available. To start with, all boreholes were packed off and closed. The injection took place in one hole at the time. When the injection was started, one or a few of the other boreholes were opened in order to speed up the resin spread. During some of the injections, a resin breakthrough was observed in sections which were kept under atmospheric pressure. Resin was allowed to bleed from these holes for a couple of minutes before the section was shut in, in order to increase the pressure and create a boundary.

4.4.2 Resin injections

Resin was injected in boreholes KXTP1, KXTP2, KXTP3 and KXTP7. The injections in KXTP1, KXTP3 and KXTP7 were successful, while the injection in KXTP2 did not succeed due to a packer failure. Technical specifications for the resin is given by *[Birgersson et al, 2000]*.

The injected resin was labelled with dyes to give the following colours:

- KXTP7: blue,
- KXTP3: red,
- KXTP1: green.

A fluorescent dye, Uranine, was in addition added to all resin mixtures in order to facilitate the subsequent analysis of the resin thickness. The hardener was not labelled.

The field notes from the resin injections are given in *[Birgersson et al, 2000]*. A short summary of the resin injections are given below.

Resin injection in borehole KXTP7

Resin labelled blue was injected in borehole KXTP7. A total resin volume of a few 100´s ml´s was injected during about 9 hours. Boreholes KXTP5 and -6 were kept open and used as drainage holes. Resin breakthrough was seen in the inner part of the lowest sampling hole (200 mm hole used for extraction of core for laboratory experiments) in the target structure. The injection pressure was most of the time kept between 30 and 55 bar.

Resin injection in borehole KXTP3

Resin labelled red was injected in borehole KXTP3. A total resin volume of about 2000 ml was injected during about 4 hours. Borehole KXTP4 was kept open and used as drainage hole. Resin breakthrough was observed in borehole KXTP4. The injection pressure was most of the time kept between 35 and 55 bar.

Resin injection in borehole KXTP1

Resin labelled green was injected in borehole KXTP1. A total resin volume of about 1500 ml was injected during about 6.5 hours. Boreholes KXTP2 and KXTP9 were kept open and used as drainage holes. Resin breakthrough was observed in borehole KXTP2. The injection pressure was most of the time kept between 30 and 45 bar.

Resin injection in borehole KXTP2

Injection had to be stopped after about 15 minutes due to packer failure.

Table 4-1 Summary of performed resin injections at the Pilot Resin site.

Injection hole	Hydraulic conductivity	Injection time	Injected volume[1]	Injection pressure	Resin breakthrough	Pressures
KXTP7	Low	9 hours	A few 100´s ml´s	Up to 55 bars (natural pressure ≈ 6 bar).	In the lower sampling hole in the target structure after about 1 h. Distance ≈ 0.5 m.	No pressure increase in the other boreholes.
KXTP3	Medium	4 hours	One or a few 1000´s ml´s.	Up to 55 bars (natural pressure ≈ 10 bar).	Resin breakthrough in KXTP 4. Distance ≈ 0.5 m. No resin breakthrough in the drift.	Pressure increase in borehole 4 (expected). No pressure increase in the other holes.
KXTP1	High	6.5 hours	About 1500 ml´s.	Up to 45 bars (natural pressure ≈ 20 bar).	Resin breakthrough in hole KXTP2.	No observed pressure increase.
KXTP2	High	Injection had to be stopped after about 15 minutes due to packer breakdown.				

[1] The "injected volume" refer to the volume of resin that was injected into the rock. This volume is hard to quantify since part of the resin emerged in the adjacent boreholes that were kept opened until resin breakthrough was observed. The volumes that emerged into these boreholes can not be exactly quantified.

4.5 Injection equipment

Mechanical single packers (length about 30 cm) were installed in eight of the nine KXTP-holes. An inflatable packer (length about 1 m) was installed into hole KXTP2.

Dummies (diameter ~ 50 mm) were installed in the packed off borehole sections in order to reduce the volume. Usage of these dummies resulted in a volume of about 500 ml per m borehole compared to about 2500 ml/m for the corresponding borehole without a dummy. The lengths of the packed off borehole sections were between 0.6 m and 2.9 m, see Table 3-3. This give volumes of 300 up to 1450 ml in the boreholes.

The injections of dye-labelled water and iso-propanol were carried out using a piston pump with the following technical data;

- 3 heads,
- capacity 1 l/h and head (-> 3 l/h),
- pressure 60 bar.

Water taken from the lowest part of the F-tunnel (water from the pump station) was mixed with Rhodamine B and injected using the piston pump. The concentration of

Rhodamine was about 132 ppm which gave a strong red colour. Iso-propanol was mixed with Rhodamine B and injected using the same piston pump. The concentration of Rhodamine was about 200 ppm which gave a strong red colour.

The resin injection was carried out using a specially designed injection pump. The two components were continuously mixed in proper proportions (4 units of resin and 1 unit of hardener) and the mixture was injected. The injection pump is described in *[Birgersson et al, 2000]*.

4.6 Summary of the resin injections

It was during all injections possible to inject resin for several hours. This was a very positive outcome, since it prior to the injections was estimated that it should only be possible to inject resin for about one hour.

It was possible to inject relatively large volumes of resin into the structure. The injected volume in the structures should cover an area of square metre(-s) assuming a fracture aperture of 0.1-1 mm. This was a positive result compared to what was expected.

The injection pressures were up to about 50 bar above the natural pressures, but no significant pressure increases were observed in the adjacent boreholes. This indicates that the pressure drop was located in the vicinity of the injection hole.

The mixing of the two components that constitute the injected resin was carried out continuously based on mixing the two fluids emerging from the cylinders, see *[Birgersson et al, 2000]*. It was however not possible to maintain the constant mixing ratio (4:1) during the entire injections. The injection system will therefore be rebuilt before being used again.

5 Excavation/sampling procedure

The sampling of the site for resin impregnated fractures started with drilling of the twelve (10+2) Ø 56 mm exploration boreholes (the KXTRI boreholes), each with a length of about 4 m, to assess the resin spread. These cores were inspected for resin occurrence, see section 5.3 and *[Birgersson et al, 2000]*. This information was incorporated in a CAD-model in order to guide the subsequent sampling using large diameter coreholes.

The sampling of the resin impregnated fractures was carried out using large diameter core holes (Ø 200 mm and Ø 146 mm). The drilling of the large diameter holes were in some cases carried out near perpendicular to the impregnated fractures. It was therefore foreseen that the cores could break along zones of weakness, i.e. in the fractures, due to vibrations and shear forces during the drilling. Furthermore, large diameter cores are quite heavy which will induce a large unsupported weight if the holes are drilled in a near horizontal direction.

The rock therefore had to be stabilized prior to the large diameter drilling. This was achieved by drilling a small diameter pilot hole (Ø 36 mm) that was used for stabilization using a 20 mm rod. The pilot hole was overcored by drilling a large diameter hole. The drilling of the large diameter hole was restricted to a length of about 1 m. The length of the pilot hole was therefore about 1 m, see Figure 5-1. The drilling of a pilot hole and the subsequent overcoring was repeated until the desired depth was obtained.

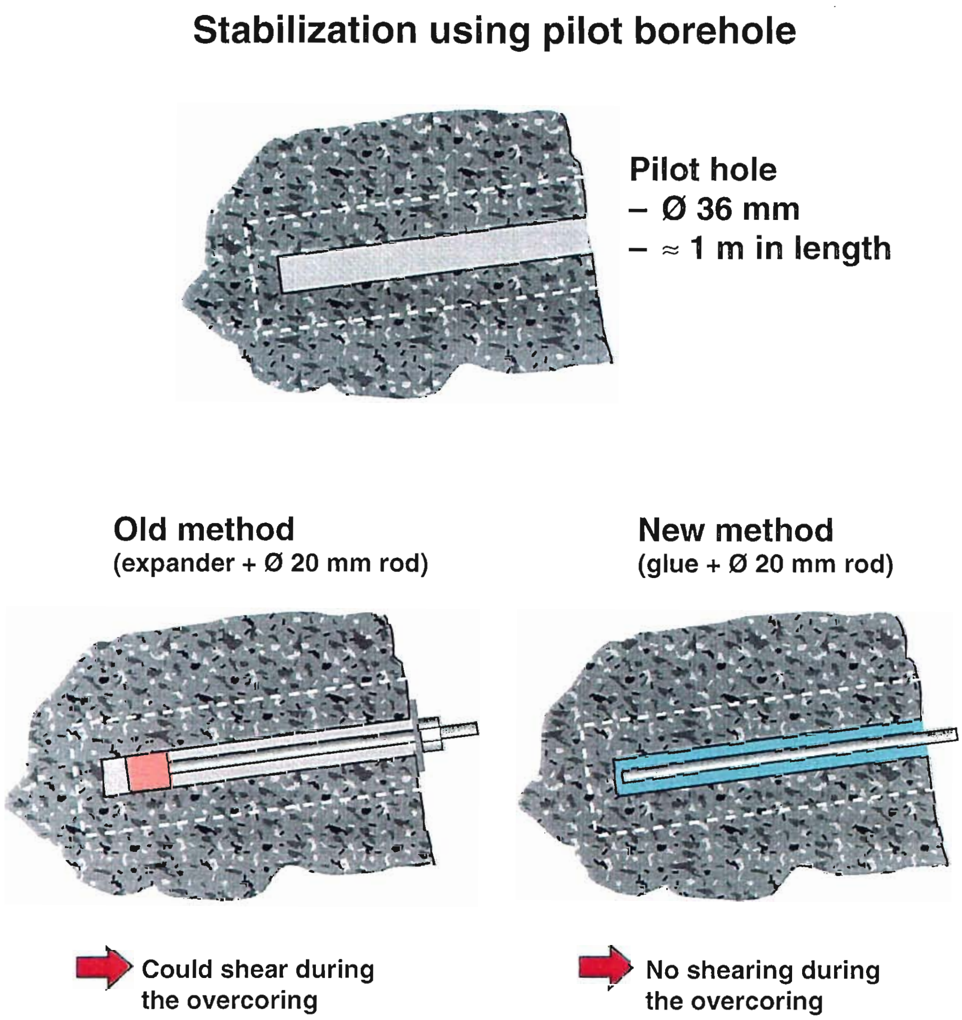


Figure 5-1 The drilling arrangements for large diameter core sampling of the site.

The "Old method" was based on stabilizing the core by using an expander and a rod. The "New method" was based on stabilizing the core by using glue and a rod. The overcoring and core breaking techniques were changed as well.

5.1 Large diameter drillings - "Old method"

The pilot hole was used to stabilize the rock section prior to the overcoring with the large diameter boring. This was achieved by using an expander and a Ø 20 mm diameter steel rod in order to fix the rock prior to the overcoring with the Ø 200 mm hole, see "Old method" in Figure 5-1. Breaking of the core was carried out using a wedge. However, this method resulted in several unwanted core breaks, some of them in fractures which were impregnated with resin. Most of these core breaks were a result of:

- Heavy unsupported cores.
- Practical problems using the wedge.
- Rotations during the drilling causing shearing.

The core breaks indicated a need for a new sampling methodology.

Boreholes KXTE1-3 were drilled using this old method. The core sections taken for analysis of the resin thickness were all taken from these cores.

5.2 Large diameter drillings – "New method"

The old core break technique was based on removing the core barrel and using a wedge to break the core. Removing the core barrel may have caused unwanted core breaks due to the heavy unsupported cores. The use of the wedge was quite problematic and probably also caused unwanted core breaks. Finally, the expander-rod-fix method was not as rigid as expected and could therefore not prevent rotations of the core during the drilling.

The expander-rod-fix method was substituted for a new method that was based on filling the pilot hole (Ø 36 mm) with resin and a 20 mm rod. After curing, this resulted in a more rigid fixation that, to a large extent, prevented rotation of the core during the drilling. The drawback with this method compared to the expander-rod-fix method is that the fixation of the resin take some hours. Therefore, drilling 3-4 metres will take quite a long time since each core uptake is limited to about 1 m, see Figure 5-1.

The drilling arrangement was changed from a Ø 200 mm single tube drilling ("Old method") to Ø 146 mm triple tube drilling ("New method"). The triple tube method prevented rotation of the core during the drilling. Furthermore, the core break was achieved by using the drill rig which implies that the core barrel did not have to be removed. This implied that the problem associated with the core breaking using the wedge and the heavy unsupported cores were avoided.

The number of unwanted core breaks were reduced with this new drilling arrangement. Boreholes KXTE 4-6 were drilled using this new method.

For further discussions about the drilling arrangements, see *[Birgersson et al, 2000]*.

5.3 Compilation of resin occurrence in the KXTE-cores

A summary of the findings of resin in the six KXTE-cores is given below. A more comprehensive description is given in Appendix 2 and in *[Birgersson et al, 2000]*.

5.3.1 KXTE1, length 3.84 m

Resin was observed at 2.83 m and 3.04 m. Both these fractures were opened during the drilling. A closer inspection of the cores showed a fracture in the section 1.95-2.83 m that seems to contain resin.

5.3.2 KXTE2, length 3.71 m

Resin was found at 1.90 m (and some resin at 0.77 m). Both these fractures were opened during the drilling. A closer inspection of the cores showed that the section 1.50-1.95 m seems to contain resin.

5.3.3 KXTE3, length 4.17 m

Resin was found at 1.55 m. A fracture that was suspected to be filled with resin was found at 1.13 m. The fracture at 1.55 m was opened during the drilling. The fracture at 1.13 m was intact. A closer inspection of the cores showed that the section 0.86-1.55 m contains resin.

5.3.4 KXTE4, length 3.51 m

An intact section with a cluster of fractures was found at 0.9 m. Red dye can be observed, but no resin. An open fracture with red resin was found at 1.4 m. The resin has very poor bonding to the fracture surfaces.

5.3.5 KXTE5, length 3.50 m

The section 1.7-1.9 m may have fractures with resin.

5.3.6 KXTE6, length 3.32 m

The section 0.6-0.9 m contains resin, but was more or less destroyed due to the drilling problem.

5.4 Summary of resin occurrence in the KXTE cores

A summary of the resin findings in the six KXTE cores that could be used for aperture measurements is given in Table 5-1. The sections given in the table were recovered intact.

Table 5-1 Compilation of main resin occurrence in the KXTE cores.

Core	Core section [m]	Section length [m]	Comment
KXTE1	1.95-2.83	0.88	Probably resin.
KXTE2	1.50-1.95	0.45	Probably resin.
KXTE3	0.86-1.55	0.69	Contains resin.
KXTE4	-	-	No candidates
KXTE5	1.7-1.9	0.2	Might contain resin.
KXTE6	1.7-2.0	0.3	Contain resin. Core destroyed.

It can be seen in Table 5-1 that about 2.5 m of the KXTE cores contain or may contain fractures which have been impregnated with resin. The core sections taken for analysis for resin thickness were taken from KXTE1 and KXTE3. The resin sampling holes KXTE1 and KXTE3 are illustrated in Figure 5-2. The indicated discs illustrate the location of the fracture planes used for resin thickness analysis.

It can be seen from Figure 5-2 that the two fracture planes have quite different dips and strikes and that they are located quite close to the drift wall. The fracture making up Sample 3b (012/88) is located about 1.2 m from the drift and the fracture making up Sample 1b (251/58) about 2.4 m from the drift.

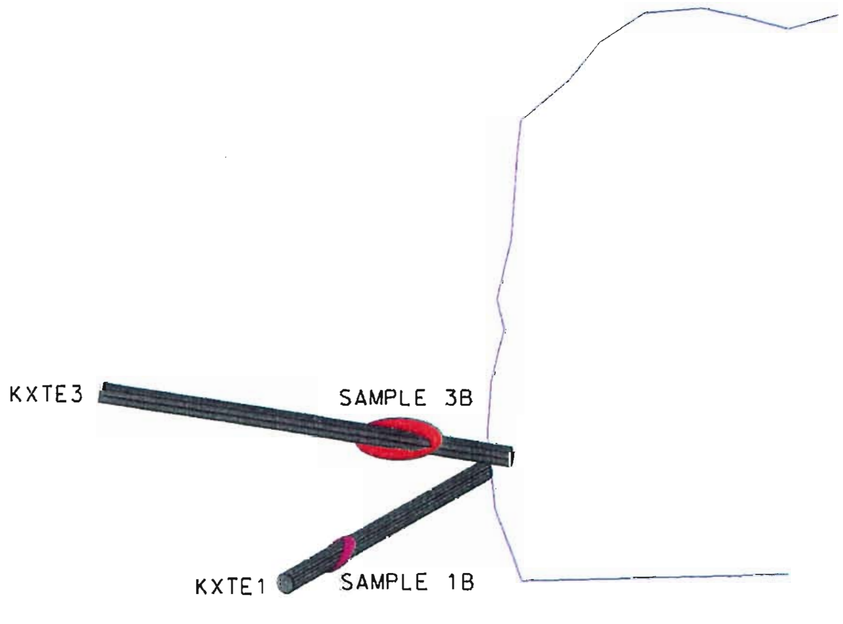


Figure 5-2 Resin sampling holes KXTE1 and KXTE3 (vertical section seen from west) The indicated discs illustrate the location of the fracture planes used for resin thickness analysis.

6 Analysis of pore space data

The main objective of the Pilot Resin Experiment is to develop and test methodologies which can be used to describe the aperture distribution of a selected fracture, and characterise the fracture pore space at *in situ* fracture conditions.

One objective with the pore space data analysis was to perform the analysis of the collected data using two slightly different techniques. The techniques and detailed results from the resin thickness measurements are given in a stand alone report *[Gale and Hakami, 1999]*. A short description is given in this chapter.

Samples of the two different resin impregnated fracture planes, Samples 1b and 3b, were collected and mapped for the thickness of the resin filled fracture pore space, the observed voids, and contact areas (between fracture surfaces).

The two employed techniques that have been applied to measure the fracture apertures in the resin filled fractures are:

- an *image analysis* system developed at Royal Institute of Technology, Stockholm (KTH)
- a *photo-microscope* technique developed by Fracflow Consultants Inc., St John, Canada.

The two techniques are quite similar in principle. They both imply measurement of resin layer thickness in sections cut orthogonal to the fracture surface. The main difference is that the ”photo-microscope” technique is based on continuous traces (manual digitising) of the fracture surface profiles on a series of overlapping photographs whereas the ”image analysis” technique is based on individual measurements at a given separation on continuous digital binary images along the section profile.

The main objectives of this work were threefold:

- to conduct a comparison of the measurements obtained using the two different techniques,
- to demonstrate the reliability of aperture measurement data,
- to evaluate the possibilities for development and improvement of the pore volume characterization methods for future applications in the TRUE project.

6.1 Data collection

The selected core samples were strapped and glued together to avoid damage during cutting. The first cuts through each fracture plane were made perpendicular to the core axis. The core was then cut parallel to the fracture plane to form a 50 to 70 mm thick slab with the fracture plane in the middle of the slab.

6.1.1 Photo-Microscope Technique

The resin thickness and/or aperture measurements, carried out by Fracflow Consultants Inc., were completed using a photo-microscope to provide enlarged images of the resin filled fractures and a digitizer to provide the coordinates of the perimeter of the fracture aperture and the location and lengths of the contact areas between the adjoining walls of the fracture surface.

Each profile was viewed under a microscope and a series of photographs were taken along each profile. The combination of the magnification of the microscope and the enlargement of the area by printing the photograph produced about a 1:18 enlargement of the resin filled fracture plane.

In both techniques, if there was no detectable thickness of resin at the measurement point and the adjoining walls of the fracture appeared to be touching, the point was recorded as a "contact point", and the aperture variable was assigned a value of zero. Also, the location of the upper and lower edges of the fracture walls at voids, where no resin had penetrated, were recorded. Contact length was calculated as the distance, along the measurement profile, along which the measured upper and lower fracture surface coincide.

The top and bottom of each fracture trace, contact points, and areas of resin filling and voids were outlined by matching the photographic image with the microscope view. The upper and lower edges of the resin filled fracture plane were digitized by tracing the outlined fracture traces with the mouse of the digitizing tablet. Contact zones, voids (zones that were not filled with resin) and zones of crushed material, impregnated with resin, were digitized and classified separately. The resin thickness and fracture aperture were calculated from the digitized data as the distance from lower edge to upper edge, orthogonal to the profile axis. Measurements were made successively at points along each profile with a constant separation between the data points and the measurements were filtered during data processing to provide a measurement approximately every 0.07 mm.

6.1.2 Image Analysis Technique

Measurements were made by Itasca Geomekanik using the image analysis system IBAS at KTH (Royal Institute of Technology, Stockholm). Automatic measurements were made using successive images grabbed from a video camera attached to a microscope.

Between each image capture the sample was moved one image width under the microscope.

Measurement routines have been designed to detect the areas with resin in the image and to make a binary image, i.e. dividing the image into two categories only: fracture aperture and fracture wall rock. In the binary images the position of lower and upper fracture surface is automatically measured at every 70 μm distance. With the magnification used in this case, each image corresponds to 3.5 mm profile length and contains 1024x1024 pixels. The accuracy of the measurements increases with the quality of the image. Higher accuracy is achieved with a high magnification on the microscope and a large contrast between the resin and the rock.

6.1.3 The analysed samples

The mineralogy and texture of the two fracture samples were examined using stereomicroscope and transmission microscopy on thin sections from selected parts of the fractures. Both fractures, although different, are representative of the types of conductive fractures usually observed at the Äspö HRL.

Sample 1b

This fracture belongs to a group of tension fractures that have fracture infillings consisting of idiomorphic calcite crystals. The main part of the fracture consists of one single fracture with a fairly constant aperture. The surfaces of the fracture are generally fairly rough, suggesting that no movement has occurred along the fracture, see Figure 6-1. The resin impregnation of the fracture is complete and there is very little contact noted between the fracture surfaces.

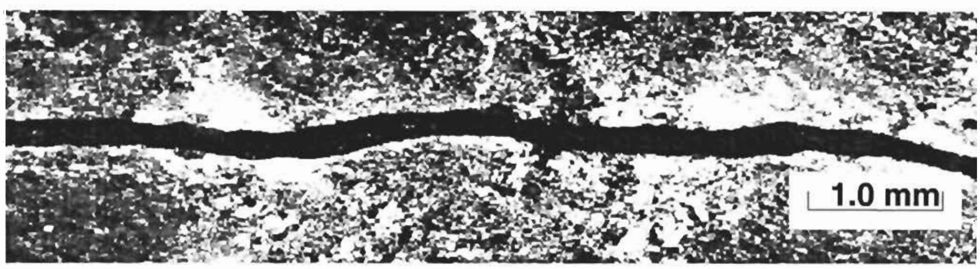


Figure 6-1 Image example. Typical section from Sample 1b. Fairly constant aperture. Fairly rough fracture surfaces.

Sample 3b

Sample 3b belongs to another group of fractures that has been observed at Äspö, which are generally characterised by hydrothermal alteration of the adjacent wall rock.

Generally, the fracture surfaces of Sample 3b are smooth and the aperture is fairly constant, except in areas with infilling material, suggesting that a movement has occurred along the fracture, see Figure 6-2. Portions of Sample 3b consists of void spaces or areas not filled with resin.

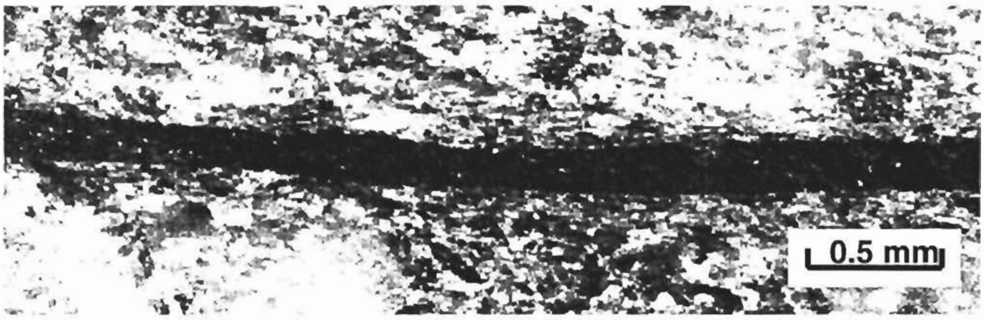


Figure 6-2 Image example. Typical section from Sample 3b in area without contacts. Fairly constant aperture between contacts. Smooth surfaces.

6.2 Pore space statistics

Both fracture planes that were analysed were cut into four equal size quadrants. The resin thickness in quadrants I, II and III were measured using the "image analysis technique" (KTH). Quadrant IV was measured using the "photo-microscope technique" (Fracflow). Table 6-1 summarises, for both samples, the statistics for each quadrant and the total sample. For each quadrant and for the total sample, the data from the profiles are lumped together and the statistics calculated on all data. It can be seen from the table that the mean aperture is fairly stable between quadrants in both samples. No major differences can be seen between results obtained using the two methods.

The mean aperture in the resin impregnated areas is in the same order for both samples, 281 μm and 295 μm, respectively. Also the coefficient of variation of the aperture is in the same order for both fractures, 37 % and 39 %, respectively. The difference in character between the two samples is revealed in the larger percentage of contact areas for Sample 3b, and also a larger percentage void area for this sample.

As one element in the check on data quality and accuracy, repeated measurements were conducted with the image analysis system on one part of a profile using different magnifications and separations between the measurement points. The results from this check indicates that the aperture distribution parameters are insensitive to the changes in measurement conditions for the imposed variations. The choice of magnification and measurement point or data separation can therefore be based on the particular application of the data and on the time and cost limitations. High accuracy may be more important in cases with small apertures. Short data separation distances may be needed when the spatial correlation is small and when details of the surface topography are to be studied.

Table 6-1 Summary statistics of data from complete samples and sample quadrants.

Fracture Sample	Mean Aperture Resin [μm]	Coefficient of variation [%]	Contact Area [%]	Void area [%]	Mean Aperture All data [μm]
1bI	308	33	0.5	0	284
1bII	280	32	1.6	0	260
1bIII	240	41	2.3	0	221
1bIV	290	39	0.02	0	289
1bTotal	**281**	**37**	**1.0**	**0**	**266**
3bI	310	27	31	18	218
3bII	327	31	21	9	258
3bIII	282	39	37	17	179
3bIV	278	46	13	27	268
3bTotal	**295**	**39**	**22**	**20**	**239**

Sample 1b has only a few contact points representing a contact length of approximately 1 % of the total of all profile lengths. The typical contact points in Sample 1b are only 100-200 μm long. In contrast, the contact length calculated for all data from Sample 3b is 22 % of the total of all profile lengths. The variation between profiles is large; from 0% up to 56% for different profiles on the same fracture sample.

The percentage of "voids" in the fracture cross-sections appears to be related to the pore space structure, especially the distribution of contacts. In Sample 1b the aperture geometry is often complex, primarily due to rock fragment inclusions and branching. Still this has not hindered the resin from fully penetrating into this sample. On the other hand, Sample 3b is not fully filled with epoxy resin although its mean aperture is of the same order of magnitude as Sample 1b. The results thus indicate that void areas occur mainly due to the existence of contact areas that block the pathways and prevent the resin from penetrating fully into the fracture or from displacing other fluids that may be present in these pores. The aperture measurements generally show that the mean aperture in void areas is larger than the mean aperture of the resin filled part of the same profile. This may have two explanations:

1) the fracture surface edges break during sectioning and grinding such that the aperture becomes larger than in the undisturbed situation because there is no resin to support the edges of the fracture,

2) the air inside the fracture gets trapped preferably in the larger aperture areas since the water seeks the fine pores and the air or gas seeks the larger pores.

Both processes most likely contributed to the larger mean apertures that were observed and both would bias the measurements towards larger apertures.

6.2.1 Aperture distribution

An example of a frequency histogram of aperture is given in Figure 6-3. For each histogram, the mean aperture, median, standard deviation, coefficient of variation, maximum and minimum, and the upper and lower quartile of resin thickness (in micrometres) are calculated and plotted along with the histograms. The histogram presented in Figure 6-3, relevant to Sample 1b, is based on more than 33000 data points (aperture measurements).

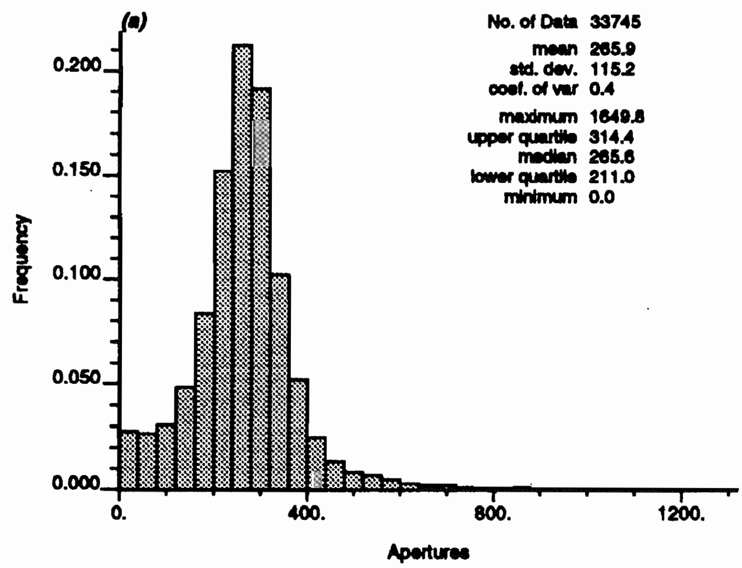


Figure 6-3 Example of a histogram showing aperture (μm) distribution of Sample 1b (integration of all four quadrants). Contact areas are included in the analysis.

The generally symmetrical nature of the distribution of the logarithm of apertures, without the contact areas, for Sample 1b suggests that the apertures are log-normally distributed. However, the distribution of the logarithm of apertures for Sample 3b is skewed and does not appear to follow a log-normal model as closely as Sample 1b.

6.2.2 Analysis of spatial variability

The spatial continuity of apertures was determined by carrying out semi-variogram analyses on both samples using the complete aperture data sets (resin + voids + contacts).

Figure 6-4 shows examples of variograms and fitted models in the X and Y directions for analysed data from Sample 1b. The experimental variograms rise from the origin (no nugget effect) and more or less level off at distances of about 3 to 5 mm, suggesting a practical range of about 3-5 mm. The value at which they level off, i.e. the initial sill, varies with direction and the quadrant analysed.

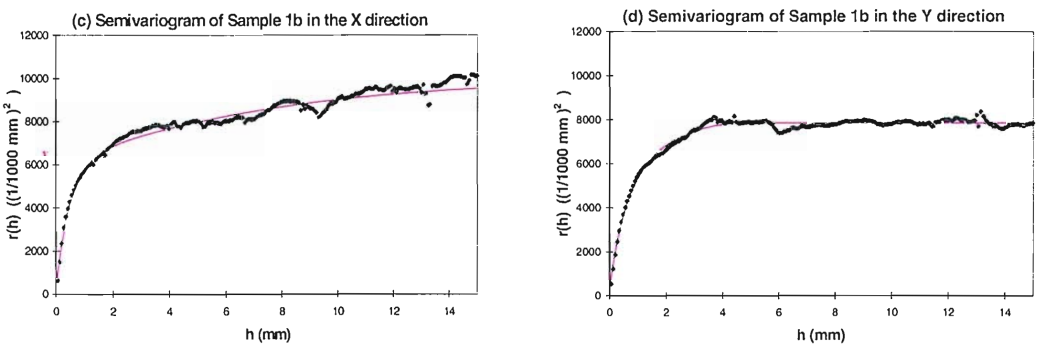


Figure 6-4 Sample 1b. Semi-variograms for X- and Y-directions based on all four quadrants.

It can be seen that the variogram in the Y direction show a fairly constant sill, suggesting strong continuity with distance. In the X direction, the data still show a increase in the difference with distance. For both Sample 1b and 3b, the fitted models in both X and Y directions can be closely described by a nested model comprising of two exponential models.

It should be noted that the spatial continuity on the studied (decimetre) length scale is low in both samples, in the order of a few millimetres. Analysis of spatial continuity of measurements at a larger (metre) length scale, with a larger separation between measurement points, would most likely capture a larger scale correlation where the presently observed correlation would be contained as a nugget effect. Hence, to capture the anticipated nested structures of continuity, measurements with a small (70 μm ?!) separation over a longer length segment of a fracture are required.

6.3 Comparison of measurement techniques

Both pore space mapping methods give the same magnitude of aperture, and similar standard deviations. Both methods have sufficient accuracy for fractures with a mean aperture larger than about 100 μm. For measurement of fractures with a smaller aperture the magnification of the measurement images must be increased to give a reasonable accuracy, which makes the measurements more time consuming. Also, tighter fractures may be difficult to impregnate with resin, resulting in more voids.

Both measurement techniques should be improved with increased colour contrast between the epoxy resin and the natural materials. In previous measurements, a resin with a strongly fluorescent colour proved to function well using UV-light and a corresponding filter in the microscope. Among the colours, blue is judged to be the most preferable to obtain a good contrast.

The photo-microscope technique was the fastest technique employed in this project. The time needed for the image analysis technique is more dependent on the particular image contrast conditions of a specific fracture sample. The possibilities for automatization of the image analysis technique, and higher analysis speed, increase with good image contrast between rock and resin.

The photo-microscope method may therefore be preferred when extensive profiles are to be measured and the fracture geometry or information is not very complex. The image analysis technique may be preferred when there is a need to attach different information to each separate data point, for example if the geometrical pattern is complex or if information about fracture filling materials is also to be recorded. In the photo-microscope approach, the photographs and negatives provide a permanent record of the fracture section. Similarly, in the image analysis technique the digital images can be saved and used for additional geometrical or geological analysis, or for illustration purposes. This aspect of both techniques is particularly valuable in cases where the rock samples are destroyed after measurement, for example due to cutting of very thin sample slabs.

7 Supporting experiments

7.1 Resin bonding experiment

During the coring of the fracture plane samples, the bonding of the fracture planes by the resin was found to be weak and many of the cores separated along existing fractures. The bonding of the fractures appeared to be much weaker and much more incomplete than the bonding of similar fracture planes during experiments in the laboratory. For experimental reasons, the resin injection procedures in the field incorporated several changes from those used to inject resins in the laboratory samples. In order to determine if these changes were the cause of the poor bonding in the large diameter cores from the Pilot Resin Experiment site, controlled resin bonding experiments were conducted in the laboratory on two fracture samples from the Pilot Resin site.

7.1.1 Experimental procedures

The changes made to the laboratory resin injection procedures when the approach was applied in the field are summarized in Table 7-1. As indicated in the table, in the laboratory work, upon completion of the flow tests using distilled water, the sample was flushed with clean iso-propanol, the fracture plane was vacuumed to remove most of the alcohol prior to injecting a dyed resin. In the Pilot Resin Experiment, the *in-situ* water had a much higher salinity and the iso-propanol that was injected following the flow and tracer tests, to displace the *in-situ* water, contained Rhodamine B. In addition, both a normal dye, as used in the laboratory, and Uranine dye were added to the resin. In the field, the resin was injected into the rock mass immediately after the injection of the alcohol was completed. Due to the risk that the fracture planes would be resaturated with *in-situ* water, the resin was injected without attempting to reduce the amount of

Table 7-1 Comparison of resin injection conditions in the field and laboratories.

alcohol in the fracture planes.

Stages	Laboratory	Field
1. Flow and tracer test	Fresh water	High salinity water
2. Alcohol injection	Clean alcohol	Alcohol with Rhodamine B
3. Resin injection	Resin with normal dye	Uranine dye + normal dye. No reduction of the amount of alcohol in the fracture plane.

Since Rhodamine B has a tendency to adhere to fracture surfaces, it was added to the alcohol in the Pilot Experiments to make it easier to determine what parts of the fracture system that were hydraulically connected as evidenced by the penetration of the alcohol into the fracture planes. Uranine dye, which is florescent, was added to the resin so that the pore structure of samples collected from the fracture plane could be examined using image analysis techniques.

Examination of fracture surfaces in the cores collected after the *in-situ* resin injection suggested that the Rhodamine B may have formed a thin film of powder, or residue on the fracture surfaces which may have contributed to the poor bonding of the resin to the fracture surface. It was also noted during resin injection in the field, that the Uranine dye is hydrophilic and tends to separate from the resin and form a greenish layer on top of the resin which may also have contributed to the poor resin bonding observed in these samples.

The purpose of the resin bonding laboratory experiments was to determine what role the water chemistry, water salinity, the addition of the Rhodamine B to the iso-propanol and the addition of the Uranine to the resin dyes, singly or in combination played, in the apparent reduction of the bonding between the fracture planes.

Two, 200 mm diameter core samples with a section of the fracture plane, from one of the main fracture planes that intersected the drift wall of the Pilot Resin site were used in the laboratory experiments. Testing procedures consisted of first saturating the fracture planes with Äspö type water, conducting flow tests at selected normal stresses, followed by injection of iso-propanol with the final step being the injection of resin. For the first fracture sample, normal dye and Uranine dye, in concentrations similar to those used in the field experiments, were added to the resin. The resin was injected into the first sample at a normal stress of about 15 MPa with an injection pressure of approximately 0.15 MPa and the normal stress level was maintained for approximately 24 hours until the resin had cured.

Based on the results of the bonding test on the first sample, the second sample was loaded twice, once to 15 MPa followed by unloading and then reloading to 1.0 MPa, followed by alcohol injection and then resin injection. For Sample #2, only Uranine dye was added to the resin. The resin was injected immediately after the alcohol and without any attempt to remove the alcohol from the fracture plane.

7.1.2 Results of resin bonding strength tests

Once the resin had hardened, each sample was completely unloaded and subjected to bonding strength tests. After failure, the surfaces of the resin filled fractures were examined in detail. In general, the resin was fairly thick over most of the fracture trace which indicates a relatively large average fracture aperture which is consistent with the high flow rates that were measured on these samples.

The resin to rock bonding in Sample #2 was much stronger. In three of the four blocks, failure clearly occurred through either fresh rock or by breakage of old epidote filled veins with the new fracture occasionally crossing the original resin filled fracture. The bonding strength of Sample #2 was approximately 20 to 40 times greater than Sample #1.

7.1.3 Discussion of resin bonding tests

The results of the these experiments indicate that water chemistry, iso-propanol and the addition of Uranine have little effect on the resin bonding. Instead, based on the results of the testing of these two samples, it appears that the apparent separation of resin from the rock that was observed in some samples is related to stress relief when the static load is removed from the fracture plane, or destressed by over coring. The fact that the resin used in Sample #2, which had higher concentrations of Uranine, formed a strong bond with the fracture surface indicates that the Uranine has little or no effect on the resin bonding strength.

It is clear that where the resin has a fresh or clean rock surface to bond to, it bonds very strongly. Obviously, the resin dyed with Uranine and regular color dyes can impregnate and bond to the fracture walls and minerals under the conditions that exist *in-situ* at the TRUE-1 site. For the successful recovery of cores with resin filled fractures that parallel old brittle vein material, careful drilling procedures will have to be utilized followed by careful reconstruction of the core fragments in order to preserve the resin impregnated fracture pore space.

7.2 Fracture pore space in degassing samples

In addition to the two sections of resin impregnated fracture planes that were collected and analyzed, two samples of a natural fracture plane were recovered by overcoring the target structure for the Pilot Resin Experiment. These Ø 200 mm core samples were used in laboratory experiments for the two-phase flow experiment.

The photo-microscope approach was used to map the fracture pore space and contact area. Contact zones, voids (zones that were not filled with resin) and zones of crushed material, that were impregnated with resin, were digitized and classified separately. Both samples have high percentages of contact points. The mean resin apertures (excluding contact points) were found to be 176 μm and 232 μm respectively. These apertures are slightly lower than the apertures measured in Samples 1b and 3b, see Chapter 6.

7.3 Degassing experiment

Pilot injection-withdrawal field tests with gas (N_2) saturated water have been conducted at the Pilot Resin site using single-well and dipole configurations *[Jarsjö, 1997]*. The main objective with these experiments was to investigate whether flow reduction due to degassing can be observed in borehole tests.

The pilot injection-withdrawal test sequence consisted of constant pressure borehole inflow tests and pressure recovery tests. The relation between borehole pressure and steady-state flowrate obtained in these tests indicated that degassing does not cause flow reduction for radial borehole inflow at evolved gas contents of 1.5 to 2.5 %.

In the dipole test, gas saturated water was injected in one borehole and withdrawn in a nearby borehole. This configuration ensured an enhancement of the evolved gas content to 15 % in the outflowing water. When lowering the borehole pressures below the bubble pressure of the gas down to atmospheric pressure during the degassing test, the transmissivity was reduced to 50 % of the original transmissivity. Degassing is considered to be the most likely cause for this reduction. Repeat tests above the bubble pressure indicate that the redissolution of the gas phase was slower than the formation of the gas phase.

8 Discussion and conclusions

8.1 Discussion and conclusions

8.1.1 Site selection

Site

The site selected for the Pilot Resin Experiment was quite suitable with regard to the overall purposes of the experiment. The site was however more structurally and hydraulically complex than first assumed.

One drawback with the Pilot Resin site is that its near-drift location. The use of ordinary drill and blast schemes makes it likely that the site is damaged close to the tunnel periphery and disturbed due to stress rearrangement. This implies that the obtained results are not necessarily valid for undisturbed rock further away from the drift. It should however be remembered that the main objective with the performed Pilot Resin Experiment was to develop techniques to be applied at other locations.

Compatibility to the TRUE-1 site and other potential target structures

The transmissivity at the Pilot Resin site is several orders of magnitude lower compared to the TRUE-1 site and other potential target structures. This implies that it may have been more difficult to inject resin over longer distances, but also less problem with the "natural" water flow in the fracture. The TRUE-1 site, and possibly also other potential target structures, are probably harder to work in because of:

- Higher water pressures.
- Larger water flow rates.

It is therefore possible that new and more complicated problems will occur when injecting resin in the TRUE-1 site and in other potential target structures. It should however be noted that one factor that complicated the injections at the Pilot Resin site was the large hydraulic gradient, > 100 m/m. The hydraulic gradient at the TRUE-1 site, and possibly at other potential target structures, is expected to be significantly lower, which will facilitate the spreading of the resin.

8.1.2 Site characterization

Enough characterization

A large part of the work carried out was focused on the site characterization. This resulted in a good knowledge about the site, but it might have been better to have spent more time/resources on the resin injection/excavation/evaluation procedure.

Useful/unuseful information

The core logging and the hydraulic tests were very useful for the building of the descriptive model. The TV-logging was valuable for the orientation of the cores. The tracer test did not add much information.

Suitable number of boreholes

Nine boreholes, the KXTP holes, were drilled into a quite small site. The large number of boreholes at the quite small site gave problems with mutual disturbances. Furthermore, the large number of boreholes implies that a large part of the work was focused on the geological/hydrogeological characterization. More effort could instead have been spent on the resin injection/excavation.

8.1.3 Resin and resin injection

Resin and resin injection

The curing time for the resin as well as the resin spread was found to be good. This is a very positive outcome, since one of the concerns prior to the experiment was that the curing time might be too short to allow acceptable penetration.

Rhodamine B has not been found to be a good agent to tag the water flow paths within the injected fractures. Rhodamine B may have affected the colour of the resin and may therefore have complicated the evaluation of resin origin. The water and iso-propanol injected prior to the resin should therefore be labelled with other types of dyes in future experiments. Performed post experiment resin bonding experiments have shown that water chemistry, iso-propanol and the addition of Uranine have little effect on the resin bonding. Rather it appears that the apparent separation of resin from the rock that was observed in some samples is related to stress relief when the static load is removed from the fracture plane, or destressed by over coring drilling.

The injection system should be rebuilt and tested in order to avoid problems with the mixing.

Tracers

The following tracers were used in each injection sequence:

- Rhodamine + water.
- Rhodamine + iso-propanol.
- One dye + Uranine in the resin.

It is concluded that too many tracers were used. It was not possible to determine the origin of the dyes observed on the fracture planes and in the resin. Labelling the flow paths with Rhodamine B was not successful. The use of Rhodamine B should be avoided in the future. Future experiments should be based on usage of as few tracers as possible, i.e. one blue dye + Uranine or, if possible, only Uranine.

It may be possible that the characterization of the resin spread in future experiments may be partially based on TV-inspection of pilot holes. Then it is an advantage if the resin is labelled using a fluorescent dye (i.e. Uranine) since that may facilitate the *in-situ* determination of resin occurrence in the fractures intersecting the borehole.

8.1.4 Excavation/sampling procedure

Drilling arrangement

The methodology for obtaining pore space data from epoxy resin and subsequent excavation and analysis as applied in the Pilot Resin Injection Experiment has shown to be workable. However, the use of large diameter coring (200 mm) has been shown to be associated with problems related to the ability to keep the collected samples bonded during the drilling and subsequent extraction and handling process. This problem has been associated with:

- The stress relief when the static load acting on the injected fracture planes is removed.
- The handling of the large mass of the cores in combination with essentially horizontal boreholes.

The arrangement with drilling "sampling" holes, Ø 56 mm, prior to the sampling of the site using large diameter drillings was necessary. It was not possible to predict the resin spread prior to the drilling of the Ø 56 mm holes except for some "qualified guesses" that could be made based on resin breakthroughs in adjacent boreholes during the resin injections.

Sawing/crushing

It was very hard to observe any resin filled fractures based on visual observations of the cores from the Ø 56 mm drillings. For more detailed inspection, the cores had to be "opened" by sawing or crushing. A lot of fractures were opened by crushing the cores using a hammer. This method was successful in terms of finding fractures containing resin. It would have been impossible to carry out any certain observations of resin occurrence unless the cores had been opened. One major drawback with this method is that the cores were destroyed for any further analysis of resin thickness.

Sample salvage

When Sample 2c was collected, the fracture was broken. In order to salvage this sample, the fracture was glued together using a transparent epoxy resin. After the sample preparation it was observed that it was not possible to distinguish between the epoxy used in the *in-situ* injection and the epoxy used to glue the fracture back together. It was therefore decided not to carry out any measurements on this sample, since the measurement uncertainties would have been too large. Therefore, we do not have any suitable method for salvaging fractures that have been opened.

Pore space analysis

Both the image analysis and photo-microscopic methods give the same magnitude of aperture, and similar standard deviations. Both methods have sufficient accuracy for fractures with a mean aperture larger than about 100 μm.

Both measurement techniques can be improved with increased colour contrast between the epoxy resin and the natural materials of the rock.

The photo-microscope technique has been the fastest technique employed in this project. The time needed for the image analysis technique is more dependent on the particular image contrast conditions of a specific fracture sample. The possibilities for automatization, and higher analysis speed, increase with good image contrast between the resin and the rock.

Sampled fracture area

The analysis of the fracture aperture was restricted two fracture samples, each covering an area of a few square decimetres. Therefore, a very small area of the impregnated fractures has been investigated. The analysis of the fracture aperture is time consuming and will probably not be possible to carry out on larger areas than a few square decimetres in the resin experiments at the TRUE-1 site. An alternative might be analysis of a number of "resin islands" on a larger area.

8.1.5 Discussion regarding the resin injection at the TRUE-1 site

For application at the TRUE-1 site the foreseen injected parts of Feature A will be located some 10-15 m into the rock with a focus on the triangle formed by the KXTT3, KXTT1 and KXTT4 intersections.

The transmissivity of injected features at the Pilot Resin site is considerably lower (one to two orders of magnitude) compared to that of Feature A at the TRUE-1 site and other potential target structures. This implies that it may have been harder to obtain a good resin spread, but also less problem with the "natural" water flow and water pressure in the fracture.

The bonding of the resin to the fracture surfaces was at several locations found to be very weak. The observed bonding problems may become even larger at the TRUE-1 site, or at other potential target structures, compared to the Pilot Resin site due to even larger stress releases.

One factor that complicated the injections at the Pilot Resin site was the large hydraulic gradient, > 100 m/m. The hydraulic gradient at the TRUE-1 site, and possibly at other potential target structures, is significantly lower which will facilitate the spreading of the resin.

The target structure at the TRUE-1 site is located about 10-15 m away from any drift. This will make the sampling of the target structure quite complicated and expensive. One way to sample the target structure is to drill large diameter (Ø 96-146 mm) triple tube holes subparallel to the investigated feature and study the resin thickness/aperture in those parts of the fracture plane that are recovered in these cores. Alternatively, the target structure could be accessed by excavating a drift to the vicinity of the target structure and sample the structure by short large diameter (Ø 96-146 mm) triple tube holes.

Both techniques for measuring the fracture aperture could be used in future experiments. The photo-microscope method may be preferred when extensive profiles are to be measured and the fracture geometry or information is not very complex. The image analysis technique may be preferred when there is a need to attach different information to each separate data point, for example if the geometrical pattern is complex or if information about filling materials is also to be recorded.

The sensitivity analysis performed using the image analysis system demonstrates that the amount of data generated can be decreased by using a greater distance between measurement points without affecting the aperture statistics.

8.1.6 Main conclusions

The resin injection followed by excavation and aperture measurement has been demonstrated in the Pilot Resin Experiment to be a useful method that can give information about the connected pore space.

The developed technique makes it possible to:

- Continuously mix and inject resin for time periods up to about 10 h.
- Inject resin over distances of metre(s) into a low transmissive structure.
- Sample the impregnated structures by large diameter core holes.
- Analyse and evaluate pore space data.

The conclusions related to the aperture measurements can be summarized as:

- The average aperture of the analysed samples are 240 and 270 μm, respectively, with a coefficient of variation of about 40 %.
- Evaluated variograms of the aperture mapped by the epoxy indicate practical ranges varying between 0.003 to 0.005 m.

The methodology was successful at the Pilot Resin site. For application of the developed methodology at the TRUE-1 site we expect to take advantage of the lower hydraulic gradient at the TRUE-1 site which is about 1% of that faced at the Pilot Resin Site, which is expected to entail an improved resin spread. The fact that the transmissivity of Feature A is about an order of magnitude higher than that faced in the Pilot Resin Injection experiment may counteract the benevolent aspects of the gradient since the background flow is given by the product of the two entities.

9 References

Birgersson, L., Lindbom, B., Tracer Retention Understanding Experiment, Resin injection programme – Literature survey and conceptual platform, SKB, 1995.

Birgersson, L., Gale, J., Winberg, A., Tracer Retention Understanding Experiment (TRUE). Resin Injection Programme – Test Plan for the Pilot Experiment. SKB Progress Report HRL-96-02.

Birgersson, L., Gale, J. and Hakami, E., First TRUE Stage – Pilot Resin Experiment – Background Information, 2000.

Dollinger, H., Bühler, C., Frieg, B., Bossart, P., GTS: Excavation Project: Dipole Epoxy Resin Impregnation Experiments, NAGRA, Interner Bericht 95-91E, November 1995.

Frieg B., Dollinger H., Bühler C., Personal communication, 1995.

Gale J.E., Personal communication, 1995.

Gale, J. and Hakami, E., First TRUE Stage – Pilot Resin Experiment – Pore Space Analysis, SKB Äspö HRL IPR-99-14.

Hakami E., Pore Volume Characterisation, Aperture distribution of a highly conductive single fracture, SKB PR 25-94-30, 1994.

Jarsjö, J., Groundwater Degassing: Pilot Injection – Withdrawal field test with gas saturated water, SKB HRL-97-02.

Jarsjö, J., Hydraulic Conductivity Relations in Soil and Fractured Rock: Fluid Component and Phase Interaction Effects, Doctoral Thesis, Royal Institute of Technology, 1998.

Möri, A., Bühler, C., Haag, P., Ota, K., GTS: Connected Porosity (CP) – Visualising the pore space in crystalline rock using fluorescent acrylic resin, NAGRA, Interner Bericht 96-22, October 1996.

Winberg, A., Tracer Retention Understanding Experiments (TRUE), Test plan for the first TRUE stage, Äspö PR 25-94-35, 1994.

Winberg, A. (editor), First TRUE Stage – Tracer Retention Understanding Experiment Descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site, SKB ICR 96-04, 1996.

Appendix 1, The activities and the manual readings of the pressure gauges during the interference tests

Table A1-1 Interference tests at the Pilot Resin site. List of activities

Date, Time	IDCODE	Activity	Comment
960401 10:30.	KXPT1-9	Manual pressure readings	See Table A1-2
960401 10:31.	KXPT1	The packer was removed	
960401 10:42.	KXPT1	The transducer was removed	
960401 15:23.	KXPT2	The packer was removed	It was pulled out with the help of the car
960401 15:24.30	KXPT2	The transducer was removed	
960401 18:39.	KXPT3	The packer was removed	
960401 18:40.	KXPT3	The transducer was removed	
960401 19:28.	KXPT9	The packer was removed	
960401 19:35.	KXPT9	The packer was reinstalled The dummy was not extended	New section: 0.95m-b
960402 09:30.	KXPT4	The packer was released, but was stuck in the borehole	
960402 10:10.	KXPT2	The packer was reinstalled The dummy was extended 1.85 m	New section: 0.73m-b
960402 10:15.	KXPT1	The packer was reinstalled The dummy was extended 0.925 m	New section: 0.76m-b
960402 10:33.	KXPT2	The transducer was connected	
960402 10:37 .	KXPT1	The transducer was connected	
960402 10:55.	KXPT3	The packer was reinstalled The dummy was extended 0.85 m	New section: 1.15m-b
960402 11:04.	KXPT4	The packer was expanded	Section: 2.3m-b
960402 11:05.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 11:06.	KXPT3	The transducer was connected	
960402 13:45.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 13:50.	KXPT4	The packer was released, but was stuck in the borehole. When attempting to remove the packer by means of the car, the inner pipe was broken.	

The table is continued on next page.

Table A1-1, continued

Date, Time	IDCODE	Activity	Comment
960402 15.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 16:20.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 16:21.	KXPT4	The packer was expanded	Section: 2.3m-b
960402 16:22.	KXPT4	The transducer was connected	
960402 17:05.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 17:11.10	KXPT9	The borehole was opened	Start of interference test
960402 17:25.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 18:00.05	KXPT9	The borehole was closed	Start of recovery
960402 19:21.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 19:30.35	KXPT8	The borehole was opened	Start of interference test
960402 20:05.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 20:15.00	KXPT8	The borehole was closed	Start of recovery
960402 21:45.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 21:50.05	KXPT1	The borehole was opened	Start of interference test
960402 22:30.	KXPT1-9	Manual pressure readings	See Table A1-2
960402 22:50.02	KXPT1	The borehole was closed	Start of recovery
960403 08:18	KXPT1-9	Logger data was transferred to PC	
960403 08:25.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 08:36.20	KXPT3	The borehole was opened	Start of interference test
960403 09:12.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 09:22.02	KXPT3	The borehole was closed	Start of recovery
960403 11:14.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 11:23.03	KXPT4	The borehole was opened	Start of interference test
960403 12:15.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 12:16.15	KXPT4	The borehole was closed	Start of recovery
960403 13:45.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 13:55.04	KXPT2	The borehole was opened	Start of interference test
960403 14:40.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 14:47.01	KXPT2	The borehole was closed	Start of recovery
960403 16:05.	KXPT1-9	Manual pressure readings	See Table A1-2
960403 16:04.	KXPT9	The transducer was removed	
960403 16:11.	KXPT9	The packer was removed	
960403 16:25.	KXPT9	The packer was reinstalled The dummy was extended 0.85 m	Section: 0.95m-b
960402 16:27.	KXPT9	The transducer was connected	
960403 17	KXPT1-9	Logger data was transferred to PC	

b = end of the borehole.

Table A1-2 Manual readings of the pressure gauges during interference tests at the Pilot Resin Site

Date time	Pressure (bar)								
	KXTP1	KXTP2	KXTP3	KXTP4	KXTP5	KXTP6	KXTP7	KXTP8	KXTP9
1/4 10:30	14.5	25	10.9	11.8	0	1.1	0	4	0.5
2/4 11:05	18.2	18.3	0	0	0	0	0	1.9	18.3
2/4 13:45	17.8	18.1	10.1	11.	0	2	0	4	18.0
2/4 15	17.8	18.1	0	0	0	2	0	2	18.0
2/4 16:20	17.8	18.1	0.	0	0	2	0	4	18.0
2/4 17:05	17.9	18.1	10.0	10.9	0	1.1	0	4	18.1
2/4 17:25	3	3	7.2	8.1	0	1.2	0	3	**open**
2/4 19:21	18.05	18.2	10.3	11.2	0	2.2	0	4.1	18.2
2/4 20:05	18	18.2	9	10.	0	2.1	0	**open**	
2/4 21:45	18	18.2	10.1	11. 2	0	2.3	0		
2/4 22:30	**open**	1.7	6.6	7.6	0	2.0	0	2.4	2.
3/4 08:25	18	18	10.4	11. 3'	2	1.9	0	4	18.1
3/4 09:12	17.5	18	**open**	0	2	1.8	0	1.8	18
3/4 11:14	17.95	18.05	10	10.8	2	2.6	0	4	18.1
3/4 12:15	17.9	18.05	0	**open**	2.05	1.1	0	0.8	18
3/4 13:45	18.0	18.15	9.95	10.4	2	2.5	0	3.95	18
3/4 14:40	0	**open**	6	7	2	2	0	2.6	0
3/4 16:05	18.9	19.0	10.2	11. 2	2	2.6	0	4	19

open - borehole kept open.

Appendix 2, Resin occurrence in sampling cores KXTE1-3

The sample preparation and resin thickness analysis is described in *[Gale and Hakami, 1999]*.

Three sections from the drill cores taken at Äspö was cut in Oskarshamn and thereafter sent to KTH according to Table A2-1. The "samples" in Table A2-1 are sections of the three Ø 200 mm cores expected to contain resin filled fractures. During the core mapping there was more evidence of resin inside fractures in the Ø 200 mm cores as compared to the 146 mm cores, and therefore samples from the Ø 200 mm cores were chosen for the measurements. If desired further samples may be selected from the Ø 146 mm cores and the Ø 200 mm cores.

Some of the fractures in the cores were also separated during drilling or core recovery and these fracture planes have been glued back together after recovery using clear epoxy resin.

Table A2-1 *Selected parts of Ø 200 mm drill cores (grey). Location in borehole and observations made from the drillcore mapping is given. Samples marked * contains fracture which has been glued back together.*

Sample	Position in borehole, m	Fracture content, observed resin, etc.
KXTE1.a	2.12 - 2.30	Contains intact fracture. Small angle with core axis. Red/Violet resin or dye?
KXTE1.b	2.30 - 2.52	Continuation of fracture in a.
KXTE1.c	2.53 - 2.83	Continuation of fracture in a. Also another fracture which has been glued together. Red/violet resin on 80%. This fracture has about 45 degrees. Angle to core axis. (core break)
KXTE2.a	1.50 - 1.65	Contains intact fractures. (might be small since they are not seen around the core)
KXTE2.b	1.65 - 1.75	-"-
KXTE2.c *	1.75 - 1.95	Contains fracture which is glued back together. Small angle against core axis. Red/violet/green resin. (core break).
KXTE2.d *	1.95 - 2.26	Continuation of fracture in c. Ends at about 2.10.
KXTE3.a	0.86 - 1.12	Contains intact fracture with small angle to core axis. Red/violet resin? Intersection with P7.
KXTE3.b	1.12 - 1.36	Continuation of fracture in a.
KXTE3.c	1.36 - 1.55	Continuation of fracture in b. Also crossing fracture with almost perpendicular orientation.

Appendix 3, Results from the tracer tests

Tracer injection in borehole KXTP2 gave a fast breakthrough in KXTP1 (<0.5 h) and a very high recovery (37%), see Figure A3-1. The high recovery is partly an effect of the very small pumping (5 ml/h) performed in KXTP1 which increase the zone of influence around the borehole. However, the recorded mass recovery and fast travel time indicates a major flow path between the two boreholes. The breakthrough in KXTP9, see Figure A3-2, is much slower (5.5 h) and has a low mass recovery (0.1%) indicating a minor flow path.

The injection of Rhodamine WT in KXTP3 gave no breakthrough other than in the tunnel.

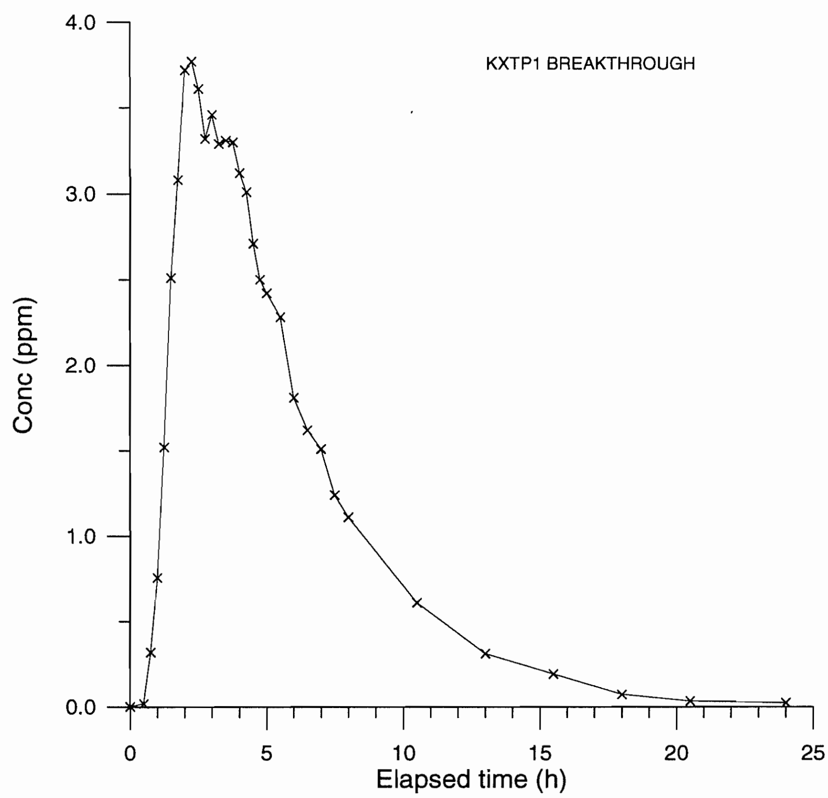


Figure A3-1 *Tracer concentration as a function of time in KXTP1 (injection in KXTP2).*

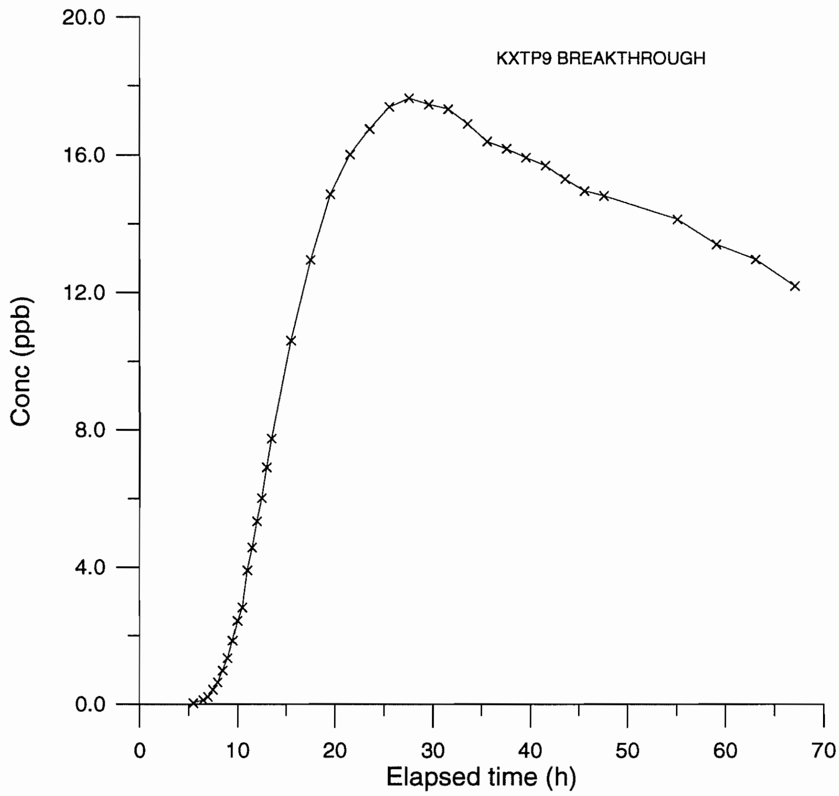


Figure A3-2 *Tracer concentration as a function of time in KXTP9 (injection in KXTP2).*