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The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes.

Evaluation report on Task No 1, the LPT2 large scale field experiments

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Anders Ström, Swedish Nuclear Fuel and Waste Management Company

October 1995

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THE ÄSPÖ TASK FORCE ON MODELLING OF GROUNDWATER FLOW AND TRANSPORT OF SOLUTES

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Keywords: Äspö, crystalline rock, groundwater flow, transport of solutes, modelling, pumping test, tracer tests, site investigation

ABSTRACT

The work within the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes constitutes an important part of the international cooperation within the Äspö Hard Rock Laboratory. The group was initiated by SKB in 1992 and is a forum for the organisations to interact in the area of conceptual and numerical modelling of groundwater flow and transport.

The work within the Task Force is being performed on well defined and focused Modelling Tasks. As the first task, a large scale field experiment was chosen. This consisted of a long term pumping test, dilution tests as well as a series of tracer tests. The modelling work performed on Task No 1 has been evaluated by the Äspö Task Force. The experiences are discussed from the modelling point of view, the Äspö data collection point of view and the site characterisation point of view.

Eleven different groups have modelled Task No 1 using different conceptual and numerical methodologies for simulating flow and transport in fractured rocks. The task was above all a learning exercise for the modelling groups entering the Task Force and for the Task Force organisation as such.

With respect to groundwater flow, all models represented the measured data well. Therefore, the capacity exists to perform three-dimensional groundwater flow modelling on a site scale. In general, the data supplied for Äspö, including the geologic structural model, provided a good representation of the real system. However, a few consistent errors in the modelling work indicate minor errors in the geologic structural model of the Äspö site.

If calibration of transport parameters is made reasonable modelling results are obtained for the tracer tests. However, the low recovery obtained in the tests was not completely understood. Hence, there is a need to consider if any important processes have been disregarded in the modelling of conservative tracer transport.

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EXECUTIVE SUMMARY

The Äspö Hard Rock Laboratory (Äspö HRL) was constructed as part of the preparations for a deep geological repository of spent nuclear fuel in Sweden. The work within the Äspö Project has been divided into three phases; the pre-investigation, the construction, and the operating phase. The last phase began in 1995. The operating phase is aimed at research and development on models for groundwater flow and radionuclide transport, test of methods for construction and handling of waste and, finally, pilot-tests of important parts of the repository system. The Äspö HRL project cooperates internationally with nine organisations, all in the field of nuclear waste management. An important part of this cooperation is the work within the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes which was initiated by the Swedish Nuclear Fuel and Waste Management Company (SKB) in 1992.

The modelling work within the Task Force is linked to the experiments performed at the Äspö Laboratory. As the first Modelling Task, a large scale field experiment called LPT2 was chosen. This was the final part of the characterisation work for the Äspö site preceding the construction of the laboratory in 1990. LPT2 consisted of a long term pumping test, dilution tests as well as a series of tracer tests.

The first modelling task was above all a learning exercise for the modelling groups entering the Task Force and for the Task Force organisation as such. Furthermore, the aim of the tracer tests was primarily to confirm the geologic structural model of Äspö and not to identify transport processes. The latter is to be addressed by future experiments at Äspö. In this report, the modelling work for Task No 1 has been evaluated accordingly.

Eleven different groups have modelled Task No 1 using different conceptual and numerical methodologies for simulating flow and transport in fractured rocks. A wide range of approaches has been utilised, from rather straightforward concepts using assumptions of one-dimensional flowpaths for the tracer tests, to advanced discrete fracture network modelling using site fracture data, calibration and conditioning. All the modelling approaches used, which represent the whole spectrum of possible methodologies, have the capacity of simulating the LPT2 set of tests, both for flow and transport of solutes. The LPT2 exercise has shown that all modelling approaches are adequate for the purpose of analysing the groundwater flow characteristics of Äspö in the site scale.

More specifically, it was noted that the groundwater pressure field, which is not very sensitive to variations of the hydraulic conductivity field, may be modelled with sufficient accuracy using an equivalent-continuum model. However, the flow distribution in the rock requires a model with a realistic hydraulic conductivity distribution. If an inflow pattern or transport paths are to be modelled a more sophisticated approach like a stochastic continuum or a discrete fracture network model is required. These different approaches put different requirements upon the characterisation of the modelled volume, with increasing detail of resolution and conceptual refinement with decreasing geometrical scale.

The modelling work performed on Task No 1 is discussed further from different perspectives. The resulting experience may be seen from the modelling point of view, the Äspö data collection point of view and the site characterisation point of view.

All the modelling groups did utilise the Äspö base model which constitutes a geological-/geochemical/geohydrological synthesis of all available data from the site investigations at a certain time. In general, it may be concluded that this base model of Äspö was very good for constructing a site scale model representing the main features of the field experiment. However, the modelling efforts of Task No 1 have indicated some minor inconsistencies in the geologic structural model for Äspö. This makes it possible to update the site structural model. A well-established geologic structural model is an essential starting point for successful modelling.

For the first time, new approaches have been applied for a real site using Äspö data. The difference in approaches is also apparent in the use of data from the site. Obviously, different modelling approaches put different requirements on site characterisation. It was concluded that there is a lack of transport parameters for the Äspö site. Improved knowledge of transport parameters should be strived for at an early stage of a site characterisation programme.

SAMMANFATTNING

Äspölaboratoriet byggs som en del i förberedelserna för ett djupförvar för använt kärnbränsle i Sverige. Arbetet inom Äspöprojektet är indelat i tre faser; förundersökningarna, konstruktionen och experimentfasen. Den sistnämnda fasen påbörjades under 1995. Experimentfasen är inriktad på forskning och utveckling av modeller för beskrivning av grundvattenflöde och transport av lösta ämnen, på tester av metoder för konstruktion och för hantering av avfallet, samt för pilottester av viktiga delsystem i förvaret. Äspöprojektet har ett stort internationellt deltagande med för närvarande nio organisationer, alla inom avfallsområdet. En viktig del av samarbetet utförs inom den sk Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes som initierades av Svensk Kärnbränslehantering AB (SKB) 1992.

Den modellering som genomförs inom Äspö Task Force ska vara knuten till experimenten som utförs på Äspö. Det storskaliga fältförsöket LPT2 valdes som en första uppgift. Detta var den sista delen i förundersökningsprogrammet för Äspö. LPT2 bestod av en långtidspumptest, utspädningsmätningar och ett antal spårförsök.

Denna första uppgift inom Task Force-gruppen var framför allt en upplärningsövning för de grupper som kommit med i samarbetet och som inte tidigare utnyttjat data från Äspö. Det var även en bra erfarenhet för Task Force-organisationen. Det bör vidare noteras att spårförsöken inom LPT2 framför allt var inriktade på att ge information om de viktigaste vattenförande strukturerna och inte var avpassade för att ge besked om dominerande transportprocesser i berget. Den senare frågan kommer att behandlas av kommande försök vid Äspö. Utvärderingen i denna rapport har utförts med detta i beaktande.

Elva olika grupper har genomfört Task No 1. De har använt konceptuellt såväl som numeriskt olika modeller för beskrivning av grundvattenflöde och transport av i vattnet lösta ämnen. Hela skalan av möjliga metoder har utnyttjats; från antaganden om endimensionella transportvägar längs sprickor i berget för simulering av spårförsöken, till användande av avancerad diskret sprickmodellering i tre dimensioner där sprickinformation från platsen kombinerats med kalibrering och konditionering. Samtliga metoder har förmåga att modellera LPT2-försöken, både vad gäller grundvattenflöde och transport. Task No 1 har visat att alla utnyttjade metoder med framgång kan användas för att simulera grundvattenflödesförhållanden i km-skalan för Äspö.

I detalj kan vidare konstateras att grundvattentryckfältet tillräckligt väl kan modelleras med en ekvivalent kontinuummodell, eftersom det inte är speciellt känsligt med avseende på variationer i hydraulisk konduktivitet. När det gäller flödets fördelning i berget krävs en modell med en mer realistisk beskrivning av hydraulisk konduktivitet. En mer sofistikerad metod krävs om inflödeskarakteristik eller flödesvägar ska simuleras i detaljskalan, t ex en stokastisk kontinuumbeskrivning eller en diskret sprickmodell. Dessa olika angreppssätt ställer olika krav på karakteriseringen av det modellerade området, med ökade krav på upplösning och detaljrikedom i modellen i takt med minskad geometrisk skala.

Modelleringen som genomförts i Task No 1 diskuteras vidare med olika utgångspunkter. Erfarenheter kan dras ur ett modelleringsperspektiv, ur datainsamlingsperspektiv och ur kommande platsundersökningars perspektiv.

Samtliga grupper har utnyttjat den geologiska, geokemiska och geohydrologiska syntes av data som tagits fram för Äspö vid olika tidpunkter under projektets framskridande. Denna basmodell för Äspö bedömdes som mycket bra för att konstruera en modell i km-skalan vilken representerar de väsentliga strukturerna under LPT2-försöken. Modelleringen för Task No 1 har indikerat vissa brister och ofullkomligheter i strukturmodellen för Äspö. Denna kan därför justeras för framtiden. En bra strukturmodell är en väsentlig utgångspunkt för framgångsrik modellering av grundvattenförhållanden på en plats.

Nya angreppssätt och beräkningsmodeller har tillämpats för första gången med data för en verklig plats. Skillnaderna mellan modellerna ger sig även till känna när det gäller utnyttjandet av data från Äspö. En annan slutsats var att det fanns brist på information om transportegenskaper från Äspö efter förundersökningarna. Det bör strävas efter ökad kunskap om transportegenskaper i ett tidigt skede av kommande platsundersökningar.

1 INTRODUCTION

The long term safety of a deep geological repository for spent nuclear fuel is dependent on engineered and natural barriers. The prerequisites of the bedrock in a deep repository based on the KBS-3 concept are primarily threefold /SKB, 1994/:

- That the bedrock be *mechanically stable* in the short and long term perspectives, so that the spent fuel canisters will not be damaged during critical time periods.
- That the repository environment be *chemically stable*, so that uncontrolled corrosion of the canisters will not take place during the designated period.
- That *slow groundwater flow and nuclide retention* ensure that no harmful doses of released radioactivity reaches the biosphere, even if the engineered barriers fail.

The third factor implies the appropriate knowledge to be able to predict groundwater movements and solute transport through large volumes of rock during long time periods in order to evaluate the consequences of possible release of radionuclides from the repository. This has also meant that modelling of groundwater flow and transport of solutes is one of the main activities in research programmes for nuclear waste management in different countries.

The complexity of the studied processes and the time span in question make it necessary to use mathematical models and computer programs in safety assessment studies. The scientific background of the conceptual, mathematical and numerical models is crucial for the reliability of the results. The work performed in order to show that existing models do accurately describe the reality is a central part of the research programmes. This work is sometimes referred to as "validation" or "confidence building".

The Äspö HRL /SKB, 1995/, is an underground research facility operated by the Swedish Nuclear Fuel and Waste Management Company (SKB). The layout of the Äspö HRL is shown in Figure 1-1 below.

The laboratory is located in the vicinity of the Oskarshamn nuclear power plant on the east coast of Sweden approximately 300 km south of Stockholm. Pre-investigations and site characterisation started in 1986. Excavation started in October 1990 and was completed in February 1995. Based on the pre-investigation, predictions were made for geology, groundwater flow and drawdowns, hydrochemistry and rock stability for the period of the excavation of the access tunnel. An important part of this work was the characterisation of hydraulic properties of the rocks and numerical modelling of drawdowns and flow to the tunnel during the excavation period.

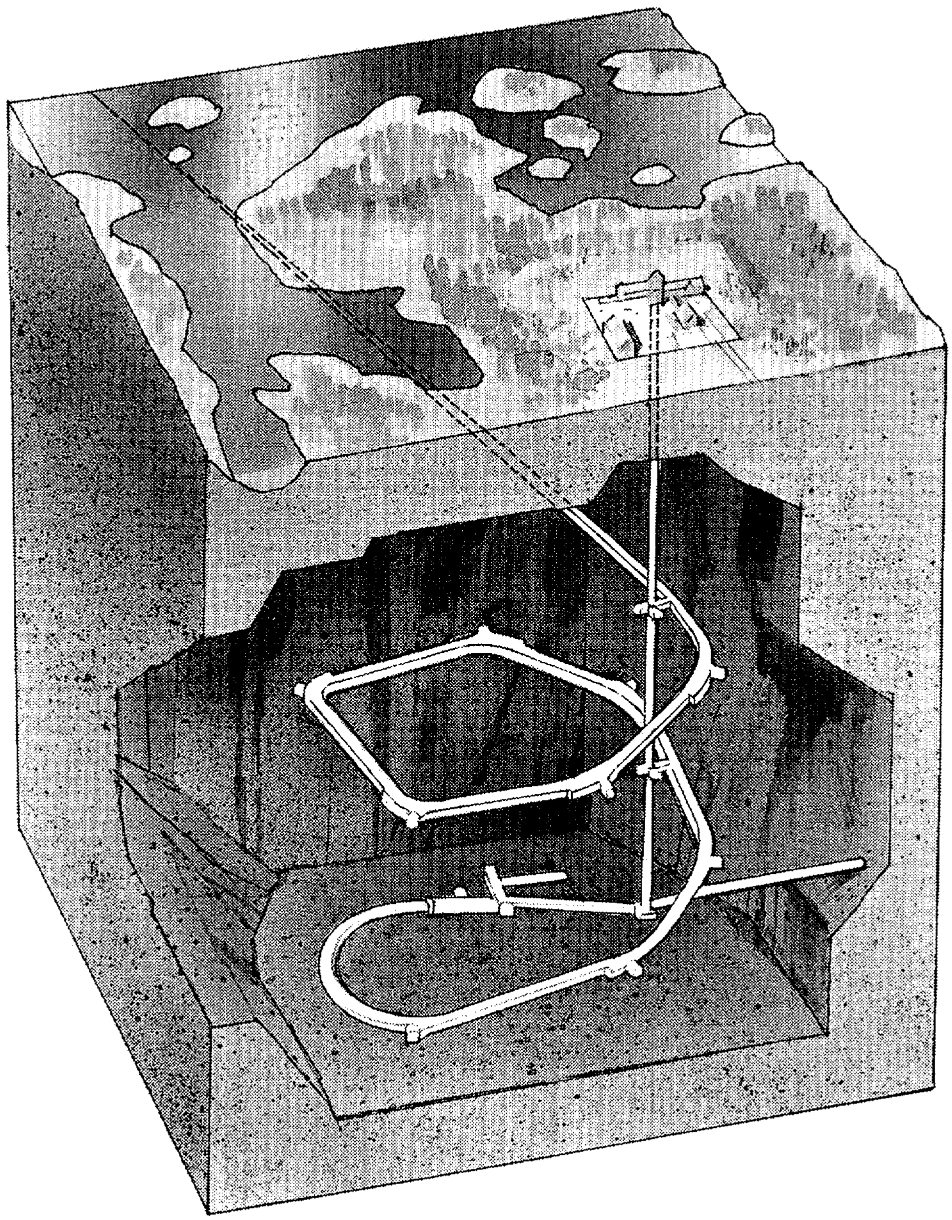

Figure 1-1 *Layout of the Äspö Hard Rock Laboratory /SKB 1995/.*

This work also involved a number of interference pumping tests often combined with tracer tests, that were analysed as training and calibration exercises for the numerical model of the site. A major test of this kind was the second Long Term Pumping Test (LPT2) conducted 1990/1991. The test lasted for three months and was combined with a large scale converging tracer test.

The Äspö HRL project is an international one, with participants from other countries with similar research and development programmes. An important stage goal for the project is to "test models of groundwater flow and nuclide migration", which complies with similar objectives for the other participating organisations. In order to meet this demand a modelling Task Force was attached to Äspö HRL much in the same spirit as the OECD/NEA Stripa Project /SKB, 1987/, where a Task Force was established as a peer group in order to supervise and evaluate the parallel modelling studies of an experimental volume in the Stripa mine.

The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes was initiated in the autumn of 1992. The Charter for the Äspö Modelling Task Force states among other things:

"*Purpose:* The Task Force shall be a forum for the organisations supporting the Äspö HRL Project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate and contribute to such work in the project."...

"*Participants*: ...Each organisation supporting the Äspö HRL is invited to form or appoint a Modelling Team, that performs modelling of HRL experiments selected by and/or suggested to the Task Force."...

"*Scope:* The Task Force may review all modelling work on fracture flow and solute transport made by the Project. The Task Force will select specific experiments made or to be performed by the Project for parallel modelling efforts by more than one team...".

This paper summarises the main conclusions of the groundwater modelling associated with the LPT2 pumping and tracer tests. In the Äspö HRL International Task Force, parallel modelling efforts with different approaches based on this large scale experiment have been carried out.

The Task Force chose the LPT2 experiments as the first modelling exercise with the following purpose:

- To be a learning experience for the modellers, for the Task Force project and for the understanding of the site as well as of flow and transport characteristics in fractured rock.
- To establish boundary conditions for future modelling exercises.
- To compare modelling approaches and computer codes.
- To establish a context for future experiments at Äspö HRL.

Altogether 11 modelling groups representing 6 organisations have carried out the task, as listed in Table 1-1.

Table 1-1. **Organisations and modelling groups of Task No 1, the LPT2 simulations at Äspö. SKB ICR means the Äspö International Cooperation Report Series.**

ORGANI-SATION	MODELLING TEAM	REPRESEN-TATIVE	REPORT
ANDRA	BRGM I	Barthélémy	SKB ICR 94-16
	BRGM II	Noyer	SKB ICR 94-15
	ITASCA	Billaux	SKB ICR 94-14
CRIEPI	CRIEPI	Igarashi	SKB ICR 94-08
PNC	PNC/Golder	Uchida	SKB ICR 94-09
	Hazama Corp	Kobayashi	SKB ICR 94-07
SKB	CFE	Svensson	SKB TR 92-32
	KTH	Moreno	SKB ICR 94-05
TVO	VTT	Taivassalo	SKB ICR 94-12
		Hautojärvi	SKB ICR 94-11
UK Nirex	AEA Technology	Holton	SKB ICR 95-XX

This report summarises the modelling activities for Task No 1. The aim is to focus on conclusions and not to cover in detail all the modelling work that has been performed, see Table 1-1 for references.

Chapter 2 summarises the LPT2 experiments, defines the Modelling Task as well as the objectives. Chapter 3 is devoted to the modelling approaches used for Task No 1, whereas Chapter 4 concerns the application on the Äspö LPT2 data as well as modelling results. Chapter 5 is a discussion and conclusion section where unresolved issues are also identified. Chapter 6 presents overall conclusions. The appendices include a data and documentation overview, executive summaries of all modelling work reported and a modelling evaluation Questionnaire for Task No 1.

WATERBEARING FRACTURE ZONES AT ÄSPÖ

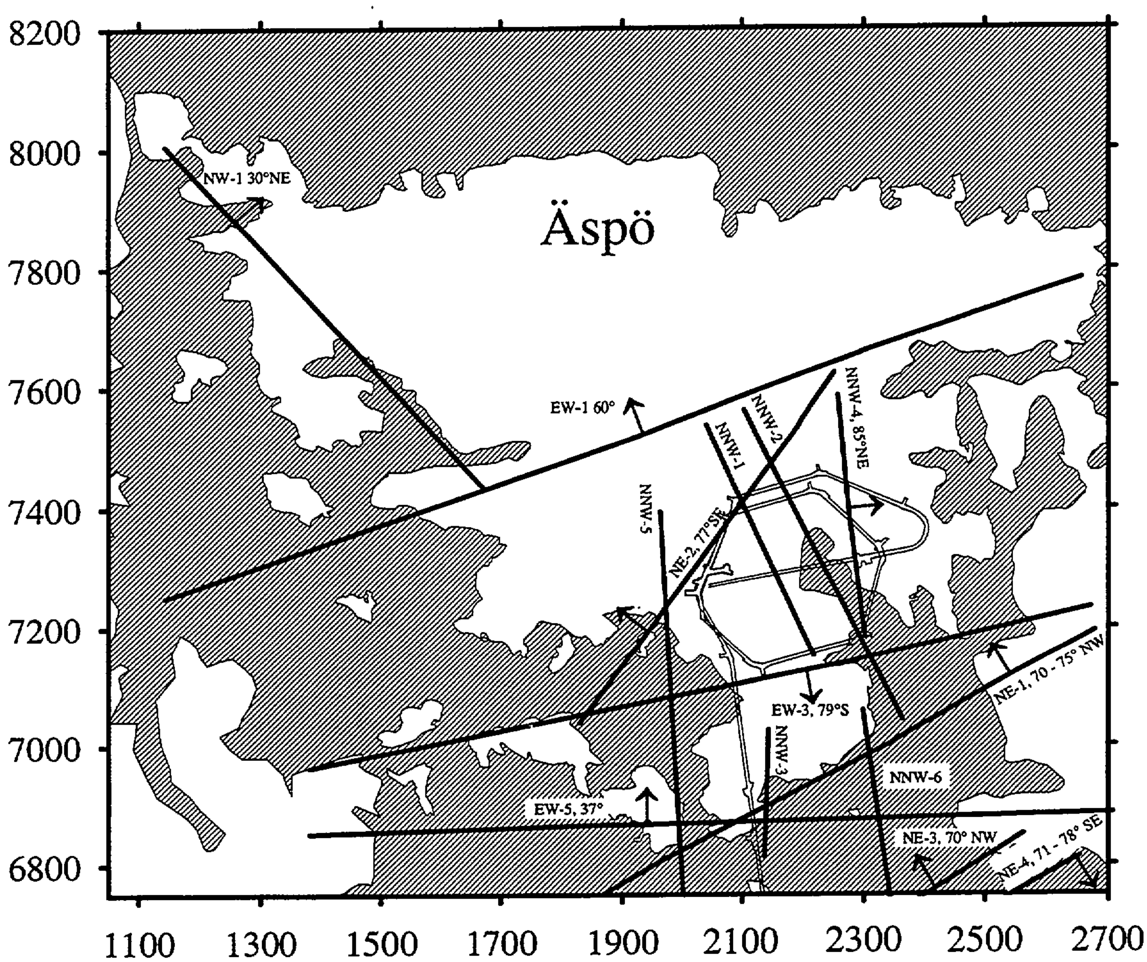

Figure 2-2 *Water-bearing fracture zones in the target area. The geologic structural model is according to the interpretation in SKB TR 91-22, /Wikberg et al, 1991/. The axes are given in the Äspö system of coordinates. The layout of the Äspö tunnel is also included in the figure even though it did not exist at the time of the LPT2 tests.*

SKB ÄSPÖ HRL SITE AREA

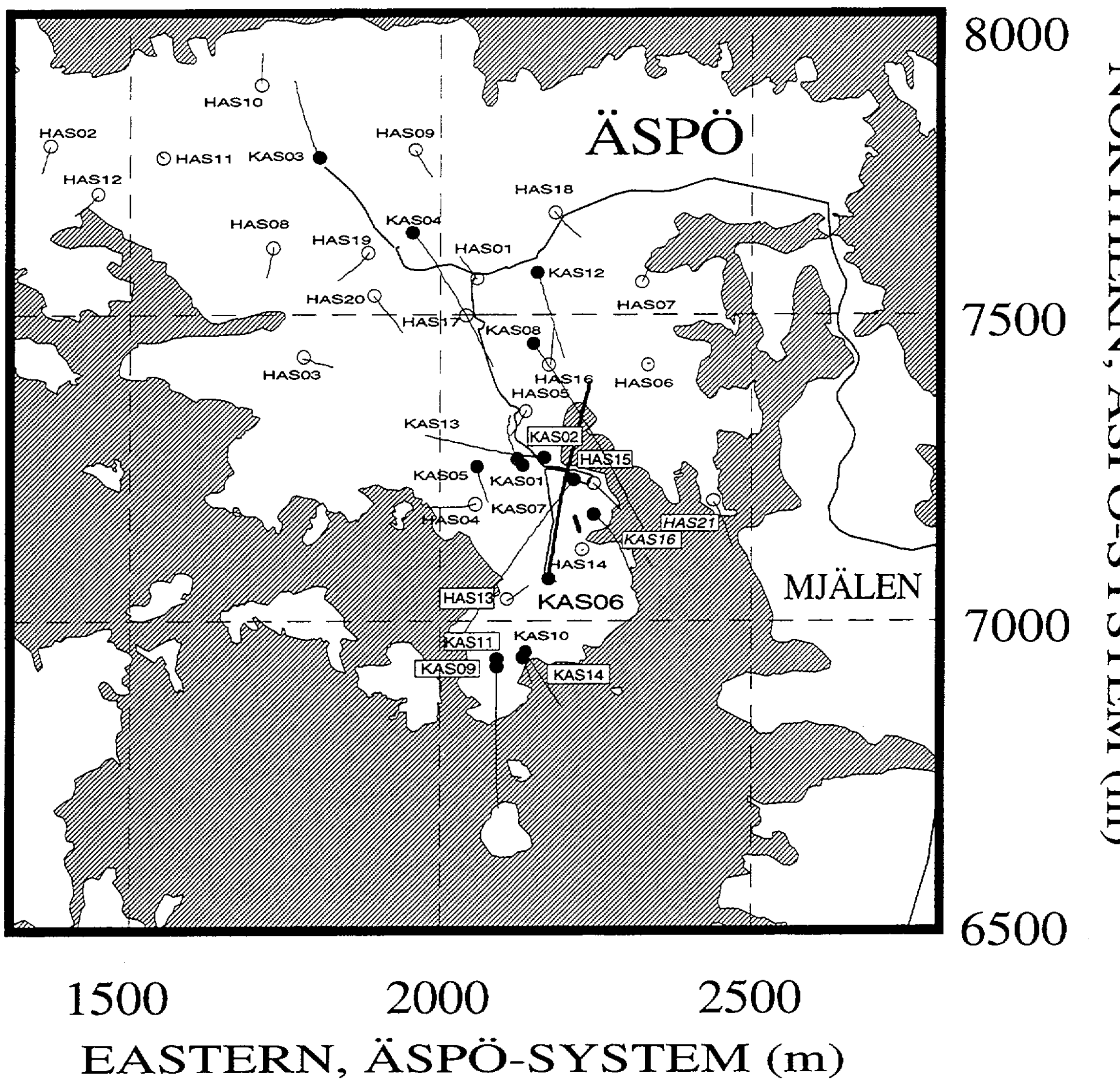

Figure 2-3 *The island of Äspö. Location of boreholes. The borehole KAS06 was pumped during LPT2. In KAS02, KAS05, KAS07, KAS08 and KAS12 tracers were injected during the tracer tests. The coordinates are given in the Äspö system of coordinates.*

2.1.2 The pumping test

Method

In all observation boreholes (except HAS01, KAS01 and KAS10) between two and six sections were isolated using packers. Automatic registrations of drawdown were made in most sections.

In the cored boreholes KAS02-05 and KAS07-14 the electric conductivities of the groundwater were measured at two different levels in each borehole. In addition, the precipitation and the barometric pressure during the pumping test were recorded and documented.

Results

The inflow to the withdrawal borehole KAS06 during pumping has mainly been estimated from spinner measurements, except for inflow from the fracture zone EW-3 which was estimated from tracer measurements. The total inflow, 2.25 l/s, was estimated to be distributed between the zones as shown in Table 2-1.

Table 2-1. The estimated inflow distribution to the pumping borehole KAS06 during LPT2.

Fracture zone	Length interval in KAS06[1]	Percentage of total inflow
EW-3	60-70	15 %
NNW-1	217	21 %
EW-5	312-399	33 %
NNW-2	448	26 %
EW-X	558-596	5 %

1) Metres along borehole below casing top

A distance-drawdown plot was also prepared, see Figure 2-4. In this plot the total drawdown in each observation section at stop of pumping versus the squared distance to the pumping borehole is shown.

As indicated by the drawdown plots in the Appendix 2 figures of Rhén et al, /1992/, the pumping borehole, the central boreholes as well as the boreholes on southern Äspö had reached steady-state or almost steady-state conditions at the end of pumping.

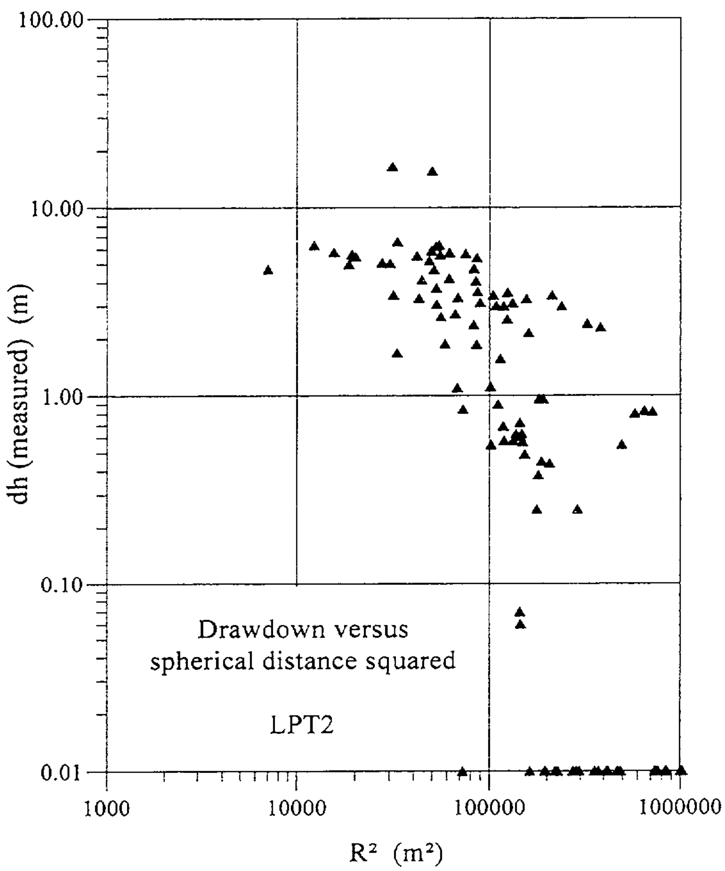

Figure 2-4 *Distance-drawdown graph at stop of pumping during LPT2.*

The transmissivities of the fracture zones have been estimated by analysing the drawdown responses in borehole sections, assumed to be intersected by fracture zones. The results were compared with what can be expected from the current geologic structural model /Wikberg et al, 1991/. Deviations were found, both with respect to extensions and to transmissivities of fracture zones, but the general conclusion was that the results from LPT2 supported the current structural model.

2.1.3 The tracer experiment

Method

Dilution measurements were performed in candidate boreholes both in natural conditions and during pumping of the borehole KAS06 to find suitable tracer injection sections for the tracer test. Altogether ten borehole sections with varying lengths were used for the dilution measurements. Out of these, six sections were selected for injection.

Tracers were injected in packed-off sections which intersected the fracture zones. Injections of tracers were made in the boreholes KAS02, KAS05, KAS07, KAS08 and KAS12. The arrival of the tracers were monitored in the withdrawal borehole KAS06. The breakthrough curves were measured at eight different levels in KAS06 and from the total discharge water.

Three radioactive isotopes (In-114, I-131, Re-186 with half-lives of 49.5 days, 8.0 days and 3.8 days respectively) and one fluorescent dye tracer (Uranine) were injected in four borehole sections into the fracture system around the pumped hole. One tracer per injection point was used.

Towards the end of the tracer test two additional tracer pulses were injected in a second run in two borehole sections not used in the previous run. Figure 2-5 illustrates the LPT2 tracer test. The boreholes of main interest are shown in relation to the fracture zone geometry.

Results

Tracer injections were made in six borehole sections. Table 2-2 defines these borehole sections. The tracers In-114 and I-131 (injected in KAS02-4 and KAS07-4 respectively) were not recovered in the withdrawal hole, KAS06. Recoveries of Uranine from the injection in KAS05-3 and of Re-186 from KAS08-3 were very uncertain. The only certain breakthrough curves observed in the LPT2 test originated from the injections of Uranine in KAS12-2 (borehole length 279-330 m) and of Re-186 in KAS08-1 (borehole length 503-601 m).

As an example, the breakthrough at sampling level 4 (390 m) in KAS06 of the tracer injected in KAS08-1 is shown in Figure 2-6.

Table 2-2. **Definitions of the borehole sections used for tracer injection during LPT2.**

Borehole section	Borehole length interval (m)	Tracer
KAS02-4	309-345	In-114
KAS05-3	320-380	Uranine
KAS07-4	191-290	I-131
KAS08-1	503-601	Re-186
KAS08-3	140-200	Re-186
KAS12-2	279-330	Uranine

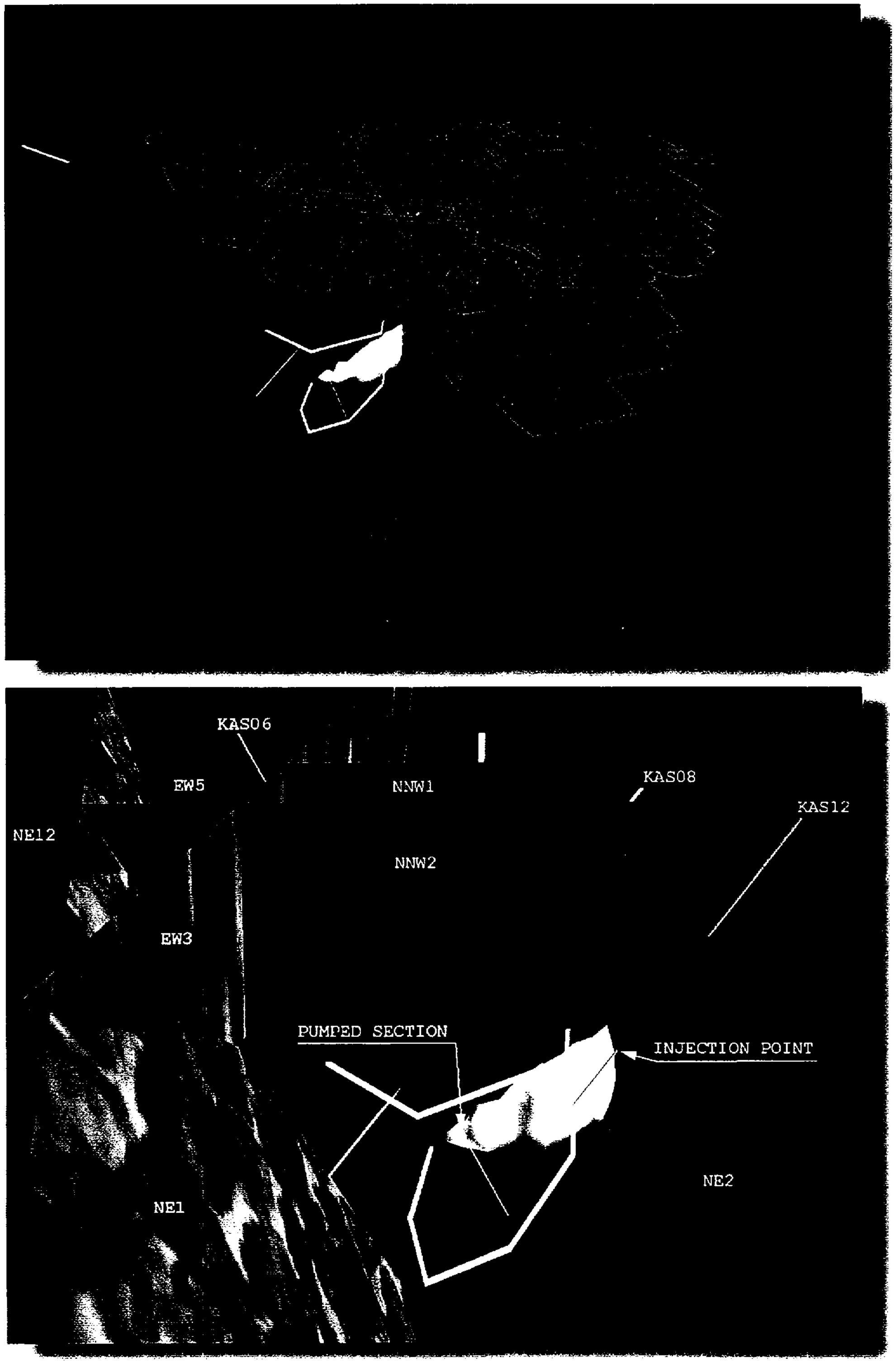

Figure 2-5 *Illustration of the fracture zone geometry in the area of interest for the LPT2 tracer tests. The pumping borehole KAS06 is shown in relation to the fracture zones. The most interesting injection boreholes are also depicted, KAS08 and KAS12. The tracer test in KAS12 is illustrated in the figure by an isosurface of concentration after 30 days pumping time. The illustration is based on the SKB/CFE analyses and the geologic structural model used herein. The top figure shows the selected view in relation to the Äspö island.*

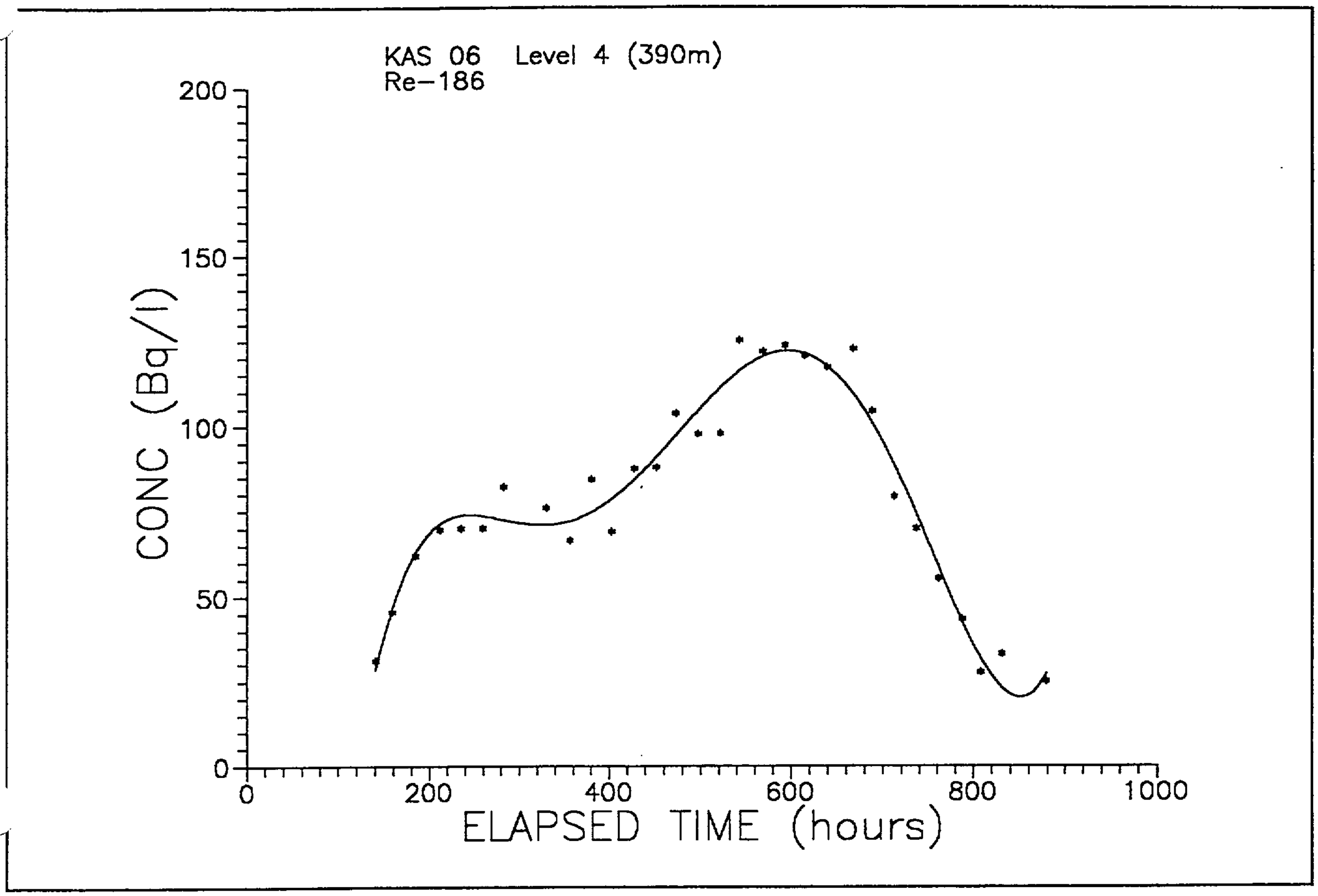

Figure 2-6 *Breakthrough of Re-186 at sampling level 390 m in KAS06. Experimental data points and fitted five-degree polynom (solid line). From /Rhén et al, 1992/.*

Among the interpretations, dispersivities were estimated to be one tenth to up to one fifth of the flow path distance and the Peclet numbers to be 4-11, where the lower values are representative for EW-5 and the higher ones for NNW-1 and NNW-2.

2.1.4 The tracer dilution measurements

Method

Tracer dilution measurements were carried out in 12 boreholes, in 22 different packed-off sections, at depths varying from 40 to 800 meters.

The measurement of groundwater flow through a borehole section is based on dilution of an added chemical substance that is mixed in the groundwater in the borehole section. The concentration in the water is then determined at regular intervals. The decrease of tracer concentration as a function of time is proportional to the groundwater flow through the section. This way of measuring groundwater flow is termed dilution technique. The borehole section lengths were chosen after studying the water conducting fracture zones intersecting the borehole and varied from 7 to 145 m. The major part of the flow measurements were performed in the boreholes in the southern part of Äspö since this was the target area for the Äspö Hard Rock Laboratory.

Results

In total 68 dilution measurements have been performed. The flow through the tested borehole intervals during natural gradients was generally between 0 and 35 ml/min and the variation seemed, according to the scarce data, to decrease with depth or at least the flow was lower, below about 400 m depth as seen in Figure 2-7.

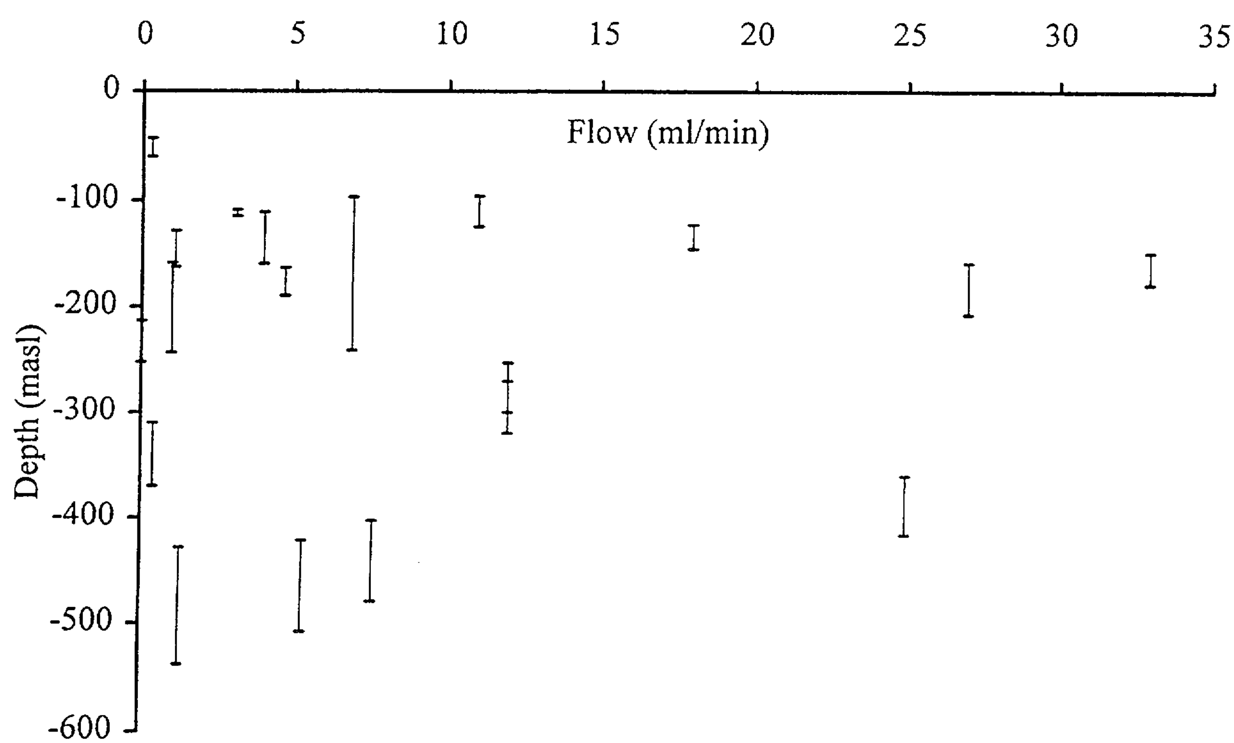

Figure 2-7 *Measured flow, through borehole sections, versus depth below ground level during natural gradients (dilution measurements). From /Rhén et al, 1992/. Measurements from different boreholes are included in the plot.*

2.2 THE OBJECTIVES OF THE LPT2 EXPERIMENTS

This section outlines the objectives of the LPT2 set of experiments. The objectives can be regarded from differing points of view and this has to be kept in mind throughout this evaluation report.

2.2.1 The objectives of the LPT2 experiments for the Äspö HRL project

The LPT2 experiments were performed as the final part of the pre-investigation phase of the Äspö Hard Rock Laboratory project. They were designed to evaluate site scale responses and included a large number of monitoring boreholes. The objectives of LPT2 for the pre-investigation phase may be summarised as follows:

- Verify major conductive structures, especially connectivity between structures. This will confirm the preliminary geologic structural model as well as the geohydrological interpretation.
- Act as a calibration case for the site scale groundwater flow model.
- Attempt to provide data on transport of solutes on the site scale at Äspö.

2.2.2 Key issues for the experiment to deal with as a part of site characterisation

The analyses performed in the Äspö Task Force may help in understanding the usefulness/value of this type of experiment in a site investigation programme. This concerns all parts of the experiment, ie the pumping test, the dilution test as well as the tracer test. The following issues should be considered when evaluating LPT2:

- Are all the different parts of the LPT2 experiments a necessary part of a site pre-investigation phase?
- What parts of the LPT2 data set are necessary/useful in order to build confidence in the flow and transport models of the site? Does the experiment provide a useful data set for modelling?
- What modifications of the LPT2 type of experiment may be made in order to have a(n even) more useful data set?

These and other issues have been considered when evaluating Task No 1.

2.3 TASK NO 1

This section defines Task No 1 of the Äspö Modelling Task Force and also outlines the available database.

2.3.1 Definition of Task No 1

The LPT2 set of experiments was used as Task No 1 when the Äspö Task Force group was initiated. The large scale site experiment was regarded as a good starting point for participants joining the Äspö TF group. Table 2-3 defines the Task No 1.

Table 2-3. Definition of Task No 1.

Task No 1: LPT-2 set of experiments	
	the pumping test
	the tracer tests
	the dilution tests
Divided into two subtasks:	
Task No 1A:	**groundwater flow modelling**
Task No 1B:	**transport modelling**
Performance measures	
Task No 1A - groundwater flow:	
1.	Drawdown-distance plots of measured and predicted drawdowns
2.	Listing of drawdowns
3.	Transient drawdowns for key points
4.	Groundwater flow at the injection sections. Compare with dilution measurements
5.	Inflow distribution in pumping borehole to compare with spinner measurements
Task No 1B - transport:	
1.	Simulated breakthrough curves for each injected tracer
2.	Tracer recovery and flow trajectories

2.3.2 The rationale for using LPT2 as a Modelling Task

The LPT2 experiments were chosen as Task No 1 of the Äspö Task Force. It was the most extensive hydraulic test performed so far in the area and provided a large and well-documented database. Furthermore, a large number of short term pumping tests complement the database. The *reasons* for choosing LPT2 as the first modelling Task are rather obvious but may be summarised as follows:

- LPT2 is a well-defined introductory test case for the Task Force modelling representatives of different organisations.
- LPT2 provides an understanding of the Äspö area in the site scale.
- Modelling of LPT2 provides boundary conditions for future modelling tasks.
- Modelling of LPT2 provides an opportunity for modelling approach intercomparison.

2.3.3 The available data base for Task No 1

Data and documentation have periodically been distributed from the Äspö Task Force secretariat to the participating organisations and the modelling groups. An overview is presented in Appendix 1. The starting point for all the modellers was provided by /Wikberg et al, 1991/ which constitutes a geological, geochemical and geohydrological conceptual model based on all pre-investigations of the Äspö HRL. Briefly, the other data deliveries contained:

- Experimental data from the LPT2 tests
- Map of the Äspö island topography
- Additional tests, eg short term pumping tests
- Fracture mapping from outcrops
- Corelogs from 12 boreholes on the Äspö island
- Tunnel mapping data, for the tunnel length up to 1500 m
- Interpreted results from water injection tests in single boreholes
- Updated fracture zone geometry data set
- A compilation of undisturbed piezometric levels and their uncertainty
- Complementary set of fracture data, core logging data

An important aspect on data deliveries concerns quality assurance procedures. All data has proper references and was extracted, whenever possible, from GEOTAB, the SKB geoscientific database. Whenever necessary, data was delivered as datafiles. Altogether about 32 Mbyte of information on diskettes for Task No 1 was transferred from SKB to the different modelling groups. Most of the information was on fracture data, an information source which was utilised by just a few of the groups, see discussion in section 3.2.2. However, the distributed data is also expected to be used for future tasks within the Äspö TF group.

3 MODELLING APPROACHES APPLIED TO TASK NO 1

This chapter summarises the modelling performed for Task No 1. Extensive work has been carried out by 11 different teams during a period of two years. The main characteristics of the modelling approaches are reviewed in this chapter. The section will relate the modelling work for Task No 1 to what may be regarded as state-of-the-art modelling concepts for flow and transport in fractured rocks. The approaches for each team will then be reviewed.

3.1 GENERAL - GROUNDWATER FLOW AND TRANSPORT MODELS FOR FRACTURED ROCKS

It should be mentioned here that the term conceptual model as outlined in /Olsson et al, 1994/ is used throughout this report:

"A model description consists of the following components:

- a conceptual model which defines the geometric framework in which the problem is solved, the dimensions of the modelled volume, descriptions of the processes included in the model, and the boundary conditions,
- data which are introduced into the conceptual model, and
- a mathematical or numerical tool used to produce output data.

Contradictory to common practice in geohydrology modelling it is proposed that the term conceptual model is restricted to define in what way the model is constructed, and that this is separated from any specific application of the conceptual model."

Predictive modelling of water flow and transport in fractured, low-permeable rock is very complex since the flow is concentrated within fractures. Different types of conceptual and numerical models are used today and these models represent different idealisations of water flow and chemical transport through fractured rock. Three different groups or classes of approaches are illustrated in Figure 3-1. There are of course many other possible divisions of conceptual models for flow and transport.

However, if accepting this structure the approaches may briefly be outlined as follows. The discrete fracture network approach (DFN) is intuitively attractive, as the model is built up from a statistical description of fracture geometric and hydraulic properties. Statistics that describe distributions of fracture location and spatial structure, fracture size, fracture orientation, fracture transmissivity and intensity are needed. Fracture populations are then simulated based on these statistics. The primary flow paths are assumed to result from networks of interconnecting fractures.

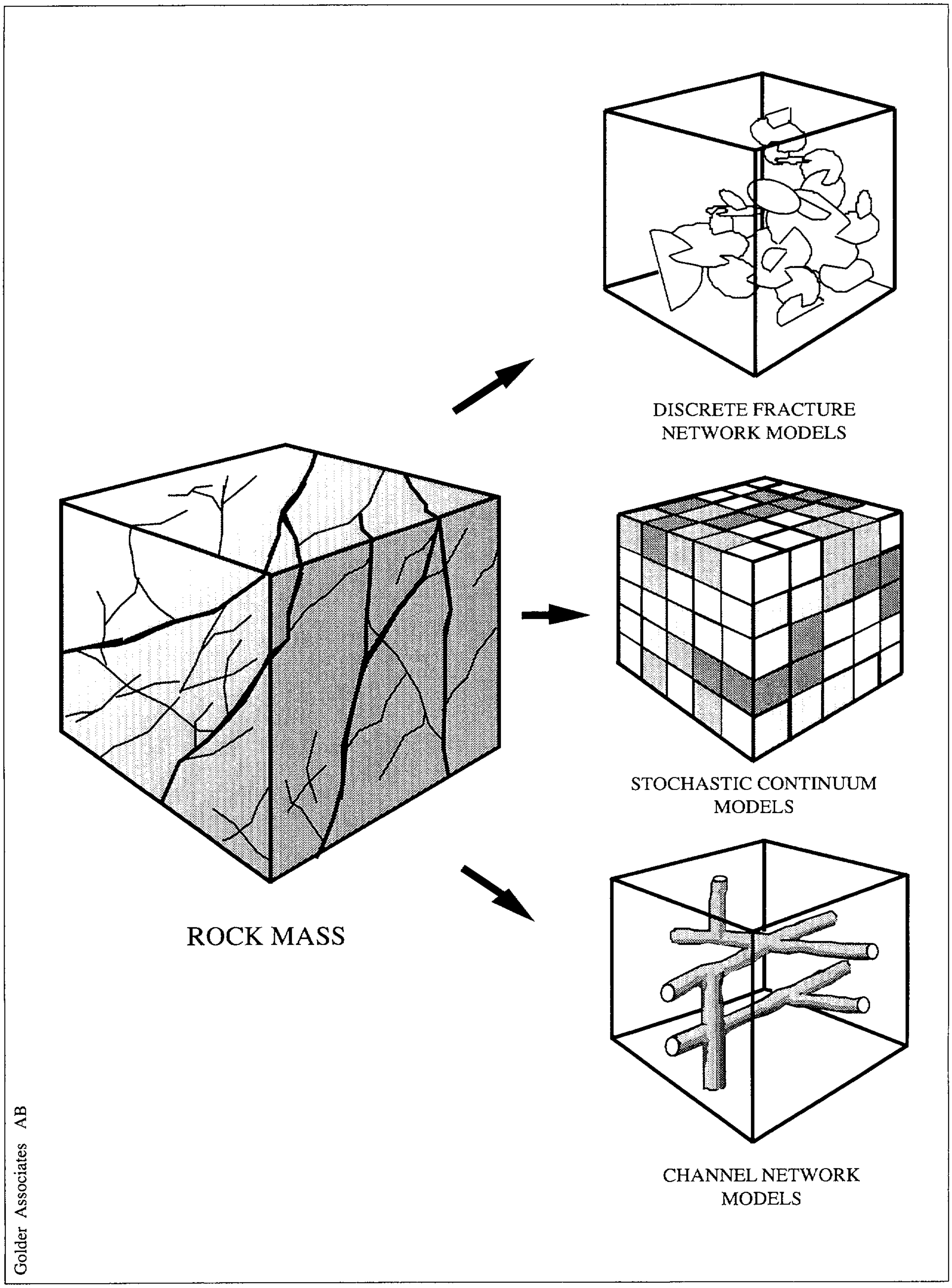

Figure 3-1 *Comparison of different approaches for conceptual modelling of water flow and transport. Figure is from /Geier et al, 1992/.*

The stochastic continuum approach (SC) is based on the idea that a formation can be described in terms of physical parameters (hydraulic conductivity, storativity etc) that vary in space according to spatially random functions. This is also called the geostatistical approach. Some advantages are that extensive theory and statistical procedures for analysis exist, as well as the possibility to model site-scale regions and to perform conditional simulation. Stochastic continuum models are in principle no different from other equivalent porous media models as regards the description of the physical processes.

Finally, the basic concept of a channel network model (CN) is that flow within a fracture network is confined to discrete, effectively one-dimensional pathways known as channels, which intersect at various intervals. A procedure for estimating channel properties directly from field data has been proposed /Gylling et al, 1994A/. Most of the parameter values may be estimated from packer tests carried out in boreholes. Independent measurements of the channel widths are needed. These may be carried out in tunnels and drifts. However, measurements in tunnels and drifts are rather uncertain since the construction work may drastically change the hydraulic conditions around tunnels as compared to undisturbed rock mass.

More information about these modelling concepts may be found in /Geier et al, 1992/ and /Follin, 1992/.

The choice of approach when performing safety or performance assessment of a deep geological repository depends on the purpose of modelling, on the geometric scale of interest and on the available site data.

A large part of performance and safety assessment is dealing with uncertainties. These may be of very different kinds. One kind of uncertainty is conceptual model uncertainty meaning that different modelling approaches may result in different outcomes. There is an obvious need for reducing this type of uncertainty.

There is also a need to increase the general understanding of the processes governing radionuclide transport in fractured rocks in order to build confidence in the results from radionuclide migration modelling and safety assessments. One way of achieving this is by experimental and modelling work in conjunction with underground research laboratories.

3.2 OVERVIEW OF MODELLING APPROACHES APPLIED TO TASK NO 1

Altogether 11 different groups have performed work on Task No 1 so far. More work is anticipated by organisations that joined the international part of the Äspö HRL project at a later stage. However, their work will not be included in this evaluation report.

Table 3-1 lists the modelling groups of Task No 1. The main characteristics of the approaches will be further outlined in the next section.

Table 3-1. **Summary of the modelling teams working with the LPT2, Task No 1, during 1992-1994. Reports and computer codes are also included.**

MODELLING TEAM	REPORT	COMPUTER CODE
ANDRA/BRGM I	SKB HRL ICR 94-16	MARTHE/SESAME
ANDRA/BRGM II	SKB HRL ICR 94-15	ROCKFLOW
ANDRA/ITASCA	SKB HRL ICR 94-14	CHANNET/TRIPAR
CRIEPI	SKB HRL ICR 94-08	FEGM/FERM
PNC/Golder	SKB HRL ICR 94-09	FracMan/MAFIC
PNC/Hazama	SKB HRL ICR 94-07	SETRA/ARRANG
SKB/CFE	SKB TR 92-32	PHOENICS/PARTRACK
SKB/KTH	SKB HRL ICR 94-05	CHAN3D
TVO/VTT I	SKB HRL ICR 94-12	FEFLOW
TVO/VTT II	SKB HRL ICR 94-11	-
UK Nirex/AEA	SKB HRL ICR 95-XX	NAMMU/NAPSAC

3.3 SUMMARY DESCRIPTION OF SPECIFIC MODELLING OBJECTIVES AND APPROACHES FOR EACH MODELLING TEAM

This section summarises the specific modelling objectives and the main modelling approach characteristics of each modelling team contributing to Task No 1. A separate document will later provide a Model and Code Specification and will give further details about the different modelling approaches utilised. Furthermore, each modelling team has reported how the approaches were specifically applied to the Äspö site.

Table 3-2 gives an overview of the different methodologies applied to Task No 1. The row sequence in the table has been chosen subjectively by the authors. Differing modelling approaches are found far apart whereas rather similar methods are shown close together. The table also goes from continuous methodologies down to discontinuous ones.

It should be noted that a great variety of modelling approaches have been used to simulate the LPT2 tests. They differ in conceptual description of flow and transport in fractured rock as well as in numerical implementation. Some of the codes allow for calculations of both pressure and salt concentration fields by iterative solution of coupled flow and transport equations whereas others have neglected the effect of density differences.

Table 3-2. **Äspö Modelling Task Force. Overview of modelling methodologies applied to Task No 1, simulation of the LPT2 experiments. Explanations: FEM- Finite Element Method, FDM-Finite Difference Method, FVM-Finite Volume Method, D-vel=Darcy velocities, K-Hydraulic conductivity, FZ-Fracture zone.**

	Simulation code	Continuum/-Discontinuum	Stochastic/deterministic	Treatment of uncertainties	Density effects	Coupling flow-transport	Numerical method applied to flow
CRIEPI	FEGM/FERM	CONT	DETER	No	No	Directly coupled (D-vel)	FEM
TVO/VTT I	FEFLOW	CONT	DETER[3]	- spatial variability of K - sensitivity tests	No[1]	-	FEM
ANDRA/BRGM II	ROCKFLOW	CONT	DETER	No	No[2]	Directly coupled (D-vel)	FEM
ANDRA/BRGM I	MARTHE/SESAME	CONT	DETER	No	Yes	Part Tracking	FDM
SKB/CFE	PHOENICS/PARTRACK	CONT	STOCH[4]	rock mass conductivity	Yes	Part Tracking	FVM
PNC/Hazama	SETRA/ARRANG	CONT	STOCH[4]	spatial variability of K	No	Part Tracking	FEM
NIREX/AEA	NAMMU/NAPSAC	CONT/DISC	STOCH[4]	spatial variability of K	No	Part Tracking	FEM
PNC/Golder	FracMan/MAFIC	DISC	STOCH	FZ hydraulic properties	No	Part Tracking	FEM
ANDRA/ITASCA	CHANNET/TRIPAR	DISC	DETER	fracture properties	No[1,2]	Part Tracking	FEM
SKB/KTH	CHAN3D	DISC	STOCH[4]	spatial variability of K	No	Part Following	FDM
TVO/VTT II	-	DISC	DETER	No	No	-	Analytical

1=density effects considered in separate study.
2=salinity varying in space but constant in time. Salinity field from MARTHE simulation.
3=Stochastic simulations of the flow rate through the tracer injection sections.
4=Statistical distributions used for different features in the models, but only one realisation utilised.

Furthermore, uncertainties of the hydraulic and transport properties of rock are treated differently. Some of the modelling groups did not consider this at all. Others concentrated on the spatial variability of the hydraulic conductivity observed at Äspö in the simulations for LPT2. Accordingly, a few groups had stochastic or statistical elements in their modelling. A truly stochastic approach, in the sense that a large number of realisations are simulated and the results are analysed statistically, have only been performed by PNC/Golder.

ANDRA/BRGM I

The group did not specify any additional objectives besides those described in Chapter 2 concerning the general objectives of Task No 1 as a Modelling Task.

A 3D, porous medium model called MARTHE, was used for deterministic groundwater flow calculations for the Äspö site. Density driven flows were computed by iterative coupling of flow and salinity transport calculations. Fracture zone transmissivities were superimposed on rock mass permeabilities by using a specific algorithm based on geometrical calculations. The idea was to take account of the important fracture zone characteristics in an otherwise regular domain without modelling the geometrical extent of the zones explicitly.

For transport simulations a random walk particle tracking method named SESAME, was applied to compute the velocities based on the groundwater fluxes provided by MARTHE. The hypothesis of a single porosity model was used.

ANDRA/BRGM II

Besides the overall objectives, Task No 1 was an opportunity to improve and test a new, automatic mesh generator. The complicated structure geometry of the Äspö site provided a good opportunity for this feasibility study.

The code utilised (ROCKFLOW) is a programme system for simulating flow and transport processes in fractured media. It is a dual porosity code taking into account flow through porous matrix and through fractures. The calculations also considered a prescribed density distribution which is heterogeneous in space but invariant in time. This distribution was interpolated from the MARTHE calculations described above.

The transport equation includes advection, molecular diffusion and hydrodynamic dispersion, radioactive decay and linear sorption. However, the transport simulations for LPT2 were not part of the report available at the time of the evaluation of Task No 1.

ANDRA/ITASCA

The specific objective was to apply a model as simple as possible but still reproducing the main characteristics of the Äspö site, ie the importance of fracture zones and channelling of flow and transport in fractured rocks. The aim of the tracer transport simulations was to assess the suitability of the model for analysing a large scale tracer test.

CHANNET, a discrete stochastic model, is based on the assumption that flow and transport take place in a network of 1D-channels. Each fracture zone is represented by a 2D, regular channel grid. This plane is supposed to be a disk. Flow in channels obeys Darcy's law. Full mixing is assumed at channel intersections. A simple inverse modelling technique was utilised in order to optimise equivalent fracture zone transmissivities for the Äspö site. This was done on the basis of measured drawdowns from the LPT2 test.

A 3D regular grid may be superimposed to represent the sparsely connected average rock. For the transient simulations of LPT2 this feature was used to mimic the behaviour of the storage effect of the rock mass.

For modelling tracer transport a particle tracking method was used to simulate advective-dispersive transport in an interconnected network of 1D-channels, TRIPAR.

All computations did not cover the effect of water density contrasts due to salinity. However, salinity effects were studied separately.

CRIEPI

No additional, specific objectives were mentioned besides those described in Chapter 2 concerning the general objectives of Task No 1 as a Modelling Task.

FEGM/FERM, a 3D analysis of the groundwater flow and solute transport at the Äspö site during LPT2 was applied. The conceptual model is an equivalent continuum approach including an implicit method for taking account of fracture zone properties. The permeability of blocks which cross a fracture zone was calculated as a volume average of the fracture zone and the rock mass. Deterministic analysis was performed. The approach took no account of differences in salinity.

The tracer simulation model was coupled with the hydrology part through the Darcy velocity field. A dispersive component was included in the 3D transport model.

PNC/Golder

Besides the overall objectives, Task No 1 was a good opportunity for PNC to test different approaches to model flow and transport in fractured rocks. The present study covered the application of a *discontinuous* approach, a discrete fracture model on a site scale.

The simulations consisted entirely of discrete fractures which were generated using the FracMan computer code. The model contained two major fracture types: fracture zones, which were located deterministically according to the geologic structural model of Äspö; and fractures outside the fracture zones, which were generated stochastically.

Two separate methodologies were used for fracture zone representation. In the first approach planar regions containing discrete fractures represented the zones, in the second they were modelled as single fracture planes with a stochastic continuum variation of the hydraulic properties of those planes.

For tracer test simulations a particle tracking approach was utilised. Particles were moved through the fracture network by advection with a dispersive component.

PNC/Hazama

Besides the overall objectives, Task No 1 was a good opportunity for PNC to test different approaches to model flow and transport in fractured rocks. The present study covered the application of an equivalent *continuous* approach.

A 3D, heterogeneous continuum model (SETRA) for fractured rock was applied. In short, fracture data was used for inference of fracture length and density. A measure of the representative elementary volume (REV) was subsequently obtained through Crack Tensor Theory. For these REVs, the permeabilities were estimated by using single-hole hydraulic tests. Geostatistics and conditional simulation were utilised in order to generate a heterogeneous field and to simulate groundwater flow.

Particle tracking was used for transport simulation. The effective porosity was calibrated from the measured breakthrough curves.

SKB/CFE

The modelling work performed by this group forms part of the ongoing work within the Äspö HRL project. A series of analyses have therefore been performed during the last six years and the LPT2 analysis is just one more step towards a good understanding of the Äspö site from a geohydrological perspective.

PHOENICS, a 3D, porous medium model based on a general equation solver, was used for stochastic groundwater flow calculations of the Äspö site. Density driven flows were computed by iterative coupling of flow and salinity transport calculations. Fracture zone transmissivities were superimposed on rock mass permeabilities by using a specific algorithm based on geometrical calculations.

For transport simulations a particle tracking procedure (PARTRACK) was applied to compute the velocities based on the groundwater fluxes provided by PHOENICS. The dispersion process was accounted for in the transport simulations.

SKB/KTH

Besides the overall objectives, Task No 1 was a good opportunity to test the channel network model on a specific site. The model is still in a development phase.

The channel network model (CHAN3D) is a 3D stochastic model based on the assumption that fluid flow and transport take place in a network of channels. The model is based on field observations in drifts and tunnels that show that there are strong channelling effects in fractured rock. Each member of the channel network is assigned a hydraulic conductance. The channel conductance is larger in the areas where fracture zones are located.

Solute transport was simulated by using a particle following technique /Robinson, 1984/. The difference as compared to particle tracking is that in particle following, one particle at a time is followed from the start point to its destination. The time is recorded for each part of the route and summarised at the end. In particle tracking, a number of particles are followed at the same time.

Particles arriving at a channel intersection were distributed in the outlet channel members with a probability proportional to their flow rates. Dispersion of the solutes was mainly caused by the difference in travel times for the solutes due to the different paths and flow rates, but the matrix diffusion process may also have contributed to the dispersion.

Other entities used for transport simulation were the specific area in contact with the groundwater flow, rock matrix porosity, diffusivity and sorption capacity for sorbing species.

TVO/VTT I

It must be emphasised that the model of the Äspö site has been developed not only to simulate the LPT2 tests but also to understand the geohydrology of the Äspö site. Further analyses are anticipated.

A 3D code (FEFLOW) has been applied for deterministic as well as stochastic continuum analyses of the LPT2 experiments. However, the stochastic part was limited to a specific study of the influence of the heterogeneity of the bedrock. For LPT2, the bedrock heterogeneity was considered when calculating the flow rate through the tracer injection sections.

Simulations were performed for both geologic structural models available at the Äspö site during Task No 1. Calibration, conditioning and sensitivity tests were regarded as important elements of the study.

In addition, it was shown that the influence of density driven flow on the drawdown of the pressure is negligible during LPT2.

The modelling team focused on the groundwater flow part of LPT2 whereas the other TVO team studied the tracer experiments.

TVO/VTT II

The work had a limited scope in that the analyses performed by this second TVO/VTT team were restricted to the tracer experiments of LPT2. It should be seen as a complementary part to the other TVO/VTT team.

Based on considerations of the results of the tracer tests for different tracers in LPT2, the assumption was made that the tracers arrived via essentially one transport route within the fracture zone NNW-2. If this is the case the modelling effort for the tracer test is rather straightforward.

An advection-dispersion model as well as a model similar to the matrix diffusion model in this single transport path was utilised for the tracer breakthrough analyses. A fit of transport parameters was possible.

As a second and separate part of the LPT2 analyses, the breakthrough data was analysed by a deconvolution technique.

UK Nirex/AEA Technology

AEA Technology has carried out coupled continuum and fracture network modelling of the Äspö LPT2 pumping test. The continuum/fracture network model consisted of a near surface weathered region, modelled as an effective porous medium; a set of fracture zones, located deterministically according to SKB's structural model of the site; and finally a statistically generated background of fractures.

Several models were developed to explore aspects of conceptual uncertainty. The simplest model consisted of only the fracture zones as specified by the structural model given by SKB TR 91-22. In this case the fracture zones were represented as planar features with the prescribed hydraulic properties. Subsequent models built upon these basic structural features. They included coupling the fracture network with an equivalent porous media weathered region to represent the near surface. The properties of the major fault zones were modified slightly to obtain a better fit to the experimental results. Other models included statistically generated populations of background fractures to scope their effect on the computed drawdowns.

4 APPLICATION ON ÄSPÖ LPT2 DATA AND MODELLING RESULTS

This chapter summarises the modelling results of Task No 1. Extensive work has been carried out during a period of two years and the main results are reviewed. The executive summaries of each modelling group are included in Appendix 2. They will provide further details.

4.1 MODELLING APPROACHES APPLIED TO LPT2

The modelling exercise has been unique in that 11 groups have analysed the same experiment and data set using different methodologies. Table 4-1 gives an overview of these approaches and in particular how they were applied to the LPT2 simulations. Note that the modelling performed by UK Nirex/AEA is not included in this chapter. The work is still in progress and will be finally reported with Task No 3, which focuses on the hydraulic impact of the Äspö tunnel. A few comments related to Table 4-1 are listed below:

- As already mentioned in Table 3-2, a few of the groups considered the effect salinity had on fluid flow and transport. In these cases, assumptions regarding the salinity distribution along the lateral boundaries had to be made. Water densities were here imposed as functions of depth below sea level. These boundary conditions are very uncertain.
- The treatment of the top boundary conditions on the island of Äspö differed among the groups. Constant hydraulic heads have been utilised as well as an infiltration flux boundary condition. Some groups also compared the simulated infiltration rates with potential recharge estimated from hydroclimatic calculations.
- The base of the modelling work was in all cases the geologic structural model as provided by SKB. This base model is a synthesis of geological, geophysical, geochemical and geohydrological information from the Äspö site given at a certain time during the project. As seen in the table, two different base models have been available during Task No 1. The first one is called TR 91-22, /Wikberg et al, 1991/, and is the base model as interpreted after the pre-investigations of the Äspö site during 1986-1990. The second one is termed Data Distribution No 4 and this refers to the data delivery to the Task Force modelling groups in February 1993. This updated model is described in /Stanfors et al, 1993/ and was based on additional borehole investigations as well as the first 1475 m of the Äspö tunnel. Some of the conclusions of the LPT2 analyses have to be read bearing in mind that there were actually two structural models available.

Table 4-1. Äspö Modelling Task Force. Overview of how the different modelling groups applied their approaches to the LPT2 simulation. See also Table 3-2.

	Simulation code	Size of region modelled (km^3)	Size of numerical model (ss flow)	Boundary conditions for modelled domain	Boundary condition for KAS06	Geologic structural model utilised	Calibration of	Conditioning	Tracer tests simulated
CRIEPI	FEGM/ FERM	1,8*2,0*1,3	109 000 nodes	Top:GW levels Vert: h.s. pres	flow rate distr	SKB TR 91-22	-FZ geometry -Dispersivities -Eff. porosity	No	-KAS08-1 -KAS12-2
TVO/VTT I	FEFLOW	Radius=2 km Depth=1.5 km	18 000 elements (FEM)	Top:GW levels Vert: h.s. pres	head/total inflow	SKB TR 91-22 & Data Distr No 4	-Top b c -T-values for FZ -Extent of FZ -Specific storativity	Yes	pathlines for 3 tests
ANDRA/BRGM II	ROCKFLOW	1,8*1,8*1,2	15 000 nodes	Top:infiltration Vert: h.s. pres	flow rate distr	Data Distr No 4	-Permeability -T-values for FZ -Infiltration	No	-
ANDRA/BRGM I	MARTHE/ SESAME	1,8*1,8*1,2	19 500 nodes	Top:infiltration Vert: h.s. pres & salinity	flow rate distr	Data Distr No 4	-T-values for FZ* -Eff porosity -Dispersivities	No	-KAS05-3 -KAS08-1 -KAS08-3 -KAS12-2
SKB/CFE	PHOENICS/ PARTRACK	2,1*1,7*1,3	112 000 nodes	Top:infiltration Vert: h.s. pres & salinity	flow rate distr	SKB TR 91-22	- FZ geometry - T-values for FZ	No	All 6 tests performed
PNC/Hazama	SETRA/ ARRANG	0,9*0,5*0,8	14 500 nodes	Top:GW levels Vert: h.s. pres	flow rate distr	SKB TR 91-22	Effective porosity	No	-KAS05-3 -KAS08-1 -KAS12-2
PNC/Golder	FracMan/ MAFIC	1,1*1,0*1,0	3000 elements (FEM)	Top:infiltration Vert: h.s. pres	head/total inflow	SKB TR 91-22	A number of transport parameters	Yes, spinner data	All 6 tests performed
ANDRA/ITASCA	CHANNET/ TRIPAR	2,4*2,4*1,2	80 000 nodes	Top:infiltration Vert: h.s. pres	total inflow	Data Distr No 4	-T-values for FZ (optimised) -Channel shape factor	No	-KAS08-1
SKB/KTH	CHAN3D	1,0*0,7*0,7	66 000 nodes	Top:infiltration Vert: h.s. pres	head & flow rate distr	Data Distr No 4	No	No	All 6 tests performed

*=Modest calibration, termed sensitivity tests.
h.s. pres = hydrostatic pressure assigned. s s = steady state. bc = boundary conditions.

Note that TVO/VTT I has executed the task using both base models and obviously had the opportunity of examining the sensitivity on the LPT2 simulation results of the base model. However, if modelling approach comparison had been the ultimate goal, then all the exercises should preferably have been performed using the same base model.

- A model is said to be *calibrated* when a comparison between simulated results and the available measured data gives differences which are considered to be negligible. The available data and the data quality of a site decides the importance of calibration and the amount of work necessary. When performed in an automatic manner the procedure is called *inverse modelling*.
  Conditional simulation means a procedure in stochastic modelling for creating realisations of the studied property. These realisations are all compatible with the measured data.
- The amount of calibration efforts differs among the groups, from the extensive and structured calibration work of TVO/VTT I to no calibration at all as in the case of SKB/KTH. Calibration using the pumping test implies adjustment of fracture geometry and especially the fracture zone transmissivities.
  By using the tracer tests, adjustment of transport parameters may be performed, such as effective porosity, dispersivities, channel shape factors etc. Note that ANDRA/ITASCA has utilised an inverse modelling technique in order to calibrate the flow model.
- Finally, note that some groups have not actually simulated the tracer tests of LPT2. Three groups have modelled all six tracer tests. The VTT/TVO II group is not included in Table 4-1 since they have specifically dedicated their efforts to the tracer transport part. The KAS08-1 and KAS12-2 tracer tests have been simulated in their work.

4.2 DATA UTILISED

The starting point of the modelling studies performed has been the SKB Technical Report TR 91-22. This presents a geological, geohydrological and geochemical model of Äspö as interpreted when summarising the pre-investigation data from Äspö. Task No 1 involved a number of data deliveries as described in section 2.3.3. It is possible to identify the main complementary data sets utilised by the different modelling groups. Table 4-2 presents a summary of these data sets.

Apparently, much of the fracture data delivered was not used by the modelling groups. Only ANDRA/ITASCA, PNC/Golder and PNC/Hazama have utilised this information to some extent. However, in the case of PNC/Golder they actually needed more information concerning fracture orientations and accordingly performed an extra field campaign in the autumn of 1992. The tunnel fracture mapping delivered was just up to tunnel length 1500 m. This type of information will be more useful in future Modelling Tasks.

Table 4-2. Main data sets used for Task No 1. The data sets in the left hand column have been divided according to the data distributions during Task No 1.

Modelling Group Data set	ANDRA /BRGM I	ANDRA /BRGM II	ANDRA/ ITASCA	CRIEPI	PNC/ Golder	PNC/ Hazama	SKB/ CFE	SKB/ KTH	TVO/ VTT I
Experimental data from the LPT2 tests	X	X	X	X	X	X	X	X	X
Spinner survey in KAS06	X	X		X	X	X	X	X	X
Additional pumping tests at Äspö, e g LPT1 and short term tests							X		X
Outcrop fracture mapping					X	X			
Corelogs from boreholes on Äspö					X	X			
Tunnel mapping data, up to 1500 m tunnel length			X		X				
Results from single hole packer tests					X	X		X	X
Updated fracture zone geometry, Data Distribution No 4	X	X	X					X	X
Compilation of undisturbed piezometric levels and their uncertainty									X
Complementary set of core logging data									

The additional pumping tests at Äspö have only been used by two groups. These tests could have been useful for independent calibration of the groundwater flow models.

4.3 LPT2 SIMULATION RESULTS, EXAMPLES

In order to make a more structured comparison of the results of Task No 1, two sets of performance measures were set up as outlined in section 2.3.1, one for flow and one for tracer transport simulations.

The reports written by the modelling groups provide a comprehensive overview of the modelling results. This section covers a few of the details. The first set of performance measures concerned the modelling of flow and drawdown of the pumping test. A fairly typical result of the steady-state simulations is shown in Figure 4-1, which is a distance-drawdown plot, ANDRA/BRGM I.

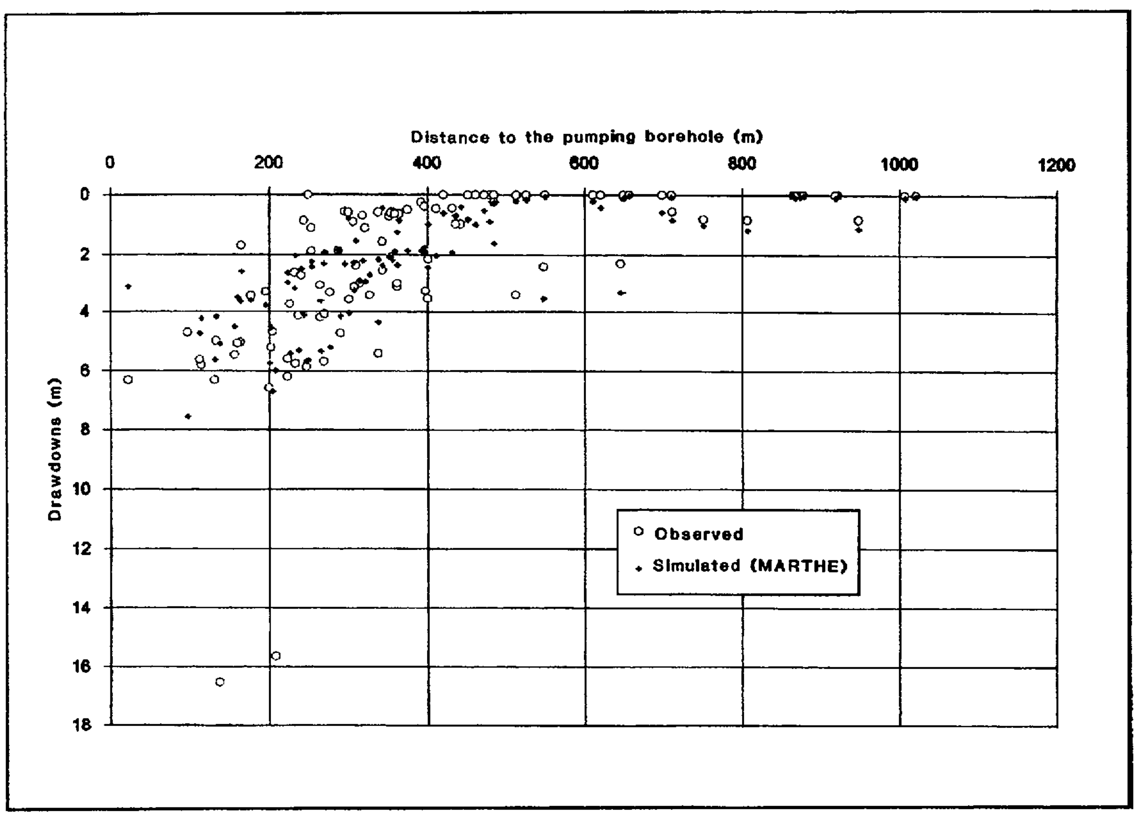

Figure 4-1 *Drawdown-distance plot at steady state, /ANDRA/BRGM I, 1994/.*

From the figure it is clear that the measured drawdowns agree with the calculated ones. However, there were two measured sections in borehole KAS07, where the measured drawdown by far exceeded the calculated ones. This is common for most groups and was evidently caused by a missing conductive zone in the geologic structural model. TVO/VTT I suggested that there is a hydraulic structure in the NNW-direction intersecting KAS07. ANDRA/BRGM I on the other hand proposed one or several EW-X features that should be included in the base model in order to increase the hydraulic connections. In appendix 2 a number of plots are given showing maps that include the difference between measured and calculated drawdowns.

Transient drawdowns were not presented by all groups, since some have only made steady state simulations. However, Figure 4-2 shows a number of calculated drawdowns as a function of pumping time by Taivassalo et al, /1994/. From the figure it is clear that the drawdown time history is well reproduced including the irregularities caused by the changes in pumping rate.

In the transient simulations performed by ANDRA/ITASCA, the storage effect of the fracture zones and the rock mass were analysed. It was concluded that it is necessary to take account of the rock mass storage component in order to explain the evolution of drawdowns at later times, ie more than 10 days of pumping.

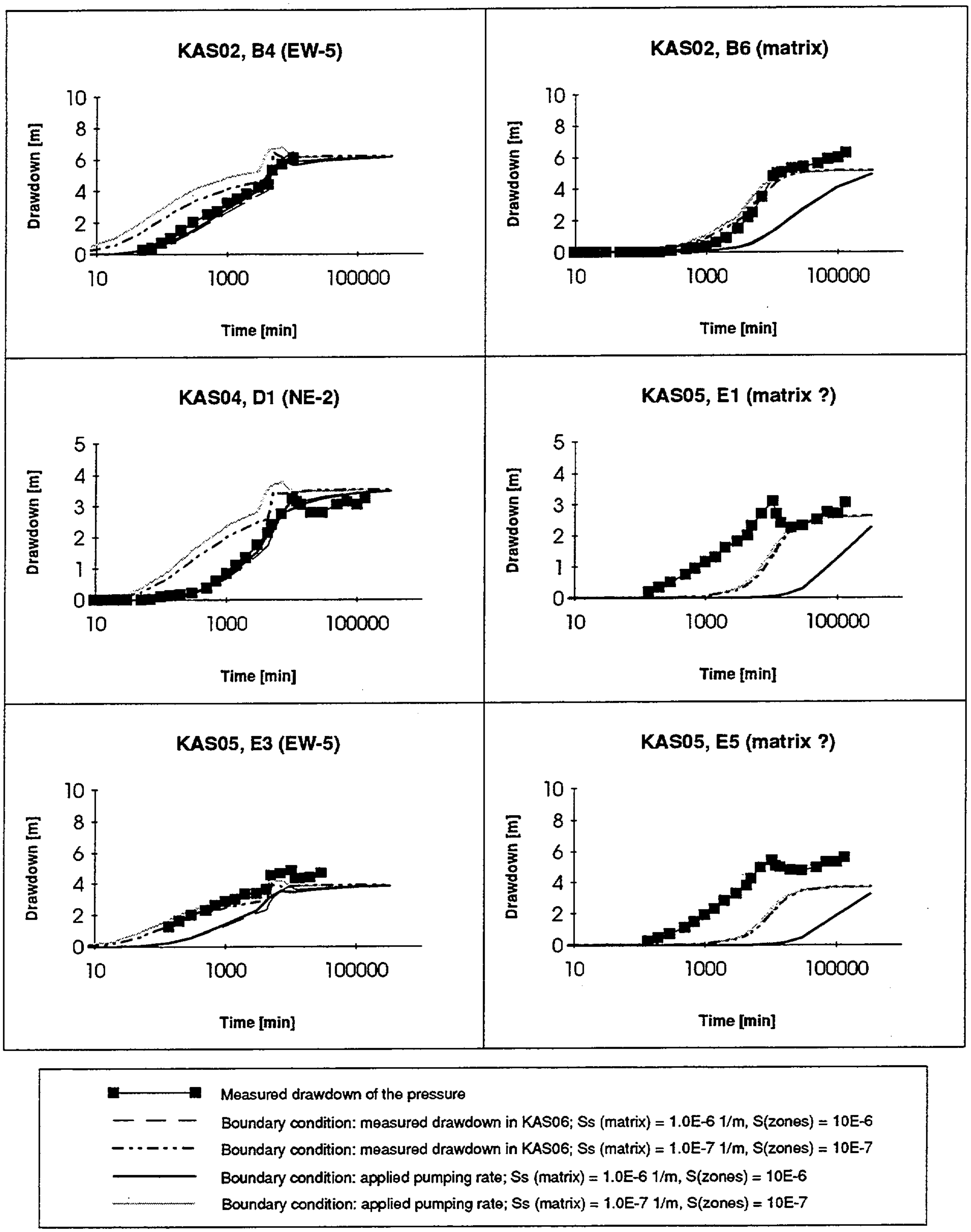

Figure 4-2 *Calculated and measured pressure drawdowns as a function of time in six observation sections for LPT2, /Taivassalo et al (1994)/. The computed results are for the calibrated model. The geologic structural model in TR 91-22 has been utilised.*

Concerning the inflow distribution in the pumping borehole KAS06, this could be compared with the spinner survey made in this hole. However, the calculations were performed in different manners which did not allow for direct comparison. Some groups used the measured inflow distribution as a boundary condition whereas others utilised the pressures measured in the withdrawal borehole as boundary condition. Nevertheless, in Table 4-3 some simulated results are presented. Further information is found in each of the group reports.

Table 4-3. The estimated inflow distribution to the pumping borehole KAS06 during LPT2 together with simulated values from two modelling groups. Both PNC/Golder and TVO/VTT I have used the first geologic structural model presented in SKB TR 91-22.

Fracture zone	Observed percentage of total inflow	PNC/Golder (Sep Model) results	TVO/VTT I results (calibrated)
EW-3	15 %	0 %	15 %
NNW-1	21 %	18 %	21 %
EW-5	33 %	46 %	34 %
NNW-2	26 %	26 %	29 %
EW-X	5 %	10 %	0 %

Finally an example from the transport calculations is illustrated in Figure 4-3. It shows the tracer breakthrough from section KAS08-1 calculated by /Uchida et al, 1994/. The discrete fracture model was used and transport parameters have been calibrated to measured data to get a good fit, since no site-specific transport properties were available a priori. Nevertheless, the calculated curve reflects the field results well.

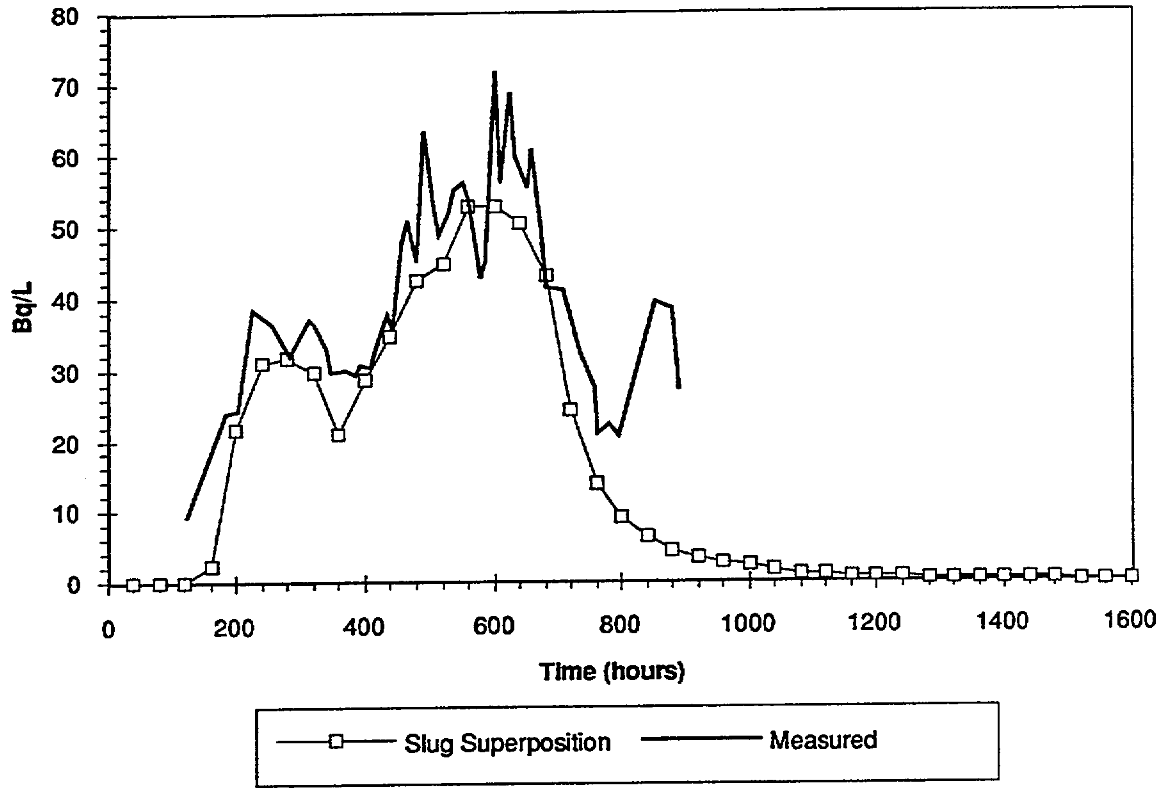

Figure 4-3 *Tracer recovery in KAS06 from KAS08-1 injection, /Uchida et al, 1994/.*

4.4 COMPARISON OF RESULTS

4.4.1 Task 1A - groundwater flow

The steady state simulations of drawdowns for LPT2 in relation to the Äspö geography are shown for each modelling group in Appendix 2. The drawdown distance plots are also included. They are presented here in a common format. Note that the "distance" definition used is the one referred to in /Rhén, 1991/, ie the reference point in the pumping borehole KAS06 is the hydraulic centre point.

In order to make an overall comparison of the flow part of Task No 1 modelling results, a number of integrated measures were calculated for the steady-state simulations of LPT2. In fact, several attempts to estimate the performance of the numerical calculations have been made and are presented in Table 4-4. Some are related to the mean error of the simulation results and some to the accuracy. The non-weighted measures are simple and convenient. These are complemented with distance weighted measures. The reason for this is that in the non-weighted measures, a few bad simulation results far away from the pumping borehole may be drowned by a large number of good predictions near it.

Table 4-4. Definitions of the overall evaluating measures of the groundwater flow part of Task No 1, Steady-state conditions are modelled.

MEAN ERROR

Non-weighted drawdown:

$$dh = \frac{\sum_{i=1}^{n} (h_i^m - h_i^c)}{n}$$

$$dh(abs) = \frac{\sum_{i=1}^{n} \left| h_i^m - h_i^c \right|}{n}$$

Two-dimensional weighted drawdown:

$$dh(\ln r) = \frac{\sum_{i=1}^{n} \left(h_i^m \cdot \ln \frac{r}{r_o} - h_i^c \cdot \ln \frac{r}{r_o} \right)}{n}$$

Three-dimensional weighted drawdown:

$$dh(r) = \frac{\sum_{i=1}^{n} \left(h_i^m \cdot \frac{r}{r_o} - h_i^c \cdot \frac{r}{r_o} \right)}{n}$$

ACCURACY

Non-weighted drawdown:

$$Dh = \sqrt{\frac{\sum_{i=1}^{n} (h_i^m - h_i^c - dh)^2}{n-1}}$$

Two- and three-dimensional weighted drawdown:

$$Dh(r) = \sqrt{\frac{\sum_{i=1}^{n} \left(h_i^m \cdot \frac{r}{r_o} - h_i^c \cdot \frac{r}{r_o} - dh(r) \right)^2}{n-1}}$$

$$Dh(\ln r) = \sqrt{\frac{\sum_{i=1}^{n} \left(h_i^m \cdot \ln \frac{r}{r_o} - h_i^c \cdot \ln \frac{r}{r_o} - dh(\ln r) \right)^2}{n-1}}$$

n: number of points with measured data, used to compare with calculated points
h: piezometric level (freshwater head)
index m: measured value
index c: calculated value
r: spherical distance between point of application in pumping well and observation section, in metres
r_o: reference radius, r_o = 1 m in the calculation shown.

Table 4-5. The summarised evaluating measures of the groundwater flow part of Task No 1. Steady-state conditions are modelled. Definitions according to Table 4-4.

Modelling team	dh	dh(abs)	dh(lnr)	dh(r)	Dh	Dh(lnr)	Dh(r)
ANDRA/BRGM I	0.04	1.24	0.03	-52.90	2.08	11.34	534.22
ANDRA/BRGM II	-0.23	2.05	-1.77	-278.44	3.11	16.98	931.49
ANDRA/ ITASCA	0.54	1.48	2.89	143.95	2.61	14.46	748.20
CRIEPI	0.77	1.56	4.24	198.19	2.52	13.54	613.03
PNC/Golder (March model)	-1.65	2.20	-9.11	-452.45	2.85	15.52	822.80
PNC/Golder (Sept. model)	0.30	1.28	2.42	156.39	2.14	11.54	510.13
PNC/HAZAMA	1.22	2.33	6.97	356.52	2.88	14.89	562.04
SKB/CFE	0.00	0.96	-0.09	-24.54	1.59	8.85	462.11
SKB/KTH	-4.87	5.54	-25.30	-1014	4.98	24.20	990.18
TVO/VTT I	-0.04	1.10	-0.02	47.24	1.78	9.89	503.89

Table 4-5 is depicted in Figure 4-4.

It is difficult to compare results and therefore different means of comparison have been made. Seen together they provide a good overall impression, as seen in Figure 4-4. It should be noted that PNC/Hazama and SKB/KTH have not simulated the drawdowns far away, but just below 600 m and 400 m respectively. Naturally, this influences the measures for these groups.

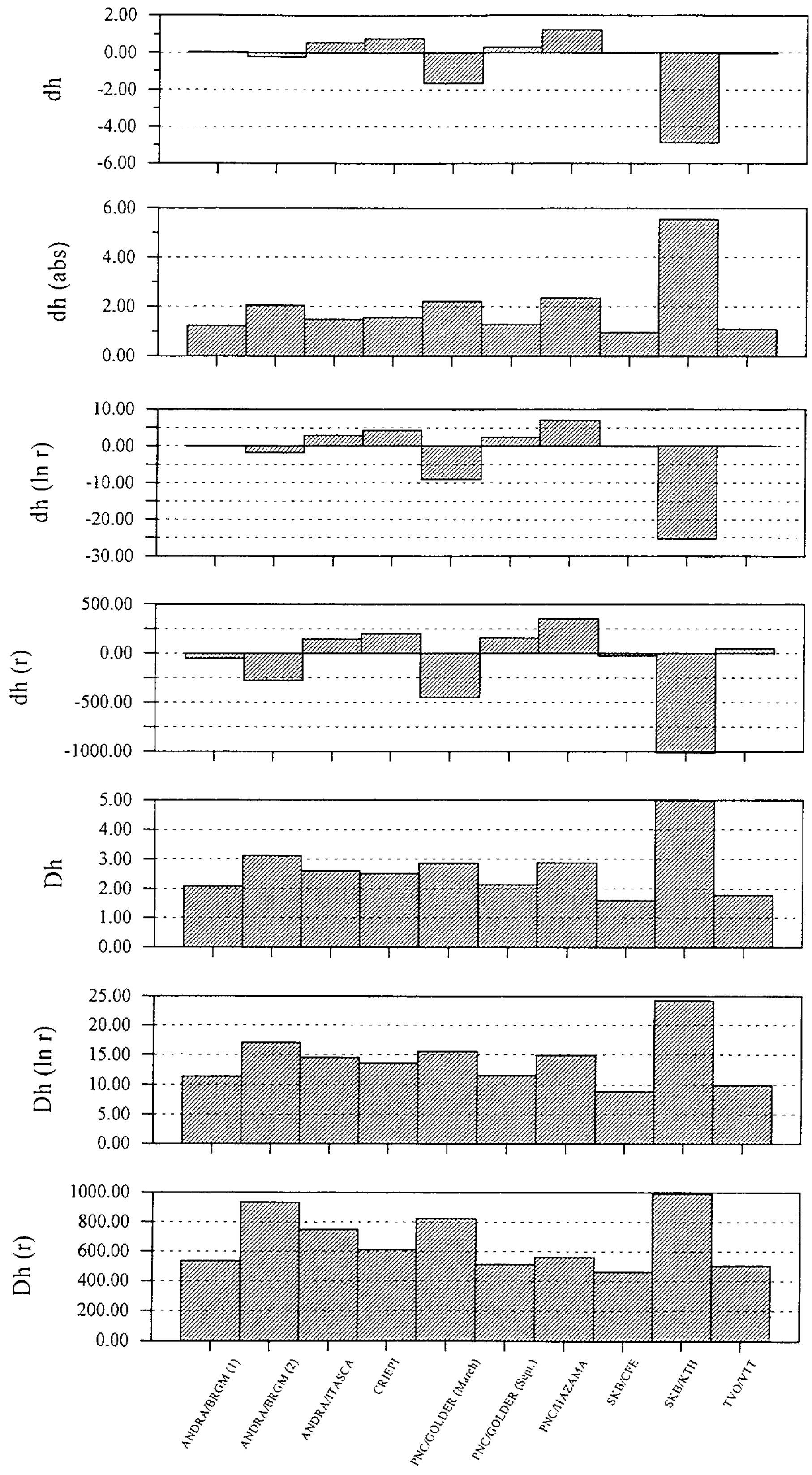

Figure 4-4 *Overall measures on the steady state groundwater flow part of Task No 1. Measures as defined in Table 4-4.*

It seemed that groups such as SKB/CFE and TVO/VTT I, which all performed a systematic calibration of fracture zone transmissivities (see Table 4-1), had lower *dh(abs)* and *Dh* values, see Table 4-4. It appeared that those discrete models that have not been calibrated are worse in describing the drawdowns during LPT2, e g SKB/KTH and PNC/Golder (March model).

Using a continuum representation of the fractured rock, TVO/VTT I concluded that the agreement between the measured and the simulated drawdowns was satisfactory even before their calibration phase. The pressure field seemed to be rather insensitive to the bedrock properties. This conclusion is of course dependent on the amount of effort made regarding the analyses and understanding of the area, the type of data taken into account etc. If one has a "bad starting position", calibration will help considerably.

Thus, the above serves as a reminder not only to look at the pressure field for modelling result comparison, there are also other entities to consider in order to get a thorough evaluation.

Another point of interest is how the data used for calibration relates to the performance measures of the Modelling Task. Independent calibration should preferably be performed. There were data available for this in Task No 1, eg short term pumping tests and the LPT1 test. However, Modelling Task No 1 did not specify that this was the way to proceed. However, TVO/VTT I and SKB/CFE did use independent calibration of their LPT2 models. For example, TVO/VTT I did not calibrate their model to obtain a perfect fit with the LPT2 results. They performed an overall calibration using several pumping tests instead. They used LPT1 results as well as the short term tests of KAS12, KAS13, KAS14 and KAS16.

TVO/VTT I executed the task using both geologic structural models, (/Wikberg et al, 1991/ & /Stanfors et al, 1993/), with the main emphasis on the updated model. They actually examined the sensitivity on the LPT2 simulation results of the available base model. They concluded that the differences in the structural models did not significantly influence the groundwater flow simulation results of LPT2.

Regarding the drawdown-distance plot of ANDRA/BRGM II, they stated that they were aware of the fact that their simulated results far away from the pumping borehole could have been affected by boundary effects.

So far in this section, steady-state and transient drawdowns during LPT2 have been discussed. However, there were also other performance measures defined for the groundwater flow modelling, see section 2.3.1. These have not been presented by all groups. It is not straightforward to make a comparison either.

Concerning the inflow distribution in the pumping borehole KAS06, this can be compared with the spinner survey made in this hole, see Table 2-1. However, some groups used this inflow distribution as boundary conditions, eg PNC/Hazama, CRIEPI, SKB/KTH, to the simulation of drawdowns whereas others did perform simulations, eg PNC/Golder, TVO/VTT I. SKB/KTH concluded that the best agreement when simulating drawdowns is when they used the inflow distribution to KAS06 as boundary conditions. Naturally, these differences in treatment of the information make it hard to produce an overall comparison of simulated inflow. Therefore, it was decided not to make an overall comparison of these results.

In addition, the groundwater flux at the injection sections had been simulated and compared with results from point dilution measurements described in section 2.1.4. This had only been simulated by a few of the modelling groups and is not discussed further in this report. This is a very hard comparison to make. The measurements strongly depend on local conditions around the boreholes, such as skin effects and local hydraulic gradients.

4.4.2 Task 1B - transport

The aim of the tracer test of LPT2 was to determine hydraulic connections and not primarily to determine large scale transport parameters. Therefore Task No 1B should be evaluated accordingly. As mentioned in Table 4-1 not all the groups have actually analysed the tracer tests. Furthermore, only three groups have simulated all six tracer tests.

Regarding the experiments, four different tracers were injected in six sections in five boreholes. Two of these injections, originating from KAS12-2 and KAS08-1 could be clearly detected in the withdrawal borehole. Generally, the modelling results of Task No 1B for the KAS08 and KAS12 injections were quite satisfactory. The simulations confirm the field results well. However, this is very much due to the calibration of transport parameters which has been performed by most groups.

By analysing the experimental breakthrough curves for the two recovered tracers in LPT2, TVO/VTT II concluded that the curves showed a very similar behaviour. This indicated that it was very unlikely that the curves represented different, independent, transport paths. Therefore, they analysed the tracer tests using just one transport path and the test results were possible to reproduce using this approach. Finally, TVO/VTT II suggested that a study of transport phenomena and parameters should include a series of measurements, eg with different flow rates or other parameters that could be varied.

The fact that no breakthrough was obtained for a few of the tracers has been discussed by the modelling groups. PNC/Golder predicted breakthrough curves comparable to the KAS08 and KAS12 breakthroughs for all of the injection locations, not just those which had observed breakthrough. They calibrated the transport parameters using the KAS08-1 and KAS12-2 breakthrough data. Using this information, three of the four remaining tracers produced simulated breakthrough within the experimental time of 2000 hours. They stated that the possible reasons for the discrepancy were several and included the following:

- Adjustment of transport properties: Breakthrough would ultimately occur from those intervals and would occur after the end of the experiment.
- Poor connectivity: The connections between the injection pathways and KAS08 were not as strong as implied in the geologic structural model that was used.
- Flow path tortuosity caused by incomplete mixing at fracture intersections.
- Masking by multiple injections: Breakthrough may be masked by breakthroughs from earlier injections.

The group also suggested that the first three reasons could have been evaluated by repeating the experiment using higher pumping rates and longer test times.

The conclusions of the modelling work will be discussed further in the following chapter.

5 DISCUSSION AND CONCLUSIONS

The modelling studies performed for Task No 1 must be evaluated bearing in mind that different groups joined the task with somewhat different objectives. It must be clearly stated, that the exercise is not a competition in modelling. The general conclusions should reveal some of the strengths and weaknesses of groundwater flow and transport modelling in fractured rock. Moreover, the evaluation has been made in several steps and with the close cooperation of the modellers. An important issue has been to identify similarities and differences between the results from different modelling methodologies. A number of questions, see Appendix 3, were therefore put to the modellers and to the Task Force delegates in a Modelling Questionnaire, and some of these will be discussed below.

5.1 CONCLUSIONS REGARDING THE PERFORMANCE OF THE MODELLING APPROACHES APPLIED

Task No 1 has been modelled by 11 different groups using different conceptual and numerical methodologies for simulating flow and transport in fractured rocks. A wide range of approaches have been utilised, from rather straightforward concepts using assumptions of one-dimensional flowpaths for the tracer tests (TVO/VTT II) to advanced discrete fracture network modelling using site fracture data, calibration and conditioning (PNC/Golder).

As outlined in Appendix 3, a comparison between the different modelling teams indicates that markedly different approaches for groundwater flow result in relatively similar outputs. The question is how sensitive the output is to the underlying conceptual model and also, which are the sensitive elements of the models? In the answers to the Questionnaire, the modellers stress that it depends on the output that is referred to. The pressure field is rather insensitive to the conceptual model whereas the transport outputs, like breakthrough curves are more sensitive. The sensitive elements are mainly the boundary conditions and the representations of the fracture zones in the model. For transport calculations, the flow porosity is also a critical factor. The discrete fracture approach is a conceptual model that involves another set of sensitive parameters.

Task No 1 has shown that all the modelling approaches used, representing the whole spectrum of possible methods, have the capacity to simulate the large scale LPT2 set of tests, both for flow and transport. The evaluation of the modelling in the Äspö Task Force has shown that this type of modelling is both useful and feasible for describing groundwater movements in a fractured crystalline rock. The pressure field, which is not very sensitive to variations of the hydraulic conductivity field, may be modelled with sufficient accuracy with an equivalent-continuum model. The flow distribution in the rock requires a model with a realistic hydraulic conductivity distribution. If inflow pattern or transport paths are to be modelled a more sophisticated approach like a stochastic continuum or a discrete fracture network model is required. These different approaches put different requirements upon the characterisation of the modelled volume, with increasing detail of resolution and conceptual refinement with decreasing geometrical scale.

The purpose of Task No 1 has not been modelling approach discrimination and the performance measures have been defined accordingly. Future experiments at the Äspö Laboratory will allow for model or process discrimination when using a series of measurements with different flow rates or other parameters that could be varied.

It must also be pointed out that Task No 1 was no blind prediction exercise. A very large site database was available beforehand which allowed for calibration using, for example, the tracer test data. Future tasks will include modelling and experiments undertaken simultaneously.

A specific issue is that varying density effects have both been considered and neglected in the different studies. A few teams have specifically analysed quantitatively the effect of neglecting the existing salinity. TVO/VTT I showed that for the simulation of the drawdowns during LPT2 the consideration of density effects changed the results by no more than 5 %. For natural conditions the situation may be quite the opposite. In conclusion, for the LPT2 test which is a very large perturbation of the natural geohydrological conditions, the salinity effects may be disregarded.

A few of the modellers mentioned large discrepancies in actual recharge and available water for infiltration. In order to recover a piezometry close to the observed levels, it was necessary to use a much lower recharge rate, 5.5 mm per year compared to 120 mm per year, as concluded by e g ANDRA/BRGM I. There are mainly two reasons why the effective recharge is much smaller than the potentially available net precipitation. First a large portion of the surface of Äspö consists of bare rock with small recharge capacity. Second, and probably more importantly, is the fact that under natural conditions most of the infiltrating water is drained towards wet areas, bogs and marshes, and small streams of Äspö after a very short flow distance as groundwater. This implies that under natural conditions the groundwater reservoirs are filled up, but also that the effective recharge may increase substantially if Äspö is drained by a tunnel.

Calibration efforts were performed by most groups. Calibration seems to be necessary in order to build confidence in a groundwater flow model on the site scale. This was especially true for the discontinuous approaches of Task No 1. Furthermore, calibration also indicates how sensitive the outputs are. Transport predictions rely heavily on calibration of transport parameters, such as fracture aperture and dispersion coefficient, for an accurate result for the breakthrough curves.

Moreover, it is very important to have data sets available for independent calibration of the models set up for a site. The modelling tasks and their performance measures should be defined accordingly. The predictive capacity of the models is the most interesting aspect from the safety assessment point of view. In Task No 1, independent calibration was performed by just a few teams since this was not specified in the Task definition.

A few of the modelling groups seemed to have used too small a model region in order to correctly simulate the drawdown effects of the pumping test. This may be seen in the integrated measures presented in Table 4-4.

Regarding the tracer tests, the general tendency was that the predicted travel times for the tracers that arrived were too short. Particularly, a few of the tracers injected never arrived in the pumping borehole during LPT2. New information from the construction phase of the Äspö HRL confirms that the reason was poor connectivity. The existence of the assumed structure EW-5 has not been confirmed by tunnel data.

Nevertheless, there is a general consensus that a more fundamental understanding of transport of solutes in fractured rocks is necessary, with regard to process discrimination, pathway identification and obtaining transport parameters for models. Low tracer recovery observed may be caused by a number of processes, and it is important to resolve the dominating processes, and identify how these can be incorporated in flow and transport modelling. In order to do that, a series of experiments in different scales are required as well as further model development.

5.2 CONCLUSIONS REGARDING THE TECHNICAL PERFORMANCE OF THE LPT2 EXPERIMENTS

The initial objectives of the LPT2 tests as outlined in section 2.2.1 were all fulfilled by the experiment.

In the Äspö site characterisation programme, the LPT2 experiments and some earlier large scale interference tests have been the cornerstones in the process of identifying the major conductive fracture zones. This is also true for determining the orientation and hydraulic properties of the zones. Through the LPT2 test the conductive structures and their properties at southern Äspö were verified. It should also be noted that the LPT2 tracer test has been designed to act as a connectivity test and not for determining the dominating transport processes. The tracer test gave clear information on the arrival of two tracers and also some data regarding large scale transport properties of the conductive zones.

However, two technical problems regarding the test should be mentioned. First, the combination of dilution measurements with tracer injection has been advantageous, since it indicates the change of groundwater flux due to pumping. However, it gives an injection pulse with a varying concentration, which may lead to difficulties for evaluation and modelling. This is further discussed in Rhén et al, /1994/. Secondly, it is unsatisfactory that several tracers failed to reach the extraction well. They should have done so since the well was the only sink in the region.

Among the reasons why the tracers never arrived during LPT2 it has been argued that breakthrough would ultimately occur from those intervals and would occur after the end of the experiment. It may also be the case that the connections between the injection pathways and KAS08 were not as strong as implied in the geologic structural model used or it may be due to flow path tortuosity caused by incomplete mixing at fracture intersections. These three reasons could have been qualitatively evaluated by repeating the experiment using higher pumping rates and longer test times. However, these additional experiments would be of no help to the process identification.

New information from the construction phase of the Äspö HRL confirms that the reason was actually poor connectivity. The existence of the hydraulic structure EW-5 has not been confirmed by tunnel data and the structure is now not part of the current geologic structural model as a continuous hydraulic feature. This explains why some tracers never arrived in the withdrawal hole since their main pathway should have been through the EW-5 structure.

5.3 CONCLUSIONS REGARDING THE ÄSPÖ DATABASE

The existing Äspö database has been the basis for all modelling groups. In general the modelling groups have not used any extra data sets besides those provided by the Task Force Secretariat. Only limited editing and some explanations for external use have been added for Task No 1. One exception is PNC/Golder, who made a surface outcrop mapping in order to obtain data on fracture orientations for their discrete fracture method. In several cases, though, modelling groups have asked for advice on additional information in the Äspö Progress Reports series.

An evaluation of the modelling reports on Task No 1 has shown several shortcomings in the Task No 1 data set:

- The geologic structural model on the site scale provided by SKB did not contain any information regarding fracture zone extensions. The reason for this is that the pre-investigations at Äspö focused on the actual site for the laboratory. Therefore, it was up to the modellers to decide if the zones should continue out to the model boundary or if they should end at other fracture zones. This affected the results in Task No 1 as well as their comparison, at least far away from the target area.
- The infiltration rates provided in the documentation were not very useful.
- Storage coefficients for fracture zones and rock mass have not been interpreted in the Äspö area.
- There are large uncertainties in the assumed salinity distribution for the site.

- There are also uncertainties in hydraulic conductivity data interpreted from borehole packer tests. This is due to the evaluation concept chosen and also, to a lesser degree, due to measurements errors.
- A discrete methodology for modelling Äspö on the site scale may lack some information. For the Channel Network approach this issue is addressed by /Gylling et al, 1994B/.

On a more specific note, the analyses of LPT2 have shown some indications of common discrepancies with the Äspö structural base model provided. By using this information the Äspö Project can update the interpretations of fracture zones, as well as their extent and hydraulic properties. As mentioned, the existence of the hydraulic structure EW-5 has been revised. Another conclusion from the modelling exercises is that there seems to be a highly transmissive connection between boreholes KAS06 and KAS07. This could be explained by the introduction of a NNW-structure. There are also uncertainties regarding the hydraulic properties of the EW-3 structure.

It should be noted here that one group, TVO/VTT I, did the LPT2 work for both available geological/geohydrological base models and concluded that the differences in these interpretations did not significantly change the simulation results of the groundwater flow part. They both represented the main features of the field experiment very well.

The overall conclusion is that the available database of Äspö and of the LPT2 experiment was satisfactory and sufficient for the purpose of calibrating a site scale groundwater flow model.

5.4 CONCLUSIONS REGARDING LPT2 AS PART OF A SITE INVESTIGATION PROGRAMME

A site characterisation programme for fractured rocks should preferably focus on the three key factors outlined in Chapter 1, ie the mechanical and chemical stability of a site as well as on groundwater flow and nuclide migration characteristics. Concerning the last factor a few important site characterisation issues may be identified for large scale field experiments:

- Verification of the existing geological/geohydrological/geochemical interpretation models.
- Verification of the large scale dominating hydraulic features.
- Understanding of the existing groundwater flow system and recharge conditions.
- Test of the modelling ability in the 100 m to the 1 km scale.
- Synthesis of relevant field data in a structured, closed form.

In the groundwater flow and transport perspective the following conclusions were identified regarding large scale pumping tests:

- Some modelling groups concluded that two or three large scale pumping tests like LPT2 would be necessary in order to gain non-ambiguous knowledge of the dominating hydraulic structures. Generally speaking, it is evident that one test should preferably be available for model calibration purposes. However, it would be beneficial to have another similar test available for model confirmation.

- Information regarding extensions of hydraulic fracture zones for the site were evidently missing. This is valuable information for the modelling.
- The data set used was the result of a rather extensive site characterisation programme for fractured rocks. Data for transport modelling was lacking, except for the LPT2 tracer tests. Improved knowledge of transport parameters should be strived for at an early stage of a site characterisation programme.
- Different modelling methodologies put different requirements on site characterisation. The discrete fracture modelling approach requires additional data collection, which should be included in a characterisation programme if such modelling was to be utilised, e g fracture orientation data as discussed in section 5.3.

5.5 UNRESOLVED ISSUES

There is a number of unresolved issues both in the structural base model of Äspö and in the conceptual models describing flow and transport of solutes in fractured rocks as the results of the modelling have shown.

5.5.1 Understanding of flow and transport characteristics of the Äspö site

As expected, the minor inconsistencies in the flow modelling are mainly related to the geologic structural model provided. Even though the overall impression is that the base model is a good interpretation of the site, all of the important conductive structures are evidently not included and there should also be some adjustments of the assigned hydraulic properties. For example, there is a general discrepancy in drawdown between modelled and measured results in two sections in borehole KAS07. This is evidently caused by a missing conductive zone in the geologic structural model.

As regards transport modelling, no effective characterisation method for transport parameters has yet been demonstrated as part of a site pre-investigation programme. Although, the reason why certain tracers did not arrive during the LPT2 tracer tests has been identified, an improved fundamental understanding of transport of solutes in fractured rocks is necessary with regard to process discrimination, pathway identification and obtaining transport parameters for models. The low recovery observed during the LPT2 tracer tests may be caused by a number of processes, and it is important to resolve the dominating processes, and identify how these can be incorporated in flow and transport modelling.

5.5.2 Conceptual models for flow and transport

There is a vast number of different conceptual and numerical models describing flow and transport in the geosphere. The evaluation of the modelling in the Äspö Task Force has shown that this type of modelling is both useful and feasible for describing groundwater movements in a fractured crystalline rock. The pressure field, which is not very sensitive to variations of the hydraulic conductivity field, may be modelled with sufficient accuracy with an equivalent-continuum model. The flow distribution in the rock requires a model with a realistic conductivity distribution. If an inflow pattern or transport paths are to be modelled a more sophisticated approach like a stochastic continuum or a discrete fracture network model is required. These different approaches place different requirements upon the characterisation of the modelled volume, with increasing detail of resolution and conceptual refinement with decreasing geometrical scale.

Model approach discrimination has not been the goal of Task No 1. Nevertheless, the advantages and disadvantages of different methodologies have been demonstrated in the LPT2 work. The site characterisation of Äspö evidently did not provide all the information in terms of transport parameters for the Channel Network approach. Here a model-specific unresolved issue can be identified.

The continuing work of the Äspö Task Force group will help to show and maybe quantify the conceptual model uncertainty that arises from the large number of possible descriptions of flow and transport in fractured media. An on-going Modelling Task will include the use of the calibrated models from Task No 1 as well as forward modelling of the hydraulic impact of the Äspö tunnel - Task No 3. Other planned Modelling Tasks will focus on the small scale flow and transport characteristics in single fracture zones at Äspö. This will allow process identification.

6 OVERALL CONCLUSIONS

The purpose of integrated safety assessments is to perform calculations in order to give quantitative predictions of the safety for a proposed deep repository. All this is done within the framework of chosen scenarios. The complexity of the studied processes and the time span in question make it necessary to use mathematical models and computer programs. An estimation of groundwater fluxes through the repository and the pattern of groundwater flow in the surroundings forms a central part of the repository performance assessment.

The scientific background of the conceptual, mathematical and numerical models is crucial for the reliability of the results from the safety assessment. The work performed in order to show that existing models describe the reality with sufficient detail is a central part of research programmes. This work is sometimes referred to as "validation" or "confidence building". The work within the Äspö Task Force should contribute to increased confidence in the ability to perform modelling of groundwater flow and transport of solutes.

LPT2, the large scale pumping and tracer tests at the Äspö Hard Rock Laboratory in Sweden were chosen as the first Modelling Task for the modelling groups joining the Äspö International Task Force on Modelling of Groundwater Flow and Transport of Solutes.

Task No 1 has been modelled by 11 different groups using different conceptual and numerical approaches for simulating flow and transport in fractured rocks. The objectives for taking part in the Modelling Task Force differed within each participating group. A wide range of methodologies have been utilised, from rather straightforward concepts using assumptions of one-dimensional flowpaths for the tracer tests to advanced discrete fracture network modelling using site fracture data, calibration and conditioning.

6.1 MODELLING

In conclusion, all the modelling approaches utilised, representing the whole spectrum of possible methodologies, have the capacity to simulate the LPT2 set of tests, both for flow and transport of solutes. However, the tracer experiments have focused on determining hydraulic connections and not on transport process identification. This affects the evaluation of the modelling performed. Accordingly, the conclusion is that Task No 1 has been a successful exercise in site scale geohydrology modelling.

It was not the purpose of Task No 1 to discriminate between modelling approaches. However, the exercise has shown the amount of effort needed for doing site scale modelling using different concepts. Data usage varied and some data was even missing for a few modelling groups. Generally speaking, different modelling approaches are suitable in different phases of a site performance assessment, depending on the geometric scales etc. The LPT2 exercise has shown that all modelling approaches are suitable for analysing the groundwater flow characteristics of a large scale pumping test.

More specifically, it is possible to conclude that site scale modelling, on a km-scale, using a discrete feature modelling approach is feasible and useful. This was not the case a few years ago. Furthermore, the discrete model based on channels in a network has also proven feasible to use on the site scale. As far as is known, this was demonstrated here for the first time. It appeared that calibration of a groundwater flow model is especially important when using a discrete approach.

It is very important to have data sets from a site available for independent calibration of the models. From a safety assessment point of view, the predictability of the models is the most interesting feature. Therefore, future modelling tasks and their performance measures should be defined accordingly.

All the modelling groups did utilise the Äspö geologic structural model which constitutes a geological/geochemical/geohydrological synthesis of all available data from the site investigations at a certain time. It may be concluded that the base model provided was very good for constructing a site scale model representing the main features of the field experiment. A well-established geologic structural model is a necessary starting point for successful modelling.

Data acquisition was not a problem for the continuum approaches utilised. Much of the Äspö site characterisation work has been performed within this framework.

Improved fundamental understanding of transport of solutes in fractured rocks is necessary with regard to process discrimination, pathway identification and obtaining transport parameters for models. Input parameters to transport modelling, such as flow porosity, channel properties etc, had to be estimated based on previous experience from large field experiments.

6.2 ÄSPÖ SITE DATA

New information from the construction phase of the Äspö HRL confirms that the reason why certain tracers never arrived in the withdrawal hole during the tracer tests was poor connectivity. The existence of the hydraulic structure EW-5 has not been confirmed by tunnel data and the structure is not part of the current geological structure model as a continuous hydraulic feature. This explains why some tracers never arrived since their main pathway should have been through the EW-5 structure. The modelling efforts of Task No 1 have actually contributed to this important updating of the structural model.

The experimental data from Äspö includes uncertainties which naturally affect the modelling results and the conclusions of the work on Task No 1. The issue of uncertainties in experimental data has neither been addressed by any modelling group nor been provided in terms of data by the Task Force Secretariat.

The overall conclusion is that the available database of Äspö and of the LPT2 experiment was found to be satisfactory and sufficient for the purpose of calibrating a site scale groundwater flow model.

6.3 LARGE SCALE FIELD EXPERIMENTS

In the groundwater flow and transport perspective a number of conclusions were identified regarding large scale pumping tests. It is evident that one test like LPT2 should preferably be available for groundwater flow model calibration purposes. However, it would be beneficial to have another similar test available for model confirmation. Task No 1 included a data set which was sufficient for groundwater flow modelling on the site scale whereas data on transport parameters was lacking. Improved knowledge of transport parameters should be strived for at an early stage of a site characterisation programme. Some modelling methods require additional data collection, e g discrete models, which should be included in a site characterisation programme if such modelling was to be utilised.

6.4 SUMMARY

In conclusion, the performed evaluation of the modelling of groundwater flow and transport in the International Äspö Task Force has shown that this type of site scale modelling is both useful and feasible for describing groundwater movements in a fractured crystalline rock. A general conclusion is that the versatile computing tools of today calculate what the conceptual model and its realisation of the specific case describes. The reliability of the model is dependent on:

- The appropriateness of the conceptual model.
- The existence and geometry of the major conductive elements since they govern the flow through the model.
- The hydraulic and transport properties of the different structural elements.

The approach used depends on the variable to be modelled. The hydraulic head, which is not very sensitive to variations of the hydraulic conductivity field, may be modelled with sufficient accuracy with an equivalent-continuum model. The flow distribution in the rock requires a model with a realistic conductivity distribution as well as an understanding of the excavation damage zone effects. If an inflow pattern or transport paths are to be modelled a more sophisticated approach like a stochastic continuum or a discrete fracture network model is required. These different approaches place different requirements on the characterisation of the modelled volume, with increasing detail of resolution and conceptual refinement with decreasing geometrical scale.

The main conclusions of Modelling Task No 1 are listed below:

Groundwater flow:

- All models represent the measured LPT2 data well.
- The capacity exists to perform groundwater flow modelling on a site scale.
- The data supplied for Äspö, including the geologic structural model, provides a good representation of the real system.
- A few consistent errors in the modelling work indicate minor errors in the geologic structural model of Äspö site.

Transport:

- Calibration of transport parameters can be utilised and provides reasonable results for LPT2.
- There is a lack of transport parameters (input data) for Äspö.
- The low recovery during the tracer tests was not completely understood. Therefore, regarding transport processes, the question of whether any important processes have been disregarded when modelling conservative tracers remains unanswered.

ACKNOWLEDGEMENTS

We would like to thank all the modellers of Task No 1 for their dedicated work from autumn 1992 until late 1994. We would also like to thank the Task Force delegates for the fruitful discussions at the Task Force meetings. This report is based on these contributions.

Ingvar Rhén and Torbjörn Forsmark of VBB/VIAK are gratefully acknowledged for their efforts in preparing the comparison of the performance measures of Task No 1A.

Finally, many thanks to Izabella Hallberg of GeoPoint AB for editing the language.

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Appendix 1

Data distributed to the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes

Task No 1 - the LPT2 experiments:

• **Data distribution No. 1:** (October 1992)

- Data on two diskettes corresponding to the data presented in the three reports:

  Rhén I. 1991. Information for numerical modelling 1990. General information. **SKB HRL PR 25-90-17a**
  Rhén I. 1991. Information for numerical modelling 1990. Calibration cases. **SKB HRL PR 25-90-17b**
  Forsmark T. 1992. SKB - Äspö Hard Rock Laboratory. General information and information for numerical modelling 1992. Calibration cases for LPT2 and tests in KA1061A and KA1131B. **SKB HRL PR 25-92-14**

- The topography of the Äspö area was delivered on a map.

• **Data distribution No. 2:** (November 1992)

Fracture data extracted from the SKB database GEOTAB was delivered on two diskettes. The data may be divided into two different categories:

- Fracture mapping from outcrops.
- Corelogs from 12 boreholes on the Äspö island.

The technical description "Äspö Task Force, Data Delivery No 2, Fracture data", Stefan Sehlstedt, November 1992, describes the data in detail including a proper reference to the data in GEOTAB. Furthermore, the SKB Technical Report TR 91-01 describing the geological data in GEOTAB was distributed.

• **Data distribution No. 3:** (December 1992)

Tunnel mapping data extracted from the SKB database GEOTAB was delivered on one diskette. The data covers the tunnel length up to 1500 metres.

Another diskette contained water injection test results from single boreholes of the Äspö Island. Altogether 7 boreholes have been tested. This set of data has also been extracted from the SKB GEOTAB database.

Data was described in two separate documents appended to the data distribution letter.

- "Äspö Task Force, Data Delivery No 3, Tunnel mapping data", Stefan Sehlstedt, December 1992;
- "Äspö Task Force, Data Delivery No 3, Single Hole Water Injection Data", Margareta Gerlach, December 1992.

The documents include proper references to the data in GEOTAB.

Furthermore, the SKB Technical Report TR 91-07 describing the hydrogeological data in GEOTAB was distributed.

• **Data distribution No. 4:** (February 1993)

An geological structure model at the Äspö site scale. Hydraulically active fracture zone geometric data was distributed. Data was delivered as coordinate lists and figures, SKB HRL PR 25-93-05. This was an updated version as compared to the description presented in SKB TR 91-22.

• **Data distribution No. 5:** (June 1993)

Complementary information regarding the LPT2 experiment.
The first Technical Note, 25-92-62G, contained some further information regarding the injection and sampling of tracers during the LPT2 experiment. The other Technical Note, 25-92-63G, described a complete set of undisturbed piezometric levels and also the estimated natural variation of these levels. A diskette was appended to this report.

• **Data distribution No. 6:** (November 1993)

Complementary core logging data.
The fracture data has been extracted from the SKB database GEOTAB and contains core logging data from 14 boreholes in the Äspö area. Note that data from 2 new boreholes have become available as compared to the data distribution No 2, these are KLX01 and KBH02. Furthermore some tables have been updated and/or corrected. New tables have been added, for example one of the tables have been updated with oriented fractures for the boreholes KAS02-KAS06. The appended documentation, SKB HRL Technical Document Nr 25-93-016, describes the distributed data in detail. Data was distributed on two diskettes.

Documentation recommended for the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes, Task No 1

Overview reports:

Stanfors R, Erlström M, Markström I. 1991. Äspö Hard Rock Laboratory. Overview of investigations 1986-1990.
SKB TR 91-20

Wikberg P, Gustafson G, Rhén I, Stanfors R. 1991. Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations 1986-1990.
SKB TR 91-22

Bäckblom G, Gustafson G, Stanfors R, Wikberg P. 1990. A Synposis of predictions before the construction of the Äspö Hard Rock Laboratory and the process of their validation.
SKB HRL PR 25-90-14

Task No 1 - LPT2:

Rhén I, Svensson U, Andersson J-E, Andersson P, Eriksson C-O, Gustafsson E, Ittner T, Nordqvist R. 1992. Äspö Hard Rock Laboratory: Evaluation of the combined long term pumping and tracer test (LPT2) in borehole KAS06.
SKB TR 92-32

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SKB HRL Technical Note 25-92-62G

Rhén, I Forsmark T. 1993. SKB - Äspö Hard Rock Laboratory. Information for numerical modelling. Undisturbed piezometric levels and uncertainty of piezometric levels.
SKB HRL Technical Note 25-92-63G

Complementary documentation for modelling purposes:

Rhén I. 1991. Information for numerical modelling 1990. General information.
SKB HRL PR 25-90-17a

Rhén I. 1991. Information for numerical modelling 1990. Calibration cases.
SKB HRL PR 25-90-17b

Forsmark T. 1992. SKB - Äspö Hard Rock Laboratory. General information and information for numerical modelling 1992. Calibration cases for LPT2 and tests in KA1061A and KA1131B.
SKB HRL PR 25-92-14

Documentation of the SKB GEOTAB-database:

Sehlstedt S, Stark T. 1991. Description of the geological data in SKB´s database GEOTAB.
SKB TR 91-01

Gerlach M, Gentzschein B. 1991. Description of hydrogeological data in SKB´s database GEOTAB.
SKB TR 91-07

Appendix 2

Executive summaries+
Condensed conceptual model description+
Results, performance measures 1&2

This appendix includes all executive summaries for the 11 different modelling groups for Task No 1.

We have also included a condensed conceptual model description for the LPT2 modelling as prepared by the different groups. The selection of these is not complete.

A condensed presentation of performance measures 1&2 for Task No 1A is also appended.

EXTENSIVE SUMMARY
ANDRA/BRGM I - MARTHE/SESAME

The BRGM contribution to ANDRA Task Force on Äspö site modelling was divided into three projects, all with the same objective: modelling of natural and forced hydrodynamic behaviour, plus tracers tests achieved during the LPT2 experiment. Those three projects differed by the codes they used:

- a finite difference (F.D.) code MARTHE, used for hydraulic simulations, and a hydrodispersive model SESAME for transport computations by a particle tracking method;

- a discrete stochastic code CHANNET (Channel Network), taking into account the fracture porosity only, for both hydraulic and transport simulation;

- a finite element (F.E.) dual porosity code ROCKFLOW, for both hydraulic and transport simulations.

The present report is dedicated to the first project, with the MARTHE and SESAME codes. The F.D. method offers the interest of an easy and quick gridding with parallelepipedic cells, but with the disadvantage of imposing the same shape to all the cells, which does not allow a really good adequacy between the grid and the geometry of the fracture medium.

This main disadvantage is greatly reduced with the introduction of an algorithm previously developed by Urban SVENSSON. This one consists in determining, by means of a geometric calculation, the intersections of fractures with the faces of each cell, then calculating the exchange coefficients between the cells, resulting from the superimposing of fracture transmissivities over matrix permeabilities. Calculation of the intersections of each fracture with each cell boundaries allows a precise evaluation of the exchange coefficients through the six boundaries of each cell of the model grid, taking into account the real dip of the fractures. In this way, it was possible to create a grid of 19,488 parallelepipedic cells, corresponding to a 1,800 x 1,800 m x 1,235 m volume, in which the 22 fractures planes of the SKB conceptual model were taken into account.

In the absence of information on fractures extensions, some hypotheses were made on these data, detailed in the report. Transmissivities of fractures were chosen very close to the SKB values, while uniform permeability of 10^{-8} m/s was assigned to the whole matrix. Densities and heads were imposed on lateral boundaries as functions of depth under sea level.

By computing both pressure and salt concentration fields by iterative resolution of coupled flow and transport equations, it was possible to model the natural conditions supposed to represent the hydraulic steady state. For the infiltration rate on the Äspö island it was necessary, in order to recover a piezometry close to the observed levels, to retain a much lower rate than the recharge estimated from hydroclimatic calculations (5.5 mm/year instead of more than 120 mm/y). This discrepancy had already been mentioned by U. SVENSSON who found with the

PHOENICS code a recharge value of 3 mm/year.

Except for this point, the results obtained were rather satisfactory: the natural piezometric state was reproduced with a good accuracy, while sensitivity tests brought into light the importance of different parameters such as the matrix conductivity, the water salinity variation with depth, the transmissivities of the fractures and the infiltration rate.

For the LPT2 pumping test simulations, the inflow distribution, measured during spinner test, was distributed amongst the four conductive faults which intersect KAS06. A uniform specific storage coefficient was assigned both for matrix and fractures, in addition with a free storage coefficient in unconfined zones.

An analysis of the sensitivity of the calibration parameters revealed the following:

- very little changes of the density field during the pumping test,

- specific storage coefficient between 5.10^{-7} m^{-1} and 5.10^{-8} m^{-1}

- free storage coefficient range from 2 % to 5 %,

- need to extend the lateral boundaries of the model,

- need to decrease the vertical transmissivity at sea bottom, assuming a fracture clogging by sea deposits.

A rather good agreement between measured and simulated drawdowns was obtained, in particular in fractures EW-3, EW-5, NNW-2 and NE-2, while a substantial under-estimation of drawdowns was simulated in fracture NNW-1.

Globally, it appears that the SKB conceptual model is a good compromise, and modelling it with MARTHE yields reasonable fit to the measures, with parameters close to those of SKB's model.

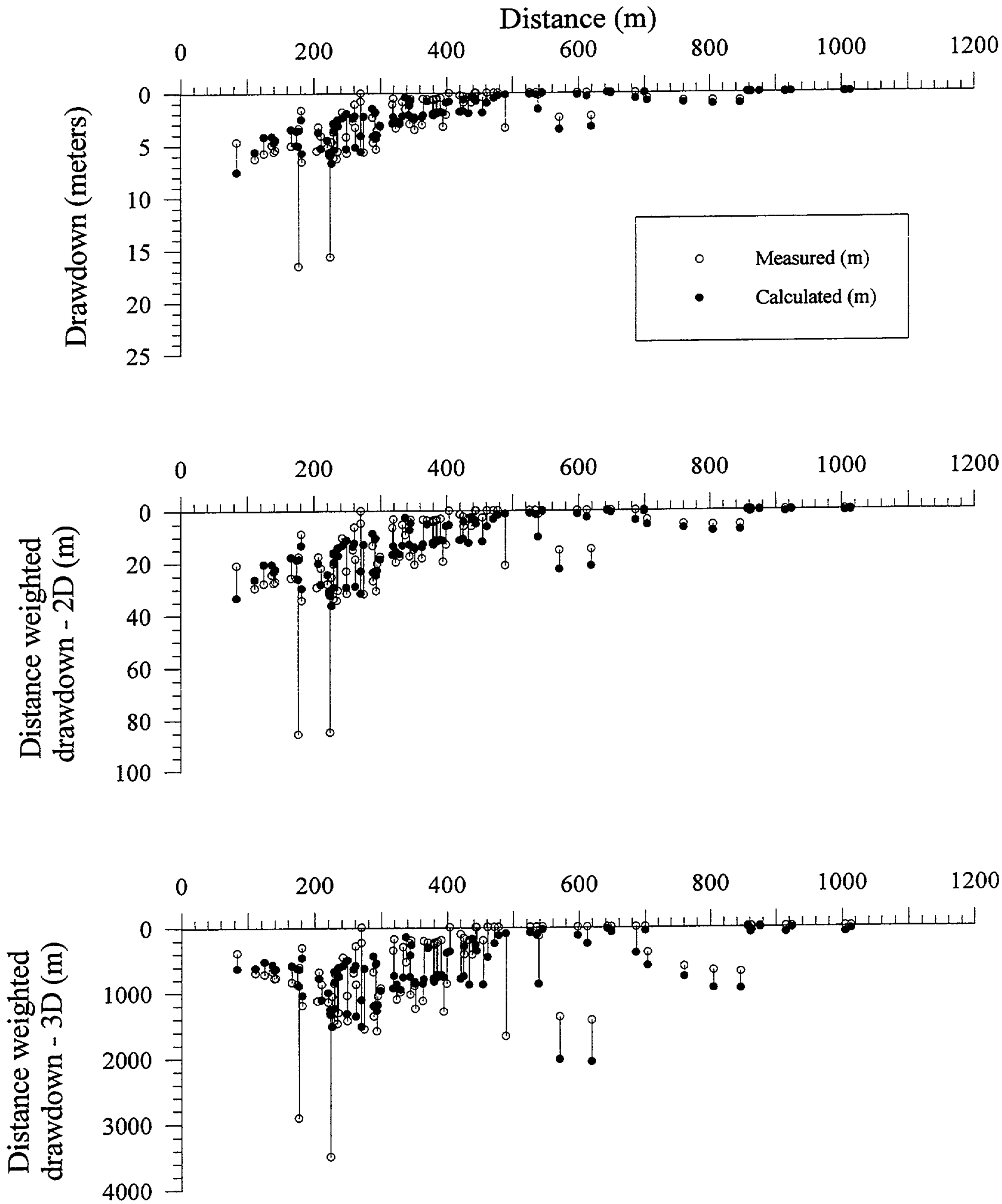
The transport simulations were performed with SESAME, using a Random Walk particle tracking method, computing the velocities from the fluxes calculated by MARTHE with the hypothesis of a single porosity model.

The six tracer experiments were simulated, and the model was calibrated on the breakthrough curves of Uranine and Rhenium-186, the both tracers detected in the pumping borehole KAS06. The tracer tests were modelled as series of pulses injected in various borehole sections, taking into account the recovery rates (28% and 30% respectively).

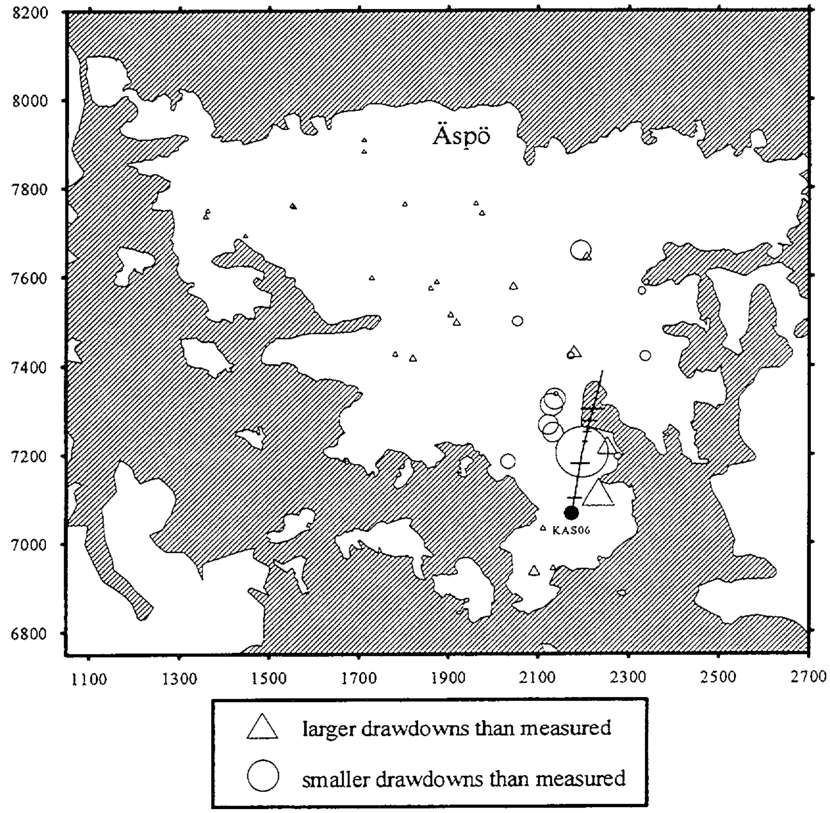
The results obtained are good in fractures NNW-2 and EW-5, but there is a problem regarding the intersection of KAS06 with the fracture NNW-1, where simulations give almost no tracer while measures show effective breakthrough curves. This might confirm an indication of a local problem on connection between fractures, as for the transient state modelling. One or several EW-X fractures added in the conceptual model should increase hydraulic connections, and possibly improve the tracer simulations concerning NNW-1.

It can be noticed that there is a good coherence of the hydrodispersive parameters deduced from the Uranine and Rhenium-186 tracer tests: $\alpha_L = 20$ m, $\alpha_T = 1$ to 3 m, $\omega = 9.10^{-5}$ to 30.10^{-5}. Hypotheses can be proposed to explain the rather low recovery rates.

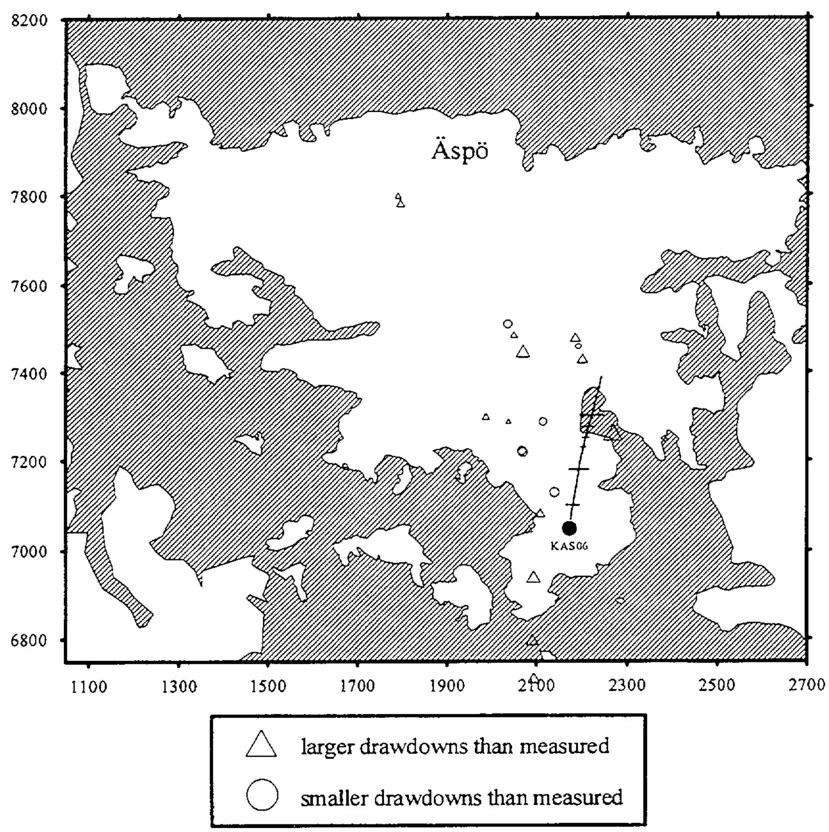
ANDRA/BRGM(1)
Results from Marthe. Differences between measured and calculated drawdowns.



ANDRA / BRGM (1) 0 - 75 metres



ANDRA / BRGM (1) 200 -400 metres



SUMMARY ANDRA/BRGM II - ROCKFLOW

The BRGM contribution to ANDRA Task Force on Äspö site modelling was divided into three projects, all with the same objective: modelling of natural and forced hydrodynamic behaviour plus transport tests, using the results of LPT2 experiment. Those three projects differed by the code they used:

- a finite difference (F.D.) code MARTHE;

- a discrete stochastic code CHANNET taking into account the fracture porosity only;

- a finite element (F.E.) dual porosity code ROCKFLOW.

The present report is dedicated to the third project which offers a double interest:

- to approximate as accurately as possible the geometry of the fractured medium (which is much easier with a F.E. code than with a F.D. code);

- to take into account both types of flow, in porous medium and in large individualized fracture zones by a suitable representation of porous matrix with 3D hexaedric elements and of fractured zones by plane 2D elements.

On the other hand, if MARTHE is able to compute both pressure and salt concentration fields by iterative resolution of coupled flow and transport equations, the ROCKFLOW module DM (Dichte Modell) designed for this task was not completely ready at the time the study was initiated and it was necessary to use a simplified version DMRED which computes flow in a known and invariant in time but variable in space density field. We made the choice to use the field calculated by the F.D. code MARTHE and to consider that this computed density field was close to the actual one. We also assumed that the pumping did not significantly affect the salinity distribution and then that the concentration field was invariant with time during LPT2 experiment. Hypotheses we made on geometry are very close to those retained by previous authors like /U. SVENSSON, 1990/. In the absence or information on fracture extensions, we had to make some hypotheses, which are detailed in the report. Hydrodynamic parameters were chosen in the range of observed data; for the infiltration rate on the island, it was necessary, to recover a piezometry close to observed map /M. LIEDHOLM, 1990/, to retain a much lower rate than the recharge estimated from hydroclimatic calculations (5.5 mm/year instead of 128 to 218 mm/y). This discrepancy was already observed by Svensson /U. SVENSSON, 1990/ who found with PHOENICS code, a value of 3 mm/year.

Because of too many uncertainties on hydrodynamic parameters (storage coefficient of porous matrix and fractures, matrix conductivity, water salinity variation with depth) and on geometric parameters (lateral extension of fractures, model boundaries) it was illusive to attempt a precise model calibration. Instead, we concentrated on testing the feasibility of an accurate representation of Äspö site with its 22 individualized fractures, by finite element techniques. Our mesh generator which had never been used on such a complicated geometry behaved quite well and so did the different ROCKFLOW modules we used, SM and DMRED with the different types of solvers. It was also an opportunity to improve the mesh generator by introducing the use of refinement planes.

Considering those points, it is possible to write that results in both natural steady state and in transient state to render LPT2 pumping were rather satisfactory. We recovered the natural piezometric state with a good accuracy and brought to light the importance of different parameters such as:

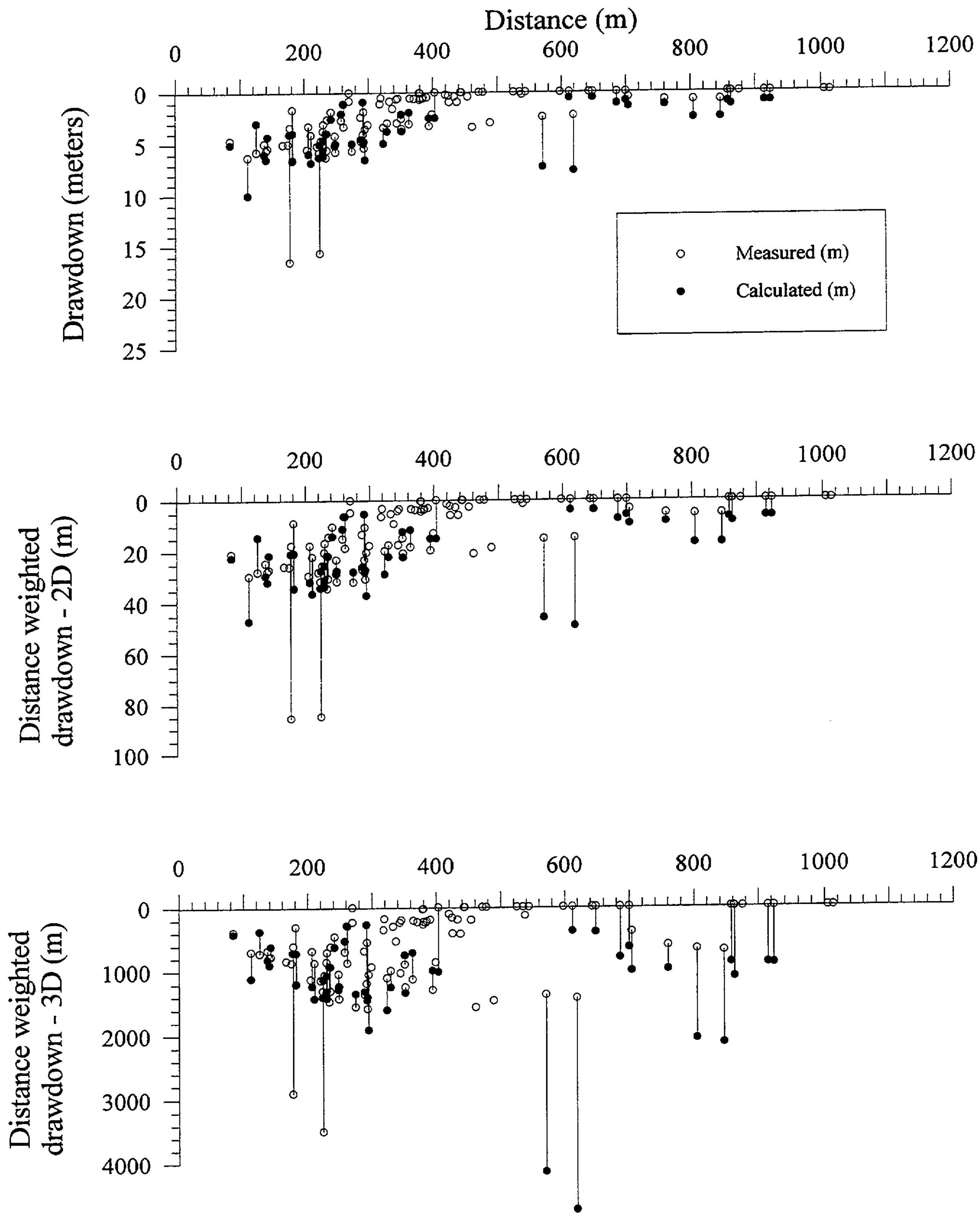
- the matrix conductivity;
- the water salinity variation with depth;
- the infiltration rate.

For the pumping test simulations, it was necessary to make some assumptions on yield distribution between the fractures intersected by the borehole KAS06 and between the 4 nodes of the 2D fracture plane element intersected by the pumping. The results shown in the report are piezometric and drawdown maps at end of LPT2 and drawdown evolutions versus time at different observation sections. Computed results are globally close to observed results except at larger time values when a stabilization occurs, due probably to the prescribed head boundaries which are too close.

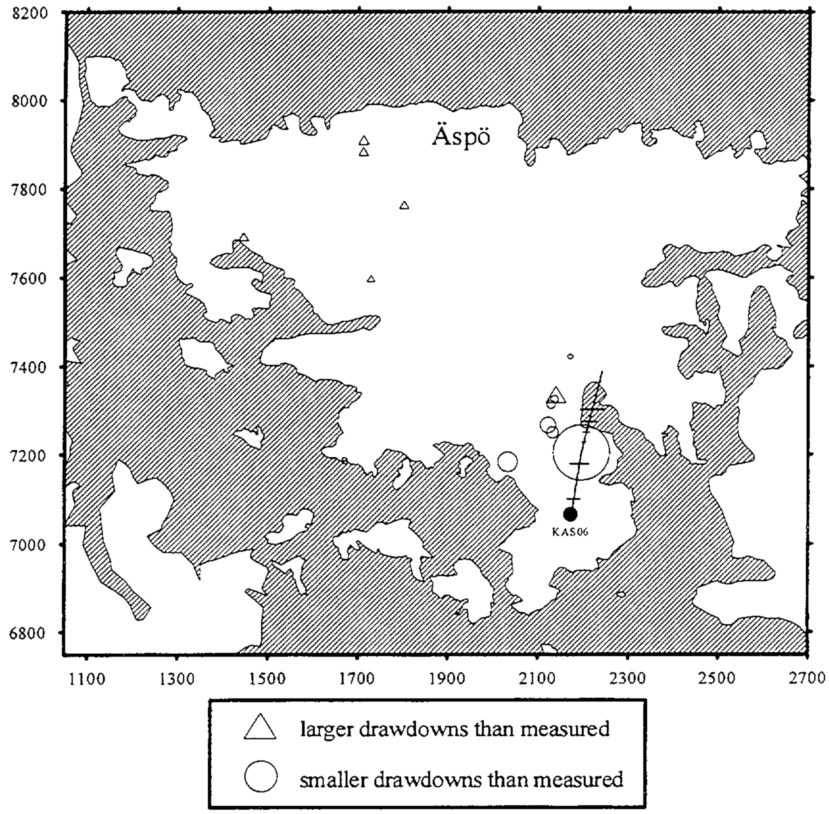
An attempt to push away the lateral boundaries did not significantly change the results in transient state. So we tried to decrease the vertical transmissivity at sea bottom, assuming a fracture clogging by sea deposits. With this modification, all drawdown evolution curves were delayed and only a few of them were improved. It would be necessary to push the sensibility analysis a bit further and perform some more tests to really improve the drawdown evolution curves. This work is still in progress as well as the transport experiment simulations during LPT2.

ANDRA/BRGM(2)

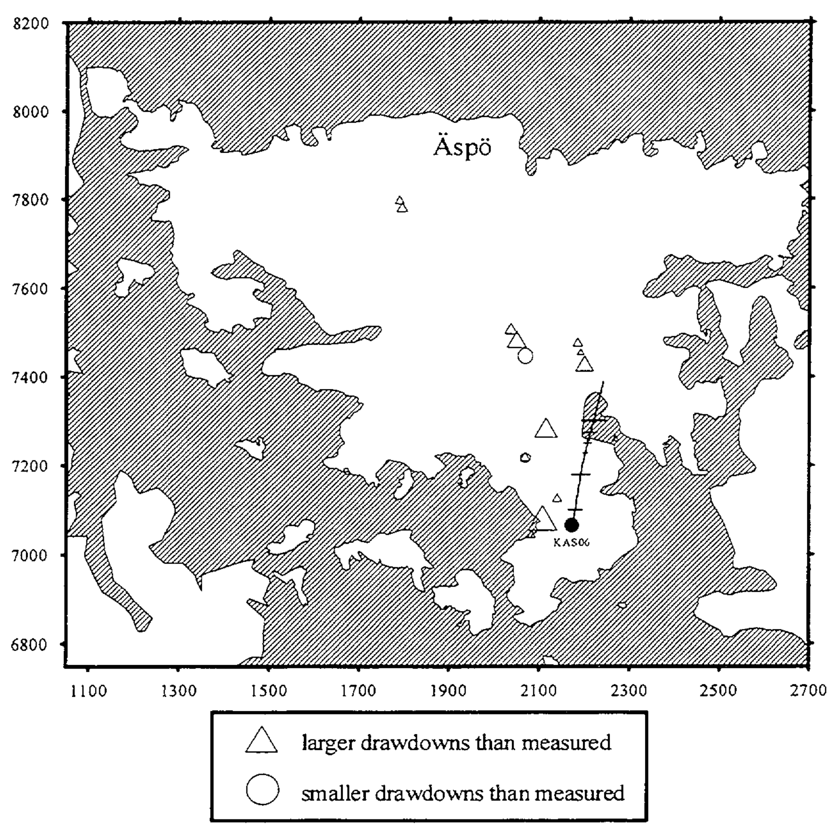
Results from ROCKFLOW. Differences between measured and calculated drawdowns.



ANDRA / BRGM (2) 0 - 75 metres



ANDRA / BRGM (2) 200 - 400 metres



EXECUTIVE SUMMARY ANDRA/ITASCA - CHANNET

The Äspö Hard Rock Laboratory (HRL) is being constructed in preparation for the deep geological repository of high-level nuclear waste in Sweden. ANDRA signed a cooperation agreement with SKB, the Swedish Nuclear Fuel and Waste Management Company. This includes participation in a Task Force on Modelling of Groundwater Flow and Transport of Solutes. As part of its involvement in this Task Force, ANDRA has asked several french teams to model a 92 days-long pumping and tracer test named LPT2. This report presents the modelling effort by an ITASCA Consultants-BRGM team.

The model assumes that all flow and transport take place in a network of one-dimensional channels. A geometrical study is first performed. The extension of fractures zones is assessed from available data on borehole intersections. The connectivity of the average rock outside fracture zones is studied using fracture traces mapped in part of the access drift. This study shows that the average rock is connected : flow paths may exist at site scale outside fracture zones. However, representing these flow paths by an equivalent porous medium is likely to be erroneous.

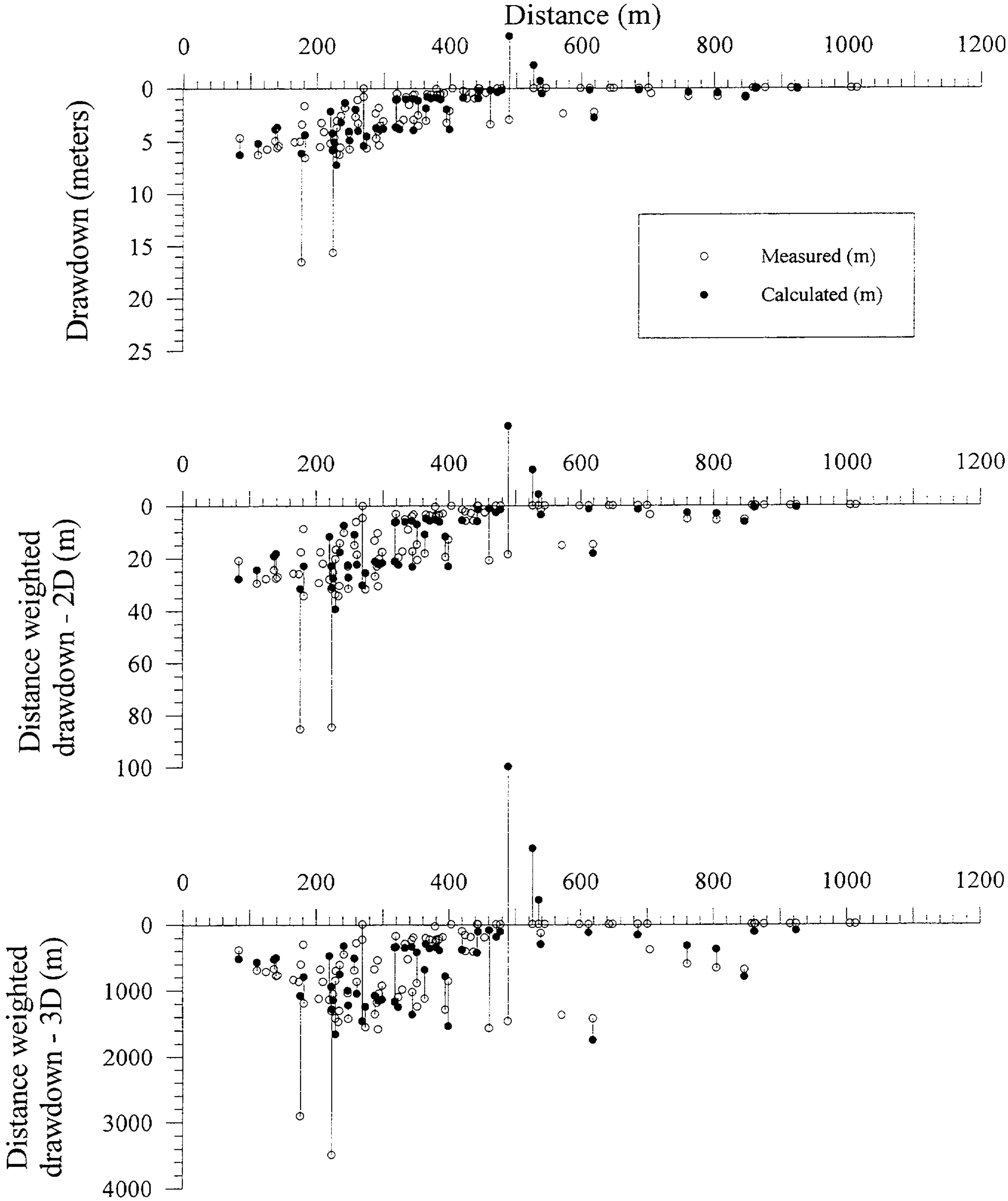
A parameter study of the influence of fracture zone transmissivity contrasts on the drawdown field at the end of the pumping test shows that the results of the test provide enough information to constrain, within one order of magnitude, the transmissivity of eight out of the ten zones most influenced by the pumping. However a few zones situated close to the test cannot be characterized properly. In order to gain a non-ambiguous knowledge of the large scale conductors properties in a site such as Äspö, two or three pumping tests such as LPT2 would probably be necessary.

Transient-state simulations of the test were performed, first assuming flow is restricted in fracture zones, then taking into account the storage effect of the average rock. Fracture zones-only storage can explain the response of the system during the first ten days. However, average rock storage must be taken into account to reproduce the evolution of drawdowns at later times. This was done by adding to the fracture zones channel network a sparse three-dimensional regular grid. Such an approach produces drawdown curves close to the measured ones, except for a few notable exceptions and properly accounts for the discrete nature of flow.

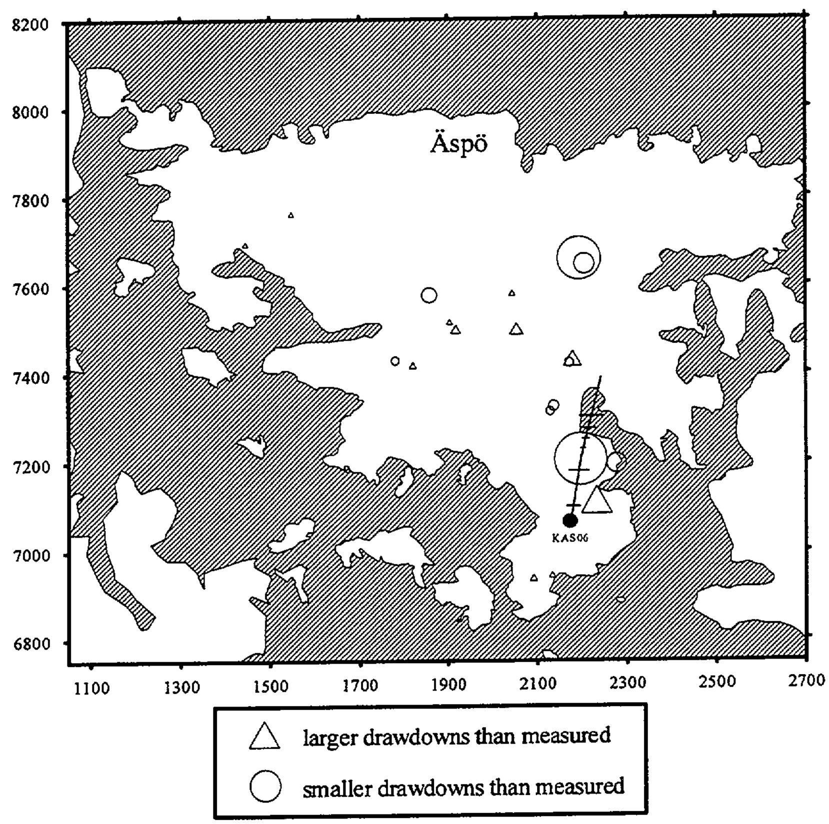
Preliminary tracer transport simulations were aimed at assessing the suitability of the channel model for modelling a large scale tracer test. A breakthrough curve was correctly reproduced. However the model cannot simulate tracer losses.

The channel network model we used, because it is very flexible, allowed a number of parametric studies. This is the main advantage of such a model, and makes it particularly useful during the first phases of a site investigation, when many still valid hypotheses must be tested.

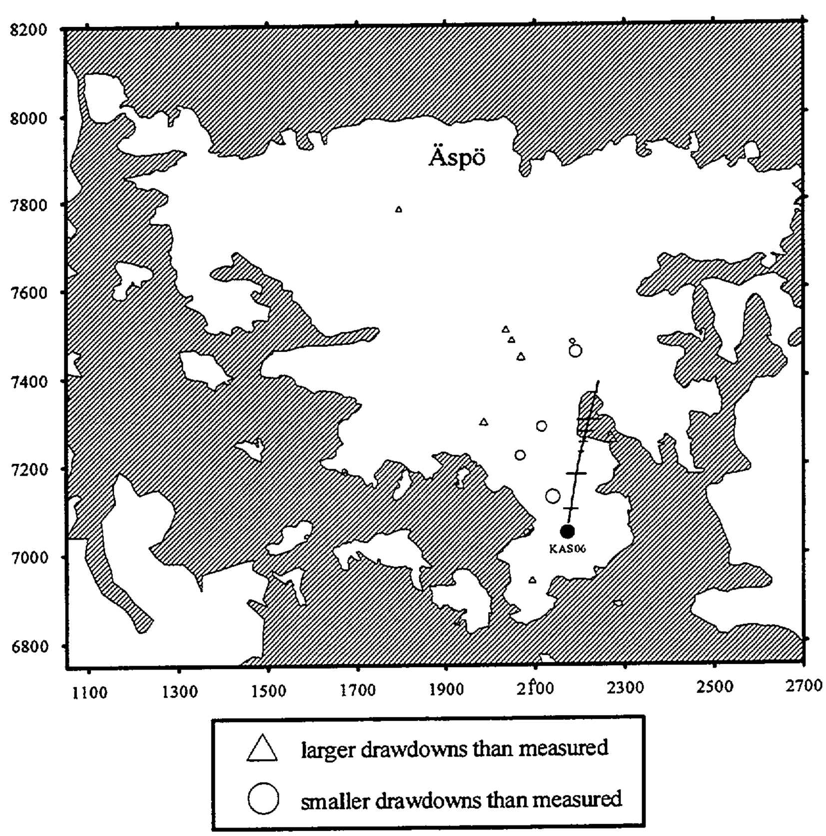
ANDRA/ITASCA
Results from CHANNET. Differences between measured and calculated drawdowns.



ANDRA / ITASCA 0 - 75 metres



ANDRA / ITASCA 200 - 400 metres



EXECUTIVE SUMMARY CRIEPI - FEGM/FERM

A three-dimensional smeared fracture model was applied to groundwater flow and tracer migration during the LPT-2 experiment. The smeared fracture model, which offered several of the advantages of a discrete fracture model and a porous media model, was combined with a three-dimensional groundwater flow simulation code called FEGM and a three-dimensional solute migration simulation code called FERM. These codes calculate both steady-state and unsteady-state conditions based on the finite-element method. Hydraulic parameters such as permeability coefficients and specific storage coefficients of finite-element meshes intersecting fractures are calculated with volume-weighted values of the fractures and the matrix by using this model so that complex fractured configurations could easily be treated.

The entire island of Äspö was included in the region for groundwater flow analysis, while the area in the vicinity of the pumping borehole KAS06 was taken out for tracer migration analysis. The input parameters were determined according to the conceptual model constructed by SKB.

The simulated results of the steady-state groundwater flow agreed fairly well with the final measured drawdowns during pumping at KAS06, although considerable discrepancies in drawdown were found in several sections, as shown in Figure 1 of Äspö ICR 94-08. Furthermore, the simulated results were not greatly dependent upon the total number of finite elements. This indicates that the smeared fracture model is effective, since the use of an enormous number of finite-element meshes is not needed when simulating an approximate groundwater flow through fractured media. The considerable disagreement found in several sections may be due to differences in connectivity between the smeared fracture network used here and the real fracture network. The simulated results of the unsteady-state groundwater flow were largely dependent on the mesh diagram used as well as the specific storage coefficients of the fractures. It is possible to evaluate the specific storage coefficient of each fracture by fitting the simulated drawdown curves to the observed ones more closely, although a rough estimate of the coefficient was obtained by assuming the same coefficient for all the fractures.

A particle pathway from KAS08, Ml to KAS06 was selected for tracer migration analysis because of a relatively short Darcian time. The trajectories are illustrated in Fig.2 of Äspö ICR 94-08. This indicates that several fractures may be involved in the tracer migration from KAS08, M1 to KAS06. The simulated breakthrough curve of the tracer, Rhenium-186, in the groundwater of KAS06 was in good agreement with the observed one, assuming that the tracer recovery ratio was 10%, as shown in Fig.3 of Äspö ICR 94-08. This suggests that more water-conductive zones intersect the tracer injection borehole, the pumping borehole and/or the related fracture zones than first considered, reducing the recovery of the injected tracer.

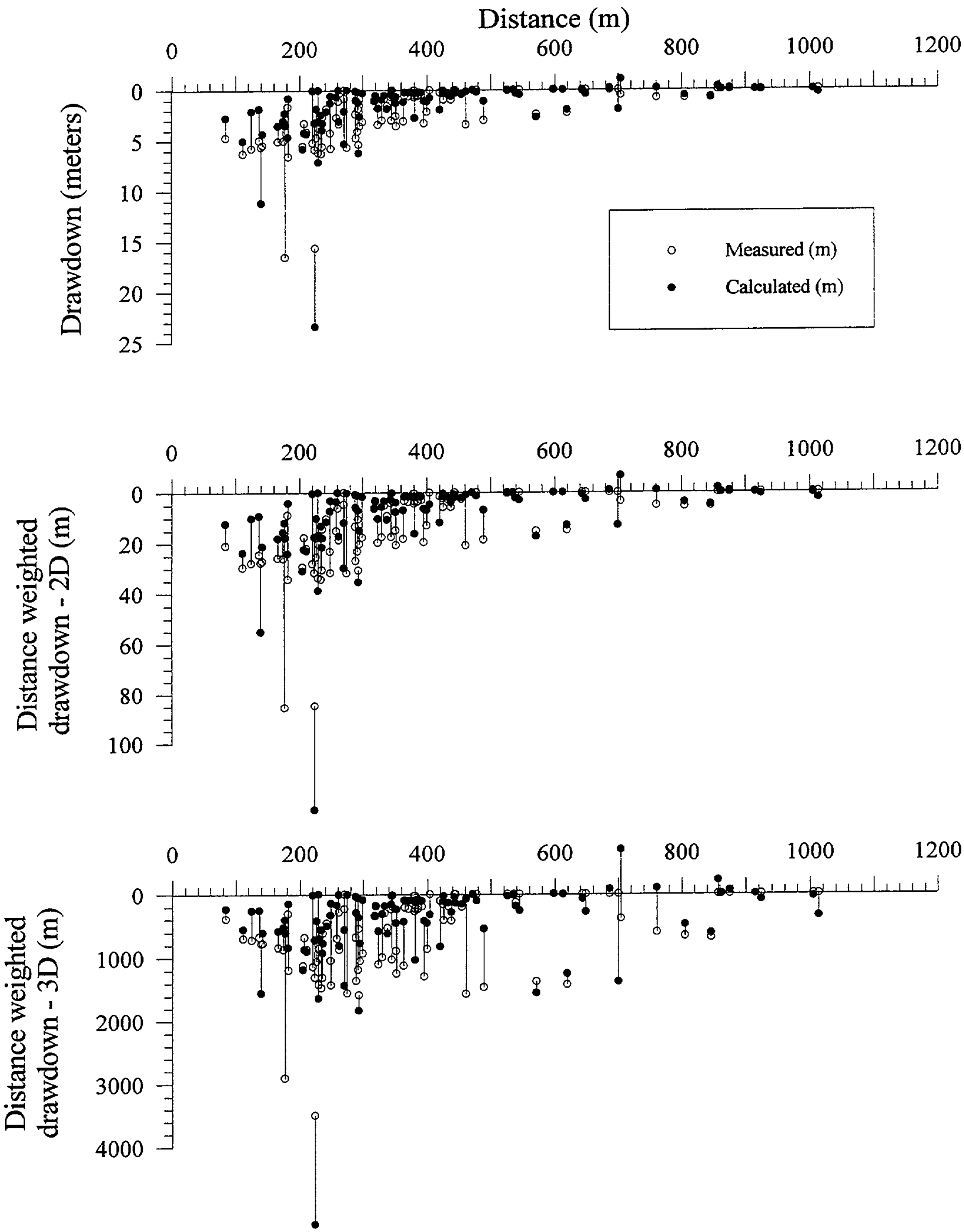
Condensed description of the groundwater flow model of the Aspo site used by CRIEPI

CRIEPI'S GROUNDWATER FLOW MODEL OF THE ASPO SITE Porous media model with smeared fractures	
Process description Continuity description (mass rate) Equation of motion (Darcy's law including unsaturated infiltration)	
CONCEPT	DATA
Geometric framework and parameters	
3D box divided into 14020 and 104040 Sixteen 2D fracture zones, planar with limited extent (location, orientation, size)	Size : 1.8*2.0*1.3 km Fracture network based on the conceptual model constructed by SKB
Material properties	
Transmissivity or hydraulic conductivity Specific storage coefficient	Transmissivity based on the values estimated by SKB
Spatial assignment model	
Transmissivity : Deterministic assignment Elements crossing fractures calculated as volume-weighted in properties	Transmissivity based on the values estimated by SKB
Boundary conditions	
Upper : Fixed pressure head on Aspo constant head at sea Lower : No flow Side : Prescribed pressure (hydrostatic) Salinity : Constant	Contour map data
Numerical tool FEGM	
Output parameters Pressure head, total head, Darcy velocity, trajectories, flux	

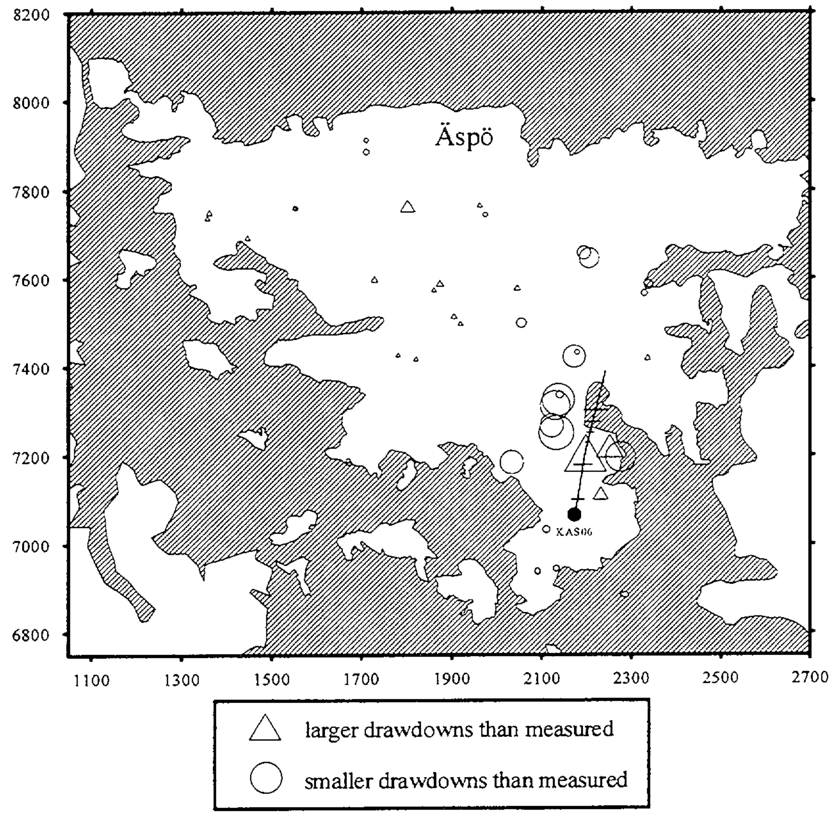
Condensed description of the tracer migration model of the Aspo site used by CRIEPI

CRIEPI'S TRACER MIGRATION MODEL OF THE ASPO SITE Porous media model with smeared fractures	
Process description Mass balance description (convection, dispersion, diffusion, adsorption, decay, and decomposition)	
CONCEPT	DATA
Geometric framework and parameters	
3D box divided into 88000 2D fracture zones, planar with limited extent (location, orientation, size)	Size : 0.4*(0.3-0.45)*0.5 km Fracture network based on the conceptual model constructed by SKB
Material properties	
Darcy velocities Dispersivity Diffusion coefficient, distribution coefficient, decay constant, reaction rate constant	Darcy velocities calculated by FEGM Dispersivity estimated by SKB not used
Spatial assignment model	
Dispersivity : Deterministic assignment Elements crossing fractures calculated as volume-weighted in properties	Dispersivity based on the value estimated by SKB
Boundary conditions	
Upper, side : Concentration gradient equal to zero	
Numerical tool FERM	
Output parameters Concentration distribution at a specific time, concentration change at a specific point	

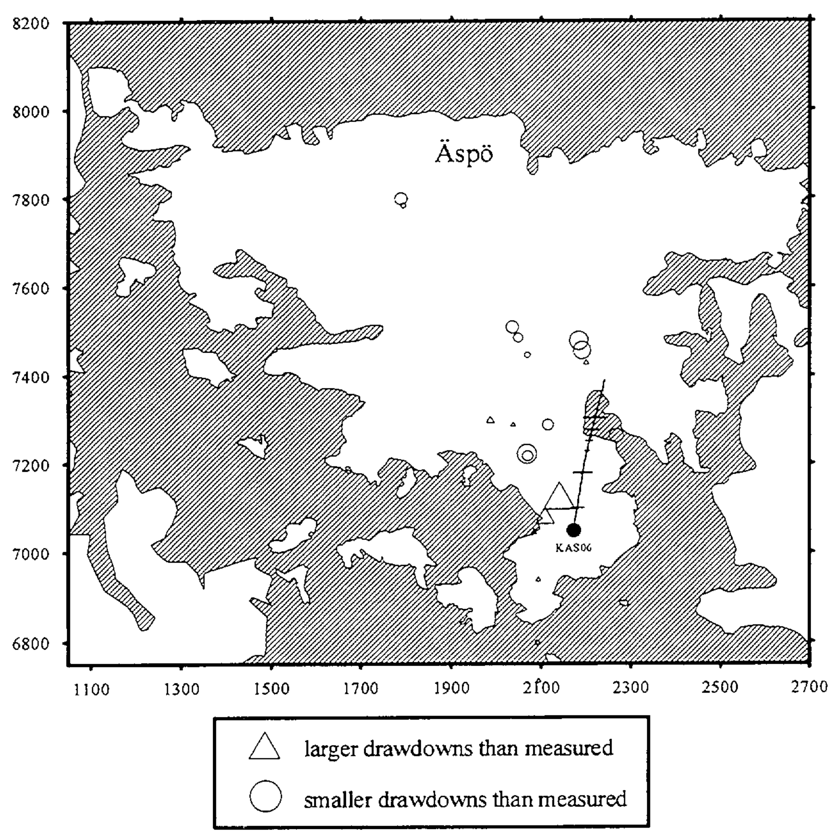
CRIEPI
Calculated drawdowns from steady-state analysis using fine mesh diagram compared with measured drawdowns



CRIEPI, LEVEL 0 - 75 metres



CRIEPI, LEVEL 200 - 400 metres



EXECUTIVE SUMMARY PNC/GOLDER - FracMan/MAFIC

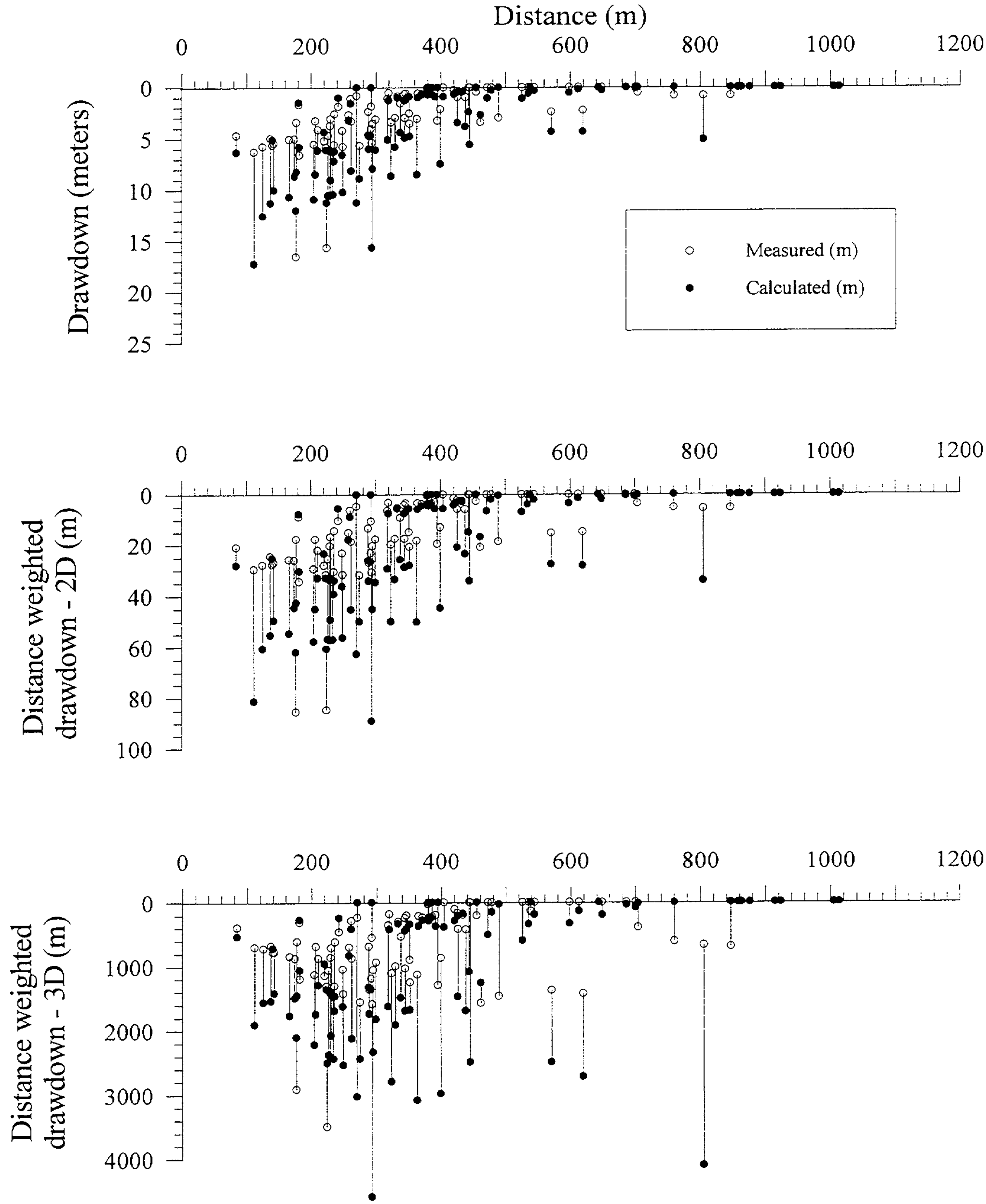
This report presents the results of discrete fracture simulations of the Äspö LPT2, large-scale pumping and tracer test, at the SKB Äspö Hard Rock Laboratory. This work was carried out under the international cooperation program of the Äspö Task Force on Groundwater Flow and Transport of Solutes.

The simulations consisted entirely of discrete fractures which were generated using the FracMan computer code. The scale of simulation was approximately a one-kilometre cube. The discrete fracture model contains two major fracture types -- fracture zones, which were located deterministically according to SKB's conceptual model of the Äspö site, and fractures outside the fracture zones which were generated stochastically. The geometric and hydraulic properties of each group were developed from the SKB modelling database, except for non-zone fracture length which we developed from our own mapping of surface outcrops. Clearly, it is not possible to model all the fractures in 1-km rock mass, hence, a key factor in preparing a simulation is the truncation of the fracture population to the most important hydraulic features.

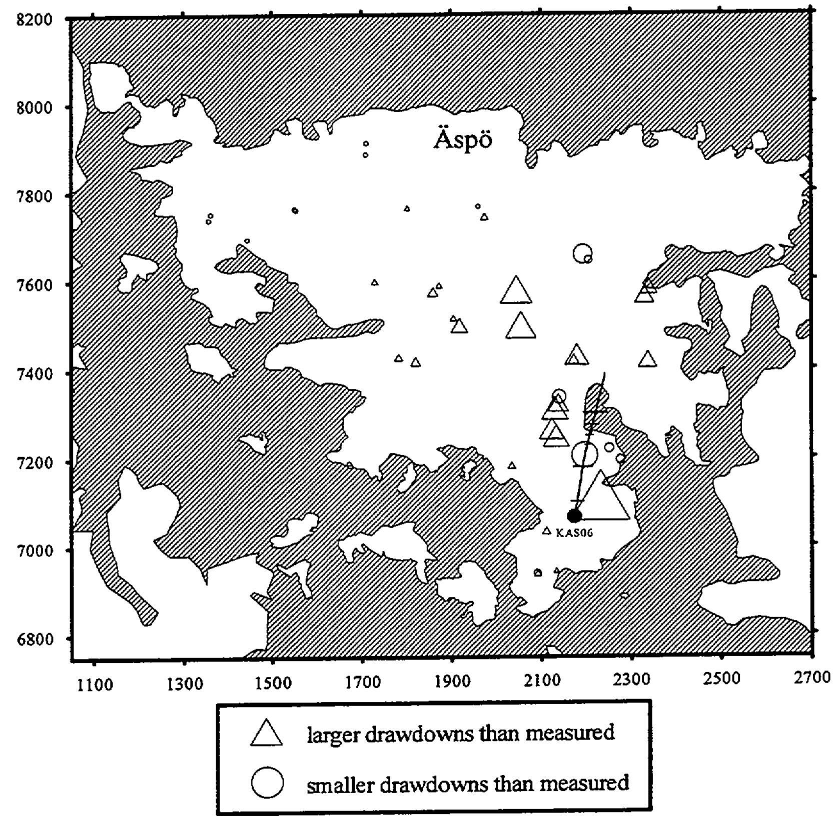
Two separate models were prepared for the March and September, 1993, task force meetings respectively. The March model represented the fracture zones as 10-m thick planar regions containing populations of 30-m radius discrete fractures. The September model represented the fracture zones as single planes, which were discretized on a 20- to 30-m scale for a geostatistical assignment of properties. The September model also include conditioning of the properties to the borehole data. The March model more realistically represents the connectivity within fracture zones, however, the September model was more efficient numerically. Both models generally reproduce the drawdown and transient pressure interference responses of the experiment. The tracer breakthroughs were simulated using only the September model. Calibration runs of the transport model varied the mean transport aperture, aperture variance, and aperture correlation length. The mean aperture affects the initial breakthrough; aperture variance controls dispersion and thus the shape of the breakthrough curve; and correlation length did not noticeably affect the results. The transport simulations can be adjusted to closely match the experimental results. Due to the low recovery of tracer in the experiments (<30%), these matches require normalization of the simulated results to the total mass recovered. The simulations also produced breakthrough from only two tracer injection zones. Three of the four non-responding zones were connected to KAS06 through the EW-5 fracture zone which may have a significantly larger effective transport aperture than the calibration case due to its thickness and complexity of fracturing. The discrepancy in recovery percentages between the simulations of the responding test zones and the experiment requires further resolution.

The results of this modelling exercise show that a discrete fracture model can be applied at kilometre scales if the flow is dominated by a small portion of fracture population. The results also show that the SKB conceptual model is consistent with the field measurements.

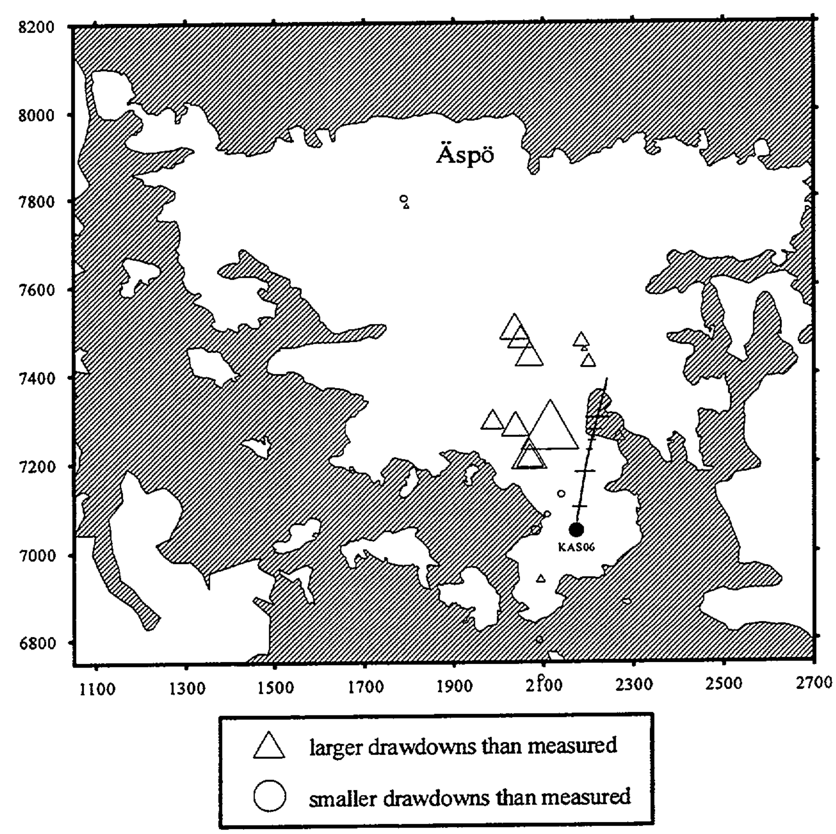
PNC/GOLDER
LPT-2 Distance-Drawdown (March Model)



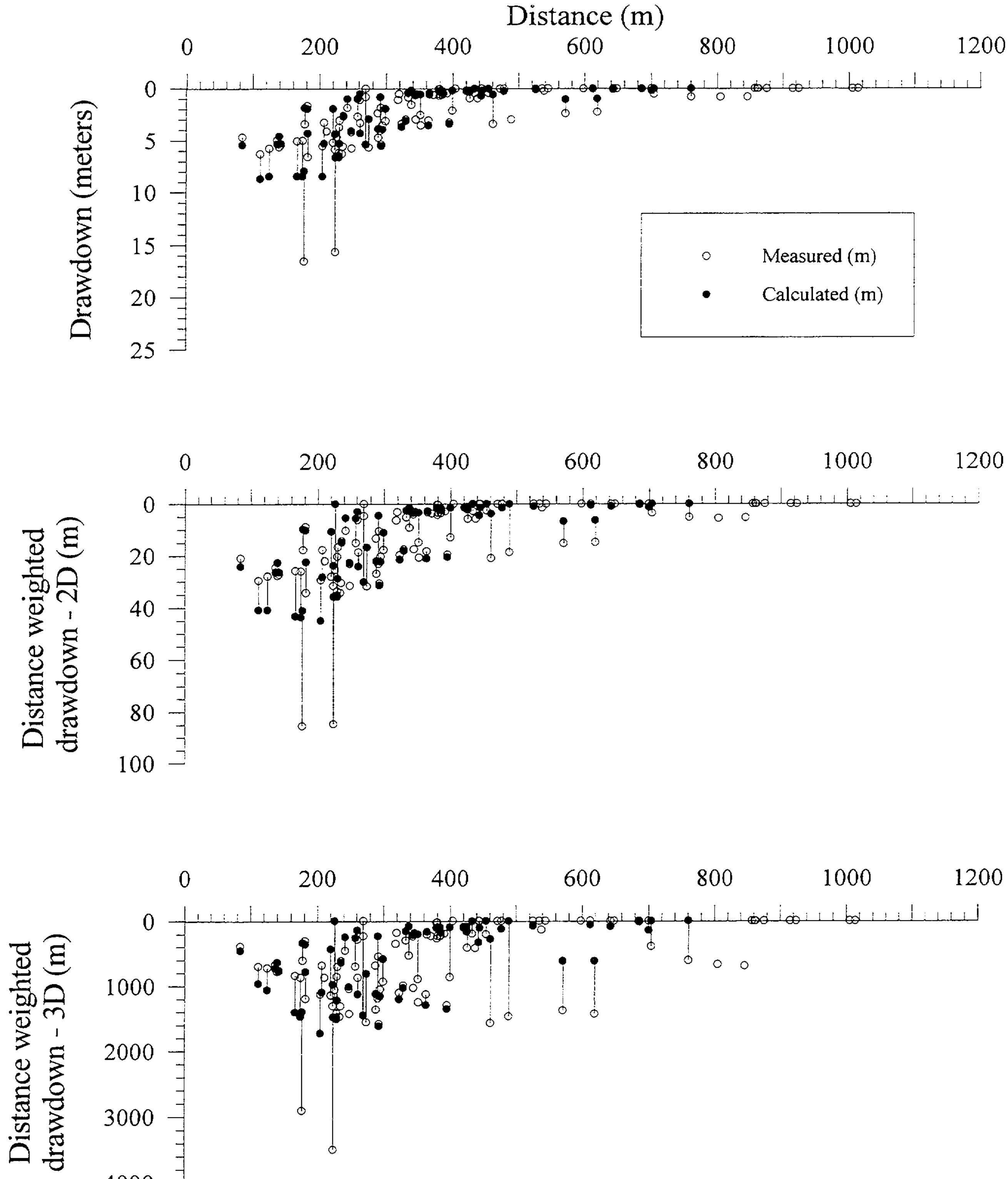
PNC/GOLDER (MARCH MODEL), LEVEL 0 - 75 metres

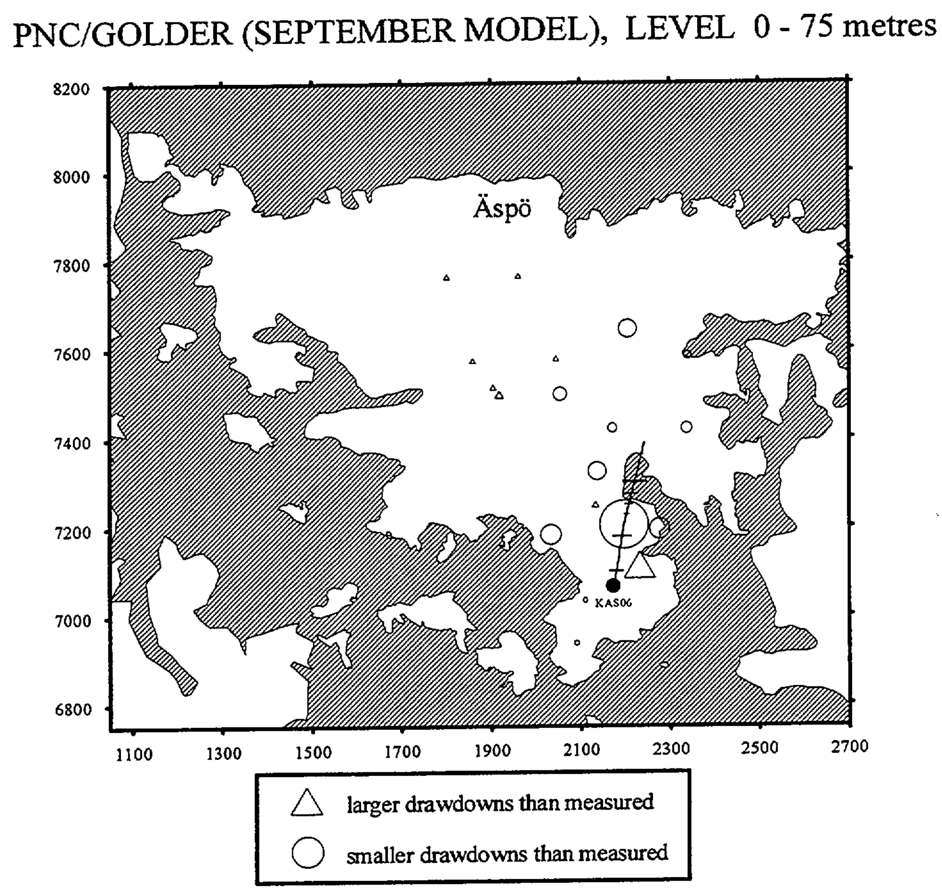


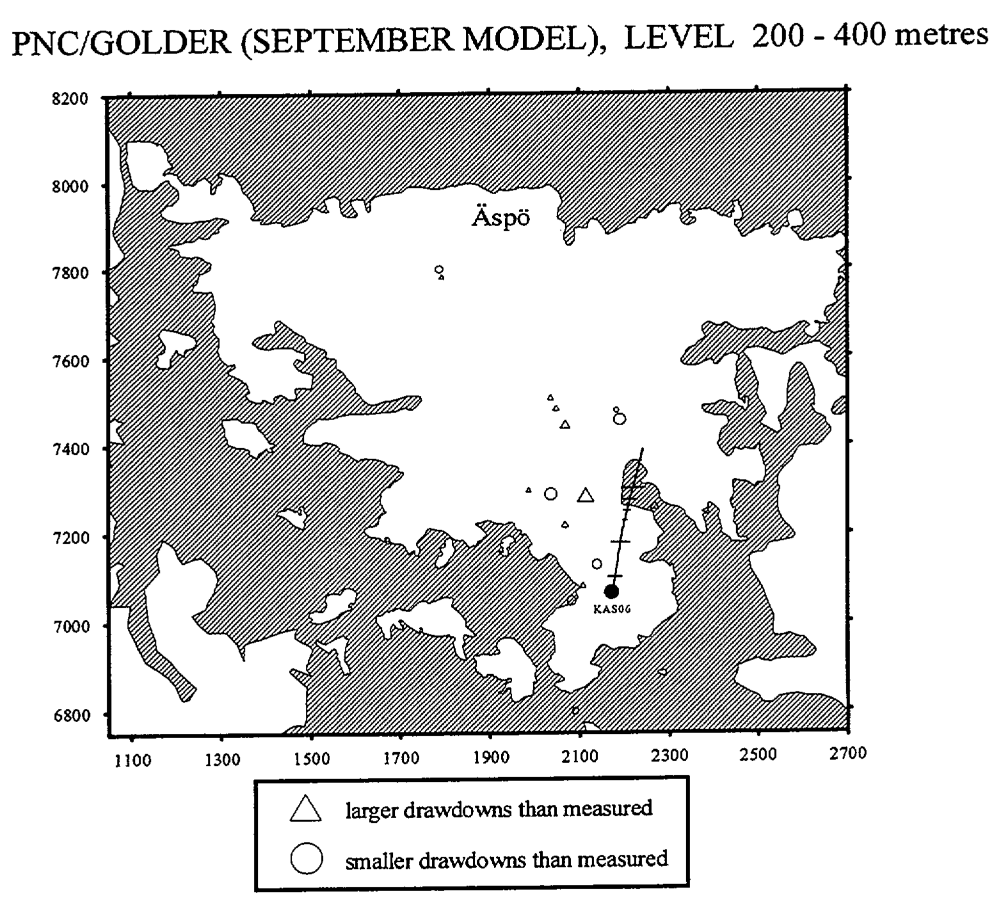
PNC/GOLDER (MARCH MODEL), LEVEL 200 - 400 metres



PNC/GOLDER
LPT-2 Distance-Drawdown (September Model)




PNC/GOLDER (SEPTEMBER MODEL), LEVEL 0 - 75 metres
8200
8000
7800
7600
7400
7200
7000
6800
1100
1300
1500
1700
1900
2100
2300
2500
2700
Äspö
KAS06
larger drawdowns than measured
smaller drawdowns than measured


PNC/GOLDER (SEPTEMBER MODEL), LEVEL 200 - 400 metres
8200
8000
7800
7600
7400
7200
7000
6800
1100
1300
1500
1700
1900
2100
2300
2500
2700
Äspö
KAS06
larger drawdowns than measured
smaller drawdowns than measured

EXECUTIVE SUMMARY PNC/HAZAMA

The methods to model flow in a fractured rock mass can be roughly divided into a discontinuous approach and an equivalent continuous one. In this report, an equivalent continuous approach is tested. Among many equivalent approaches, the Crack tensor theory, which has been proposed by Oda (1986), is used to treat a number of fractures and to examine the dependency of the parameters on volume. Moreover, the equivalent continuous medium is modeled by a stochastic method to present the heterogeneity of the medium. For modelling of Äspö test site, the large certain fracture zones, i.e., EW3, NE2 and EWl, are presented by two dimensional plane elements of which location is decided according to the geological conceptual model. On the other hand, a series of NNW fracture zones and EW5, the probably confirmed fracture zones, are modeled by the equivalent continuous approach.

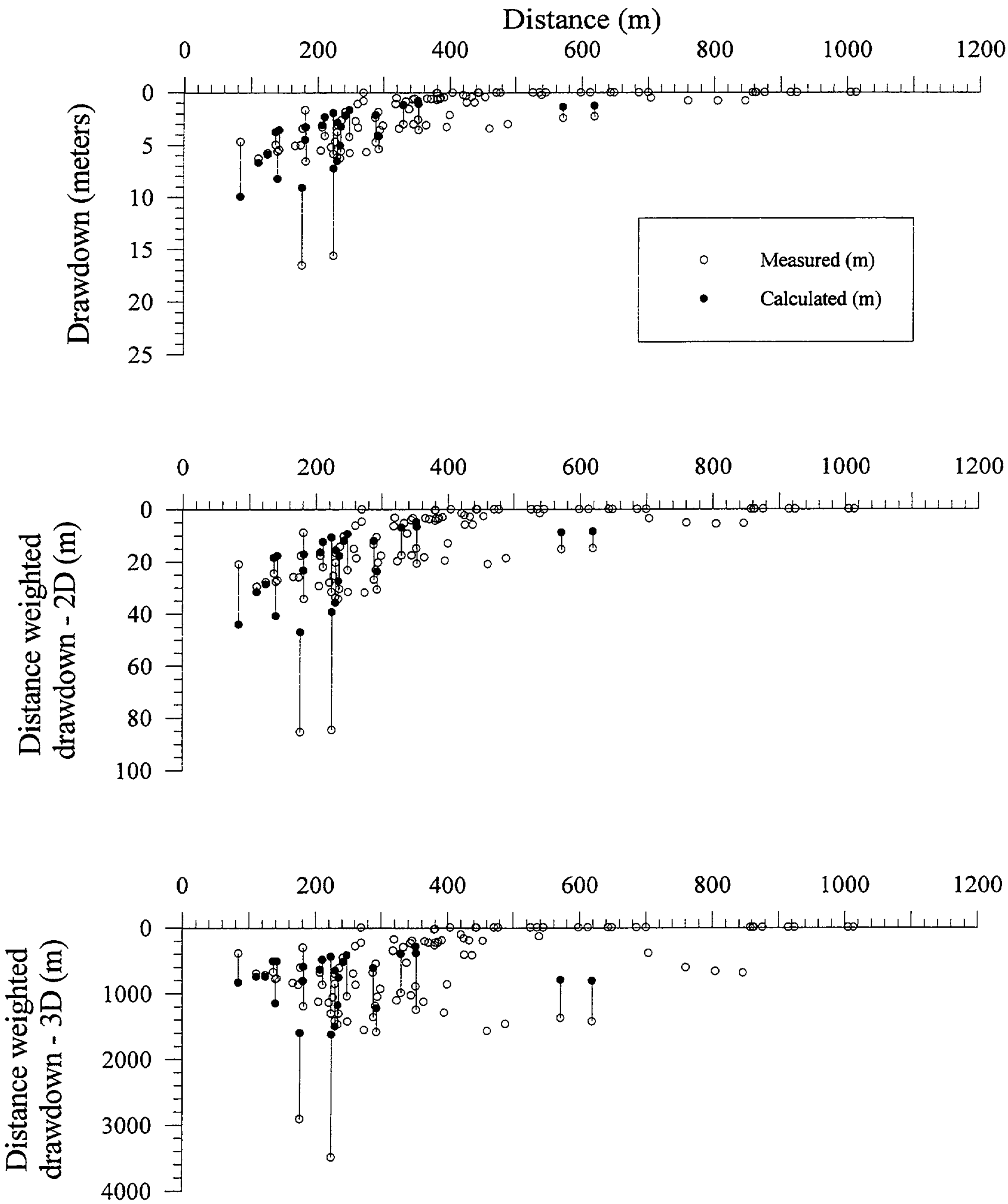
The following steps are carried out to make a continuous heterogeneous model for the probably confirmed fracture zones. Figure 1 of Äspö ICR 94-07 shows the flow-chart of the analysis. Firstly, the probability model of fracture length and fracture density, which are difficult to measure in the field, are inferred from the observed data. The newly developed method is introduced. Secondary the representative elementary volume (REV) is examined by using the theory by Oda, called the Crack tensor theory in this report, with the information of fracture geometry. This is because the dependency of the results on the mesh size is avoided. The permeability has to be fundamentally defined from the solution of the boundary values problem and has to be considered as the value at a point to apply the geostatistics method.

Thirdly, the permeability corresponding to the REV is derived from the field test data by using the arithmetic and geometric averaging methods. Fourthly, the heterogeneity of the medium is represented by the conditional simulation of the geostatistical approach. In this approach, the mechanical dispersion phenomena are understood to be caused from the heterogeneous velocity vector distribution due to the heterogeneous permeability field. So a macro-dispersion phenomenon is expressed by the random process in the model. Lastly, the flow and transport analyses are carried out for each realized medium and the comparison with measured data are performed. The breakthrough curve is calculated by the ensemble of the arrival time of the particles of each realized model.

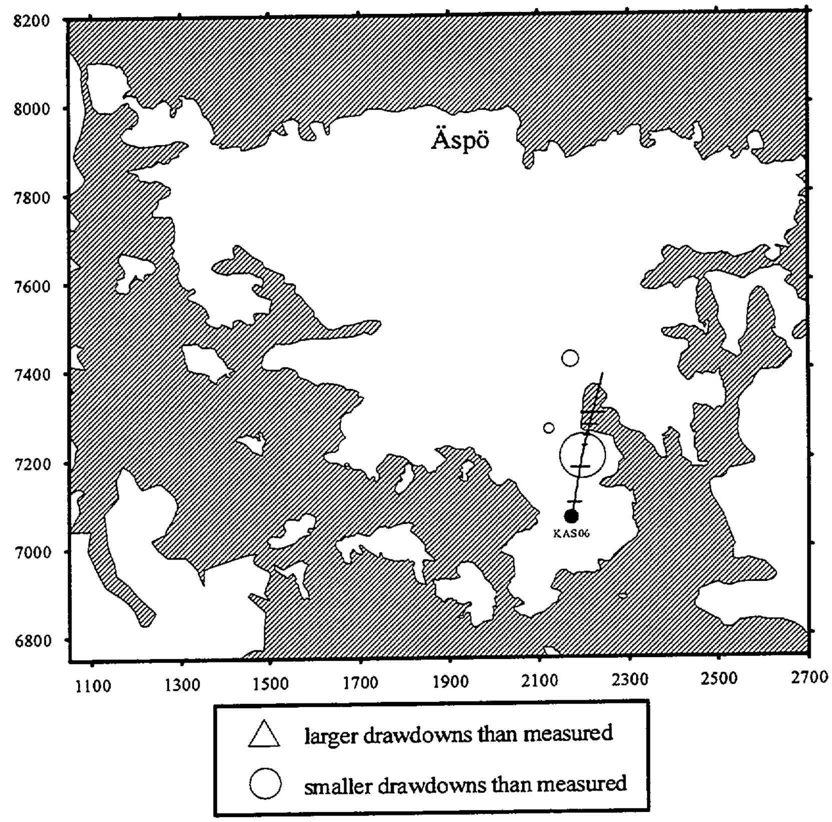
As the results, it is found that the probability density function of the fracture length can be estimated to be a log normal distribution and the representative elementary volume of the Äspö area is estimated to be about 30m cube. Moreover, it is also found better that the permeability measured at a single borehole test is averaged using an arithmetic mean rather than the geometric mean. Since the arithmetic mean can reflect an odd value, it is inferred that the measured high permeability has much effect on the permeability of the volume of REV. This may mean good connectivity of the high permeability parts. For flow analyses, the drawdown of the head measured at observation holes are well simulated by the calculation using the permeability averaged with an arithmetic mean as shown in Figure 2 of Äspö ICR 94-07. The flow rate through a hole is underestimated by the calculation. The calculated maximum flow rate has a better agreement with the measured results. For transport analyses, the calculated breakthrough curve has a relatively good agreement with the measured ones as shown in Figure 3 of Äspö ICR 94-07. However, the breakthrough curve can be calculated for the tracer which was not measured in the field because the tracer is moving into the pumping-up hole in the simulation.

PNC/Hazama

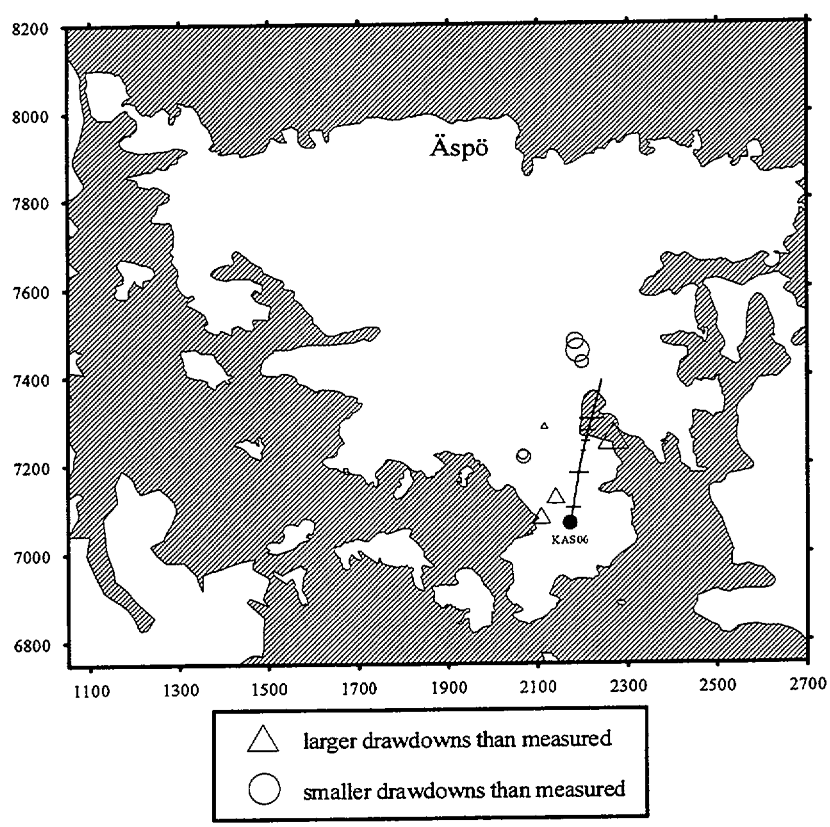
Comparison between calculated and measured drawdown



PNC/HAZAMA, LEVEL 0 - 75 metres



PNC/HAZAMA, LEVEL 200 - 400 metres



SUMMARY SKB/CFE - PHOENICS/PARTRACK

The PHOENICS/PARTRACK system has been used to simulate the Long term Pumping and Tracer test (LPT2) carried out at the Äspö Hard Rock Laboratory (HRL) site. The simulations included pressure responses and tracer transport.

The studied domain measures 2.1 x 1.7 x 1.3 km^3, centred around the HRL. Around twenty major fracture zones have been identified in this volume. Transmissivities have been estimated for these, based on geophysical and hydraulic methods. Also the "good rock" in between the zones has been ascribed conductivity properties, following certain statistical distributions.

The LPT2 was performed as a pumptest, with withdrawal of water in KAS06. Observations of drawdown were carried out in about 100 borehole sections. The tracer tests were carried out by injection of tracers in six borehole sections and the observed concentrations in KAS06 were then recorded.

A basic concept in the simulation model is the sub-division of the domain into control volumes or cells. Each cell has a pressure value (and other scalars like salt) and a flow vector associated to each cell wall. The velocity is determined using Darcy's law using the cell pressures and a conductivity determined at the cell-wall. The conductivities take the explicitly determined fracture zones, mentioned above, into account. Tracer transport is simulated using "marked fluid elements" in a particle tracking technique, with some novel features.

Simulations were carried out both before and after the field experiment. The simulations before the experiment had the purpose to test the predictive capability of the model and also to provide scoping calculations of, for example, typical transport times. Simulations after the experiment had the objective to evaluate the model and the field data were also used to develop the model further.

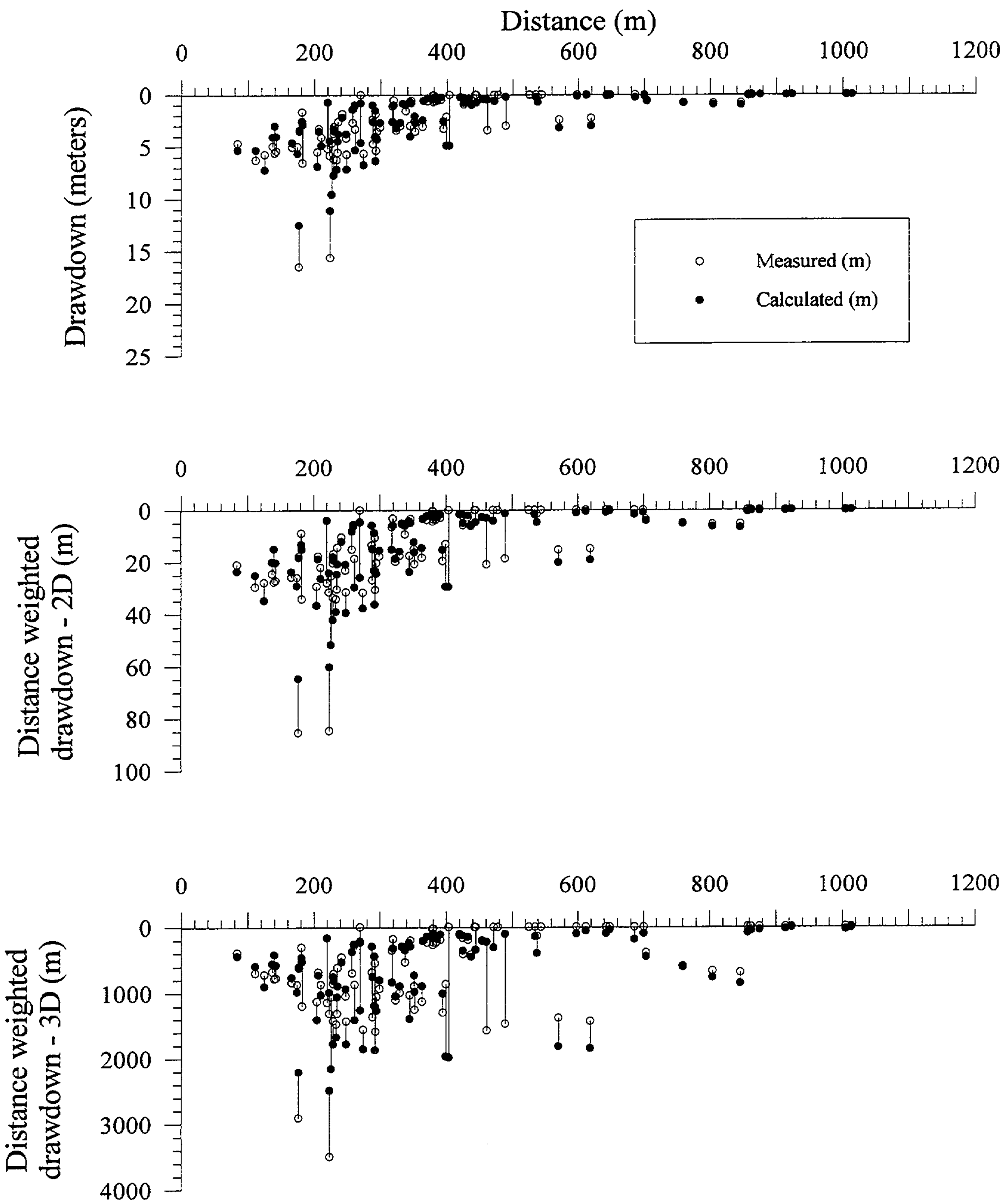
Results from simulations include a comparison of drawdowns and breakthrough curves for the tracer. The flow model was tuned to take some experiences from the LPT2-experiment into account; the transmissivities of EW-3 and EW-5 were adjusted. For the tracer transport the porosity was used as a calibration parameter, to get the peak value in the breakthrough curve in agreement with the field measurements.

The main conclusion from the study is that the PHOENICS/PARTRACK-system can simulate the LPT2-experiment in a realistic manner. The comparison with the drawdown measurements is regarded as satisfactory and the calibrated porosities are in general agreement with estimates from field data. It should however be noted that the model to some degree has been tuned to fit the measured data. Another conclusion from the study is that a simulation model is a useful tool for analysing the conceptual model. The predicted drawdown pattern, and its sensitivity to changes in fracture zone transmissivities, may give indications for a revision of the conceptual model. Predicted pathlines for a tracer give information about connectivity and possible divisions of a tracer in fracture zone crossings. A simulation model can thus be used as a synthesis of information gathered from various sources.

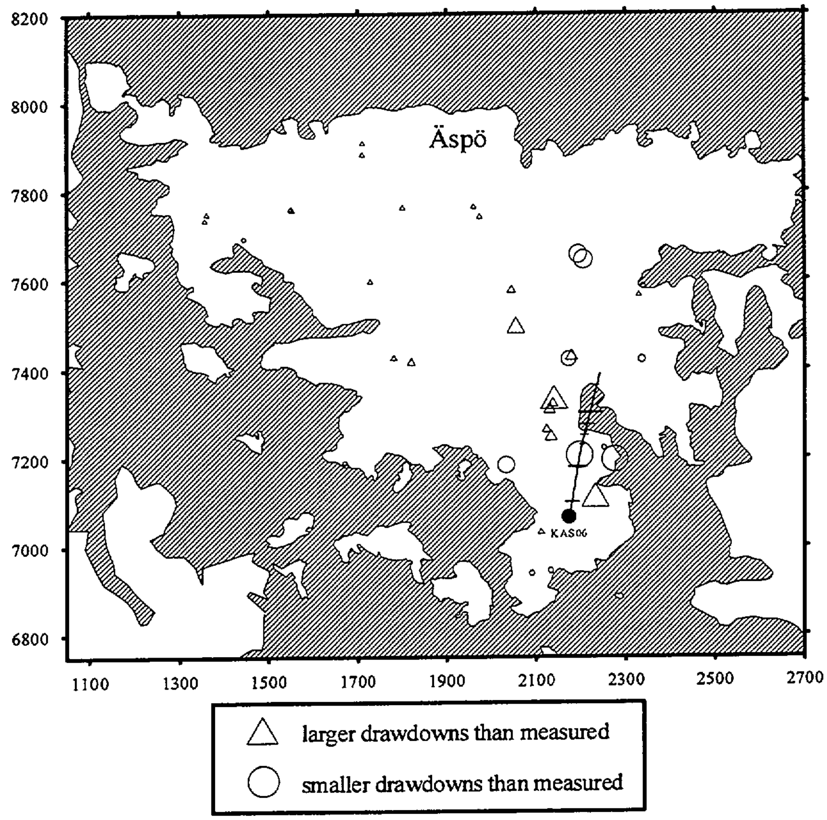
Condensed description of the groundwater flow model of the Äspö site used within the Äspö HRL Project.

CONCEPTS	DATA
GROUNDWATER FLOW MODEL OF ÄSPÖ SITE Stochastic continuum model	
Scope: natural flow, flow to laboratory tunnel, cross-hole tests (calibration)	
Process description Continuity equation (mass rate) Equation of motion (Darcy's law including density driven flow)	
Geometric framework and parameters	
3D box divided into: 2D fracture zones, planar with limited extent (location, orientation, size) Rock Mass Units (location of boundaries) Subvolumes (cells) between fracture zones	Size: 1.9x1.5x1.3 km Zone geometry from geologic model (descriptions basis for selection of "important zones") Regular grid of 20 m cubes Spatial distribution of 5 rock mass units (RMU) with 50 m thick slabs (with depth)
Material properties	
Zones: Transmissivity (T_i) Subvolumes: Hydraulic conductivity, isotropic (K_j) Salinity field	T and K from hydraulic borehole testing Salinity measurements in boreholes
Spatial assignment method	
Transmissivity: Deterministic assignment Hydraulic conductivity of cells: log-normal distribution based on RMU, depth. K and σ dependent on cell size	Transmissivity: single- and cross-hole testing Stochastic distribution of K from borehole testing
Boundary conditions	
Upper: fixed infiltration rate on Äspö, constant head at sea and peat areas Lower: no flow Side: prescribed pressure (hydrostatic) Salinity: prescribed initial conditions, linear increase with depth Tunnel: skin for rock and zones, prescribed pressure (atmospheric)	Infiltration data Salinity of Baltic Sea, salinity measurements in boreholes
Numerical tool PHOENICS	
Output parameters Pressure, density (derived parameters: flux, salinity)	

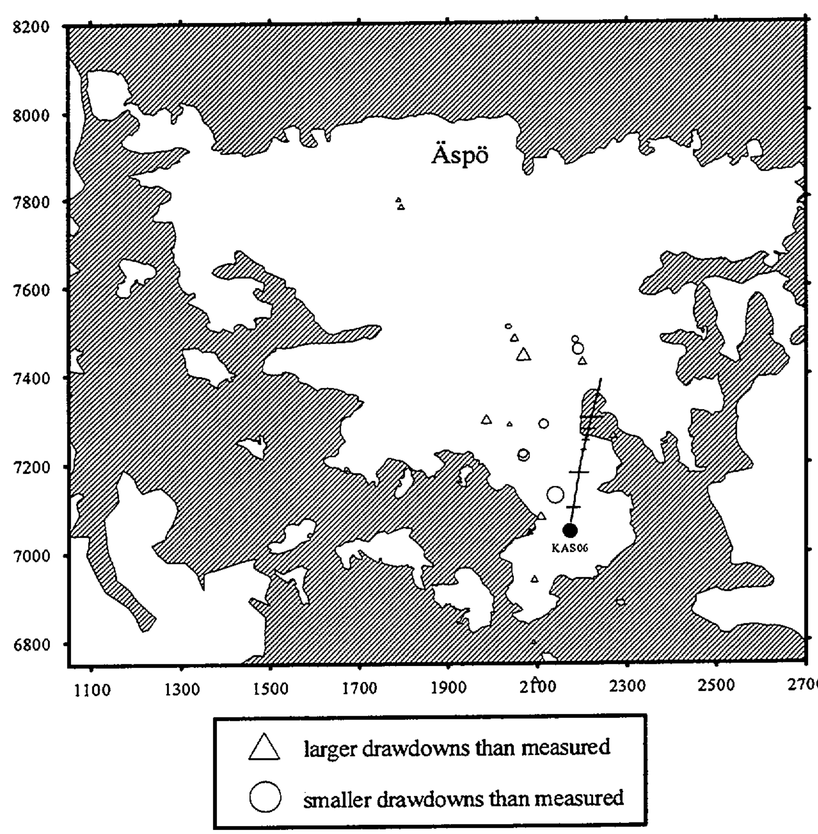
SKB/CFE
Measured and calculated drawdowns
during LPT-2



SKB/CFE, LEVEL 0 - 75 metres



SKB/CFE, LEVEL 200 - 400 metres



SUMMARY SKB/KTH - CNM

The Channel Network Model is used to study the Longterm Pressure and Tracer test (LPT2) carried out in the Hard Rock Laboratory (HRL) at the island of Äspö. This test includes three major parts: several pumping tests, a tracer experiment and a tracer dilution experiment.

There are several identifiable fracture zones in the experimental site. The location of these fracture zones has preliminarily been determined by surface observations as well as geophysical and hydraulic methods. The fracture zones have been confirmed by investigations of the cores from the boreholes, by spinner and hydraulic head measurements and from observations during the tunnel excavation.

In the Channel Network Model, CNM, it is assumed that fluid flow and solute transport take place in a network of channels. Data for the model can be obtained from borehole transmissivity measurements and observations on fracture widths. One important aspect of the present model is that it is simple enough to be able to accommodate the transport of sorbing solutes and especially solutes that diffuse into the rock matrix and sorb in the interior of the matrix.

The dimensions of the model volume were chosen to be 1000*700*700 m in the south to north, east to west and downward direction, respectively. Our target volume starts at normal sea level and reaches a depth of 700 m. The model location was placed so that the most important boreholes in the LPT2 experiment, KAS01-02, KAS04-08 and KAS12, were included in the model.

The Longterm Pumping and Tracer test was performed with withdrawal of water in the open borehole KAS06. The maximum drawdown in borehole KAS06 was 51.77 m. When the pumping had created a steady state pressure head pattern the steady state drawdowns were measured in several boreholes. Most of them were divided into sections with packers, so that the drawdown could be obtained at a vast number of locations. In the drawdown simulation study, we have concentrated our interest to the boreholes KAS02, KAS04-KAS08.

When a steady hydraulic head gradient was developed, the tracer test was initiated. Injections were carried out in six borehole sections in KAS02, 05, 07, 08 and 12. The method of injection was either a decaying pulse injection or an intermittent decaying pulse injection. Four different tracers were used in the test; three radioactive isotopes and one fluorescent dye. Uranin injected in KAS12-2 and Rhenium-186 injected in KAS08-1 were both clearly detected in KAS06. The other tracers were not observed in the withdrawal hole during the observation time.

Borehole data were used to obtain the standard deviation of the channel conductance distribution and the flow wetted surface Data from the fracture zones and the rock mass were used to get the mean conductance for the respective locations. Owing to lack of data, some parameters had to be estimated based on previous experience from large field experiments.

Once the model was developed for the Äspö site using the data described above the steady state

pumping tests were simulated. There were no calibrations or conditioning done in these simulations. When the particle following was carried out to simulate the tracer tests there was no attempt to perform any fitting or calibration in order to better match the experimental measurements at Äspö HRL.

We have simulated the steady state drawdown tests. Simulations of the transient pumping test were not performed. First, simulations were done with the CNM for the pressure tests. We have simulated the steady state drawdown tests. No simulations of the transient pumping test were performed. Several types of boundary conditions on the model ground level were tested, constant infiltration (10, 30 and 150 mm/year) and constant hydraulic head. A more conductive layer near the surface was also used in some simulations. When the experimentally determined hydraulic head was used in KAS06, a large inflow was obtained. A larger drawdown than in the field experiment was also, generally, obtained. Therefore, in a set of simulations the experimentally measured inflows to KAS06 were used, with a better agreement.

When tracer tests were simulated, a reasonably good agreement was obtained for the tracer injected in KAS12, section 2. In the tracer tests, the simulated concentrations were larger than the experimental ones. Considering that no adjustable parameters were used and that some entities such as the flow porosity and matrix diffusion properties were chosen based on previous experience from other sites, the deviations between experimental data and simulations are not surprising. In several cases, no tracer was detected in the experiment, whereas the output concentrations from the simulations were.

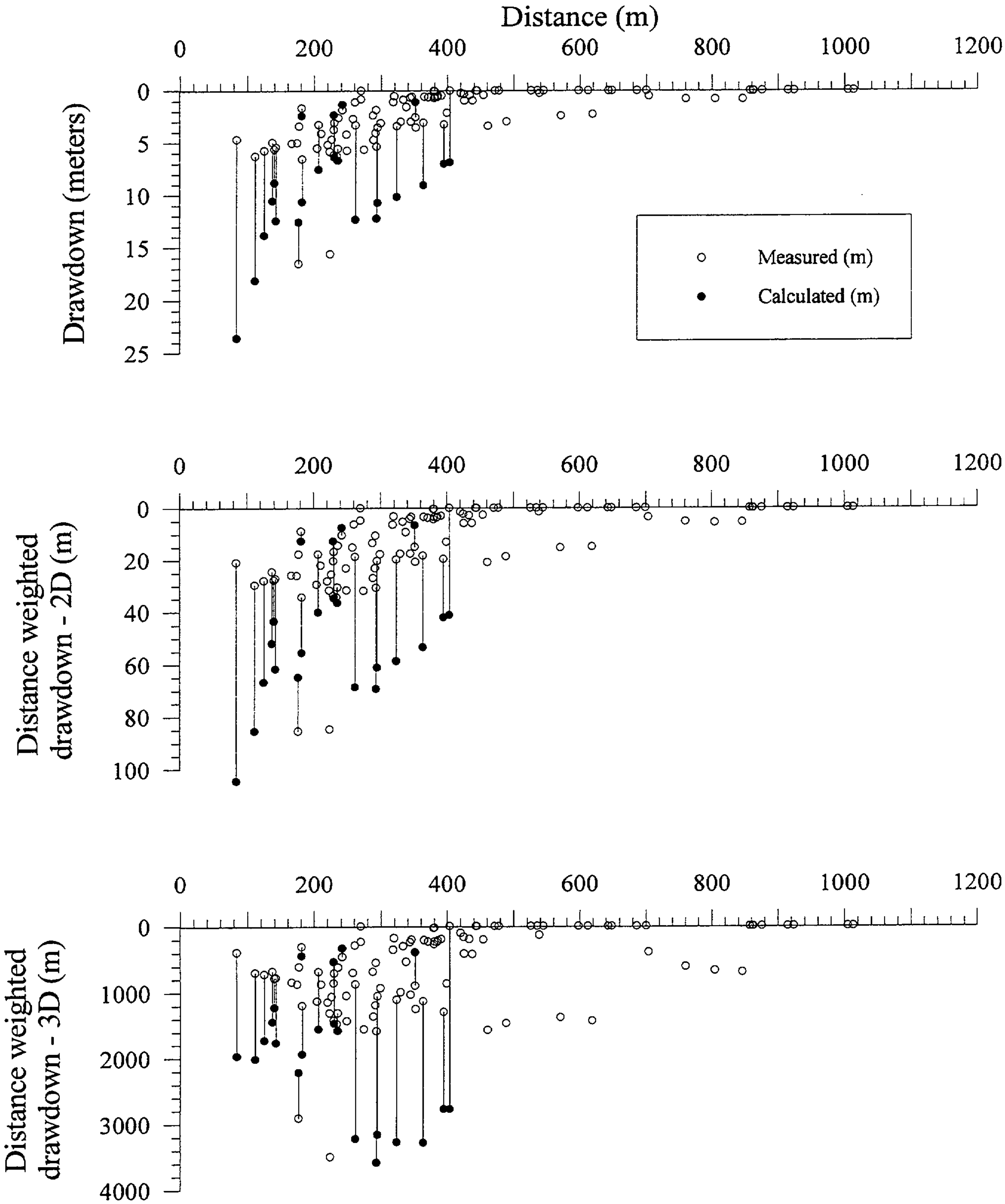
Table 1. Condensed conceptual model description of the Channel Network model used for simulations of drawdown in the LPT2 experiment carried out at Äspö HRL.

SIMULATION MODEL FOR LPT2 DRAWDOWN TEST Channel network model	
Process description Equation of continuity (flow balances) Equation of motion (flow driven by head gradient)	
CONCEPTS	DATA
Geometric framework and parameters	
3D box divided into:	Size: 1.0x0.7x0.7 km
3D fracture zones (planar with a thickness), some with limited extent	Zone geometry, location and extent from geological structural model
Standard deviation in K	Hydraulic packer tests
Material properties	
Zones: Channel conductivity K	Transmissivity data
Rock mass: Channel conductivity K	K from rock mass measurements
Spatial assignment method	
Channels within fracture zones, K from log-normal distribution with mean $K(T_i)$ Channels within rock mass K from log-normal distribution with mean K(rock mass)	Zone geometry, location and extent from geological structural model
Boundary conditions	
Upper: Infiltration	Infiltration based on precipitation and assumptions about run-off and evaporation
Lower: No flow	
Sides: Constant head	
Withdrawal borehole: Inflow or drawdown	Inflow and drawdown data
Numerical tool Channel Network model	
Output parameters Hydraulic head, flowrate distribution	

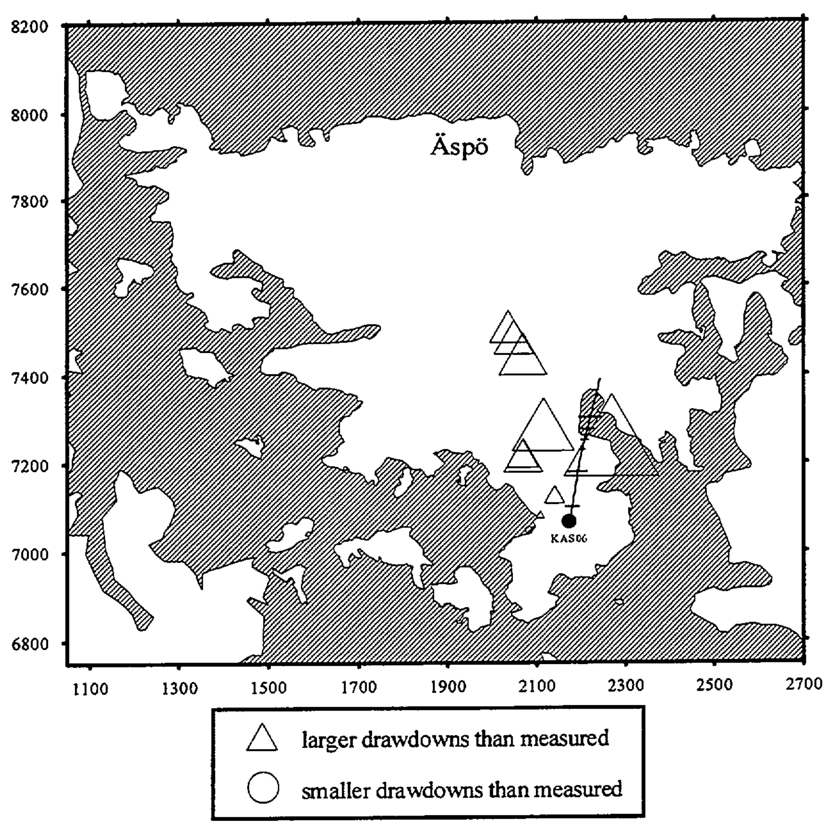
Table 2. Condensed conceptual model description of the Channel Network model used for simulations of tracer tests in the LPT2 experiment carried out at Äspö HRL.

SIMULATION MODEL FOR LPT2 TRACER TEST Channel network model	
Process description Mass balance (advection, matrix diffusion and dispersion)	
CONCEPTS	DATA
Geometric framework and parameters	
3D box divided into:	Size: 1.0x0.7x0.7 km
3D fracture zones (planar with a thickness), some with limited extent	Zone geometry, location and extent from geological structural model
Material properties	
Flow distribution	From drawdown simulation with CNM
Flow wetted surface	Hydraulic packer tests
Diffusion coefficient	Estimated based on data from other sites
Sorption capacity	Non-sorbing tracers used
Flow porosity	Unknown, parameter variation tested
Spatial assignment method	
Locations for injections and detection	Injection and detection location data, borehole data and zone geometry
Dispersion due to heterogeneous flow field	Flow distribution from drawdown simulation with CNM
Boundary conditions	
Injection: Injection patterns	Injection data
Numerical tool Channel Network model and particle following algorithm	
Output parameters Residence time distribution, breakthrough curves and particle trace	

SKB/KTH
according to figure 11 in report
increased permeability near top



SKB/KTH LEVEL 200 - 400 metres



EXECUTIVE SUMMARY TVO/VTT I

Background and objectives

The Äspö Hard Rock Laboratory (HRL) is currently constructed below the island of Äspö. Extensive field investigations have been carried out to study the properties of the bedrock. The LPT2 test is a long-term pumping and tracer test, which was performed to identify and characterize the major water-bearing structures of the bedrock.

Groundwater flow conditions during the LPT2 test were analyzed in this study by means of numerical simulations. Five other pumping tests and undisturbed flow conditions were also examined and modelled when calibrating the models. The main motivation of this study was our effort of developing a site-scale model characterizing the groundwater flow at Äspö.

During the modelling study, the structural model for the Äspö site evolved. Both the base and updated structural models were considered but this study concentrated on the updated model.

Modelling approach

The heterogeneity of the bedrock was taken into account throughout the study. The bedrock was divided into identified fracture zones and the remaining rock matrix. The zones intersected by a withdrawal hole were conceptually treated in two parts: the near-field area of a zone and the rest of it. The spatial variation of the hydraulic properties was also considered.

The numerical simulation method varied depending on the quantity and scale studied. On a site scale, the fracture zones as well as the rock matrix were each represented by a homogeneous feature, and the calculation of the pressure (drawdown) was based on the concept of an equivalent continuum in each subdomain. To estimate the flow rate through the tracer injection sections, stochastic simulations were also applied. The FEFLOW code developed at VTT was used in the numerical simulations.

The geometry of the fracture zones was followed in finite element meshes. When simulating the pumping tests, only the influence of pumping on the pressure drawdown field was calculated. The drawdown measured in the withdrawal holes was used as a boundary condition, and the inflow to the withdrawal holes was calculated. No-flow boundary conditions were assigned for the island area. The pressure at the other boundary nodes was assumed to remain. The type of the boundary conditions on the bottom and side faces is not critical because of the large size of the simulation model.

The initially employed values of the transmissivities and hydraulic conductivity were based on the values reported. The final values were found through the calibration process.

Calibration

The base model was calibrated only tentatively utilizing the two long-term pumping tests, LPT1 and LPT2. The transmissivities of a few zones were adjusted to improve the agreement of the simulation results with the field data. A satisfactory agreement was obtained with modest modifications.

In calibrating the updated model, besides the LPT1 and LPT2 tests, the pumping tests performed in KAS12, KAS13, KAS14 and KAS16 as well as undisturbed flow conditions were examined. The transmissivities of the zones intersecting the withdrawal holes were conditioned to obtain the measured distribution of the inflow. Several other zones were also considered in fitting the drawdown field. The average cross-zone transmissivities and near-field transmissivities of the zones were handled separately. Since the undisturbed pressure field is mainly determined by the salt concentration, the undisturbed flow conditions are not very useful in the calibration.

Several modifications were incorporated in the updated model. The extent of the most conductive parts of two zones (EW-5 and NE-1) was reduced. The average transmissivity was modified significantly only for zone EW-3. The near-field transmissivities were modified up to two orders of magnitude compared to the calibrated values. Several other possible explanations for the discrepancies between the field data and the simulation results were studied: the influence of additional zones, various orientations of the present zones, the highly-conductive surface layer and the low-conductive sea bottom were examined as well. The calibrated models reproduce the main features of the field experiments.

Simulation results for the LPT2 test

The performance of the models was evaluated by comparing the calculated drawdown, the inflow distribution and the flow rate through the injection sections with the field data. The computed steady-state drawdown for LPT2 along the cored boreholes is presented with the experimental data in the figure included in the Executive Summary of Äspö ICR 94-12. The agreement in the drawdown is satisfactory even before the calibration. The differences between experimental and computational results can mainly be explained by the simplifications inherent to the model. The time-dependence of the simulated drawdown was examined in comparison with the field data.

The calculated total inflow to the withdrawal hole was close to the pumping rate applied even with the initial parameters. The distribution of the inflow differed from the experimental data, however.

The agreement between the simulation results and the field data was the poorest for the amount of water flowing through the tracer injection sections. The groundwater flow rate is mainly defined by a local value of the transmissivity, and it is obvious that the average groundwater fluxes calculated from the cross-zone transmissivities do not coincide with the field data. By employing stochastic simulations, flow rate distributions that cover the field values could be obtained in most cases.

Conclusions

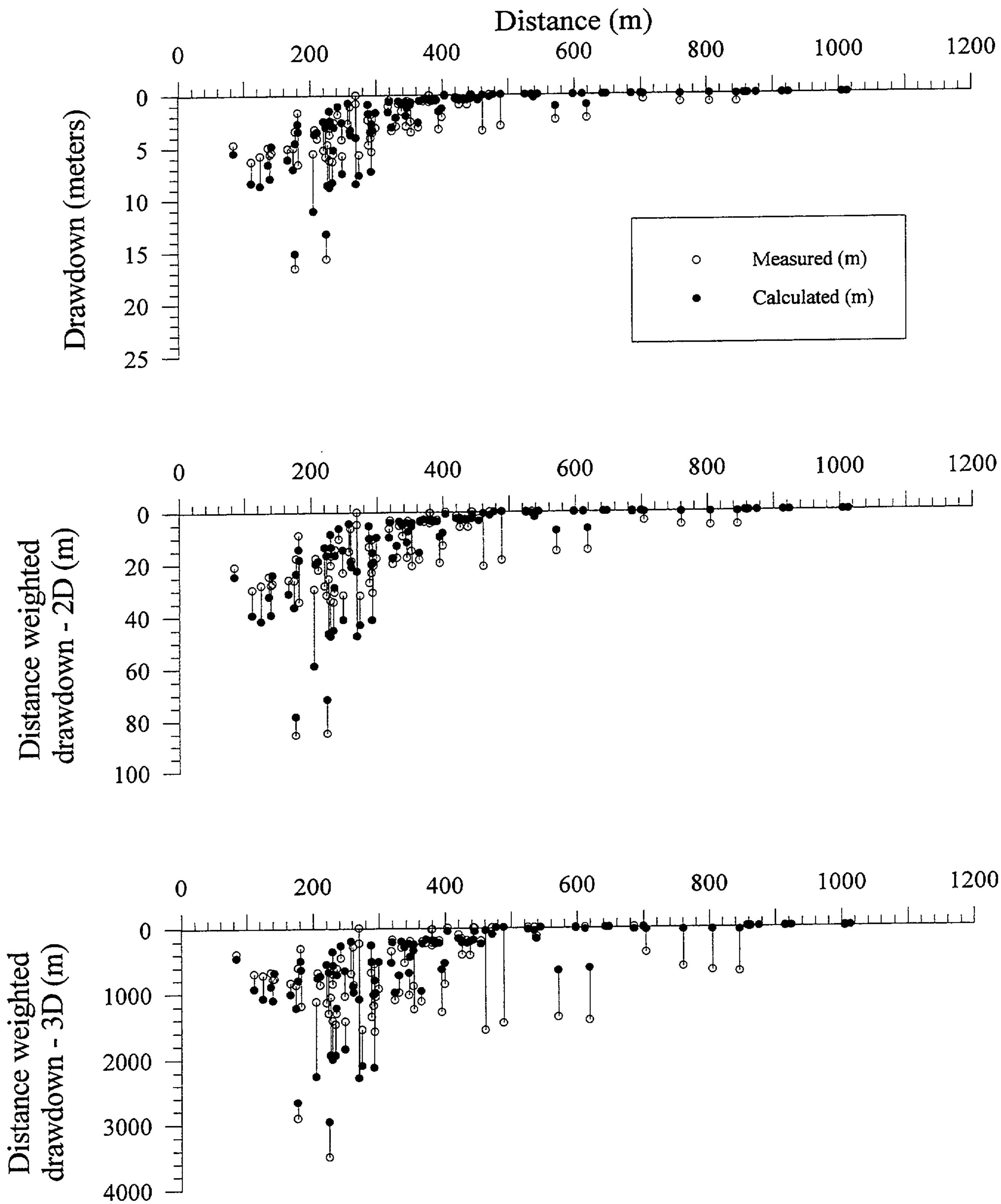
The selected modelling approach proved to be successful. When applied separately on each subdomain, the concept of an equivalent continuum is satisfactory for modelling the drawdown, which was the primary parameter in the calibration and in evaluating the performance of the models. In addition, the continuum approximation supports the fast computation of the drawdown field, which was essential because several pumping tests were applied in the calibration.

The fast and largely automatized software system applied for creating element meshes made it possible to model six pumping tests and to use several structural models including a number of fracture zones. The approach also facilitated the phase of exploring investigations in which the influences of additional features in the simulation model were examined.

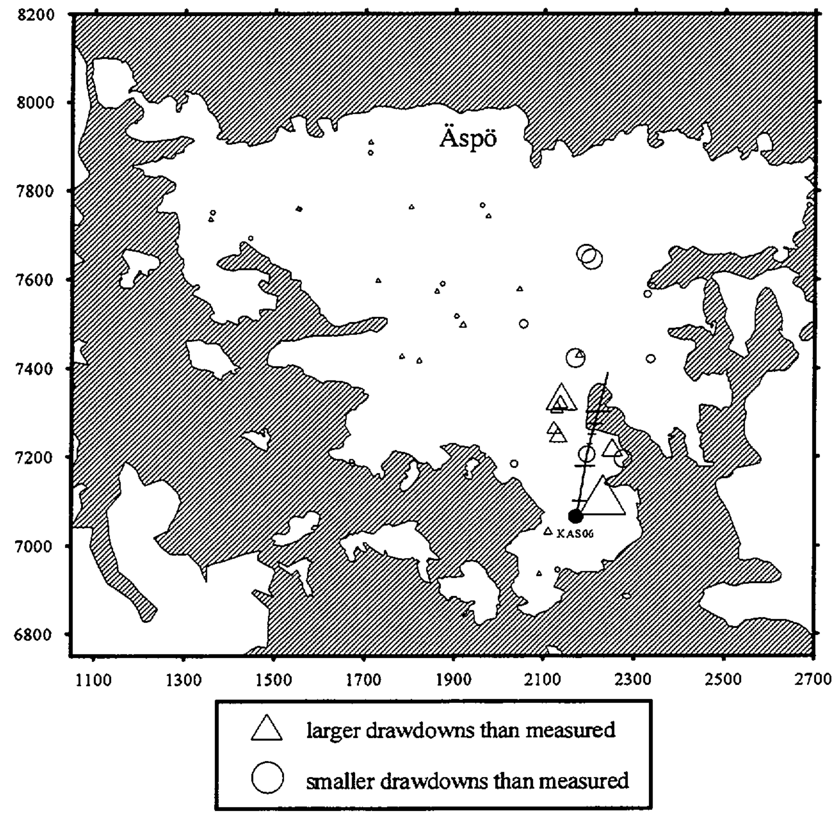
The simulations for the LPT2 test and especially the calibration phase as well as the sensitivity and uncertainty studies helped us to understand better the flow system at the Äspö site. A surprising observation was that the initial models were simulating relatively well the drawdowns only for LPT1 and LPT2. The initial simulation results especially for the pumping tests in KAS12, KAS13 and KAS16 differ significantly from the field data. After the calibration, the model simulated most pumping tests successfully but the results of the pumping tests in KAS14 and especially in KAS16 were much more difficult to explain. The equivalent transmissivities of the zones that are far from any of the withdrawal holes can, however, be significantly larger or smaller.

Considering groundwater flow, both the base as well as the updated structural models for the Äspö site are largely plausible. Most of the differences in the structural models did not influence the simulation results of LPT1 and LPT2. Yet this study indicates the following modifications in the structural model: a connection between KAS 12 and NNW-2, an additional zone intersecting KAS13, and the extent of NNW-1 and NNW-2 smaller in vertical direction. Regarding the properties, the simulations indicate that the transmissivity of EW-5 is high for at least a restricted part around KAS06, NNW-1 is anisotropic having a highly-conductive part around the intersection point with KAS07, the northern part of NNW-1 possesses a large conductive and the transmissivity of the southern part of NNW-2 high. The simulations also strengthen the earlier conclusion that large uncertainties are associated with EW-3.

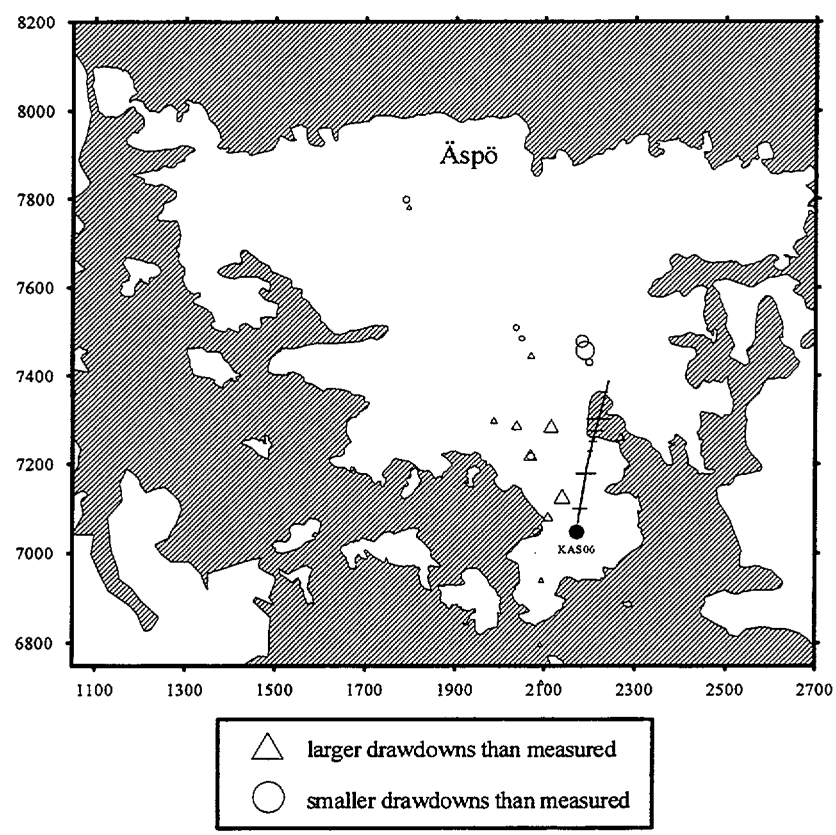
TVO/VTT
Measured and calculated drawdowns



TVO/VTT, LEVEL 0 - 75 metres



TVO/VTT, LEVEL 200 - 400 metres



SUMMARY TVO/VTT II

The modelling of the so called LPT-2 pumping and tracer test was performed as part of the work of the Task Force on groundwater flow and tracer transport of the Äspö HRL project.

Tracers were injected in the following borehole sections: In-114 in KAS02-4 (B4), Uranine in KAS05-3 (E3), I-131 in KAS07-4 (J4), Re-186 in KAS08-1 (M1), Re-186 in KAS08-3 (M3), and Uranine in KAS12-2 (DB). The tracers In-114 and I-131 were not recovered in the withdrawal borehole KAS06. Recoveries of Uranine from the injection E3 and Re-186 from the injection M3 are very uncertain. The only certain breakthrough curves observed in the LPT-2 test originate from the injections DB (Uranine from KAS12-2) and M1 (Re-186 from KAS08-1).

The break-through curves were measured at eight different levels in the withdrawal borehole and from the total discharge water. All of the curves showed a very similar behaviour for each of the two recovered tracers. This could be explained by a somewhat different water inflow distribution than measured in the spinner test. The analysis of the tracer test was thus based on the hypothesis that Uranine from KAS12-2 and Re-186 from KAS08-1 arrived in the withdrawal borehole KAS06 via essentially one transport route within the fracture zone NNW-2 each.

Theoretical model curves were convoluted with the intermittent decaying pulse injection rates and compared with the measured break-through curves. Two types of models were used. A conventional advection-dispersion model with Fickian dispersion and a "matrix diffusion" type of model where diffusion from a flow channel to stagnant areas in the flow field is possible. Both models give fair agreement with the measured results and it would be very difficult, if not impossible, to distinguish between the models or any combination of them.

A deconvolution technique was applied to extract the system behaviour as an impulse response from the given injection and break-through data. Deconvolutions are in practice often numerically difficult and the problems are as such ill-posed because of errors and limited amount of data. The oscillations in the solutions may come from the mathematics of the problem but it is, in principle, impossible to know certainly. If a problem has such properties that the deconvolution is very sensitive to certain kind of oscillations, great care should be taken in interpreting those features in the results being physical.

The results of both kinds of modelling show a relative high dispersion which is not necessarily Fickian. Peclet numbers in the order of 4 is obtained for both of the tracers or alternatively a value of 18-22 $h^{1/2}$ for the u-parameter in the "matrix diffusion" like model. The flow velocities are relatively low compared to the hydraulic transmissivity value of $4 \bullet 10^{-5}$ m^2/s of the fracture zone NNW-2. The fracture aperture is in the order of several centimetres when the transport is interpreted to take place in a single fracture. "Bottle necks" have to limit the transmissivity and flow in this case and the ratio of the volume aperture (from transport time) and the hydraulic aperture (as in the parallel plate model) is relatively large, in the order of 50.

A few things should be taken into account if the option for model independent analysis of

breakthrough data is wanted to be reserved. First good quality data on the injection and breakthrough is needed. This point was fulfilled well in the LPT-2 test. Secondly multiple and especially regularly repeated injections makes the deconvolution analysis very unstable and sensitive to errors. This was unfortunately the case in the LPT-2 test.

If transport phenomena should be studied and transport parameters determined it is better to do this for each transport path or channel separately. Even then the task is difficult enough both for direct and inverse modelling. In the LPT-2 injection sections were very long from that point of view and several paths might have occurred. The analysis showed, however, that the results can be explained by just one single path for each of the recovered tracer. A serious study of transport phenomena and parameters requires at least a series of measurements e.g. with different flow rates or other parameters that can be varied.

SUMMARY UK Nirex/AEA Technology (DRAFT)

AEA Technology has carried out coupled continuum and fracture network modelling of the Äspö LPT2 pump test at the SKB Äspö Hard Rock Laboratory (HRL) on behalf of UK Nirex Ltd.

The modelled region covered the Äspö island, an area of about 1.3 km by 1.5 km to a depth of 0.5 km. The continuum/fracture network model consisted of a near surface weathered region, modelled as an effective porous medium; a set of fracture zones, located deterministically according to SKB's structural model of the site; and finally a statistically generated background of fractures.

Several models were developed for the fifth Task force meeting at Kuhmo, Finland to explore aspects of conceptual uncertainty. The simplest model consisted of only the fracture zones as specified by the structural model given by SKB [1]. In this case the fracture zones were represented as planar features with the prescribed hydraulic properties. Subsequent models built upon these basic structural features. They included coupling the fracture network with an equivalent porous media weathered region to represent the near surface. The properties of the major fault zones were modified slightly to obtain a better fit to the experimental results. Other models included statistically generated populations of background fractures to scope their effect on the computed drawdowns.

On the whole the background fractures had a secondary effect on the simulated drawdowns and only appeared to be important on a local scale when more detailed conditioning of borehole KAS06 was performed. Subsequent calculations performed after the Kuhmo meeting looked at the robustness of the structural model by investigated the sensitivity of measures of goodness of fit of the simulations of the experiments to the presence of an extra horizontal feature and to the structural heterogeneity. The results revealed that the performance measures ds and Ds (Wikberg et al, SKB 91-22) were relatively insensitive to the presence of a transmissive feature. In fact there is only minimal change in the Ds and ds for a transmissivity of 10^{-5} m^2s^{-1}. Structural heterogeneity was introduced by modifying every 10th row of elements in the fault zones to one fifth of the transmissivity. This results in a plane that is anisotropic with a transmissivity of 0.92 the base case in the direction parallel to the stripes of transmissivity and 0.71 times the base case in the direction perpendicular to the stripes. This process was repeated with the stripes oriented along strike and along dip. The results revealed that the simulations were insensitive to reduced transmissivity along strike, but more sensitive to reduced transmissivity along dip (i.e. horizontal permeability barriers).

The modelling performed to simulate the LPT2 pump test demonstrated that the SKB conceptual model is with a few minor exceptions (the upper section of KAS07) consistent with the experimentally observed drawdowns and is controlled by the fault zones and insensitive to a hypothetical transmissive horizontal feature, but more sensitive to anisotropy along the dip of the fault zones.

Appendix 3

ÄSPÖ Hard Rock Laboratory - Questionnaire for Task No 1 - the LPT2 experiment Summary

In order to prepare for the review report of Task No 1 the Äspö Task Force group decided to produce a number of questions and distribute these to all modelling groups. This section summarises the obtained answers. By necessity the summary will be subjective. The summary is based on responses from the following groups:

ANDRA/ITASCA - Daniel Billaux
CRIEPI - Toshifumi Igarashi
PNC/Hazama - Akira Kobayashi
PNC/Golder - Masahiro Uchida
SKB/CFE - Urban Svensson
SKB/KTH - Björn Gylling
TVO/VTT I - Veikko Taivassalo
TVO/VTT II - Aimo Hautojärvi

To avoid confusion, note that by "the given base model" we mean the geological structural model as interpreted by SKB, e g SKB Technical Report TR 91-22. By "conceptual model" we mean assumptions of processes and mechanisms for flow and transport adopted by the modelling teams.

May 31, 1994

Anders Ström/
Gunnar Gustafson

Questionnaire for Task No 1
Summary of answers from modelling groups

1 Comparison between the various modelling teams indicates markedly different approaches which result in relatively similar outputs.

a To what extent do you believe the output of your calculations is sensitive to your conceptual model?

0 % {---} 100 %

b What are the sensitive elements?

c What kind of data/experiments could be useful for further testing of your concepts/models/results? Under what circumstances do you believe the differences in the conceptual models will be possible to distinguish?

ANSWER:
The calculation results are of course completely dependent on both the "given base model" and the "conceptual model". In this question we try to focus on the impact on the results of the chosen conceptual model for flow and transport.

1a
It depends on what kind of output we are referring to. The groundwater pressure field is rather insensitive to the conceptual model, especially far away from the pumping borehole. However, transport outputs like breakthrough curves are more sensitive. This fact is reflected in the wide variety of answers, 5-80 %. In some cases there may also be a confusion about what is regarded as the conceptual model and what is the given base model.

Furthermore, as indicated by some of the groups, it may be discussed whether the approaches implemented on this geometric scale are that different as indicated in the question header.

1b
The sensitive elements of the models also depend on what kind of output we are interested in. As far as the groundwater head field is concerned, it is very much affected by the boundary conditions as well as the representation of the fracture zone transmissivities in the model.

The TVO/VTT group stated specifically that the pressure field is sensitive only to the transmissivities of the structure NE-2 and the zones which are intersected by the withdrawal hole KAS06. This was based on a sensitivity study.

Concerning the inflow to the withdrawal borehole KAS06, the local hydraulic conductivity used is a very sensitive element.

For the transport calculations different parameters such as the specific surface available for sorption very much affect the results.

The concepts used by the modelling groups of Task No 1 include both stochastic and deterministic approaches. Stochastic modelling provides in some cases an additional level of sensitive elements.

The discrete fracture network approach adopted by the PNC/Golder group represents one conceptual model. For flow calculations the sensitive elements are the conductive fracture frequency, fracture size and transmissivity. For transport calculations: the dispersion length and the transport aperture and its variability.

1c
It should be noticed that PNC/Golder regarded LPT2 as an excellent experiment for discriminating between their two different conceptual models for fracture zone description within their discrete feature framework.

One suggestion for a useful field experiments for testing of models/concepts and for discriminating between approaches is a similar kind of pumping and tracer test as LPT2 but this time applied on a smaller scale. Preferably, a sequence of experiments on different scales should be performed.

In addition to this, certain special approaches for flow and transport description requires other types of experiments. For example the PNC/Golder group (DFN modelling) would like to see tests of the connectivity of the rock by doing what is called a rock block experiment. Furthermore, they would like to see interference tests in single boreholes.

The SKB/KTH group (CN modelling) asks for independent observations of the important parameters for transport modelling. The channel properties vary very much and observations of for example the specific surface available for sorption needs to be made in many different ways.

2 *It is important to establish the common base used for the various modelling groups.*

a *To what extent have you used additional data-/information over and above the given base model and the data distributed?*

0 % {--} 100 %

b *What are the extra data sets used and how did you get them?*

ANSWER:
To be more precise than in the introduction to the Questionnaire we mean by

the given base model: the geological structural model as interpreted by SKB, SKB Technical Report TR 91-22, as well as all data sets and reports formally distributed by SKB to the modelling groups.

Note that the fracture zone geometry interpretation as given in SKB TR 91-22 were updated in February 1993 in Data Distribution No 4. This was mainly based on the first part of the tunnel construction, SKB HRL Progress Report 25-93-05. This means that during Task No 1 there were two slightly different fracture zone geometry sets available including their geohydrological interpretation.

In general, there seems to be a satisfaction among the modelling groups regarding the delivered data from the Äspö site.

2a
Most of the modelling groups have not used any extra data sets. (The answers vary between **0 and 13 %**.)

2b
Extra data sets used:

* PNC/Golder performed a **surface outcrop mapping** in August 1992. This data set has given fracture orientation and size information for non-zone fractures in the discrete fracture network model utilized. The extra fracture data has now been included in the SKB GEOTAB database and is therefore available on request for other modelling groups.

* **Personal communication**. Some of the modelling groups have used data/information from different Äspö Progress Reports or scientific papers based on advice from people within the Äspö project. This kind of personal communi-

cation is also used in order to make priorities in the large Task No 1 data set delivered.

3 To what extent did you use calibration runs to adjust the parameters of your model? If so, what data did you use for this purpose?

ANSWER:
Calibration runs have been performed by most of the groups. It seems to us that the TVO/VTT and the PNC/Golder group have performed the most extensive calibration efforts. Some modelling groups have calibrated their flow models, others have also calibrated their transport models.

What has been calibrated?
What data was used for this purpose?

SKB/CFE:
- Location and transmissivity of the fracture zone EW-5. The transmissivity of fracture zone EW-3.
- A number of short-term pumping tests and LPT2.

SKB/KTH:
No calibration

PNC/Hazama:
- Effective porosity for transport modelling.
- Available breakthrough curves.

PNC/Golder:
PNC/Golder has used two different conceptual models for describing the fracture zones in their discrete feature model of Äspö. Only one of these was used for calibration and simulation of tracer breakthrough.
- Transport parameters (dispersivity, transport aperture and its variability) and the correlation length of transmissivity in the stochastic continuum description of the fracture zone planes.
- Breakthrough curves of tracers injected in KAS08-1 and KAS12-2.

CRIEPI:
- The width and the extent of fracture zones.
  Transport parameters: longitudinal and lateral dispersivity
- Head data of the LPT2 test. Breakthrough curves.

TVO/VTT:
TVO/VTT has utilized the basic fracture zone geometry (TR 91-22) as well as the updated set (Data Distribution No 4) in their analyses.

- Transmissivities of some fracture zones:
  * EW-3, NE-1a, NE-2, NNW-2 (TR 91-22)
  * Information not available (D D No 4)
- This was based on the following data sets:
  * LPT-1, LPT2 (TR 91-22)
  * 4 short-term pumping tests, LPT-1, LPT2 and undisturbed piezometric levels. (D D No 4)

ANDRA/ITASCA:

- Transmissivities of some fracture zones.
- {Information not available.}

4 Comparison of the results from the various groups indicates common discrepancies with the given base model, from which one may infer there to be defects/errors/uncertainties in the given base model.

a To what extent have you experienced difficulties in matching features/parameters described in the given base model?

0 % {---} 100 %

b Where have you observed such discrepancies between measurements and predictions and what inferences regarding the given base model can be drawn?

c Did you actually change the base model provided by SKB in your modelling work? How, and why did you change it?

d In light of this, what is the reliability of data for Task No 1?

ANSWER:
Below we will try to list some of the discrepancies in the given base model. Views from modelling groups who have not performed any calibration are regarded as less interesting.

4a
15-60 %.

4b
Discrepancies between measurements and predictions:

* The geological structure model in terms of some of the fracture zones (location and T-values) need to be adjusted in order to comply with measured data. High hydraulic conductivity values from single borehole packer tests did not always match the given base model. This was concluded by a number of groups.

* More specifically, one of the groups remarked that there are about six high transmissivity values in the single hole packer test data from borehole KAS02 near 450 m depth which look erroneous. (However, these data were not included in the data delivery to the TF groups. They are found in some reports, K_{Lugeon}.) (PNC/Golder)

* The drawdown measured in borehole section KAS07-J6 was not possible to obtain in the simulations. (ANDRA/ITASCA)

* There seems to be a high transmissive connection between KAS06 and KAS07. The simulated drawdowns are not as high as measured, in spite of calibration efforts. This could be explained by the introduction of a local heterogeneity-/anisotropy in the structure NNW-1. (TVO/VTT)

* There are circumstances which indicate that the fracture zone EW-5 consists of a large number of fractures. (PNC/Golder)

* The extent of NNW-1 might be smaller than in the present interpretation. This would explain the small drawdowns observed north of KAS06 (in KAS04). (TVO/VTT)

* The predicted flow rates through the tracer injection sections were not 100 % satisfying. (TVO/VTT)

* Inflow to KAS06 from zone EW-3 was not reproduced. (ANDRA/ITASCA)

  A general overestimation of the inflow to KAS06 was simulated by another modelling group. (SKB/KTH - no calibration)

* There was not a good match in the breakthrough curves for each of the KAS06 sections, especially not for the KAS12 injection. (PNC/Golder)

4c
This question is more or less covered by the calibration question No 3 and the discrepancy topic above. In general, transmissivity values have been changed somewhat as compared to the given base model.

4d
Some specific comments regarding the given base model and its reliability:

* There is a mismatch between the spinner survey results and the single hole packer test data (PNC/Hazama)

* The number of data points after 7 days of pumping was too few. The assessment of curves was sometimes difficult. (ANDRA/ITASCA)

* The delivered fracture data from the tunnel was regarded as unnecessary complex. (ANDRA/ITASCA)

Concerning the reliability in general, the answers covers a range from "adequate" to "very good".

5 *Concerning Task 1B specifically:*

a How did your model predict other tracers besides those injected in the sections KAS08-1 and KAS12-2?

b If your model recovered the tracers from other injections, what was the most likely reason why the model was not able to reproduce the actual measurement?

c What kind of additional experiments are suggested in order to explain other tracers?

During LPT2, four different tracers were injected in six borehole sections in five boreholes. Two of these injections, originating from KAS12-2 and KAS08-1 could be clearly detected in the withdrawal borehole.

ANSWER:
5a&b
Two of the modelling groups have only modelled the injection in KAS08-M1 so for them the question is not applicable. Other groups did only consider KAS08 and KAS12.

However, the PNC/Golder group has predicted breakthroughs comparable to the KAS08 and KAS12 breakthrough for all of the injection locations, not just those which had observed breakthrough. They calibrated the transport parameters using the KAS08-1 and KAS12-2 breakthrough data. Using this information, three of the four remaining tracers produced simulated breakthrough within the experimental time of 2000 hours. They state that the possible reasons for the discrepancy are several and include the following:

* Adjustment of Transport Properties: Breakthrough would ultimately occur from those intervals but would **occur after the end** of the experiment. This explanation does not require any change in the given geometric model.

* **Poor connectivity**: The connections between the injection pathways and KAS08 were not as strong as implied in the used conceptual model.

* Flow path **tortuosity** caused by incomplete mixing at fracture intersections.

* **Masking by Multiple Injections**: Breakthrough may be masked by breakthroughs from earlier injections.

It may be interesting to observe that three of the non-responding zones, which were successfully modelled, have EW-5 as their main pathway. EW-5 is a very diffusive fracture zone since it may consist of a large number of fractures.

The first three explanations could have been evaluated by repeating the experiment using higher pumping rates and longer test times.

The SKB/KTH modelling group predicts breakthrough curves for all the injection points. For other simulated tracer experiment than KAS08-1 and KAS12-2 the output was very outspread and in low concentration. This means that tracers flow into the collection hole through many paths with different properties.

The mismatch between the measurements and the simulation is explained by the implementation of fracture zones in the model or possibly by boundary condition effects.

5c
Additional experiments in order to resolve the problem of other tracers:

* Much more information would have been obtained from LPT2 by repeating the experiment using higher flow rates and longer test times.

* More fundamental understanding about transport processes is necessary. The observed tracer losses are still an unresolved issue. Hopefully some of these questions may be answered in the forthcoming experimental program at the Äspö Laboratory.

* The injection intervals should be short and well defined at points having a flow rate of a certain magnitude necessary for giving a good outcome of the experiment.

* Tracer experiments with continuous injection during a longer time may give more information.

6 General question:

- ***What was your main interest in Task No 1?***

ANSWER:
There are different motives for the modelling teams participating within the Äspö Task Force and especially for Task No 1. They may be summarized as:

* Feasibility. New concepts and models are applied with realistic data at a specific site. Modelling performed using one of the most interesting data bases available. Need to test performance assessment models.

* Understanding of fractured rock. Give more insight into rock heterogeneity. Understanding transport processes.

* Understanding of the site. Necessary for the forthcoming experiments in the area which will turn out to be future modelling tasks in the Äspö Task Force.

List of International Cooperation Reports

ICR 93-01
Flowmeter measurement in borehole KAS 16
P Rouhiainen
June 1993
Supported by TVO, Finland

ICR 93-02
Development of ROCK-CAD model for Äspö Hard Rock Laboratory site
Pauli Saksa, Juha Lindh,
Eero Heikkinen
Fintact KY, Helsinki, Finland
December 1993
Supported by TVO, Finland

ICR 93-03
Scoping calculations for the Matrix Diffusion Experiment
Lars Birgersson[1], Hans Widén[1],
Thomas Ågren[1], Ivars Neretnieks[2],
Luis Moreno[2]
1 Kemakta Konsult AB, Stockholm, Sweden
2 Royal Institute of Technology, Stockholm, Sweden
November 1993
Supported by SKB, Sweden

ICR 93-04
Scoping calculations for the Multiple Well Tracer Experiment - efficient design for identifying transport processes
Rune Nordqvist, Erik Gustafsson,
Peter Andersson
Geosigma AB, Uppsala, Sweden
December 1993
Supported by SKB, Sweden

ICR 94-01
Scoping calculations for the Multiple Well Tracer Experiment using a variable aperture model
Luis Moreno, Ivars Neretnieks
Dept. of Chemical Engineering and Technology,
Royal Institute of Technology, Stockholm, Sweden
January 1994
Supported by SKB, Sweden

ICR 94-02
Äspö Hard Rock Laboratory. Test plan for ZEDEX - Zone of Excavation Disturbance EXperiment. Release 1.0
February 1994
Supported by ANDRA, NIREX, SKB

ICR 94-03
The Multiple Well Tracer Experiment - Scoping calculations
Urban Svensson
Computer-Aided Fluid Engineering
March 1994
Supported by SKB, Sweden

ICR 94-04
Design constraints and process discrimination for the Detailed Scale Tracer Experiments at Äspö - Multiple Well Tracer Experiment and Matrix Diffusion Experiment
Jan-Olof Selroos[1], Anders Winberg[2],
Vladimir Cvetkovic[2]
1 Water Resources Eng., KTH
2 Conterra AB
April 1994
Supported by SKB, Sweden

ICR 94-05
Analysis of LPT2 using the Channel Network model
Björn Gylling[1], Luis Moreno[1], Ivars Neretnieks[1],
Lars Birgersson[2]
1 Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden
2 Kemakta Konsult AB, Stockholm, Sweden
April 1994
Supported by SKB, Sweden

ICR 94-06
SKB/DOE Hard Rock Laboratory Studies Task 3. Geochemical investigations using stable and radiogenic isotopic methods
Bill Wallin[1], Zell Peterman[2]
1 Geokema AB, Lidingö, Sweden
2 U.S. Geological Survey, Denver, Colorado, USA
January 1994
Supported by SKB and U.S.DOE

ICR 94-07
Analyses of LPT2 in the Äspö HRL with continuous anisotropic heterogeneous model
Akira Kobayashi[1], Ryo Yamashita[2], Masakazu Chijimatsu[2], Hiroyuki Nishiyama[3], Yuzo Ohnishi[3]
1 Iwate University, Iwate, Japan
2 Hazama Corporation, Ibaraki, Japan
3 Kyoto University, Kyoto, Japan
September 1994
Supported by PNC, Japan

ICR 94-08
Application of three-dimensional smeared fracture model to the groundwater flow and the solute migration of LPT-2 experiment
T Igarashi, Y Tanaka, M Kawanishi
Abiko Research Laboratory, Central Research Institute of Electric Power Industry, Abiko, Japan
October 1994
Supported by CRIEPI, Japan

ICR 94-09
Discrete-fracture modelling of the Äspö LPT-2, large-scale pumping and tracer test
Masahiro Uchida[1], Thomas Doe[2], William Dershowitz[2], Andrew Thomas[2], Peter Wallmann[2], Atsushi Sawada[1]
1 Power Reactor and Nuclear Fuel Development Co., Tokai, Japan
2 Golder Associates Inc., Seattle, WA, USA
March 1994
Supported by PNC, Japan

ICR 94-10
Äspö Hard Rock Laboratory
International workshop on the use of tunnel boring machines for deep repositories
Äspö, June 13-14 1994
Göran Bäckblom (ed.)
Swedish Nuclear Fuel and Waste Management Co.
October 1994
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1 Earth Sciences Division, Lawrence Berkeley National Laboratory, USA
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