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Äspö Hard Rock Laboratory – Feasibility and usefulness of site investigation methods

Experiences from the pre-investigation phase

Karl-Erik Almén (ed.)[1], Pär Olsson[2], Ingvar Rhén[3], Roy Stanfors[4], Peter Wikberg[5]

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ÄSPÖ HARD ROCK LABORATORY - FEASIBILITY AND USEFULNESS OF SITE INVESTIGATION METHODS

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ÄSPÖ HARD ROCK LABORATORY

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Keywords: site characterization, geology, geohydrology, groundwater chemistry, transport of solutes, rock mechanics, investigation methods, instruments, evaluation of methods

ABSTRACT

One of the main goals set up by SKB for the Äspö HRL project is to "test the quality and appropiateness of different methods for characterizing the bedrock with respect to conditions of importance for a final repository". An extensive investigation programme was carried out during the project's pre-investigation phase that in part was based on experience from SKB's previous site investigations and in part entailed the testing of new or other unestablished methods.

Previous technical reports have described the methods that have been used and the results, models and predictions that have been produced. All the methods used are discussed in the present report in terms of how they have contributed in different analysis stages to the total geoscientific characterization of the rock at Äspö. The usefulness of each method for modelling and prediction on different scales is evaluated, and aspects of the practical execution of the methods under different conditions are discussed.

The report sheds light on the importance of dividing large investigation programmes such as this one into suitable stages to get an opportunity to evaluate the results obtained and plan in detail the investigations in the next stage. Furthermore, the way in which the characterization / modelling work on different geometric scales has been done for the different investigation stages is discussed, along with whether this has been found to be a suitable approach. The importance of pursuing an interdisciplinary strategy throughout the pre-investigation process cannot be overemphasized. For the planning, execution, analysis and reporting of the results of the pre-investigations, this has been guaranteed by an organization in which an interdisciplinary group has been in charge of the investigations, together with the project manager.

SAMMANFATTNING

Ett av de huvudmål som SKB satt upp för projekt Äspölaboratoriet är att "pröva kvalitet och användbarhet för olika metoder att karakterisera berggrunden med avseende på förhållanden av vikt för ett slutförvar." Under projektets förundersökningsfas genomfördes ett omfattande undersökningsprogram som dels baserades på erfarenheter från SKB:s tidigare platsundersökningar och dels innebar prövande av ny eller annan icke etablerad teknik.

Tidigare tekniska rapporter har publicerat de metoder som använts och de resultat, modeller och prediktioner som arbetats fram. I föreliggande rapport diskuteras alla de använda metoderna med avseende på hur de bidragit i olika analyssteg för den totala geovetenskapliga karakteriseringen av Äspös bergvolym. Nyttan av varje metod för modellering och prediktering i olika skalor har värderats likaväl som aspekter på metodernas praktiska genomförande under olika förutsättningar diskuteras.

Rapporten belyser betydelsen av att omfattande undersökningsprogram som detta delas upp i lämpliga steg, för att få möjlighet att stämning av uppnådda resultat och detaljplanera nästa stegs undersökningar. Vidare diskuteras hur karakteriseringen/modelleringen i olika geometriska skalor gjorts för de olika undersökningsstegen och om detta befunnits vara en lämpligt tillvägagångssätt. Betydelsen av att hela förundersökningsprocessen genomsyras av tvärvetenskapligt agerande kan inte nog poängteras. Såväl för planering, genomförande, analys och rapportering av förundersökningarna har detta kunnat garanteras genom en organisation där en tvärvetenskapligt sammansatt grupp tillsammans med projektledaren ansvarar för undersökningarna.

PREFACE

The research and development work in the Äspö Hard Rock Laboratory project is one of the efforts undertaken in order to prepare for future work at the candidate sites for a deep repository.

One purpose of the project was to test suitable methodology for pre-investigations from the surface and in boreholes from the surface, and verify the methods by comparing the results of these investigations with later observations made during tunnelling and sinking of shafts in the pre-investigated rock volume.

PURPOSE OF THIS REPORT

The purpose of this report is to present an evaluation and discussion of the feasibility and usefulness of methods for investigation, conceptual modelling and prediction which were used during the pre-investigation phase of the Äspö Hard Rock Laboratory (HRL) project.

Evaluations and discussions made in this report are based on the state of knowledge available at the end of the pre-investigation phase. Hence, the results of the construction phase, i.e. underground observations, are not taken into account. Supplementary evaluations of the methodologies, taking experience from the construction phase into account, will be made later.

OUTLINE

Chapter 1 gives an general introduction to the Äspö HRL Project.

Chapter 2 gives an overview of the pre-investigation programme, where the general characterization strategy and the investigations on different scales are presented.

In **chapter 3** the conceptual modelling work is discussed, in order to clarify the modelling strategy of the project. The development of models on different scales in the different investigation stages will be described and brief presentation of the models will be given at the end of the pre-investigation phase.

An evaluation of the strategy and methods is presented in the subsequent chapters. In **chapter 4** the usefulness of different investigation methods for the conceptual modelling of the Äspö site is evaluated and discussed. The structure of this evaluation is based on the subjects identified for the prediction work.

In **chapter 5** all methods are evaluated separately in terms of feasibility and usefulness for the characterization of the Äspö rock volume.

Finally, **chapter 6** discusses the general investigation strategy and offers some comments as to whether, based on the current stage of knowledge, the same investigation programme (strategy and methods) should be used, or if not what changes should be made if the Äspö HRL project were to be repeated.

NOTE

All discussions and conclusions presented in this report concern experiences from the pre-investigation phase of the Äspö HRL project and the geological setting of the Äspö rock volume. This must be taken into consideration when applying conclusions from the Äspö HRL project to other projects and other rock conditions.

ACKNOWLEDGEMENT

The authors wish to express their gratitudes to a great number of persons who have been involved in the pre-investigation of the Äspö HRL project; in the field investigations, analysis, modelling and evaluation work. They have all contributed, in one way or another, to the evaluation of usefulness and feasibility of methods presented in this report.

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TABLE OF CONTENTS

Page

Page

1 INTRODUCTION

1.1 BACKGROUND

In 1977, an extensive research programme was set up in Sweden to demonstrate the suitability of using deep geological formations for the disposal of high-level nuclear waste. The Swedish disposal concept involves an excavated repository at a depth of about 500 m in crystalline rock, see Figure 1-1. The spent fuel is first encapsulated in copper canisters, which are placed in deposition holes from a system of tunnels. Blocks of swelling bentonite clay surround the canisters in the holes. Upon sealing of the repository the tunnel galleries are backfilled with a mixture of sand and bentonite.

The geoscientific research of the Swedish Nuclear Fuel and Waste Management Co (SKB) concerns crystalline rock and the proposed disposal concept. The most important properties of the rock volume hosting a nuclear waste repository are */SKB 91/*:

- long-term mechanical stability,
- long-term chemical stability, and
- low groundwater flow and transport capacity for radionuclides from the repository up to the biosphere.

These factors and parameters have to be investigated, monitored and analyzed.

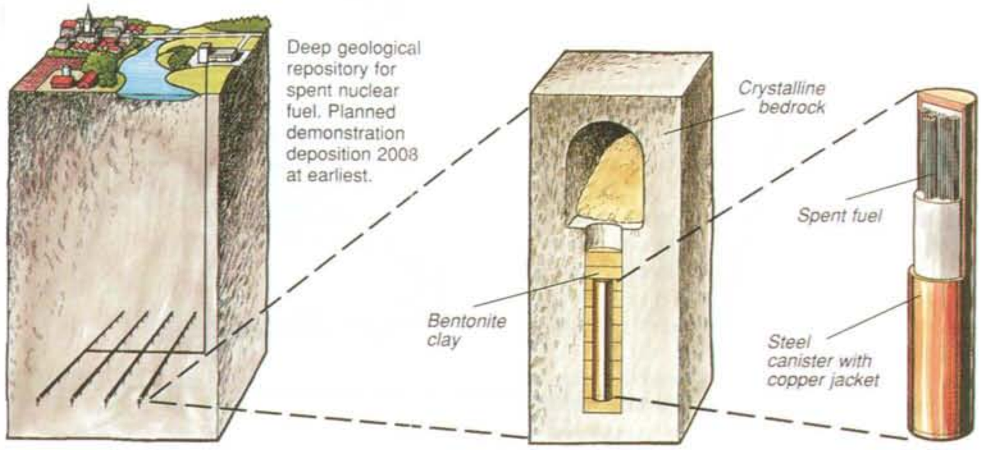


Figure 1-1. *Conceptual Repository Design.*

Since 1977, some eight Study Sites in Sweden have been investigated in order to characterize different rock types with a view to waste disposal. These investigations have only involved measurements from the surface and in boreholes drilled from the surface. Based on these investigations, geological, hydrological and groundwater chemical characteristics of the rock formation have been determined. Conceptual models of the rock volumes have been developed and numerical modelling of groundwater flow and radionuclide migration from the repository and up to the biosphere has been performed */KBS-3/*.

There is a need to verify directly the results obtained from surface and borehole investigations by systematic observations from shafts and tunnels down to the depth of a deep repository. The construction of the Äspö Hard Rock Laboratory (HRL), see Figure 1-2, provides excellent opportunities for such verification. This verification will permit greater confidence in our ability to judge the suitability of prospective sites for a deep repository even before detailed underground investigations of these sites have been made.

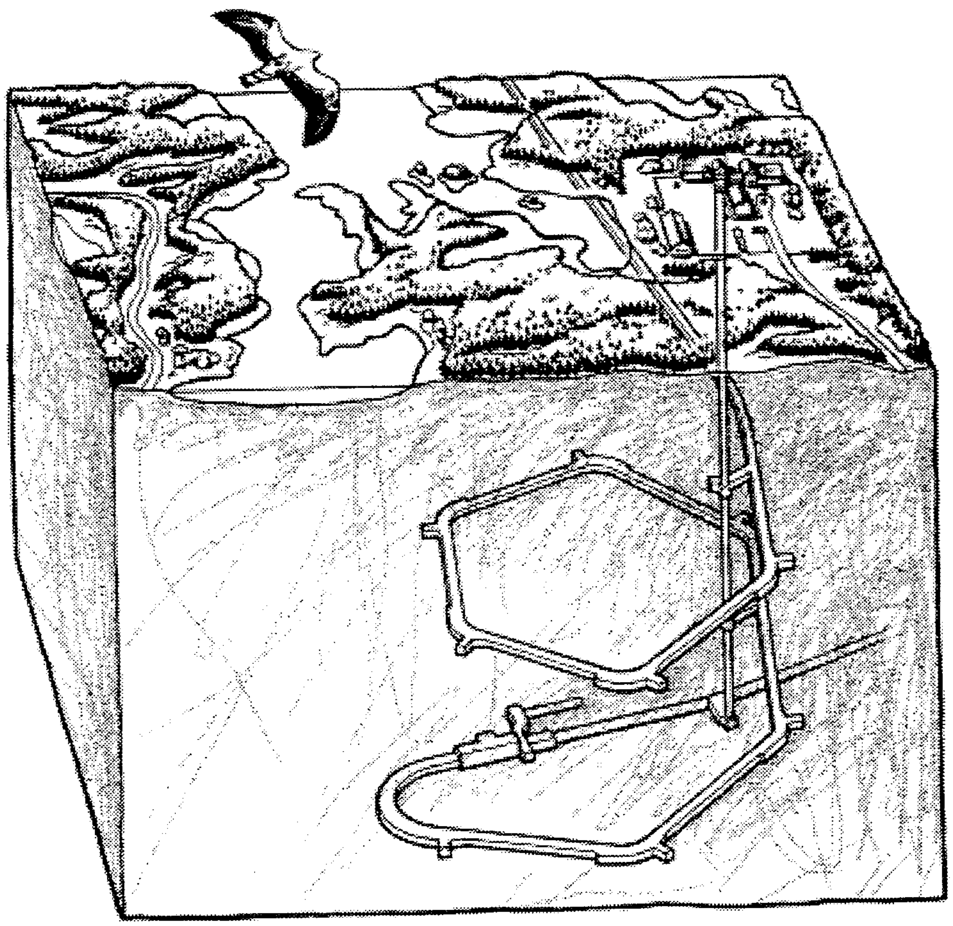


Figure 1-2. *Schematic design of the Äspö Hard Rock Laboratory.*

1.2 THE ÄSPÖ HARD ROCK LABORATORY PROJECT

1.2.1 Goals

The overall goal for SKB is to construct a safe repository for spent nuclear fuel. According to present plans the first part of the deep repository will be ready for operation around 2010. The site of the deep repository will be selected in 2000. That decision will be preceded by surface-based site investigations at two sites followed by detailed investigations from an underground system of tunnel, shafts and boreholes at the candidate repository site */SKB, 1992/*.

In preparation for the future work at the candidate sites SKB decided to build an underground rock laboratory */SKB, 1989/*.

Main goals

The main goals of the research and development work at the Äspö Hard Rock Laboratory (HRL) are to :

* Test the quality and appropriateness of different methods for characterizing the bedrock with respect to conditions of importance for a final repository.

* Refine and demonstrate methods for how to adapt a final repository to the local properties of the rock in connection with planning and construction.

* Collect material and data of importance for the safety of the final repository and for confidence in the quality of the safety assessments.

Stage goals

To meet the overall schedule for SKB siting programme, the following stage goals have been set up for the activities at the Äspö HRL:

Prior to the siting of the deep repository for spent fuel the activities at the Äspö HRL shall serve to:

1. **Verify pre-investigation methodology**
Demonstrate that the investigations at ground level and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.

2. **Finalize detailed characterization methodology**
Refine and verify the methods and the technology needed for characterization of the rock in the detailed site investigations.

As a basis for optimization of the deep repository system and for safety assessment prior to the siting application it is necessary to:

3. **Test models for groundwater flow and radionuclide migration**
   Refine and test, on a large scale at repository depth, methods and models for describing groundwater flow and radionuclide migration.

Prior to construction of the deep repository the following shall be done at planned repository depth and under representative conditions:

4. **Demonstrate construction and handling methods**
   Provide access to rock where methods and technology for high quality in the design, construction and operation of a deep repository can be refined and tested.

5. **Test important parts of the repository system**
   Test, investigate and demonstrate on a full scale different components that are of importance for the long-term safety of a deep repository system.

1.2.2 Project description

The Äspö Hard Rock Laboratory Project was initiated in 1986 and has been divided into the following phases:

* **Pre-investigation phase, 1986 – 1990**
  Stage goals 1 and 3 are addressed in this phase of the project.

* **Construction phase, 1990 – 1994**
  Stage goals 1, 2 and 3 are addressed in this phase of the project.

* **Operational phase, 1995 –**
  Stage goals 2, 3, 4 and 5 are addressed in this phase of the project.

The Äspö HRL is sited on Äspö Island, in the vicinity of the Simpevarp Nuclear Power Plant, north of Oskarshamn, see Figure 1-3. The ongoing construction work will result in a tunnel system from the surface down to a depth of approximately 450 m, see Figure 1-2. The operational phase will allow various experiments relevant to nuclear waste disposal to be conducted.

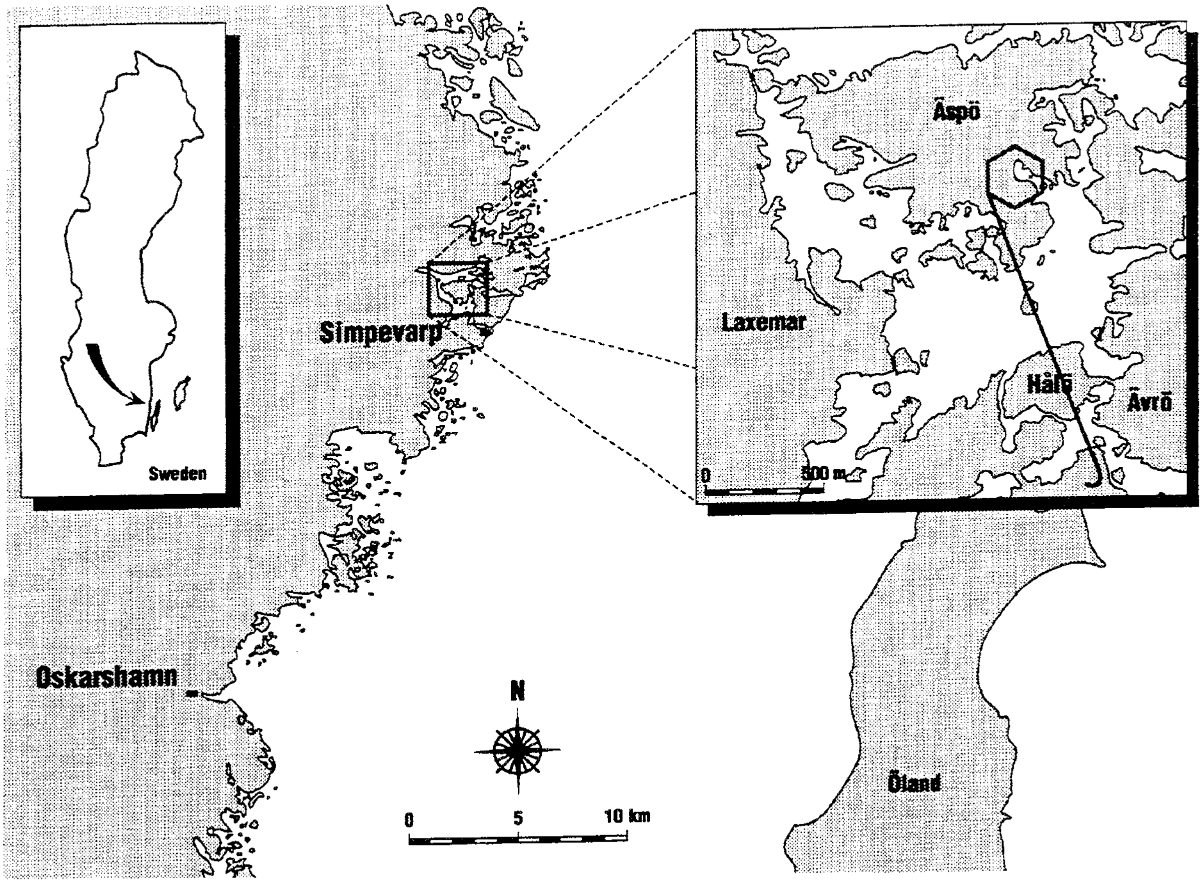


Figure 1-3. *Location of the Äspö Hard Rock Laboratory.*

2 THE PRE-INVESTIGATION PROGRAMME

2.1 SITE CHARACTERIZATION STRATEGY

Strategy for verification of pre-investigation methodology

With reference to Section 1.2 the first phase of the project was the pre-investigation phase. The aim of the pre-investigation phase was to **investigate and characterize** the Äspö rock formation prior to the construction of underground tunnels and shafts, as the first step towards the stage goal to *verify pre-investigation methodology.*

Based on these investigations **models of the rock were developed and predictions were set up** of rock character and groundwater behaviour during forthcoming tunnelling, see Figure 2-1. During the construction phase the **models and predictions will be compared with observations** from under ground and measurements of the groundwater changes caused by the tunnelling. Evaluation of these **comparisons will form the basis for verification of the pre-investigation methods.**

Site investigation strategy

Site characterization is a multi- and interdisciplinary task that necessitates integration in planning, data acquisition, evaluation and presentation / reporting. In order to facilitate such integration in the investigation strategy for the pre-investigation phase of the Äspö HRL, three main tasks were defined */Bäckblom et al., 1990/*:

* **The pre-investigation shall proceed in stages.** Evaluations shall be made and reported after each stage. This provides an opportunity to document what is achieved in each stage and enables the investigators to interpret all data simultaneously, see Section 2.2.

* **The investigated area shall be described on different geometrical scales** appropriate for the planning of a real repository, see Sections 3.1 and 3.2.

* **The characterization work shall pertain to five key issues of relevance for design and/or performance assessment and/or safety assessment.** The designated key issues are the geological-structural model, groundwater flow, groundwater chemistry, transport of solutes and mechanical stability. These key issues shall serve as a basis for the predictions, see Sections 3.1 and 4.1.

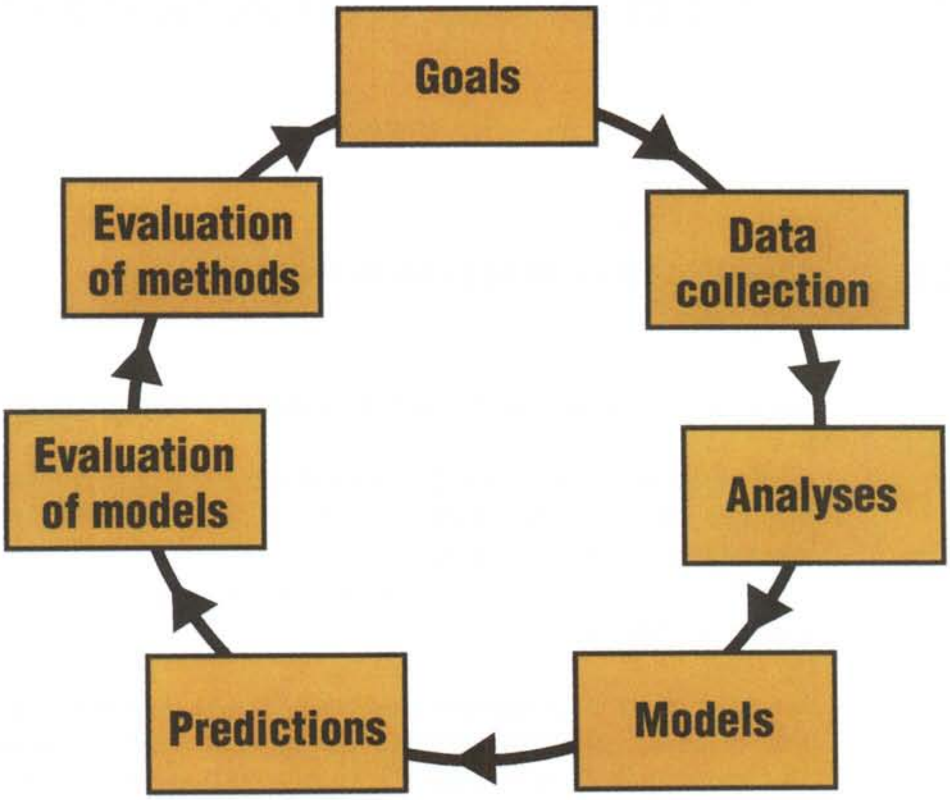


Figure 2-1. *The strategy for the verification of the pre-investigation methods.*

2.2 OVERVIEW OF THE PRE-INVESTIGATION PROGRAMME

The pre-investigations for the Äspö Hard Rock Laboratory started in late 1986 and was finished in late 1990. The pre-investigation phase was divided into the following stages:

* The siting stage	(1986 – 1987)
* The site description stage	(1987 – 1988)
* The prediction stage	(1989 – 1990)

The areas covered by the different stages are shown in Figures 2-2 and 2-3.

An overview of all investigations performed and all reports published from the project is given in *Stanfors et al. /1991/*. An overview of investigation methods and instruments used is given in *Almén and Zellman /1991/*. The evaluation of the three investigation stages and conceptual modelling on the different scales is presented in *Wikberg et al. /1991/*. Predictions, on different scales, of geological, hydrological and chemical characteristics of the rock and the groundwater expected to be found in the tunnel and how the tunnel system will influence the groundwater conditions were made in *Gustafson et al. /1991/*.

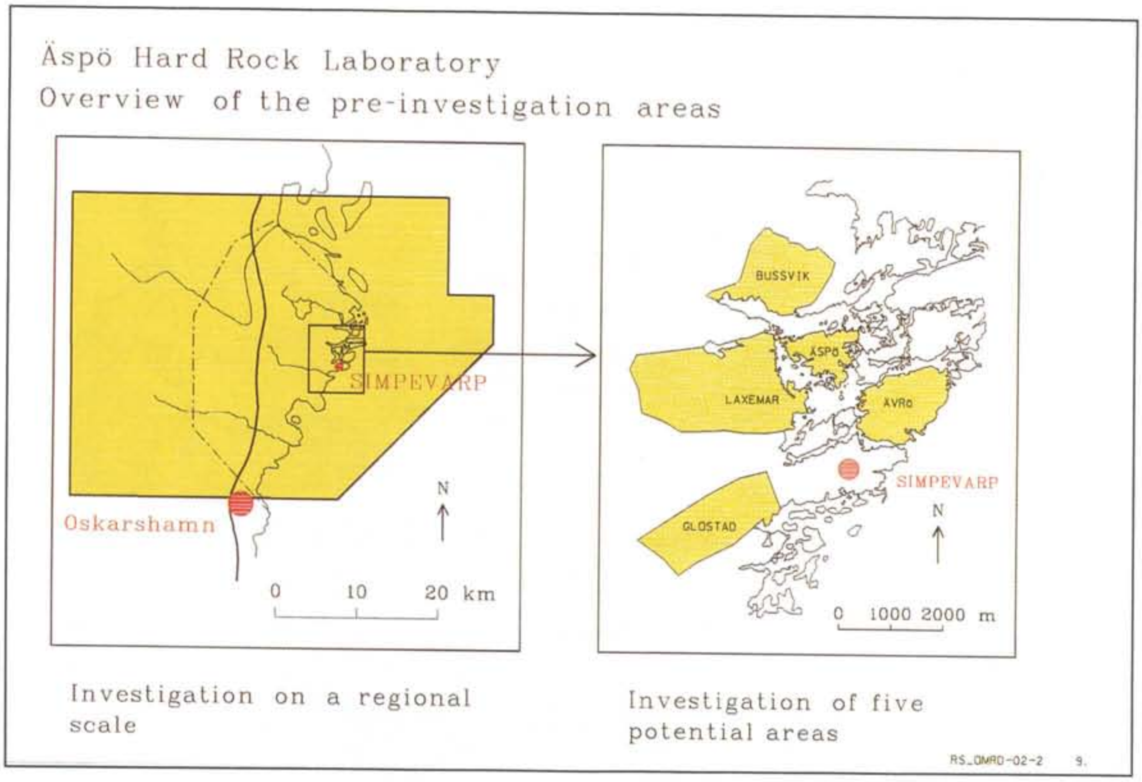


Figure 2-2. Overview of pre-investigation areas in the siting stage.

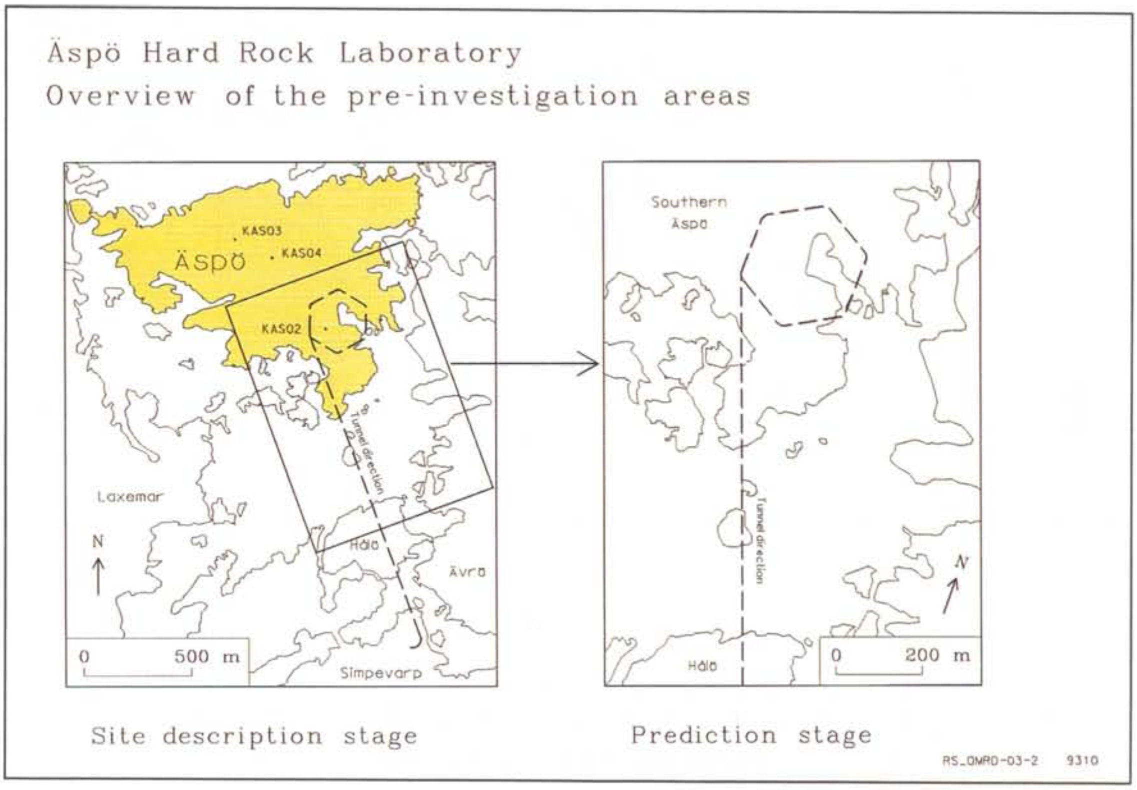


Figure 2-3. Overview of the Äspö site in the site description stage and the prediction stage.

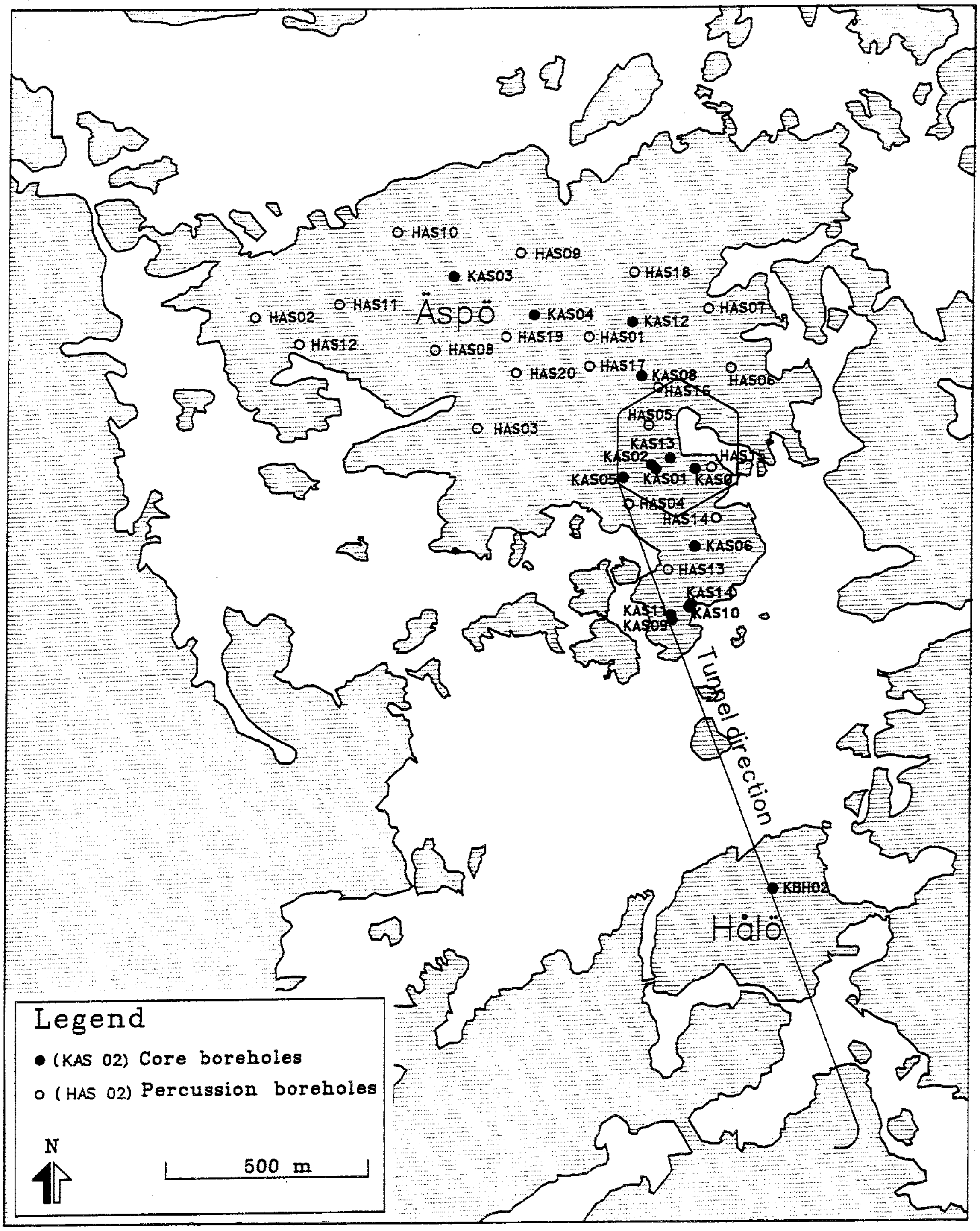


Figure 2-4. *Location of boreholes on Äspö.*

Drilling and investigation of different types of boreholes constituted an important part of the pre-investigations, see Figure 2-4. Beside Äspö, the investigations also included the reference sites Laxemar and Ävrö.

3 OVERVIEW OF THE CONCEPTUAL MODELLING WORK

3.1 CONCEPTUAL MODELLING STRATEGY IN GENERAL

With reference to the second task of the site investigation strategy being used in the project (Section 2.1), the conceptualization of the investigations shall be based on different geometrical scales appropriate for the planning of a real deep repository. The following scales are relevant to the conceptualization, see Figure 3-1:

* **Regional scale, >>1000 m**
  The description on this scale provides an overview of the geological and tectonic conditions and the groundwater flow in the area surrounding the repository, and forms a basis for the selection of a suitable rock volume for the repository.

* **Site scale, 100 – 1000 m (repository scale)**
  The description on this scale will be used for repository layout and for the far field evaluation in a siting application.

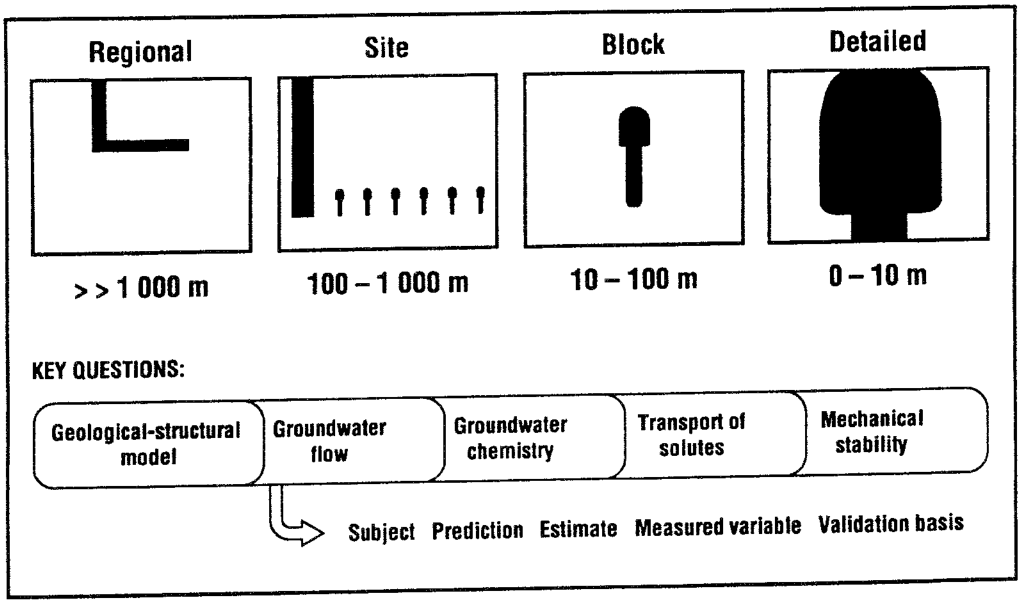


Figure 3-1. Overview of geometrical scales and key questions relevant to the characterization of the host rock of a deep repository.

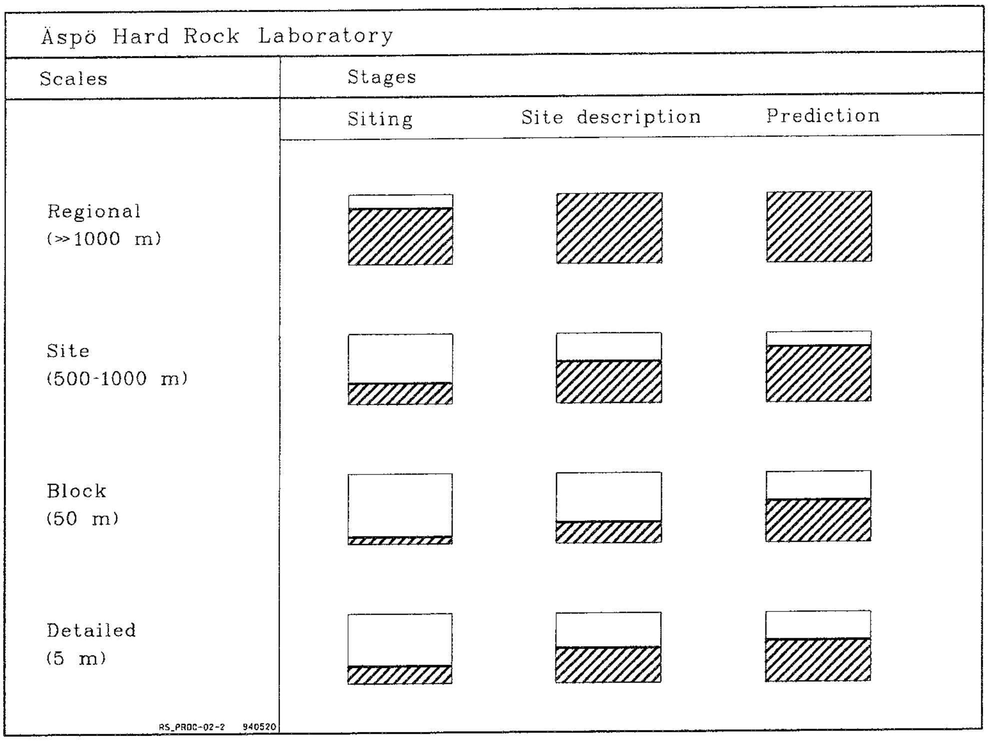


Figure 3-2. Schematic illustration of the development of the models in relation to the expected total knowledge after the detailed investigations from the tunnel. The degree of knowledge varies between the key questions at different stages, but the figure approximately shows the development in different modelling scales.

* **Block scale, 10 – 100 m**
  The description on this scale will be used for detailed layout of deposition tunnels and for the near-field to far-field performance assessment.

* **Detailed scale, 0 – 10 m (canister scale)**
  The description on this scale (the near field) will be used for selection of canister positions and refers to the zone (including the disturbed zone) near the buffer and the canister.

By using several geometric scales it is possible to present both deterministically identified features and statistically defined properties in a meaningful way and in reasonable detail. Thus, on the site scale, structures and lithological bodies are deterministically located and characterized, whereas on the detailed scale, the properties of certain rock units and their ranges of variation are based on statistical analyses.

The rock volume involved in the investigations will be reduced during the course of the pre-investigations, while the detail of the characterization will increase. Accordingly, the modelling of the different scales will not be done in parallel. The regional scale model will mainly be based on the siting-stage investigations while the detailed scale model will mainly be based on later-stage investigations, see Figure 3-2.

With reference to the third task of the site investigation strategy, conceptualization has been based on key questions of relevance to design, performance assessment and/or safety assessment. These key questions are the geological-structural model, groundwater flow, groundwater chemistry, transport of solutes and mechanical stability, see Figure 3-1. These key questions also serve as a basis for the predictions in the Äspö HRL project.

3.2 THE CONCEPTUAL MODELLING OF THE PRE-INVESTIGATION PHASE

3.2.1 Description of the different scales

In keeping with the conceptual modelling strategy presented in Section 3.1, the characterization of the Äspö site and the region surrounding the Äspö site has been done on four different geometrical scales, summarized below. Further description of the modelling results is given in an Appendix to this report and in *Wikberg et al. /1991/* and *Gustafson et al. /1991/*.

Regional scale modelling

The Regional scale model covers some 1000 km^2 and involved the area shown in Figure 3-3. The regional scale model was predominantly developed during the siting stage and accordingly mainly based on data gathered during that stage of the project. Further minor adjustments of the regional scale model were made at later stages of the pre-investigations.

Site scale modelling

The site scale model was developed for the rock volume on the Äspö Island and in less detail also for the Laxemar and Ävrö pre-investigation areas.

The site model of Äspö covers some 1 km^2 of Äspö Island, see Figure 3-3. The framework for the site scale modelling was the existing regional scale model. Refinement of the site scale model was mainly done during the siting stage and the site description stage when extensive investigation data was gathered. Further refinement of the site scale model was done during the prediction stage based on results from further deep borehole investigations.

The site scale models of Laxemar and Ävrö were sub models of the regional model, derived from a few percussion boreholes and one deep borehole on both sites. However, the Ävrö site was omitted due to the landowner's plans for that site.

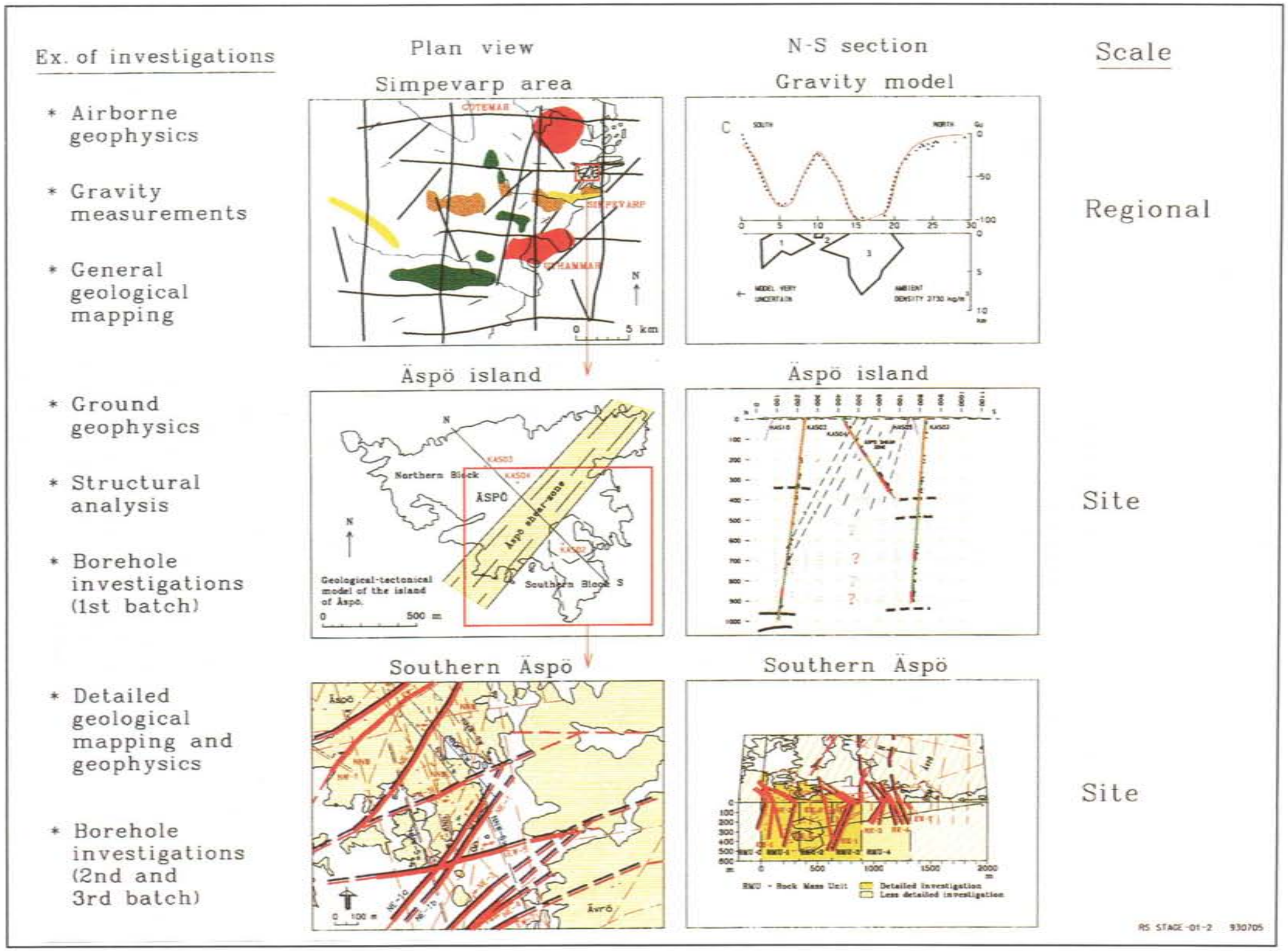


Figure 3-3. Illustration of conceptual modelling on the regional scale and the site scale.

Block scale modelling

The purpose of the 50 m block-scale models is to describe the rock on a scale of interest for positioning of the deposition tunnels and assessments of the transport of radionuclides from leaking canisters through minor zones to major flow paths. In all stages, generic 50 m blocks were made in order to describe what was considered typical 50 m blocks within the volume investigated, see Figures 3-4 and 3-5. In the siting stage, generic rock blocks were made for Äspö and Laxemar areas. In the prediction stage an attempt was made to describe 50 m blocks for specified parts of the tunnel, see Figure 3-4. The purpose of this prediction was to see to what extent it is possible to make detailed descriptions of 50 m blocks at positions specified in advance.

The block scale models were refined mainly during the site description and the prediction stage investigations, see Figure 3-2.

Detailed scale modelling

The general purpose of the 5-m detailed-scale models is to describe the rock on a scale of interest after the positioning of deposition holes and for the assessment of the near field rock, including the disturbed zone. However, as the deterministic description of the rock on this scale cannot be made until during the excavation of deposition tunnels, the aim of modelling rock blocks of 5x5x5 m in this project was to develop generic detailed models of different rock types in the Äspö bedrock.

The detailed scale modelling was always made in parallel with block-scale modelling. In all stages, generic 5 m blocks were made in order to describe what was considered typical 5 m blocks within the investigated volume, see Figures 3-4 and 3-5. Each block described one of the four main rock types found in the investigated area, Småland granite, Äspö diorite, greenstone and fine-grained granite. The hydrogeological and chemical characteristics are generic.

3.2.2 Investigation and modelling in the Siting Stage

The first stage of the pre-investigation phase, **the siting stage** (1986 – 1987), included regional investigations based mainly on airborne geophysics and topographical data, see Figure 2-1. Magnetic, electromagnetic, radiometric and gravimetric maps were plotted from the geophysical surveys, while digital terrain models were constructed from the topographical database. The maps were used for structural analysis on a regional scale.

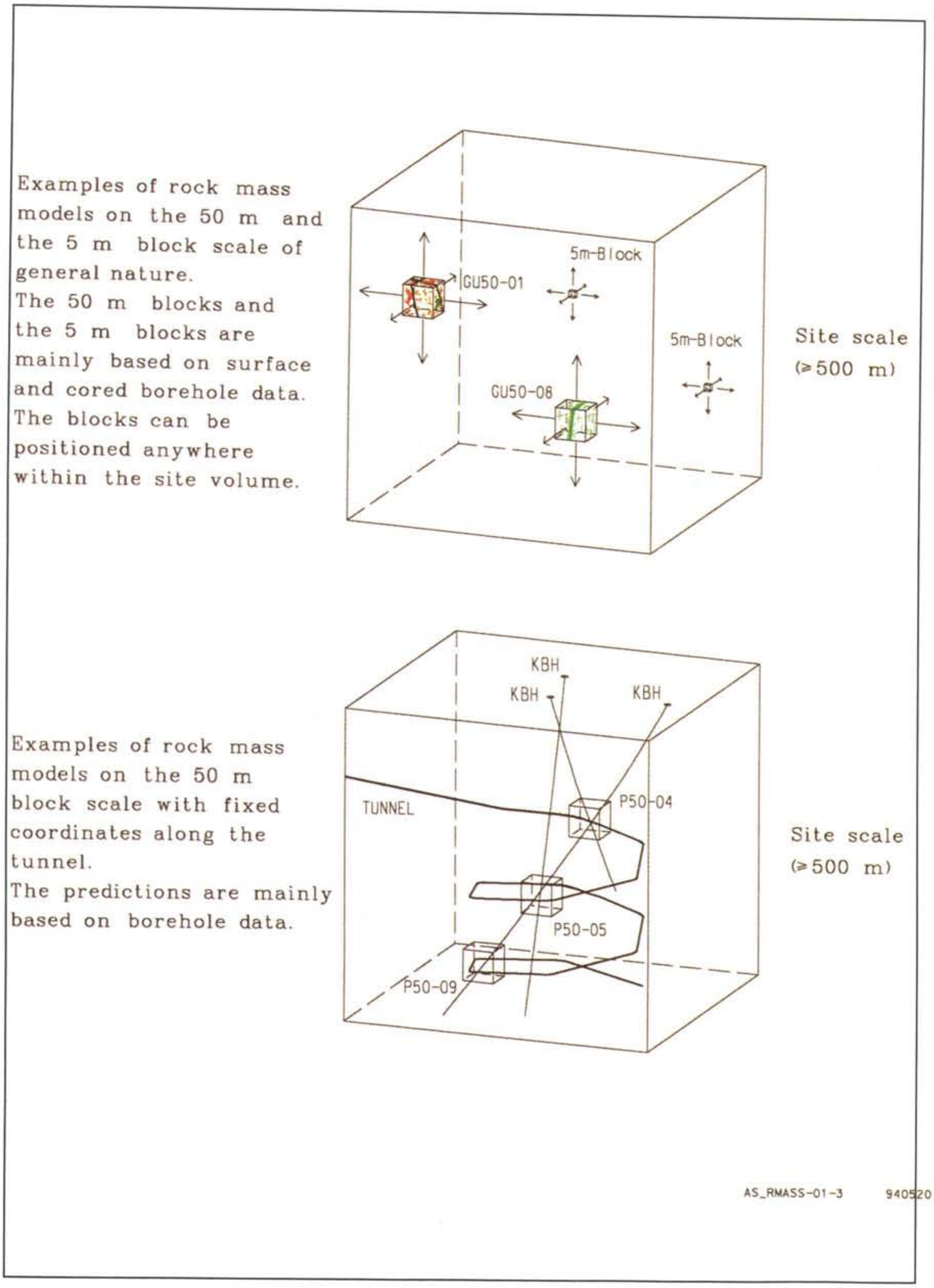


Figure 3-4. *Examples of the position of rock mass models within the site scale:*
- *Generic distributed 50 m and 5 m blocks.*
- *Coordinate positioned 50 m block at prediction stage.*

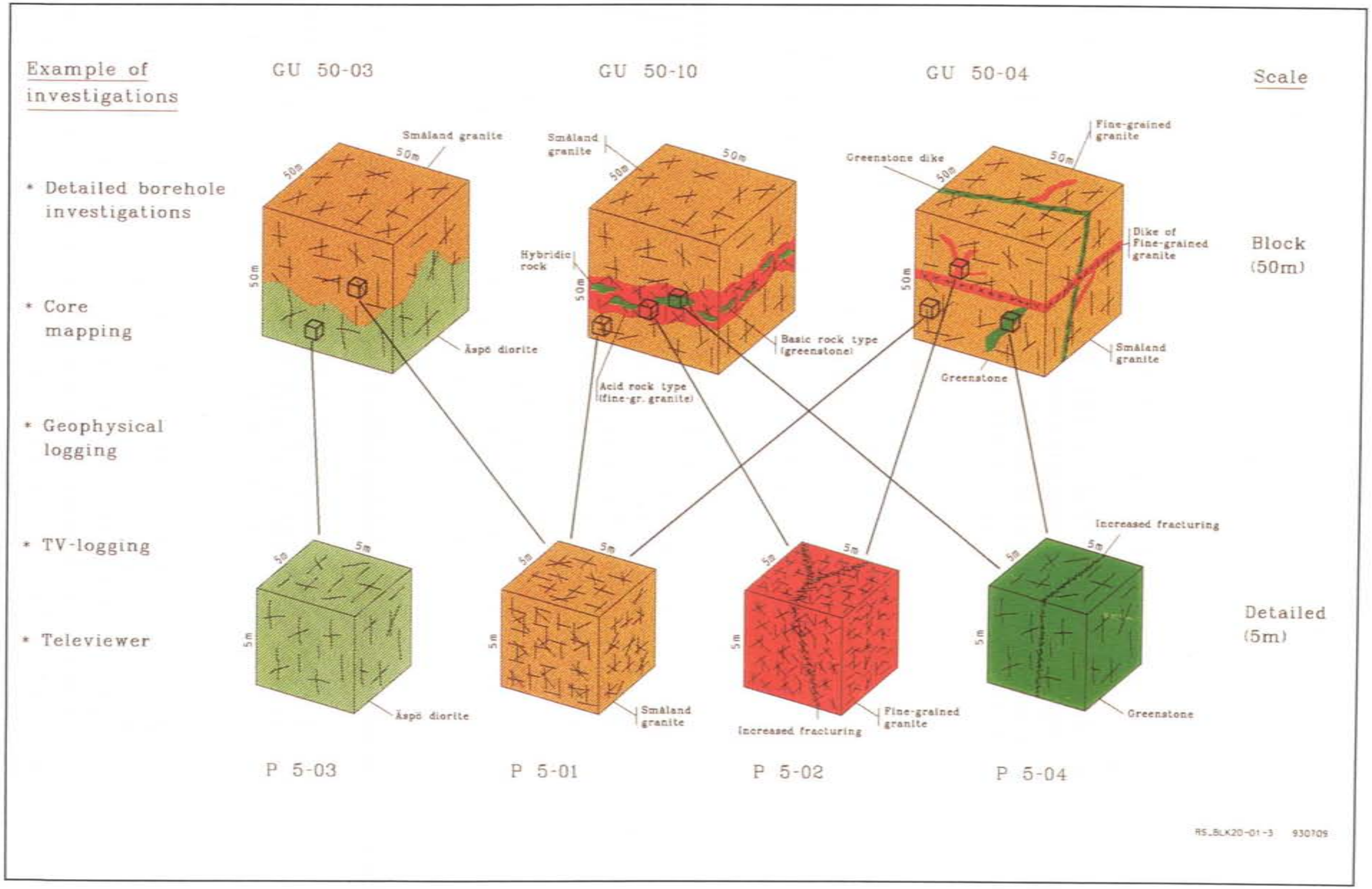


Figure 3-5. Illustration of conceptual modelling in the block scale and the detailed scale.

The siting stage also included investigations from the ground surface of five potential areas for the Hard Rock Laboratory, see Figure 2-1. Geological mapping and geophysical measurements were performed. Shallow percussion holes were drilled in three of the areas, Äspö, Ävrö and Laxemar, with examination of cuttings, geophysical logging, groundwater sampling and hydraulic testing.

The evaluation of the first pre-investigation stage, the siting stage, */Gustafson et al., 1988/* was based on the results of the regional investigations of geology, geohydrology and groundwater chemistry.

Based on data obtained from this first stage, Äspö Island was chosen as a preferential site for the laboratory */Gustafson et al., 1988/*. An important part of the report was the initial geological prediction of Äspö, made before results had been obtained from any cored boreholes.

For the geological-structural model, airborne geophysical (magnetic, electromagnetic and radiometric) measurements were interpreted and lineament interpretation of terrain models was used to identify the major fracture zones and their extent. By means of surface mapping, petrophysical measurements of rock samples and ground geophysics (gravity, refraction seismics etc), different types of geophysical anomalies were identified and the indicated fracture zones were characterized.

The hydraulic character of the rock masses and the fracture zones was evaluated from the data in the well records of Kalmar County in combination with the structural model. Moreover, a number of percussion-drilled holes were tested by single-hole air-lift pumping and interference pumping. A generic groundwater flow model was set up on this basis.

Groundwater chemical data were obtained from the above-mentioned well records and from sampling of percussion-drilled boreholes, resulting in a generic model of groundwater composition for Kalmar County.

3.2.3 Investigation and modelling in the Site Description Stage

In the next stage, **the site description stage** (1987 – 1988), three deep cored boreholes (KAS02, KAS03 and KAS04) were drilled at Äspö, see Figure 2-2. An extensive measurement programme was carried out in the boreholes */Stanfors et al., 1991/*, according to logistics and methodologies as described in *Almén and Zellman /1991/*. In this stage, more detailed geophysical ground surface measurements were performed on Äspö. These included VLF, resistivity, magnetic, radiometric, seismic refraction and reflection measurements. Detailed geological mapping of a surface bedrock profile was carried out as well. Based on the borehole measurements and the surface investigations, revised conceptual models were developed for Äspö */Gustafson et al., 1989/*. One deep cored borehole was also drilled at the Laxemar area, to be used as a reference area.

From this conceptual model of Äspö describing the general lithology, the major structures, the local fracture systems, geohydrological and groundwater chemical characteristics, it was found that the most suitable area on the island was the southernmost part.

The evaluation of the second pre-investigation stage, the site description stage, */Gustafson et al., 1989/* made use of the regional conceptual model in the above report to develop the first site-specific groundwater models. The report also presents the result of the first three deep boreholes and conceptual models based on the data. These conceptual models formed the basis of a new numerical groundwater flow model which was later used to predict the outcome of a long-term pumping test performed in 1989 and to calculate the impact the excavation of the laboratory will have on the ambient groundwater situation.

Geological-structural models were devised from the data obtained from all surface investigations, shallow percussion holes and the deeper cored boreholes KAS02, KAS03, KAS04 and KLX01.

Geohydrological modelling incorporated geohydrological data from the same boreholes.

Geohydrochemical models were set up based on data from analyses of samples from KAS02, KAS03 and KLX01 and from the percussion-drilled boreholes.

3.2.4 Investigation and modelling in the Prediction Stage

The aim of the third stage of the pre-investigations, **the prediction stage** (1989 – 1990), was to perform a more detailed characterization of the southern part of the island and to set up the previously mentioned predictions, see Figure 2-2 */Wikberg et al., 1991 and Gustafson et al., 1991/*. Accordingly, four new deep, cored boreholes were drilled during this stage, KAS05-08, supplemented by five shallow percussion-drilled holes, HAS13-17. The directions and depths of these holes were defined in order to penetrate, determine the direction of, and characterize fracture zones and other important structures or anomalies in the rock mass. Among important borehole measurements, hydraulic interference tests were performed for three-dimensional verification and characterization of major hydraulic conductors.

In this last stage of the pre-investigation phase a number of supplementary boreholes, KAS09-14 and HAS18-20, were also drilled in order to investigate the area of the access tunnel to the Laboratory (in the revised layout the tunnel enters the target rock volume from the south) and to improve the knowledge of some fracture zones on southern Äspö.

At the end of the pre-investigation phase, a large-scale pumping and tracer test was performed in order to simulate the effect of the construction a large underground facility and to verify and characterize the connectivity between major groundwater conductors.

The modelling in the prediction stage included an up-date of the siting-stage models with respect to the data obtained from additional cored holes. In the prediction stage, geological, hydrogeological and chemical modelling was done jointly for the major fracture zones determined in the site description stage. Much emphasis was put on defining the degree of accuracy for the different fracture zones: certain, probable or possible.

The site description stage modelling included an additional investigation of the area between Äspö and Simpevarp, because the entrance tunnel to the underground facility was moved to Simpevarp. The reason for this is that the environmental impact of the construction work is smaller in this case than if the entrance had been located on Äspö.

4 EVALUATION OF THE INVESTIGATION METHODS WITH REGARD TO USEFULNESS FOR THE CONCEPTUAL MODELLING

4.1 EVALUATION PROCEDURE

4.1.1 Basis of the evaluation

Among the strategic decisions taken at the start of the Äspö HRL was the identification of key questions covering all the important aspects of layout, performance assessment and other safety related aspects. All the details of the conceptual models are sorted under these key questions. The key questions as presented in the predictions are – on every scale – geological-structural model, groundwater flow, (groundwater) chemistry, transport of solutes and mechanical stability */Gustafson et al., 1991/.*

Geological-Structural model

The **geological-structural model** represents a simplification of the real physical medium, i e the geometry and character of different rock types and structures of different scales. The geological-structural model also forms the basis of the conceptual models of the geosphere for other disciplines, like geohydrology, etc. The model is also of vital importance for the design of the repository as the repository volume will be selected to avoid major fracture zones. Deposition tunnels and canisters will be positioned to avoid the major flow paths, which may or may not be congruent with the major fracture zones.

Groundwater flow

Groundwaterflow is a key question, as it influences the service life of the (copper) canisters and the dissolution of the spent fuel. The description of the groundwater flow provides a necessary, but not sufficient, basis for calculating the transport of nuclides from the repository to the biosphere if the canisters should fail.

Groundwater chemistry

Groundwater chemistry is a key question as it reflects the chemical situation around a repository. The chemical situation influences the corrosion of the canisters and the dissolution of the waste and provides a necessary, but not sufficient, basis for calculating the transport of nuclides from the repository in case the canisters should fail.

Transport of solutes

Transport of solutes is a key question as it provides a necessary, but not sufficient, basis for calculating radiation doses, which represent the only threat to the environment from a sealed final repository.

Mechanical stability

Mechanical stability is of interest both in a short- and a long-term perspective. Mechanical stability is a necessary condition during construction. The long-term issue is to identify potential zones of instability, so that the repository and canisters will not be affected by movements that may be caused during e.g. a deglaciation.

4.1.2 Outline of the evaluation

The evaluation of the investigation and analysis methods in this chapter is made with regard to feasibility and usefulness for conceptual modelling of the Äspö rock volume. The outline of this evaluation is based on the subjects for which predictions were set up at the end of the pre-investigation phase */Gustafson et al., 1991/*. The subjects are grouped according to the five key questions described in Section 4.1.1. Predictions were made on three of the four geometrical scales which were used for the modelling of the rock, see Table 4-1. (No predictions were made on the regional scale.)

For every subject the process of developing a parameter value is described in this chapter. All methods used in these processes are presented, discussed and judged with respect to precision, usefulness, etc for the modelling and prediction work. In this stage the results of the documentation work during the construction phase have not been taken into account. In chapter 5 the individual methods will be discussed separately.

When the main tunnel of the Äspö HRL is finished, the predictions and the conceptual models will be validated against the outcome of documentation and measurements from the tunnel, shaft and underground boreholes. This validation will in turn be the basis of the final evaluation of pre-investigation methods in the Äspö HRL project.

Table 4-1. Presentation of subjects and scales for which predictions were made at the end of the pre-investigation phase.

Key question	Subject	Regional and site scale	Block scale	Detailed scale
Geological-structural model	- Lithological unit	x		
	- Rock boundaries	x	x	
	- Rock composition		x	
	- Mylonite		x	
	- Rock type charact.			x
	- Fracture systems		x	x
	- Major fracture zones	x		
	- Minor fracture zones	x	x	
	- Single open fractures		x	
Groundwater flow	- Hydraulic conductivity	x		x
	- Water-bearing zone	x		
	- Conductive structure		x	
	- Frequency (T)		x	
	- Flow distribution		x	
	- Head at boundary	x		
	- Pressure in boreholes	x		
	- Flow into tunnel			
	+ total	x	x	
	+ zone	x		
	+ tunnel parts (legs)	x		
	- Groundwater flux	x		
	- Salinity boreholes/legs	x	x	
	- Point leakage			x
	- Disturbed zone			
	+ axial flow and pressure near conductive structure		x	
	+ pressure (conductivity, axial flow)			x
Groundwater chemistry	- Composition of groundwater in major fracture zones of different rock types	x		x
	- Quality changes		x	
	- Redox conditions			x
Transport of solutes	- Flow paths	x		
	- Arrival time	x		
	- Saline interface	x		
	- Natural tracers	x		

Key question	Subject	Regional and site scale	Block scale	Detailed scale
Mechanical stability model	- Rock quality - Rock stress - Long term stability - Mechanical charact. - Fracture surface properties	x x x	x x	 x x

4.1.3 Outline of presentation

The structure of the presentation in chapter 4 is as follows:

4.x **KEY QUESTION** (Geological-Structural model etc).

4.x.x **Subject or group of subjects** under the Key Question (Lithological units – rock composition – ...)

General

General introduction of the subject or group of subjects.

Methods

Presentation and discussion of methods used for evaluating parameter values of the subjects.

Judgement – x scale

Discussion of feasibility and usefulness of the different methods for the characterization, in different modelling scales. The models are judged with regard to the degree of usefulness (very useful, useful, less useful and not applicable) for the Äspö HRL pre-investigation phase. The judgements are presented in tables, one for each subject or group of subjects.

4.2 METHODS FOR THE GEOLOGICAL-STRUCTURAL MODELLING

4.2.1 Introduction

The main purpose of the geological investigations in the initial stage is to give a brief description on a regional scale of the rock type distribution and the structural pattern in the target area. At a later stage, further investigations are performed to characterize the rock mass in greater detail.

The goal is to describe the composition and heterogeneity of a selected rock volume. This includes a precise description of the distribution of rock types, major and minor fracture zones and the fracture geometry and minerals in the rock mass.

In order to describe the geological-structural model a number of subjects were used with reference to different scales. An overview of the subjects is presented in Figures 4-1, 4-4 and 4-5.

4.2.2 Lithological units – rock composition – rock boundaries – mylonite – rock type characteristics – fracture systems (Table 4-1)

General

The conceptualization of a rock mass should always be based on a brief petrographic description, which makes it possible to evaluate geophysical data. The subject "Lithological units" refers to an overall distribution of the main rock units on a regional scale, while "Rock composition", "Rock boundaries", "Mylonites", "Rock type characteristics" and "Fracture systems" refer to a more detailed description of small-scale structures and petrographic variation on the block and detailed scales, see Figure 4-6. "Rock type characteristics" refers to the mineralogical composition and petrophysics of the four most frequent rock types in the Äspö area: Småland Granite, Äspö diorite, Fine-grained granite and Greenstone. The predicted blocks should mainly be regarded as typical examples of these four rock types. */Sehlstedt et al., 1990, Kornfält and Wikman, 1987/.* Judgement of usefulness of the different investigation methods is presented below and summarized in Table 4-2.

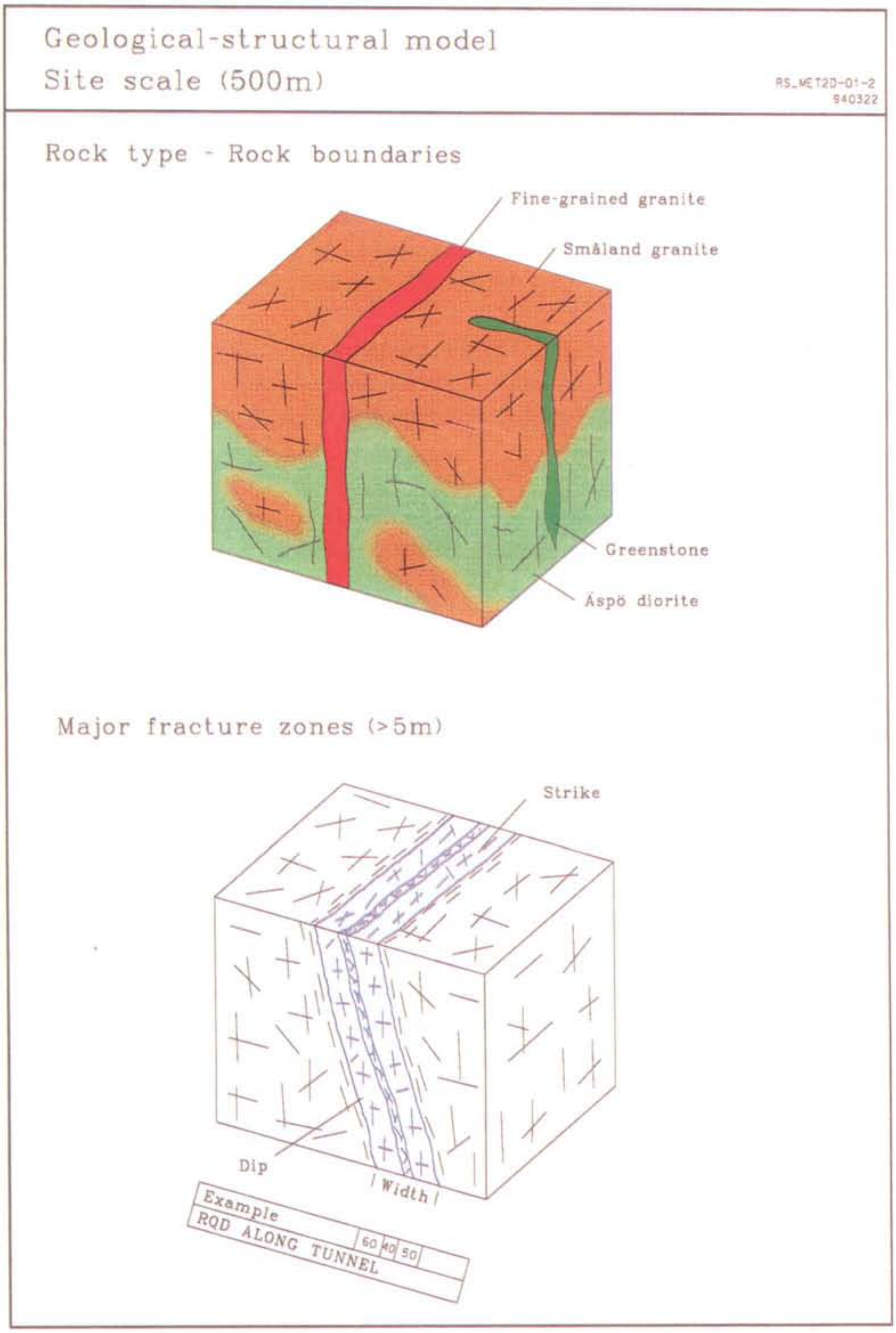


Figure 4-1. *Overview of the subjects Lithological unit, Rock boundaries and Major fracture zones of the geological-structural model, addressed in the site scale.*

Table 4-2. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness: Regional, Site scale	Usefulness: Block scale	Usefulness: Detailed scale	Notes
Rock type/ rock boundaries	**Airborne geophysics**				
	- Magnetic	3	-	-	
	- VLF	-	-	-	
	- EM	-	-	-	
	- Radiometric	1	-	-	
	Petrophysical measurements*	2	2	2	**Necessary for evaluation of geophysical data*
	Gravity measurements	2	-	-	
	Geological overview surface mapping	3	-	-	
	Core mapping	3	3	3	
	Geophysical borehole logging				
	- Sonic	2	2	2	
	- Magnetic susceptibility	2	2	2	
	- Gamma-gamma	2	2	2	
	Percussion borehole investigations				
	- Drilling rate	1	1	-	
	- Examination of drill cuttings	1	1	-	
	Geological detailed surface mapping	-	3	3	
Rock composition/ mylonite	**Geological detailed surface mapping**	-	3	3	
	Core logging	-	3	3	
	Geophysical borehole logging				
	- Sonic	-	2	2	
	- Magnetic	-	2	2	
	- Gamma-gamma	-	2	2	
	Petrophysical measurements				
	- Density	2	2	2	
	- Susceptibility	2	2	2	
	- Porosity	1	1	1	
Rock type/ characteristics	**Mineralogical investigations of rock samples**	-	-	3	
	Core mapping	-	-	3	
	Geophysical borehole logging				
	- Sonic	-	2	2	
	- Magnetic	-	2	2	
	- Gamma-gamma	-	2	2	
	Petrophysical measurements				
	- Density	-	2	2	
	- Susceptibility	-	2	2	
	- Porosity	-	2	2	
Fracture systems	**Absolute orientation of fractures in boreholes**				
	TV logging	-	2	2	
	Televiewer	-	2	2	

Very useful = 3 Useful = 2 Less useful = 1 Not applicable = -

Methods

Airborne geophysics

Airborne magnetic, electromagnetic and radiometric investigations gave an initial general idea of the distribution of the major rock types on this scale – especially between granite and older rocks, basic intrusions and diapirs of younger granite. */Nisca, 1987/.*

Petrophysical measurements

Petrophysical laboratory measurements of rock samples supplemented by an overview surface mapping described below contributed to the evaluation of the aerophysical data for the regional map of the main rock extent. The measurements comprised density, magnetic susceptibility and IP (induced polarization). In a later stage of the investigation density and porosity measurements were used to distinguish between Småland granite and Äspö diorite. */Nisca, 1988/.*

Gravity measurements

Gravity data confirmed the depth extent especially of diapiric younger granites and bodies of basic rocks. */Nylund, 1987/,* see Figure 4-3.

Overview surface mapping

Data from overview surface mapping of road cuts, quarries and major outcrops combined with information from available geological maps make it possible to compile a brief description of the main rock units on a regional scale. */Kornfält and Wikman, 1987/.*

Analysis

Integrated analysis of data from the above described methods resulted in an initial regional description of the main rock units, see Figure 4-2.

Borehole investigations

Mapping of solid rocks on the surface contributed to a good understanding of the two-dimensional extent of the main rock types. In order to get a three-dimensional lithological model borehole, investigations were performed, comprising core mapping and geophysical logging.

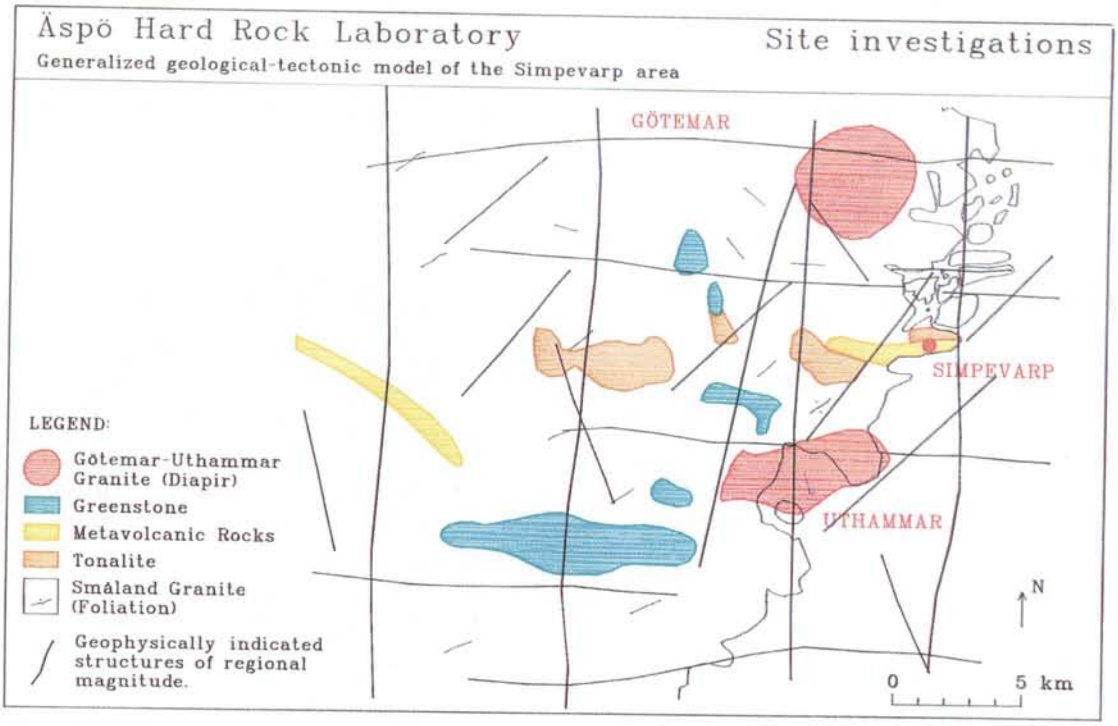


Figure 4-2. *Extent of rock units on a regional scale. /Wikberg et al., 1992/.*

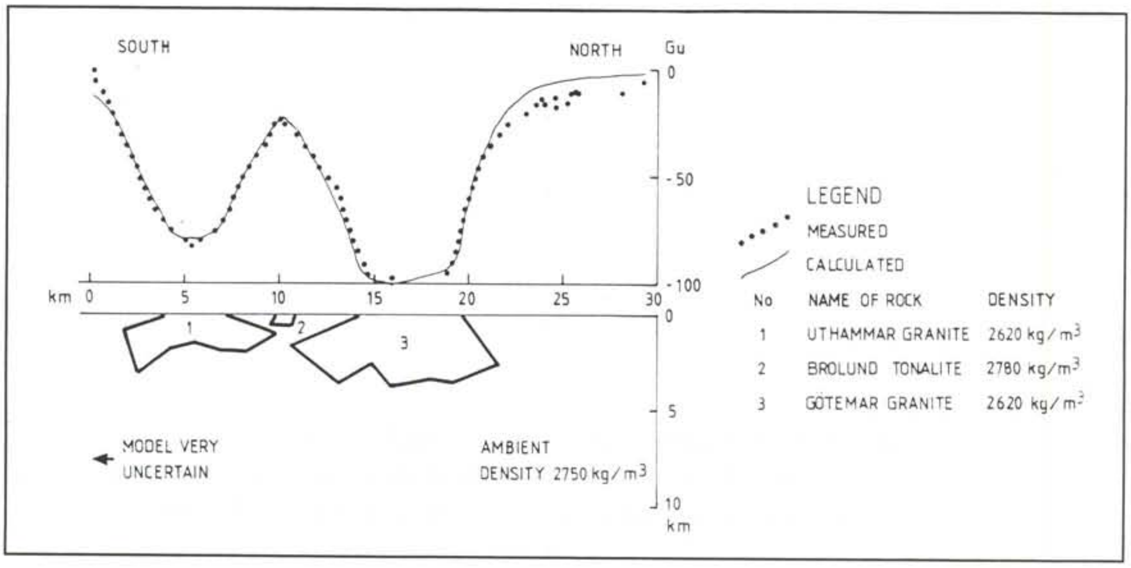


Figure 4-3. *Computed gravity model along a 30 km long profile across the investigated Simpevarp area. /Nisca, 1987/.*

Geological-structural model

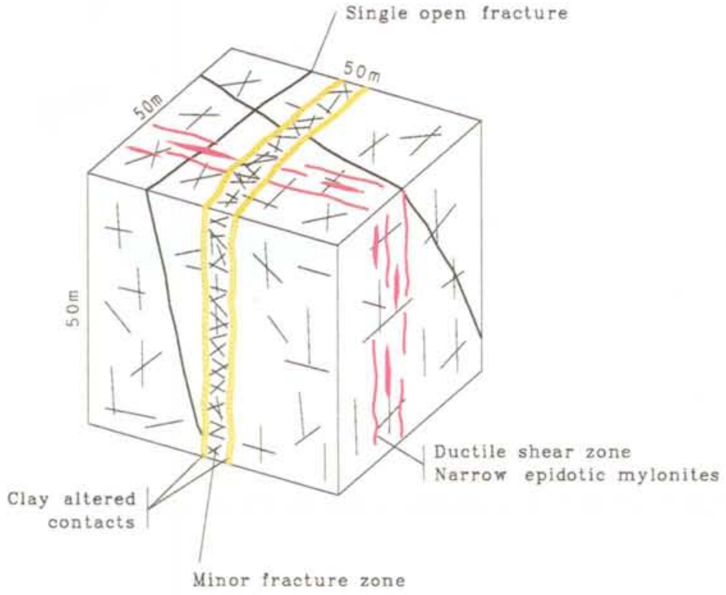
Block scale (50m)

RS_MET2D-02-2
940322

Single open fractures

Mylonite

Minor fracture zones (<5m)



Rock composition

Occurence and extension of greenstone and fine-grained granite in host rock

Rock boundaries

Number of rock boundaries

Fracture system

Main fracture set orientation

Figure 4-4. *Overview of the subjects Single open fractures, Mylonite, Minor fracture zones, Rock composition, Rock boundaries and Fracture systems of the geological-structural model, addressed in the block scale.*

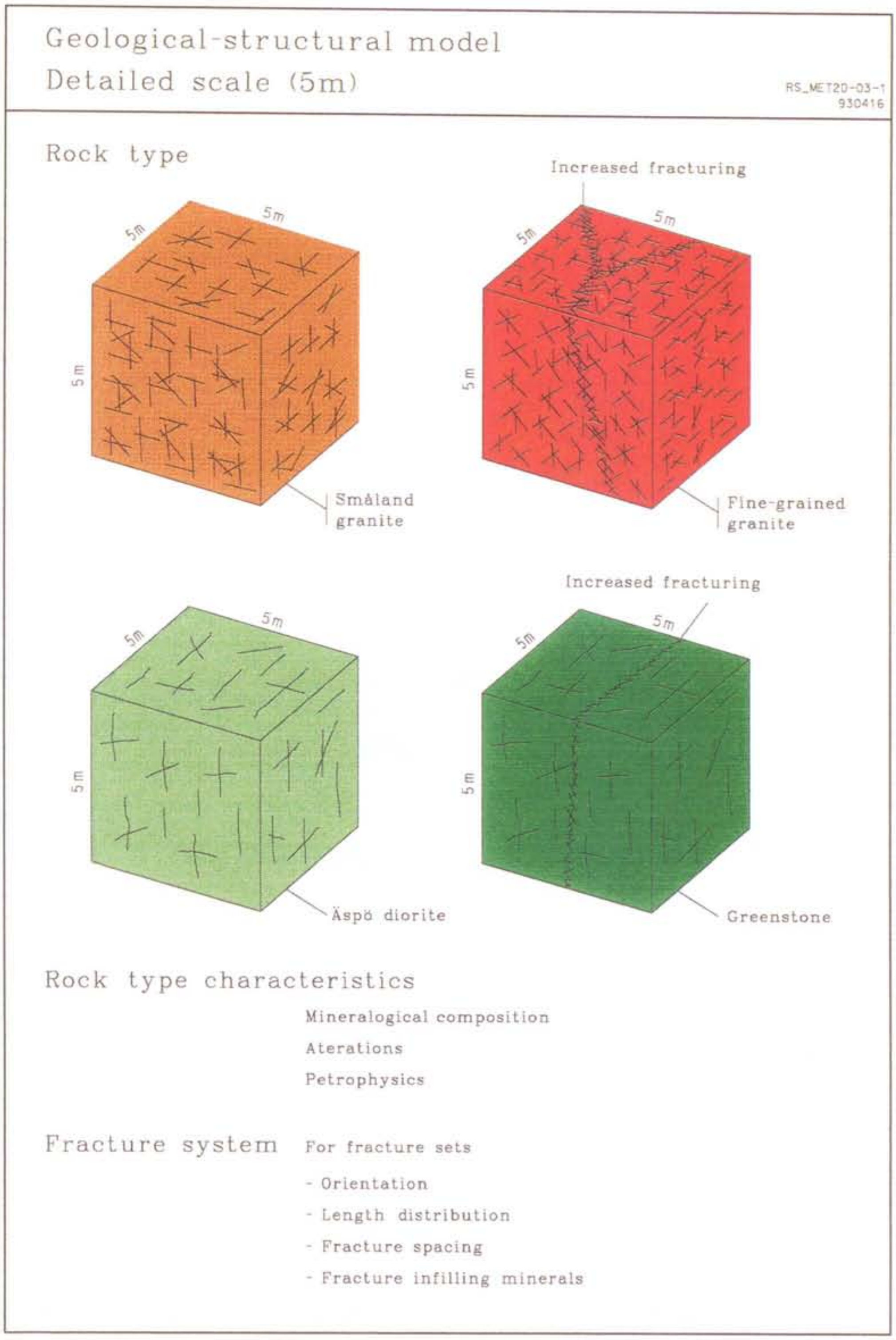


Figure 4-5. *Overview of the subjects Rock type characteristics and Fracture system of the geological-structural model (for the four main rock types), addressed in the detailed scale.*

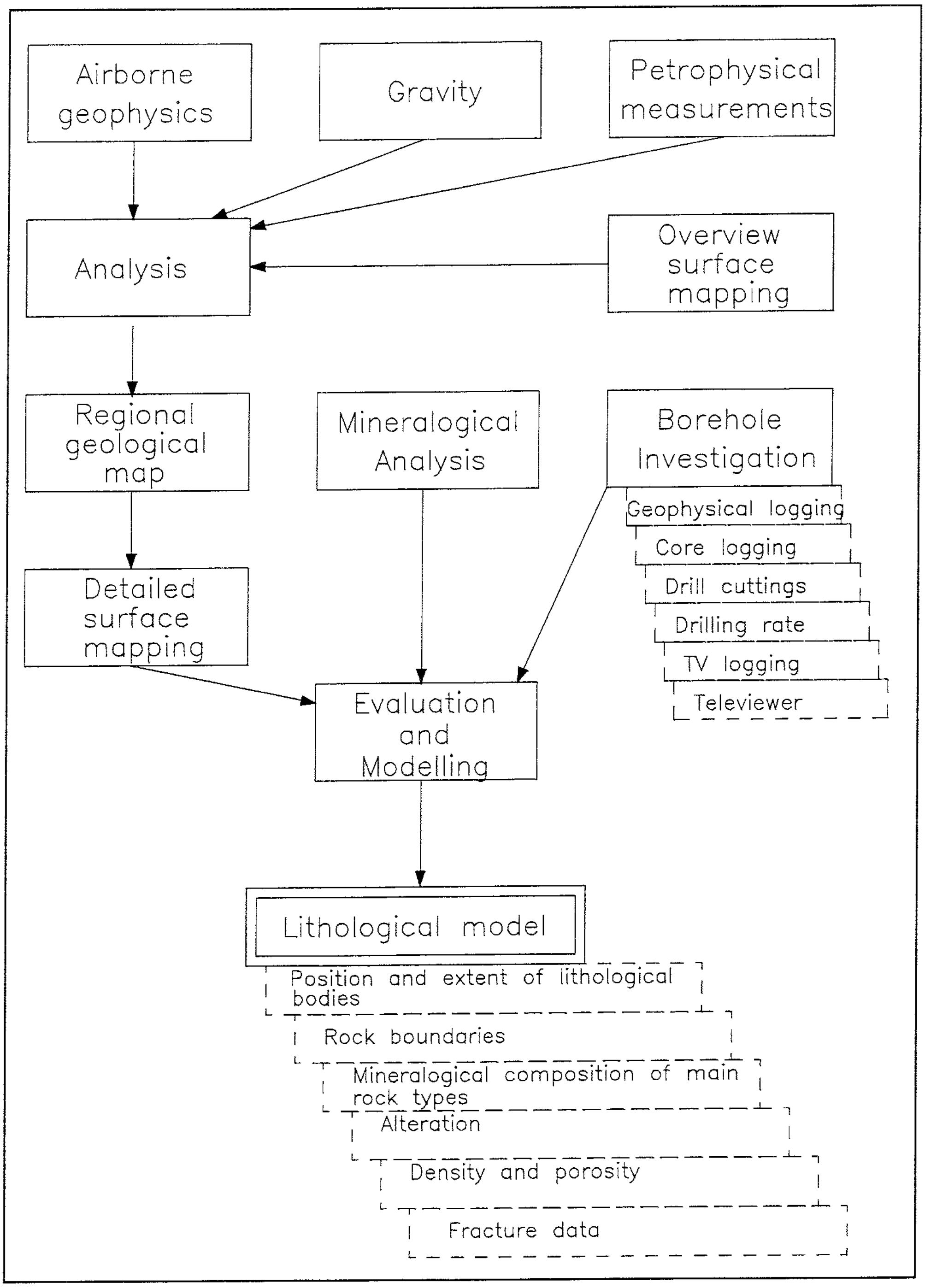


Figure 4-6. *Pre-investigation methodology. Lithological characterization.*

Geological documentation of cored and percussion drilled holes

The drill cores were mapped and gave information on rock type, rock boundaries, mylonites and fracturing. This information contributed to the 3D modelling of the rock mass. Geophysical logging data were used as a complement to the core mapping.

During drilling of the percussion boreholes, feed pressure and drilling rate were recorded continuously. The drilling rate was measured in a very simple manner. The time for every 20 cm of advance was determined, providing an adequate resolution for this purpose. Samples of the drill cuttings was examined with a binocular microscope for rock type classification. */Stråhle, 1988/.*

Geophysical logging

The complete geophysical logging program carried out generally in the boreholes comprised the following logging methods:

- gamma-gamma (density),
- neutron (cored boreholes only),
- borehole deviation,
- caliper (cored boreholes only),
- sonic,
- natural gamma,
- single-point resistance,
- self potential (SP),
- magnetic susceptibility,
- normal resistivity (1.6 m),
- lateral resistivity (1.6-0.1 m),
- temperature,
- borehole fluid resistivity.

Geophysical borehole logging – especially the sonic log, natural gamma, magnetic susceptibility and gamma-gamma logs – are relevant for lithological characterization of the rock mass.

The rock type classification was mainly based on density logging combined and checked by thin section analyses of the core */Sehlstedt & Stråhle, 1989/.*

Detailed surface mapping

Detailed surface mapping along cleaned trenches crossing the main direction of foliation gives very good information on rock boundaries small-scale structures, mylonites and petrographic variations of the main rock types. The method is comparatively cheap and also gives valuable fracture data. */Kornfält and Wikman, 1988/.*

Mineralogical investigation of rock samples

Sampling of the main rock types was done on the surface and on drill cores. The rock type characterization is based on microscopical investigations and chemical analysis of rock samples. Modal analysis was used for classification of the main rock type */Kornfält and Wikman, 1987 and 1988/.*

Judgement – Site scale

The gravity and aeromagnetic methods were found to be very useful, especially for studies of a regional nature, i.e. for investigating the boundaries of the Götemar-Uthammar diapirs in three dimensions and the basic rocks of large extent. The densities and magnetic contents of these granitic rocks usually differ from those of the surrounding rocks, and they were therefore good targets for both of these methods. Based on these investigations it was possible to carry out an initial three-dimensional lithological-tectonic modelling on the regional scale.

The petrophysics, based on physical measurements in the laboratory of a large number of representative samples, is necessary for making a good interpretation of the geophysical data.

Judgement – Block scale

The sonic log and the magnetic susceptibility and gamma-gamma logs seem to be very relevant for the lithological characterization of a heterogeneous rock mass such as the one in the Äspö area. There is in particular a significant correlation between high gamma radiation and the fine-grained granites in the boreholes.

A combination of the density (gamma-gamma) and magnetic susceptibility logs was preferred for the rock type classification.

Judgement – Detailed scale

Detailed geological mapping on the surface combined with drill core analysis are the best methods to investigate rock composition, rock boundaries and mylonites on the block scale. The density borehole log gives the best information concerning the difference between Småland granite and Äspö diorite. Microscopic examination of thin sections supplemented with chemical analysis is the best way to make rock type characterization and classification.

4.2.3 Major fracture zones

General

One of the main tasks in the characterization of a rock mass is to investigate which of the geological structures will have the most important rock-mechanical and hydraulic significance, see Figure 4-8.

Of a great many structures mapped on Äspö the term "Major fracture zone" is used for a feature with a width of more than about 5 m and an extent of several hundred metres where the frequency of natural fractures is at least two times higher than the mean fracture frequency in the surrounding rock. A judgement of the usefulness of the different investigation methods is presented below and summarized in Table 4-3.

Table 4-3. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness			Notes
		Regional, Site scale	Block scale	Detailed scale	
Major fracture zones	**Airborne geophysics**				
	- Magnetic	3	-	-	
	- VLF	2	-	-	
	- EM	2	-	-	
	- Radiometric	-	-	-	
	Interpretation of lineaments	3	-	-	
	Ground geophysical profiling				
	- VLF*	2	2	-	* Disturbed by saline water
	- Magnetic	2	2	-	
	- Seismic refraction	3	3	-	
	Structural geological mapping	3	3	-	
	Seismic reflection	1	-	-	
	VSP	2	-	-	
	Ground radar investigation	2	2	-	** Restricted due to saline water
	Borehole radar measurements**	1	1	-	
	Geophysical borehole logging				
	- Sonic log	2	2	-	
	- SP log	2	2	-	
	- Caliper	2	2	-	
	- Resistivity	2	2	-	

Very useful = 3 Useful = 2 Less useful = 1 Not applicable = -

Methods

Airborne geophysics

Geophysical data – especially magnetic and electric – obtained by aerial survey were used to interpret the location and character of presumed major fracture zones. */Nisca, 1987/.*

Interpretation of lineaments

Lineaments in the Simpevarp area have been interpreted from four different digital terrain models processed using EBBAII image analysis techniques, see Figure 4-7.

The aerophysical results – which were also processed using this system – have been compared with the results from the digital terrain models. */Tirén et al., 1987/.*

Ground geophysical profiling

Ground geophysical profiling was used to confirm the aerophysical and topographic indications of major fracture zones. Low magnetic intensity due to oxidation, VLF anomalies and low seismic refraction velocities contributed to the characterization of the fracture zones. */Stenberg and Sehlstedt, 1989/.*

Structural-geological mapping

Fracture mapping and a structural characterization study of the main fracture zones were performed based on analyses of terrain features, geophysical data and topographical contour maps. */Ericsson, 1987, Talbot et al., 1988, Talbot and Munier, 1989/.*

Seismic reflection

Two seismic reflection profiles were recorded across Äspö Island for the main purpose of testing the ability of this method to map especially low-dipping and horizontal fracture zones in crystalline bedrock. */Plough and Klitten, 1989/.*

Ground radar investigation

Three ground radar N-S striking profiles were measured in the southern part of Äspö in order to test the ability of this method to locate shallow low-dipping fracture zones.

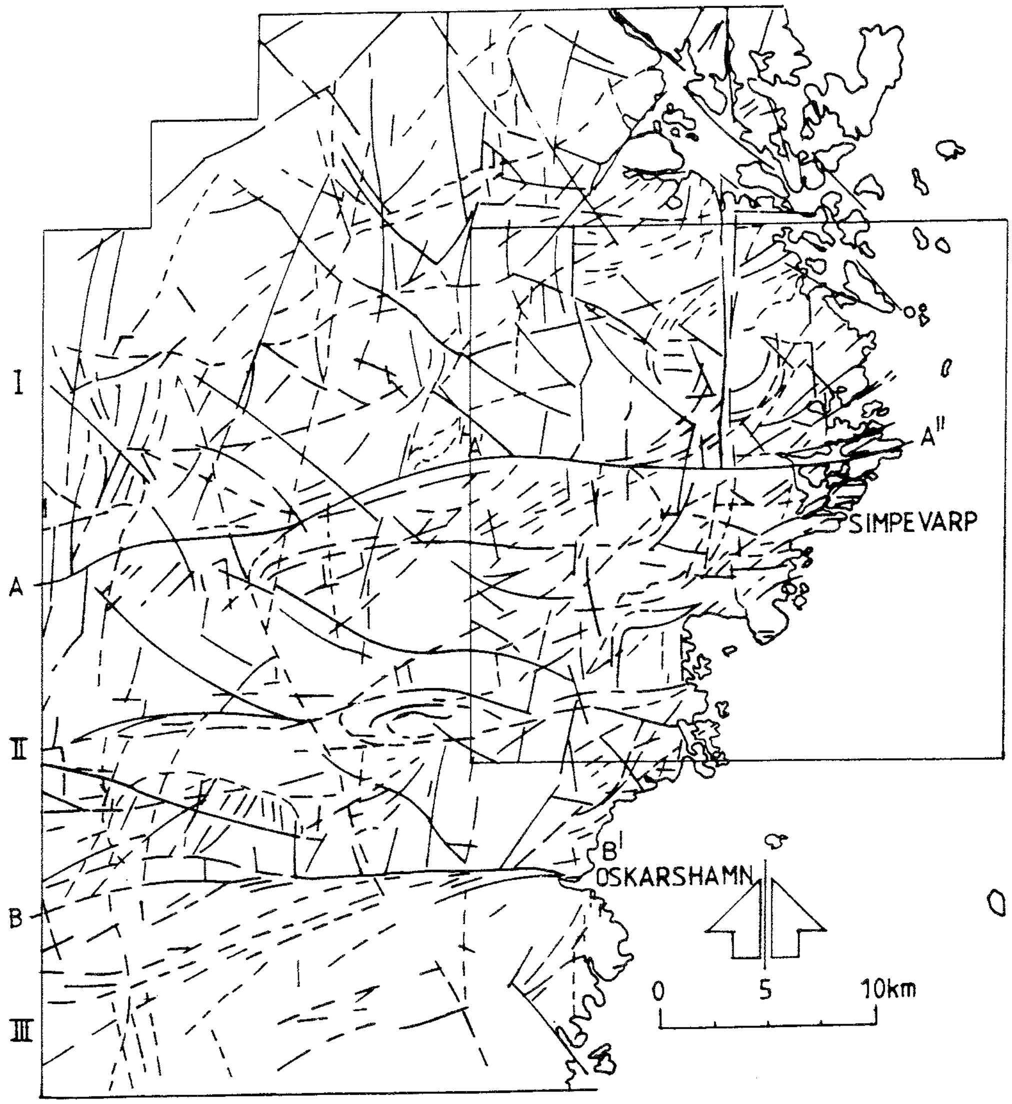


Figure 4-7. Lineament interpretation.

Borehole investigations

Geological structural analysis contributed to a rather good understanding of the two-dimensional extent of the major fracture zones in the Äspö area. In order to get a three-dimensional model of the major fracture zones and to characterize them, a core drilling program was carried out in three different campaigns. Core mapping gave information on fracturing and rock quality of the fracture zones. */Sehlstedt and Triumf, 1988/.*

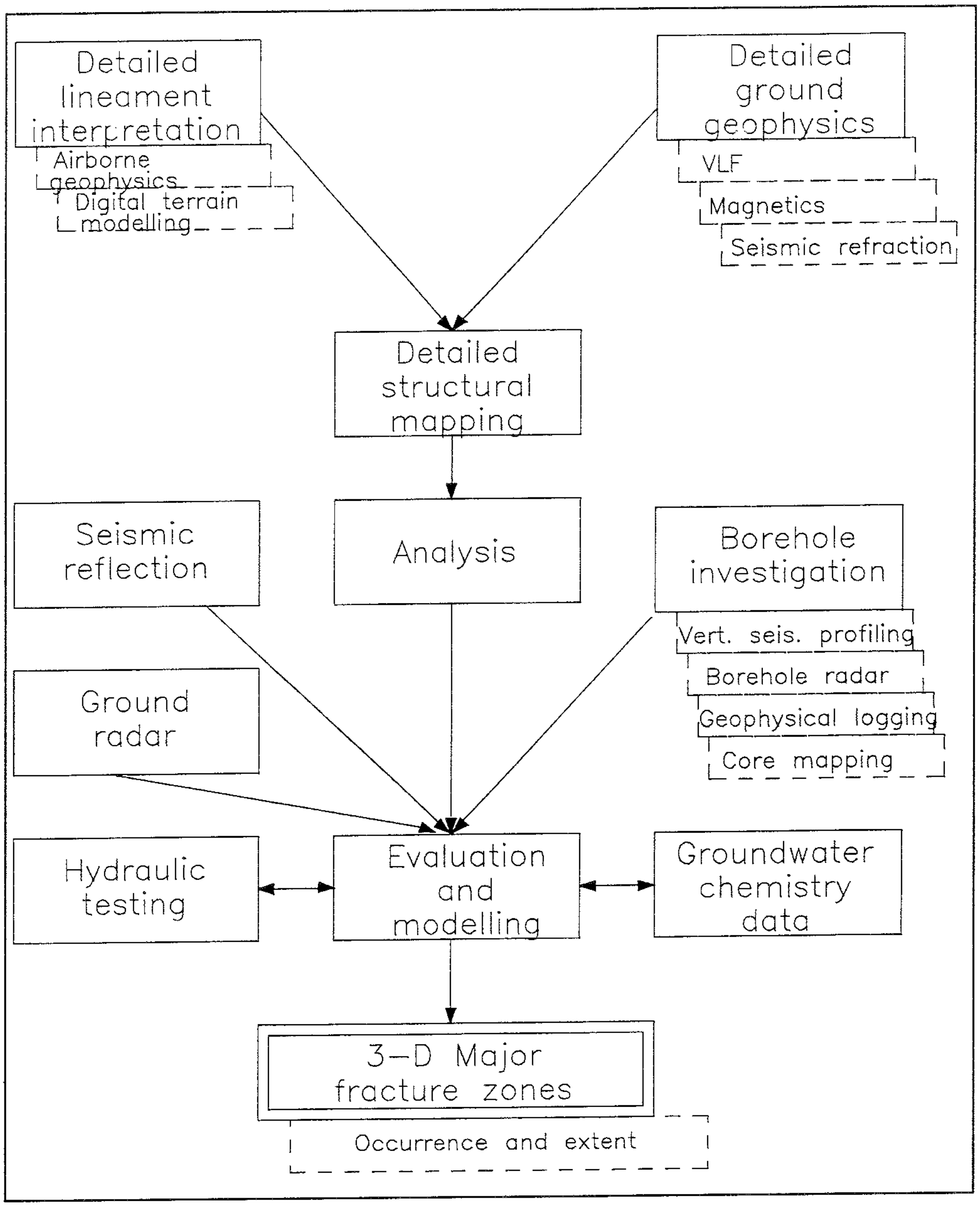


Figure 4-8. *Pre-investigation methodology. Structural-geological characterization. Major fracture zones.*

Geophysical logging

The complete geophysical logging program carried out generally in the boreholes comprised the following logging methods:

- gamma-gamma,
- neutron (cored boreholes only),
- borehole deviation,
- caliper (cored boreholes only),
- sonic,
- natural gamma,
- single-point resistance,

- self-potential (SP),
- magnetic susceptibility,
- normal resistivity (1.6 m),
- lateral resistivity (1.6-0.1 m),
- temperature,
- borehole fluid resistivity.

The aim of the "major fracture zone" interpretation was to describe the geophysical logging data in terms of fracturing and hydrogeology. The sonic logging, single point resistance, normal resistivity, caliper and self-potential methods were mainly used for delineation and classification of fracturing in cored borehole walls.

Borehole radar measurements

Borehole radar measurements were made in all the cored boreholes in order to get information on the orientation of the fracture zones. The radar measurements were performed as single-hole measurements using omni-directional dipole antennas with a 22 Mhz frequency or directional radar antenna using a 60 Mhz frequency. */Niva and Gabriel, 1988 and Carlsten 1989, 1990/.*

Vertical seismic profiling (VSP)

As a complement to the borehole radar investigation, a VSP survey was carried out in borehole KAS07 on southern Äspö down to a depth of 410. */Cosma et al., 1990/.*

Judgement – Site scale

The aeromagnetic method was very useful on the regional scale for mapping possible major fracture zones in which oxidation of magnetite to non-magnetic minerals can cause magnetic minima. Aeromagnetic and VLF measurements seem to be far superior to the EM measurements for interpretation of possible fracture zones. Coincident magnetic and VLF fracture zones may be of special interest in the search for the most permeable major fracture zones. It is important, however, to check the aerogeophysical data with ground investigation methods before final interpretation. The VLF measurements, however, are greatly disturbed by the salt water in the coastal area outside Simpevarp.

Lineament interpretation of relief maps and structural analysis based on different digital models on a regional scale seem to be a very good basis for further site investigation work, especially when this interpretation has been compared with the topographic expression of aeromagnetic lineaments.

The reflectors indicated using the seismic reflection method can only in part be correlated with zones with increased frequency of low-dipping fractures in drill cores. The correlation seems to be greatest for reflectors at greater depths judging from borehole indications. To be useful in detecting fracture zones with low dips, much more development of both field techniques and data processing is needed before this method can be regarded as practicable for fracture zone identification in crystalline rocks.

Judgement – Site scale and Block scale

Ground geophysical methods were useful on the site scale for more detailed investigations of major fracture zones in some areas. The VLF method may, under favourable circumstances (though it is greatly disturbed by the salt water), indicate water-bearing fracture zones. As a complement to the VLF, resistivity and magnetic measurements, which were partly severely disturbed by man-made installations and saline water, seismic refraction has been very useful in locating, and characterizing fracture zones.

Ground radar measurement data gave some interesting correlations with borehole radar reflections from structures/rock contacts, but further development is needed before this method can be regarded as a useful complement to seismic reflection, VSP and borehole radar for identification of low-dipping fracture zones.

Single-hole radar reflections give valuable information on the orientation of fracture zones – especially those intersecting the borehole at rather low angles. A number of prominent structures were indicated in the boreholes using the directional antenna and dipole antenna radar measurements, which corroborated the presumed orientation of most of the major fracture zones and some of the minor zones interpreted.

VSP results from KAS07 were found to be important as a complement to the borehole radar data, especially after three-dimensional processing using a new technique with Image Space filtering, which has been developed for seismic reflection studies in crystalline rock.

The results form the caliper log, and the electric logs were of greatest interest in detecting fractures and fracture zones. It seems, however, to be rather unnecessary to use three different electric logs which give largely identical results, so in most of the geophysical logging surveys, only the single-point resistance log was used. Analysis of structural mapping, combined with lineament data and geophysical data, is very important in final location and characterization of major fracture zones.

4.2.4 Minor fracture zones and single open fractures

General

When mapping structures in the Simpevarp area the term "Minor fracture zone" is used for a feature with a width of less than about 5 m. On southern Äspö steeply dipping structures of this kind have been found to have an enechelon character and an extent of less than about 100 m. They are often good hydraulic conductors, see Figure 4-9.

The term "Single open fracture" is mainly used for persistent open fractures – up to 1 dm wide – which have been found to be important hydraulic structures on southern Äspö. They seem to anastomose in an en-echelon pattern – like the minor fracture zones – across the Äspö-Hålö area. Judgement of the usefulness of the different investigation methods is presented below and summarized in Table 4-4.

Table 4-4. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness			Notes
		Regional, Site scale	Block scale	Detailed scale	
Minor fracture zones/ Single open fractures	**Seismic refraction**	3	3	-	
	Detailed geological mapping	3	3	-	
	Core mapping	2	2	-	
	Geophysical borehole logging				
	- Caliper	2	2	-	
	- SP	2	2	-	
	- Resistivity	2	2	-	
	Borehole radar*	2	2	-	*Restricted due to saline water
	VSP	2	2	-	
	Detailed geophysical mapping				
	- Magnetic	2	2	-	
	- Resistivity**	2	2	-	**Disturbed by saline water
	- VLF**	2	2	-	
	Absolute orientation of fractures in boreholes				
	- TV-logging	-	2	-	
	- Televiewer	-	2	-	

Very useful = 3   Useful = 2   Less useful = 1   Not applicable = -

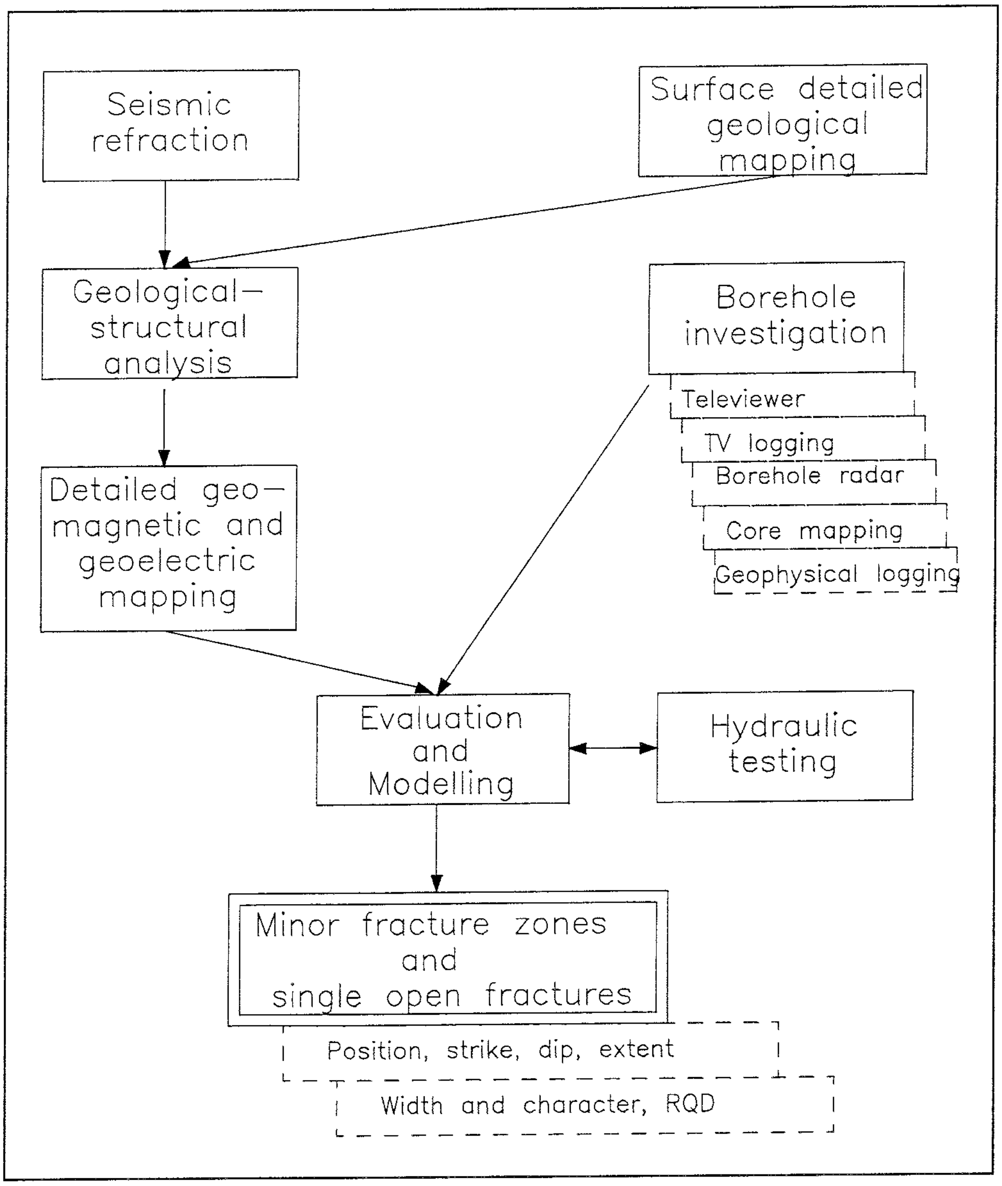


Figure 4-9. *Pre-investigation methodology. Structural-geological characterization. Minor fracture zones.*

Methods

Seismic refraction

As a complement to the electric and magnetic measurements, which were partly severely disturbed by man-made installations and saline water, seismic refraction has been used to locate minor fracture zones on Äspö. */Sundin, 1988 and Rydström et al., 1989/.*

A 22-channel seismic instrument of SEMAB type was used in these investigations and the signals were generated by explosives.

The investigations on southern Äspö were performed with geophones at 2.5-m centres and shot points at about 12.5-m centres, especially in order to detect minor, narrow fracture zones.

Detailed geological mapping

Very detailed mapping was performed along cleaned trenches across the island. A geological map to a scale of 1:2000 was prepared, and a classification of the rocks based on chemical and mineralogical analyses is presented.

As a supplement to the structural/geological mapping on outcrops and roadcuts, a study of structural elements, including a fracture mapping programme, was performed along the trenches to obtain results for use in geohydrological and rock mechanics model studies. Data concerning 4500 mapped fractures – such as orientation, length, aperture and fracture filling – are presented. */Kornfält and Wikman, 1988/.*

Borehole investigations

The cored borehole KAS13 was drilled in a direction which was specially intended to locate NNW-trending minor fracture zones indicated on southern Äspö. Core mapping data and borehole radar measurements in KAS13 complemented the results from a VSP survey (KAS07) and confirmed the geological and geophysical indications from surface investigations. */Stråhle, 1988/.*

A number of geophysical borehole logs were used in order to detect and characterize minor fracture zones and single open fractures. To obtain their absolute orientation, TV logging and Televiewer measurements were performed. */Fridh and Stråhle, 1989/.*

Detailed geomagnetic and geoelectric mapping

As a part of the investigation of the structural pattern of Äspö, detailed ground magnetic and electric mapping were carried out. Magnetic measurements were made every fifth metre along profiles in an east-west direction, with profiles at 10 metre centres in the geomagnetic survey and at 40 metre centres in the geoelectric survey. Different geometrical arrangements of currents and potential electrodes can be used in geoelectrical mapping. In order to effectively map relatively narrow zones (2 m thick), and low-resistivity zones near the surface, a 5-10-5 metre dipole-dipole configuration was used.

A combined analysis of geomagnetic and geoelectric data has been carried out, especially with respect to fracture zone delineation. */Nisca and Triumf, 1989/.*

Judgement – Site scale

The seismic refraction profiles on Äspö were performed mainly to check topographic and geophysical lineaments indicating possible minor fracture zones on the site scale. The thickness of the overburden along these profiles is nowhere calculated to exceed 10 m and a number of pronounced – mostly only some metres wide – low velocity zones (2000-3500 m/s) were recorded. These indications correspond in most cases very well to other indications of narrow fracture zones.

In order to investigate the pattern of the minor fracture zones and the boundaries of the different bedrock units on a more detailed scale, ground geophysical measurements were made over the entire island of Äspö. The combination of detailed geoelectric and geomagnetic data provided very good basic information concerning the possible extent and orientation of fractures and fracture zones, but it is very important to try to correlate the geophysical indications with geological features in the field. Most VLF measurements were strongly disturbed by the saline water and man-made installations in the Äspö area and have for this reason not been very useful.

To check the correlation between the ground geophysical indications (magnetic and resistivity) and structures seen on the ground, a systematic investigation was performed along the trenches. A very good correlation (more than 80%) was found, especially between magnetic indications and different geological structures, However, it is interesting to note that only about 25% of the correlated structures were fracture zones and that as many as 15% apparently corresponded to "single fractures".

Judgement – Block scale

The correlation between magnetic indications and "single fractures" is in very good agreement with the results from a very detailed ground susceptibility study along the cleaned trench on southern Äspö. Increased susceptibility values for zones up to some metres wide were found in red stained zones close to these fractures, probably due to oxidation of the magnetite in the bed-rock.

Recognition of small-scale structures, such as minor fracture zones and single open fractures, and their orientation within and near the site area on Äspö was achieved by means of detailed surface mapping along cleaned trenches across the island. The results of these investigations, complemented with subsurface information, have been very useful in the geological characterization of rock volumes in the site area.

Single-hole radar reflections give valuable information about the orientation of minor fracture zones – especially those intersecting the borehole at rather low angles. A number of prominent structures were indicated in the boreholes using the directional antenna and dipole antenna radar measurements which corroborated the presumed orientation of some of the minor zones interpreted.

VSP results were found to be important as a complement to the borehole radar data, especially after three-dimensional processing using a new technique with Image Space filtering, which has been developed for seismic reflection studies in crystalline rock.

The results of the caliper log and the electric logs were of greatest interest in detecting fractures and minor fracture zones.

The use of the TV logging and Televiewer methods for absolute orientation of fractures in core boreholes was accompanied by many problems. It is, for example, very difficult to identify the same feature in the core as in the TV log and Televiewer records, due to less exact depth measurements. This seems to be a general problem which concerns all measurements, especially in deep boreholes.

From our experience of the different orientation methods available today it is obvious that it is very difficult to obtain a reliable picture of the orientation of fractures at depth using borehole information only.

4.3 METHODS FOR THE GEOHYDROLOGICAL MODELLING

4.3.1 Introduction

The purpose of the geohydrological investigations is to sample data needed for the calculations of the groundwater flow within a repository volume, both during construction of the repository and during the operational phase. In order to carry out these calculations we need the flow properties for the volume, such as the **transmissivities of major conductive zones** and the **hydraulic conductivity** or **transmissivity of fractures in the rock between the major zones**. The two latter properties have to be described statistically, as we don't think it is possible to identify minor conductive structures (zones) and fractures deterministically. We also need to know the **boundary conditions** for the volume. In this case we need to know the hydraulic head or gradient at the model boundaries. In order to evaluate pumping tests (to get transmissivities) and calibrate numerical groundwater flow models, we need to measure the **pressure and salinity** at different points within the volume. It is also useful to estimate the **groundwater flux** for calibration of the numerical model. Much of the above data is collected during the pre-investigations.

Investigations will continue during the construction of the repository. Some of them will be similar to those carried out during the pre-investigations, as for example pressure measurements in the boreholes, and some will be new. However, the methods used during the construction phase will not be presented in this report, and the subjects are only briefly outlined below.

An overview of the methods and their usefulness for modelling and predicting geohydrology of the Äspö site is presented in the following sections and summarized in Table 4-5.

Table 4-5. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness		
		Regional, Site scale	Block scale	Detailed scale
Water-bearing zones	Drilling documentation - percussion holes	2	-	-
	Drilling documentation - cored holes	2	-	-
	Air-lift tests	2	-	-
	Clean-out and pumping test of borehole	2	-	-
	Spinner or flowmeter measurement of the borehole	3	-	-
	Injection tests - 3 m packer interval	1	-	-
	Injection tests - 30 m packer interval	1	-	-
	Interference tests - test section between two packers	3	-	-
	Interference test - open borehole	2	-	-
	Interference test - open borehole - long time	3	-	-
	Other methods (geological and geophysical investigations)	3	-	-
Hydraulic conductivity	Available geohydrological investigations in the area of interest	2	-	1
	Injection tests - 3 m packer interval	3	-	3
	Injection tests - 30 m packer interval	3	-	-
	Air-lift tests	3	-	-
	Clean-out and pumping test of borehole	3	-	-
	Interference test - open borehole	3	-	-
	Core mapping	-	-	3
Conductive structure	Injection tests - 3 m packer interval	-	3	-
Flow and pressure in conductive structure and axial flow along tunnel from conductive structure	Not treated in this report			
Boundary conditions and pressures in the rock volume	Groundwater monitoring	3	-	-
	Borehole deviation measurements	3	-	-
Flow into tunnel Inflow from zones Inflow to tunnel legs	Not treated in this report			

Subject	Methods	Usefulness		
		Regional, Site scale	**Block scale**	**Detailed scale**
Flux Distribution	Dilution test	3	-	-
Salinity in boreholes	Geophysical logging	1	-	-
	Pumping for chemical sampling	3	-	-
	Air-lift pumping of packed-off sections	2	-	-
	Chemical sampling in water circulation sections	3	-	-
	Electrical conductivity measurements in borehole sections	1	-	-
Disturbed zone	Not treated in this report			

Very useful = 3 Useful = 2 Less useful = 1 Not applicable = -

4.3.2 Water-bearing zones

General

In the conceptualization of the rock mass it is assumed that a number of major conductive structures can be identified as to position, extent and properties. Considering only flow, and not transport, the properties we need to know are transmissivity and storage coefficient and their distribution within a zone.

We need to know these properties as these major conductive structures are the main and fastest flow path and to some extent control pressures within the volume. Several methods have been used to identify their properties, position and extent, see Figure 4-15. Examples of major conductive structures are shown as blue lines in Figure 4-10.

Methods

Drilling documentation – percussion holes

Inflow rates and increased fracturing are assessed during drilling. The rock type is also assessed from cuttings. From these investigations it is possible to identify a possible intersection between the borehole and a fracture zone. (Example of documentation is shown in *Stanfors et al. /1991/*).

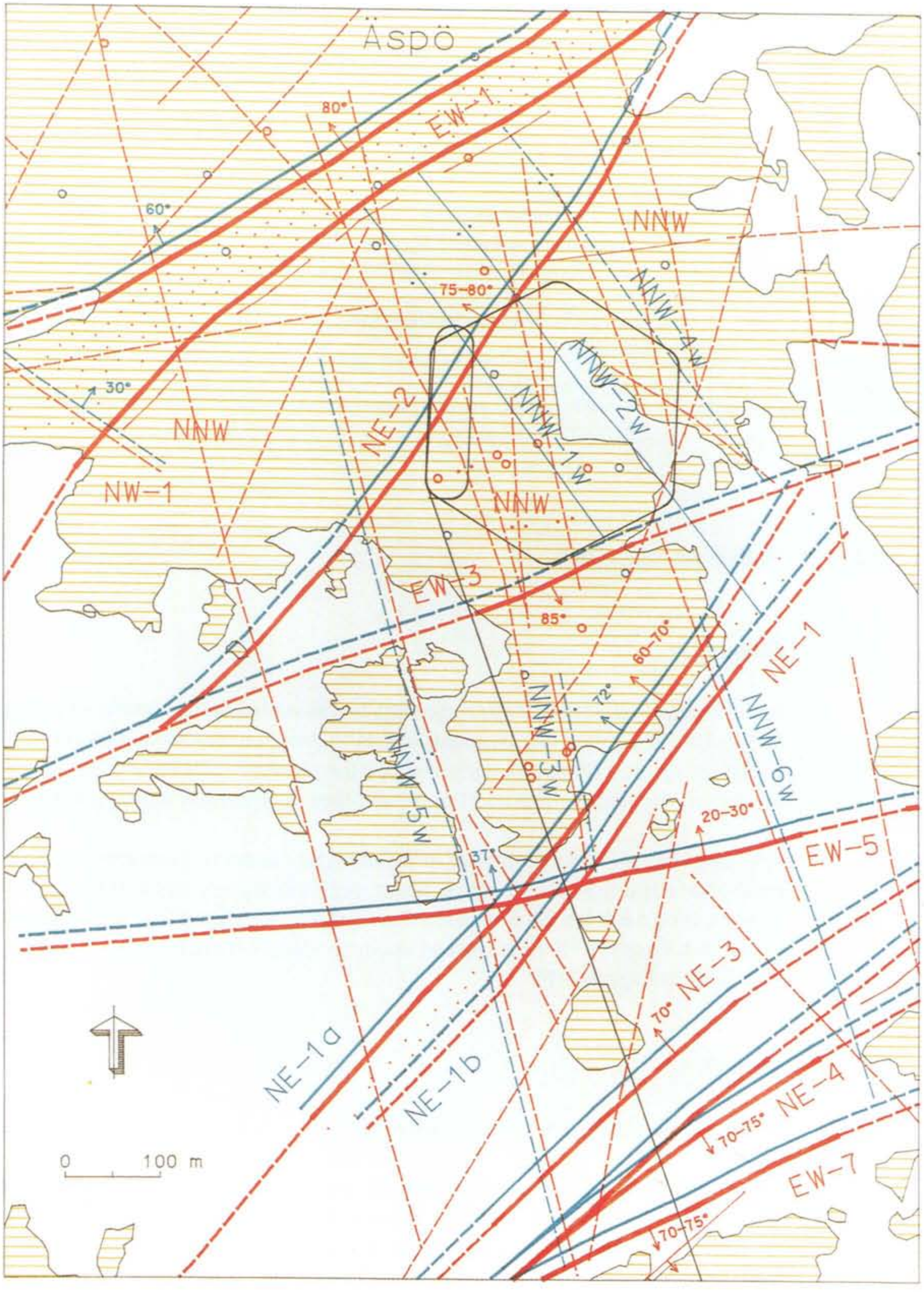


Figure 4-10. *Fracture zone interpretation in the target area for the Äspö Hard Rock Laboratory /Gustafson et al., 1991/.*

Drilling documentation – cored holes

The core is mapped and provides information on rock type, fracture coating and fracturing. From these investigations it is possible to identify a possible intersection between the borehole and a fracture zone. (Example of documentation is shown in *Stanfors et al. /1991/*).

Air-lift tests

Generally the air lift test has been performed for 100 m sections of cored holes. Percussion holes, generally with drill depth 100-200 m, have also been air-lift tested. Drawdown and recovery have normally been approximately 1 h + 1 h, see Figure 4-11. (Example of evaluated air-lift tests is found in *Rhén et al. /1991/*).

Clean-out and pumping test of borehole

In order to clean-out cored holes they are pumped for approximately one day. By measuring drawdown and recovery in the pumped borehole it is possible to get a first estimate of the transmissivity as seen from the borehole and the skin factor for the borehole. If pressures are observed in surrounding boreholes, directions and positions of major fracture zones may be indicated. (Examples of evaluated tests in *Rhén et al. /1991/*).

The flow regime is evaluated from the pressure response in the borehole and generally radial flow was assumed for the evaluation of the pressure-time curve.

Spinner or flowmeter measurement in boreholes

During the clean-out pumping the borehole is flowmeter logged. These measurements give the inflow distribution along the borehole and give both an estimate of the location of the intersection between the fracture zone and the borehole and also an estimate of the transmissivity of the fracture zone if the transmissivity from the clean-out pumping is distributed along the borehole according to the inflow rate (see Figures 4-12 and 4-13). (Examples of evaluated flowmeter measurements in *Rhén et al. /1991/*).

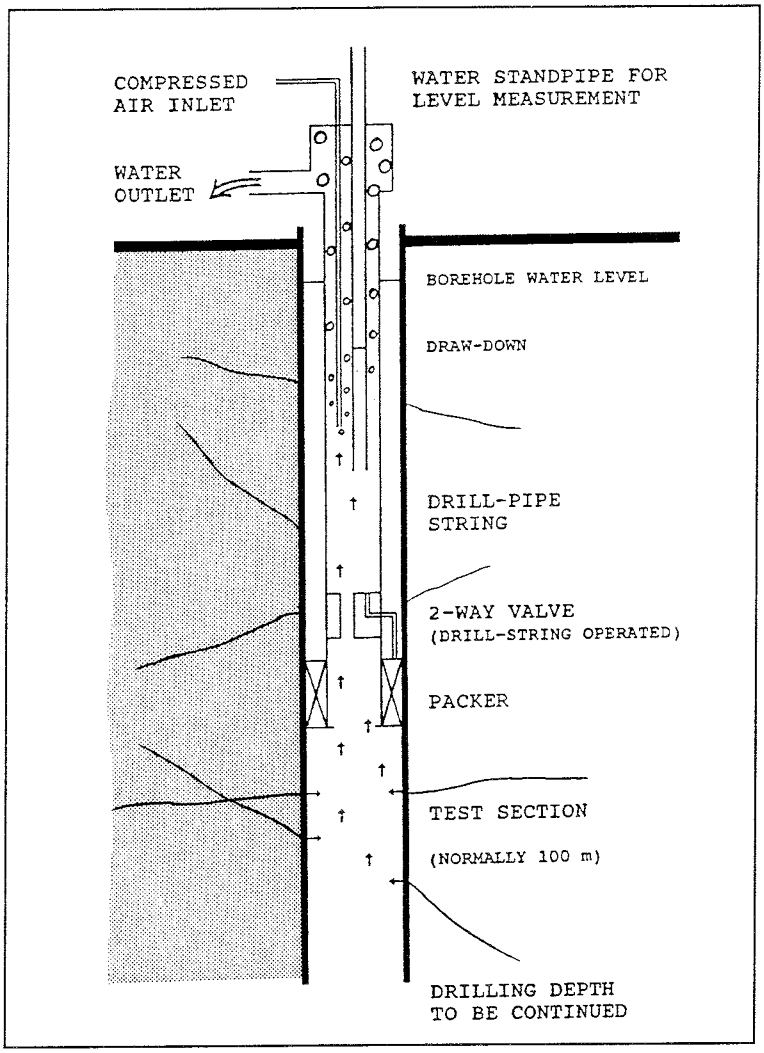


Figure 4-11. *Air-lift pumping carried out in conjunction with core drilling /Almén and Zellman, 1991/.*

Injection tests – 3 m packer interval

Injections tests with injection and recovery periods of approximately 10 + 10 minutes have been used. Constant pressure, normally 200 kPa above static pressure, was used during the injection period. The tests have both been evaluated assuming stationary conditions or transient conditions. The latter is considered to give a better estimate of the transmissivities. The evaluation for stationary conditions was based on the injection period and theory according to *Moye /1967/*. From transient tests the flow regime and the flow properties are evaluated. The evaluation for transient conditions was based on the recovery period assuming radial flow and using Agerwal time correction and transmissivity was evaluated for the 3-m section */Earlougher, 1977/*. Dividing the transmissivity by the section length 3 m gives an average hydraulic conductivity. (About 1200 tests were performed during the pre-investigations in 7 cored holes on Äspö and in one cored hole on Laxemar.) (Examples of evaluated tests in *Nilsson /1990/* and in Figure 4-13).

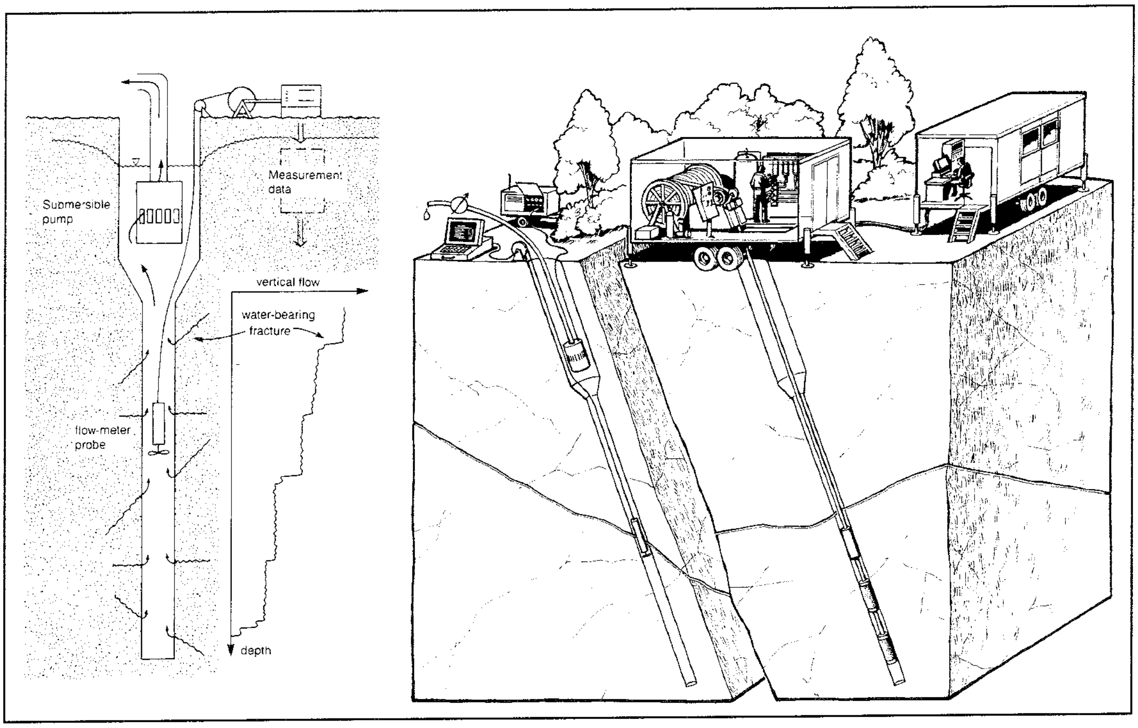


__Figure 4-12.__ Spinner or flowmeter measurement and hydraulic injection test in a borehole. /Almén and Zellman, 1991/.

Injection tests – 30 m packer interval

The injection and recovery periods were approximately 2 h + 2 h and the section length 30 m. For more details see injection test – 3 m packer interval. (65 tests were performed during the pre-investigations in three cored holes on Äspö and Laxemar.) (Examples of evaluated tests in *Nilsson /1989/*).

Interference test – test section between two packers

The interference tests has been performed as constant rate tests. If the pumped section in a borehole is surrounded by packers it is possible to test an individual fracture zone, see Figure 4-14. This procedure offers good opportunities to evaluate the flow regime for early, middle and late times and thus provides a generally good estimate of the flow properties of the fracture zone close to the borehole. The drawdown and recovery periods has generally been 3 days + 2 days. (Examples of tests are shown in *Rhén /1991/*).

The flow regime has generally indicated radial flow during some period and generally a transmissivity has been evaluated from the assumption of radial flow and the pressure-time curve.

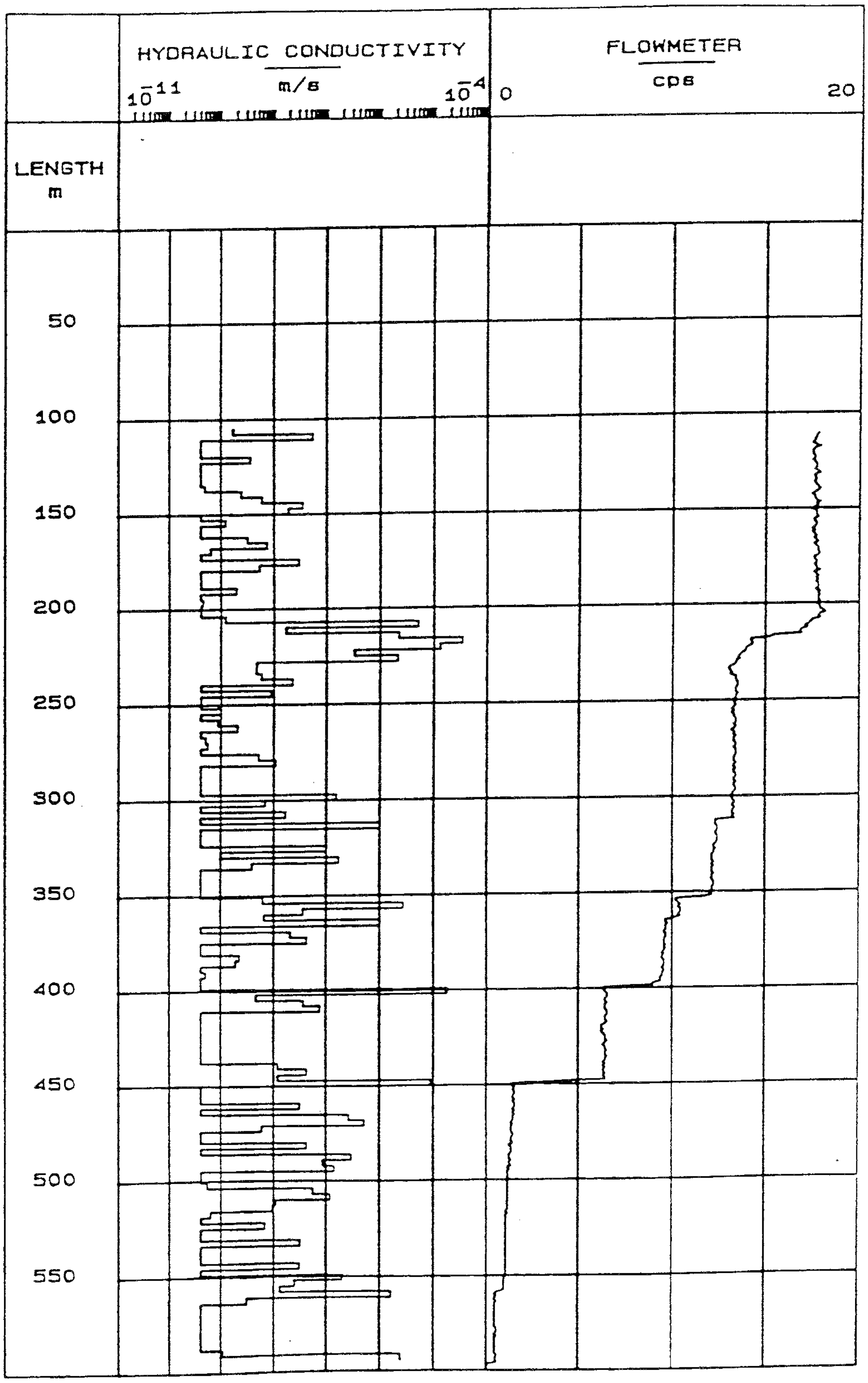


Figure 4-13. Hydraulic conductivity evaluated from injection tests in 3 m sections and flowmeter log in KAS06 /Almén and Zellman, 1991/.

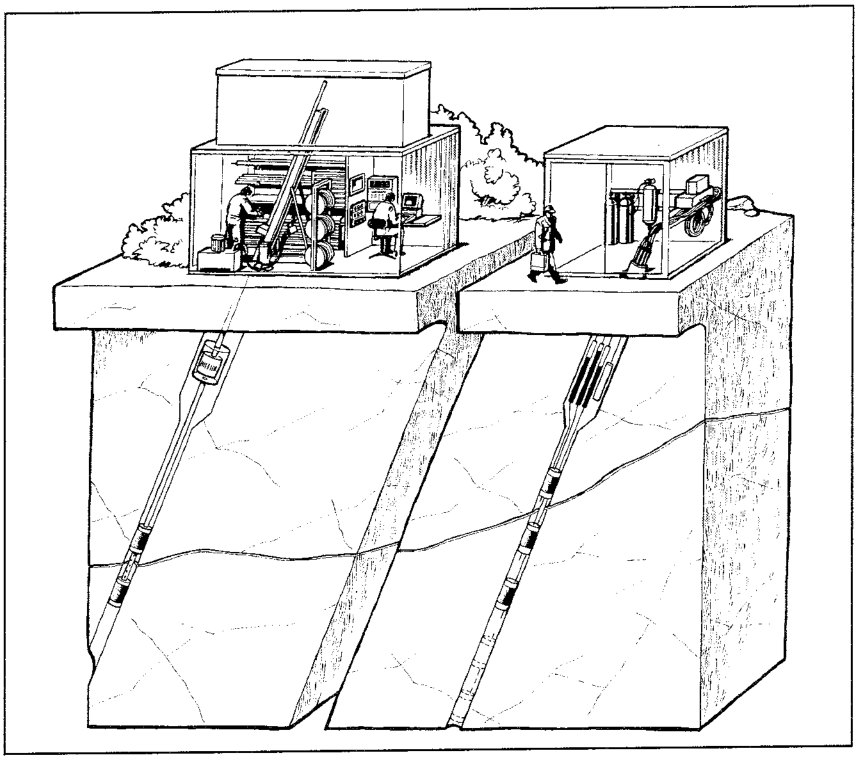


Figure 4-14. *Interference test. Pumping is done in one borehole (to the left in the figure) and pressure responses are measured in surrounding borehole sections (to the right in the figure) /Almén and Zellman, 1991/.*

Drawdown and recovery are not only measured in the pumped borehole but also in observation sections (surrounded with packers) in other boreholes. If these sections intersect the same fracture zone as the pumped one, it is possible to estimate the storativity for the fracture zone.

The responses in the observation sections also give indications of major conductive structures, positions and extents. Sometimes the indications of these major conductive structures may only be seen in the interference test but generally geological and geophysical data have to be used to support the discussion of the location and extent of the conductive structures.

Interference test – open borehole

In some of the interference tests the pumped borehole has not been packed off. In these cases you get the transmissivity of the entire borehole, as in the clean-out pumping test. Depending on whether there are one or several fracture zones intersecting the pumped borehole and how the observation sections are situated it may be possible or not possible to evaluate the storage coefficient for a zone. Compared with interference tests, it is also generally more difficult to draw conclusions on the location and extent of conductive structures where a fracture zone has been packed off. The drawdown and recovery period has generally been 3 days + 2 days. (Examples of evaluated tests in *Rhén et al. /1991/*).

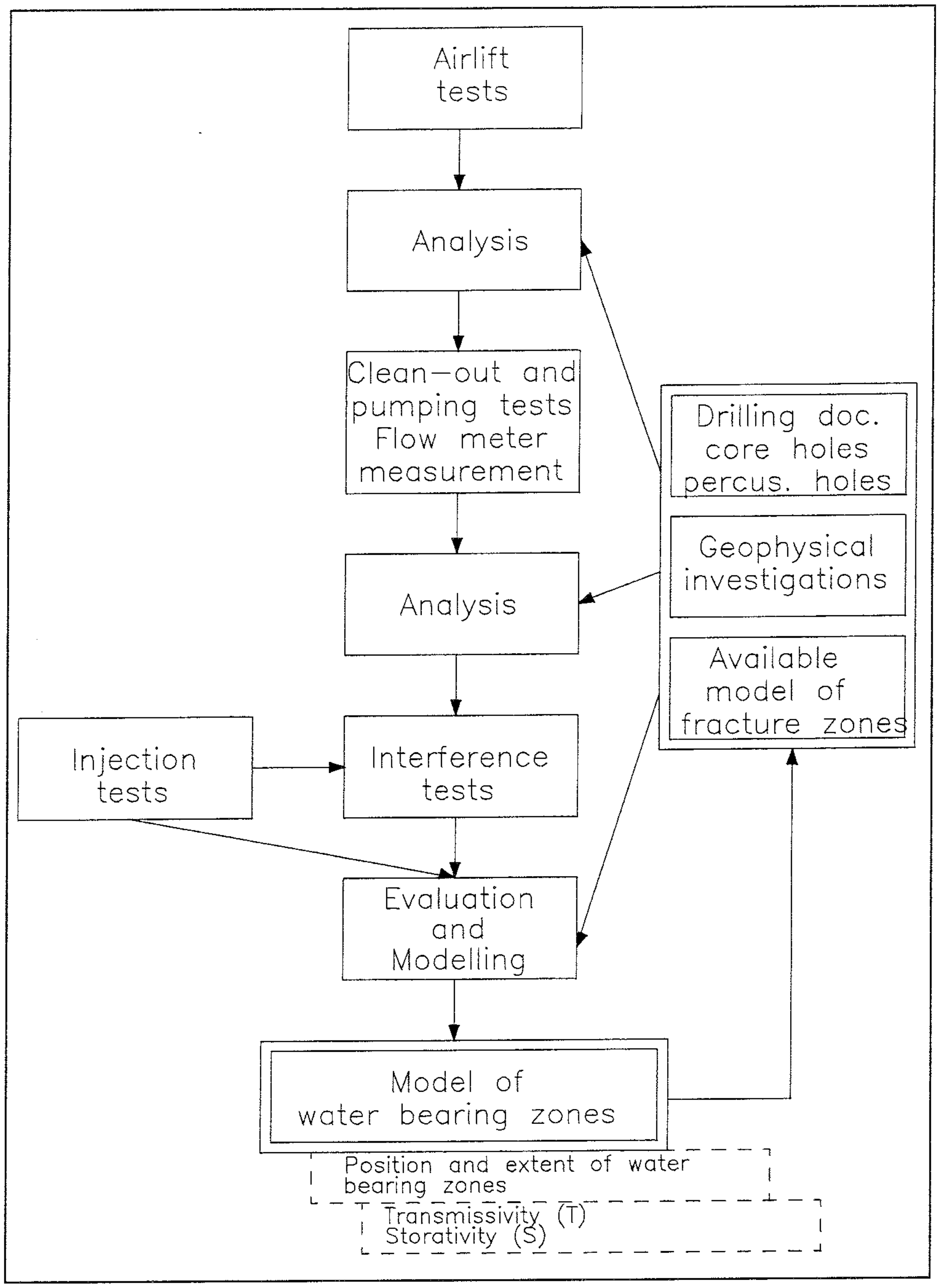


Figure 4-15. Water-bearing zones – site scale. Flow chart.

Interference test – open borehole – long-term pumping

Two interference tests were performed as Long-term Pumping Tests (LPT), with drawdown and recovery periods of 53 + 33 days and 92 + 31 days. The purpose was the same as for the other interference tests and also to get better information on the boundary condition and a larger influence radius (drawdown within a larger volume). All interference tests are valuable as calibration cases for the numerical groundwater flow model, but these long-term pumping tests are most valuable. In these tests you also have to keep a record of precipitation and changes in boundary conditions that you can measure. (Example of test in *Rhén /1991/*).

Other methods

As mentioned under *"Interference tests"*, different geological and geophysical investigations are important for defining location and extent – see Section 4.2 for more details concerning these methods.

Judgement – Site scale

The most important methods for estimation of water-bearing zone properties are:

- Clean-out and pumping test in combination with flow meter measurements.
- Interference tests – test section between two packers (3 + 2 days).
- Interference tests – long-term pumping.

However, flow meter measurements are not always performed or successful. In these cases it is important to have drilling documentation and air-lift tests, and this documentation and test should **always** be performed in a borehole. It is also not possible, at least not today, to perform flow meter measurements in the upper 100 m of the telescope-shaped cored hole. Air-lift test in this section is the only test that provides information on the transmissivity in this part of the borehole.

The injection tests can also provide information on the transmissivity of a water-bearing zone and they may give a better estimate compared to the flow meter distributed transmissivity. Generally the major water-bearing zones have a high or rather high transmissivity and the best suited method for these structures is pumping within a packed-off section because it may be difficult to achieve a high injection flow rate (in order to get greater pressure changes and better measurement resolution). The injection tests are, however, needed for other reasons, to obtain statistics on the hydraulic conductivity.

A major fracture zone should be penetrated by several boreholes in order to get estimates of the variability of properties and also to get more clear responses for interpretation of the position and extent of the zone.

Very conductive structures may have to be pumped using the air-lift method in order to get flow rates great enough to create measurable pressure responses in the pumped borehole and the observation boreholes. However, drawdown become very erratic due to flow rate fluctuations, which mainly affect the drawdown measurements in the pumped borehole. Drawdown curves are always better for interpretation and therefore air-lift pumping should not normally be used for interference tests, if expected responses are acceptable with an ordinary pump.

Here it must also be pointed out that in order to ensure a successful interference test, other hydraulic tests and drilling activities must be planned so they don't affect the drawdown from the interference test.

It is also very important to have a geological model of the fracture zones when the interference tests are evaluated. The geohydrological tests can in many cases support the geological interpretation of a fracture zone's direction and extent. However, major water-bearing zones which consists of several interconnected fractures with large extent and high transmissivity may be difficult to find by means of geological and geophysical measurements. It may only be possible to find these conductive structures by interference tests. How well you succeed in finding these structures is dependent on the location and the number of borehole observations used for a test. A possible direction for these structures may be the direction of the maximum rock stress.

During the evaluation of the pre-investigations it was found that the absolute pressure at the point of intersection between a borehole and a fracture zone was a variable that was used in the analysis. The static pressure was evaluated from the injection tests. However, the choice of pressure transducer was not intended to give good accuracy of the undisturbed pressure in the fracture zones. In the future, if good accuracy of the undisturbed pressure in the fracture zones is needed, expensive pressure transducers will probably have to be bought and special calibration procedures performed.

4.3.3 Hydraulic conductivity

General

On the site scale, when the major water-bearing zones have been defined deterministically, the flow properties of the rock mass between these structures must also be defined. If we intend to use a porous-medium model we need to know the spatial distribution of hydraulic conductivity. Generally we assume that we can only obtain the probability distribution of the hydraulic conductivity within defined sub-volumes of the repository volume. We may assume a random distribution of the hydraulic conductivity (from a given probability distribution) for each cell in the numerical model or some spatial correlation when generating the hydraulic conductivity field. If we intend to use a discrete-fracture flow model we need statistics on fracture shapes, locations, directions and transmissivities.

Hydraulic conductivity seem to be scale-dependent, see Figure 4-17. At this point, we don't have a complete understanding of this scale dependency, and it is therefore important to perform tests on different scales (measurement sections as well as duration of test) to get a better understanding. */Wikberg et al., 1991/*.

On the detailed scale, hydraulic conductivity is studied for each defined major rock type. The reason for doing this is of course that different lithological units may have different hydraulic properties. If there is a difference, it may be a reason for defining sub-volumes on the site scale as lithologically defined sub-volumes. It is also one aspect to take into consideration when planning the layout of the repository. The flow chart for hydraulic conductivity is shown in Figure 4-18.

Methods

Available geohydrological investigations in the area of interest

As a starting point for a regional investigation, useful information can be found in the national water-well archive and possibly from other investigations in the area. Specific capacity, drill depth, rock type etc are found in the national water-well archive, and pumping tests, injection tests etc may have been performed in other investigations.

Injection tests – 3 m packer interval

Injections tests, with a packer interval of 3 m, in 7 cored holes on Äspö and one on Laxemar have been the source of the statistics on hydraulic conductivity within sub-volumes on Äspö, see Figure 4-16. (To some extent these injection tests have also been used to estimate the statistical distribution of the fracture transmissivities.) These tests have also been used to describe the relationship between hydraulic conductivity and standard deviation of hydraulic conductivity and depth. (The test is outlined in more detail in Section 4.3.2.)

The injection tests with a 3 m packer interval have been the basis for relating hydraulic conductivity to lithological units.

Injections tests – 30 m packer interval, Air-lift tests, Clean-out and pumping tests and Interference test – open borehole

The tests above and the injection test with the 3 m packer interval have been used to study the scale dependency of the hydraulic conductivity, see Figure 4-17. (For more details on the methods, see Section 4.3.2.)

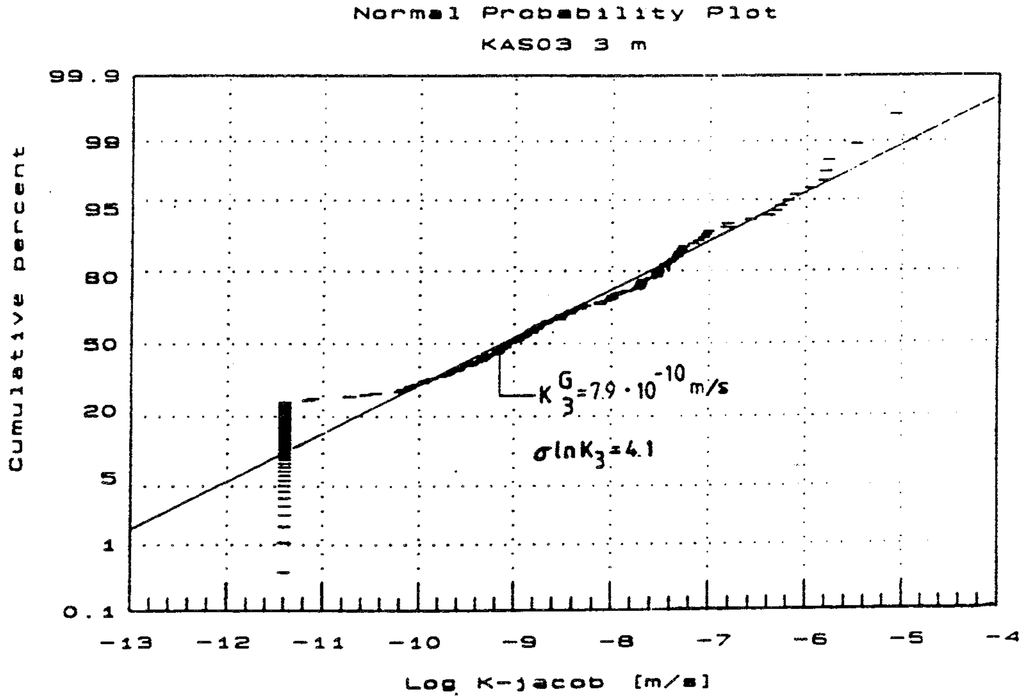


Figure 4-16. *Cumulative plot of log conductivity for 3 m sections in KAS03 /Wikberg et al., 1991/.*

Core mapping

Core mapping has been the basis for relating individual injection tests to lithological units. In several cases the packer interval straddles two or more rock types, as the test section is generally moved a packer interval down (or up) after each test, regardless of rock type distribution in the borehole. Normally these samples with two or more rock types are excluded from the statistics on a single lithological unit.

Judgement – Regional and Site scale

As a starting point for a regional investigation it is very useful to use information from the national water-well archive and available investigations in the area. At a low cost it is possible to obtain rough estimates of the hydraulic conductivity of the bedrock in the area, possibly also divided on lithological units. The investigations may also possibly give some indications of conductive structures.

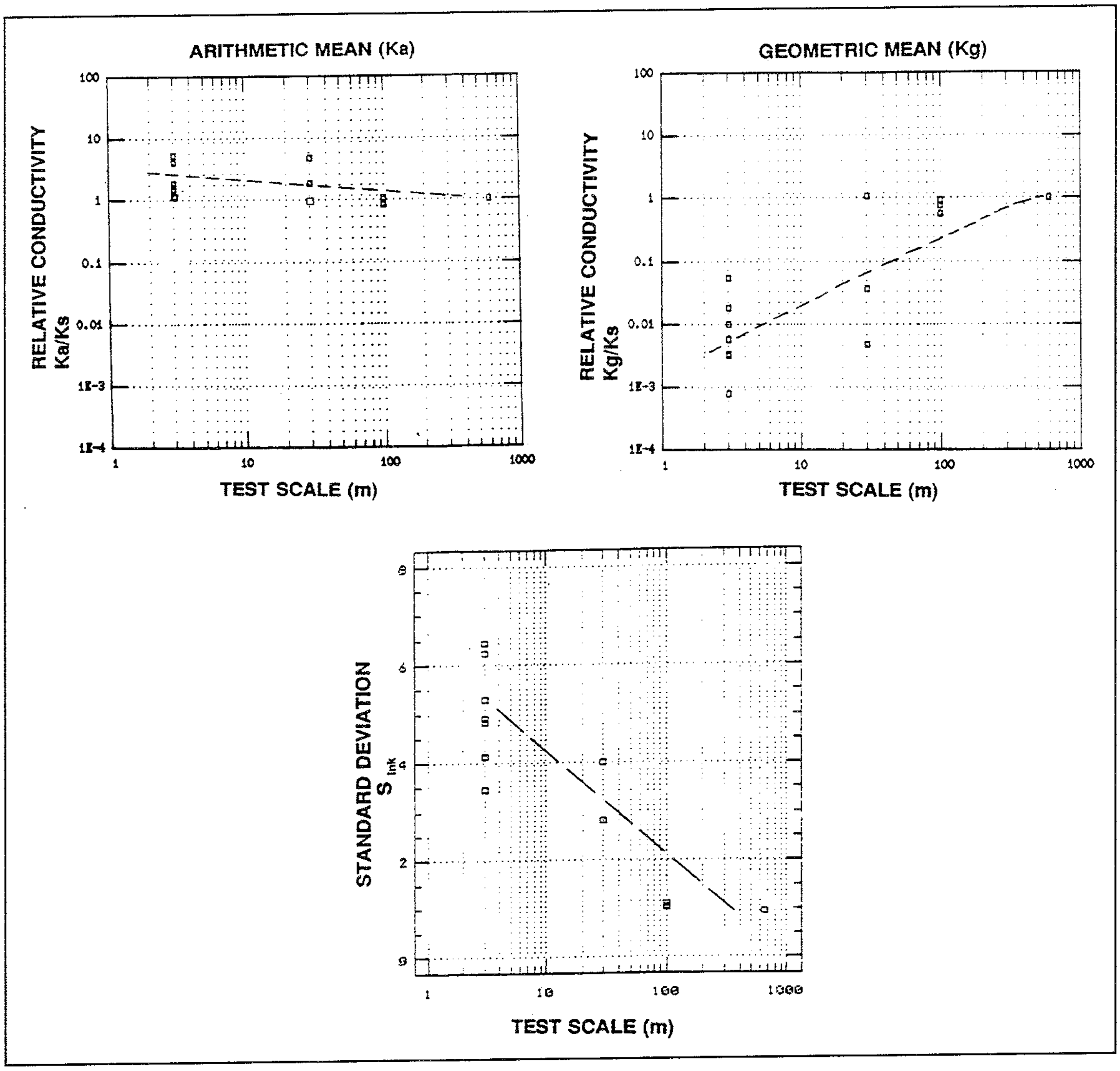


Figure 4-17. Relative hydraulic conductivity and standard deviation for different test scales. K_s = the average hydraulic conductivity calculated from the transmissivity value evaluated from the test on the entire borehole /Wikberg et al., 1991/.

It is important to have a large number of injection tests well spread within the repository volume so that representative statistics of the hydraulic conductivity can be calculated. However, it is very difficult to say how many tests are needed and what test scale(s) (time and packer interval) that should be used. The first point is dependent of how heterogenous the rock is (how many sub-volumes that can and should be defined) and the second how the data will be used (type of numerical groundwater flow model). If there is no fully accepted way to scale the hydraulic conductivity and its standard deviation test at different scales are needed in order to establish empirical relationships.

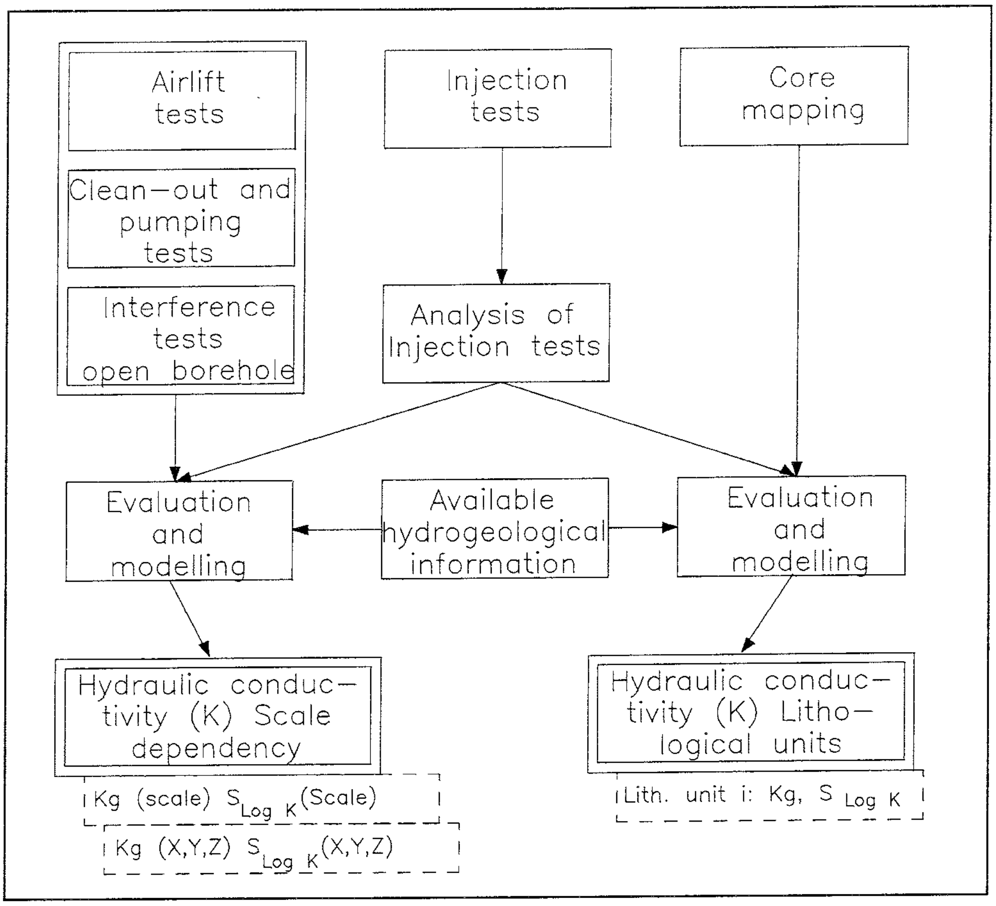


Figure 4-18. *Hydraulic conductivity – site scale and detailed scale. Flow chart (K_g = geometric mean of hydraulic conductivity; X,Y,Z are coordinates; S = standard deviation).*

Judgement – Detailed scale

The test section length may be important if evaluated hydraulic conductivities are to be divided into different lithological units. It is generally difficult to get large samples of some rock types because they represent a small volume of the total volume and/or they are found as small bodies or thin sheets within the repository volume.

It is also important that the length measurement to the location of the test section in the borehole is correct, in order to be certain that the test can be compared with core data or geophysical data. For some testing equipment and logging tools the measured depths must be corrected for the weight of the equipment and the inclination of the borehole.

4.3.4 Conductive structure

General

In crystalline rock the porosity is made up of a number of fractures of different sizes and with different widths. This means that, depending on test methods and fracture geometry, one or several fractures are tested. If several fractures are tested their interconnections will also affect the test result. However, if radial flow is assumed around a test section, which seems to be the case in many tests, the transmissivity can be evaluated for the test section. You can obtain statistics of the transmissivity of that particular test scale, but you can also obtain statistics on the distance between transmissivities exceeding a certain limit if you have a long borehole, see Figure 4-19.

With this type of statistics it is possible to discuss the probability of finding a rock volume of a certain size which is not intersected by a conductive structure with a transmissivity exceeding a chosen limit.

Methods

Injection tests – 3 m packer interval

The basis for estimating the distance between conductive structures with a transmissivity exceeding a specified limit has been injection tests with a packer interval of 3 m. (For details of the method, see Section 4.3.2.)

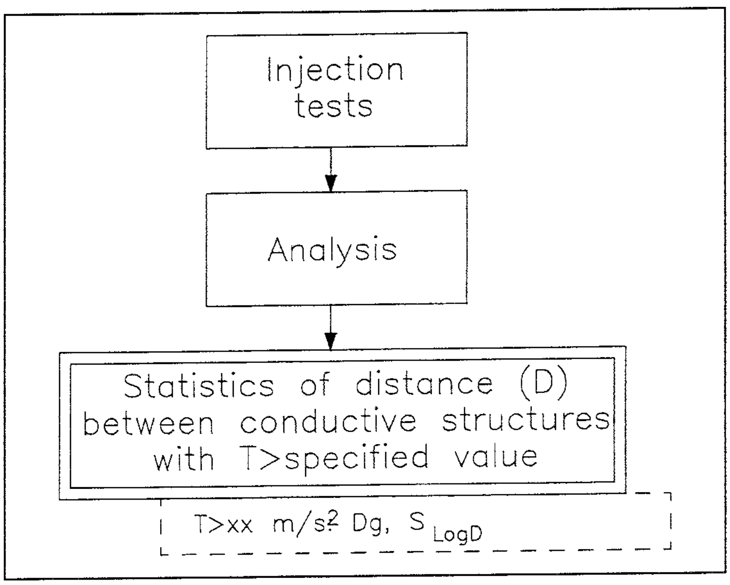


Figure 4-19. *Conductive structure – block scale. Flow chart (T = transmissivity).*

Judgement – Block scale

It is important to decide on a suitable packer distance if the statistical distance between conductive structures with a transmissivity greater than a specified value is to be estimated. Probably the packer distance cannot be particularly long, since the distances between canisters will probably be rather short and also the chosen transmissivity will be rather low.

Flow meter logging could be an alternative method. However, one big problem is that if longer sections of a borehole are logged, the inflow from high-transmissive fractures will mask low-transmissive fractures. The estimate of the transmissivity distribution along the borehole is also probably better with injection tests compared with flow meter logging due to the drawbacks measured above and because of the borehole skin which is probably present during the flow meter logging.

4.3.5 Flow and pressure in conductive structure and axial flow along tunnel from conductive structure

General

Conductive structures intersecting the tunnel and the disturbed zone may be more permeable compared with the rock where the canisters are located. It is therefore important to understand the hydraulics of the disturbed zone and conductive structures, as they may be possible flow paths from a deep repository.

The flow and pressure in conductive structures and the axial flow in the disturbed zone along the tunnel will be studied during the excavation of the Äspö HRL and during the operating phase. The pre-investigation was not intended to provide information on these subjects.

4.3.6 Boundary conditions and pressures in the rock volume

General

The boundary conditions of a rock volume are given as the flow or the hydraulic head over each boundary or part of boundary within the rock volume.

The pressure of the pore water may also be measured in a number of points within the rock volume. These pressures may be the undisturbed pressures or the pressure changes due to, for example, excavation of the repository, see Figure 4-21).

In the rock mass the boundary conditions and the pressures are estimated from water level and pressure measurements in boreholes. Basic information for estimating groundwater recharge are precipitation, potential evapotranspiration and run-off. The latter three are not discussed in this report because these measurements are done by SMHI (Swedish Meterological and Hydrological Institute) and are considered to be well established.

Groundwater flow modelling of the repository will be done with numerical models. In order to do the modelling you need the hydraulic properties within the numerical model and also the boundary conditions, expressed as head or gradient, of the volume modelled.

It is also important to have the natural, undisturbed, pressures within the model, as these and the boundary conditions will generally be the starting conditions for the numerical simulations.

During the excavation of the repository the water level will probably fall due to flow into the repository tunnels. It is important to measure the pressure changes in the rock mass, as these data can be used to test the conceptual model of the rock mass and also to be a "final" calibration example for groundwater modelling after the repository has been built.

Methods

Groundwater monitoring

During the first phase of the pre-investigations water levels are measured by manual levellings and with pressure transducers connected to data loggers during pumping tests.

As soon as possible after the borehole has been clean-out pumped, the borehole is generally sectioned with a multipacker system, see Figure 4-20. (1-3 packers have been used in percussion boreholes and up to 6 in cored holes). Small pressure tubes (outer diameter = 6/inner diameter = 4 mm or 8/6 mm) run from the measured section up to a position above the uppermost packer where the pressure tubes are connected to water stand-pipes (28/22 mm or 63/55 mm). The pressure transducers are mounted in these water stand-pipes, and generally a miniature packer has been positioned above the pressure transducer. The miniature packer has been used to minimize the well bore storage effects in the observation sections during pumping tests. The diameter of the percussion holes has been 110-162 mm. The cored holes have been drilled with a telescope shape, the uppermost 100 m with a diameter of 155-167 mm and the lower part with a diameter of 56 or 76 mm. The reason for the telescope-shaped borehole is that you need space in the borehole for mounting a submersible pump during the pumping tests and to have enough space for the water stand-pipes.

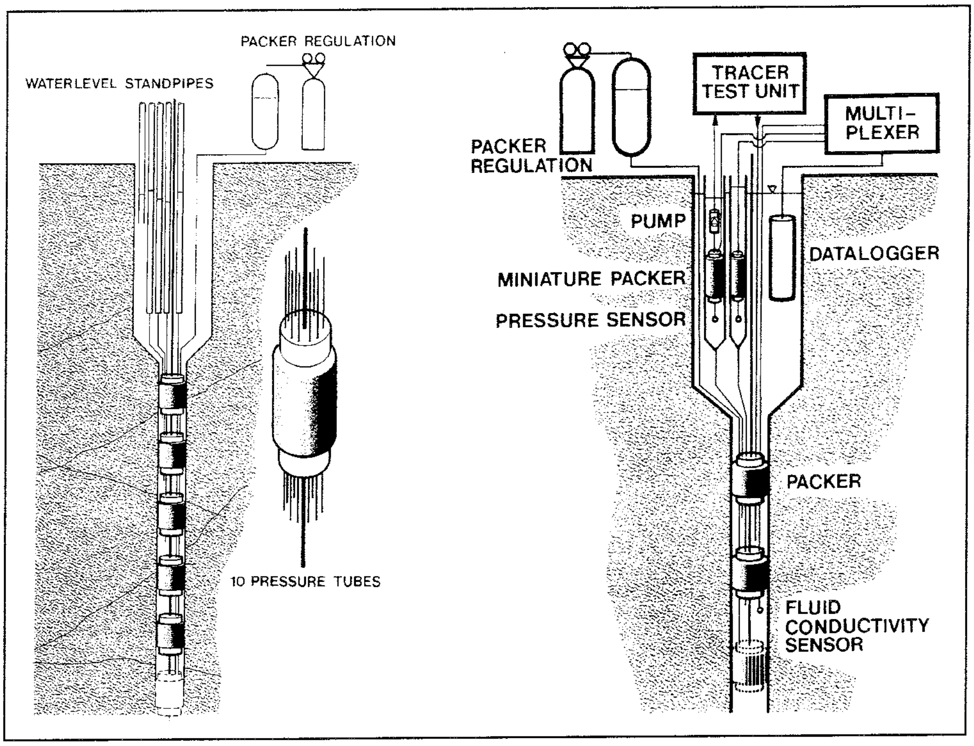


Figure 4-20. *Groundwater monitoring. /Almén and Zellman, 1991/.*

Left: *Multi-packer system in a telescope shaped borehole.*
Right: *Schematic set-up of monitoring system with the Borre data logger. The figure also shows water circulation equipment for one section, the tracer test unit and the fluid conductivity sensor.*

After the packers and water stand-pipes have been lowered in the borehole, the water stand-pipes are air-lift pumped until the electrical conductivity of the water has stabilized. The density of the water can then be estimated from the electrical conductivity.

The reason for estimating the density of the water in the water stand-pipe and pressure tubes is that density is needed in order to estimate the pressure in the monitored section.

During the pre-investigation phase piezometric levels were measured by data loggers and manual levellings. During the construction phase the following measuring programme is used. The piezometric level is measured every 2 or 4 hours in all sections connected to data loggers. The borehole loggers, which are connected to the site office by radio communication, measure every 8 minutes and store the value if it has changed more than 0.2 m compared to the previously stored value, or if the last value was stored more than 2 h ago. Manual levellings are made once a week for those sections which not are measured with data loggers.

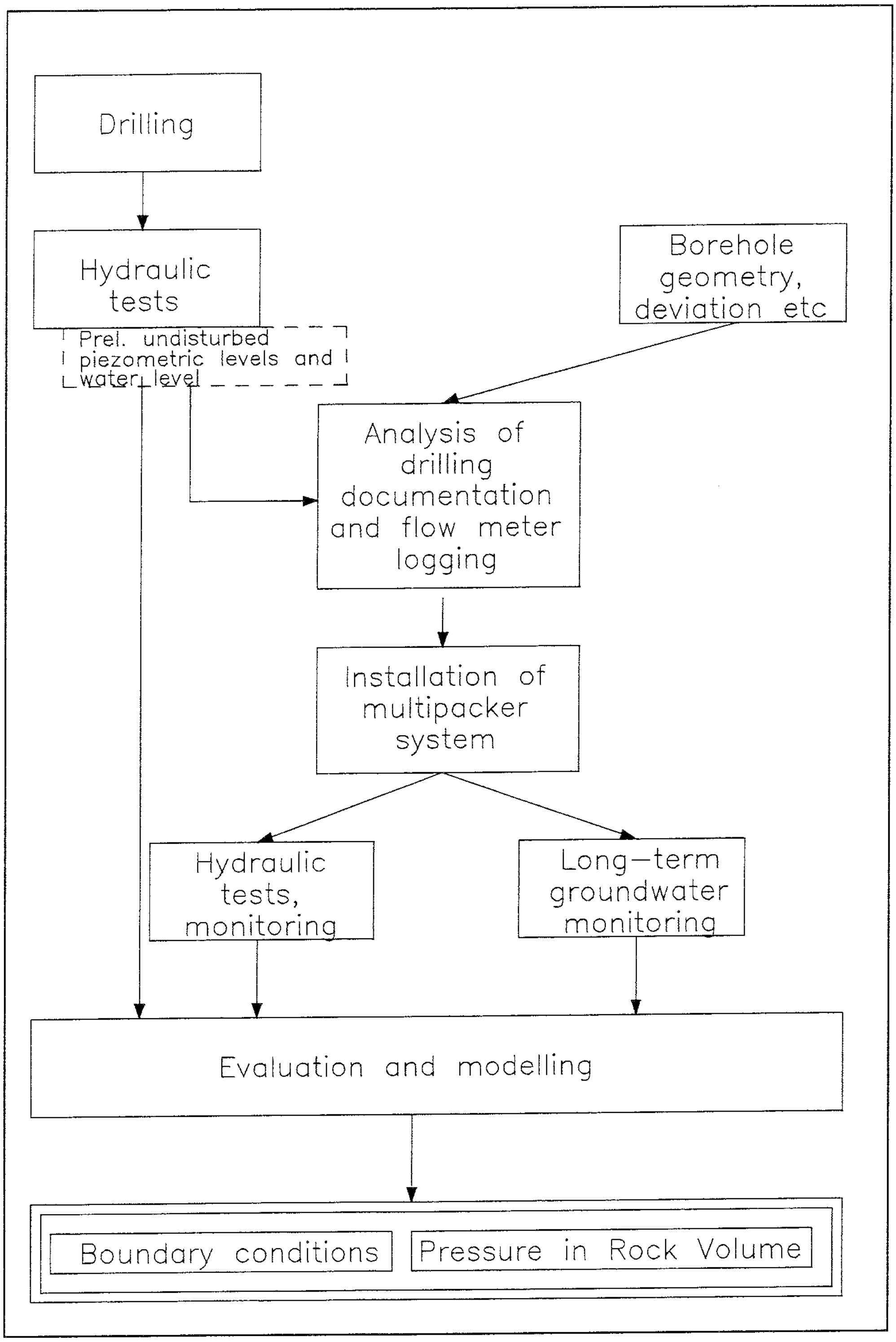


Figure 4-21. *Boundary conditions and pressures – Flow chart (X,Y,Z are coordinates, t = time).*

Manual levellings for all sections are normally made once every month in order to calibrate the readings from the data loggers.

Measurement frequencies are greater during pumping tests. The minimum scanning rate has been 2 s. (One channel used on a Borre logger). (An example of the reported groundwater monitoring is found in *Nyberg et al. /1992/*).

Borehole deviation measurements

The coordinates (x, y, z) of the top of the casing must always be measured. This is normal engineering work and is not commented on here.

However, it is also important to know the coordinates for the rest of the borehole. For short boreholes it may be sufficient to know the drill depth and borehole direction. Borehole deviation must generally be measured in long boreholes if the coordinates of the borehole have to be known with some certainty.

Judgement – Site scale

The boreholes should be equipped with packers as soon as possible for three reasons. First, this prevents water from circulating in the borehole and thus mixing of water from different zones. Second, it provides better possibilities for evaluating interference tests. And third, it permits regular monitoring of the undisturbed pressure.

The boreholes should be spread over the investigation area and what possibly will be the boundaries of the numerical model. Some boreholes may be short but a number of the boreholes must be long and intersect the major water-bearing zones. For the evaluation of interference tests, 2 or 3 borehole sections should penetrate each important water-bearing zone.

The telescope-shaped boreholes equipped with PEM pipes from the packers with pressure transducer mounted in the pipes work well from the following stand points:

- It is easy to change each transducer.
- It is easy to calibrate each transducer.
- You can use transducers with high resolution (3.5 bar transducers have been used in the observation boreholes and 10 bar in the pumped boreholes).

The problems with the system – seen during the construction phase – are:

- You have to lower the transducers repeatedly if the water level in the pipes falls.
- Manual levellings in the PEM pipes become more and more difficult as the water level falls because of friction between the levelling probe and the PEM pipe, the pressure tubes to the miniature PEM packer and the tube to the pump (if there is a pump in the PEM pipe).

- If the water level falls to 50-100 m below the ground surface there may be problems with removing and reinstalling both packers in the borehole and PEM packers in the pipes, depending how they are pressurized. The PEM pipes may also be deformed due to higher pressure outside than inside the pipe, which can cause problems with removing or installing pumps or PEM packers.

The measurement frequency during pumping tests and during continuous monitoring has been sufficient.

There have been some problems with monitoring. Transducer have broken, manual levellings failed etc, causing rather long periods of data loss from individual borehole sections. During the excavation of the Äspö HRL the monitoring system has been improved, and the system will be improved further. A large measurement system like the monitoring system at the Äspö HRL consists of a large number of pressure transducers, data loggers etc and is rather expensive to maintain.

4.3.7 Flow into tunnel – inflow from zones – inflow to tunnel leg

Site scale – general

The inflow to the repository tunnel is important to measure because it forms a part of the data set that will be needed when the drawdown around the finished repository is used to check the conceptual model and also to serve as a "final" calibration of the groundwater flow model.

However, the pre-investigations were not intended to provide information on these subjects and they are therefore not commented on here.

4.3.8 Flux distribution

General

By means of dilution measurements in borehole sections it is possible to estimate the flow rate through the borehole section. They can be performed during natural, undisturbed conditions or during stressed conditions (pumpings for example). This flow rate may be used to estimate the flow rate in the rock or a fracture zone outside the borehole. However, this calculation involves several difficulties and generally the estimated flow rate in the rock or fracture zone must be regarded as a very approximate value, see Figure 4-22.

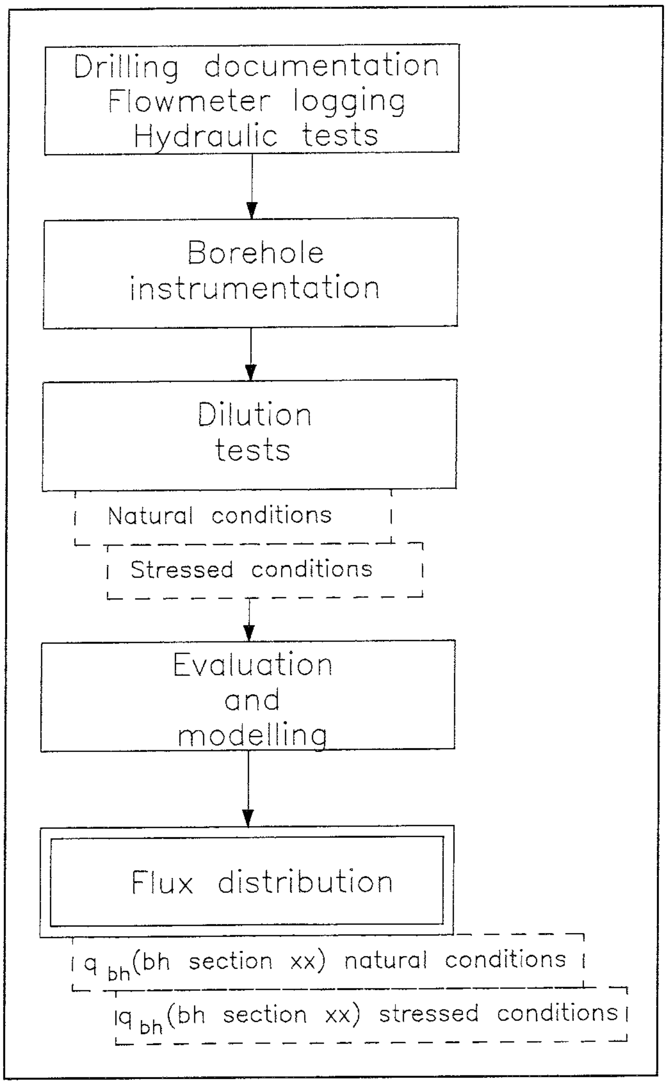


Figure 4-22. Flux distribution – Flow chart.

Pressures and salinity are measured in boreholes to determine the natural conditions and to measure the changes during tests and during excavation of the tunnels in order to get data for groundwater flow modelling. Even though the dilution rates are uncertain, as mentioned above, they are useful as a complement to pressures and salinity for interpreting the flow field in the rock mass.

Methods

Dilution test

The equipment for dilution tests is shown in Figure 4-20. Water is circulated through a borehole section and a tracer test unit by a pump. Tracer is added to the circulating water and the reduction in tracer concentration is measured, see Figure 4-23.

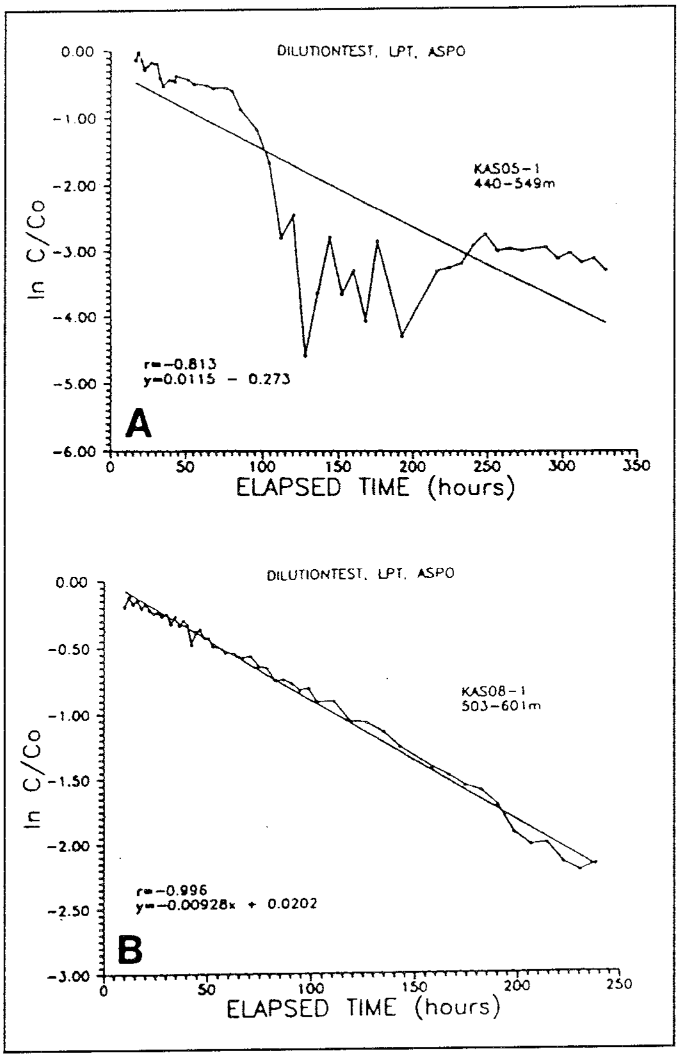


Figure 4-23. *Dilution curves; A: uneven dilution, B: smooth dilution /Rhén et al., 1992/.*

At Äspö one or two borehole sections in each cored hole have been equipped with water circulation equipment, which is used for tracer injection during tracer tests, for dilution measurements and chemical sampling. It is not possible to have more than two circulation sections if more than four packer are installed, due to a limited number of pipes through a packer. The method and some results are presented in *Ittner et al. /1991/*.

Judgement – Site scale

The dilution tests work well as long as the drawdown is moderate. Today, 1994, the pumping system has been modified to make it more useful for dilution measurements and chemical sampling. The dilution measurements become difficult when the drawdown is more than approximately 50 m. The first reason is that the pumps have a limited lift height and the second is that it is difficult to lift out and reinstall the pumps because of deformation of the PEM pipes due to the pressure outside the PEM pipes.

Dilution tests generally become better if the test sections in the boreholes are short. The reason is that there is a smaller volume to circulate and mixing is improved. The fractures intersecting the borehole may also have the same hydraulic head increase, thus eliminating flow along the borehole.

However, sometimes it is difficult to decide where a fracture zone begins and ends in a borehole, and it may be difficult to define perfect packer positions.

Another limitation is that the maximum number of packers that can be installed (if all sections are to be measured) is 6. As the boreholes are generally long, the chosen packer positions must be a compromise.

4.3.9 Salinity in boreholes

General

The density of groundwater is a function of its salinity and temperature. The measurements must be made under undisturbed, natural conditions in order to carry out groundwater flow simulations. Methods used to determine the salinity are shown in Figure 4-24. The changes in salinity during the construction of the tunnel are used to verify the conceptual model and also to calibrate the numerical model.

Methods

Geophysical logging

The resistivity of the borehole fluid has been measured every 0.1 m in some of the cored holes in order to determine the salinity distribution along the borehole. Sudden jumps in the fluid resistivity indicate possible water conductors. (Examples of results in *Almén and Zellman /1991/*).

Pumping for chemical sampling

In some of the boreholes, specified sections of the boreholes have been pumped for rather long periods in order to get representative samples of the water, see Section 4.4. Salinity and electrical conductivity are two among many variables that are measured.

Air-lift pumping from packed-off sections

As mentioned previously in Section 4.3.6 the PEM pipes from the packers are air-lift pumped and the electrical conductivity of the emerging water is measured. If the pipes are pumped long enough the water will represent the test section. (Examples of data in *Nyberg et al. /1992/*).

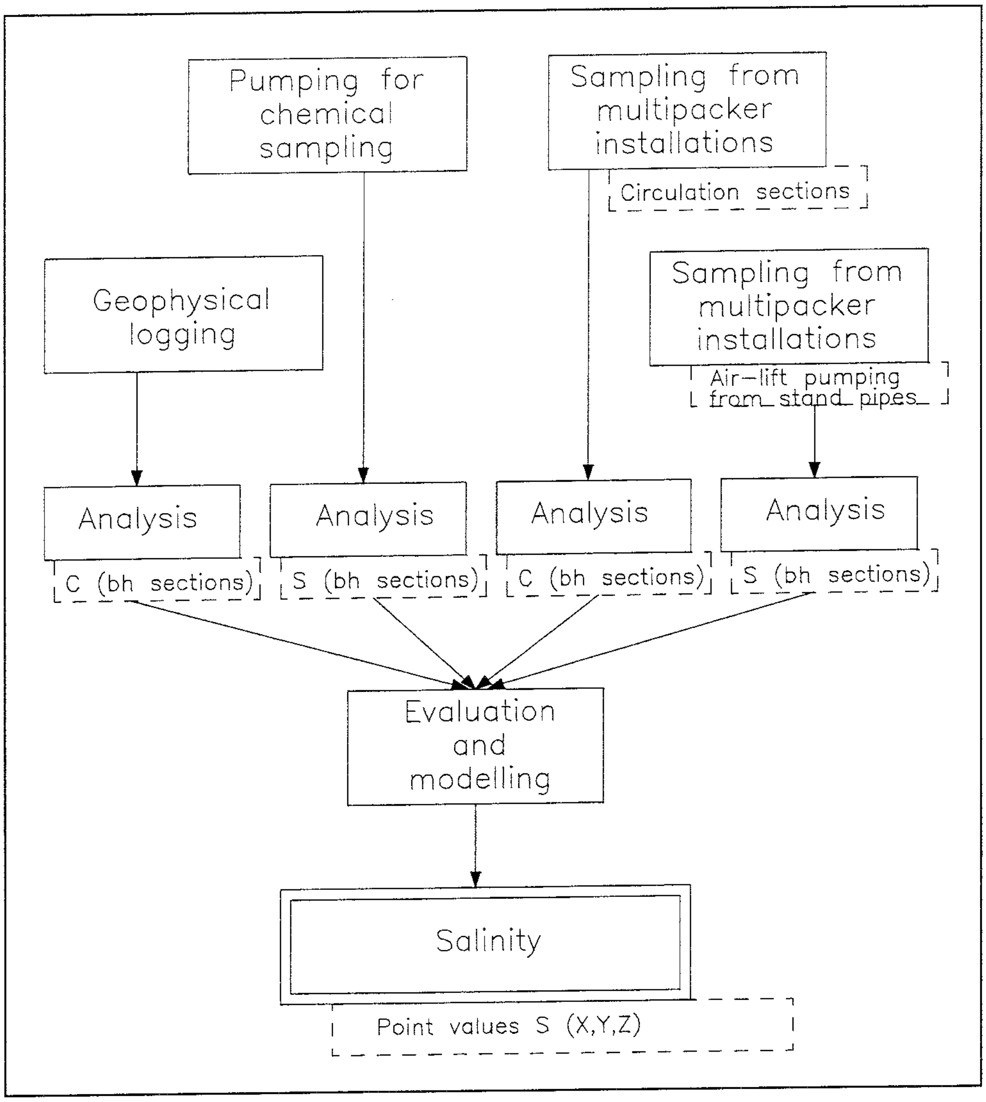


Figure 4-24. *Salinity – flow chart (C = electrical conductivity; S = salinity; X,Y,Z is coordinates).*

Chemical sampling in water circulation sections

Generally one or two sections in the cored holes are equipped with instruments for water circulation, enabling water samples to be taken. See Sections 4.3.8 and 4.4 for more details.

Electrical conductivity measurements in borehole sections

In most of the cored holes, one or two borehole sections are equipped with a conductivity sensor mounted at a certain level between two packers. Data loggers record electrical conductivity with the same frequency as the water levels in the pipes. (Examples of data in *Nyberg et al. /1992/*). The purpose was to simplify the measurement of fast changes.

Judgement – Site scale

Chemical sampling in water circulation sections and pumping for chemical sampling is probable the only method for obtaining good estimates of the salinity of the water in a certain borehole section.

Geophysical logging is more approximate and the salinity distribution along the open borehole may be disturbed due to internal circulation. Geophysical logging is also only possible when the borehole is open and thus it is only the initial – undisturbed – condition that can normally be measured with the method.

The salinity estimated from the air-lift pumping of the PEM pipes is probable fairly representative of the salinity of the water in the PEM pipes, but it is uncertain whether it is representative of the borehole section. The reason for this is that air-lift pumping has not always been performed long enough to pump out a volume 2-3 times the borehole section volume plus the volume in the PEM pipe. Pumping of low conductive borehole sections is rather time-consuming.

The electrical conductivity measurements in the borehole sections do not seem to be satisfactory. It is not possible to calibrate the conductivity sensors without taking the packers out of the borehole (which is why no calibration has been done after installation of the packers) and the conductivity sensors seem to be unstable.

4.3.10 Disturbed zone

General

The properties of the rock mass closest to the tunnel are expected to be different compared to the undisturbed rock. The reasons for these changes may be increased fracturing due to the blasting, gas intrusion from the blasting, gas dissolution in fracture apertures due to rock stress changes and possibly other reasons.

It is important to understand the hydraulics of the disturbed zone, as it may represent a possible flow path from a deep repository.

The pre-investigations were not intended to provide information on the disturbed zone. The disturbed zone will be studied during the excavation of the Äspö HRL and during the operating phase.

4.4 METHODS FOR GROUNDWATER CHEMICAL EVALUATION AND PREDICTION

4.4.1 Introduction

The purpose of the groundwater and geochemical investigations is to collect the data necessary for describing the distribution and the variation of chemical composition within the target area. These results are useful for the safety assessment with respect to the stability of the technical barriers and the long-term stability of the chemical system of the repository. Judgements of the usefulness of the different methods for modelling and predicting groundwater chemistry of the Äspö site are presented in the following sections and summarized in Table 4-6.

Geochemical investigations, mainly of fracture-filling minerals, are important for evaluating how the chemical environment will evolve with time. However, the most important aspect of the fracture mineral analyses is to verify the conclusions drawn from the groundwater chemistry data. Geochemistry has therefore not been separated into predictable subjects.

The groundwater chemistry of the low-permeable rock is very important for the stability of the engineered barriers in a repository. It is nevertheless nearly impossible to get a representative groundwater sample of the low-conductive rock via surface boreholes. For this reason no prediction is made of the chemistry of the groundwater in low-permeable rock, $K<10^{-8}$ m/s.

Table 4-6. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness		
		Regional, Site scale	Block scale	Detailed scale
Groundwater chemistry in major fracture zones	**Sampling in percussion-drilled holes**			
	- 3P	2	-	-
	Sampling in cored holes			
	- SDD	1	-	-
	- SPT	2	-	-
	- CCC	3	-	-
	Clean-out pumping	1	-	-
	Spinner survey	2*	-	-
Quality changes and redox conditions	**Sampling**			
	- CCC	-	2	-
	- SDP	-	1	-

Very useful = 3 Useful = 2 Less useful = 1 Not applicable = -

* Not used as a single method.

4.4.2 Groundwater chemistry in major water-bearing fracture zones

General

The identified major fracture zones are commonly also the major water-bearing features[1]. Their hydraulic properties can vary considerably over several orders of magnitude. Because of this the chemistry of the groundwater in the different zones can vary. Investigation methods are illustrated in Figure 4-25.

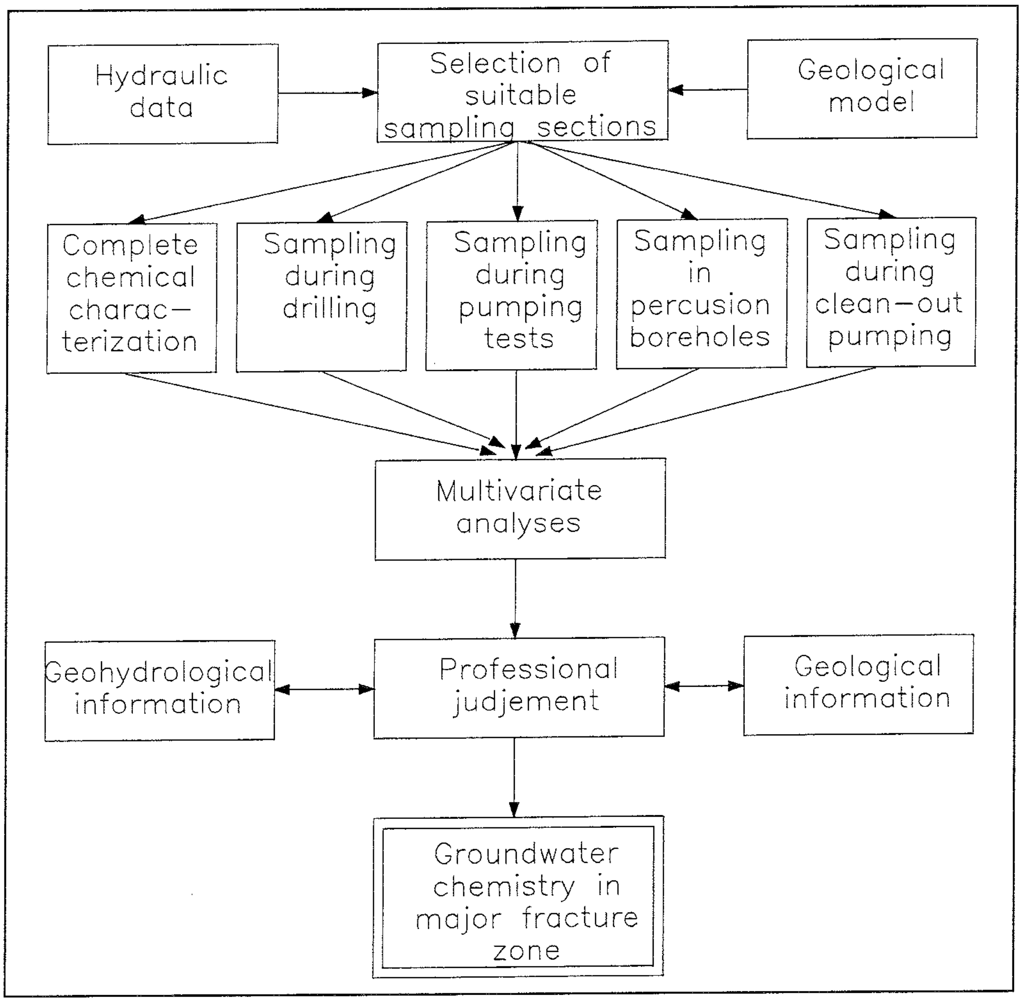


Figure 4-25. *Groundwater chemistry in major fracture zones – flow chart.*

[1] Depending on the rock stress situation and the genesis of the fracture zones, single open fractures can be more water-conducting than large fracture zones. In such cases, groundwater sampling and predictions are also made for the conductive single fractures.

Methods

Sampling in percussion boreholes (3P)

Points of intersection with water-bearing fractures are identified based on results from the drilling of percussion boreholes. On this basis a deep section of the borehole is packed off and pumped for one day. Groundwater samples are collected in the beginning and at the end of the pumping period. The samples are analyzed for main constituents: sodium, calcium, potassium, magnesium, silica, chloride, bicarbonate, sulphate, and additionally for oxygen-18 and deuterium.

Sampling During Drilling (SDD) of cored holes

Generally air-lift test have been conducted at every 100 m of length during the drilling of the cored boreholes. At the end of the pumping period of one hour a groundwater sample is collected. The sample is analyzed for main constituents and drilling water marker.

Sampling during clean-out pumping

When coring is finished, water is pumped out for one day in order to get rid of drilling debris and drilling water. At the end of the pumping a water sample is collected and analyzed for drilling water marker.

Spinner or flow meter measurements and geophysical logs

During clean-out pumping, water-conducting sections of the borehole are identified by the spinner survey. The results are used to select groundwater sampling sections. A combination of different geophysical logs has been evaluated for the same purpose, to find the water-conducting sections in the borehole.

Sampling during interference Pumping Tests (SPT)

Pumping tests of packed-off borehole sections are useful for groundwater chemical characterization. During the pumping, which lasts for 3 days, the mobile field laboratory is connected to the flowing water, which is analyzed daily for main constituents, redox-sensitive trace elements, and on the last day also for isotopes.

Complete Chemical Characterization (CCC)

Selected borehole sections (10^{-6}m/s<K<10^{-8}m/s) are sampled for approximately two weeks with the mobile field laboratory and the downhole measuring devices. The water is analyzed daily for main constituents and redox sensitive trace elements (for details, see Section 5.7). Once a week samples för isotope analyses are taken.

Judgement – site scale

The most important method for determining the chemical composition of the groundwater in major fracture zones has been the chemical characterization of the groundwater by means of the mobile field laboratory with the downhole measuring devices. The second most useful method is sampling during the interference pumping tests. A third useful method is sampling in percussion boreholes.

Sampling during drilling of the deep cored boreholes has not been useful unless combined with complete chemical characterization or sampling during pumping tests. Nevertheless, these data have been used for modelling of groundwater composition in fracture zones where no other kind of sampling was done. The results are sometimes questionable, since drilling water content has been as high as formation water content.

Sampling during clean-out pumping has not been useful, because the sample represents a mixture of all the conductive fractures from the entire borehole. The portion of drilling water was reduced during pumping, as verified by the analyses of drilling tracer.

The flow-meter or spinner survey has been the outstanding method for selecting borehole sections for complete characterization. A combination of different geophysical logs cannot provide the same exact definition of the hydraulic sections in the hole. A good picture is, however, obtained by combining fracture frequency from the core log, single point resistance and sonic logs */Smellie and Laaksoharju, 1992/.*

Complete Chemical Characterization and sampling during pumping tests are not interchangeable, since they are suited for different kinds of water-conducting sections. Sampling during pumping tests is done when the hydraulic transmissivity is greater than 10^{-5} m^2/s, whereas CCC is suited for borehole sections with a hydraulic conductivity of 10^{-6} to 10^{-8} m/s. Due to technical arrangements and the duration of the pumping tests it was not possible to obtain results on redox conditions from pumping tests. Moreover, in situ pH and Eh data and dissolved gas data can only be obtained from CCC, see discussion in Section 5.7.

A combination of CCC and SPT provides a synergy effect, since SPT is a much faster procedure and can thus be conducted in a large number of borehole sections within a relatively short time. A further advantage of SPT is the fact that the results of the interference test can be easily combined with the evaluation of the hydrochemical results.

The poor usefulness of SDD is due to the fact that the sample often contained up to 50% drilling water. The harmful effects of the drilling, the introduction of large quantities of drilling water, has been focused in the drilling at Äspö, where the so called telescope-type drilling technique[2] was used. The advantage compered to ordinary core drilling is that more water is pumped out of the borehole than what was pumped down as drilling water. This procedure was not sufficient to obtain representative samples during drilling. Further improvement of the drilling technique or an improved sampling technique is needed in order to get useful samples during drilling. However, the samples collected in both the CCC and the SPT campaigns were free from drilling water.

The groundwater chemistry of major fracture zones has not been defined on the block scale and the detailed scale.

4.4.3 Quality changes and redox conditions

General

The drainage into the tunnel system is expected to cause an enhanced water circulation in the surrounding rock volume. The enhanced water circulation causes water to mix in a different proportion than was the case under undisturbed conditions.

The investigated groundwaters are generally reducing at a depth of a few tens of metres, even though in some cases oxidizing waters are found at depths of 100 m. An oxidizing groundwater has an absence of ferrous iron, sulphide and manganese and has uranium in high concentrations (ppm levels). Dissolved oxygen in a measurable quantity solely defines oxidizing conditions. Reducing conditions are defined by the presence of ferrous iron, sulphide and manganese together with low uranium concentrations (ppb levels).

The enhanced water circulation might cause oxidizing groundwater to be transported to great depth because of fast flow in some conductive zone in the rock mass. This has been identified already in the pre-investigation phase of the project. However, the phenomenon is currently being studied, see Figure 4-26, in a fracture zone at Hålö where the tunnel is causing drainage at depth of 70 m. Geohydrological, geochemical isotopic and biological investigations are included, and the preliminary conclusion is that the drainage is not affecting the penetration depth at this particular location.

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[2] The telescope type drilling technique is an ordinary core drilling to 100 m. Before drilling is continued the hole is reamed to a diameter of 110 mm, making it possible to pump out the water from outside the drill rod when drilling is continued.

Quality changes can be of different types. A quality change resulting from sampling activities must be considered to the part of the evaluation and modelling (see Section 5.7). Another type of quality change is caused by the construction of the tunnel system, by which the undisturbed conditions are changed.

Oxygen in the air will diffuse into the rock matrix of the tunnel walls, causing an oxidation of the reducing minerals. At the same time the reducing groundwater seeping out from the rock contains dissolved iron which is oxidized and forms precipitates on the tunnel walls. At present there are no methods available that could be used to investigate these processes or provide a basis for predicting it. Co-precipitation phenomena are being investigated from the precipitated iron hydroxide. Methods for investigating quality changes and redox conditions are illustrated in Figure 4-26.

Methods

Complete Chemical Characterization

See Section 4.4.2.

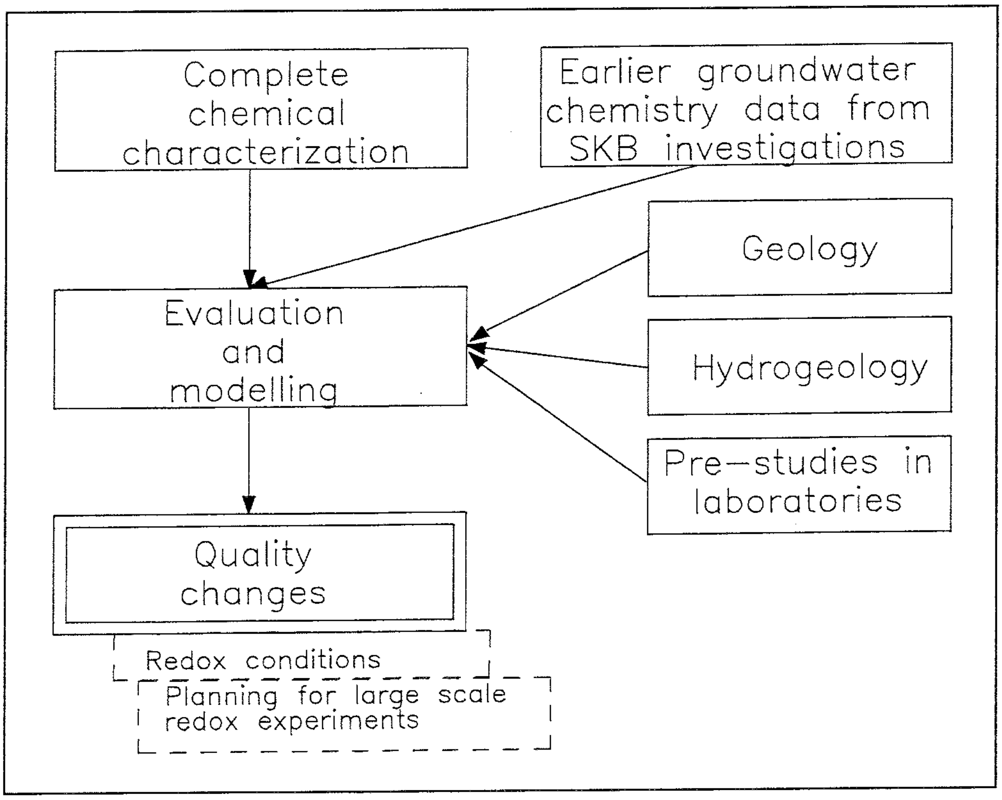

Figure 4-26. *Quality changes and redox conditions – flow chart.*

Sampling During Pumping tests

See Section 4.4.2.

Judgement – block scale

CCC was suited to defining the redox conditions in the groundwater whereas SDP failed, probably due to technical arrangements and perhaps too short a pumping time.

4.5 METHODS FOR MODELLING AND PREDICTING TRANSPORT OF SOLUTES

4.5.1 Introduction

The performed modelling of groundwater flow and transport in the Äspö project have shown that this type of modelling is both useful and feasible for describing groundwater movements in a fractured crystalline rock. An important factor to consider is the purpose of the modelling exercise. Three main purposes can be identified:

1. Modelling as a part of the characterisation, in order to assess the structure and connectivity of the rock volume.
2. Modelling of the natural and post closure conditions.
3. Prediction of conditions during excavation and placement periods.

Different tracer tests can thus be made in order to evaluate **flow paths** and **arrival time**, which in turn can be used to estimate the transport properties of the rock. In order to better estimate the groundwater flow it is important to understand the distribution of the **salinity** and **natural tracers** in the rock volume.

The groundwater chemistry data is useful for describing the groundwater flow situation, since the evolution and the mixing processes are dependent on the flow conditions, such as dispersion and residence time. Groundwater composition therefore can be used for verification and further refinement of the conceptual groundwater flow and transport models.

The chemical composition in general and the isotopic signatures in particular are useful for defining the origin and the residence time of the groundwater. However, the whole basis for a successful modelling of solute transport is that the numerical model is consistent with the conceptual groundwater flow model in the positions where the specific predictions are made as well.

During the pre-investigations only initial attempts have been made to test and model transport of solutes with non-sorbing tracers. During the operational phase of the Äspö HRL, different non-sorbing tracers and reactive transport will be focused upon. Judgements of the usefulness of the different methods for modelling and predicting groundwater chemistry of the Äspö site are presented in the following sections and summarized in Table 4-7.

Table 4-7. Presentation of usefulness of different investigation methods.

Subject	Methods	Usefulness		
		Regional, Site scale	Block scale	Detailed scale
Flow path and arrival time	Tracer test	3	-	-
Natural tracers	Sampling in percussion boreholes Sampling during drilling Sampling during interference tests Complete chemical characterization Monitoring of chemistry and the natural groundwater flow in permanently packed-off borehole sections	- 1 3 1 3		
Saline interface	See *Table 4-5*			

A general conclusion is that the versatile computing tools of today calculate what the conceptual model and its realization of the specific case describes. This means that a general hierarchy of entities to make a reliable model is:

1. The conceptual model of the system.
2. The structural model.
3. The properties of the structural units.

This means that if at one level all is wrong, the lower levels will probably also be wrong.

The approach to use is dependent of the entity to model – groundwater flow in large volumes may be addressed by the equivalent porous media approach, but fluxes in small scale requires a discrete fracture approach. These different approaches place different requirements upon the characterisation of the modelled volume, with increasing detail resolution and conceptual refinement with decreasing geometrical scale.

There seems to be a general consensus that a more fundamental understanding of transport processes is necessary. In order to obtain this experiments in different scales accompanied by modelling are required. However, there is a general tendency to underestimate travel time with the commonly used modelling concepts, which may to some extent be comforting.

4.5.2 Flow paths and arrival time

General

The flow within a rock volume is governed by boundary conditions, transmissivity of water-bearing zones and hydraulic conductivity between the water-bearing zones, as described in Section 4.3.

The following experiences were encountered.

Methods

Tracer test

During the last phase of pre-investigations one large-scale tracer test, called Long-term Pumping Test 2 (LPT2), was carried out and during the excavation of the tunnel one small tracer test was carried out in NE-1.

During LPT2 tracers were injected into six borehole sections with intermittent decaying pulse injection, see Figure 4-27. The tracer is circulated by a pump from a tracer test unit down to a section between two packers and back up to the tracer unit, see Figures 4-20 and 4-28. The tracer injection started about 400 hours after the pumping of the borehole KAS06 started.

In the pumped borehole KAS06 water samples were taken with a multi-level sampling device and from the pumped-up water, see Figure 4-29.

Judgement – Site scale

Tracer tests have to be performed in order to obtain transport parameters, see Figure 4-30. The tests are rather difficult, expensive and time consuming to perform. It is therefore important to plan the test itself well and also to avoid disturbance from other activities, such as drilling.

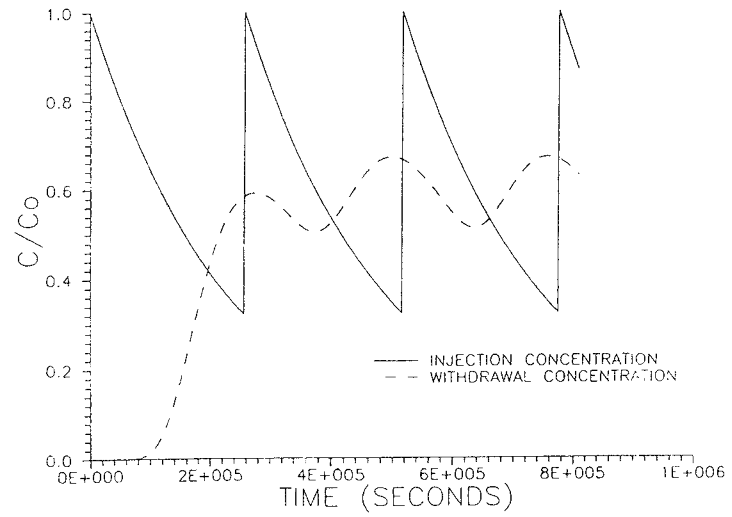

Figure 4-27. *Intermittent decaying pulse injection. Example of a theoretical breakthrough curve resulting from an intermittent decaying pulse injection in a stream tube 70 m long and with a cross sectional area of 1 m² /Rhén et al., 1992/.*

The general tendency is that the predicted travel times for the tracer that arrived are too short. Particularly, some of the tracers that were injected in some sections in the tracer tests never showed up in the pumping borehole. Some of this may depend on errors in the structural model but also poor calibration of transport parameters, because model calculations predicted that they would arrive. Another reason may be, that the test time may have been too short. There is, however, a general agreement, that more fundamental understanding of transport processes is necessary. Observed tracer losses may be caused by a number of processes, ant it is important to resolve which ones are important, and how they can be incorporated in flow modelling. In order to do that, a suite of experiments in different scales are required as well as theory development.

4.5.3 Natural tracers

General

The distribution of salinity in the Äspö groundwater makes it possible to identify the flow taking place in major fracture zones and conductive single fractures. In addition to this, oxygen-18 and tritium data are used. The hydraulic head is the driving force for the water flow. The magnitude and the direction of the gradient is based on the predicted inflow to the tunnel. Investigations including natural tracers are illustrated in Figure 4-31.

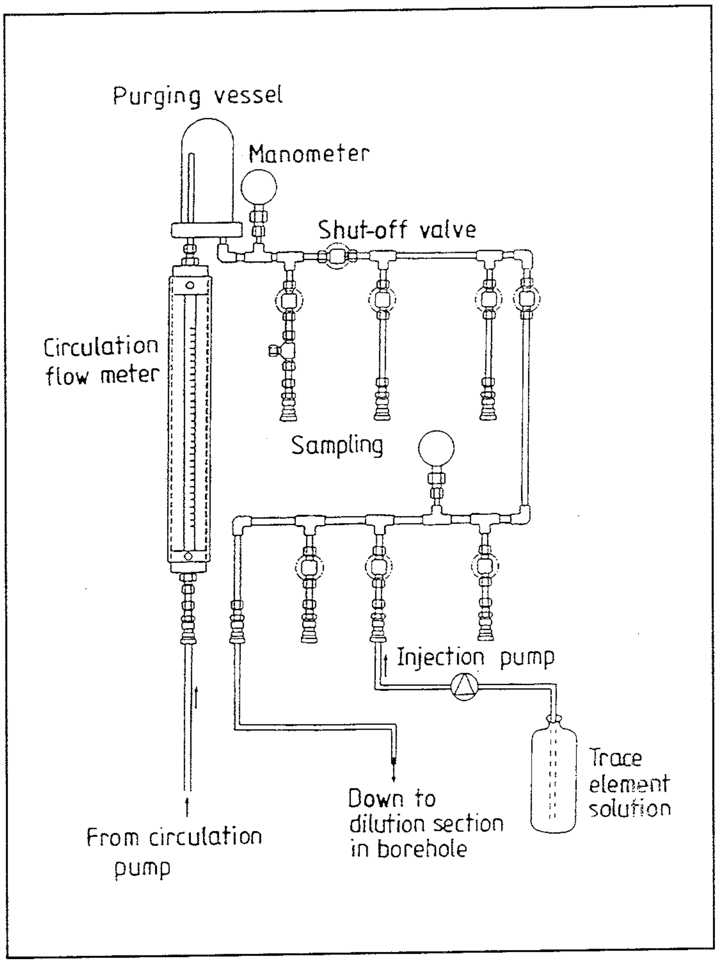

Figure 4-28. Schematic illustration of the tracer unit for tracer injections into the circulation system and water sampling /Almén and Zellman, 1991/.

Methods

Sampling in percussion boreholes

See Section 4.4.2.

Dilution measurements

See Section 4.5.2.

Sampling during drilling

See Section 4.4.2.

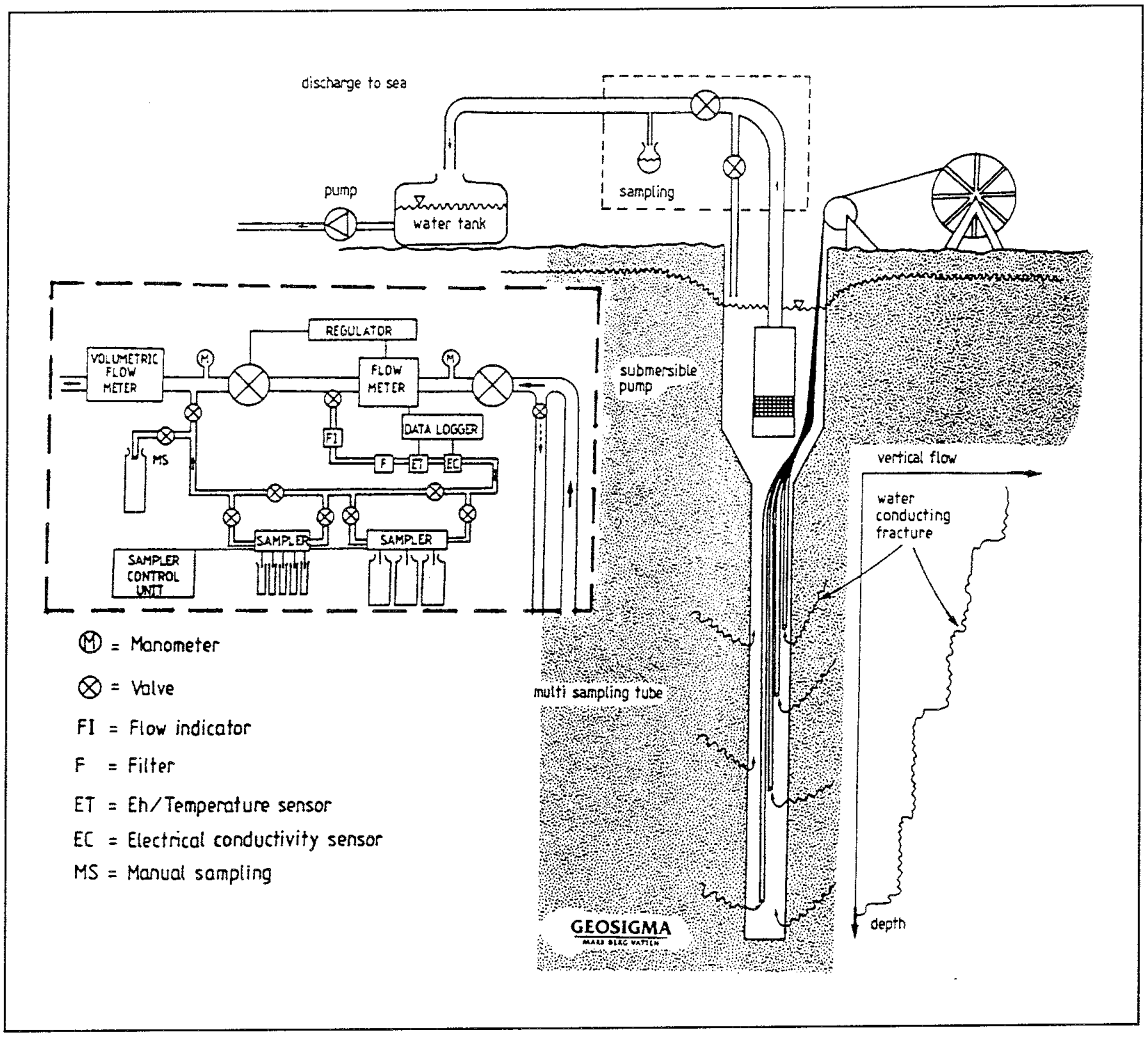

Figure 4-29. *Equipment set-up for tracer test carried out during LPT2. On-site recording and analysis of tracers in the pumped water and in-situ sampling of water in inflow sections of the borehole (identified from flow meter logging) by a multi-level sampling device /Almén and Zellman, 1991/.*

Sampling during interference tests

See Section 4.4.2.

Complete Chemical Characterization

See Section 4.4.2.

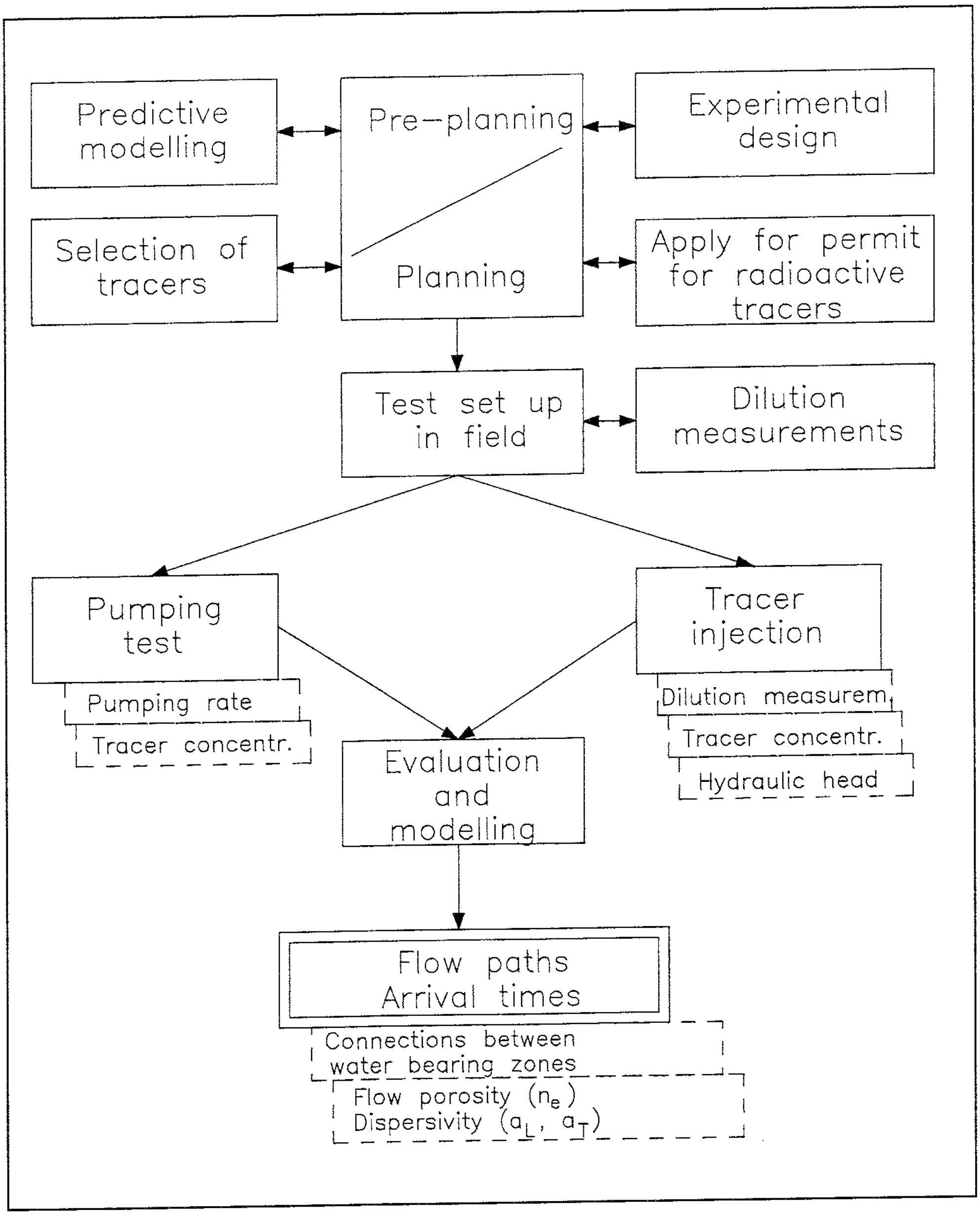

Figure 4-30. *Experiment flow chart to identify flow paths and arrival time.*

Monitoring of the chemistry and the natural groundwater flow in permanently packed off borehole sections

After completion of the investigations in the deep cored holes, a permanent packer arrangement was installed. With this arrangement it was possible to monitor the pressure in up to six borehole sections and sample water from two sections. The level of the sections is selected at installation and cannot easily be changed afterwards.

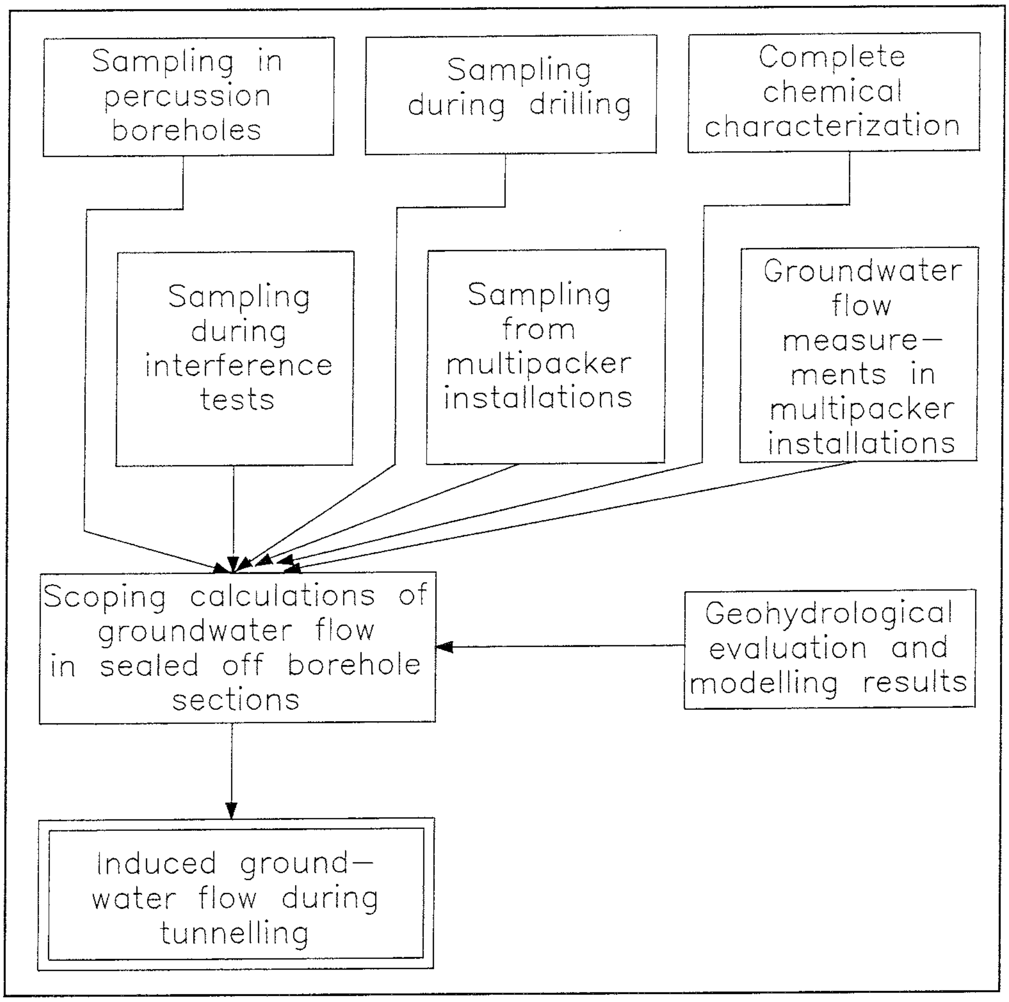

Figure 4-31. *Flow chart for analysis of natural tracers.*

Judgement

The most important methods for characterisation of solute transport under natural conditions on the site scale have been complete chemical characterization and sampling during pumping tests. Both of these methods focus on a specific water-conducting borehole section which has previously been identified by e.g. spinner surveys. Due to the high pumping capacity of the pumping test, that method has been more useful for identifying the direction of the connectivity, i.e. if the change is towards more or less saline water, implying downwards or upwards contact.

The different "tracers" do not necessarily point in the same direction. In some cases a highly saline groundwater can have tritium concentrations indicating a proportion of modern water in an old water. It is therefore more important to use several natural tracers than to select the most useful sampling method. In any case it is always important to have a representative sample. For this reason it is impossible to use the data obtained during drilling and clean-out pumping, since they are often contaminated by drilling water (for details, see Section 5.7).

The usefulness of the different isotopes can be described briefly.

Oxygen-18 is useful for describing the temperature of the recharged meteoric water. Because the temperature has changed dramatically since the most recent glaciation, the oxygen-18 values can be used to indirectly define the residence time of the water. This method is useful for giving a semi-quantitative residence time, based on present historic knowledge of the salinity Baltic and the climate changes in the Baltic Basin.

Carbon-14 is the classic groundwater age determination method. For deep groundwater the analyses are performed on the bicarbonate dissolved in the water, or on the organic carbon (fulvic and humic acids) dissolved in the water. In order to give correct results these substances should be conservative, i.e. have the same history as the water. This is, however, never the case and therefore the carbon-14 date cannot be directly interpreted as the age or residence time of the water. Typically the analyses performed on the bicarbonate give too high age, whereas the analyses performed on the organic carbon are perhaps more correct. At Äspö all carbon-14 data are obtained from the bicarbonate, since the content of organic substances was too low for analyses.

Tritium is a good tracer for determining the proportion of modern water. Tritium levels above a background of ca 0.3 TU (tritium units) clearly indicate the presence of water that has infiltrated the ground since fusion bomb tests in the atmosphere were started in the late 1950s. In the period since then the amount of tritium in precipitating rainwater has varied from 2500 TU in 1963 to a present-day value of about 100 TU.

To evaluate the history and the residence time of the groundwater it is necessary to be able to evaluate the different isotope data, and put them in relation to other natural tracers, i.e. cloride.

4.5.4 Saline interface

General

The salinity of groundwater increases with depth at several places. Depending on the salinity distribution with depth and the type of groundwater flow problem to be studied, it is necessary to include density driven flow (depending on salinity) in order to model the groundwater flow correctly. Variation in the salinity field before and during the construction phase is also a useful data set for interpretation of the groundwater flow in the rock mass.

The fresh/saline water interface was calculated for the Äspö rock mass by means of the groundwater flow model, including predicted seepage to the tunnel.

Methods

Measurement of the saline interface is presented in Section 4.3.9.

Judgement – Site scale

Natural tracers, including salinity and isotope data, have been used as a complementary data set in order to understand the natural hydrologic conditions as well as the structure and connectivity of the rock. No doubt, these data can be of more extensive use provided that we gain a more thorough understanding of their coupling to the hydrogeology and groundwater exchange in an area. A special problem at Äspö was that the large scale, long term transients of the groundwater conditions were not considered until late in the project. A process where characterisation, modelling and hydrochemistry is coupled closely together from the very start is therefore strongly advocated for future site investigations.

4.6 METHODS FOR MECHANICAL STABILITY MODELLING

4.6.1 Introduction

Prior to the excavation of the Äspö laboratory predictions were presented for the rock-mechanical conditions. The predictions covered conditions such as rock quality, rock stress, stability, mechanical characteristics and fracture properties */Gustafson et al., 1991, Stille and Olsson, 1989 and 1990/*.

The predictions were based on selected investigations performed in the comprehensive pre-investigation programme. The methods used for the rock-mechanical stability modelling are briefly described in the following. The usefulness of the different methods is then discussed.

In some cases the investigation methods have been used for predictions on different scales. Their usefulness has then been discussed separately for different scales.

The results from the different investigations have earlier been reported in several reports. Judgement of the usefulness of the different investigation methods is summarized in Table 4-8.

Table 4-8. Judgement of usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL.

Subject	Methods	Usefulness		
		Regional, Site scale	Block scale	Detailed scale
Rock quality	**Study of terrain, topographical mapping and exposed rock**	2	1	-
	Seismic refraction	2	1	-
	Borehole investigations			
	- Core logging	3	3	-
	- Water loss measurements	3	2	-
Rock stress	**Rock stress measurements**			
	- Overcoring	3	2	1
	- Hydraulic fracturing	3	2	1
Long term stability-stability*				
Mechanical characteristics				
- Compressive strength	**Unconfined compressive tests**	-	-	3
	Empirical references	-	-	2
- Elastic moduli	**Unconfined compressive tests**	-	-	3
	Empirical references	-	-	2
- Poisson's ratio	**Unconfined compressive tests**	-	-	3
	Empirical references	-	-	2
- Brittleness ratio	**Unconfined compressive tests**	-	-	1
	Empirical references	-	-	1
Fracture surface properties	**Shear testing**	-	-	2
	Graphical references	-	-	2
	Empirical characterization	-	-	2

Very useful = 3 Useful = 2 Less useful = 1 Not applicable = -

*Note: *Prediction of long-term stability will be based on a number of parameters, including rock quality and rock stress. The methods used for prediction of stability are therefore similar as for these individual parameters. Other factors that also affect stability are the geometry of the underground opening and the excavation method used.*

4.6.2 Rock quality

General

A general overview of the rock quality will contribute important information that could be used for making an initial stability model for an area.

To quantify the rock quality the Rock Mass Rating system, RMR, was applied.

Rock quality is dependent on a number of geological parameters such as rock type, fracture frequency, fracture properties etc. Final stability conditions will also be affected by rock stress and water conditions and the geometry of the underground opening.

On the site scale, rock quality and the distribution of rock quality along the tunnel were also determined based on what rock types are present and the presence of fracture zones or other anomalities in the structural model. To characterize rock quality on the site scale, similar methods were used as for creating a geological structural model with identified rock types, location and orientation of fracture zones and water-bearing structures.

On the block scale, rock quality was determined based on the properties of the various rock types and their distribution.

Methods

Study of terrain, topographical mapping and exposed bedrock

A visual inspection of the areas was performed to get general information on the occurring rock types. Rock type properties, such as fracture frequency, degree of weathering, and preliminary mechanical characteristics were also observed, see Figure 4-32.

Seismic refraction

Seismic refraction profiles were used to obtain information on seismic velocities. Profiles were performed both on land surface and in sub-sea areas.

Borehole investigations

For characterization of rock quality, coring drilling and core mapping were performed in a number of holes. The holes were drilled in different orientations to obtain information on the existence of steep and sub-horizontal fractures.

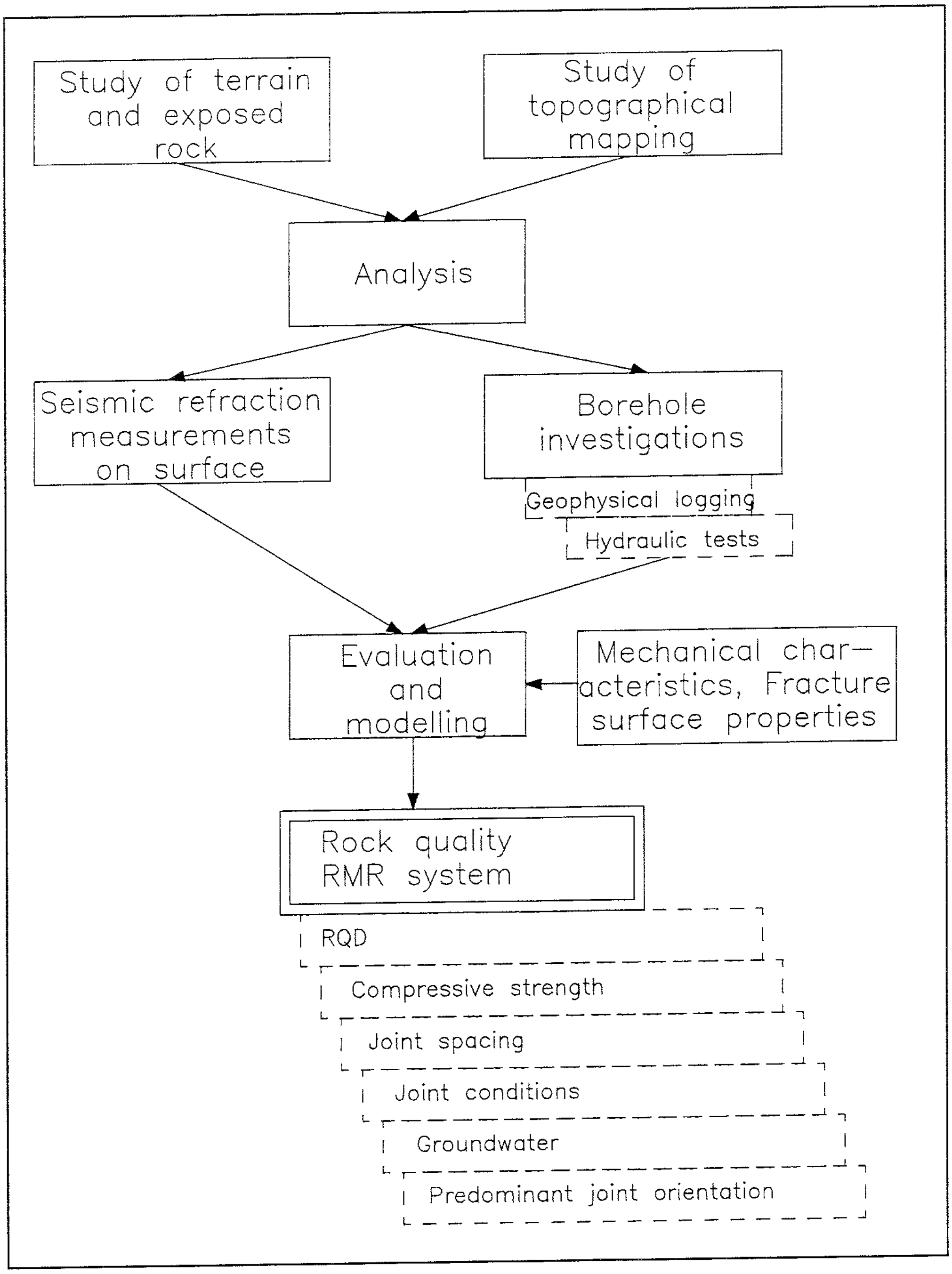

Figure 4-32. *Flow chart of the rock quality investigations.*

The cores were logged to give further information on the distribution on different rock types and to determine their fracture frequencies (RQD), fracture distance and fracture surface properties (JRC, JCS and fracture fillings). RQD = Rock Quality Design is a classification system for drill-cores, JRC = Joint Roughness Coefficient, JCS = Joint Compressive Strength.

Testing of mechanical characteristics and fracture surface properties

See 4.6.5 and 4.6.6.

Judgement – Site scale

Visual inspection was useful to obtain general information on the bedrock quality in the area. Although the inspection only provided information representative for the surface, it served as a good basis for further investigations and interpretation of other investigations. Surface information on general rock type characteristics can in many respects be extrapolated to rock conditions in deeper areas.

The information from seismic refraction investigations provides only a very rough idea of rock quality, however, and was not used in evaluation of rock quality.

The visual inspection was also valuable for a classification of the area for further comparisons with experiences gained from other projects and investigations under similar rock conditions.

The results from the core logging provided valuable information on rock quality and quality distribution.

Judgement – Block scale

The detailed logging of cores provided very useful information on the distribution of different rock types and their rock quality.

4.6.3 Rock stress

General

On the site scale, rock stress conditions will help in determining the orientation of existing fracture zones. Rock stress conditions also affect hydraulic pathways in the area. Changes in rock stress conditions may also release future movements in existing fracture zones. Current rock stress conditions are also a major factor which in determining general stability conditions in the area.

A lot of experience in measurement of stress orientations and magnitudes has been gained from other projects. If it can be confirmed that the rock stress conditions at a new site conform to general behaviour, then experiences from other sites can be applied.

One of the main objectives of determining rock stress conditions is to verify that the present stress levels are normal, i. e. not exceptionally high or low.

For the site- and block-scale the rock stresses were estimated as the average rock stress condition to be anticipated within a rock volume of site or block size. For the detailed scale the rock stress conditions were estimated for individual readings within the rock mass.

On the block scale, variations in rock stress conditions are important to ascertain. Variations in rock stresses on the block scale will determine the potential for e. g. rock burst and stability problems due to low stresses and provide important data for numerical stability modelling of underground facilities.

Variations in rock stresses on the detailed scale will provide information on local variations in different stability aspects.

Methods

Rock stress measurements

Rock stress measurements were performed in three deep boreholes to get a general idea of the stress conditions in the area, see Figure 4-33.

Two holes were located on the southern part of Äspö and one on the northern part. The measurements in two of the holes were performed by hydraulic fracturing and in one hole by overcoring. The majority of the readings were obtained by hydraulic fracturing */Bjarnason et al., 1989/*.

Judgement – Site scale

The measurements provided valuable information for the interpretation of current rock stress magnitudes and orientation. Hydraulic fracturing was used to get a greater number of readings, while the overcoring technique is usually believed to provide higher accuracy, especially in determining stress orientation.

Judgement – Block scale

The measurements provided valuable information on rock stress conditions on the site scale. To get a clear picture of rock stress conditions on the block scale, more measurements are recommended.

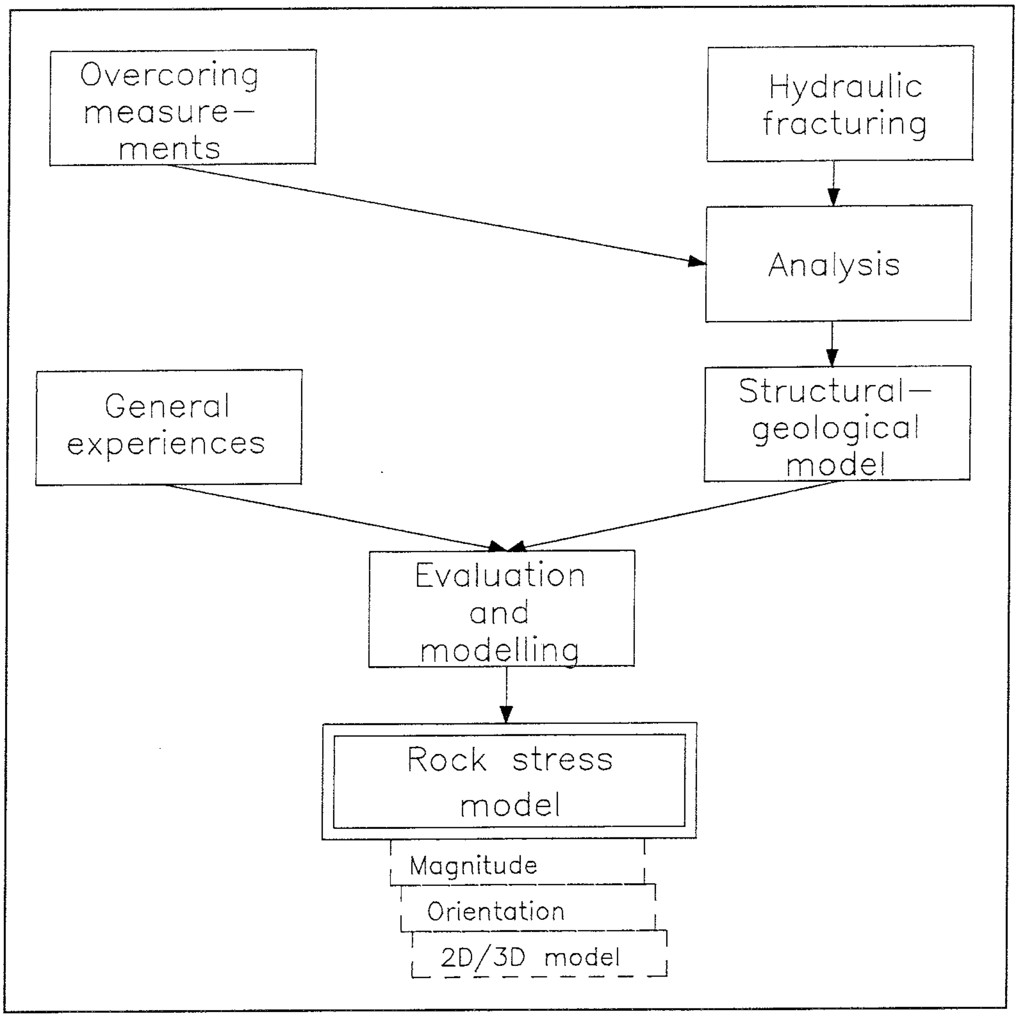

Figure 4-33. Flow chart of the rock stress investigations.

Judgement – Detailed scale

The orientation and magnitude of rock stresses have proved to be unsuitable for prediction on the detailed scale. The large variation of rock stresses in a rock mass, as well as between individual measurements, makes it extremely difficult to make a representative prediction on the detailed scale.

4.6.4 Long-term stability – Stability

General

By long-term stability is meant stability against future potential movements in the rock. Potential movements is supposed to be concentrated within existing fracture zones.

It is very difficult to predict future movements with any accuracy today. A general evaluation can be made based on the orientation of the major principal stresses in combination with the shear strength and orientation of existing fracture zones.

Stability conditions on the block scale are dependent on factors such as rock quality, rock stress conditions and the geometry of the underground facility.

Stability conditions for different tunnel geometries were not studied in the Äspö project.

From a construction point of view it is also essential to discuss suitable support measures to achieve desirable rock stability in the excavated underground facility */Stille et al., 1990/*.

Methods

Prediction of stability is based on a number of parameters including rock quality and rock stress. For estimation of rock quality the RMR system (CSIR Geomechanics classification) was applied. The RMR system (Rock Mass Rating) comprises individual estimations of rock strength, RQD, joint spacing, joint conditions and groundwater conditions. Finally an adjustment is made for the effect the main joint orientation has on the type of facility in question. The methods used for stability prediction were therefore similar to those used for the individual parameters. The methods used for stability analysis may include limit equilibrium analysis and ground reaction curve in order to study stability and sensitivity to stress changes, see Figure 4-34.

Judgement – Site scale

Together with the geological structural model, the information gained on rock quality and rock stress conditions was valuable for a discussion of long-term stability. However, it is not possible to define the accuracy or realism of the conclusions of the discussion based only on this work.

Judgement – Block scale

The methods described above and based on fracture surface properties, rock quality and rock stress were adequate for predicting stability conditions on the block scale.

The investigations proved to be adequate for a discussion of required support measures in the tunnel.

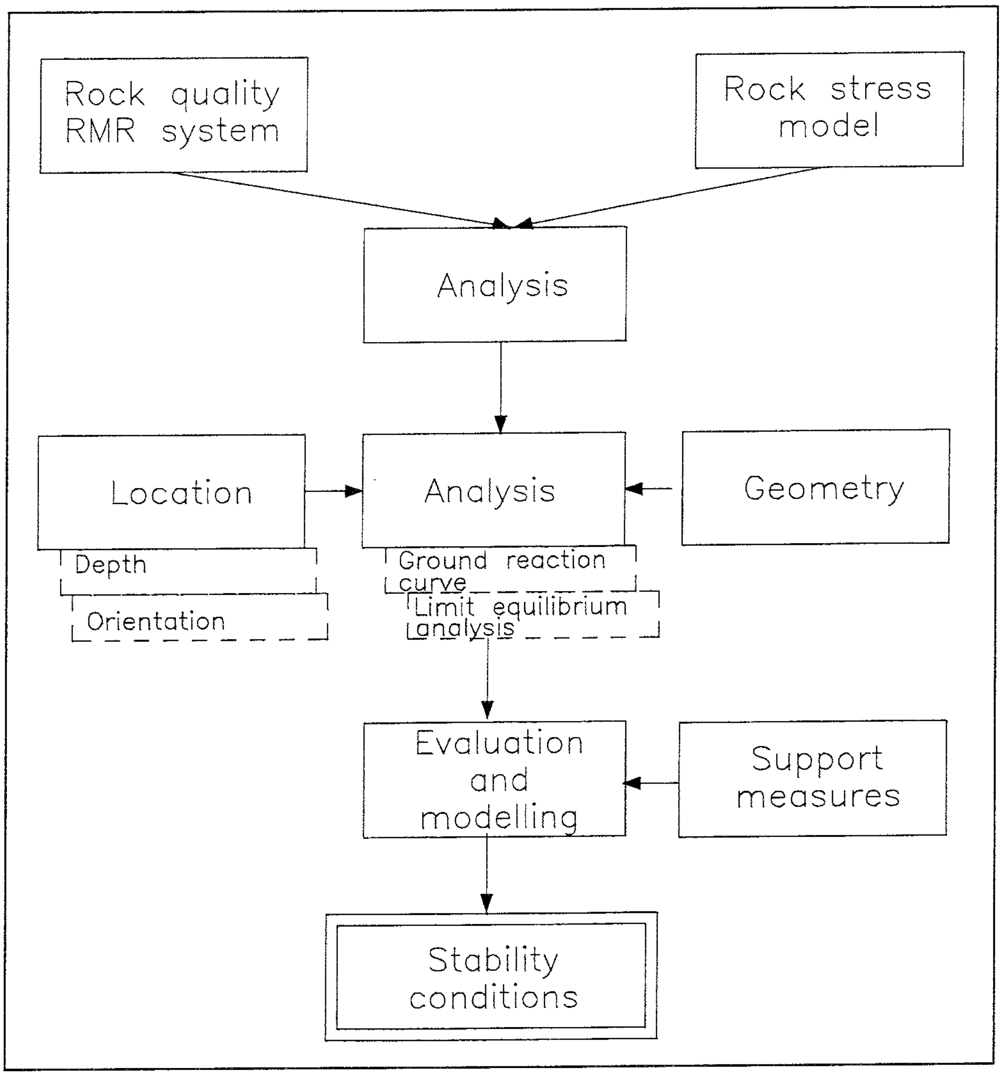

Figure 4-34. *Flow chart of the Long Term Stability investigation programme.*

4.6.5 Mechanical characteristics

General

To analyze stability conditions on the block and detailed scale, the mechanical characteristics of the rock must be investigated. The mechanical characteristics predicted prior to the excavation are rock strength, elastic moduli, Poisson's ratio and brittleness ratio */Stille et al., 1989/.*

In rock conditions dominated by hard rock, investigations to determine mechanical characteristics and their frequency should be concentrated on defining a range or approximate value of the parameters of interest.

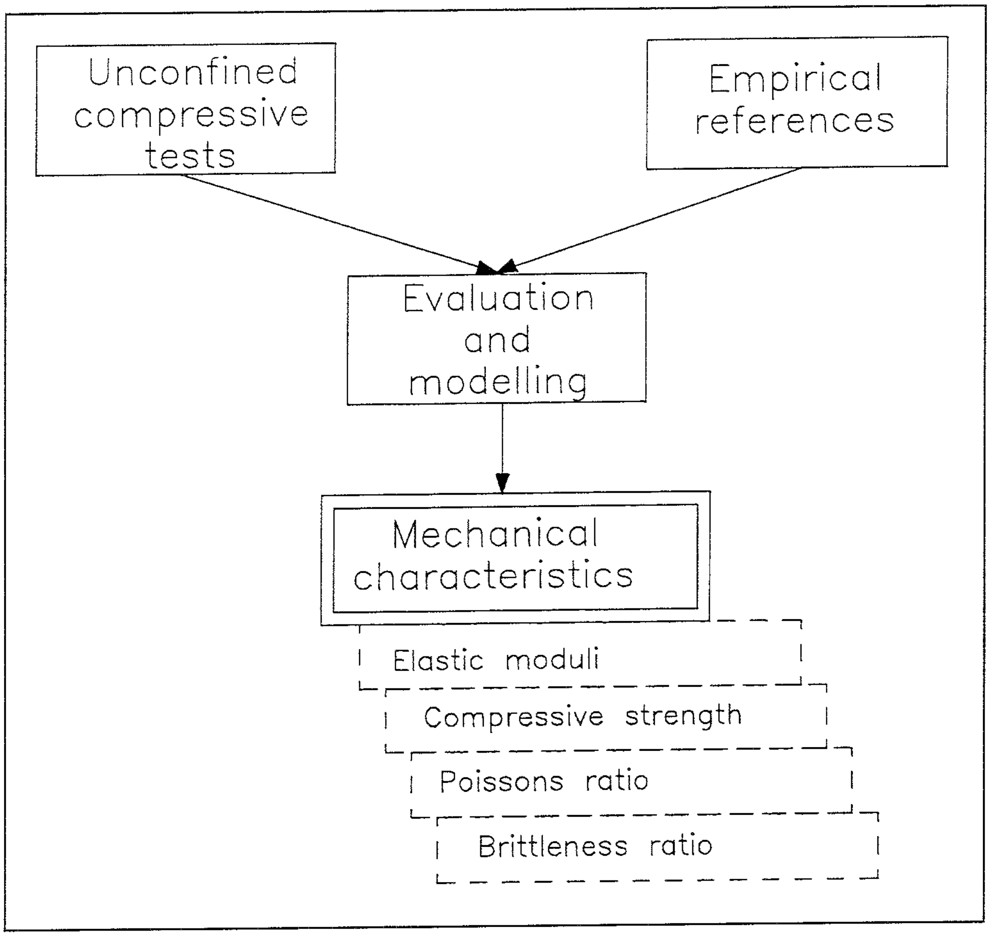

Figure 4-35. *Flow chart of the mechanical characteristics programme.*

Methods

Unconfined compressive test

The mechanical characteristics were defined by uniaxial compressive tests on core samples. The cores used for the testing were all taken from one single borehole. The specimens were prepared before testing was performed. The compressive tests were carried out in a press with very high stiffness. The high stiffness was necessary to detect deformations during failure, which determined the brittleness ratio /*Brown, 1981*/, see Figure 4-35.

Empirical references

The mechanical behavior of Scandinavian rock types is in general fairly well known. A comprehensive documentation has been accumulated over the years and a considerable body of experience is available.

With general information on the conceptual geological model and what rock types are present an initial prediction of mechanical behavior can be made based on experience from other projects.

Judgement – Detailed scale

The uniaxial compressive tests were very useful in establishing a range of what values of compressive strength, elastic moduli and Poisson's ratio could be expected. Although only a small number of tests were performed on each rock type, the testing was very valuable for further quantification of the general properties of the different rock types on the detailed scale.

Brittleness testing is rather difficult to perform and can only indicate if brittle rock is to be anticipated. Brittle rock could generate failure of intact rock, commonly described as rock burst. Rock burst is, however, a very complex phenomenon which is generally difficult to predict. All additional information that could possibly contribute to the discussion of the risk for rock burst is therefore valuable.

General experience of the mechanical characteristics of different rock types is very valuable when setting up a prediction and should always been taken into account.

4.6.6 Fracture surface properties

General

The fracture surface properties predicted prior to the excavation were Joint Roughness Coefficient and Joint Compressive Strength */Stille et al., 1989/*. These values constitute important information for quantification of stability conditions in different rock types.

Methods

Laboratory testing – shear testing

The Joint Roughness Coefficient was determined by shear testing in the laboratory. Existing joints were sheared after being grouted into a steel cylinder. Shearing was performed several times with different normal loads, see Figure 4-36.

Graphical references

The JRC values were also determined by comparing fractures with graphical references in well established textbooks */Brown, 1981/*.

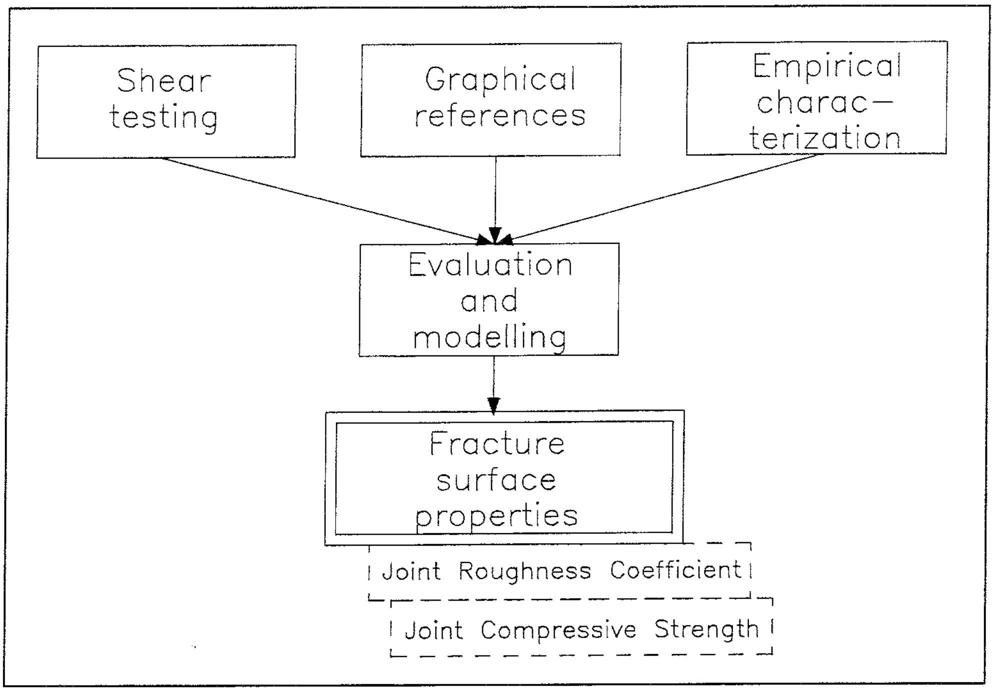

Figure 4-36. *Flow chart of the fracture surface investigations.*

Empirical characterization

Joint Compressive Strength was based on testing of JRC values. JRC values determine by empirical characterization the JCS for different rock types */Brown, 1981/.*

Judgement – Detailed scale

Shear testing of cores to determine JRC proved to be vaulable, but the testing procedure is rather involved and only a few samples were tested.

The use of graphical references was valuable for determine the JRC values. The use of graphical references enables many tests to be performed since the testing procedure is quick and does not require any sophisticated instruments.

The empirical characterization of JSC values did not provide reliable information. A more proper way to determine the JSC value would be to perform the Schmidt Hammer test on a large number of representative joint surfaces */Brown, 1981/.*

5 DISCUSSION OF THE USEFULNESS OF THE DIFFERENT METHODS

5.1 BACKGROUND

While the evaluation in chapter 4 was concerned with the usefulness of the different investigation methods in the process of developing modelling and prediction parameters, this chapter discusses each method separately. The advantages and disadvantages of the method for different purposes and under different conditions, when used individually or in combination with other methods, are aspects that will be addressed.

5.2 LINEAMENT STUDIES

5.2.1 General

Lineaments in the Simpevarp area have been interpreted on a regional scale using EBBA II image analyses of digital altitude data. Structural analysis of terrain features on a more detailed scale, based on topographical maps, was used as a complement to the regional lineament study.

5.2.2 Lineament interpretation using EBBA II techniques

The main purpose of using this method was to reveal the major extensive lineaments (which are possible fracture zones) and large rock blocks in an approx. 25 x 50 km area. The EBBA II image processing system has been used on five different digital terrain models: Hill-shading, Residual elevation, Edge texture, Line texture and Iso-elevation. All these models are based on altitude data but reveal different aspects of the landscape and thus emphasize different characteristics. Relief maps produced by hill shading techniques may reveal the extensive lineaments and large scale rock blocks. Residual elevation maps give some idea of the relative quality of the bedrock as regards the degree of fracturing and major rock block configurations.

Edge texture maps provide a measure of the density of structures. Different types of lineaments, such as valleys and slopes, can be distinguished and the aspect of the slopes is indicated, see Figure 5-1.

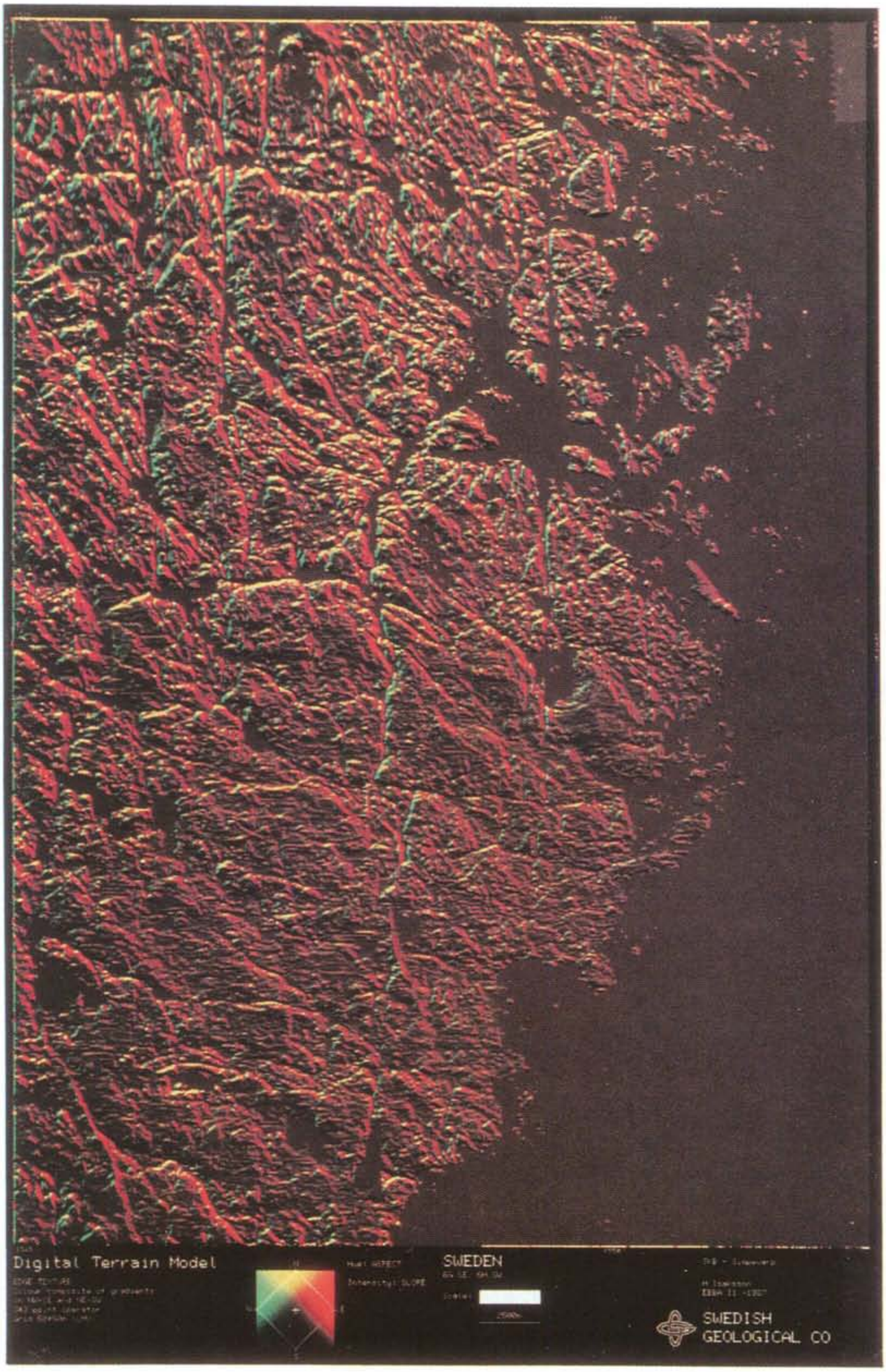

Figure 5-1. *Digital terrain model: Edge texture /Tirén et al., 1987/.*

Line texture maps, though very directionally dependent, can indicate neotectonic structures, since they particularly reveal sharp and narrow structures. Line texture maps can indicate extremely flat surfaces as areas with a uniform greytone. Relatively narrow passages (up to 100 – 200 m wide) with a uniform greytone may indicate wide fracture zones covered by soil.

Iso-elevation maps combined with residual elevation maps are useful for defining rock blocks and for studying the relative vertical displacement of blocks of different orders.

Lineament interpretation of relief maps and structural analysis based on different digital models on a regional scale seem to provide a very good basis for further site investigation work, especially when this interpretation has been compared with the topographic expression of aeromagnetic lineaments.

There is often a high correlation between the topographic lineaments and structures on the ground, but it can be difficult to identify the nature of the structures and to recognize gently dipping structures in an area of such low relief as Äspö.

Advantages

Possible to conduct the lineament study at an early stage of the pre-investigation without field work.

Disadvantages

The study requires altitude data which – if not already available – are rather expensive to acquire. Correlation with airborne geophysical data is necessary to obtain a good result.

5.2.3 Structural studies based on topographical maps

Structural analysis of terrain features on a more detailed scale was performed as a complement to the regional study of lineaments in the Simpevarp area. The study was based on topographical maps (scale 1:4 000), with a 0.5 m contour interval.

There is often a good correlation between regional and local studies of lineaments in a given area. Studies of lineaments on regional and local scales complement each other. Major lineaments are conspicuous on the regional scale but are often expressed as gentle open structures on the local scale and may therefore be overlooked in an interpretation of a very small area. The regional study provides the framework for the local study.

Advantages

A good and inexpensive method on the local scale as a complement to the lineament study on the regional scale.

Disadvantages

Not very useful in topographically smooth areas.

5.3 GEOPHYSICAL METHODS

5.3.1 General

Geophysical methods have been used in order to support the lithological and structural analysis of the Simpevarp area. Airborne geophysical surveys (magnetic, horizontal loop EM, VLF and radiometric) at the regional stage of the pre-investigations were later supplemented by more detailed profile measurements from the ground surface (magnetic, VLF, resistivity, gravity and seismics).

5.3.2 Airborne geophysics

The main aim of the airborne geophysical survey was to obtain a general basis for lithological and structural geological modelling on a regional scale of the Simpevarp area. The survey was performed at an initial stage of the pre-investigation work. The magnetic, and to some extent also the radiometric, method was used in order to reveal high magnetic massifs of basic rocks and low magnetic circular granitic structures.

The magnetic method and the electric methods were also used for mapping possible fracture zones.

Aeromagnetic methods combined with gravity measurements were found to be very useful, especially for studies of a regional nature, i.e. for investigating the boundaries of the Götemar-Uthammar diapirs in three dimensions. The magnetic content of these granitic rocks usually differs from that of the surrounding rocks and they were therefore good targets for both these methods. Based on these investigations it was possible to carry out an initial three-dimensional lithological-tectonic modelling on a regional scale.

The aeromagnetic method was also used for mapping possible fracture zones in which oxidation of magnetite to non-magnetic minerals causes magnetic minima. Aeromagnetic and VLF measurements seem to be far superior to EM measurements for interpreting possible fracture zones. Coincident magnetic and VLF fracture zones may be of special interest in the search for the most permeable fracture zones. It is important, to check the aeromagnetic data with ground investigation methods before final interpretation. The VLF measurements, however, are strongly disturbed by the salt water in the coastal area outside Simpevarp. The high outcrop density in the area in question made the radiometric measurements valuable in the bedrock interpretation work.

Petrophysical data, based on physical laboratory measurements of a large number of representative samples, are necessary for making a good interpretation of the geophysical data.

Advantages

Possible to perform at an initial stage of the pre-investigation without field work. Provides a very good basis for overview lithological (magnetic) and structural (magnetic and electrical) models.

Disadvantages

Very expensive surveys if existing data are not available.

5.3.3 Gravity

The gravity method was found to be very useful, especially for investigation and three dimensional lithologic-tectonic modelling of the anorogenic granitic diapirs and the extensive basic rocks. The gravity data enabled a rough estimate to be obtained of the depth of these diapirs and basic rock masses.

Advantages

Possible to make a depth estimate of a rock body.

Disadvantages

Detailed measurements are time consuming, especially when elevation data are not available.

5.3.4 Petrophysical measurements

Petrophysical data, based on laboratory measurements of physical properties (density, magnetic susceptibility, induced polarization and porosity) of a large number of representative rock samples, are necessary for making a good interpretation of airborne and ground geophysical data. The rocks can be classified based on petrophysical data and a comparison with field and laboratory petrographical data.

Advantages

Easy to get good samples from drill cores.

Disadvantages

More difficult to sample in the field.

5.3.5 Ground surface VLF, resistivity and magnetic investigation

Magnetic, VLF and resistivity profilings were performed in order to:

- Check the width and character of the airborne geophysical indications of fracture zones, see Figure 5-3.
- Indicate minor fracture zones where the bedrock is covered with overburden.
- Locate fracture zones in the sea area between Äspö and Hålö (magnetic profiling).

These investigations were performed in the second and third stages of the pre-investigations.

The combination of detailed resistivity and geomagnetic data provided a very good idea of the possible extent and orientation of fractures and fracture zones, but it is important to carry out correlation between geophysical indications and the geological features in the field. VLF measurements were strongly disturbed by the saline water and man-made installations in the Äspö area and have for this reason not been very useful, see Figure 5-2.

Magnetic data provided a very good complement to the seismic refraction data from the sea area south of Äspö.

Advantages

VLF and magnetic investigation are fast and not very expensive methods, and can also indicate fracture zones where the bedrock is covered with overburden and in sea areas (magnetic). Resistivity is often a good method for characterization of fracture zones.

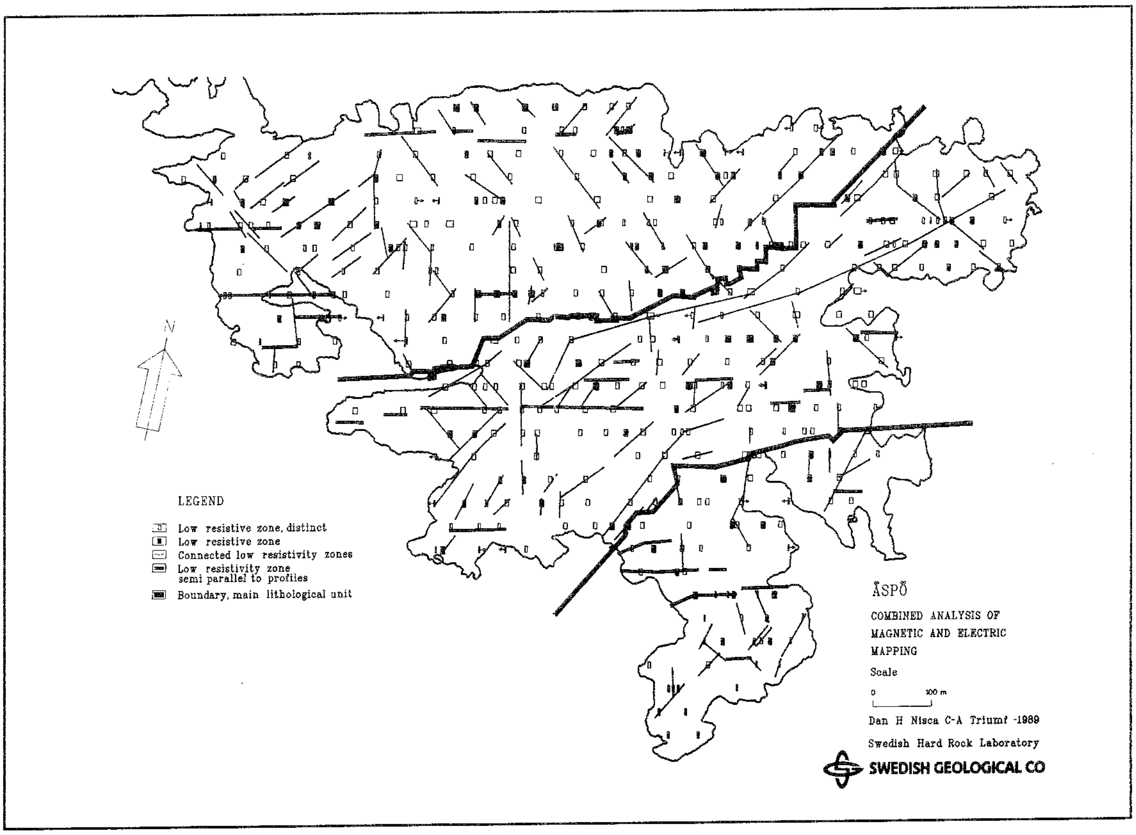

Figure 5-2. *Combined analysis of geomagnetic and geoelectric mapping /Nisca and Triumf, 1989/.*

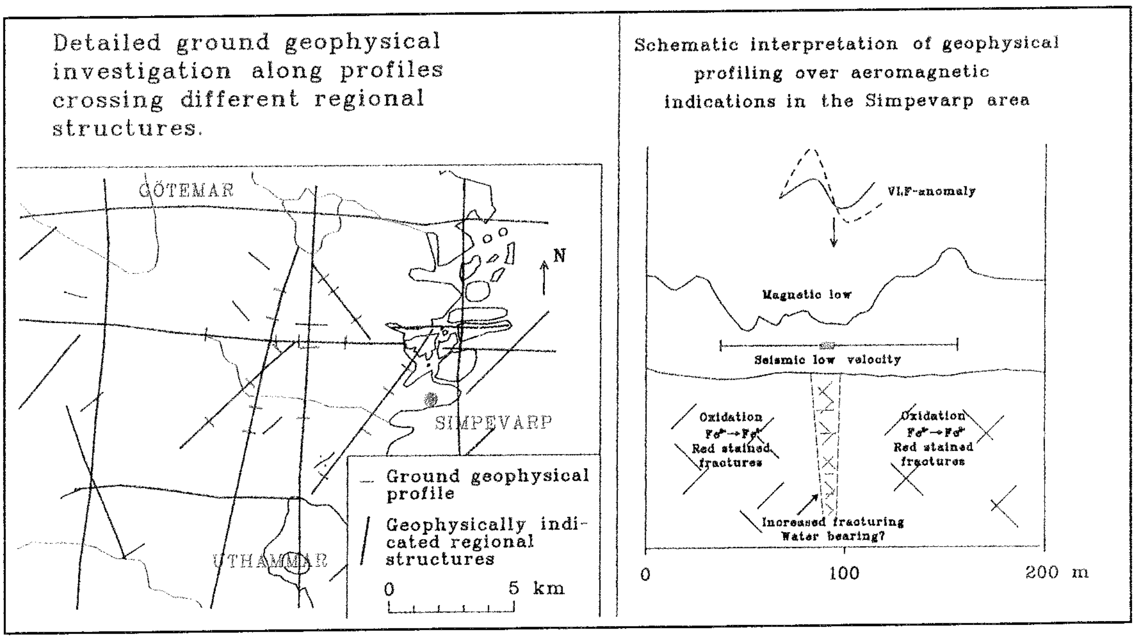

Figure 5-3. *Schematic interpretation of ground geophysical profiling of some aeromagnetic indications in the Simpevarp area.*

Disadvantages

The electrical methods are often strongly disturbed by saline water and man-made installations.

5.3.6 Seismic refraction

Seismic refraction profiling was used at an early stage of the pre-investigation phase in order to investigate indications of major regional fracture zones from aeromagnetic and lineament studies, especially in the sea area.

The seismic method is also useful for characterization of major fracture zones, specially with respect to different degrees of fracturing and clay alteration. Seismic profiling was successfully used in order to characterize the aerophysical indications of regional fracture zones.

Seismic refraction profiling across the island of Äspö confirmed some of the major fracture zones and gave a good picture of the fracture density and the rock quality in different parts of the island.

The NNW fracture zone system, which is believed to comprise a series of more or less vertically dipping narrow fracture zones trending NNW-NNE in the central part of the target area, was also to some extent confirmed by seismic indications.

To sum up it can be said that seismic refraction is a very useful method for location and characterization of steeply dipping fracture zones, especially in areas where salt water makes it almost impossible to use electrical methods. A disadvantage, however, is the need for explosives during the field work.

Advantages

Very useful method for location and characterization of steeply dipping fracture zones. Not sensitive to saline water.

Disadvantages

Need for explosives during the field work. Rather expensive method. Not useful for low-dipping fracture zones.

5.3.7 Seismic reflection

The main purpose of using seismic reflection was to test the usefulness of this method for mapping low-dipping fracture zones in crystalline bedrock. The target area was from as nearly surface as possible down to approximately 1500 metres. Two seismic profiles were recorded across Äspö island. One NW-SE line passes the cored boreholes KAS02, KAS03 and KAS04 – another one, approximately perpendicular to the first, passes close to KAS03.

The investigation was performed at an early stage of the pre-investigations.

The seismic reflectors can only to some extent be correlated with zones with increased frequency of low-dipping fractures in drill cores.

Seismic reflection may be useful for detecting fracture zones with low dips at depths of about 300 m or more, but much more development is still needed with regard to both field techniques and data processing before this method can be regarded as practicable for fracture zone identification in crystalline rocks.

Advantages

One of the few methods which could detect low-dipping fracture zones at depth */Cosma et al., 1994/.*

Disadvantages

Little experience of the method at depths down to 500 m in crystalline rock. Need for further improvements as regards data processing */Juhlin, 1990/.*

5.3.8 Ground radar investigation

The objectives of the surface radar project were to study the RAMAC borehole radar system as a ground probing radar system and to test its ability to locate reflections, especially from low-dipping relatively shallow fracture zones on the southern part of Äspö.

The ground surface radar measurements at the southern part of the Äspö site comprised reflection measurements with a centre frequency of 60 Mhz. Three profiles were measured using measurement points spaced at 0.5 m.

The three measured profiles were all N-S striking. There was no overburden along the profiles, which resulted in excellent conditions for ground probing radar measurements.

The measurements revealed several interesting reflections, probably from fractures and contact surfaces between different rock types.

For some of these reflections it was possible to correlate with indications from borehole radar measurements in the boreholes. After further development it is felt that this method will be useful, especially as a complement to seismic reflection and borehole radar for identification of low-dipping fracture zones.

Advantages

Fairly in expensive method. Seems possible to indicate thicknesses of overburden and low-dipping fracture zones.

Disadvantages

Not very much experience. Need for further development.

5.4 GEOLOGICAL MAPPING

5.4.1 General

A geological mapping programme was performed at different stages in the Simpevarp area comprising mapping of solid rocks, fracture mapping and structural geological investigations.

5.4.2 Mapping of solid rocks

In order to get an general lithological model of the investigation area the solid rock in the central area nearest to Simpevarp was mapped on a scale of 1:10 000. An overview map covering a greater, outer area was compiled on a scale of 1:50 000 at an early stage of the pre-investigations. The description that accompanies the maps is based on field work and studies of the mineralogy in thin sections and the chemistry of representative samples of the different kinds of rock in the area.

In order to get more detailed information about the geological conditions on Äspö, a more detailed mapping was performed in a second stage of the pre-investigations.

The purpose of the study was to obtain information as a bases for describing the lithological distribution and petrological characteristics of the different rocks on Äspö. Very detailed mapping was performed along cleaned trenches across the island, and a geological map on a scale of 1:2 000 was drawn. A classification of the rocks based on chemical and mineralogical analyses is presented, see Figure 5-4.

A modern petrographical description combined with airborne geophysical data was found to be very useful as a basis for the first regional lithological model.

Advantages

Fairly inexpensive and very useful method.

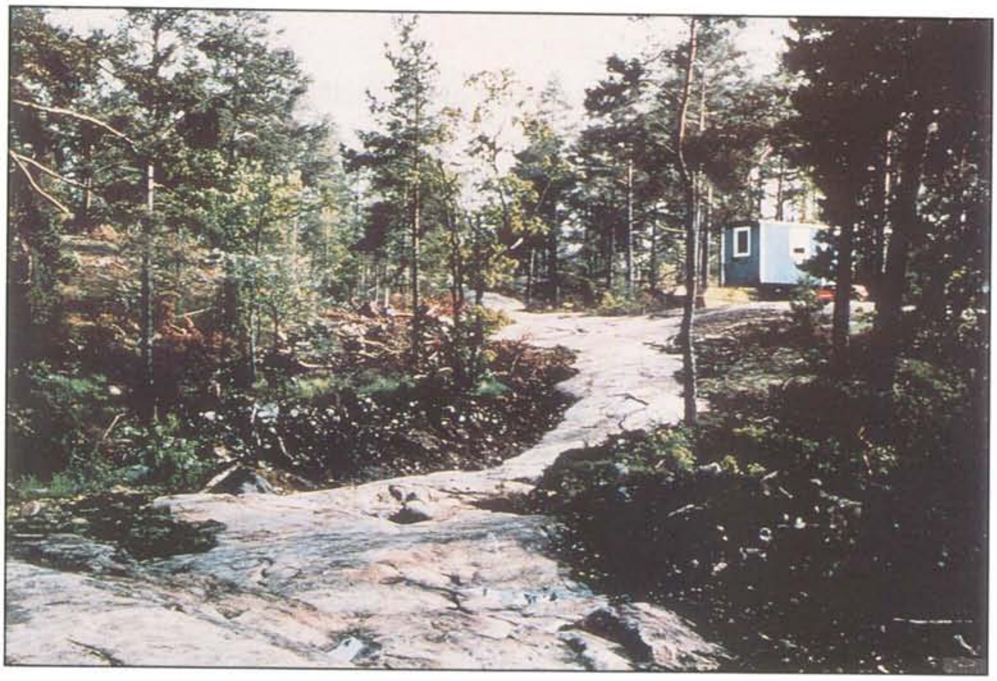

Figure 5-4. Section of Trench 1, where it passes west of core borehole KAS03.

Disadvantages

Restricted to areas with exposed rock surface.

5.4.3 Fracture mapping and geological structural analysis

A fracture mapping programme was carried out on a regional scale at an early stage of the pre-investigations. The main goal was to obtain a geometric description of the fractures with respect to strikes, dips, fracture densities and fracture lengths.

A tectonic study was also performed for the purpose of characterizing the main sets of tectonic zones identified as lineaments in the region. The field work also included a study of the fracture zones on the islands of Äspö and Ävrö.

A supplementary study of structural elements, including a fracture mapping programme, was carried out in a second stage of the pre-investigations along cleaned trenches to obtain results for use in geohydrological and rock mechanical model studies. Data on 4500 mapped fractures – such as orientation, length, aperture and fracture filling – were presented.

The results of these investigations, supplemented with subsurface information, have been very useful in the geological characterization of rock volumes in the site area.

Advantages

Fairly inexpensive and very useful method.

Disadvantages

Dependent on topographical conditions and to some degree exposed rock surfaces.

5.5 GEOLOGICAL-GEOPHYSICAL BOREHOLE INVESTIGATIONS

5.5.1 General

During the pre-investigations a drilling programme was executed at different stages involving 20 percussion boreholes and 14 cored boreholes in the Äspö area. In addition, a large number of boreholes – mainly percussion boreholes – were drilled in the surrounding area (Laxemar-Ävrö).

The purpose of the boreholes was to obtain information on the bedrock composition, orientation and characteristics of the major fracture zones and the hydraulic properties of the rock mass at increasing depth.

When drilling was finished, a large number of investigation methods were used in the boreholes, and the drill cores were mapped and investigated in the site area.

5.5.2 Drilling documentation in percussion boreholes

Continuous recording of drilling rate provides good information on the location of major fractures and fracture zones as well as some information on lithological changes in the rock mass. Geological examination of the drill cuttings provides a rough understanding of the principal rock type distribution.

Advantages

Percussion drilling is not as expensive as coring.

Disadvantages

Studies of drill cuttings provide only a very rough estimate of lithological conditions.

5.5.3 Drill core investigation

The drill cores were investigated using many different methods in order to improve our information at depth about the petrological, structural and petrophysical quality of the rock mass in the target area. The drill cores were mapped with the highest precision using the Petro Core System. Considerable attention was devoted to characterization and mapping of fractures. Basic data on fracture orientations, fracture spacing and surface characteristics of the fracture surfaces, including mineral filling and coatings, were obtained by logging of drill cores. Rock type and alteration variation along the cores were also mapped.

Examination of the colour, grainsize and structure of the cores, together with the results of the chemical and thin-section analyses and geophysical logging data, has led to a practical classification of the rock types.

A special study of fracture minerals was carried out on many of the cores from Äspö. The results of the core mapping correlate well to the results of the XRD analyses, and most of the unidentified mineral phases from the core mapping appeared to be colour and textural varieties of chlorite, hematite, fluorite, clay minerals or quartz.

Advantages

This method provides the best information on all lithological parameters.

Disadvantages

Rather time-consuming method.

5.5.4 Geophysical logging

The geophysical logging programme carried out in the boreholes generally included most of the following logging methods:

- gamma-gamma,
- neutron (cored boreholes only),
- borehole deviation,
- caliper (cored boreholes only),
- sonic,
- natural gamma,
- single-point resistance,
- self-potential (SP),
- magnetic susceptibility,
- normal resistivity (1.6 m),
- lateral resistivity (0.1-1.6 m),

- temperature,
- borehole fluid resistivity.

The temperature gradient and the equivalent content of sodium chloride were calculated using the temperature and borehole fluid resistivity methods. Temperature anomalies often indicate influx of water (open fractures).

The purpose of the interpretation was to describe the geophysical logging data in terms of lithology, fracturing and hydrogeology. The logging methods used make different specific contributions to the different subjects above, varying with the physical property measured.

The sonic logging, single-point resistance, normal resistivity, caliper and self-potential methods were mainly used for delineation and classification of fracturing in core borehole walls.

Water transport in a borehole is common and occurs when the borehole serves as a connection between water-bearing fractures/fracture zones with different hydraulic heads. The neutron log has been useful in detecting anomalies of fracture porosity. The magnetic susceptibility and natural gamma logs are good indicators of mineralogical alteration. The sonic log, magnetic susceptibility, gamma-gamma and natural gamma logs seem to be very relevant to lithological characterization of a heterogeneous rock mass such as the one in the Äspö area. There is a particularly significant correlation between high gamma radiation and the fine-grained granites in the boreholes. The results of the caliper log and the electric logs were very useful in detecting fractures and fracture zones. It seems, however, to be rather unnecessary to use three different electric logs which give largely identical results, so in most of the geophysical surveys only the single-point resistance log was used.

Advantages

Very good as a complement to core mapping for rock classification (gamma-gamma and magnetic susceptibility) and fracturing (sonic, resistivity and caliper).

Disadvantages

Evaluation of data in the form of cross plotting is rather expensive.

5.5.5 Fracture orientation methods

Different orientation methods were used to obtain information on the location of the fractures intersecting the boreholes. During the core mapping procedure the drill core was reconstructed and the relative orientation of long and short orientation sections obtained. The absolute orientation of the relatively oriented sections was obtained using a TV-logging device in KAS02, KAS03 and

KAS04. In KAS04, which is inclined, absolute orientations were also defined by the drillers, using an iron-rod indentor with a wire. A test investigation using a WBK televiewer system was also performed in boreholes KAS05 and KAS06 in order to evaluate this system with respect to its ability to detect and orient fractures in small diameter boreholes (76 and 56 mm). There were many problems during the interpretation work, especially concerning the correlation between fractures in the cores and oriented fractures recorded by the TV and Televiewer devices and exact depth measurement. Not until the ramp in the HRL penetrates the borehole area in question will we be able to evaluate the usefulness of these absolute orientation methods.

Advantages

TV logging and Televiewer are useful methods for observing absolute orientation of structures in boreholes.

Disadvantages

Very expensive methods. Correlation between fractures in the core and data recorded by the devices is very much dependent on the handling of cores during the drilling operation.

5.5.6 Borehole radar measurements

Borehole radar measurements were made in all cored boreholes and some of the percussion boreholes using the RAMAC system. The radar measurements were performed as single-hole measurements using omni-directional dipole antennas with a 22 Mhz frequency. Measurements with directional radar antenna were made as single-hole measurements in some boreholes using antennas with a 60 Mhz frequency. The radar range obtained in the single-hole reflection mode reaches down 60 metres in a borehole. A number of prominent structures were indicated in the boreholes by the directional antenna radar measurements, which corroborated the presumed orientation of most of the interpred major fracture zones and some of the interpreted minor zones. There is good agreement between the results of the present radar investigation using directional antennas and the results of earlier radar investigations using dipole antennas.

Single-hole radar reflections give very valuable information about the orientation of fracture zones – especially those intersecting the borehole at rather low angles (> 45°).

Advantages

Useful concerning orientation of fracture zones and to some extent also rock contacts.

Disadvantages

Sensitive to saline water. Difficult to make a clear evaluation of the correlation between radar reflections and geophysical structures.

5.5.7 VSP measurements

As a complement to the borehole radar investigation, a Vertical Seismic Profiling (VSP survey) was carried out in borehole KAS07 on southern Äspö. Measurements were made in this hole down to a depth of 410 m. The diameter of the hole is 56 mm. A multi-detector geophone chain and digital recording equipment were used, see Figure 5-5. Small dynamite charges (50 g) were exploded at five locations around the deep hole with offsets varying from 35 to 80 m. The charges were place in shallow water-filled boreholes. The data were then organized in profiles containing seismograms recorded at increasing depths from the same shot point. Five offset VSP profiles were thus formed for this deep hole. The trace spacing in the profiles is 5 m. The seismic range obtained was approx. 100-500 m.

VSP results from KAS07 were found to be very important as a complement to the borehole radar data, especially after three-dimensional processing using a new technique with Image Space filtering, which has been developed for seismic reflection studies in crystalline rock.

Advantages

Useful for determining orientation of fracture zones.

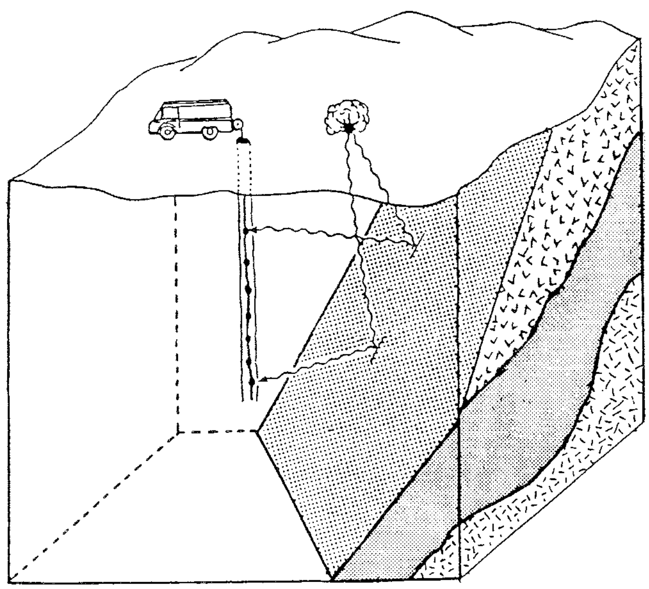

Figure 5-5. *The offset VSP geometry uses a fixed source to send signals to an array of detectors in a borehole.*

Disadvantages

Very expensive method. No clear correlation between reflections and geological structures. Not very useful for characterization of structures.

5.6 GEOHYDROLOGICAL METHODS

5.6.1 General

Geohydrological methods have been used for estimating the hydraulic properties of the bedrock and the boundary conditions, such as flow and pressures, of the investigation area. They have also been used to support the identification of geologically defined major fracture zones. In some cases only geohydrological methods have given clear indications of water-bearing zones.

5.6.2 Available geohydrological investigations in the area of interest

As a starting point for a regional investigation, useful information can be obtained from the national water-well archive and possibly from other investigations in the area. The national water-well archive contains data on specific capacity, drill depth, rock type etc, while other investigations provide results of pumping tests, injection tests etc.

Precipitation, potential evaporation and run-off can also be estimated from measurements made by SMHI.

During the regional investigation of the Äspö HRL these sources were the main information for interpreting the geohydrology in the area.

Advantages

These data and investigations are very useful as a source of rough estimates of hydraulic properties and boundary conditions. They are also feasible as data, at least from SMHI and the well archive, can be obtained relatively fast and at a fairly low cost.

Disadvantages

The usefulness of other site investigations are dependent on their quality and where they were conducted.

5.6.3 Drilling documentation

Cored holes

Cores are mapped in order to obtain information on rock type, fracturing and fracture coating. The data have been used to relate evaluated hydraulic properties to lithological units, interpret fracture zone intersections and identify packer position. (Other methods have also been used for the two latter purposes).

All drilled coreholes drilled within the Äspö HRL project have been core mapped except for a few short cored holes.

Core mapping is needed to distinguish the evaluated hydraulic properties from the effects of injection tests on lithological units. It is also important for deciding on packer positions in order to be able to position the packers where the rock is not heavily fractured.

Advantages

Coring is the only drilling method that enables the distribution of the lithological units and fracture characteristics to be determined with certainly.

Disadvantages

Expensive and time consuming.

Percussion boreholes

The lithology along the borehole is judged from drill cuttings, and the water-conducting parts and fracturing are estimated during drilling. This documentation has been done for all percussion boreholes within the Äspö HRL project.

Advantages

Although the data are uncertain they are useful as an initial documentation of the rock mass. The investigation is also quite feasible as it can be done quickly and at low cost.

Disadvantages

The estimated lithological and fracture distribution along the borehole is of course much more uncertain than in the case of a cored hole.

5.6.4 Air-lift tests

The purpose of the air-lift tests is to get an initial estimate of the transmissivity around the borehole section, which is generally about 100 m long.

(The total volume of pumped water should be measured as it may be of importance for the groundwater chemistry).

Cored holes

Core drilling has generally been interrupted about every 100 m of drilling depth in order to test the last 100 m of the borehole by means of air-lift pumping using a single packer system, see Section 4.3.2.

The data are useful as you get the first estimate of conductivity distribution along the borehole, which sometimes can be used to estimate the transmissivity of a conductive waterbearing zone. Injection tests and flowmeter measurements, in some respect, give a better resolution of the hydraulic distribution along the borehole. However, injection tests and flowmeter measurements cannot be performed in the wide, upper part, of the telescope shaped borehole (with the technique used today) and they sometimes fail and therefore air-lift tests should always be performed.

Advantages

Air-lift tests are also practical and useful as they are quite simple and fast to perform.

Disadvantages

The data quality is generally not as good as for a pumping test because the flow rate and the level measurements are less accurate compared to a pumping test.

Percussion holes

Normally a percussion drilled borehole is air-lift tested after drilling. In this case the drill string has been used to force air down to the bottom of the borehole for the air-lift pumping and the level measurements have been made in an open PEM pipe, which has been lowered beside the drill string. A cap on the casing, similar to the one mounted on the drill string for the tests in the cored hole (see Section 4.3.2), is used for the flow measurements. Generally this has been the only hydraulic test in the percussion boreholes, and has also served as clean-out of the borehole.

The air-lift tests are useful for approximate estimation of the hydraulic conductivity of the upper part of the bed rock. As mentioned above the data quality is not as good as in the case of a pumping test, but the method is judged to be quite feasible if the test is performed correctly. One problem at Äspö has been that the drillers have not been used to the test technique. The air-lift pumping period has been rather short and the cap for flow measurements and a PEM pipe for the level measurements have not been used in some cases. In these cases the data quality can be quite bad.

Some times it has been possible to make drawdown observations in other percussions holes during the air-lift pumping. These types of observations may give some indication of conductive direction in the rock mass quite early in the investigation.

Advantages

Air-lift tests are simple and fast to perform.

Disadvantages

The data quality is generally not as good as in the case of a pumping test.

5.6.5 Clean-out and pumping test of borehole

All boreholes drilled within the Äspö HRL have been clean-out pumped, which is necessary because drill cuttings may be present in the borehole. The cored holes are pumped for approximately one day and the percussion boreholes generally for a few hours.

Another purpose of the clean-out and pumping test has been to obtain an initial estimate of the transmissivity of the rock mass along the entire borehole and to estimate the skin factor for the borehole. Generally the pressure responses in surrounding boreholes have been measured in order to get some indications of directions and locations of major water-bearing zones.

Spinner or flow meter measurements have been made during the clean-out and pumping test or during pumping just before or after the test.

The clean-out and pumping test is important and useful. It is important to clean-out the borehole, otherwise there may be problems with both logging and packer installation. It is also important to pump out water after drilling of the cored holes, because although a special technique is used to minimize contamination of the rock mass with drilling fluid (telescope shaped borehole and air-lift pumping during drilling), some of the drilling fluid is pressed out from the borehole. The pumping test is useful as the evaluated transmissivity can be used together with flow meter measurements to estimate the hydraulic conductivity distribution along the borehole. Injection tests probably give a more correct hydraulic conductivity distribution along the borehole, but flow meter measurements in combination with a pumping test are fairly easy to perform and provide good indications of major water-bearing structures intersecting the borehole.

(The total volume of pumped water should be measured as it may be of importance for the groundwater chemistry).

Clean-out pumping is always needed.

Advantages

Clean-out pumping is always needed and it is possible to use the pumping both for flowmeter measurement and for an initial indication of hydraulic properties and water-bearing structures.

Disadvantages

It is generally difficult to interpret the connections between water-bearing structures, compared with pumping between two packers.

5.6.6 Spinner or flow-meter measurements

Spinner or flow measurements in a borehole are performed during pumping of the borehole. The purpose is to identify water-bearing fractures intersecting the borehole. As mentioned above the flow measurements can also be used to roughly estimate the hydraulic conductivity distribution along the borehole. Major inflows are easily identified and the inflow distribution along the borehole can also be estimated (which may be useful in a tracer test for the pumped borehole).

Most of the cored holes have been flow-meter measured from drill depth 100 m and to more or less the bottom of the borehole. The reason for not measuring the top 100 m is that the pump is placed in this wider, upper part of the borehole.

Spinner or flow meter measurements are very useful as they give good indications of water-bearing structures intersecting the borehole, which first of all is an important part of the interpretation of where major water-bearing zones intersect the borehole. Secondly, the flow measurements (and the core mapping) are important for deciding on packer positions.

Advantages

The spinner or flow measurements are also judged feasible and useful, as the tests are fairly simple and fast and should always be done.

Disadvantages

The drawback with spinner or flowmeter measurements is that fractures with lower transmissivities will not bee seen in the data if higher transmissivities are present in the borehole. Generally injection tests with a short packer distance are better for obtaining a transmissivity distribution with a wide range.

5.6.7 Injection tests

Injection tests with a packer interval of 3 m or 30 m and with an injection and recovery period of 10 + 10 minutes and 2 + 2 hours, respectively, have been performed. The purpose of the injection tests has been to estimate the distribution of hydraulic conductivity along the cored holes. These data have then been used to estimate the probability distribution of hydraulic conductivity within sub-volumes or lithological units. The injection test data and the results of the clean-out pumping tests have also been used to set up empirical relationships for the scale dependency of the hydraulic conductivity.

About 1 200 injection tests with a 3 m packer interval have been performed in 8 cored holes and about 65 injection tests with a packer interval of 30 m in three cored holes.

Injection tests are useful for estimating the probability distribution of the hydraulic conductivity for sub-volumes and lithological units. The tests are also important for obtaining statistics on the distance between conductive structures with a transmissivity greater than a specified value. Evaluation of the hydraulic conductivity under transient conditions is considered to provide a better estimate compared with stationary conditions.

Injection tests can also provide information on the transmissivities of fractured zones which are defined as to position and extent in the investigations. Tests are difficult to perform in bedrock with very low hydraulic conductivity (irregular injection flow) and very high hydraulic conductivity (too low injection flow to get clear responses). This means that normally pumping tests give better estimates of the effective transmissivity of a major water-bearing zone than injection tests.

Injection tests are rather time-consuming (and therefore expensive) and difficult to perform in the field. Among many variables measured during a test is the injected water volume. This value can be of importance for the groundwater chemistry.

Injection tests are probably necessary to some extent, even though they are expensive and time-consuming, because they provide data that cannot be sampled with other tests.

Advantages

It is generally the only method for obtaining hydraulic data on lithological units and statistics on the distance between conductive structures.

Disadvantages

Expensive and time-consuming.

5.6.8 Interference tests

The main purpose of interference tests is to:

- estimate the hydraulic properties of major water-bearing zones,
- provide indications of major water-bearing structures together with a geological and geophysical interpretation of major fracture zones.
- provide drawdown and recovery data which can be used to calibrate numerical groundwater models.

The pumped section of the boreholes has sometime been straddled by two packers (13 tests) and sometimes the entire borehole has been pumped (about 9 tests in cored holes and two in percussion holes). Clean-out and pumping tests are also interference tests when observation boreholes are used. During the first phase of the pre-investigations for the Äspö HRL, the clean-out and pumping test was mainly used to provide indications of major water-bearing structures and was followed by pumping tests of selected borehole sections. Later in the investigations the clean-out and pumping test was used as the main interference test for a borehole. In most of the tests the drawdown and recovery period was 3 days + 2 days. Two long-time pumping tests were performed in open boreholes. The drawdown and recovery periods were 53 + 33 days and 92 + 31 days.

It is important to perform interference tests to obtain the effective transmissivity of a zone. Injection tests generally give less reliable transmissivities due to the influence radius and the test technique. Air-lift tests are generally less controlled, and as normally a 100 m section is tested it is more difficult to estimate the transmissivity of the zone than if the zone is straddled by two packers. For the same reason, interference tests where the entire borehole is pumped are less accurate for estimating the transmissivities of individual zones intersecting the borehole.

To evaluate the storativity of the zone, observations in other boreholes than the pumped borehole are necessary and they must intersect the zone. The pumped zone should also be straddled by packers. The transmissivity is probably not constant on the fracture zone "plane". There may be small and large scale variations. If several boreholes intersect a major water-bearing zone it is easier to estimate the large-scale variation of the transmissivity, to estimate the storativity and to get a clearer indication of the strike and dip of the structure.

Interference tests can be rather time-consuming in planning, execution, processing of data and evaluation of data. It is very important to plan interference tests and other activities which may cause pressure responses (for example drilling) so that they don't interfere with each other. If other tests or activities causes pressure responses, they may ruin the interference test.

Interference tests are very important for the interpretation of major conductive structures and for calibration of groundwater flow models. A number of tests with pumping times of several days are always needed.

(As in the case of other pumping tests the volume of pumped water should be measured, as it may be of importance for the groundwater chemistry).

Advantages

Interference test are needed for the interpretation of major conductive structures and for calibration of numerical models.

Disadvantages

Fairly expensive and time-consuming. Other activities at the site which may cause pressure responses in the groundwater must be stopped during the tests.

5.6.9 Groundwater monitoring

The purpose of groundwater monitoring is to:

- measure the undisturbed hydraulic head in the rock mass,
- measure the pressure responses during interference tests,
- measure the changes in hydraulic head during construction of the tunnels of a repository.

The second purpose is mainly useful for identifying major conductive structures and evaluation of the hydraulic properties of major water-bearing zones.

All purposes above are important for calibration of numerical groundwater models.

At the Äspö HRL, 8 shallow percussion holes (22 - 93 m deep), 36 deep percussion borehole (100 - 200 m deep), 4 shallow cored holes (100 m deep), 17 deep cored holes (200 - 1 000 m deep) and one very deep cored hole (1 700 m deep) were drilled up to 1992. Most boreholes are equipped with packers. Generally there are two measurement sections in the percussion boreholes and up to 6 measurement sections in the cored holes. The number of observations sections during the first stage of the pre-investigations was about 35 and during the last stage over 100 sections.

The number of monitoring sections during the construction of the Äspö HRL is about 150 in boreholes from the surface. Most of the sections are monitored with data loggers and the rest are measured manually. Some of the cored holes in the tunnel are also monitored continuously with data loggers.

It is very useful and important to have a large number of borehole sections for the interpretation of interference tests, both for evaluation of the hydraulic properties of a single major water-bearing structure and to obtain indications of other major water-bearing structures. The large number of observation sections are also needed for estimation of boundary and initial conditions and for calibration of numerical groundwater flow models.

Monitoring of piezometric levels within the Äspö HRL is performed as described in Section 4.3.6. This way of measuring has its pros and cons as described in Section 4.3.6. Some changes can possibly be made to improve the reliability and flexibility of the monitoring system.

It is important for the groundwater flow modelling to obtain the undisturbed hydraulic head (and also salinity) in the rock mass. Ideally, several deep boreholes should be instrumented with packers that can measure the levels for at least one year before any major disturbances occur. This may be impossible, but plans should be made as to how and when boreholes are to be equipped and a measurement programme should be carried out so that undisturbed data can be collected.

Advantages

It is the only way to obtain piezometric data for groundwater flow modelling.

Disadvantages

May be expensive depending on the number of observations points, instrumentation and sampling frequency.

5.6.10 Dilution test

Dilution tests in boreholes are performed in order to get a local measurement of the natural flow (undisturbed flow), the flow during a pumping test or the flow during the excavation of the tunnels through a particular borehole section, see Section 4-3-8. The estimated flow rate can in some cases be translated into a flow rate in the rock. The data may provide indications of how structures are connected when used during interference tests, and the data are also useful for calibration of numerical groundwater models. Although the translated flow rates must generally be considered uncertain, the relative change (natural – disturbed flow) can be quite useful.

Advantages

It is the only way to directly measure the flow rate through the borehole. The data are useful for interpretation of the structural model and for groundwater flow modelling.

Disadvantages

Fairly expensive and time-consuming. Difficult to translate the measured flow rate into a flow rate in the rock mass.

5.7 METHODS FOR GROUNDWATER AND GEOCHEMICAL ANALYSES AND INVESTIGATIONS

The various sampling methods were described in Section 4.4. The present sections deals with the analysis procedures and the basis for evaluation of the different methods.

5.7.1 General

The usefulness of the groundwater and geochemical investigation tools is related to the representativeness of the analyzed samples. Mineral samples are not sensitive to disturbances, while groundwater samples are extremely sensitive to i.e. changing redox conditions, perturbation by mixing with foreign water and disturbances due to the borehole drilling. These aspects have been thoroughly evaluated by *Smellie and Laaksoharju /1992/*, and are reported below in 5.7.2 and 5.7.3.

5.7.2 Sampling and sample preparation

For complete chemical characterization (CCC) the groundwater is essentially pumped up from chosen water-conducting sections in the bedrock sealed off by inflatable rubber packers with an adjustable straddle length. The hydraulic conductivity of these sections averaged between 10^{-8} m/s and 10^{-6} m/s. A hydraulically operated piston pump is installed next to the packers giving a maximum flow of about 250 ml/min. It has the capacity to reduce the pressure within the sampled section by more than 1 MPa. Eh and pH values were monitored both at the bedrock surface, where the water is pumped through a flow-through cell located in the mobile laboratory, and by a downhole probe (Eh and pH) located within the sampling interval of the packer system, see Figure 5-6. Three different types of Eh probe were used: gold, platinum and glassy carbon.

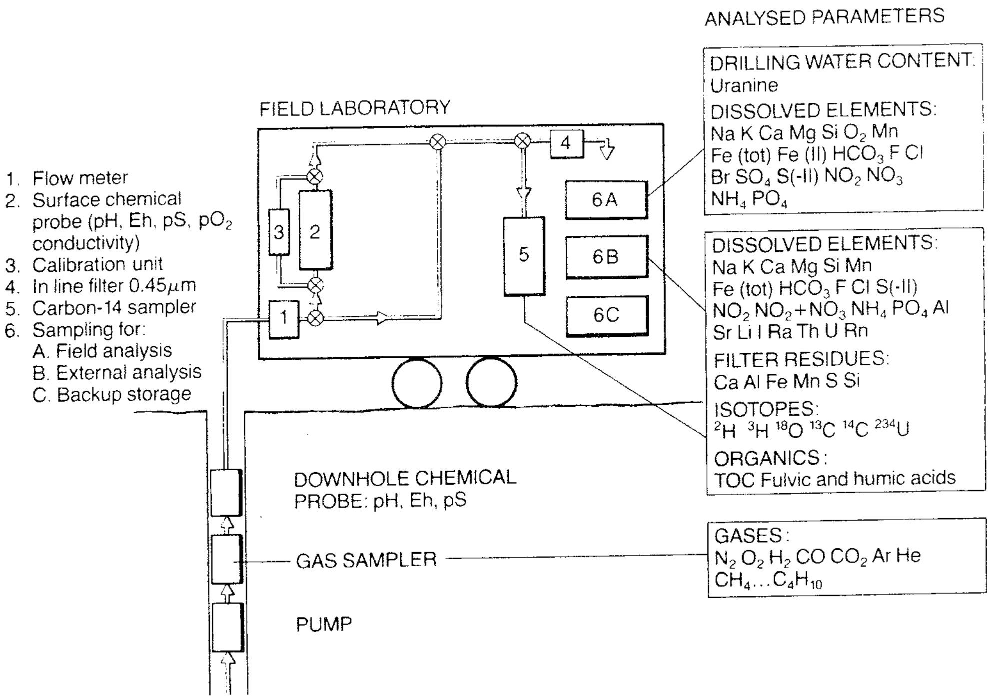

Figure 5-6. *Schematic representation of the water-flow system from borehole to analysis /Almén et al., 1986/.*

Following installation of the packers and the downhole equipment, the pump is started and the capacity is adjusted to give as high a water flow as possible without exceeding a pressure drawdown of 0.5 MPa (= 50 m H_2O). Pumping is continued until a stable groundwater composition is achieved. When equilibration of the electrodes is achieved, it is often the continuous change in the composition of the main constituents that determines the length of the sampling period. At Äspö, 2-4 weeks were sufficient for each section at flow rates which varied between 60-120 ml/min.

High quality samples are those that represent in-situ conditions. This means that excessive pumping must be avoided. However, the drilling has in most cases contaminated the undisturbed groundwater so that large volumes must be removed from the section before representative samples are obtained.

Sampling with the Mobile Field Laboratory pumps approximately 1 m^3 per day. This is the water volume of 100 m^3 to 1000m^3 of rock in the vicinity of the borehole section. In this way several days of pumping results in an integrated sampling volume of thousands of cubic metres of rock. This is therefore a sample that represents the particular part of the conductive zone or fracture which has been sampled.

Sampling in connection with the pumping tests is done at a high pumping rate but is of short duration. This sampling therefore affects a volume which is approximately 10 times larger, so the hydraulic contacts will eventually change the composition.

In contrast to the low pump extraction rates used in the complete chemical characterization protocol, groundwaters sampled during pump testing have resulted from high extraction rates (anything from 4 000 to 115 000 ml/min).

The groundwater pumped up into the mobile laboratory normally passes through an in-line 0.45 micron filter before it is collected for analysis. However, when samples for iron and manganese determinations are collected, a 0.45 micron single-use polycarbonate filter is used. This kind of filter is also used under special circumstances for determination of particle fractions in the water. In this case the water passes through a series of filters with a range of pore sizes grading from 0.45 to 0.2 to 0.05 microns. The particle fractions collected on these filters are analyzed for Fe, Al, Mn, S, Ca, Mg and Si. The filtrate is analyzed for total and ferrous iron.

The groundwater is constantly pumped up into the mobile laboratory and samples for different analyses are taken when required (immediately prior to the actual determination). Water samples collected during a one-day period are given the same sample number. Generally no preservation is needed, except for samples to be sent for external analyses or stored for reference.

Samples collected for analysis in the mobile laboratory

The sample volumes needed for the main constituent analysis are 1 litre untreated and 1 litre acidified by hydrochloric acid. Some samples must be collected in specially prepared vessels, for example:

- Hydrochloric acid is added to the empty volumetric flasks prior to sampling for iron determination.
- The samples for sulphide determination are collected in glass bottles (so called Winkler bottles with a ground glass stopper), with a calibrated volume of nearly 150 ml, and analyzed immediately.

Samples collected for control analyses or special analyses

These samples are collected on the same occasion, once a week or once per sampled borehole section.

- The control sample for sulphide is preserved by addition of sodium hydroxide and zinc acetate.
- Samples used for cation analysis by ICP-AES or AAS in external laboratories are preserved by addition of hydrochloric acid up to 1% by volume.

- A 5-litre unfiltered sample is needed for the uranium, radium, radon and thorium analyses performed at Studsvik Energiteknik.
- A 5-litre acidified sample is needed for the determination of the uranium isotope ratios at the Department of Radiophysics at the General Hospital in Lund.
- A 1-litre unfiltered sample is needed for tritium and an unfiltered 100 ml for ^{18}O and deuterium; determinations are carried out at the "Institut för Energi Teknik", Kjeller, Norway.
- A 1-litre sample is needed for tritium determination by the IAEA in Vienna.
- Sample collected for radiocarbon (^{14}C). In this case the carbonate content of 130 litres of water must be reduced to a volume of 1 litre by acidifying the water with hydrochloric acid, expelling the CO_2 with nitrogen and trapping it in a bottle containing sodium hydroxide through which the gas passes. If a tandem accelerator is available, this pre-concentration process is not necessary.

5.7.3 Analysis and Quality Assurance

For the analysis of deep groundwaters great care has to be taken to avoid changing redox conditions during sampling and analysis. The elements analyzed are those considered most important for the safety assessment of a nuclear waste repository.

The main constituents, Na, K, Ca, Mg, Cl, HCO_3 and SO_4 indicate the groundwater is residence time in the rock by showing the extent of the rock/water interaction. The anions of this group are potential complexing agents and are thus important for calculation of waste canister corrosion, dissolution and transport of the nuclides in the waste, assuming a worse case scenario where radionuclides from a damaged canister are released and transported by the groundwater.

F, Br, PO_4 and SiO_2 are useful for identifying the origin of the water and the state of equilibrium. Fe(II), $Fe_{(tot)}$ and S(-II) are primarily analyzed in order to describe the redox conditions and thus to support the Eh measurements. They also give information on the buffer capacity of the water.

The concentrations of the main constituents and redox sensitive elements are continuously analyzed in the field laboratory to obtain an immediate feed-back of groundwater composition and stability. This enables the analytical protocol to be constantly modified during the sampling campaign. Furthermore, this system enables the redox sensitive elements to be analyzed immediately without atmospheric contamination. The field analyses are carried out by ion chromatography, spectrophotometry and titration.

Uranium, radium and radon are determined by neutron activation; alpha spectrometry is also used to determine uranium in addition to measuring the $^{234}U/^{238}U$ activity ratios. Tritium and the stable isotopes ^{18}O and deuterium are analyzed by natural decay counting and mass spectrometric methods, respectively.

Most components are analyzed regularly and by more than one method. For example, one sample per pumping day was analyzed both in the field laboratory and by inductively-coupled plasma (ICP) at the Royal Institute of Technology, Stockholm. Control analyses were carried out weekly, or once at each sampled level during the pumping period, by separate laboratories, namely the Environmental Research Institute (IVL) or Miljöanalytiska Laboratoriet AB (MILAB). The laboratories involved, the analytical methods employed, and the ionic species analyzed, are listed in Table 5-1. Since 1990, the control analyses have been carried out by the Swedish Geological Company (SGAB) in Luleå.

An important part of the analytical protocol has been devoted to quality assurance evaluation of the analytical methods, the reliability of the analytical data and the storage and accessibility of the database.

Table 5-1. Methods, laboratories and detection limits of analyses performed in the laboratory and in the field. */Modified after A-C Nilsson, 1989/.*

Method	Element	Laboratory	Detection limit (mg/l)
IC ICP-AES AAS (Flame)	Na " "	MFL KTH IVL	0.1 0.04 0.005
Titr. (SIS 028119) ICP-AES AAS (Flame)	Ca " "	MFL KTH IVL	2 0.006 0.02
IC ICP-AES AAS (Flame)	K " "	MFL KTH IVL	0.1 0.04 0.005
Titr. (SIS 028121) ICP-AES AAS (Flame)	Mg " "	MFL KTH IVL	0.4 0.0001 0.001
Spect. (P-H Tamm) ICP-AES AAS (Flame)	Si " "	MFL KTH IVL	1 0.004 0.2
Spect. (P-H Tamm) ICP-AES AAS[1)]	Mn " "	MFL KTH IVL	0.01
Spect. (Ferrozine) ICP-AES AAS (Furnace) AAS (Flame)	$Fe_{(tot)}$ " " "	MFL KTH IVL IVL	0.005 0.002 0.001 0.05
Spect. (Ferrozine)	$Fe_{(II)}$	MFL	0.005
ICP-AES AAS (Flame)	Sr "	KTH IVL	0.0001 0.05

Method	Element	Laboratory	Detection limit (mg/l)
ICP-AES AAS (Flame)	Li "	KTH IVL	0.001 0.00
ICP-AES AAS (Furnace)	Al "	KTH IVL	0.009 – 0.03 0.001
Titr. (SIS 028120) FIA/Spect. (SIS 028133)	Cl "	MFL IVL	10 1
Pot. (SIS 028135) Pot. (SIS 028135)	F "	MFL IVL	0.1 0.1
Titr. (SS 028139) Titr. (SS 028139)	HCO_3 "	MFL IVL	0.5 0.5
Spect. (SIS 028115) Spect. (SIS 028115)	S^{2-} "	MFL MILAB	0.01 0.01
IC	SO_4	MFL	0.05
ICP-AES	S_{tot}	KTH	0.02
Spect. (SS 028126) Spect. IVL Method	$P\text{-}PO_4$ "	MFL IVL	0.002 0.001
Pot. (Orion Method)	I	MILAB	0.05
IC	Br	MFL	0.05
Spect. (SIS 028132)	$N\text{-}NO_2$	MFL	0.001
Spect. (SIS 028134) Indust. Method No. 329-74 W/A	$N\text{-}NH_4$ "	MFL IVL	0.005 0.01
FIA/Spect. (SIS 028133) Tecator ASN 62-01/83	$N\text{-}NO_2 + N\text{-}NO_3$	IVL	0.005
Astro. M. 2001	TOC	IVL	0.5
Neutron Activation	Natural U Ra Rn Th	Studsvik " " "	- $8.5E^{-3}$ Bq/l - $5.0E^{-4}$ µg/l
Alpha Spectrometry	$^{235}U/^{238}U$ $^{234}U/^{238}U$	Radiofysik Lund	
Natural Decay Counting Mass Spectrometry	^{3}H ^{2}H ^{18}O	Energi Teknik Kjeller "	8 TU - -
Natural Decay Counting	^{3}H	IAEA, Vienna	<0.1 TU

Abbreviations, see page 132.

Abbreviations, Table 5-1:

MFL	–	Mobile Field Laboratory
IVL*	–	Environmental Research Institute
MILAB	–	Miljöanalytiska Laboratoriet AB
IC	–	Ion Chromatography
ICP-AES	–	Inductively-Coupled Plasma Atomic Emission Spectroscopy
AAS	–	Atomic Absorption Spectroscopy
Titr.	–	Titrimetric Method
Spect.	–	Spectrophotometric Method
Pot.	–	Potentiometric Measurement
FIA/Spectr.	–	Flow Injection Analyses followed by Spectrophotometric Detection
Astro. M.	–	Carbon Analyser (ASTRO trademark)

*SGAB since 1990

5.7.4 Eh, pH and bicarbonate

The redox potential Eh, is difficult to measure in natural groundwaters. Measurements performed in the earlier SKB site investigation programme and in Äspö have been carefully evaluated and found to represent the ferric oxide – ferrous iron redox couple */Grenthe et al., 1992/.* The conclusion is that redox potential measurements are valid and that the results can be modelled by an existing redox couple in the natural groundwater. These same chemical reactions were used for predicting the redox potential values.

Most pH values differ between measurements downhole and at the surface. The difference is usually less than ±0.3 units, but differences of up to 1 pH unit have been measured. The reason for this large discrepancy is outgassing or ingassing of carbon dioxide from the water due to the decompression when the water is pumped up to surface. The magnitude of the change is related to the initial partial pressure of CO_2 and the total gas pressure.

In the same way as there is often a difference in pH values obtained at the surface and downhole, there are usually differences between values measured in a surface flow through a cell on-site and off-site. In this case as well, the partial pressure of carbon dioxide causes the changes.

An equilibrium is rapidly established between bicarbonate, carbon dioxide and carbonate in solution. Changes in the partial pressure of CO_2 will influence the bicarbonate concentration. It is therefore necessary to analyze the bicarbonate concentration on site before the CO_2 equilibration with the atmosphere affects the concentrations.

Advantages

These three parameters are the most important ones for the overall chemical situation and are also most sensitive to disturbances. They must be analyzed immediately.

Disadvantages

Need for careful planning and treatment, in addition to which the on-site analyses are expensive.

5.7.5 Uranine analyses

All water used for drilling is tagged by a fluorescent dye, Uranine. The same dye is also used to tag the water used for the hydraulic injection tests.

The content of drilling water can be analyzed with a spectrofluorimeter down to less than 0.1% contamination. A representative groundwater should have less than 1% contamination. However, the acceptable level of contamination is dependent on what purpose the sample will be used for. Samples with more than 10% contamination are still useful for determining the total salinity of the undisturbed groundwater, while for tritium analyses 1% contamination severely affects the usefulness of the sample.

Advantages

A rapid, inexpensive and safe method for determining contamination by drilling and hydrotesting.

Disadvantages

Drillers must be taught how to add the tracer correctly, and control the process.

5.7.6 Stable and radiogenic isotope analyses

Oxygen-18 is a robust datum, not sensitive to disturbances, as long as they are known. Tritium and carbon-14 on the other hand are extremely sensitive to contamination by surface-derived water from drilling or from uncontrolled short-circuiting of water-bearing sections through open boreholes. Deuterium and oxygen-18 data have been used successfully to evaluate the residence time of the different groundwater types found at Äspö. The role and usefulness of these data are best illustrated by the evaluation done by *Smellie and Laaksoharju /1992/*:

Stable isotopes

Using a plot of $\delta^{18}O$ versus δD, the Äspö groundwaters, together with near-surface fresh/brackish waters from both Äspö and Laxemar and present day Baltic seawater for comparison, are related to the global meteoric water line, see Figure 5-7. Although all the samples plot below the global meteoric line, and there is a large spread of isotopic values ($\delta^{18}O$ from -15.8 to -7.2°/$_{00}$ and δD from -124 to -62°/$_{00}$), the groundwaters are clearly meteoric in origin.

At first glance the stable isotopic data from Äspö appear to lack any kind of overall consistency. Some samples show a degree of affinity with modern Baltic waters (KAS06:3,4, and HAS13), others with near-surface fresh / brackish waters (KAS04:1, and KAS06:2), and of the remainder, the deep saline varieties (KAS02:6,7 and KAS03:7,8) tend to cluster around -13.2 to -12.5°/oo.

Within the same cluster area, but showing a slight shift to heavier $\delta^{18}O$ signatures, are less saline and shallower waters which have been sampled using low pump extraction rates and could therefore be considered "representative" of the rock mass in the immediate vicinity of the sampled location (e.g. KAS02:2,3,4,5).

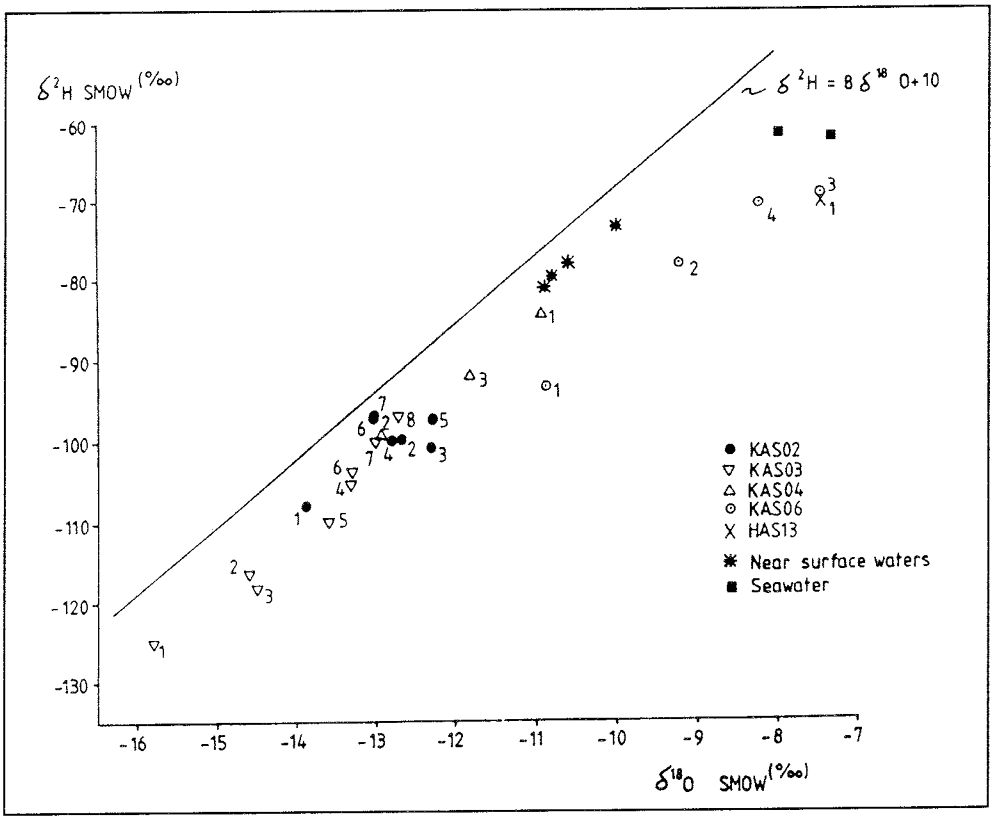

Figure 5-7. Stable isotope compositions of the Äspö groundwaters. $\delta^{18}O$ and $\delta^{18}H$ are indicative for the recharge temperature. The value of both is O (zero) for Standard Mean Ocean water (SMOW).

The influence of modern Baltic and modern near-surface fresh/brackish waters is more apparent in the KAS04 samples (KAS04:1 in particular with 4.3 TU, KAS04:3 less so), where there is a trend towards a more near-surface fresh/brackish water composition.

All the sections sampled in KAS06 have been subject to excessive extraction rates and all samples plot towards heavier isotopic compositions, having more in common with modern Baltic meteoric water. Mixing of Baltic water with mainly near-surface fresh/brackish waters is apparent from the isotopic trends.

Radiocarbon

Carbon-14 data from dissolved calcite show high apparent ages on all sampling occasions. This supports the conclusions drawn from the interpretation of the oxygen-18 data. However, given to the long residence time, many processes may have influenced the C-14 content besides radioactive decay. Thus the C-14 age should be considered more a relative than an exact age.

The deep Äspö water has a low bicarbonate content and has therefore not been possible to use for C-14 analyses.

In terms of relative age, the Baltic seawater/near-surface fresh/brackish waters should represent the most recent, youngest water components, the deep saline waters should be among the oldest, and the remainder should be of intermediate age due to the natural hydraulic and imposed mixing processes. Although not many radiocarbon data are available, there are enough to generally support these trends. There are important exceptions, however. The upper part of KAS03, which records salinities of only 1 300 to 3 000 mg/l Cl, in comparison with the deep saline waters (>12 000 mg/l Cl) has anomalously light stable isotopic signatures and also contains the least proportion of modern carbon (2-8%) measured in any of the Äspö groundwaters. As suggested above, the most ready explanation is that these samples represent ancient mixtures of seawaters diluted by cold climate recharge occurring mostly within the upper 200-250 m of bedrock.

Uranium decay series

The $^{234}U/^{238}U$ activity ratios for the Äspö groundwaters are high to very high (2.6 to 7.2), showing widespread isotopic disequilibria in the groundwaters due to excess ^{234}U caused by rock/water interaction processes. This ^{234}U excess is caused by the ingrowth of ^{234}U due to the dissolution of alpha-recoil ^{234}Th at the rock/water interfaces during the permeation of groundwater through the bedrock. The inference, therefore, is that the groundwaters are moving sufficiently slowly through the bedrock so as to allow a ^{234}U excess to accumulate. The high activity ratio values which characterize many of the Äspö groundwaters indicate long residence times, thus generally supporting the very old age of some of these waters. This is not only evident in the deep Ca-rich waters, but even fairly near the surface away from major conducting fractures.

Advantages

Radiogenic and stable isotopes are of outstanding usefulness for characterizing the history of the groundwater.

Disadvantages

Isotopic analyses are research tools and very expensive and time consuming. For many of the methods the sampling procedure is critical, since the samples are easily disturbed.

5.7.7 Stable isotope studies of calcites, sulphate and sulphide

Oxygen-18 and carbon-13 were analyzed on separated calcite phases from drill cores KAS02, KAS03, KAS04, KAS06 and KAS09. The studies were focused on open water conducting fractures */Tullborg and Wallin in Tullborg et al., 1991/.*

The results show a wide spread of data indicating that there are several calcite generations of different origin. The majority of the calcites in the open fractures are in equilibrium with, or affected by, present-day groundwater or surface water. On the other hand, no calcite precipitates were observed which indicated equilibrium with present-day Baltic Sea water. Extremely low carbon-13 values, $<-20°/_{oo}$ in a few samples, suggest the oxidation of methane or organic matter to carbonate.

The sulphur-34 content of dissolved sulphate and in pyrite were examined by */Wallin, 1992/.* The oxygen-18 content of dissolved sulphate was also included. The results point towards a multiple source for the sulphate, which could include marine sulphate, reduced sulphur from the basement and organic sulphur. All the initial sources are masked by ongoing organic sulphate reduction and mixing between marine and meteoric brines.

Advantages

In combination with stable isotope analyses of the groundwater, these analyses are invaluable for evaluating paleogeohydrology.

Disadvantages

The analysis and sample preparation procedures are time-consuming and expensive.

5.7.8 Distribution of lanthanides and rare earth elements between the water and fracture minerals

The distribution of uranium and rare earth elements (REE) between fracture minerals and groundwater has been investigated on drill cores and groundwater samples from Äspö. The same kind of investigation has been performed on samples from Klipperås. In Table 5-2 the distribution factors are listed together with laboratory K_d values selected to describe sorption within the SKB 91 safety assessment.

Table 5-2. The distribution factor for uranium and rare earth elements calculated from concentrations in groundwater and fracture minerals and the K_d values used for the SKB 91 safety assessment calculations. The distribution factor is m^3/kg.

Element	Distribution factors (K_d) Äspö	Distribution factors (K_d) Klipperås	Distribution factors (K_d) SKB 91
Sr	0.002 – 0.17	1 – 4	0.003
Rb	0.4 – 10	22 – 160	(0.003)
Ba	1 – 3	5 – 30	(0.003)
Cs	0.02 – 22	19 – 6030	0.03
Eu	48 – 1504	900 – 1400	0.2
U	0.05 – 240	10 – 97	2
Ce	47 – 3400	2900 – 6800	(0.2)
Sc	125 – 1902	2000 – 7600	(0.2)

The laboratory data, those used in SKB 91, are considered to be conservative. It is, however, obvious from the data in the table that some are in good agreement with those obtained in situ from Äspö. The large difference between the Äspö and Klipperås data is probably due to the difference in salinity. In Klipperås all groundwater is fresh, in Äspö it is saline.

Advantages

A method to validate sorption coefficients for radionuclide migration calculations.

Disadvantages

A research method, time-consuming and expensive.

5.7.9 Equilibrium modelling and mixing modelling

The interaction between the groundwater and the rock minerals will approach an equilibrium between the dissolved and the solid phases. However, some reactions are fast while some are extremely slow. Therefore, equilibrium modelling is done routinely only for those reactions which are considered to reach equilibrium, i.e. the calcite – carbonate – pH system and the ferric oxide – ferrous iron system and a few others involving the solid phases FeS, FeS_2, CaF_2, $CaSO_4$, $BaSO_4$, $Mg(OH)_2$ etc.

A completely different concept is to consider all water as the result of a continuous mixing process where the chemical reactions with the bedrock have affected the composition only to a slight extent. For the Äspö conditions mixing modelling has been superior to equilibrium modelling, probably due to the large variation in salinity. The results also confirm the assumption that the mixing process largely determines the evolution of groundwater composition.

Advantages

A combination of the two modelling approaches a better description of reality than either one of them alone.

Disadvantages

The coupled modelling of this type has not been fully developed and tested.

5.8 METHODS FOR TESTING TRANSPORT OF SOLUTES

5.8.1 General

In order to be able to understand how solutes are transported and also how to model transport of solutes, groundwater chemistry has to be sampled and transport properties of the rock have to be estimated. For radionuclide migration also the retention mechanisms are needed.

5.8.2 Groundwater chemical sampling

See section 5.7.2.

5.8.3 Tracer tests

Tracer tests are needed for estimating transport properties such as flow porosity and dispersivity. Other important transport properties are sorption and matrix diffusion, which depend on the tracer transported and the character of the fracture surface. So far the large-scale tracer tests at the Äspö HRL have been focusing on flow paths, flow porosity and to some extent dispersivity by using non-sorbing tracers.

The two tests which have been performed have been radial converging tests (pumping a borehole, KAS06, and inflow to the tunnel in NE-1) with a typical distance between injection and sampling points of 100-300 m.

Advantages

Tracer tests are useful since they makes it possible to verify the main flow paths of the investigated rock volume. The flow and transport properties, i.e. transmissivity, storage coefficient and transport porosity for these conductive structures are also determined by flow or pumping tests combined with tracer tests. Water samples taken during the test can also give information of groundwater chemistry and natural tracers.

Disadvantages

Tracer tests are expensive and time-consuming. It is therefore important to plan them carefully and especially to avoid disturbances from other activities, such as drilling. Tracer tests can in general not give data on reactive transport. Sorbtion and matrix diffusion properties must therefore be resolved in a set of experiments in a smaller scale.

5.9 METHODS FOR ROCK MECHANICAL INVESTIGATIONS

5.9.1 General

The investigations performed for rock mechanical purposes have been aimed at both providing a general overview of the rock mechanical conditions in the Simpevarp area, and providing a more detailed description of the rock mechanical characteristics of the different rock types.

Similar investigations have been used for making evaluations on the sitescale and the block scale. Laboratory testing has been performed for the evaluations on the detailed scale.

A large portion of empirical experience is included in the final judgement for all evaluations. The general rock mechanical conditions in well known hard rock areas and a large number of underground facilities in Sweden today have been successfully elucidated.

5.9.2 Study of terrain, topographical mapping and exposed rock

A field study of the terrain was carried out in an initial stage of the project. Major fracture zones located in the structural geological model were specially studied. The terrain study was found to be very useful and provided an valuable general picture of the surface characteristics of the major structural features.

The structures identified during the terrain study were also identified and confirmed on topographical maps.

The properties of different rock types were also investigated in the field during the terrain study. Properties such as fracture frequency, degree of weathering and mechanical characteristics were particularly observed.

Field and desk studies of surface characteristics are activities provide valuable information at low cost at an early stage of an investigation. Besides providing a general picture of the area, the obtained information can be used for further planning of other investigations. The information is, however, limited to the surface and should not be used for comprehensive extrapolation to the conditions in deeper portions of the rock volume.

5.9.3 Seismic refraction investigations

Seismic surface investigations were carried out to identify and describe fracture zones. The seismic velocities provided valuable information on the presence of fracture zones and the degree of fracturing, as well as on the general rock quality in the area.

However, to obtain good reliability in the interpretation of the seismic velocities, the seismic investigations must be supplemented with borehole investigations.

A disadvantage with seismic refraction investigations is that the results give a rather rough description of anomalies, e.g. fracture zones.

The accuracy of evaluations of the field data is influenced by the depth of the soil overburden on the rock. Other factors that affect accuracy are the slope of the rock surface and whether a sharp boundary can be defined between overburden and rock.

Favourable conditions are horizontal rock surfaces, little overburden and a distinct difference between the wave velocity for the bedrock and the overburden.

The major advantage with seismic refraction investigations is that large areas can be covered in a rather short time and to provide a general picture of the location and orientation of potential fracture zones. The method can be used in both saline and fresh water.

5.9.4 Borehole investigations

Borehole investigations were performed in different parts of the area. The holes were located and oriented to provide information on the presence and quality of rock in both fracture zones and areas without major fracture zones.

Borehole investigations provided very valuable information on rock quality. For some of the cored holes located in areas of special interest, the different sections of the obtained cores were classified according to the Rock Mass Rating system. The RMR is easier to apply to cores than the Q system. RMR classification of the cores provided very valuable information on the different rock classes and rock qualities present in the area. When subdivision into different rock classes was done, the classification was also used to estimate the frequency of the different rock classes.

The borehole investigations were superior to other investigation methods for prediction of the distribution of rock qualities.

To provide a reliable prediction of rock mechanical stability, the information on rock quality must be complemented with information on rock stress conditions and mechanical characteristics. Rock stress conditions and mechanical characteristics may to some degree be assumed, however, which cannot be done with the distribution and presence of different rock qualities.

5.9.5 Rock stress measurements

The main purpose of performing rock stress measurements was to get a general picture of the rock stress conditions in the Simpevarp area.

To be able to predict rock stresses on the block scale, and certainly on the detailed scale, the number of measurements must be much greater. The information gained during the measurements seems to be adequate to get a general idea of rock mechanical stability and to suggest measures to prevent potential stability problems.

The measurements were performed by means of both hydraulic fracturing and overcoring.

The measurements were performed in deep vertical boreholes. Compared with overcoring measurements the hydraulic measurements are rather easy to carry out. Most of the measurements were therefore performed by hydraulic fracturing. The overcoring method confers better reliability on the stress orientation than hydraulic fracturing.

For a general investigation of the stress conditions in a regional area such as the Simpevarp area, both methods provide valuable information for further analysis of general rock mechanical stability conditions.

The advantage of hydraulic fracturing compared with overcoring method is that the measurements can be done quickly. The measurements are performed in boreholes that have been drilled in advance, so a large number of measurements can be made. The overcoring method technique is based on measurements made during overcoring and is therefore much more time-consuming than hydraulic fracturing. Overcoring provides better information on the orientation of the stress field, however.

5.9.6 Laboratory testing of core samples

Laboratory testing was performed to define the mechanical characteristics of the different rock types and to assess surface properties.

Mechanical characteristics – i.e. unconfined compressive strength, elastic moduli, Poisson's ratio and brittleness ratio – were estimated from compressive tests of core samples. Testing was performed on approximately 10 samples of each rock type. The testing firstly provided valuable information on compressive strength, elastic moduli and Poisson's ratio. In hard rock similar to the type in question, these parameters rarely indicate limitations on the further design of the underground facilities. It is, however, valuable, to verify mechanical properties at an early stage of a project.

Other less comprehensive methods than uniaxial compressive tests can be used to determine compressive strength, e.g. point load tests. Uniaxial compressive tests are, however, favourable when there is also interest in determining elastic moduli, Poisson's ratio and brittleness ratio.

To provide information on the brittleness ratio, the uniaxial compressive tests were performed on a press with very high stiffness. The high stiffness was necessary to record deformations during failure, which determine the brittleness ratio. The load-deformation history gave an indication of the ratio of brittleness and was used to evaluate the risk of rock burst. Although, rock burst is a very complex behavior caused by a number of factors, the results of testing of the brittleness ratio provided information for better estimation of the potential for rock burst.

The laboratory testing also included shear tests of existing joints by shearing joint pieces. Testing was performed on a few samples. The results of the testing did not have any great importance for the further evaluations of rock mechanical stability conditions. The number of joints tested was too small to be representative of the different rock types. General experience of fracture surface properties, combined with geological logging of core samples, was of greater importance for the stability judgements than the laboratory testing of joints.

6 CONCLUDING REMARKS

In chapters 4 and 5 the investigation methods have been evaluated with regard to their usefulness and feasibility. As indicated in chapter 4 the role of one specific method is depending on what other methods are being used and what knowledge is being sought. In this chapter some comments are made on the strategies of the entire investigation phase, and some general experiences we wish to underline.

6.1 STRATEGY

6.1.1 Investigation stages

The pre-investigations for the Äspö HRL started in late 1986 and continued until 1990. The siting stage was finished by 1987, the site description by 1988 and the prediction stage by 1990. The siting stage mainly comprised regional investigations and regional scale modelling. It was, however, necessary, to include a semi-regional model with some potential sites surrounding the Simpevarp peninsula. The site description and the prediction stages both focused on the site scale models of Äspö and the southern part of Äspö.

It has been very useful to divide the investigation into stages and summarize the model after each stage. In this way everyone involved in the project has obtained a good overview for the future work. However, in some cases it has been difficult to define exactly what stage certain investigations belong to, since the investigations never ceased altogether. This is, however, a minor problem.

The three-stage approach for investigations is considered adequate. The siting, site description and prediction stages could have been divided slightly differently, however.

6.1.2 Key questions

To be able to investigate and evaluate the relevant aspects of the bedrock, a number of key questions were defined by the Äspö HRL project. These are considered to be important from the viewpoints of long-term safety, construction view and siting.

The key questions:

- geological-structural model,
- groundwater flow,
- groundwater chemistry,
- transport of solutes and
- mechanical stability

represent a satisfactory classification of the important aspects of the bedrock. The subjects related to each key question are also considered to be important for the investigation and modelling of the bedrock. However, some subjects have not been treated during the pre-investigation phase, but will be dealt with later at the Äspö HRL.

It should here be pointed out that subjects related to construction may not be the same as for long term safety aspects, and that the list of subjects may change due to new construction and long term safety demands.

6.1.3 Modelling scales

The investigations were performed on different scales in parallel throughout the entire investigation phase. The scales were:

– regional	>> 1 000 m
– site	100 – 1 000 m
– block	10 – 100 m
– detailed	0 – 10 m

The subjects (and related parameters) associated with each key question (Geological-structural model, Groundwater flow, Groundwater chemistry, Transport of solutes and Mechanical stability) were addressed in the site, block and/or detailed scale models. The basis for assigning a subject to a scale was that the subject should be important for the model realisation or the description on that scale.

However, these subject-related scales have sometime been confused with the investigation stage-related scales or areas. During the siting stage a large area was investigated – a "regional" area – and later a few potential areas for the "site". During the site description stage one "site" was investigated and during the prediction stage the "site", or rather a smaller part of the selected "site", was investigated. All subjects could not be analyzed during the first stages, but the important thing is that in every investigation stage subjects from all modelling scales were analyzed.

For example, the description of lithological unit is related to the detailed scale. For each investigation stage a generic model of the rock type characteristics and fracture systems for the different lithological units was made. Possibly "detailed description of lithological units" is better than "detailed scale model".

The difference between deterministic features and generic blocks has caused some confusion. In the model presented after each investigation stage, the rock mass has been presented on site scale, block scale and detailed scale. On the site scale major features and properties are defined by site-specific planar features and volumes – it is deterministic. However, the block scale and detailed scale are generic – that is, they are considered to be "typical" blocks that should be expected to be found somewhere within the investigated volume.

The prediction-stage generic blocks were made for the block scale, but 10 blocks along the tunnel system were also modelled. These 10 blocks were thus also deterministic.

6.2 INTEGRATED MODELLING

The interdisciplinary modelling work has been carried out continuously throughout the investigation phase. The simultaneous treatment of geological, geohydrological and hydrochemical data has resulted in more robust models than would otherwise have been obtained. The reason for this is simply that e.g. the hydrochemical models must be in agreement with both the geological and the geohydrological models while also describing the observed chemical conditions, and likewise for the other models.

A core group of principal investigators with responsibility for the various key questions has both planned and evaluated the results. This group and the project manager are responsible for decisions concerning the investigations and have thereby been able to refine the modelling continuously and use the results in the planning of future work.

6.3 EXPERIENCE

It is possible to divide experience into technical and conceptual. Technical problems can be avoided to some extent, but the solutions are perhaps not always economically acceptable.

The conceptual difficulties are related to that we try to make measurements to get data for model realizations based on chosen concepts, and the measurements themselves disturbes what is going to be measured. The calculation of the undisturbed situation therefore always remains uncertain to some extent. Some technical experience is presented below.

Integrated evaluation of data from geology, geohydrology and groundwater chemistry is very useful in the conceptual modelling process, especially with regard to the characterization of water-bearing structures. (From a practical point of view it is still difficult to coordinate the different investigations and to make use of the experiences of previous investigators.)

There is a need for further development of core drilling methodology. It is generally very difficult to penetrate sections of crushed and clay-altered rock using small drill bits without grouting.

Many geo-electrical pre-investigation methods are strongly disturbed by saline water. The range of radar investigations in boreholes for example is reduced. Electrical investigation methods may also be disturbed by man-made installations such as cables, power lines and containers, which is important to take into account during the planning work.

Identification and characterization of the possible existence of low-dipping structures (fracture zones) is still a problem. Seismic reflection may in some cases be useful for detecting this kind of fracture zone, but there is still a need for much more development of both field techniques and data processing before this method can be regarded as safe and practicable in crystalline rocks at depths down to approximately 500 m. VSP may also be useful, but this method too needs further development.

Today a careful evaluation of available geological field data seems to provide the most reliable information on the occurrence of low-dipping structures in a rock volume. If the low dipping structure is conductive and there are a suitable monitoring programme, interference tests can give reliable information of the occurrence.

No absolute pressure head measurements were made in the boreholes during the initial hydraulic tests. This has been a drawback for the modelling of groundwater conditions and circulation, both in the undisturbed and the disturbed situation.

Interference tests are the basis, along with the geological-structural model, for defining major hydraulic structures. They are also used for calibration of groundwater flow models on the site scale.

A large number of observation sections, pumping just one conductive structure (packed off with double packers) in a borehole, and a good geological- structural model improve the prospects of obtaining an accurate picture of the location and interconnection of major conductive structures. Pressure disturbances induced by drilling, for example in an area close to the pumping test, may more or less ruin the prospects of an evaluation. It is therefore important to plan drilling, hydraulic testing, geophysical logging, groundwater chemical sampling etc carefully.

Even though a good geological model and a few interference tests may give good indications of the location of and interconnection between major conductive structures, these few tests cannot determine the hydraulic properties of all structures. Generally, major conductive structures should be drilled through at several points and each borehole section penetrating the conductive structure should be tested individually. The drilling and hydraulic testing should be planned with this in mind.

It is also important to start continuous monitoring as soon as possible in order to obtain initial values of water level and piezometric head. The initial salinity distribution in the groundwater is also important.

The geohydrological investigations cannot solely be concerned with major conductive structures. It is also important to assess the hydraulic properties of the rock between the major conductive structures. To get representative samples it is important to have a large number of tests in boreholes well distributed within the rock volume of interest. One problem with the hydraulic tests is that they seem to be scale-dependent. So far different scales (different test section lengths) have been used in the tests and empirical relationships between geometric mean and scale as well as standard deviation and scale have been used. The scale dependency of hydraulic tests must be further analyzed.

Telescope shaped drilling has been useful in order to minimize contamination by drill water. It has also made it possible to perform interference tests with submersible pumps with quite high pumping capacities and to install water stand pipes for piezometric measurements. The advantage of the latter is that low-range pressure transducers can be used (for high resolution) and they are easy to calibrate and exchange. The drawback to date of telescope shaped drilling is that there have been fewer hydraulic investigations in that part of the borehole. Another drawback is that the salinity of the water in the pipes has to be known in order to calculate the pressure in a test section. (The pressure is needed for calibration of the groundwater flow models.) It has been found that it is not always easy to determine the salinity in the pipes due to low hydraulic conductivity of the measured test section. Due to this uncertainty and uncertainties in borehole deviation measurement, the uncertainty of the hydraulic head increases at deeper levels in the boreholes.

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ROCK DESCRIPTION OF THE ÄSPÖ HARD ROCK LABORATORY BASED ON PRE-INVESTIGATION DATA

THE REGIONAL SCALE MODELS

The geological-tectonic modelling work on the regional scale (approx. 5000 x 5000 metres) was mainly based on the results from the following investigation methods: Bedrock geology, (lineament interpretation) geophysics and structural geology.

The Simpevarp area is mainly of granitic composition. Different types of the Småland granite dominate. Acidic vulcanic rocks (Småland porphyries) are closely related to the Småland granites.

Some E-W elongated massifs of basic rocks, greenstone, are indicated. Besides the more coarse-grained types, such as gabbro and diorite, fine-grained irregular bodies and xenoliths of greenstone are found as remnants within the granite mass. Greenstone occupies only a minor part of the Simpevarp area.

Porphyritic granites are very often intruded by a fine-grained greyish-red granite which occurs both in smaller massifs and in dykes, very often following the foliation in the direction E-W to NE-SW.

Some circular-semicircular structures in the investigated area are interpreted as granite diapirs, the Götemar and Uthammar granites are two of these.

The regional tectonic model of the Simpevarp area is dominated by one almost orthogonal system of estimated major fracture zones (N-S and E-W). These zones were estimated to be about 300 to 500 metres wide and extend in the order of 20 to 50 km. The N-S fracture zones have most probably vertical-subvertical dips and seem to be of a tensional, more open character according to coincident magnetic and VLF indications. The zones trending E-W are mostly vertical, with a moderately low dip to the north or to the south. They seem to be more complicated with an early dip-slip ductile phase, indicated by intense mylonites, followed by a semi-ductile strike-slip phase and a late stage of reverse faulting with local development of thrust sets with a mainly low to moderate dip to the SSE. The fracture zones trending N-S are probably more permeable than those trending E-W.

Besides the system of the major fracture zones, there are also fracture zones trending NW and NE, forming another almost orthogonal system. These are mostly estimated to be in the order of 100 to 200 metres wide and extend 1 to 20 km.

The most prominent of the NE trending fracture zones, running immediately west of Simpevarp and crossing the island of Äspö, is indicated by mylonites in some outcrops in the granite. For many of the zones trending NW there seems to be a better coincidence between VLF and magnetic indications than for the NE trending zones. According to a general interpretation, most of the zones trending NE and NW are older than the N-S and E-W fracture zones.

Fracture zones trending NNW and NNE are geophysically interpreted as being a conjugate shear set to the tensional fracture zones trending N-S.

Most of the regional fracture zones in the Simpevarp area have been preliminarily interpreted as being vertical or sub-vertical. Both geological and geophysical indications, however, point to the possibility of more flat or low-dipping structures, especially connected to the anorogenic granites (e.g. flat pegmatite dykes in the Götemar granite area). Dykes of fine-grained granites and aplitic dykes are probably more sub-vertical or moderately dipping.

The geohydrological models were based on analyses of existing data from different aspects and hydraulic tests in percussion boreholes.

An analysis of data from water wells in the area shows a significant difference in hydraulic conductivity for different rock types. The most pervious unit is the granites of Götemar-Uthammar type. The abundant Småland granite has intermediate conductivity, and least pervious are the greenstones of the area. The data from Ävrö showed that there was a decrease in hydraulic conductivity with depth */Rhén, 1987/*.

Some fracture zones, very distinct with few open fractures and high transmissivity, were found in the Småland granite area. The areas of greenstone and with greenstone lenses were found to be less pervious. The mylonite zone, crossing Äspö from NE to SW, was found to be moderately pervious.

Measurements in boreholes situated in Laxemar, Äspö and Ävrö showed that the groundwater level (h_w) is closely related to the ground surface level (h_g). (The relationship was estimated to be $h_w = h_g/1.2$).

The geohydrochemical modelling work on the regional scale (approx. 5000 x 5000 m) was based on the results obtained from shallow percussion boreholes at Laxemar, Ävrö and Äspö. Good reference data were obtained from the well data records of the Geological Survey of Sweden (SGU). The chemistry data from wells in Kalmar County were compared with the results of analyses of water sampled from percussion boreholes. In addition, surface water from the three sites was also analyzed.

The statistical treatment of the data from the well records showed that:

* Saline water was correlated with wells with high capacity.
* Saline water was more common closer to the coast.
* The pH and carbonate system was correlated with soil thickness.

The great similarity between the data from the well records and the data from the percussion drilled holes indicated that the investigated area was typical of the surrounding Kalmar County. However, the limited data showed that saline water was present in highly conducting zones existed. The pressure head of this water was governed by the sea.

THE SITE SCALE MODELS

The geologic-tectonic modelling work on the site scale (Äspö scale, approx. 500 x 500 metres) was mainly based on improved knowledge of the lithological distribution and petrological and structural characteristics of the bedrock on Äspö, compared to the regional-scale model.

The first simple two-dimensional model devided the Äspö island into two main blocks separated by a NE-trending tectonic zone of a regional order. Småland granite with veins and xenoliths of greenstone and dykes and irregular masses of fine-grained granite dominate in both these blocks, but from about the 300-metre level downward, especially in the southern block, the Småland granite consists of more basic varieties (Äspö diorite).

The central NE-trending Äspö shear zone seems to be dip almost vertical or steeply to the north. The zone is very complex, comprising 5-10-metre-wide highly fractured parts alternating with more normally fractured rock. The oxidation of magnetite in the granitic rocks is characteristic of the entire Äspö shear zone.

The rock mass in the southern part of Äspö was estimated to be less fractured than the northern part.

The dominant rock types on Äspö are Småland granite and granodiorite-diorite. Normally there is no distinct contact between the different varieties of the granitic-dioritic rocks, which gradually blend into each other. Fine-grained granite is very common in the whole rock mass, mostly in the form of narrow dykes and veins, but also as larger irregular masses, especially at the level between about 300 and 450 metres and at the level below about 750 metres. Dark, fine-grained greenstone occurs as metre-wide lenses and xenoliths – often highly fractured and altered. Wider sections of a more coarse-grained gabbroid rock were recorded in some boreholes.

The lithological units of hydrogeological importance were considered to be Äspö diorite (least pervious), Småland granite and fine-grained granite (most pervious).

The structural features which were considered most conductive were fracture zones and single open fractures. The fracture zones cut through all types of rock, and the single open fractures are probably limited in extent and found in the brittle granites.

No significant trends for the depth dependency of hydraulic conductivity were found. It was suggested that dykes and sills of fine-grained granite, originating from the Götemar granite deep under Äspö, might explain the absence of hydraulic conductivity.

The Äspö shear zone divides Äspö into two parts. The SE part of Äspö was considered significantly less pervious than the NW part.

Ten major fracture zones (fracture systems) on Äspö and south of Äspö were described in detail as to strike, dip, position, extent and transmissivities. The main strikes were as in the previous stage, except for a new set of structures E-W.

The Äspö area consists of small run off basins, suggesting that the terrain may be subdivided into a mosaic of recharge and discharge areas, thereby giving a small average annual recharge.

Five different rock mass units (RMU) were identified. Two of them, NW Äspö and Äspö shear zone, were approximately the same as in the areas of different hydraulic conductivity in the previous stage. SW Äspö was divided into two parts and the area south of Äspö was new. The depth dependency of the hydraulic conductivity was updated and the standard deviation of the hydraulic conductivity was calculated with data from new hydraulic tests. The scale dependency and standard deviation of the hydraulic conductivity were also updated.

The geohydrochemical modelling work on the site scale (approx. 500 x 500 m) was based on the results obtained from shallow percussion boreholes. Additional information for the Äspö area was gathered from the three deep cored holes on Äspö during the siting stage. Further information was obtained from the boreholes drilled during the site description stage. No data from the prediction stage were used.

Judging from percussion boreholes at Laxemar, Ävrö and Äspö, it was clear that the fresh/saline water interface was deeper at Laxemar and Ävrö than it was at Äspö. From the three cored holes at Äspö it was evident that there were two rock blocks divided by a major shear zone. Groundwater salinity in the two rock blocks increased gradually with depth. The increase was not completely linear and not exactly the same in the two boreholes. The source of the salinity might be different in the northern and the southern part of Äspö. The ratio between calcium and sodium is very different from that in the seawater. It can be conducted that a large water-rock interaction has been taking place.

Multivariate analysis was used to classify the groundwater on Äspö. Despite the gradual increase of salinity it was possible to identify four different classes, i.e. infiltrating freshwater, mixing between freshwater and underlying relict sea water, and at great depth pre-glacial water. The four classes were identified on a purely statistical basis, whereas the origin was evaluated based on the isotopic data.

The salinity of the Äspö groundwater is the result of transient washing-out process which started at the time when Äspö rose above the sea some 3000 years ago. Since then the saltwater has been replaced by infiltrating freshwater to a depth of only a few tens of metres on average, but at certain locations much deeper. The varying salinity is balanced by variations in groundwater head and level.

The presence of relict Baltic Sea water and pre-glacial water is evident from the oxygen-18 data for the water. The existence of connecting flowpaths from the surface to the relict seawater is indicated by tritium levels showing a few parts per million of modern water.

Calcite is one of the most common fracture minerals in the fractured crystalline bedrock. Due to fast kinetics, the uppermost part of the rock use to be depleted of calcite due to weathering by infiltrating surface water. This is not the case at Äspö, which means that there is a very small recharge of freshwater. Oxygen-18 data show that the calcite has been re-equilibrated since any hydrotermal event. Therefore some water circulation does take place.

The calcite saturation index of all the waters sampled at Äspö is positive. This indicates a continuous mixing between waters of different composition. Theoretical calculations agree with the observed index.

Data from groundwater sampling carried out during drilling of the deep cored holes served as the basis for defining the chemistry of the groundwater in the conductive fracture zones, see 4.4.2.

Groundwater in different fracture zones and an indication of where the zones have been identified in the different boreholes is presented together with the geological and geohydrological evidence. All fracture zones are presented separately and summarized in one table.

THE BLOCK SCALE MODELS

Predictions on a block scale are made in order to describe and predict different kinds of rock volumes as regards rock distribution, minor fracture zones and other structures.

The parameters predicted on the block scale are estimated based mainly on data from at least one cored borehole penetrating the block in question or the rock volume close to the block.

The geologic-hydrologic description focused on blocks typical of southern Äspö. The characteristics of the ten defined blocks are presented below */Wikberg et al., 1991/*:

50-01 Småland granite with veins of fine-grained granite and/or greenstone and single open fractures

- Single open fractures are found in Småland granite and finegrained granite – probably of limited extent.
- Småland granite: $K^3_g = 1.2 \times 10^{-10}$ m/s, $S^3_{LogK} = 2.04$
  (K^3_g: Geometric mean of the hydraulic conductivity (K) in the 3-m test scale.
  S^3_{LogK}: Standard deviation of $Log_{10}(K)$, where K is for 3 m test scale.)

50-02 Äspö diorite with veins of fine-grained granite and/or greenstone and single open fractures

- Single open fractures are found in Äspö diorite.
- Äspö diorite: $K^3_g = 5.2 \times 10^{-11}$ m/s, $S^3_{LogK} = 1.8$

50-03 Contact between Småland granite and Äspö diorite

- $K^3_g = 10^{-10}$ m/s, $S^3_{LogK} = 2.1$

50-04 Småland granite with dykes of fine-grained granite and greenstone

- Dykes or the rock close to dykes:
  $K^3_g = 8 \times 10^{-9}$ m/s, $S^3_{LogK} = 2.2$

50-05 Småland granite with ductile shear zone

- $K^3_g = 10^{-8}$ - 10^{-10} m/s, $S^3_{LogK} = 1.5$

50-06 Småland granite with fracture zones

- $K^3_g = 10^{-8}$ m/s, $S^3_{LogK} = 1.5$

50-07 Småland granite with minor clay altered fracture zone

- $K^3_g \leq 10^{-8}$ m/s, $S^3_{LogK} = 1.5$

50-08 Äspö diorite with greenstone dyke

- Minor fracture zones less conductive than Småland granite
- $K^3_g = 10^{-9}$ m/s, $S^3_{LogK} = 1.5$

50-09 Småland granite with mylonite zone

- $K^3_g = 10^{-10}$ m/s, $S^3_{LogK} = 2.2$

50-10 Småland granite with hybrid rocks

- Low to medium hydraulic conductivity

Greenstone was expected to contain stagnant water with a high pH and saturated with some Fe(II)mineral. Småland granite was expected to have a lower pH and a lower redox buffer capacity. With greenstone lenses a higher iron content is expected. The 50 m blocks cannot be described in more detail.

THE DETAILED SCALE MODELS

Geological models on a detailed scale are devised for the four most frequent rock types observed in the target area: Småland granite, Äspö diorite, fine-grained granite and greenstone. The models concentrate on mineralogy, petrophysics and typical fracturing. The positions of the predicted blocks are based on information from boreholes which are penetrating the block volume.

The hydraulic injection tests on a 3 m scale were important for estimating hydraulic conductivity.

Some block characteristics are outlined below /*Wikberg et al., 1991*/:

Småland granite

The typical Småland granite is a medium-grained, porphyritic rock, varying in colour (grey-greyish red), grain size and frequency and size of the potash megacrysts.

The Småland granite is generally weakly foliated and can be classified as granite-granodiorite.

- Low to moderate hydraulic conductivity
- $K^3_g = 1.2 \times 10^{-10}$ m/s, $S^3_{LogK} = 2.0$

Äspö diorite

The Äspö diorite is a more basic variety of the Småland granite, which seems to be more common at lower levels in the Äspö area. This rock types grade petrographically from granodiorite to monzodiorite to diorite. The rock is greyish and medium-grained, often with red potash feldspar megacrysts.

- Low hydraulic conductivity.
- $K^3_g = 5.2 \times 10^{-11}$ m/s, $S^3_{LogK} = 1.8$

Fine-grained granite

Fine-grained, red to greyish-red granite is common in the whole Äspö area. The fine-grained granite occurs both in smaller massifs and in dykes in the older rocks. Often the direction of the dykes follows the foliation in a roughly

E-W to NE-SW direction. The dykes are usually about 0.5 – 5 metres, but dykes measuring 30 metres across have also been found.

The fine-grained granite is normally more intensely fractured than the Småland granite and the Äspö diorite.

- Most permeable rock unit on Äspö.
- $K^3_g = 7.9 \times 10^{-10}$ m/s, $S^3_{LogK} = 2.1$

Greenstone

Greenstone occurs both as large massifs and as small irregular lenses and sheets in the granite mass. The larger massifs are of diorite-gabbroid composition, and the fine-grained rather homogeneous black-greyish greenstone is probably a metabasalt. The greenstone has often been intruded by the fine-grained granite.

Greenstone masses more than about 5 metres wide are not very frequent on the Äspö site.

- Low hydraulic conductivity.
- $K^3_g = 5.2 \times 10^{-11}$ m/s, $S^3_{LogK} = 1.8$

FUTURE CONCEPTUAL MODELLING OF THE ÄSPÖ SITE

The interdisciplinary evaluation and modelling work presented in *Gustafson et al. /1988/, Gustafson et al. /1989/ and Wikberg et al. /1991/* was presented briefly above. A more thorough and detailed evaluation of the geohydrochemical conditions has been done by *Smellie and Laaksoharju /1992/*, and by *Rhen et al. /1992/* with regard to the outcome of a long-term pumping and tracer test.

Future interdisciplinary modelling will be updated step by step on the basis of the data collected from tunnel mapping and probe hole drilling and from supplementary investigation. Data collection also includes an extensive groundwater monitoring programme, where data are recorded at some 180 measuring points every second hour.

A final conceptual modelling is planned to take place at the end of the tunnel construction phase.

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1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
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1980
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Summaries
Stockholm, March 1981

1981
TR 81-17
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Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

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Stockholm, May 1986

1986
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1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
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1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
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[2] Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden
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