TECHNICAL
REPORT

91-21

Äspö Hard Rock Laboratory. Field Investigation methodology and instruments used in the pre-investigation phase, 1986-1990

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December 1991

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ÄSPÖ HARD ROCK LABORATORY. FIELD INVESTIGATION METHODOLOGY AND INSTRUMENTS USED IN THE PRE-INVESTIGATION PHASE, 1986-1990

Karl-Erik Almén, Olle Zellman

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Information on SKB technical reports from
1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26),
1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77),
1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31),
1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40)
and 1990 (TR 90-46) is available through SKB.

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INTRODUCTORY COMMENT

This report is No II, of four summarizing the pre-investigation phase of the Äspö Hard Rock Laboratory.

The reports are:

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

II Almén K-E, Zellman O.
Äspö Hard Rock Laboratory
Field investigation methodology and instruments used in the pre-investigation phase, 1986-1990.
SKB TR 91-21.

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

IV Gustafson G, Liedholm M, Rhén I, Stanfors R, Wikberg P.
Äspö Hard Rock Laboratory
Predictions prior to excavation and the process of their validation.
SKB TR 91-23.

The background and objectives of the project are presented in a background report to SKB R&D programme 1989 (Underground Rock Laboratory) where a detailed description of the Äspö HRL project can be found.

ABSTRACT

The Äspö Hard Rock Laboratory project started in 1986. The pre-investigation phase, 1986-1990, involved extensive field measurements from the surface as well as from boreholes, aimed at characterizing the rock formation with regard to geology, geohydrology, hydrochemistry and rock mechanics.

The field investigation methodology used in the project was based on experience from and developments during the previous SKB Study Site investigation programme. However, in some respects the techniques were changed or modified. Major changes have been possible due to a new drilling technique, telescope-type drilling.

This report describes the logistics of the investigation programme, characterized to a large extent by multi-purpose planning and performance of the activities in order to optimize the use of available resources: time, personnel and equipment.

Preliminary hydraulic testing and groundwater sampling were conducted during the drilling of each borehole. When the drilling was completed an extensive set of single-hole investigations were carried out: geophysical logging, borehole radar, hydraulic tests of different kinds, water sampling and rock stress measurements.

Multipackers were installed in the boreholes as soon as possible after the borehole investigations. The system enables monitoring of groundwater pressure, water sampling and groundwater flow measurements to be performed by means of dilution tests and tracer injection. Boreholes with such equipment were used as observation holes during interference pumping tests and long term hydraulic and tracer tests. The monitoring programme will continue during the subsequent phases of construction and operation of the Äspö Hard Rock Laboratory.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to a great number of persons who have been involved in the field investigations for the Äspö Hard Rock Laboratory project, as well as to persons who have worked with the design, servicing and maintenance of instruments used for the measurements. Thanks to their professional contributions during the course of the pre-investigation phase of the Project, highly reliable data have been collected and delivered for the interpretation and analysis procedure. They have therefore contributed significantly to the overall characterization of the investigated rock formation.

The cooperation with the project management and project research team - Tommy Hedman, Göran Bäckblom, Gunnar Gustafson, Ingvar Rhén, Roy Stanfors and Peter Wikberg - in the planning of the field investigations and preparation of this report, is greatly appreciated.

A special thanks is addressed to the following persons for their advice and technical review of the report: Olle Andersson, Calin Cosma, Olof Forslund, Bengt Frid, Bengt Gentzschein, Kent Hansson, Gunnar Hägglund, Stig Jönsson, Marcus Laaksoharju, Christer Ljunggren, Sverker Nilsson, Göran Nyberg, Thomas Sjöström, Leif Stenberg, Allan Stråhle and Per-Erik Söder.

CONTENTS

1. INTRODUCTION

1.1 Background

In 1976-1977 an extensive nuclear waste research programme, the KBS Project, was set up in Sweden in order to demonstrate the suitability of using deep geological formations for the final repository of nuclear waste. The reference concept for a radioactive waste repository in Sweden is that the spent fuel will be encapsulated in copper canisters, which will be deposited in boreholes in a tunnel gallery at some 500 m depth in a crystalline rock /KBS-3/. The primary function of the rock (the natural barrier) is to provide stable conditions as regards flow and chemical properties of the groundwater. A second function is to prevent or retard the transport of radioactive materials in the groundwater. A rock volume of approximately 4 km^2 surface area by 1 km depth therefore has to be well documented.

Over a period of ten years, a number of so called Study Sites were investigated in order to characterize different kinds of rock types. Based on field investigations, geological, geohydrological and groundwater chemical characteristics of the rock formations were determinated. Conceptual models of the rock volumes were developed and numerical modelling of groundwater flow and radionuclide migration from the repository and up to the biosphere was performed /KBS-3/.

The Study Site investigations were generally conducted in the following four phases /Ahlbom et al, 1983/

- reconnaissance for selection of Study Sites
- investigations from the surface
- borehole investigations
- evaluation and modelling.

The surface investigations on the Study Sites comprised analysis of satellite and air photos, airborne and ground surface geophysical measurements and geological mapping. A typical drilling programme included 10 deep cored holes (500-1 000 m deep) and a number of complementary shallow percussion-drilled holes. The investigation programme in the boreholes included core logging, geophysical logging, borehole radar mapping, hydraulic testing and groundwater chemistry investigations /Olkiewicz and Stejskal, 1986/, /Sehlstedt and Stenberg, 1986/, /Carlsten et al, 1986/, /Gentzschein, 1986/, /Laurent, 1986/.

When the Study Site investigations started in 1977 there was no established methodology for deep borehole investigations in crystalline rock. Therefore, an extensive development programme for measuring methods and instruments was initiated to be carried out parallel with the first investigation campaign. All new instruments were designed for measurements in small-diameter holes (56 mm diameter). Over more than one decade a large quantity of measurements have been carried out in more than 70 000 m of cored holes at some ten Study Sites. Feedback from these investigations, as regards measuring methodology and equipment performance, has resulted in a progressive increase in technical sophistication through modifications and improvements, aimed at improving the reliability of the collected data /Almén, 1983/, /Almén, 1986/. Besides the Study Site investigations described above, other geoscientific projects, such as the Finnsjön fracture zone project, have been carried out within SKB's research programme.

1.2 Äspö Hard Rock Laboratory

The overall goal of the SKB research programme is to construct a safe repository for the nuclear waste. According to present plans the repository shall be ready for operation in 2020. The site of the repository will be decided during the period 2003-2006. That decision will be preceded by pre-investigations at three sites and detailed investigations at two sites /SKB 1989, R&D Programme 89/.

The R&D work in the Äspö Hard Rock Laboratory (HRL) Project is one of the efforts undertaken in order to prepare for the work at the candidate sites. The main goals for the project are /SKB 1989, Underground Rock Laboratory/:

* 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 assesments.

The stage goals for the project are as follows:

* Verify pre-investigation methods

* Finalize detailed investigation methodology

* Test models for groundwater flow and transport of solutes

* Demonstrate construction and handling methods

* Test important parts of the repository system

The laboratory is sited on the Äspö island, close to the Simpevarp Nuclear Power Plant, north of Oskarshamn, see Figure 1.1.

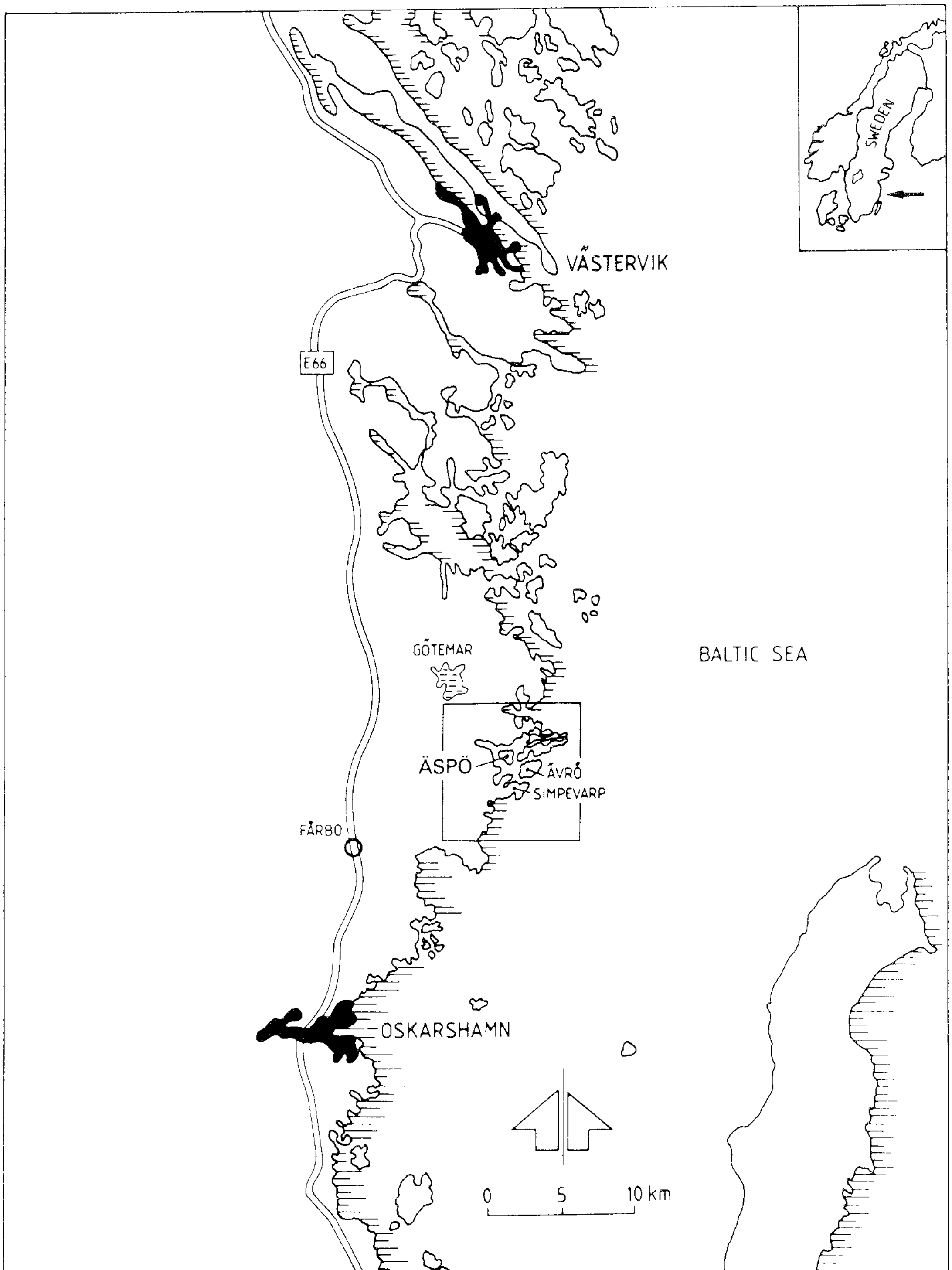


Figure 1.1 The location of the Äspö site.

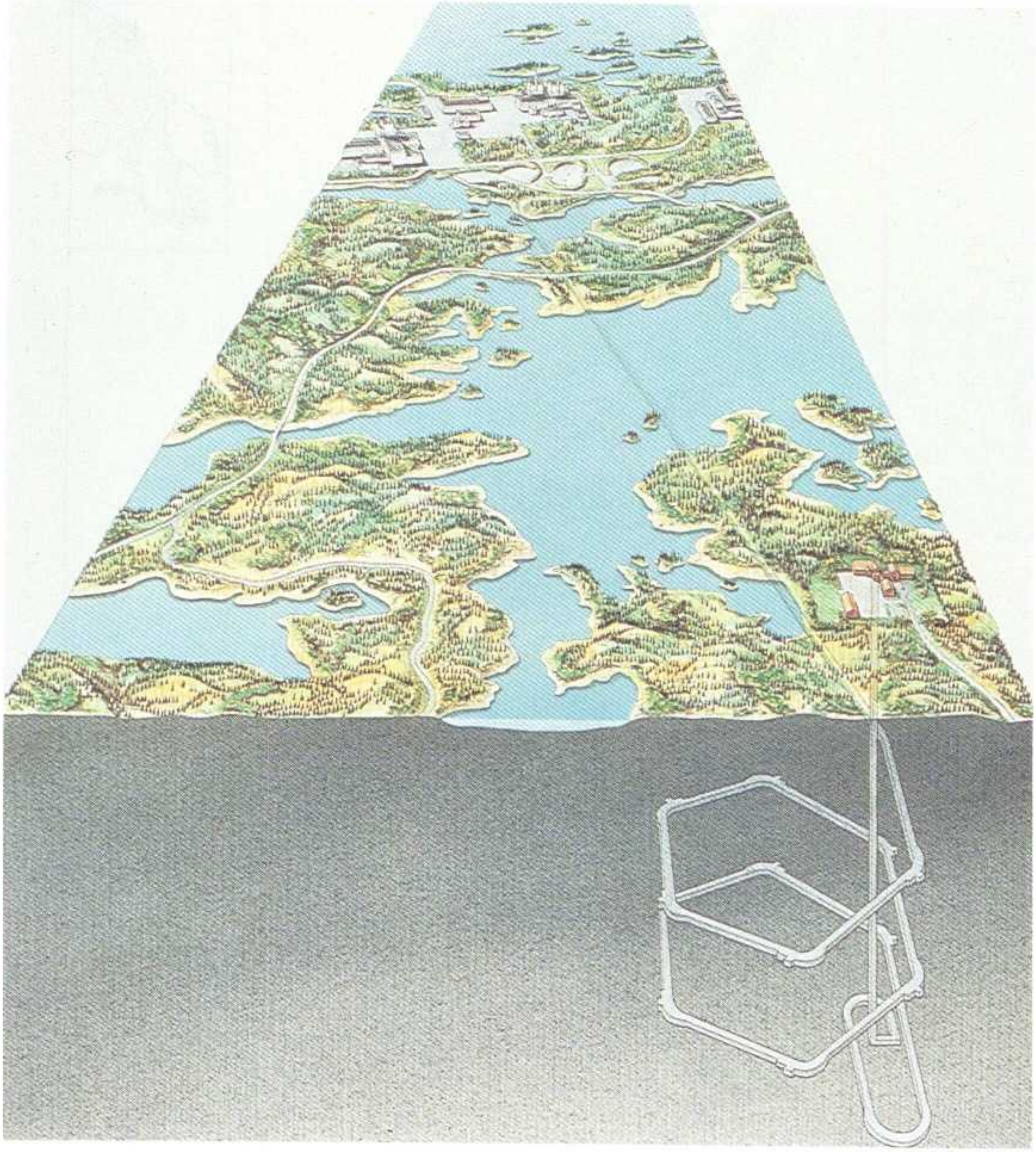


Figure 1.2 Schematic design of the Äspö Hard Rock Laboratory.

The Äspö Hard Rock Laboratory will be constructed as a tunnel system to a depth of about 500 m, see Figure 1.2. The project was initiated at the end of 1986, and has been divided into the following phases:

*	Pre-investigation phase,	1986-1990
*	Construction phase,	1990-1994
*	Operational phase,	1995-

This report will describe the field investigation methodology and instruments which have been used during the pre-investigation phase. The techniques used are based on the methodologies which were previously used in the Study Site investigation programme, but in some respects the techniques have been changed. Major changes have been possible since the introduction of a new drilling technique. The need for long-term monitoring has led to the development of a flexible multi-packer system.

The methodology will be presented in the following chapters under the headings geology, geophysics, geohydrology, groundwater chemistry and rock mechanics, with regard to investigations from the ground surface and borehole investigations. Due to the fact that the borehole investigations are more specialized for the Project than the surface investigations, as regards measurement methodology and instruments, more space has been devoted to describing these methods. An introductory chapter presents the logistics of the borehole investigations performed during the pre-investigation phase of the Äspö HRL project. A final chapter describes the database system used for data storage.

2. PRE-INVESTIGATION PROGRAMME STRUCTURE

2.1 Overview

The pre-investigations for the Äspö Hard Rock Laboratory started in late 1986. An overview of all investigations being performed and all reports being published from the project, are given in Stanfors et al /1991/.

The first stage of the pre-investigation phase, **the siting stage**, included regional investigations, mainly based on airborne geophysics - for which some of the airborne surveys were carried out for the Project - and topographical data, see Figure 2.1. Magnetic, electromagnetic, radiometric and gravimetric maps were constructed from the geophysical surveys, while digital terrain models were constructed from the topographical database. The maps were used for tectonic analysis on a regional scale.

Furtheron the siting stage included investigations from the ground surface of three potential areas for the Hard Rock Laboratory: Äspö, Ävrö and Laxemar. Geological

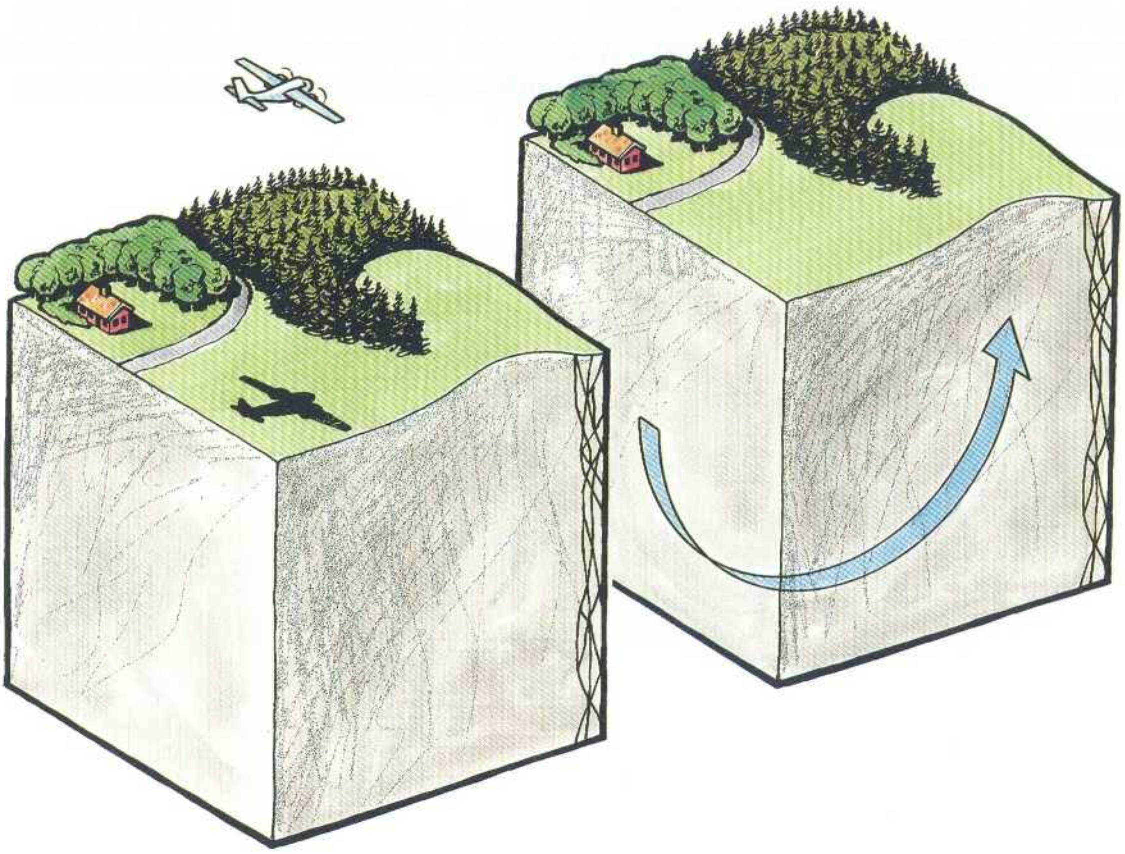


Figure 2.1 Illustration of an initial stage of the preinvestigations, airborne and ground surface measurements, resulting in a rough description of dominant structures and the groundwater flow in the rock block.

mapping and geophysical measurements were performed. Groundwater capacity and groundwater chemistry were investigated by means of an inventory of groundwater wells. This stage also included the first drilling campaign in all three areas. Shallow percussion holes were drilled with examination of cuttings, geophysical logging, groundwater sampling and hydraulic testing.

Based on data obtained from this first stage, the Äspö area was chosen as a preferential site for the Laboratory, and the first conceptual model for the Äspö area was developed /Gustafsson et al, 1988/.

In the next stage, **the site description stage**, three deep cored boreholes were drilled at Äspö, see Figure 2.2. An extensive measuring programme was conducted in the boreholes, according to logistics as presented in sections 2.2.1 and 2.2.2 and methodologies as described in the following chapters of this report. In this stage, more detailed geophysical ground surface measurements were performed on Äspö. Detailed geological mapping of a surface bedrock profile was carried out as well. Based on the borehole measurements and the surface investigations a revised conceptual model was developed for Äspö /Gustafson et al, 1989/. One deep cored borehole was also drilled at the Laxemar area, planned to be used as a reference area.

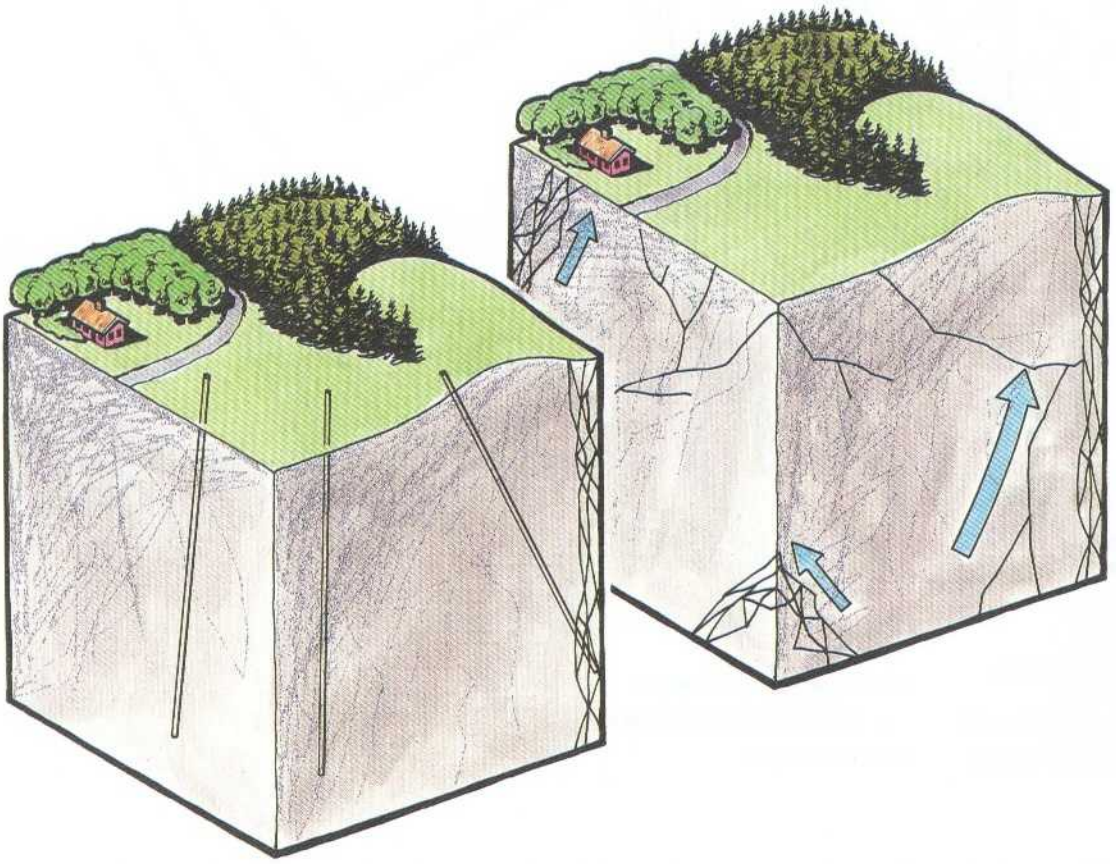


Figure 2.2 Illustration of a later stage of the pre-investigations, dominated by borehole measurements, resulting in a more detailed characterization of the geology and geohydrology of the rock block.

From this conceptual model of Äspö, describing the general lithology, the major tectonic structures, the local fracture systems, geohydrological and groundwater chemical characteristics (see Figure 2.3) it was found that the most suitable area of the island was the southernmost part.

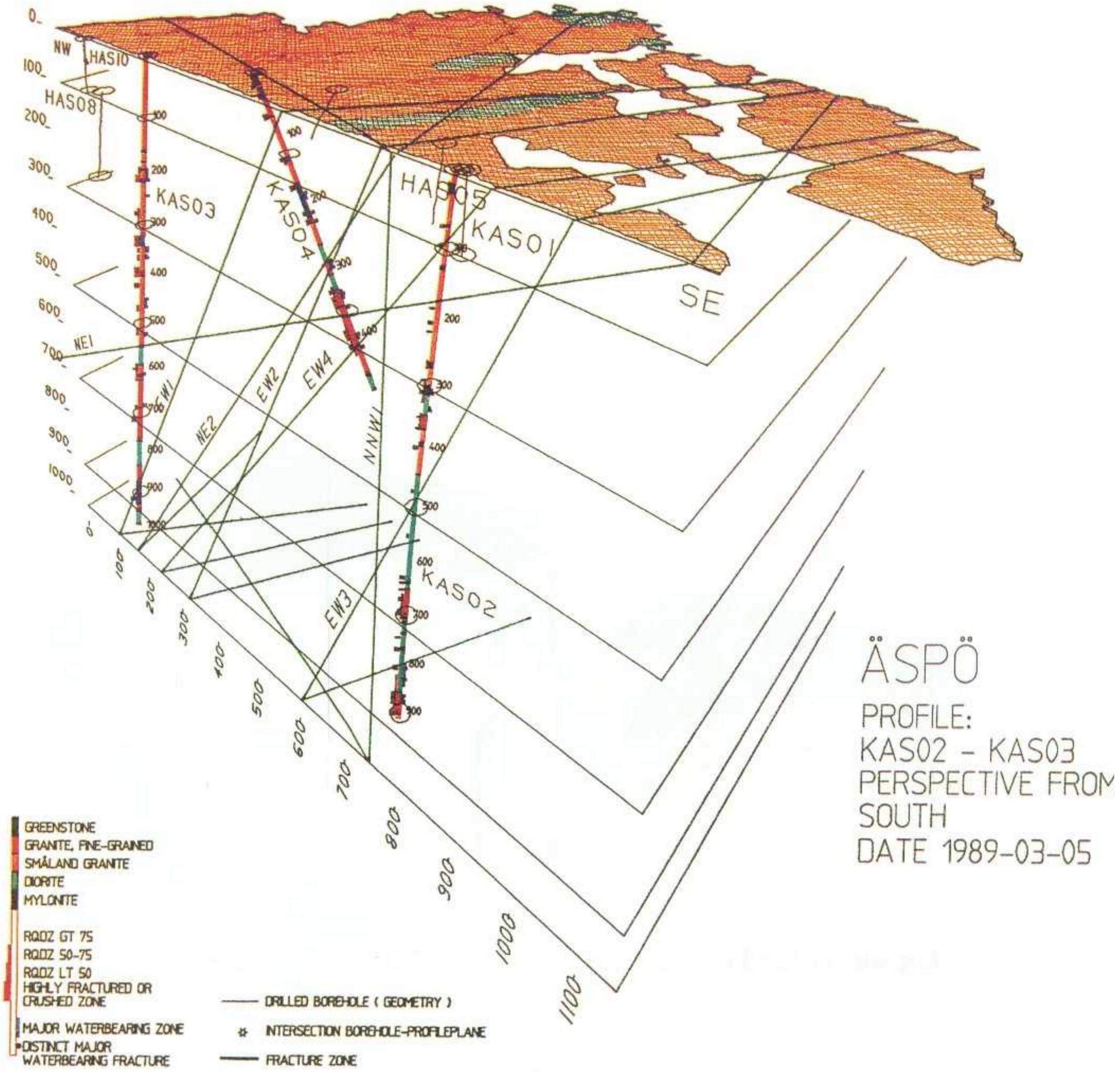


Figure 2.3 *Tentative perspective of the Äspö rock volume, based on investigations from the surface and from three cored boreholes (from Gustafsson et al, /1989/).*

The aim of the third stage of the pre-investigations, **the prediction stage**, was to perform a more detailed characterization of the southern part of the island and to predict how an underground construction will influence e g the hydraulic behaviour of the rock volume /Wikberg et al, 1991/, /Gustafsson et al, 1991/. Evaluation of this disturbance can later be used as a tool to understand the ambient conditions. Accordingly, a number of new deep boreholes were drilled, supplemented by more shallow percussion-drilled holes. The directions and depths of these holes were defined in order to penetrate, determine the directions 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 few supplementary boreholes were also drilled in order to investigate the area of the access tunnel to the Laboratory, which was to enter the target rock volume from the south.

At the end of the pre-investigation phase, a large-scale pumping and tracer test was performed in order to simulate the effect of a large underground construction and to verify and characterize the connectivity between major groundwater conductors. The results of this test were also used to calibrate the numerical model, which was later used to predict the influence of the underground excavation work on the groundwater situation, see Figure 2.4.

All data has been structured according to geometrical scales and key questions, see Figure 2.5 /Bäckblom et al, 1991/.

Throughout the entire pre-investigation phase, except when it was impossible due to other borehole activities, a monitoring programme has recorded groundwater levels. This monitoring programme also includes the reference sites Laxemar and Ävrö.

In all, 14 cored boreholes have been drilled on Äspö, ranging from 99 m to 1002 m, see Figure 2.6 / Stanfors et al, 1991/. The number of percussion drilled holes on Äspö is 20, ranging from 93 m to 200 m. At Laxemar, one 1078 m deep cored borehole and seven percussion-drilled boreholes, 100 m to 130 m, have been drilled. Three cored boreholes, 97 m to 744 m in length, and eight percussion-drilled holes, 63 m to 175 m, have been drilled at Ävrö, including boreholes drilled during earlier investigation activities.

2.2 Logistics of borehole measurements

For a borehole investigation programme, it is essential to set up a logic structure of how the borehole is to be used for the different measurements, with a view towards efficient use of time, personnel and economical resources. This is especially necessary in connection with extensive site characterization programmes, where collected information will subsequentially influence the ongoing investigation programme in order to enhance the overall outcome of the project. When early data, which in some cases may only be preliminarily evaluated, are used for the detailed planning of the

PRESSURE AND FLUX DISTRIBUTION:

In the pictures below the hydraulic head is shown (density of water = 1 000 kg/m^3)

Flux vector scale shall be multiplied with 10^{-10} to give correct flux (m/s). Vertical sections are shown in the figure below.

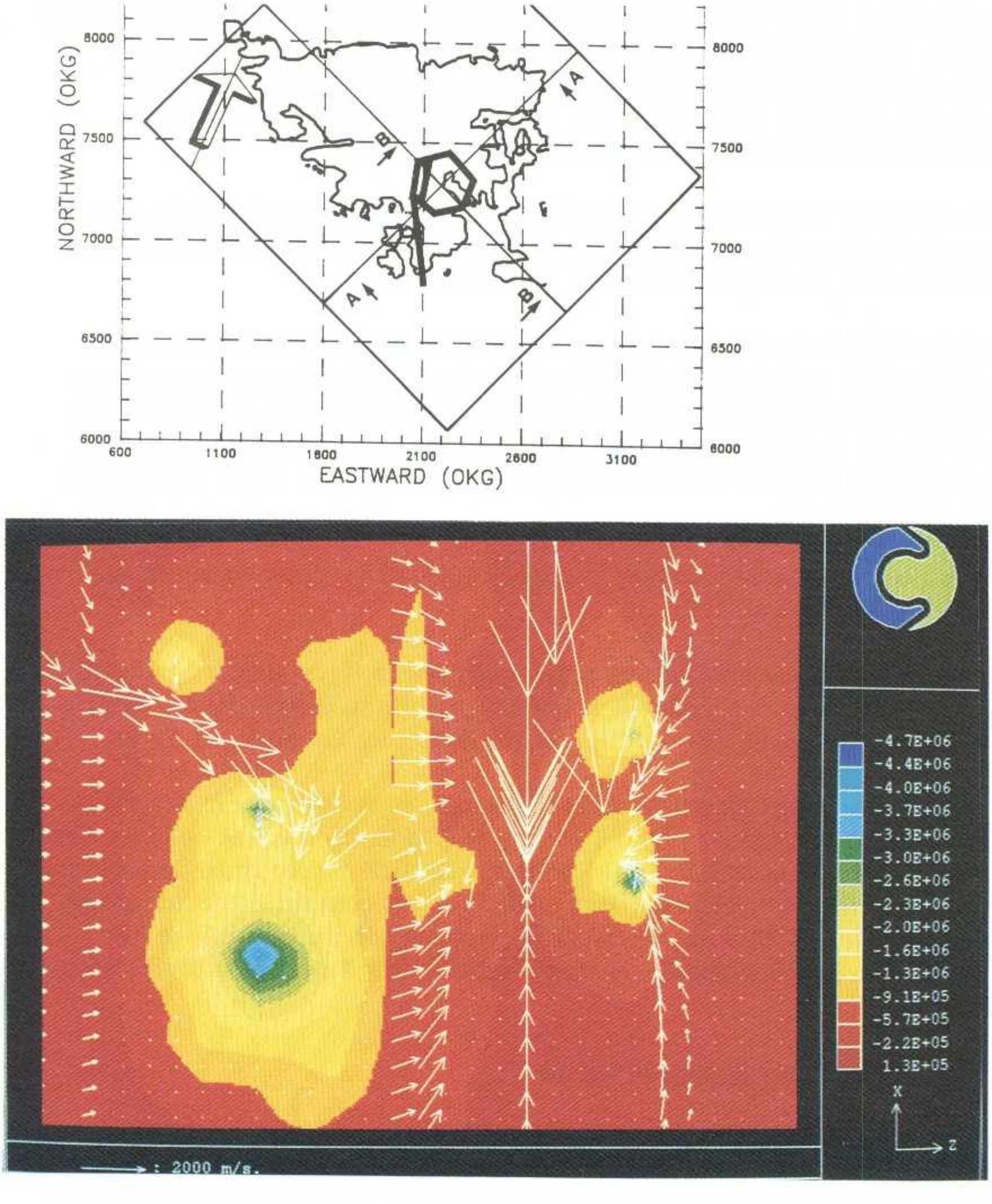


Figure 2.4 *Predictions of groundwater flow and head distribution in the Äspö rock formation, after excavation of the tunnel (tunnel length 3850 m, depth 500 m). Hydraulic head in Pa (se legend) and flux vectors of section A (from Gustafsson et al, /1991/).*

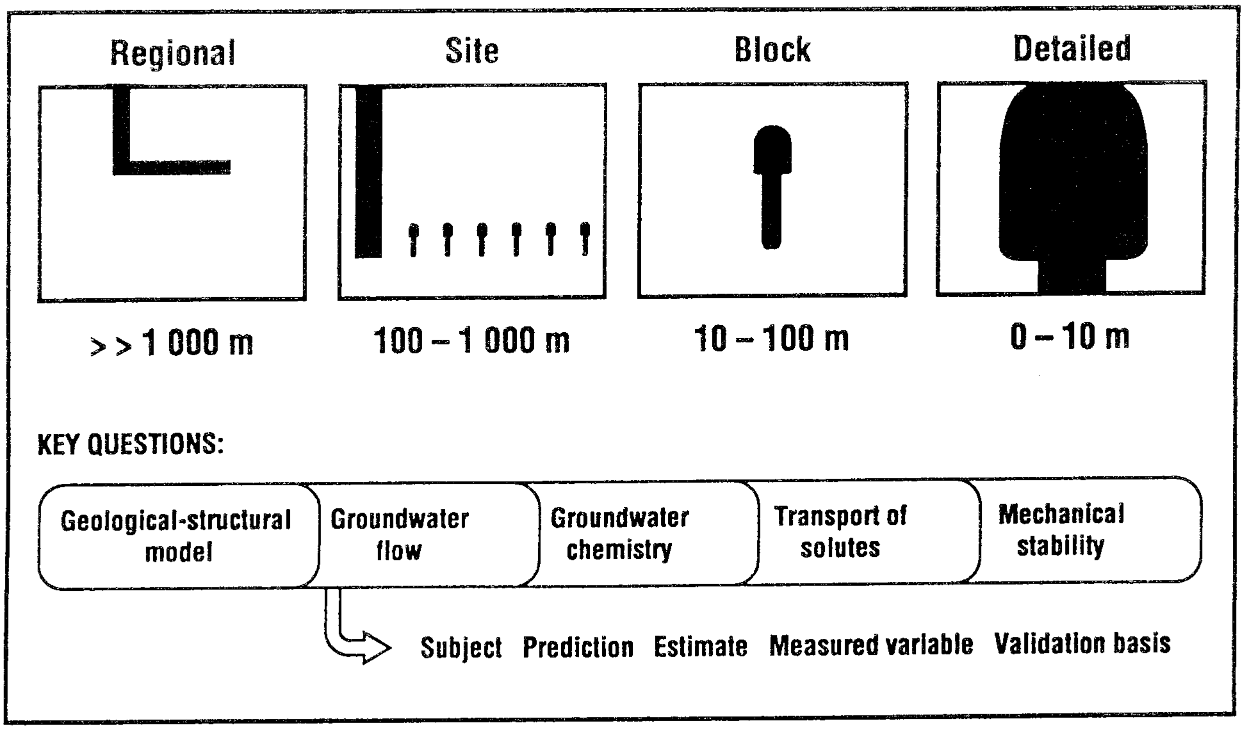


Figure 2.5 Overview of geometrical scales and key questions.

ongoing investigations, it is very important to bear in mind the level of quality of the data used; otherwise the final outcome of the programme may be jeopardized.

With effective planning, some borehole activities can be used to collect data for more than one purpose. This kind of multi-purpose planning and testing has been used extensively in the borehole investigation programme used in the pre-investigation phase of the Äspö Hard Rock Laboratory project.

The borehole investigation programme in the Äspö HRL Project has produced a large quantity of data. All the data from all the different investigations have been compiled in individual borehole reports /Borehole reports/. Moreover, most of the data are stored in the SKB database GEOTAB, as described in chapter 11.

2.2.1 Single hole investigations

A. Investigations in cored boreholes

Single-hole investigations in cored deep boreholes are normally more extensive and provides more data than single-hole investigations in percussion drilled holes. The sequence of single hole activities used in the Äspö Hard Rock Laboratory cored boreholes is therefore described first. Some of the activities have been conducted in all

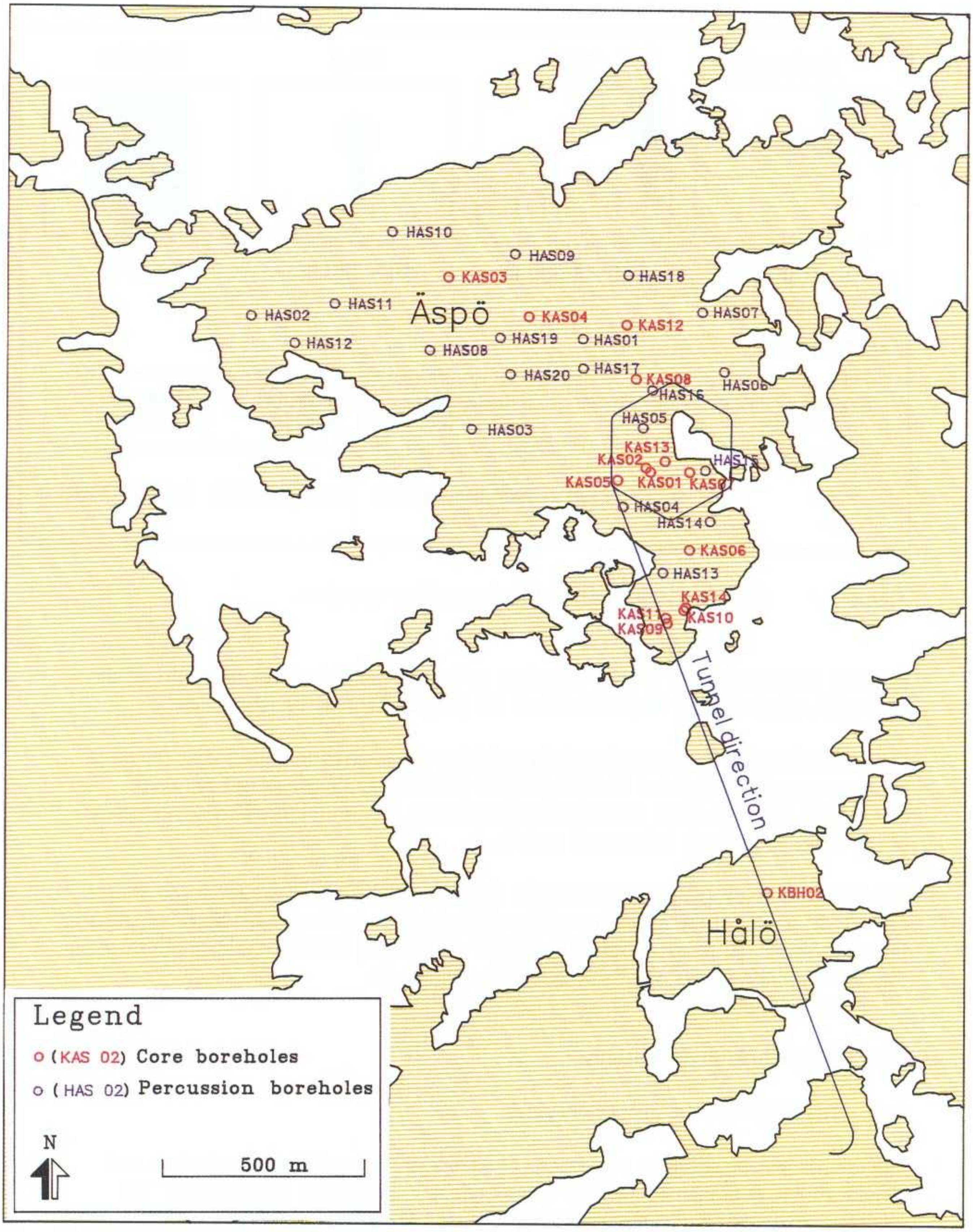


Figure 2.6 *Location of boreholes on the Äspö island.*

boreholes, while other investigations have been performed in just a few of the boreholes, see Figure 2.7 /Stanfors et al, 1991/.

A1. CORE DRILLING; using telescope-type borehole design. Drilling water tagged with tracer. Airlift pumping during drilling.

A2. MEASUREMENTS DURING DRILLING; water sampling and preliminary hydraulic testing in 100 m intervals. The technique used is airlift pumping with subsequent recording of recovery.

A2.a OVERCORING DURING DRILLING; 3-D rock stress measurements (carried out in one borehole).

A3. CORE LOGGING; first a preliminary examination of the core performed at the drill site, later followed by a detailed core logging.

A4. PUMPING TEST; high capacity pumping immediately after drilling is completed. For the purpose of cleaning the borehole, large scale hydraulic characterization and water sampling.

A5. FLOW-METER LOGGING; during pumping test of the borehole. For the purpose of identification and preliminary characterization of groundwater conductors penetrated by the borehole.

A6. GEOPHYSICAL LOGGING; a variety of parameters are measured by means of, more or less, standard logging methods.

A7. SPECIAL GEOPHYSICAL MEASUREMENTS; methods used:
  - borehole radar
  - borehole seismics
  - borehole TV
  - acoustic televiewer

A8. HYDRAULIC INJECTION TESTS; different measuring concepts regarding test time and section length. For hydrogeological characterization on a smaller scale. Carried out in most of the boreholes.

A9. COMPLETE HYDROCHEMICAL CHARACTERIZATION; using the mobile field laboratory. Carried out in some boreholes.

A10. HYDROFRACTURING; rock stress measurements. Carried out in a limited number of boreholes.

A11. GROUNDWATER LEVEL MONITORING; installation of packers for multi-sectioned monitoring of groundwater levels. Continuously ongoing with the exception of periods when other activities occupy the borehole. Shall subsequently continue during the following construction and operation phases.

A12. HYDROCHEMICAL MONITORING; water sampling from the packed-off sections of the groundwater level monitored boreholes.

A13. DILUTION MEASUREMENTS; measurement of natural groundwater flow through selected sections of the packed-off boreholes.

B. Investigations in percussion drilled holes

The investigation sequence in the percussion drilled boreholes varies according to the purpose of the individual hole, see Figure 2.8. However, a typical sequence of single-hole investigations is as follows:

B1. PERCUSSION DRILLING; with control of water capacity, rate of penetration and character of the drill cuttings.

B2. CAPACITY TEST; airlift pumping for sampling and subsequently measurement of recovery. Carried out at every 50 m and when drilling is completed.

B3. GEOPHYSICAL LOGGING; standard logging methods.

B4. BOREHOLE RADAR; carried out in few boreholes.

B5. WATER SAMPLING; performed in the first drilling campaign.

B6. PUMPING TEST; performed in the first drilling campaign.

B7. GROUNDWATER LEVEL MONITORING; measurement of natural groundwater fluctuations. Normally 1-2 monitored sections.Continuously ongoing with the exception of periods when other activities occupy the borehole. Shall subsequently continue during the following construction and operation phases.

2.2.2 Cross-hole measurements

A number of multiple borehole investigations (cross-hole or interference measurements) have been carried out in the Project. These investigations are specially valuable for the hydrological characterization in a larger scale. The following investigations have been performed.

C1. OPEN HOLE PUMPING TESTS. The pumping tests A4 and B6, described above are regarded as interference tests when other boreholes were equipped for groundwater level monitoring (A11 and B7).

C2. INTERFERENCE PUMPING TEST: Carried out in order to define the geometry and character of the groundwater conductors.

	CORED BOREHOLES KAS02-KAS14													KBH 02	KLX 01
	02	03	04	05	06	07	08	09	10	11	12	13	14		
LENGTH (M)/DIP	924/85	1002/85	481/60	550/85	602/60	604/59	601/60	450/60	99/60	249/69	380/69	406/62	212/60	706/45	702/85
CORE LOGGING															
Lithology	●	●	●	●	●	●	●	●		●	●	●	●	●	●
Thin section analyses	●	●	●	●	●	●	●	●		●	●	●		●	●
Chemical rock analyses	●	●	●											●	●
Fracture mapping + RQD	●	●	●	●	●	●	●	●		●	●	●	●	●	●
Fracture mineral analyses	●	●	●	●	●	●	●								●
TV-orientation/Televiewer*	●	●	●	●*	●*										
PETROPHYSICS															
Density + Porosity	●														●
Magn. suscep. + Remanence	●														●
Resistivity + I P	●														●
U,Th,K	●														
GEOPHYSICAL LOGGING															
Borehole deviation	●	●	●	●	●	●	●	●		●	●	●	●		●
Caliper + Magnetic suscept.	●	●	●	●	●	●	●	●		●	●	●	●		●
Sonic	●	●	●	●	●	●	●	●		●	●	●	●		●
Natural gamma	●	●	●	●	●	●	●	●		●	●	●	●		●
Density + Neutron				●	●	●	●	●		●	●	●	●		
Resistivity+Spontaneous potent.*	●*	●*	●*	●	●	●	●	●		●	●	●	●		●
Temperature	●	●	●	●	●	●	●	●		●	●	●	●		●
Borehole fluid resistivity	●	●	●	●	●	●	●	●		●	●	●	●		●
Radar	●	●	●	●	●	●	●	●		●	●	●	●		●
ROCK STRESS MEASUREMENT															
Hydraulic fracturing	●	●													
Overcoring				●											
Lab. tests	●	●													
GEOHYDROLOGY															
Airlift test, intervals	●	●	●	●	●	●	●	●		●	●	●	●	●	●
Injection test, 3m interval	●	●	●	●	●	●	●								●
Injection test, 30m interval	●	●													●
Spinner(flow meter logging)	●	●	●		●	●	●	●		●	●	●	●		
Pumping test	●	●	●	●	●	●	●	●					●		●
Pumping interference test	●	●			●	●		●		●	●	●	●	●	
Dilution test, intervals	●	●	●	●	●	●	●	●		●	●	●	●	●	
Observation, packer settings	●	●	●	●	●	●	●	●		●	●	●	●	●	
Fluid conductivity	●	●	●	●	●	●	●	●		●	●	●	●	●	
Circulation sections	●	●	●	●	●	●	●	●		●	●	●	●	●	
GROUNDWATER CHEMISTRY															
Complete chemical character.	●	●	●												●
Sampling during pumping test	●	●			●										
Sampling during drilling				●	●	●	●	●		●	●	●	●	●	●
Fracture mineral statistics	●	●	●	●	●	●	●								●
Fracture mineral chemistry	●				●										●

Figure 2.7 *Investigations in the cored boreholes.*

- Pumping from selected groundwater conductors in packed-off sections of cored holes.
- Recording responses in groundwater level monitored observation holes (A11 and B7).
- Measuring the "disturbed" groundwater flow in selected multipacker isolated sections by means of dilution measurements (A13).
- Water sampling of the pumped-up water.
- Recording of chemical parameters in pumped-up water.

C3. LONG-TERM PUMPING TESTS (LPT): For the purpose of large-scale hydrogeological characterization of the rock formation.

- Long term, high capacity pumping from open hole.
- Recording responses in groundwater level monitored observation holes (A11 and B7).
- Measuring the "disturbed" groundwater flow in selected multipacker isolated sections by means of dilution measurements (A13).

C4. TRACER TEST; carried out as radially converging tracer experiment, in conjuction with a second LPT. Carried out in order to characterize connectivity between groundwater conductors.

- pumping as for LPT.
- recording responses as for LPT.
- radioactive tracers.
- injection of four different tracers at four multipacker isolated sections.
- multilevel sampling at inflowing levels in pumping hole.

	PERCUSSION BOREHOLES HAS01-HAS20																			
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
LENGTH (M)/DIP	100/61	93/55	100/56	200/61	100/58	100/88	100/62	125/56	125/59	125/61	125/89	125/60	100/63	100/88	120/60	120/60	120/60	150/62	150/57	150/60
DRILLING DATA																				
Drill cutting analyses	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●
Thin section analyses																				
Drilling rate	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Fracture identification	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
GEOPHYSICAL LOGGING																				
Borehole deviation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Density				●									●	●				●	●	●
Magnetic suscept.	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●
Sonic				●									●	●				●	●	●
Natural gamma	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●
Resistivity	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●
Temperature	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●
Borehole fluid resistivity	●	●	●	●	●	●	●	●	●	●	●	●	●	●				●	●	●
Radar		●	●																	
GEOHYDROLOGY																				
Airlift test, intervals	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Injection test, 3m interval																				
Injection test, 30m interval																				
Spinner (flow meter logging)																				
Pumping test		●	●		●		●												●	
Pumping interference test													●							●
Dilution, test intervals																				
Observation packer settings																				
Fluid conductivity																				
Circulation sections																				
GROUNDWATER CHEMISTRY																				
Complete chemical character.																				
Sampling during pumping test		●	●		●	●	●													
Sampling during drilling																				
Fracture mineral statistics																				
Fracture mineral chemistry																				

Figure 2.8 Investigations in the percussion-drilled boreholes.

3. SURFACE INVESTIGATIONS

3.1 Lineament studies

Referring to the definition of lineament by Hobb /1912/: "Significant lines of landscape which reveal the hidden architechture of the basement are described as lineaments", studies of lineaments are essential in a rock characterization programme, especially during an early stage of the investigations. Lineament studies are carried out on topografic maps, spacecraft and airborne photos and from airborne geophysics.

A step forward in lineament studies was taken in the Äspö HRL project by using the Swedish National Land Survey (LMV) digital elevation data base. This data base contains altitude data for points on the ground surface, with a separation of 50 m within an orthogonal grid system. These altitude data were processed by the EBBA II image analysis technique, by which four digital terrain models: Hill shading, Residual elevation, Edge texture and Line texture, have been developed for the Simpevarp area /Tirén et al, 1987/, see Figure 3.1.

3.2 Geology

The geological mapping for the Äspö Hard Rock Laboratory does not significantly differ from conventional mapping, except in one way. Because of the relatively shallow overburden, trenches or pavements were prepared on the island of Äspö.

The mapping of the solid rocks was carried out in three phases. An initial overview mapping was done covering an area of about 600 square kilometres. The results were presented on maps with the scales of 1:50 000 and 1:10 000 (outer and inner area, respectively). The map with the scale of 1:50 000 was compiled from older maps and new mapping of road-cuts along major roads /Kornfält and Wikman, 1987/. For the more detailed map (1:10 000) the mapping was carried out according to methods used by the Geological Survey of Sweden. All outcrops were investigated as regards rocktypes.

The island of Äspö was mapped in more detail /Kornfält and Wikman, 1988/. All outcrops were mapped regarding rock types and tectonics, see Figure 3.2. Samples were taken for preparation of thin sections. The rocks were later classified according to Streckeisen (modal analyses). Later on chemical analyses were carried out on all the different rock types. Besides the major elements some minor elements were also analysed. These were Rb, Sr, Y, Zr and Nb. In addition to tables and diagrams, the results were presented on a map with a scale of 1:2 000 showing all outcrops.

The third phase included the above mentioned trenches, which were prepared on the island of Äspö, see Figure 3.3. The overburden was removed by an excavator. The surface of the bedrock were then cleaned with compressed air and finally high pressure

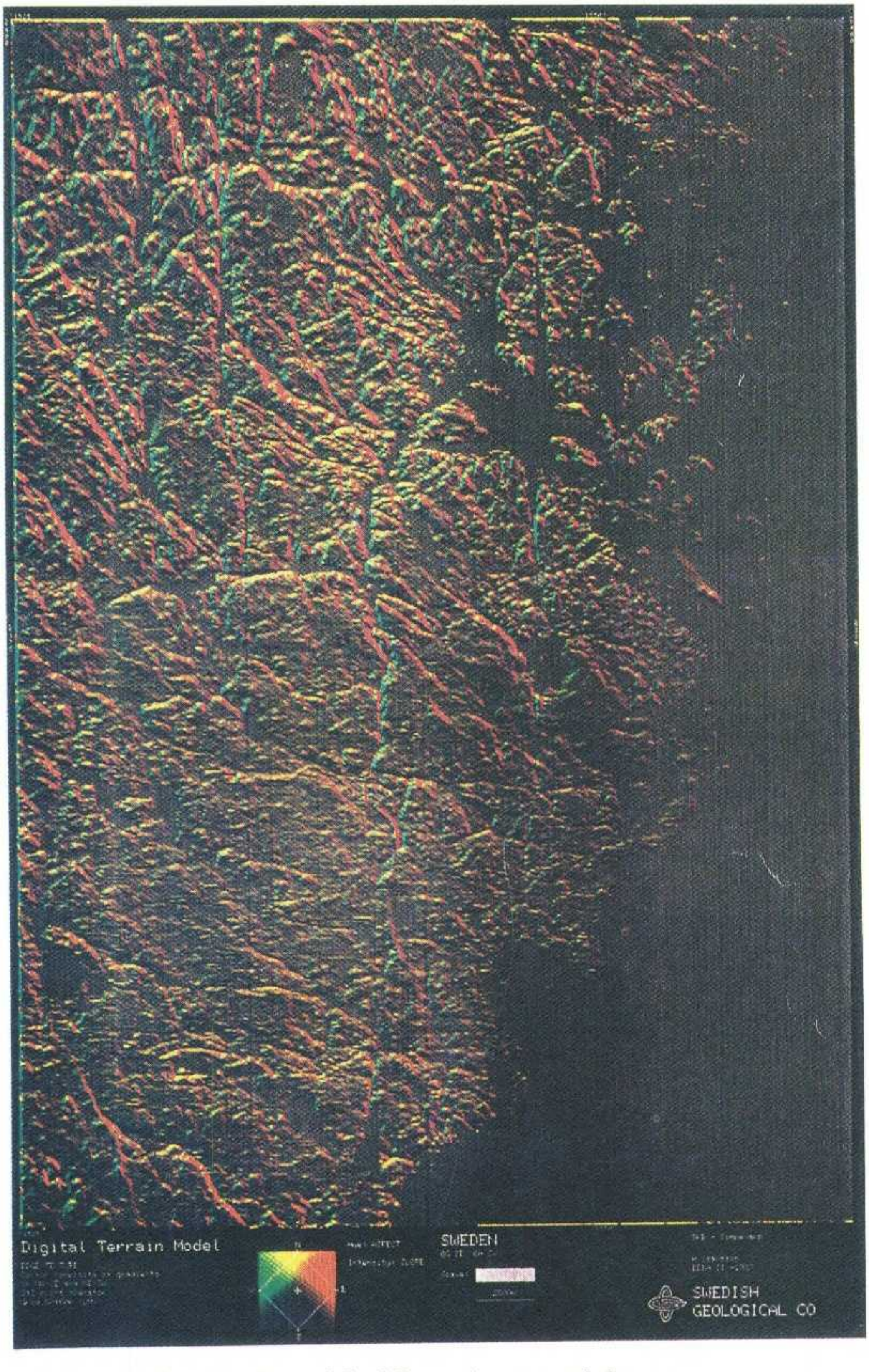


Figure 3.1 *Digital terrain model of the region around the Simpevarp area.*

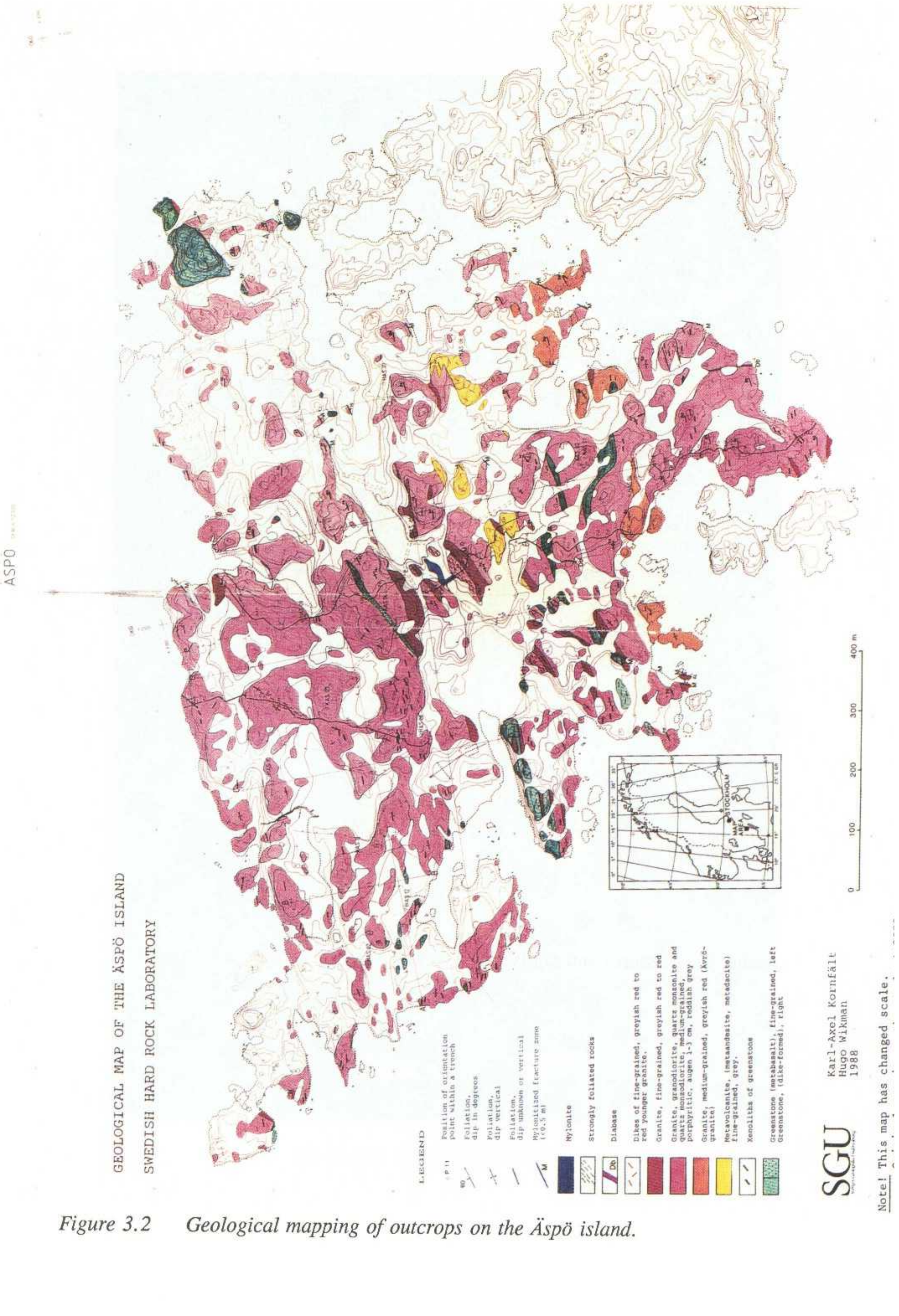


Figure 3.2 *Geological mapping of outcrops on the Äspö island.*

Figure 3.3 *Trench on the Äspö island, where the thin layer of overburden was removed for detailed geological mapping.*

water cleaning was performed. The latter technique proved to be very effective in removing lichen and moss. Altogether, 1.5 kilometres of trenches were prepared. Their width varied between 2 and 5 metres. Mapping in the trenches took place in the same way as the mapping of the island, but of course a larger scale was used.

3.3 Fracture mapping

In addition to the fracture mapping carried out during the geological mapping, described in the previous section, a more detailed fracture mapping was done /Ericsson, 1988/. The purpose of the latter was mainly to produce statistics for geohydrological and rock mechanics model studies. Because the term fracture is nongenetic, joint fissures and faults have been included. Fractures exceeding 0.5 m in length were measured and strike, dip, density and spacing were noted, see Figure 3.4. Where possible, fracture infillings and strong wall alteration were noted.

3.4 Surface geophysics

In order to support the geological, lithological and structural analysis of the area, geophysical measurements have been carried out at different stages of the pre-investigation phase of the Äspö Hard Rock Laboratory project. Measurements have been performed from the air as well as from the ground surface. As shown below, a variety of geophysical methods have been used at different occasions and for different purposes.

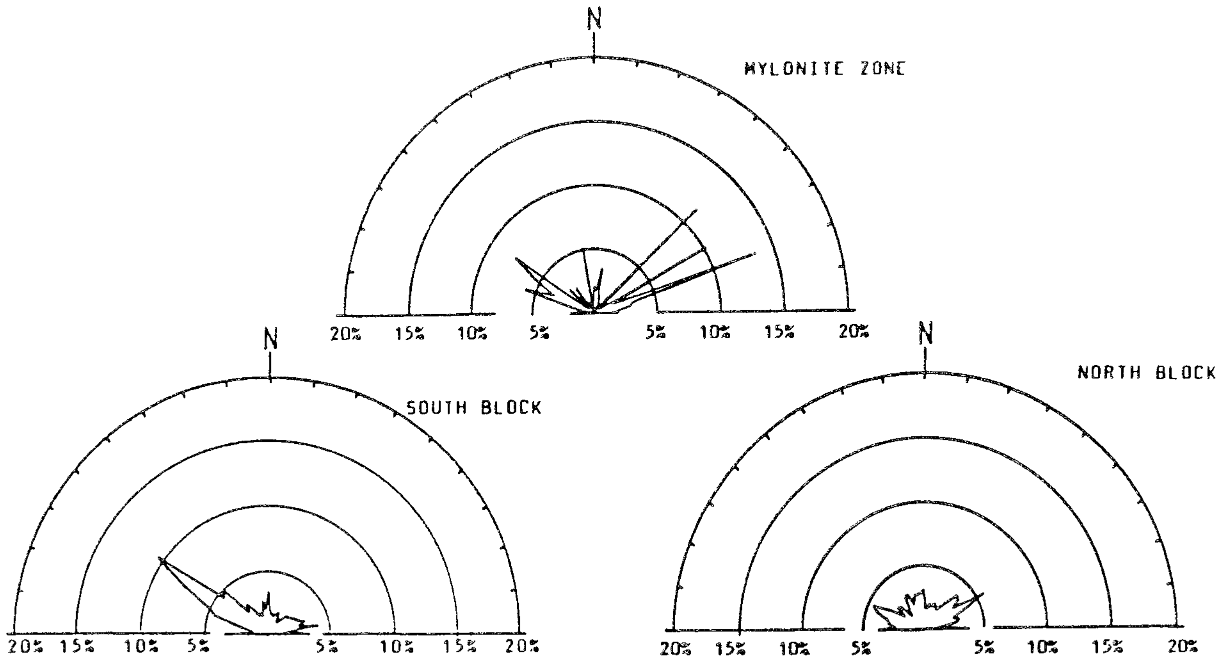


Figure 3.4 Rosette diagrams of fracture directions for different rock blocks at Äspö.

The geophysical investigations record variations in the physical properties of the bedrock. These variations reflect the presence of fracture zones, rock boundaries and distribution of rock types etc. Ground surface and airborne geophysical investigations are carried out as point measurements along an individual profile or as more dense geophysical surveys comprising measurements along a great number of parallel profiles (grid net measurements).

The different geophysical surface surveying methods will be described in the following sections, 3.4.1-3.4.6. A condensed summary of the surface geophysical measurements performed in the Äspö HRL project, with references to reports describing the measurements, is given in Table 3.1.

Interpretations are made of the datacurves which are constructed along the profiles. When dense grid net surveying is carried out, geophysical parameter maps are produced as profile maps and/or color maps. Image processing technique, using an EBBA GIS system, is applied in the interpretation of geophysical data /Nisca 1987/. This technique facilitates visualizing of information from several different geophysical methods. The GIS features help maintain the spatial relationship between different data sets. The geophysical maps are used to identify the location and direction of anomalies. Profiles crossing a selected anomaly may be resampled from the data and used in different interpretation procedures.

Interactive modelling is applied to magnetic, gravimetric, slingram and VLF profile data. This may provide additional spatial information about the geophysical target, especially if data from several different geophysical methods are used.

Interactive modelling is applied to magnetic, gravimetric, slingram and VLF profile data. This may provide additional spatial information about the geophysical target, especially if data from several different geophysical methods are used.

Table 3.1 Surface geophysical measurements being performed in the Project, with summarized information of instruments, methods and reports.

Measurement	Purpose	Instrument	Profile separation	Point separation	Reported in SKB PR
* Air-borne geophysical survey:	Regional investigation; bedrock interpretation and fracture zone identification		200 m	20 m	25-87-04 25-87-23
- magnetic		- SGAB TRIX 03			
- horizontal loop EM		- Geoinstrument SLR 84			
- VLF (two stations)		- SGAB RAMA 76, VLF 86			
- radiomeric (U,Th,K)		- SGU SPM 80			
* Regional gravity survey	Regional investigation; bedrock interpretation	LaCoste and Romberg Model G	average point density; 1 point per km^2		25-87-20
* Profile measurements across lineaments	Investigation of aeromagnetically indicated lineaments		single profiles	10 m	25-89-13
- magnetic		- GEM-Systems GSM 8			
- VLF		- ABEM Wadi			
* Surface profile measurements:	Fracture zone interpretation		single profiles		25-87-01
- magnetic		- GEM-Systems GSM 8		- 5 m	
- VLF		- Geonics EM 16		-20 m	
* Surface geophysical survey	Delineate the local pattern of fracture zones on Ävrö and Äspö				25-87-01 25-87-16
- magnetic		- GEM-Systems GSM8	- 200 m	- 5 m	
- horizontal loop EM		- SGAB EMAC 18kHa	- 200 m	-20 m	
* Detailed geophysical profile measurements	Delineate the local pattern of fracture zones		single profiles		25-88-16
- magnetic		- Scintrex MP-2		- 2.5 m	
- VLF		- Geonics EM 16 and ABEM Wadi		- 5.0 m 5.0 m	
- radiometric		- Scintrex BGS-4		- 2.5 m	
- resistivity		- ABEM SAS 300 Terrameter		- 5 or 20 m	
- vertical electrical sounding		- ABEM SAS 300 Terrameter		- electrode separation max 400 m	
* Magnetic surveying of seacovered area south of Äspö	Identification of fracture zones in the access tunnel area	- GEM-System GSM 8	20-25 m	5 m	25-89-19

Table 3.1 Contin.

Measurement	Purpose	Instrument	Profile separation	Point separation	Reported in SKB PR
* Detailed surface geophysical survey:	Delineate the local pattern of fracture zones				25-89-01
- magnetic		- GEM-Systems GSM8	- 10 m	- 5 m	
- electric		- SGAB RIPT-30	- 40 m	- 5 m	
* Supplementary geophysical survey, south part of Äspö and Hålö	Detailed information on fracture zones in the access tunnel area		single profiles		25-89-22
- magnetic		- Scintrex MP-2		- 2.5 m	
- VLF		- Geonics EM 16 and ABEM Wadi		- 5.0 m 5.0 m	
- resistivity		- ABEM SAS 300 Terrameter		- 5.0 m	
- vertical electrical sounding		- ABEM SAS 300 Terrameter		- electrode separation max 278 m	
- radiometric		- Scintrex BGS-4	- very dense point measurements		
- magnetic susceptibility		- Geoinstrument JH-8	- very dense point measurements		
* Ground surface radar measurements	Delineate the local pattern of fracture zones	RAMAC	single profiles	0,-5	25-89-12
* Regional refraction seismics	Investigation of aeromagnetically indicated lineament	SEMAB 22	single profiles	shot / geophone points 30 m / 5 m	25-89-23
* Refraction seismics at Äspö	Fracture zone interpretation	SEMAB 22	single profiles	shot / geophone 20-50 m / 5-10 m	25-87-15
* Refraction seismics along the access tunnel	Detailed idenification of supposed fracture zones	SEMAB 22	single profiles	shot / geophone land 12.5/2.5 m sea 25 / 5 m	25-89-18
* Reflection seismics at Ävrö	Identification of subhorisontal fracture zones	ABEM Terraloc-24 (explosives in shallow drillholes)	single profile	geophone points 10 m	25-87-14
* Reflection seismics at Äspö	Identification of subhorisontal fracture zones	ABEM Terraloc-24 (explosives in shallow drillholes)	single profiles	geophone points 10 m	25-89-02

3.4.1 Magnetic method

In the magnetic method, local variations in the intensity of the earth's magnetic field are measured. These variations are caused by the fact that different types of rock have different magnetization, which is normally proportional to the magnetite content in the rock. Accordingly, dykes often give distinct magnetic anomalies. Fractures and fracture zones are often indicated as a local decrease in magnetic susceptibility. This is caused by low-temperature alteration of magnetite to hematite, which lowers magnetic susceptibility. The usefulness of magnetite methods is described in greater detail by Barmen and Stanfors, /1988/.

Magnetic measurements from the ground surface have been performed at several occasions, using the GEM-Systems GSM-8 and the Scintrex MP-2 proton precession magnetometers /Stenberg and Sehlstedt, 1989/, /Stenberg, 1987/, /Triumf and Sehlstedt, 1989/, /Nisca and Triumf,1989/ and /Barmen and Dahlin, 1989/. The measuring range is 20 000 to 100 000 nT (nano Testa) with an accuracy of ± 1 nT. In order to correct for daily variations in the earth's magnetic field during the course of a survey, a base station is located within the investigation area. Measurements are made every 10 seconds.

Airborne magnetic measurements have also been performed, using the SGAB TRIX-03, a three-component magnetometer system with a measuring range and resolution of 0-140 000 nT and 0.1 nT, respectively. As an illustration of results from magnetic measurements, a magnetic gradient map, constructed from image processing of surface measurements, is shown in Figure 3.5. The densities of measuring points used in the different measuring campaigns are shown in Table 3.1.

Separate measurements of magnetic susceptibility have been performed as well, although only on limited areas. The measurements were carried out with the Geoinstrument JH-8, with a resolution of 2% of the measured value.

3.4.2 Electromagnetic methods

Two electromagnetic methods are being used in the project, Horizontal Loop EM (also called Coaxial EM or Slingram) and VLF (Very Low Frequency). In both of the methods an artificial electromagnetic field (primary field) induces a secondary field around electrical conductors in the rock. The resulting electromagnetic field is measured and analysed /Barmen and Stanfors, 1988/.

Horizontal Loop EM

In the Horizontal Loop EM method the primary field is emitted from a transmitting coil on the surveying equipment. A receiving coil is situated at a fixed distance from the transmitter. The resulting field will deviate from the primary field in intensity, phase and direction. The deviations indicate the presence of electric conductors in the ground, such as mafic dykes and fracture zones. An estimation of the dip and the depth of the cause of the anomaly can be made as well.

Horizontal Loop EM measurements can be performed from the ground surface as well as from the air; both applications have been used in the Äspö HRL project. The equipment used from the ground was the ABEM EMAC-system, see Figure 3.6. The frequency of the transmitted EM-waves was 18 kHz and the coil separation was 40 and 60 m. The airborne survey was carried out with Geoinstrument EM-system SLR 84, with a frequency of 7040 and 910 Hz and a coil separation of 17 m. The measurements record the real and the imaginary component of the resulting field as a percentage of the primary field. Profile and point separations are given in Table 3.1.

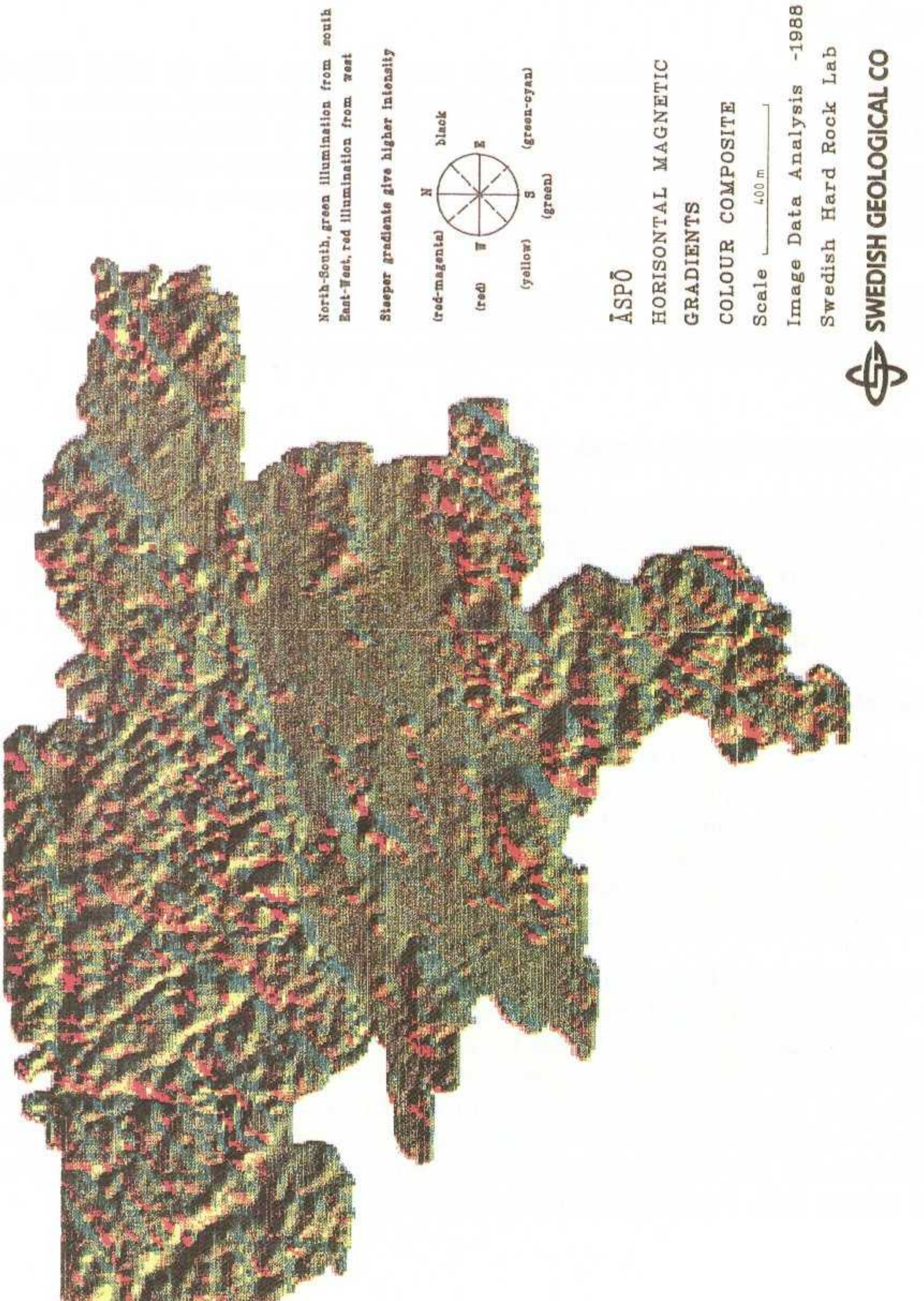


Figure 3.5 *Map of horisontal magnetic gradients, constructed from image processing of ground surface magnetic measurements.*

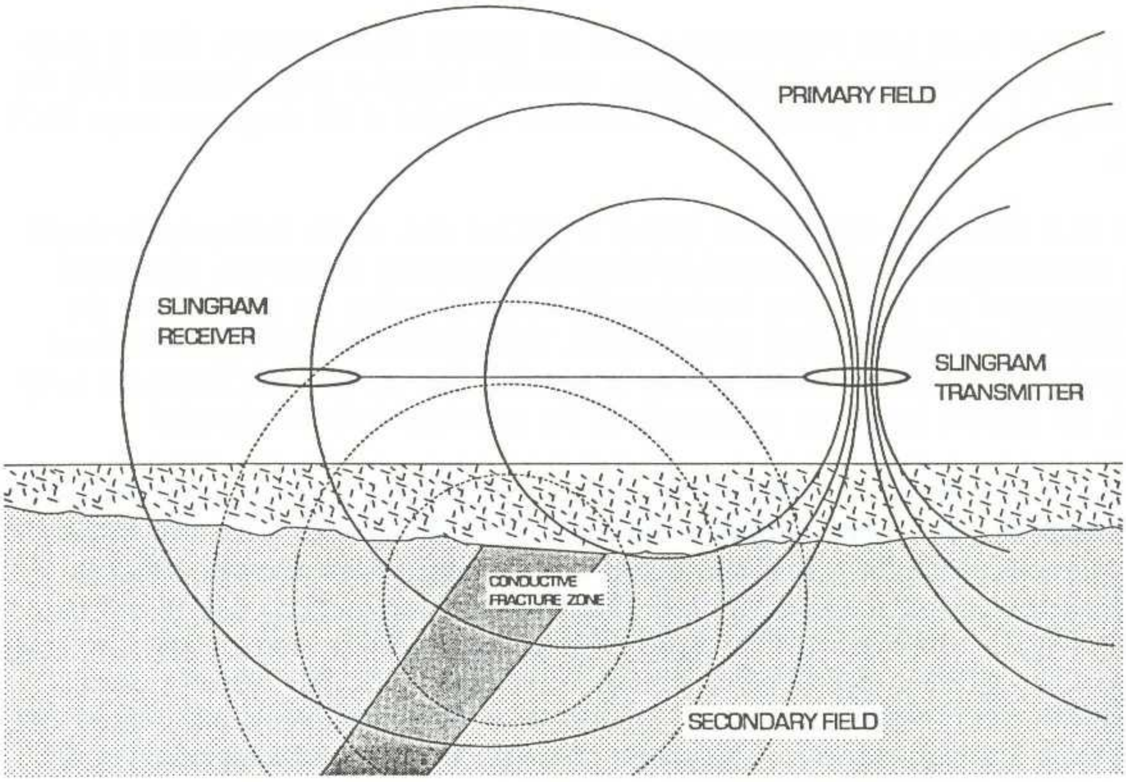


Figure 3.6 Measurements with the ABEM EMAC (Slingram), a horisontal Loop EM system.

VLF

In the VLF (Very Low Frequency) method the primary electromagnetic field is generated by strong military radio transmitters, normally located at great distances from the investigated site, see Figure 3.7. The transmitter operates in the frequency range 15-25 kHz.

The VLF instrument then consists only of a receiver unit, which measures the secondary electromagnetic field generated by electrical conductors in the rock. If possible, measurements are made using two transmitters located so that the directions to the transmitters are approximately perpendicular. This measurement configuration facilitates the detection of structures running in any direction. As with the Horizontal Loop EM, the real and imaginary components of the secondary field are recorded.

In the Project, the airborne survey was carried out with the SGAB VLF 86 system, a six-component VLF system which records orthogonal directions, with 3 components, of the electromagnetic field. In phase and out-of-phase signals are recorded. Ground surface measurements were performed with the Geonics instruments EM-16 and the ABEM Wadi, with resolutions of approximately 1% and 0.1%, respectively. The Wadi system also includes interpretation software for calculation of dips of the measured anomalies. Measurements were made against one or both of the radio transmitters GQD in Rugby, England and JXZ in Helgeland, Norway. The data recording densities for the different measurements are shown in Table 3.1.

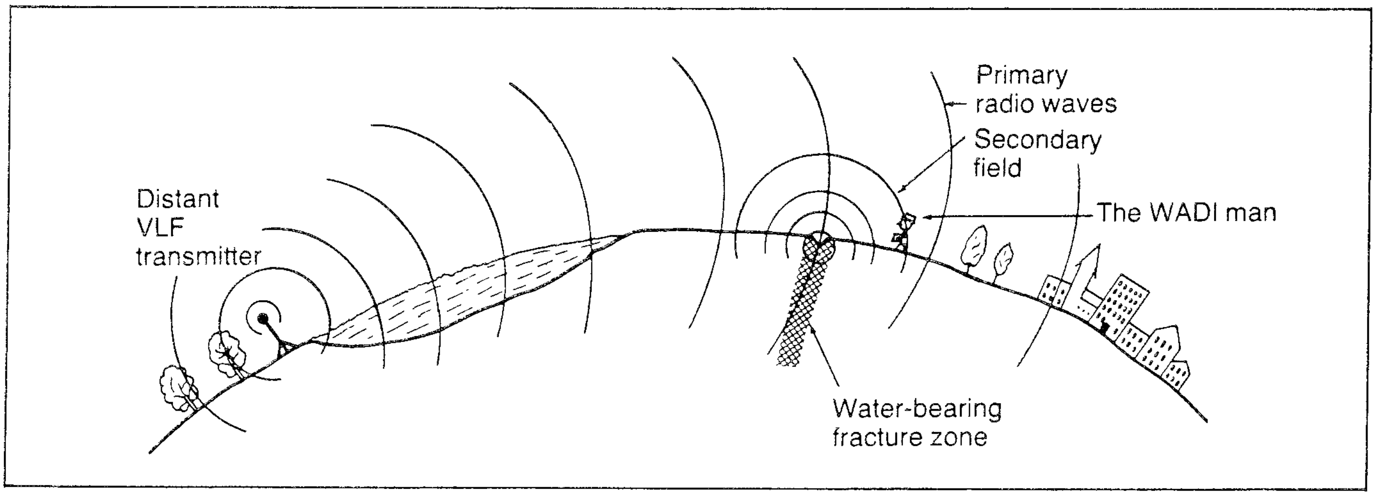


Figure 3.7 Measuring principle of the VLF method.

3.4.3 Electrical methods

Electrical resistivity measurements indicate areas with high fracture frequency and fracture zones. In the method a square wave current is transmitted between two electrodes on the ground. The potential difference is recorded between two other electrodes, see Figure 3.8. The measuring system can be set up in a number of configurations with different distances between the electrodes.

Two measurements were performed with the ABEM SAS 300 Terrameter. In one of these measurements a Schlumberger electrode configuration (AB/2 = 95m, MN/2 = 5m) was used /Barmen and Stanfors, 1988/. The other measurement were carried out with 10 m between the potential electrodes while the current electrode separation for different profiles was 92, 132, 161 and 190 m /Barmen and Dahlin, 1989/. A measurement campaign was also carried out with the SGAB Ript-30 system, using a dipole-dipole configuration of 5-10-5 meter /Nisca and Triumf, 1989/.

In addition, a couple of vertical resistivity soundings were conducted with the same ABEM SAS 300 Terrameter. The measurement configuration for vertical resistivity soundings is fixed, wide separation of the current electrodes, while the potential electrodes record data at successively increased separations from a central point. The results of the vertical resistivity soundings have been analysed using the interpretation software SVES. The SVES programme permits fitting of datapoints to 1-D models using manual or automatic variation of the parameters, thickness and conductivity of the different layers in the model.

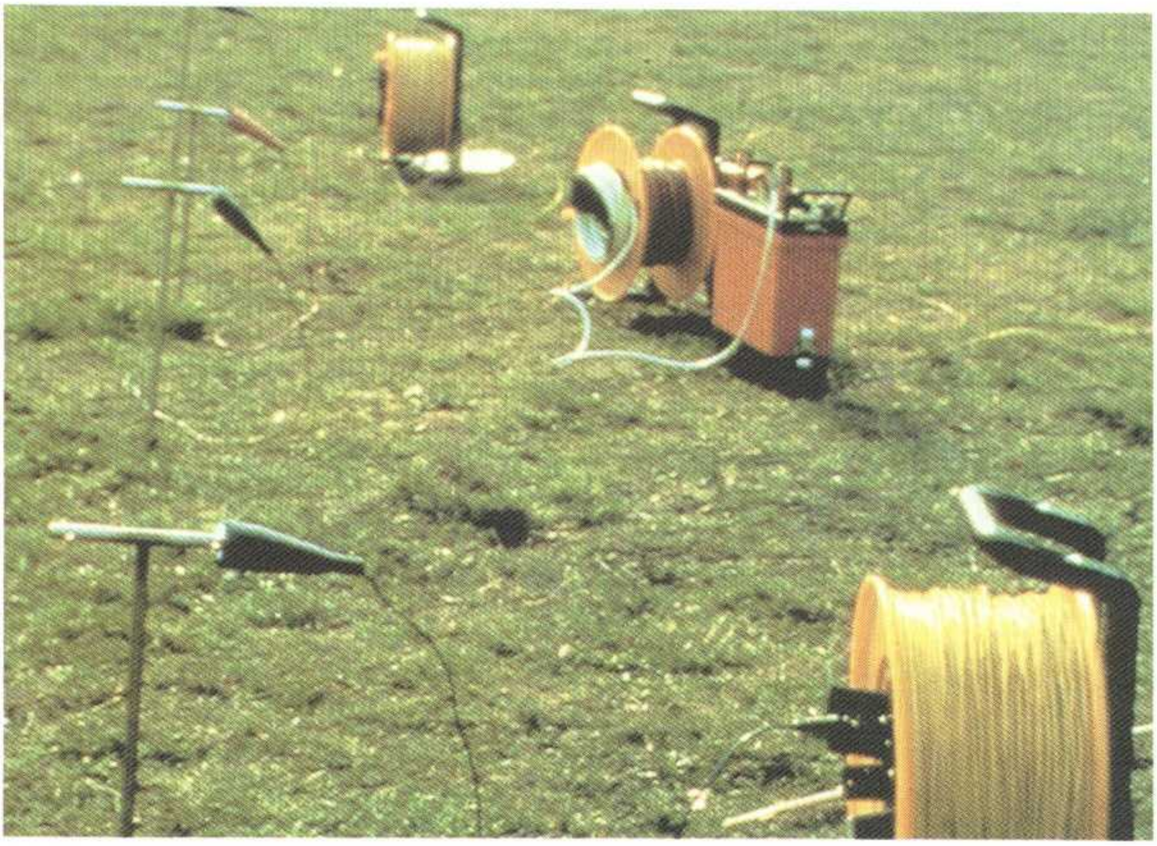


Figure 3.8 Equipment set-up for resistivity measurements with the ABEM SAS 300 Terrameter.

3.4.4 Gravimetric method

Anomalies in the gravitation field indicate rock masses of higher or lower density than the surroundings, such as mafic rock types and granitic plutons. During the pre-investigation phase of the Äspö HRL project, gravimetric measurements have been carried out on a regional scale /Nylund, 1987/.

The instrument which was used for the gravity survey is the LaCoste and Romberg Model G gravity meter. The instrument's reading accuracy is ± 0.01 mgal and the drift rate is less than 1 mgal per month. The measurements are related to the European Calibration System ESC 62 via a couple of base points connected to this system. The recorded data is processed with the program GRAVIA, which includes corrections for topography.

3.4.5 Radiometric method

Surface radiometric measurements were performed on two occasions from the ground /Barmen and Stanfors, 1988/ and /Barmen and Dahlin, 1989/. In addition measurements were also carried out from the air, in an early stage of the investigation programme, see Figure 3.9 /Nisca, 1987/. The total gamma radiation was measured with a Scintrex BGS-4 scintillation counter, with a resolution of 0.5 microroentgen per hour. The air-borne geophysical survey was conducted with the SGU gammaspectrometer SPM 80.

The dominant sources of gamma radiation are uranium (U), potassium (K) and thorium (Th). Variations in the concentrations of these elements normally correspond to mineralogic changes in the overburden or outcrops /Barmen and Stanfors, 1988/.

3.4.6 Seismic methods

The general principle of seismic investigation methods is briefly described in section 6.5.1. Surface seismic methods include refraction seismics and reflection seismics, both of which methods are being used in the pre-investigation phase of the Äspö HRL project. In both methods the acoustic wave is generated by explosives, a falling weight or a vibration source. A number of geophones, placed at increasing distance from the source, record the travel time for the seismic wave, see Figure 3.10. In order to increase the quality of measurements the seismic instruments normally have built-in processing capacity such as stacking and filtering facilities.

Seismic refraction method

Seismic refraction measurements are traditionally performed in order to determine the depth of the soil layer along a measurement profile. In the Äspö HRL project, refraction measurements have been performed in order to locate fracture zones and to determine the seismic velocities of these fracture zones. The seismic velocity provides information about the degree of fracturing in the rock mass.

Figure 3.9 Airborne geophysical surveying.

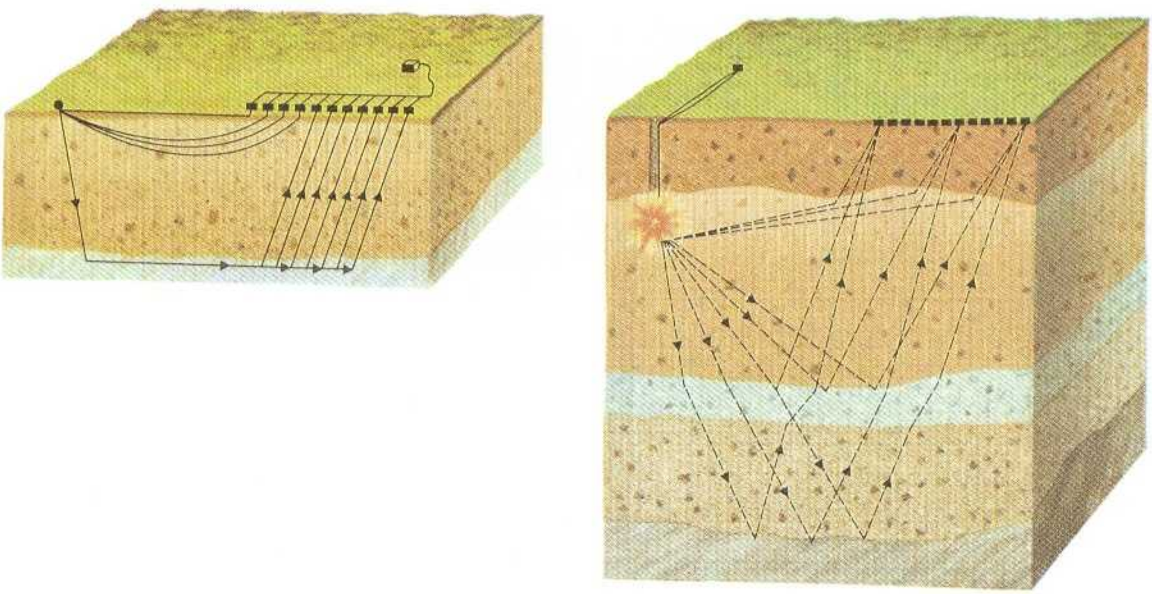


Figure 3.10 Principle of seismic refraction and reflection surveys.

Three seismic refraction campaigns have been carried out during the course of the pre-investigation phase. The equipment used was the 22-channel instrument SEMAB 22. Distances between shotpoints and geophone separations are presented in Table 3.1.

Seismic reflection measurement

Seismic reflection measurement was originally developed to locate horizontal structures at great depths, down to several thousand metres. The method is extensively used for oil exploration, often in conjunction with VSP measurements, see section 6.5. The method has rarely been used for crystalline rock characterization, especially at shallower depths, less than 1 000 m. In the Äspö HRL project, seismic reflection measurements have been carried out twice. The purpose was to detect possible horizontal or subhorizontal fracture zones in the rock, since this direction of fracture zones is difficult to identify using other geophysical methods or tectonic mapping. The measurements were carried out with the ABEM Terraloc-24, a 24-channel, 8-bit instrument which is normally used for refraction surveys. In order to increase the chance of detecting weak seismic reflectors, instruments with a resolution of 16 bits should preferably be used.

Measurements were carried out using 10 MHz geophones and 10 m point separation.The sampling rate was 2000 samples per sec and the recording time was 500 millisec, which corresponds to a recording depth of approximately 1500 m. Explosives in shallow boreholes were used as an energy source /Ploug and Klitten, 1988/.

The measurements were processed by three seismic laboratories, resulting in significantly different results, indicating the difficulties of evaluating reflection seismics in crystalline rock /Juhlin 1990/.

4. DRILLING METHODOLOGY

The first stages of a site investigation programme are dominated by surface investigations. However, relatively early in the siting process it is necessary to get direct information from deeper parts of the rock formation. For this purpose it is advisable to drill a single deep borehole or a couple of shallow boreholes, depending on what kind of information is desired. Later on during the characterization programme borehole investigations are the main source of parameter determinations. Shallow boreholes are normally drilled by means of the percussion drilling method, while deeper boreholes normally are drilled by means of the core drilling technique, see Figure 4.1.

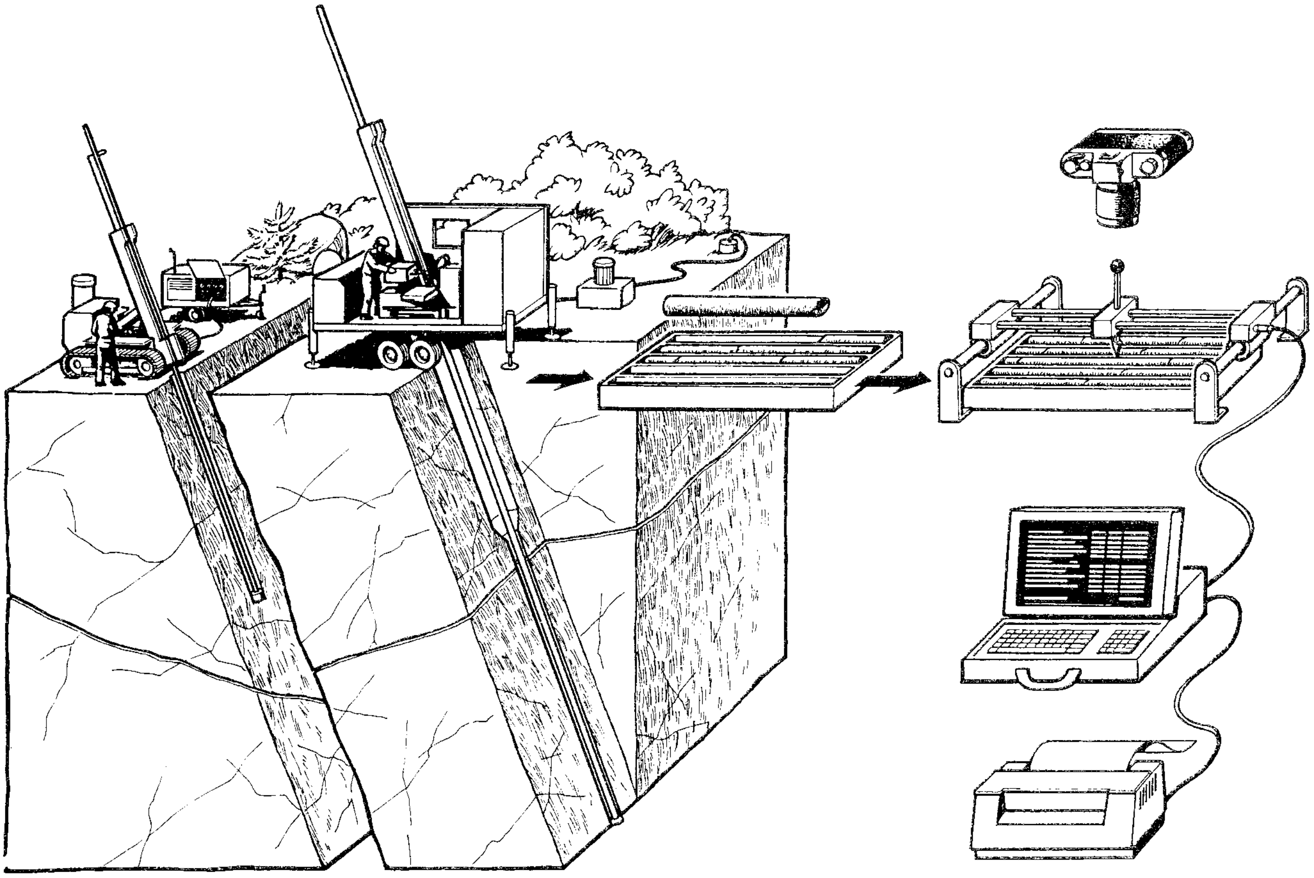


Figure 4.1 Illustration of the percussion drilling (left) and core drilling methods (right).

4.1 Percussion drilling

Percussion drilling is normally performed in the early stages of an investigation programme in order to verify geological and/or geohydrological anomalies, that have been indicated by surface investigations. With a sufficient number of boreholes, a rough idea of the hydraulic character of the investigation area can be gained. By taking water samples from these holes the hydrochemical situation can also be determined. In a later stage these percussion-drilled holes are used as observation boreholes during hydraulic interference tests and for long term monitoring of the groundwater level, described in chapter 8.

In the Äspö Hard Rock Laboratory project, the length of the percussion boreholes is normally 100 to 200 m. They were drilled with dip angles of between 55° to 90° from the horizontal. The most common diameter for percussion drilling was 115 mm (4"), but 165 mm (6") was also used for a few holes.

Figure 4.2 Percussion drill rig.

Drilling was performed by conventional percussion drill rigs, powered by compressed air and using downhole hammer, see Figure 4.2. The practical depth limit for this type of drilling machine is approximately 200 m, but when a large amount of water is entering the borehole the drilling must be interrupted at a more shallow depth. However, deeper depths and/or lot of water can be handled by using the booster technique. This entails that two or more compressors are connected in series or that some kind of pressure amplifier is connected in-line after the air compressor.

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. This provides rough information on the location of fracture zones, as well as some information on the petrological changes in the rock. Samples of the drill cuttings were taken every third meter. Geological examination of the cuttings was performed with a binocular microscope. The water flushed to the surface during drilling was measured at 2-3 different depths. A watch and a bucket were used to measure water capacity.

When drilling is terminated a pumping test is performed with the drill rig. Air-lift pumping goes on for one hour and the subsequent recovery of the water level is measured during the next hour, see section 7.1.1.

4.2 Core drilling

4.2.1 Conventional core drilling

Core drilling is the most common method for investigating boreholes, especially when information from great depth is desired. The greatest advantage at core drilling is that the core which is sampled along the entire borehole provides outstanding information on the geology of the penetrated rock. However, the core drilling technique is relatively expensive, with increasing costs for increasing borehole diameter. This diameter-related cost increase was a reason for SKB to develop downhole instruments for measurements in small-diameter boreholes.

In most cases 56 mm boreholes are used, but for special purposes 76 mm diameter boreholes are drilled. The larger holes are used, for example when 3-D rock stress measurements with the overcoring technique are performed, see section 10.2. Drilling is normally carried out with standard T-56 and T-76 drill bits and core barrels, which results in core diameters of 42 and 62 mm, respectively, see Figure 4.3.

During core drilling, flushing water is used to cool the drill bit and to transport the drill cuttings up to the surface. Due to the overpressure of the flushing water, relative to the hydrostatic pressure in the formation (especially at the drill bit), some flushing water will enter into the fractures or fracture zones. This water will contaminate the groundwater and the drill cuttings may to some degree get stuck in the narrow fractures and thereby affect the hydraulic situation.

In order to monitor the groundwater contamination, a coloured tracer (normally uranine) is added to the drilling water at a certain concentration (by mixing with drilling water in an 5 m^3 container). In order to reduce the risk of chemical reaction between very different water types, drilling water is taken from a percussion-drilled

Figure 4.3 Core-drilling rig and pieces of core.

borehole in the same rock formation. A chemical analysis is performed on the drilling water as well. All groundwater samples taken for chemical analysis are also analysed for uranine content, providing an indication of the degree of contamination (traces of drilling water) in the sample, see also chapter 9. In the Äspö Hard Rock Laboratory project a uranine concentration of 1 mg per liter was used.

A step forward in reducing the penetration of drilling water into the fractures has been taken by introducing a new drilling technique, the telescope-type drilling technique. This technique is an improved version of the core drilling method, and will furthermore make new measurements possible in the small-diameter boreholes (see section 4.2.2).

4.2.2 Telescope-type drilling technique

The new telescope-type core-drilling technique was introduced during the pre-investigation of the Äspö Hard Rock Laboratory project. The purpose of the new technique is two-fold:

* to reduce the contamination of drilling fluid and cuttings in the formation

* to improve the configuration of the borehole in order to make new types of measurements possible.

The new technique was used throughout the entire pre-investigation phase, and proved to be very successful. The technique is called telescope-type drilling, due to the shape of the borehole; the uppermost 100 m is reamed-up to 155 mm diameter, while the rest of the borehole is 56 mm or 76 mm, see Figure 4.4.

Reduced penetration of drilling water and cuttings into the fractures is obtained by reducing the hydraulic pressure in the annulus of the borehole by means of air-lift pumping. The airlift pumping creates a draw-down effect down to a depth that is dependent on the depth and capacity of major groundwater conductors, and at least some reduction of the water pressure is obtained all the way down to the drill bit.

The technique of drilling telescope-type boreholes in the Äspö HRL project was as follows:

* Conventional core drilling is done to a borehole length of 101 m. The hole diameter used is 66 mm. The next step is to ream the borehole up to 155 mm. This is done by percussion drilling. The reamed length is exactly 100 m. The borehole is cleaned with water after reaming. A capacity test of the borehole is also performed, see section 7.1.2.

* A temporary casing is installed down to 101 m, and core drilling is continued at a diameter of 56 mm, according to the method described in section 4.2.1. To avoid vibration during drilling the casing is provided with casing stabilizer, positioned every 10 m along the casing. The bottom ten metres of the casing is perforated to allow water to pass into the annulus between the casing and the borehole wall. Two 1" airtubes are mounted in the annulus. These tubes goes down to approximately 5-10 m above the perforations. Compressed air is blown

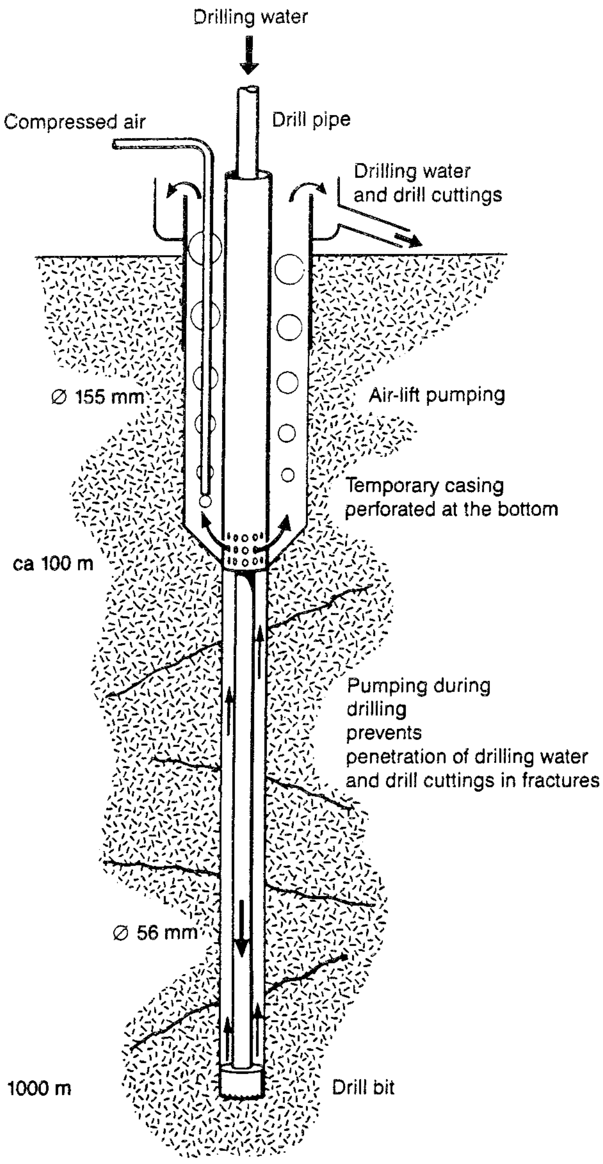


Figure 4.4 *Principle of telescope-type drilling technique with air-lift pumping for retrieval of drilling water and cuttings.*

through the tubes during the drilling operation. When the air bubbles enter the borehole, the density of the water column decreases, lowering the hydrostatic pressure in the drill pipe. The mixture of water, drill cuttings and air is then forced upwards.

The capacity of the airlift pumping from the borehole, typical for the project, was 5-10 l/min of water. A draw-down of some 40 m in the borehole was created. An electrically powered air compressor of 3-8 m^3/min flow capacity and 13 bar pressure was used. As the airlift pumping was continuously ongoing, not only during the drilling but also during interuptions and tripping in and out of the borehole, the total volume of water pumped out from the borehole was 2-3 times more than the amount of drilling water which was pumped down into the borehole.

The recovered drilling water was pumped to a series of settling tanks in order to clean the water from most of the cuttings before it was pumped out to the sea.

Every 100 m the drilling was interrupted and a hydraulic test was conducted, as described in section 7.1.2.

The drill rigs used for the core drilling in the ÄSPÖ HRL project were the Craelius Daimec 1000, the Hagby Bruk Onram and a TGB Microdrill rig.

4.2.3 Directional drilling

In order to investigate the rock volume along the planned tunnel direction beneath the sea south of Äspö, a new directional drilling method was used, developed by Devico. The hole diameter was 56 mm, as normally used. The core obtained during directional drilling was 30 mm .

The drilling unit consists of a double tube attached to a regular drill string, and operated via the ordinary drill rig. The inner tube is deviated relative to the outer tube by means of two eccentric bearings. A rubber packer, inflated by the drilling fluid pressure, keeps the outer tube in position. An inclinometer is also attached to the outer tube, signalling its position to the surface.

The drilling of the Äspö KBH02 directional borehole started from the surface with an inclination of 50° from the horizontal. After approximately 10 m of drilling, the deviation was initiated and continued for approximately 180 m. The total deviation was 40°, resulting in a inclination 80° for the subsequent 520 m of drilling, see Figure 4.5. During deviated drilling, the orientation of the hole was measured after each retrieval, i.e. every 1.5 metres.

The penetration rate during deviated drilling was approximately half of the penetration rate for conventional core drilling.

4.3 Coordinate system

Positioning of boreholes and other features in the field has been done in the Äspö coordinate system. This system is derived from the local coordinate system used by the OKG Nuclear Power Station. In relation to the "Rikets allmänna nät" (RAK), the OKG system is 15.5 gon W of N and the Äspö system is 15.45 gon W of N. The z-coordinate is the same for all three systems and is related to sea level.

In the data base, all coordinates are presented in both the Äspö system and the RAK system. Conversion between the two systems is done in the data base.

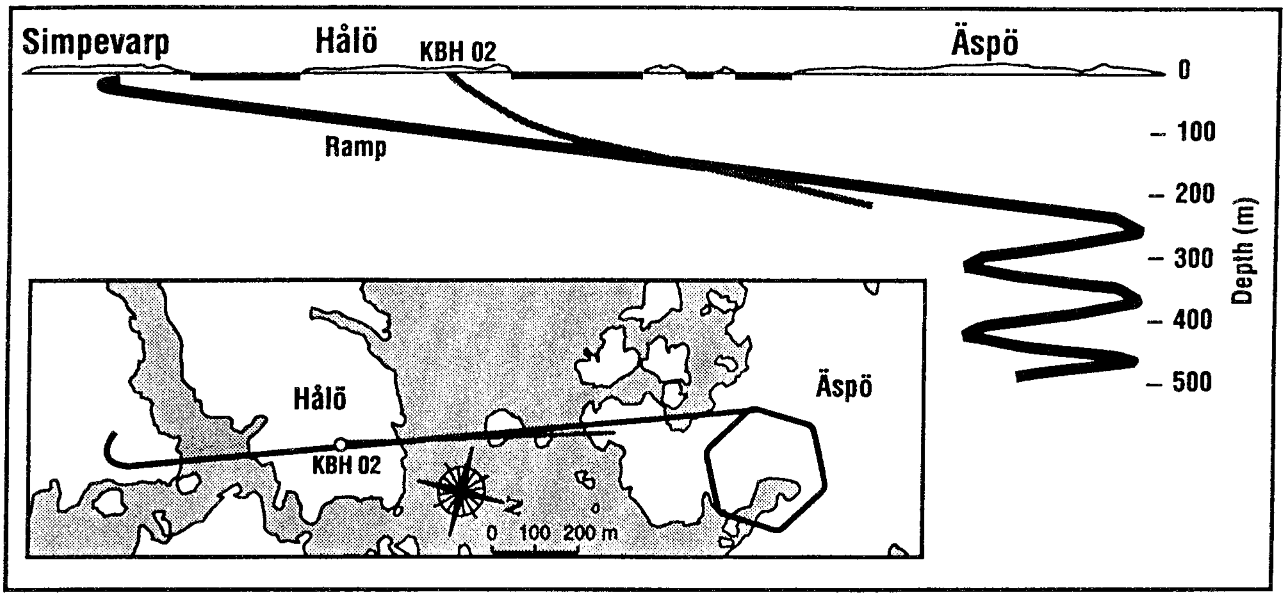


Figure 4.5 *The directional borehole KBH02, drilled in order to pre-investigate the rock along the access tunnel ramp.*

5. BOREHOLE GEOLOGY

5.1 Examination of cuttings

During percussion drilling the cuttings were sampled every fifth meter. The size of the samples is around one kilogram. After drying, the samples were examined both with and without a binocular microscope. Most of the samples were sieved in order to study the few somewhat larger rock fragments. The aim of these studies is to determine the major rock type changes and also to identify the sections of alteration. The geologists are helped by the rate of penetration graph from drilling, as described in section 4.1.

5.2 Core logging

In the Äspö Hard Rock Laboratory project, core logging has normally been carried out in two steps. In the first step the geologist makes a preliminary examination of the cores, during drilling and at the drilling site. The purpose of this initial logging was to obtain basic data for the subsequent drilling. The results are presented on drawings. Only large scale features are recorded.

In the second step a detailed mapping of the core is performed using the computerized core logging system PetroCore, developed by Petroblock, see Figures 5.1 and 5.2.

The mapping starts with a reconstruction of the core. This sometimes requires a lot of time but is necessary to measure the relative angles of the fractures. The length of each piece of core is measured using the PetroCore length measuring device and the total length for each core retrieval is compared to the length of the corresponding drilling section. A reference line is drawn along the core and the core is photographed both for slides and color prints, see Figure 4.1. Finally the cores are mapped as regards lithology and structures. The following items are determined and stored in data files (for most of the boreholes) /Stråhle, 1989/:

- Rock type
- Break (induced fracture)
- Natural fracture; natural or sealed
    - surface character
    - fracture mineral/alteration
- Vein
- Orientation of fracture or other structure;
    - dip angle relative to core axis
    - dip direction relative to reference line
- Crush zone
- Alteration
- Core loss

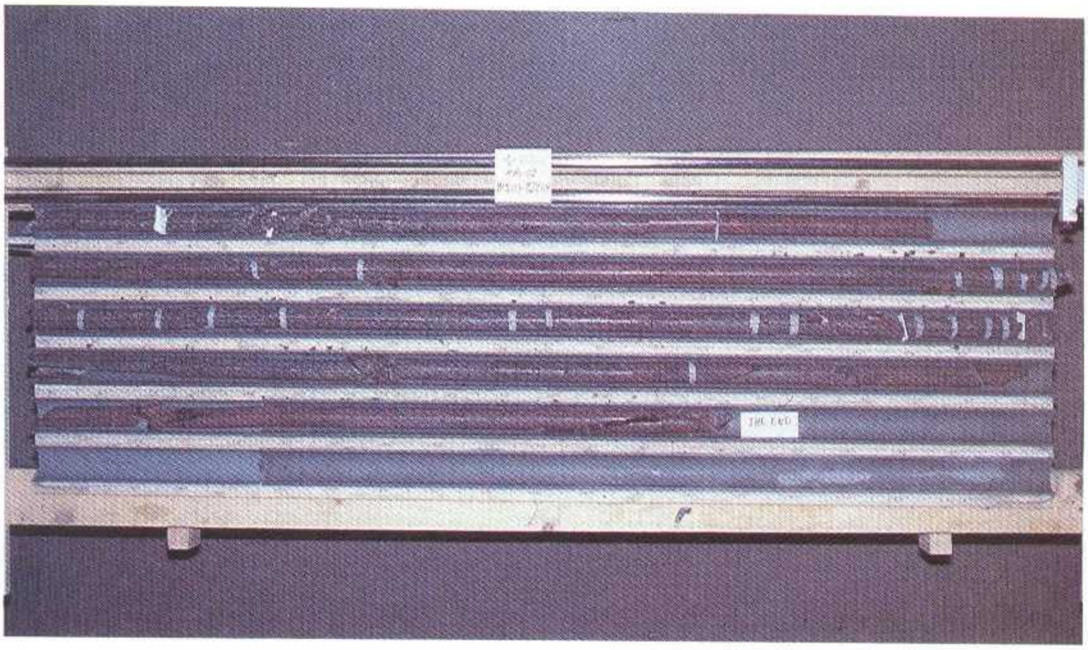


Figure 5.1 Core box with 42 mm drill cores from a 56 mm borehole.

Figure 5.2 Core logging with the PetroCore system.

The computer calculates the fracture frequency as the number of fractures for every metre interval. In the first drilling campaign another method, based on an equal number of fractures and a varying length module, was used for calculating fracture frequency. This alternative method is very accurate and responds very quickly to a small increase in the fracture density. On the other hand it may exaggerate small crush zones. The RQD (Rock Quality Designation) was calculated as the percentage of the total length of core pieces longer than 10 cm, also for every metre of core. The type of results from core logging are shown in Figure 5.3.

For a detailed description of the lithology of the rock, the results of the geophysical logging have been integrated in the evaluation work /Sehlstedt and Stråhle, 1989/.

Samples from the core are taken for different kinds of analyses. Detailed inspections on thin sections and geochemical analyses of core samples are made for detailed petrological classification of the rock types /Munier et al, 1988/. Laboratory measurements of physical properties of core samples are carried out as well /Nisca, 1988/.

Different methods for absolute orientation of the core were tested in several boreholes. Direct orientation of the "core" before being drilled out in the borehole was performed by means of two methods. One method is based on dropping an iron rod into the borehole, after retrieval of the core, making a mark on the top of the next core. In another method a borehole device was lowered and pressed against the next core top, making an imprint of the core surface. The first method is unreliable but cheap and fast. The second method works well as long as the rock is good. Both methods are dependent on inclined boreholes. Indirect methods such as acoustic televiewer and borehole TV have also been tested /Fridh and Stråhle, 1989/. These methods are described in sections 6.3 and 6.4, respectively.

The absolute orientation of the core is transferred to the relatively oriented core, and the orientation of every fracture can be obtained. The orientations of the fractures are presented in a Wulff net or Schmidt net, see Figure 5.4, and can be used for statistic analysis, in models or for comparing results from similar measurements on the surface.

5.3 Fracture filling investigation

Minerals coating the fracture are regularly determined during the core logging. However, more detailed examinations of the fracture minerals are requested for specific purpose, such as studies of interaction between the rock and the groundwater. The Fe minerals are an indicator of redox conditions and are therefore paid special attention /Tullborg, 1989/, /Tullborg et al, 1991/. In some cases correlations have been found between fracture minerals, fracture orientation and hydraulic conductivity.

For these kinds of special fracture filling investigations, a selected number of core samples are taken. The type of analysis performed on these samples depends on the type of question to be penetrated.

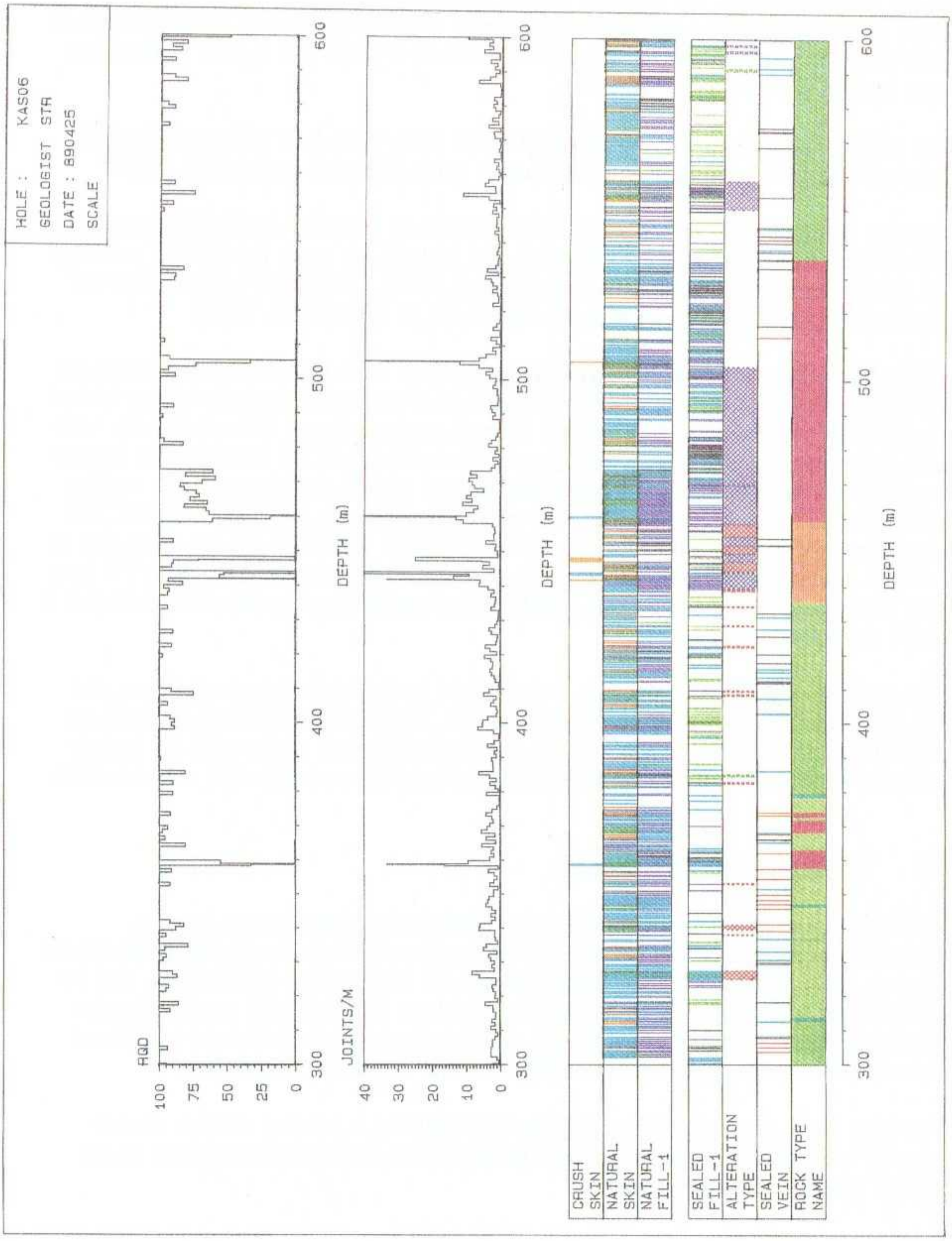


Figure 5.3 Color plots of results of core logging.

WULFF NET

LOWER HEMISPHERE POLE POINTS

BOREHOLE KAS05, 400-450 m

No. OF JOINTS: 80

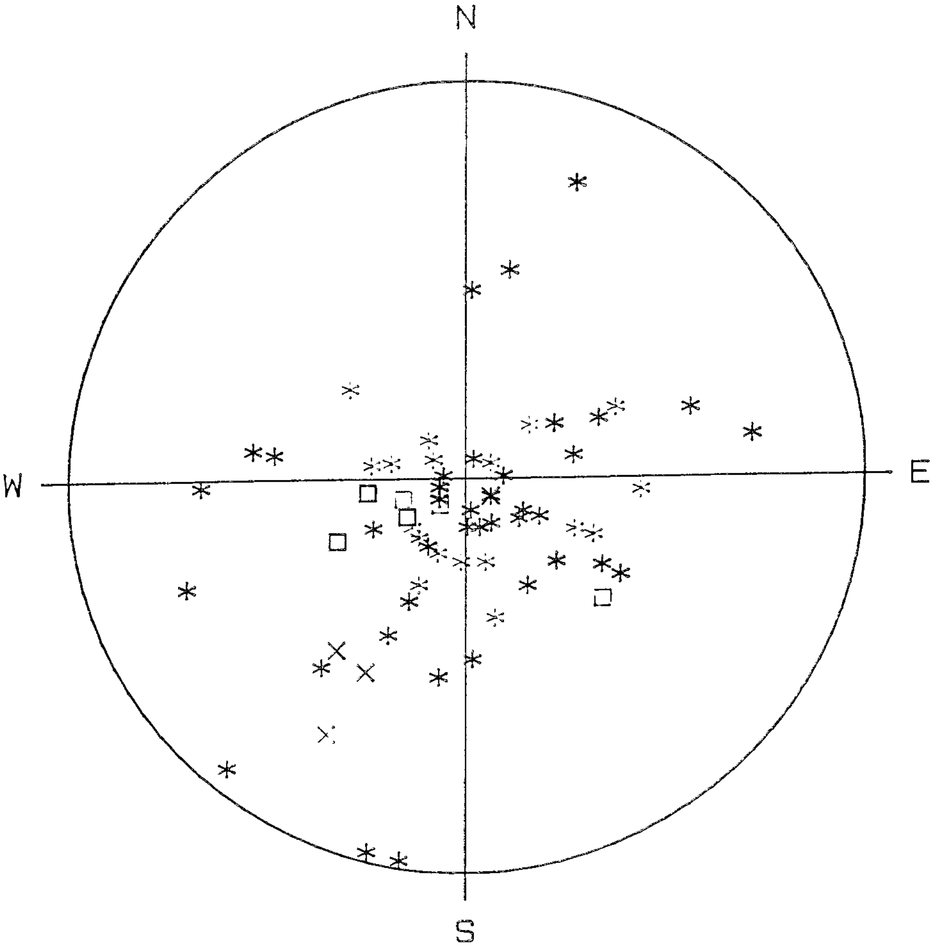


Figure 5.4 Graphic illustration of fracture orientations measured on drill cores.

6. BOREHOLE GEOPHYSICAL MEASUREMENTS

Geophysical investigations in boreholes provide indirect information on geological, geohydrological and hydrochemical parameters for the characterization of deep rock formations, see Figure 6.1. The description of these investigations is divided into separate sections dealing with geophysical logging methods, borehole radar investigations, borehole seismics, TV inspection and televiewer logging. Borehole radar and seismics can be used both in single-hole and cross-hole modes, while the other methods are used for single-hole measurements. The description is limited to methods used in the Äspö Hard Rock Laboratory project.

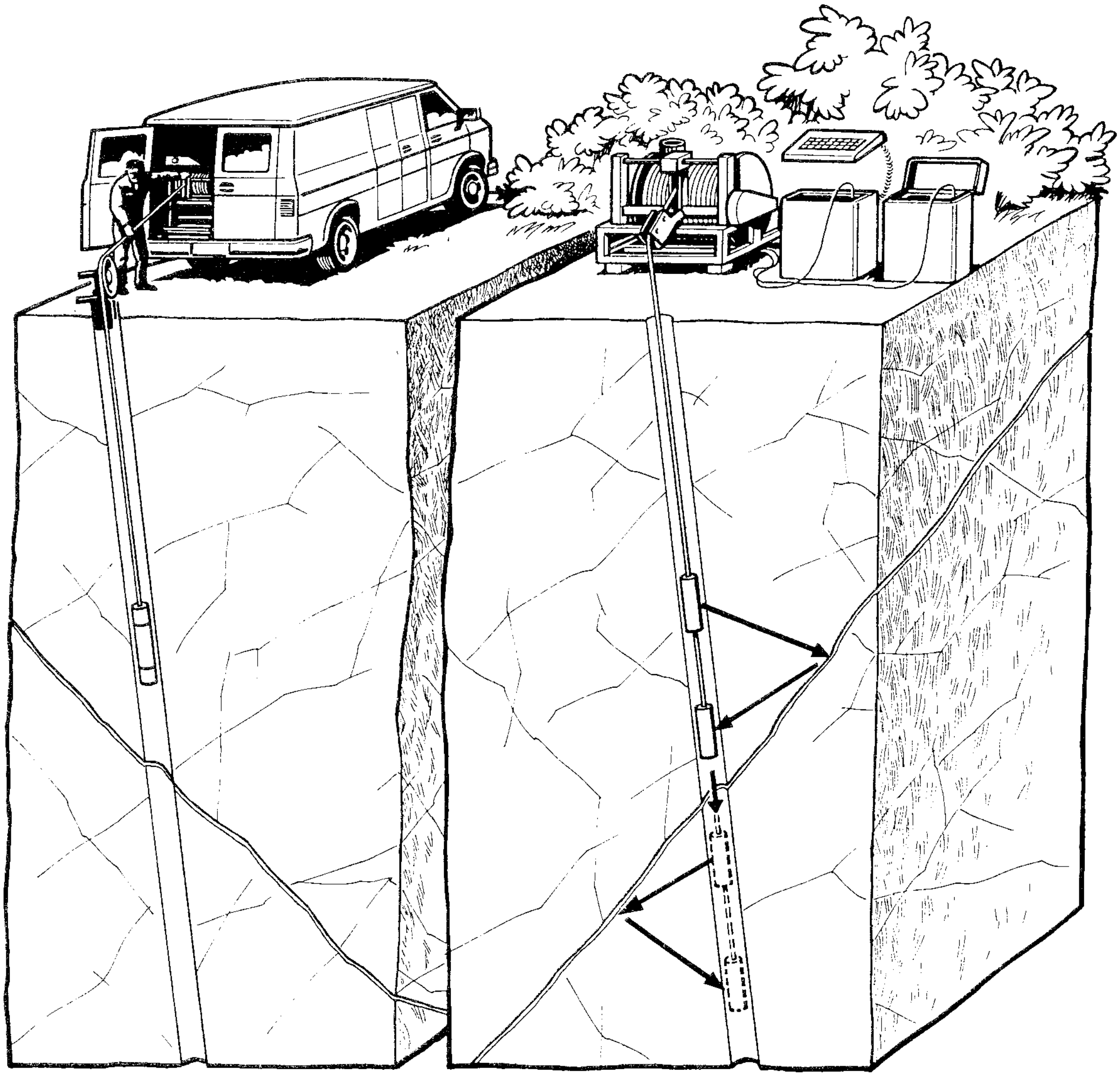


Figure 6.1 Illustration of geophysical logging and radar measurements as geophysical borehole investigation methods.

6.1 Geophysical logging

Geophysical logging is a group of single-hole measuring methods which gives information on the borehole wall and the rock volume just outside the hole /Ahlbom et al, 1983/. There are a great number of logging methods available, some of which are sensitive to electrical or magnetical properties of the rock and/or the pore water in the rock formation. Other rock properties are measured by means of radiometric or acoustic methods. Methods for determination of the borehole geometry are also included in the group of geophysical logging methods.

Geophysical logging methods being used in the Project are shown in Figures 2.6 and 2.7. Results from the measurements are presented in Sehlstedt and Triumf /1988/, Sehlstedt and Stråhle /1989/, Sehlstedt et al /1990/ and Stanfors /1988/.

6.1.1 Equipment for geophysical logging

The SGAB geophysical logging system Boremac was used in the Äspö Hard Rock Laboratory project. The system consist of a surface data collection and control unit and a logging cable with cable winch. A number of specifically designed borehole probes are used for measuring the different geophysical parameters, see Figure 6.2.

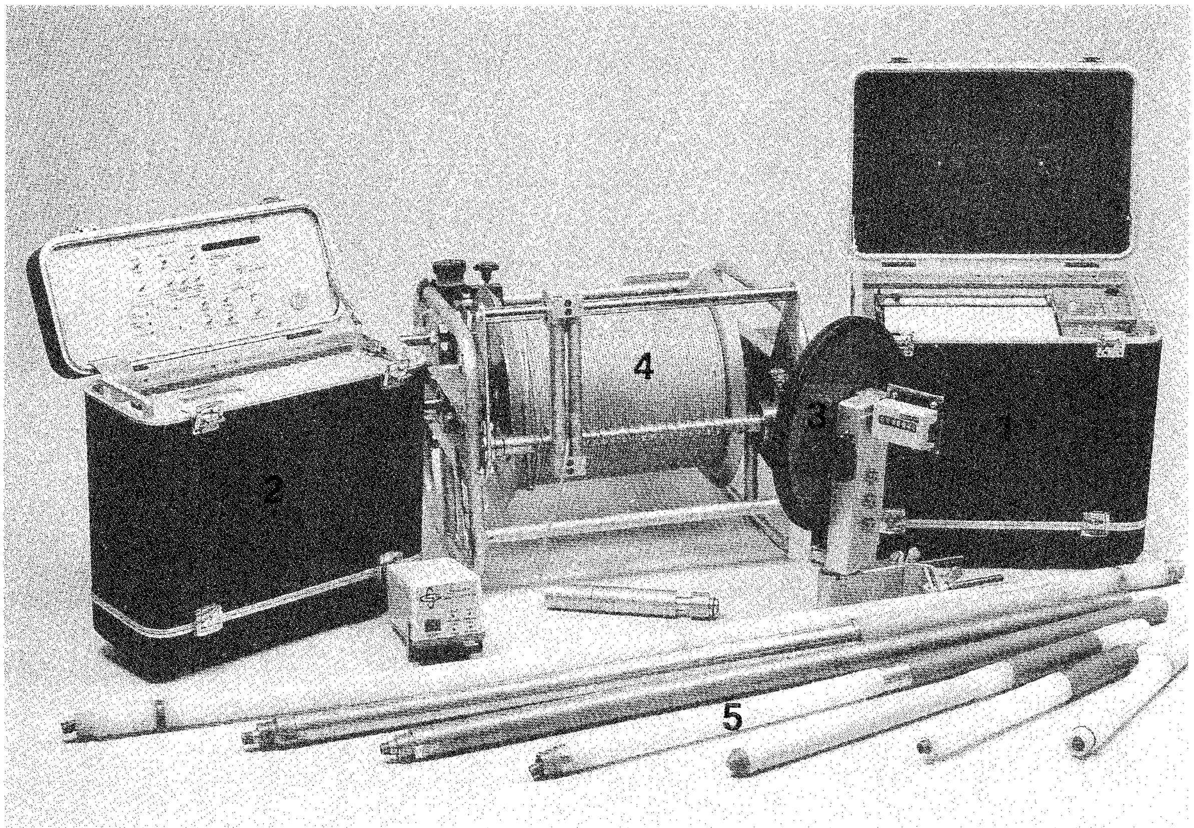


Figure 6.2 The geophysical borehole logging system Boremac: 1-2. Analogue and Digital recorders, 3. Measuring wheel, 4. Winch, 5. Probes

Data collection and control unit

The surface data collection and control unit is a one-man operated multilogger based on an IBM PC. The system is normally mounted in a van, but the lightweight unit is portable which makes it possible to log in boreholes far away from roads. A brief technical description of the system follows:

A IBM AT computer is used for data storage and checking of the measurements. A special interface card including a 12 bit A/D converter is installed in the computer. All measured data are displayed in real time on the screen and, if the operator wishes, synchronously on a matrix printer, in data tables or in graphic form. Several channels can be measured and presented simultaneously. Raw data are stored on the computer's hard disk during the measurements. Data processing, calibrations, corrections and printouts can be done in the field.

The control unit is interfaced to both the computer and the probes. It is mounted in a 19" rack system. The unit contains devices necessary for the measurement, such as amplifiers, oscillators, ratemeters and power supplies.

Communication with the probe takes place via a cable drum either with normal 3/16" steel logging cable or a special polyurethane cable. The polyurethane cable is used for high-precision resistivity measurements in high-resistivity areas.

Depth (or length) measurements along the borehole are made with a measuring wheel located at the borehole collar. In addition, the logging cable is marked every 50 metre. The overall accuracy of the depth measurements is better than 1 %.

The measuring probes connected to the cable head are designed for use down to depth of at least 1000 m of in boreholes with a diameter of 56 mm. Some of the probes are multiple parameter probes which measure more than one geophysical parameter at a time. Other surveying probes measure only one geophysical parameter. Technical information on the probes is provided in section 6.1.2.

6.1.2 Geophysical logging methods

Borehole deviation

For all kinds of borehole measurements it is of great importance to know the exact position of the measured data points. For single-hole measurements, which will be compared with each other in the interpretation process, an exact length measurement along the borehole is necessary. The length measuring technique is described in section 6.1.1.

For high-quality characterization of large rock volumes at great depth, carried out from several boreholes, the position in 3-D of the measured data-points must be well known. The declination and curvature of the borehole therefore have to be determined. The deviation of the borehole must also be taken into account when comparing groundwater pressures at depth with groundwater levels, see section 8.2.

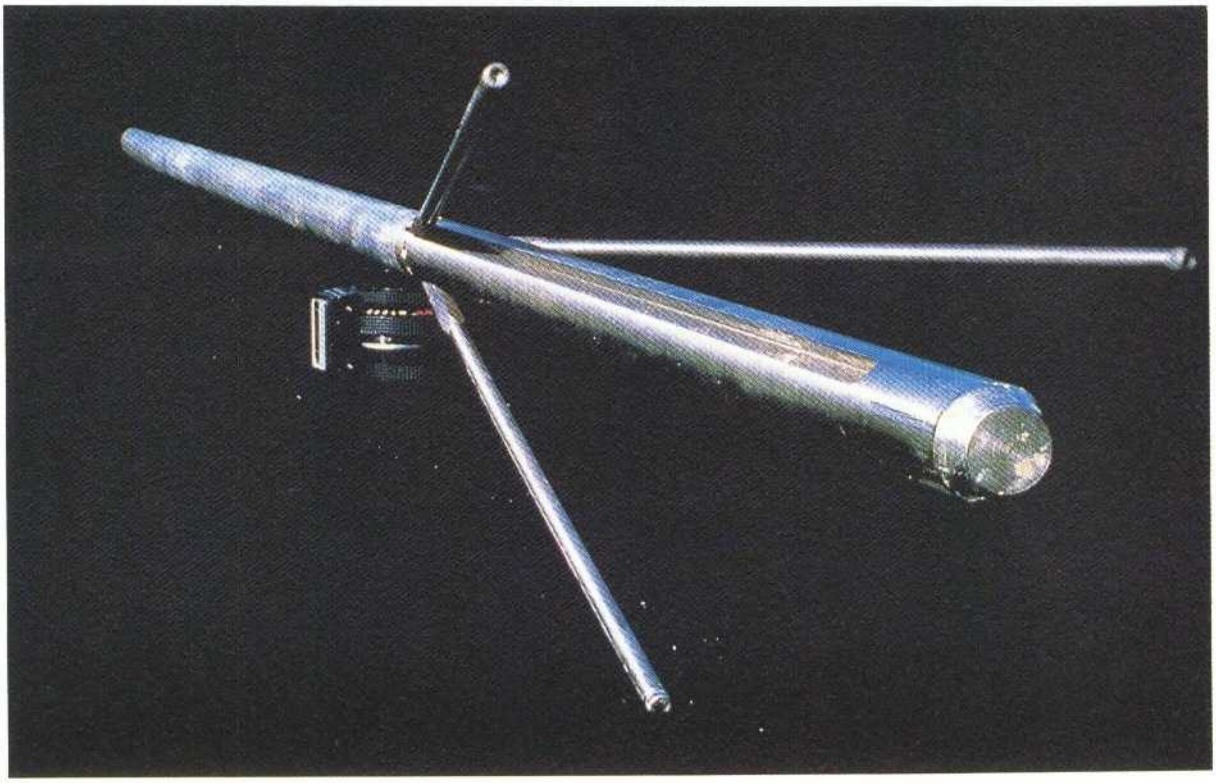


Figure 6.3 The caliper probe for borehole diameter measurements.

Borehole deviations were determined with the SGAB Boremac-D tool, which measures the inclination by means of a loaded wheel, while the declination is measured with a magnetic compass. The accuracy of the measured values is 0.1 degree for the loaded wheel and 1 degree for the compass. The accuracy in the determination of the 3-D location along the borehole is a function of the number of measurements and the accuracy of each measurement point. In practice it is estimated to be less than one meter per 100 m of borehole length.

In the Äspö HRL project deviation measurements were carried out in all the cored and percussion-drilled boreholes. Deviation and inclination values were determined every 10 m along the borehole.

Caliper log

Another geometric measurement is the caliper log, which determines the diameter along the borehole. In crystalline rock the borehole diameter normally corresponds well to the nominal drilling diameter. In some fracture zones or cross zones minor rock fall-out may occur, and will then be identified with the caliper. Diameter data is essential for interpretation of other geophysical parameters such as density. In bad quality rock it may also be of value for the selection of packer seals.

In the pre-investigation phase of the Äspö Hard Rock Laboratory project the diameter along all cored holes was determined with the MLS three-armed caliper probe, see Figure 6.3. This caliper is used in boreholes from 46 mm to approximately 500 mm. The measuring frequency along the borehole was 0.1 m. Cored boreholes as well as percussion drilled holes are measured.

Electrical logging methods

Electrical logging methods commonly available and used for SKB site investigations are spontaneous potential (SP), single-point resistance, normal and lateral resistivity and borehole fluid resistivity, see Figure 6.4. SP, also called self potential, measures natural conditions in the rock formation, while the other methods record responses from artificially generated electrical fields. Of these electrical logging methods, which are described below, single-point resistance and borehole fluid resistivity are standard methods used in the Äspö HRL Project, in cored as well as percussion-drilled holes. Some core boreholes have also been measured by means of the normal and lateral resistivity log and the SP method /Sehlstedt and Triumf, 1988/. All methods were measured with SGAB logging probes.

The SP method measures the natural or spontaneous potential in the rock surrounding the borehole, using two nonpolarizable electrodes, one of them positioned at the ground surface while the other records the potential distribution along the borehole. The measurement density used in the Project was 0.1 m.

Normal and lateral resistivity are two similar methods where an induced electrical field is used for determination of the resistivity of the bedrock. A measurement density of 0.1 m was used.

The single-point resistance method also measures an induced electrical field with an electrode system consisting of a small-borehole electrode (5 cm in length) surrounded by an insulator slightly smaller than the borehole diameter, in order to reduce the effect of a conductive fluid. The single-point method is sensitive to electrically conductive minerals, and in particular to the water content in fracture zones and in single fractures. The resistance was measured with a frequency of 11 Hz and a measurement density of 0.1 m.

The resistivity of the borehole fluid was measured every 0.1 m in the borehole for the determination of the salinity of the water in the borehole. Sudden jumps in the fluid resistivity log indicate possible groundwater conductors. The fluid resistivity log can also be used for calculations of the density profile of water along the borehole, which can be useful when analysing piezometric pressures in the formation.

Simultaneously with the fluid resistivity measurements the temperature of the water was also recorded, which can indicate levels of groundwater discharge or recharge in the borehole.

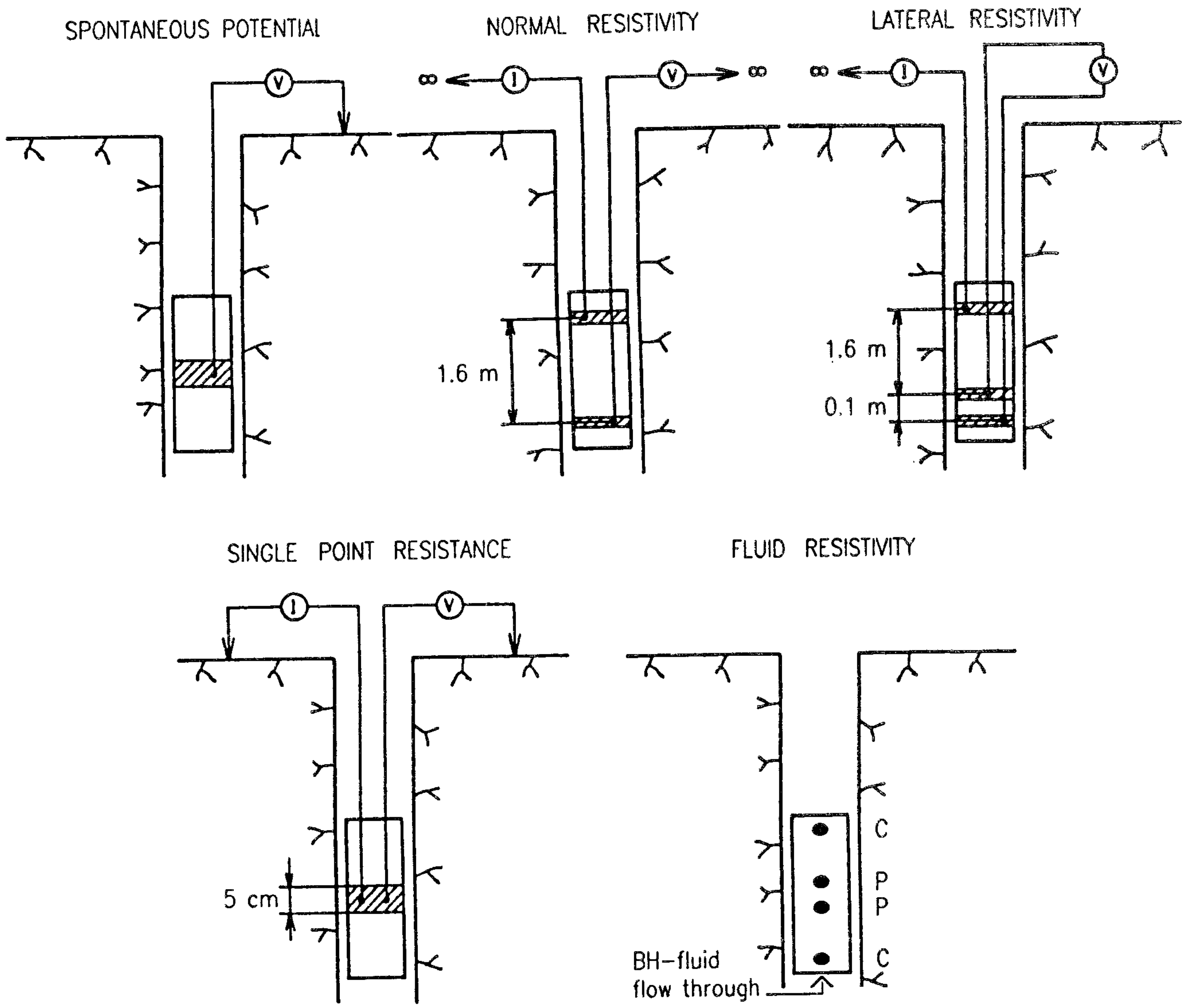


Figure 6.4 *The electrode configurations for the spontaneous potential, normal and lateral resistivity, single-point resistance, and fluid resistivity probes.*

Magnetic methods

Magnetic susceptibility is the only magnetic borehole method used in the Äspö HRL project. Measurements were performed with the Geoinstrument susceptibility probe, both in cored and percussion-drilled holes with recordings every 0.1 m. The measuring principle is based on the fact that magnetic materials influence a tuned electric resonance circuit. The probe sensor is a coil tuned to 1 kHz with a capacitor. Magnetic material close to the coil will change the resonance frequency in the circuit. These frequency variations are measured very accurately in the probe and recorded by the surface module. Since each rock type has a characteristic magnetite content, the magnetic susceptibility method is a very useful tool for the classification of crystalline rock types.

Acoustic methods

An acoustic single-hole method which has been used in the Äspö HRL project is sonic logging. The Vertical Seismic Profiling (VSP) is also an acoustic method which has been used in one borehole, as described in section 6.5. Another borehole acoustic measuring method, however not used in the Project, is the Tube Wave method, by means of which open fractures or fracture zones can be detected. The Tube Wave measurements are carried out similar to the VSP measurements, but the "tube waves", generated at points where open fractures are penetrated by the borehole, are used in the evaluation.

The sonic velocity probe used in the Project is the Simplec single transmitter dual receiver tool, which records the time for a compressional elastic wave to travel a certain distance in the formation next to the probe, alongside the borehole. The distance from the acoustic transmitter to the near receiver is 3 feet, and the distance between the near and far receiver is 1 foot. The elastic waves of 20 000 Hz frequency are transmitted in 15 Hz pulses. The measurement density along the borehole was 0.1 m. The sonic logging method was used in most of the core drilled holes and in some of the percussion drilled boreholes.

Radiometric methods

Radiometric methods measure either the natural radiation from the rock (natural gamma) or the attenuation of artificially emitted radiation (gamma-gamma and neutron), see Figure 6.5. The natural gamma method was used in almost all bore-holes in the Äspö HRL project, while the gamma-gamma and the neutron logging method were used in a selected number of boreholes. All measurements were performed with SGAB logging probes.

The chief sources of natural gamma radiation in the rock are potassium, uranium and thorium. Variations in the concentrations of these elements normally correspond to mineralogical changes in the rock, which can therefore be detected with the natural gamma method (also called the gamma method). The radiation detector in the probe is a 1.5 inch NaI crystal detector, with an energy band width from 300 keV to approximately 3 MeV. Readings are taken every 0.1 m along the borehole.

The gamma-gamma probe (or density probe) emit gamma rays of 660 keV from a 300 mCi Cs-137 source. The attenuation of gamma rays is mainly dependent on the electron density. The reduction in gamma ray intensity through the rock, close to the borehole wall, measured with a GeigerMuller tube, is considered to be proportional to the bulk density of the formation. The logging is performed by taking measurements every 0.1 m along the borehole.

The other active radiometric method used is the neutronneutron (or neutron) method. The probe contains a 5 Ci Am-241 source which emits high energy neutrons into the formation. Two He^3 detectors positioned within 0.5 m of the source measure the amount of thermal neutrons. The method measures the hydrogen content in the formation, normally reflecting the porosity of the rock, since the pores are filled with water. The method is therefore also called porosity log. However, in crystalline rock, with normally very low porosity, the recordings are greatly affected by mafic minerals. Whether anomalies reflect the presence of such minerals or fracture porosity can be determined by combined interpretation with the gamma-gamma method. The measurement frequency along the borehole was 0.1 m.

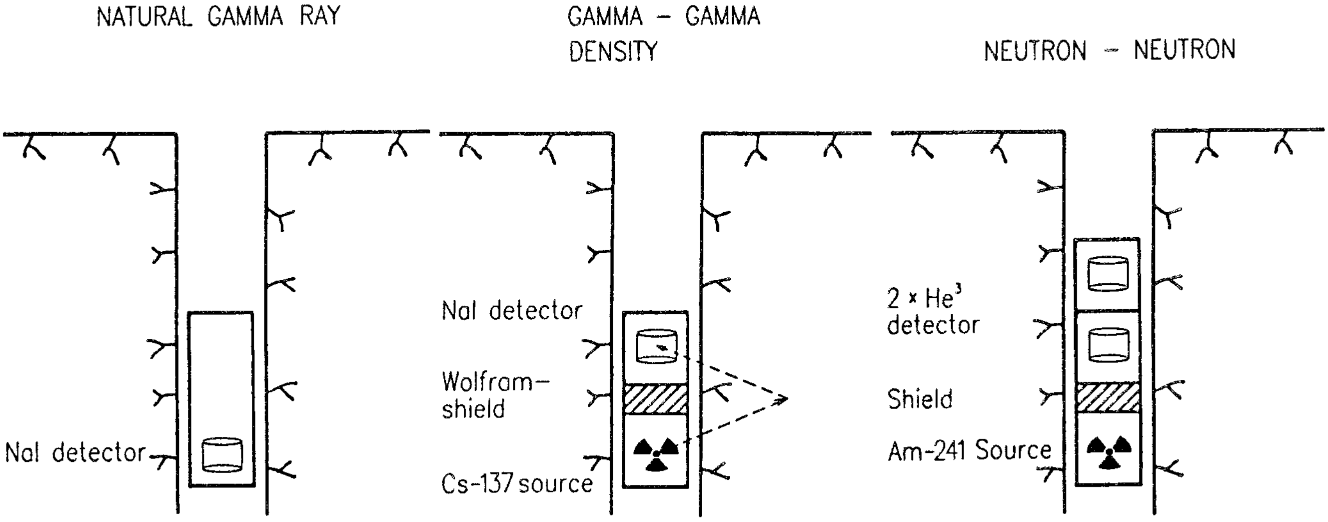


Figure 6.5 Illustration of the measuring principle for the natural gamma, gamma-gamma and neutron logging methods.

6.1.3 Data processing and presentation

The measurements with all the geophysical logging probes are performed from the surface data collection and control unit using the measurement software AQUIRE. Raw data recorded as volts, amperes, counts, etc are converted after calibration into real units such as Ohmm, microR/h, etc. For some of the methods the data processing also includes corrections for temperature, borehole diameter variations, fluid resistivity, etc.

The refined datafiles from the geophysical loggings are plotted in separate graphs presented side by side in so called composite logs, see Figure 6.6.

Some of the methods are selected for a combined computerized geophysical interpretation process. This procedure is based on the fact that some variations in the mineralogical composition of the rock types are not visible to the naked eye. But these variations can be detected by geophysical methods, especially combined interpretation by several methods. This kind of interpretation has proved to be very helpful in conjunction with core logging, since it provides a tool for classifying the surveyed rock types into two or several subgroups /Sehlstedt and Stråhle,1989/, /Sehlstedt et al, 1990/.

6.2 Borehole radar

6.2.1 General

Borehole radar is one of the very few investigation techniques that can be used to characterize the rock mass far away from the borehole. Borehole radar measurements can be performed in the single-hole reflection mode or as cross-hole measurements using reflection or tomographic methodology.

The principle of the borehole radar method is, as for other radar applications, that emitted radar waves will be absorbed and/or reflected in the bedrock, depending on the electrical character of the rock. Anomalous features such as rock boundaries, dikes, fracture zones, cavities etc are structures which can normally be surveyed with the method. Using radar frequencies between 10 and 100 MHz, structures have been detected up to a distance of 150 m from a borehole, in granitic rock. However, as the attenuation of radar waves very much depends on the resistivity of the measured media, penetration lengths vary a great deal for different rock types. The porosity, water content and resistivity of the water are also very important factors. High salinity of the groundwater, can reduce the surveying distance to some twenty or thirty metres for single-hole measurements. For cross-hole measurements, the waves only have to travel the distance once, so the surveying distance is nearly twice, that in single-hole measurements.

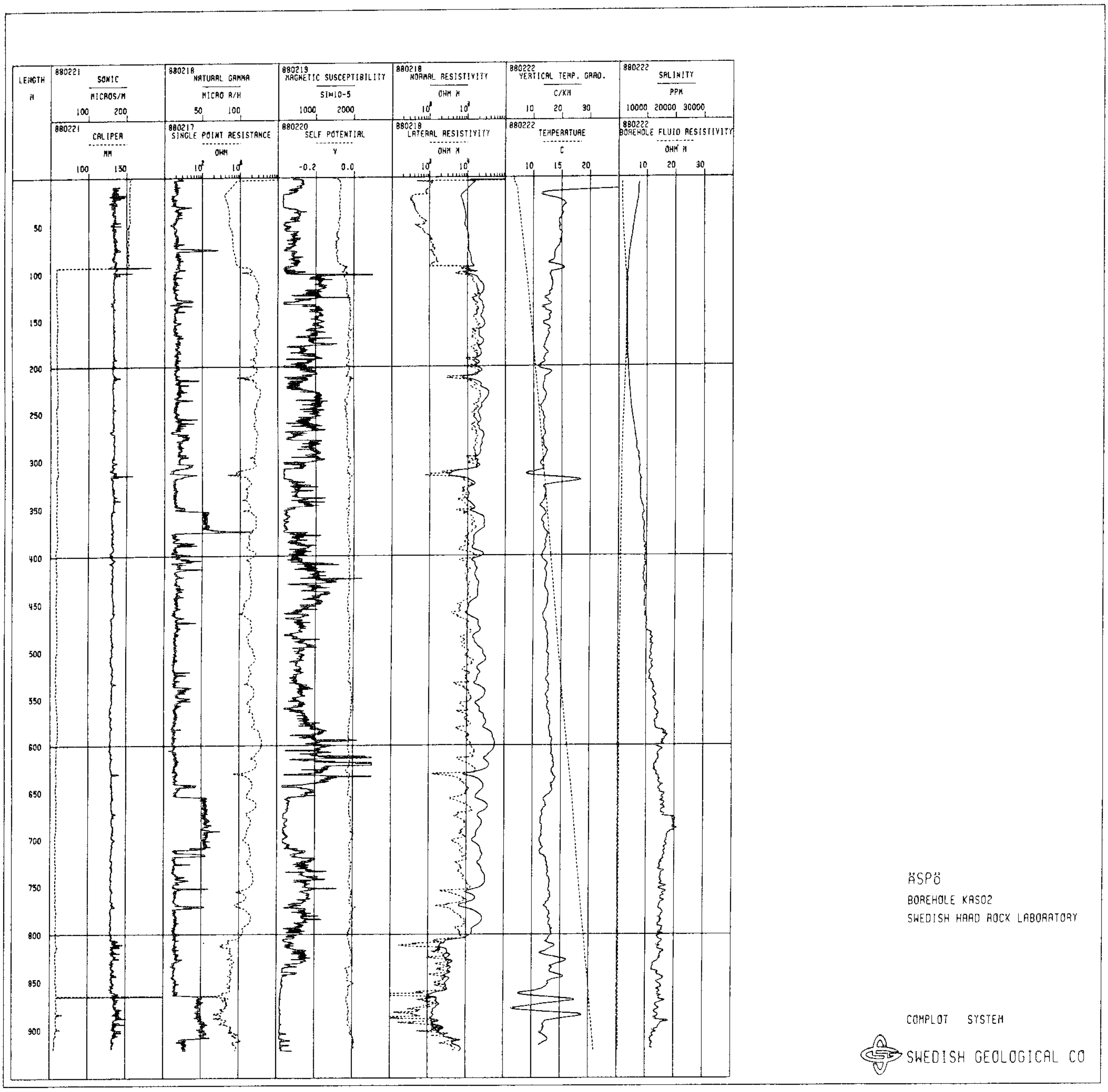


Figure 6.6 *Composite log for the geophysical loggings performed in borehole KAS02.*

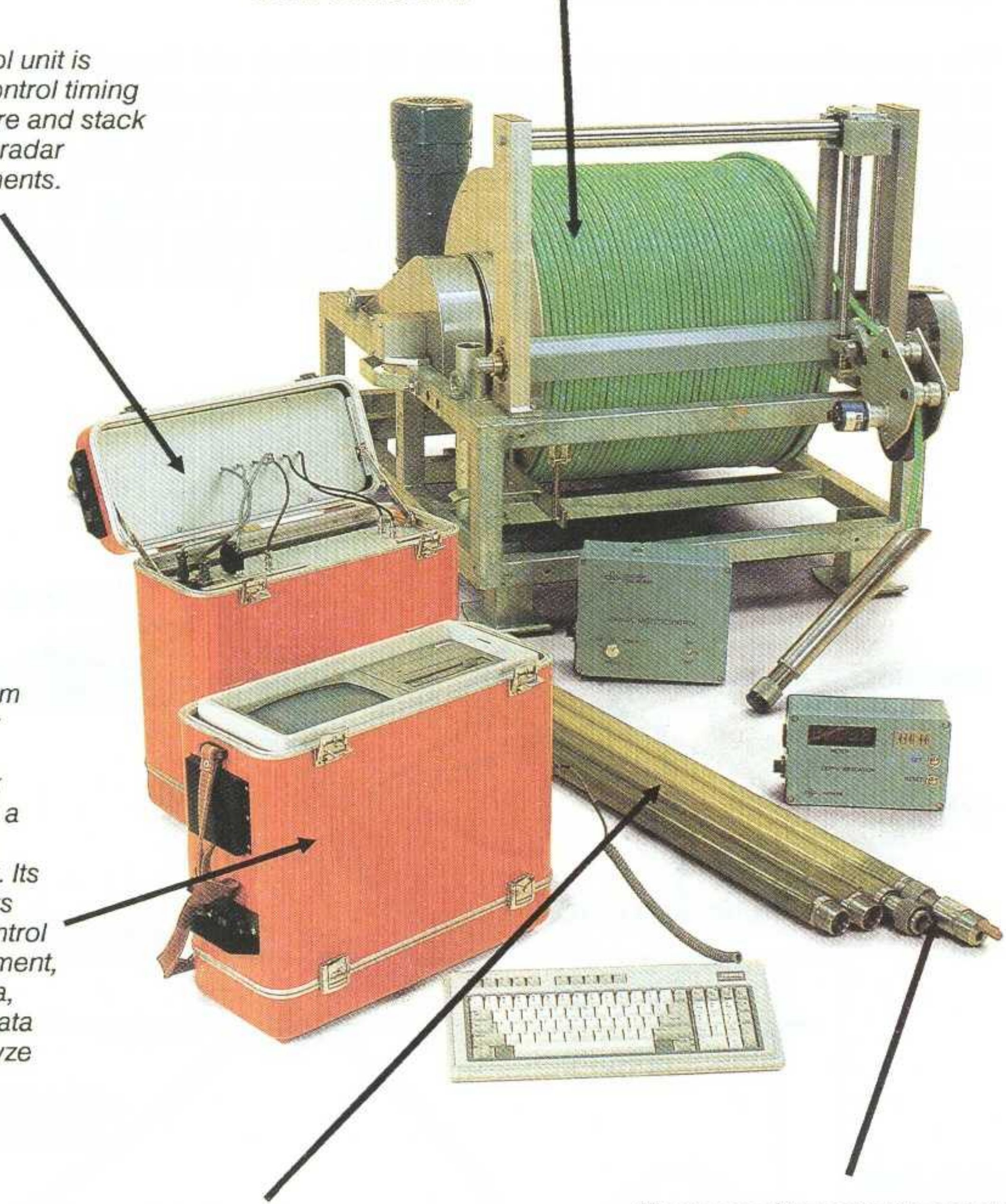
6.2.2 The RAMAC system

The borehole radar technique and its application to characterization of crystalline rock was initially developed within the framework of the International, OECD/NEA, Stripa Project. Subsequently, working for SKB, the Swedish Geological Company (SGAB) and ABEM adopted the technique for field work on a production basis by devising the RAMAC system /Olsson et al, 1989/. Still, the system is continuously undergoing improvements with regard to hardware and software for operation and interpretation.

The RAMAC system is a short pulse radar system, which for borehole measurements consists of the parts as shown in Figure 6.7. Technical specifications are as follows:

*	General	
	- Frequency range	10-80 MHz
	- Performance factor	150 dB
	- Sampling time accuracy	1 ns
	- Maximum optical fibre length	1000 m
	- Maximum operating pressure	100 Bar
	- Minimum borehole diameter	56 mm
*	Transmitter	
	- Peak power	500 W
	- Operating time	10 h
*	Receiver	
	- Bandwidth	10-200 MHz
	- A/D converter	16 bit
	- Least significant bit at antenna terminals	1 μV
	- Data transmission rate	1.2 MB
	- Operating time	10 h
*	Control unit	
	- Microprocessor	RCA 1806
	- Clock frequency	5 MHz
	- Pulse repetition frequency	43.1 kHz
	- Sampling frequency	30-1000 MHz
	- No of samples	256-4096
	- No of stacks	1-32767
	- Time window	20-11 μs

Two further developments of major importance have taken place, the directional antenna /Stripa Project report, in preparation/ and the tunnel and surface antenna /Falk, 1991/. The directional antenna has now been incorporated on a production basis, while the surface/tunnel antennas will be adapted to the RAMAC system in the near future. The complete RAMAC system permits a variety of test configurations for transmission measurements, such as borehole to borehole, borehole to ground surface, borehole to tunnel, etc.



Motor-driven winch for optical fiber cable. Two fiber links transmit the trigger signals and the timing information used in the sampling process. One link is used to transmit digital data from the receiver probe to the control unit.

The control unit is used to control timing and to store and stack individual radar measurements.

The system computer has one 5.25" disk drive and a 20 Mbyte hard disk. Its main tasks are to control measurement, store data, display data and analyze signals.

The receiver antenna detects and digitizes radar pulses. Data is then transmitted in serial form to the surface at a rate of 1.2 Mbits/s. The entire conversion and transmission sequence takes about 20 μs.

The transmitter antenna generates short radar pulses. When a trigger pulse is received the transmitter antenna discharges its transmission line, thereby creating a radar pulse about 10 ns wide.

Figure 6.7 The RAMAC borehole radar system.

6.2.3 Radar measurement methodology

Single-hole measurements

Single-hole radar measurements are carried out as reflection measurements, with the transmitter and the receiver separated by glass-fibre rods. In order to obtain good resolution close to the borehole, the separation is made as small as possible, which for crystalline rock is 5 to 15 meters.

The transmitter-receiver array is moved along the borehole and measurements are made at fixed intervals, normally 0.5 or 1 meter, see Figure 6.8. At each measuring point the radar wave travel time, from the transmitter to the receiver, is recorded and displayed on a special diagram (radargram). The radargram is interpreted regarding type of reflectors (rock structures) and directions of the reflectors, by knowing the wave propagation velocity. The velocity can be determined by Vertical Radar Profiling (VRP) measurements, i e the transmitter is kept at a fixed position at the ground surface while the receiver is moved in the borehole.

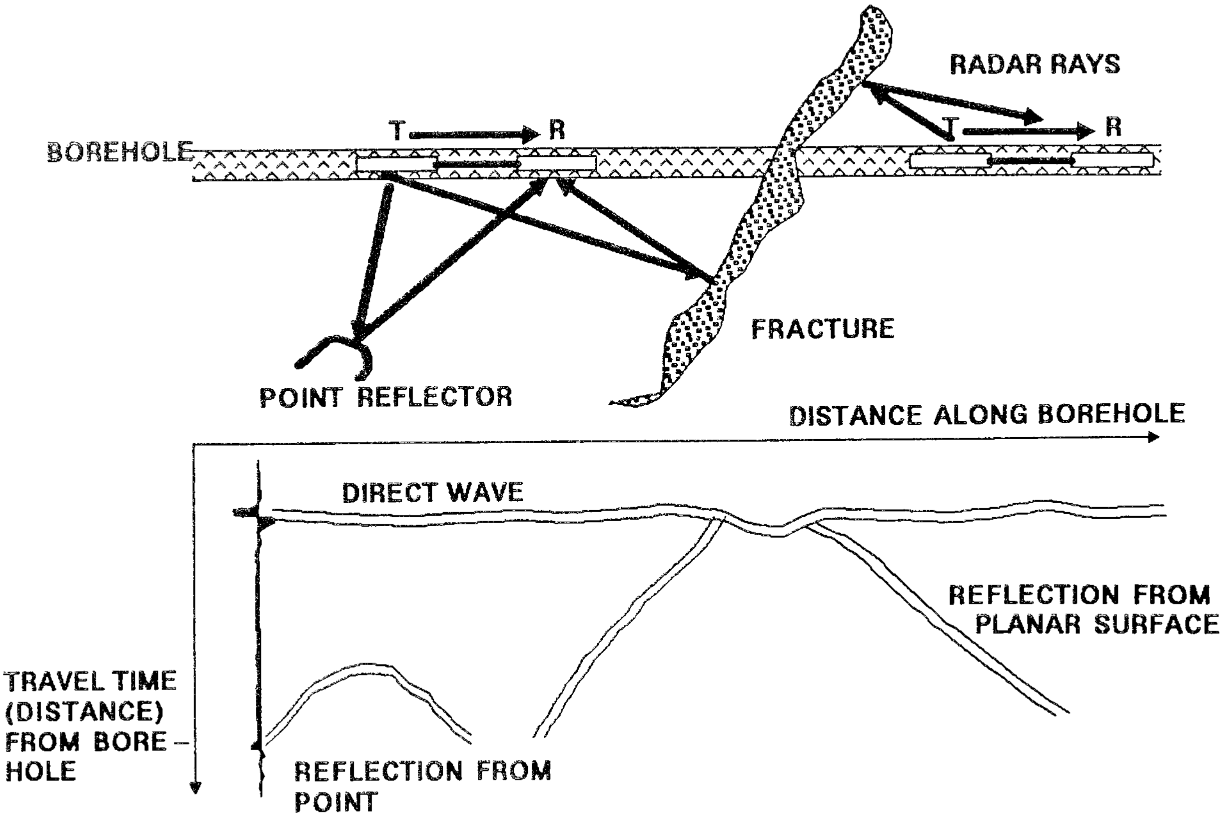
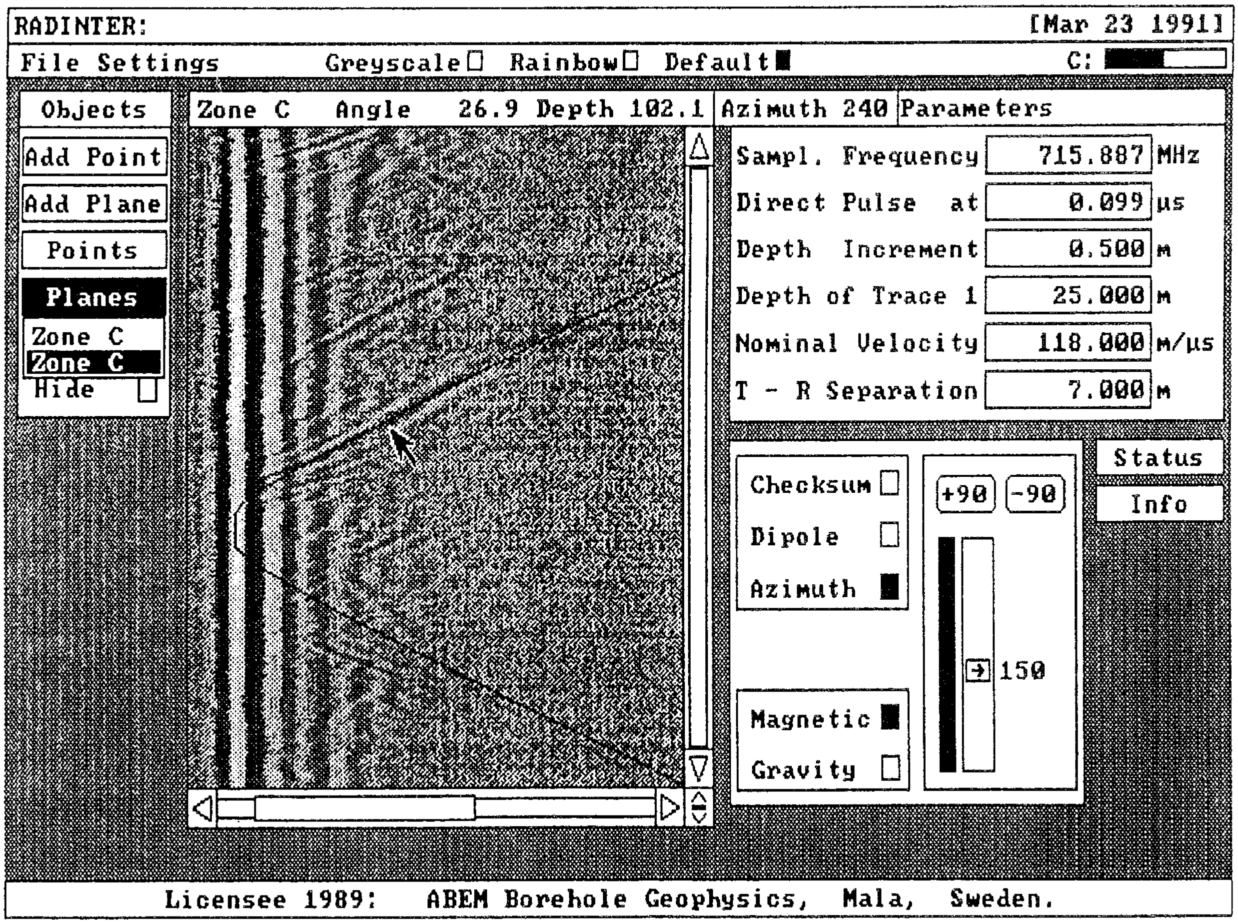


Figure 6.8 The measuring principle for single-hole reflection measurements with the borehole radar.

With normal dipole antennas the radar image is omni-directionally symmetric. Hence, it is possible to determine the angle of intersection between the borehole and a fracture plane, but the complete orientation of the plane cannot be determined. For that purpose, information must be combined from two or more boreholes.

With directional antennas, the receiver also detects two perpendicular components of the radar waves. The measurement procedure is therefore the same as for the dipole antennas, while the interpretation includes a comprehensive processing of the measured signals in order to extract directional signals for any direction around the borehole, see Figure 6.9. By identifying the direction for minimum or maximum of a particular reflector, an absolute orientation of the reflector can be determined from one single-hole measurement.



Zone C Angle 26.9 Depth 102.1

Azimuth 240

Parameters

Sampl. Frequency 715.887 MHz
Direct Pulse at 0.099 µs
Depth Increment 0.500 m
Depth of Trace 1 25.000 m
Nominal Velocity 118.000 m/µs
T - R Separation 7.000 m

Licensee 1989: ABEM Borehole Geophysics, Mala, Sweden.

Figure 6.9 Interpretation of the direction of radar reflectors on radargrams from single-hole reflection measurements with directional antenna.

In the pre-investigation phase of the Äspö Hard Rock Laboratory project, single-hole measurements were performed in most of the cored holes and in a few percussion-drilled holes /Niva and Gabriel, 1988/, /Carlsten, 1989/, /Carlsten, 1990/, see Figure 6.10. Three of the cored holes were investigated with the directional antennas.

In addition, a surface radar profile has been carried out using a prototype of the surface antennas /Sandberg et al, 1989/. The measuring and interpretation procedures for the surface measurements were basically the same as for borehole dipole measurements.

Crosshole measurements

Crosshole radar measurements can be carried out either as reflection measurements or as tomographic measurements.

Reflection measurements aim at detecting rock structures between and away from the boreholes, while tomographic measurements survey in detail the plane between the boreholes, with regard to attenuation and velocity. The separation of measuring points in tomographic surveys is normally 4-5 metres, for both transmitter and receiver. This means that a very large number of rays can be handled in the tomographic interpretation technique /Olsson et al, 1987/.

No crosshole measurement was carried out during the pre-investigation phase of the Äspö Hard Rock Laboratory.

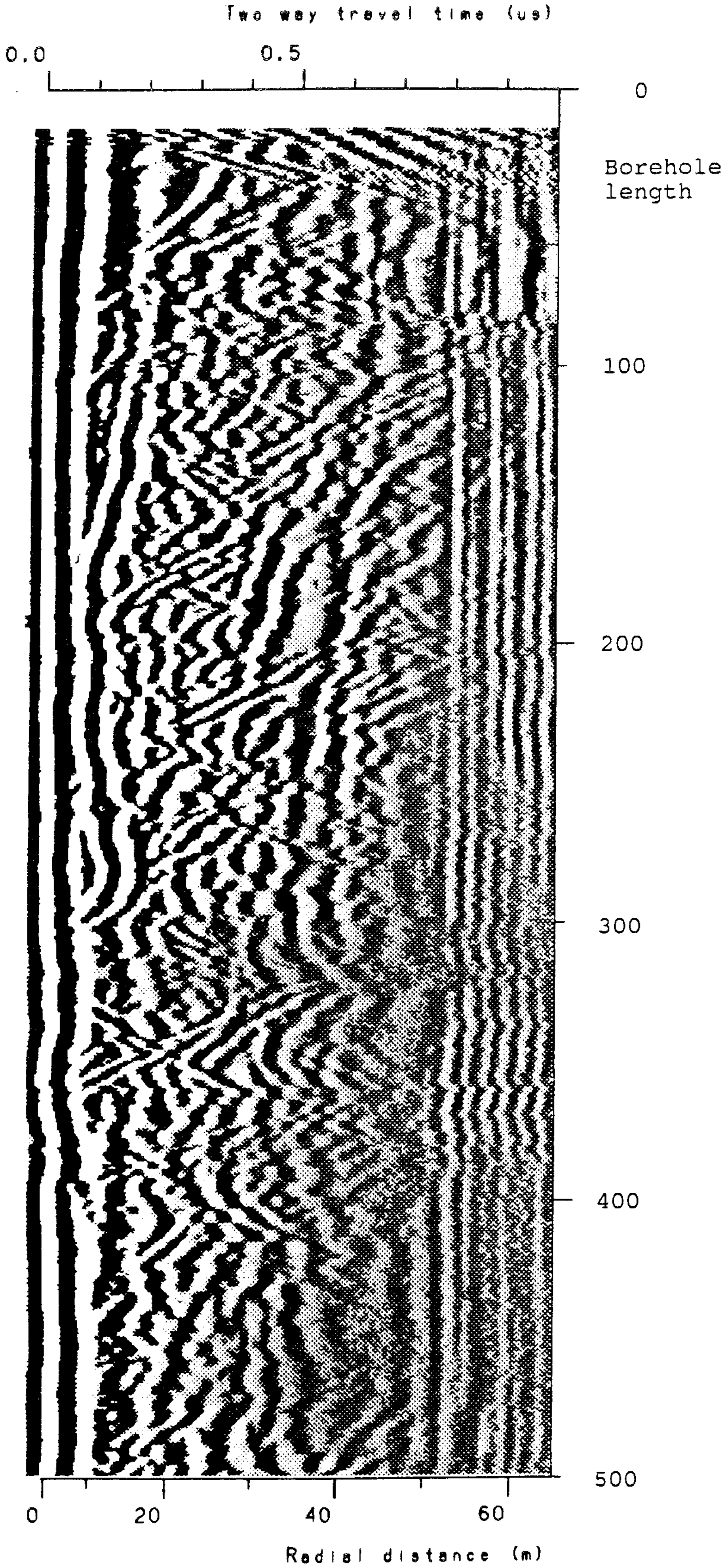


Figure 6.10 Radar reflection map (radargram) from borehole KAS02.

Special application of borehole radar

As noted earlier, the radar method is sensitive to the resistivity of the rock mass. The salinity of the pore water is therefore a parameter of interest, which can be used in special experiments.

Detected radar reflectors often represent fracture zones which can be regarded as potential water conductors. However, fracture zones and single fractures can be open, closed or partly open for water transport. These conditions are more or less impossible to detect directly from the radar image, as well as by other measurements. Introducing saline water into the fracture zone changes the resistivity, and therefore also the attenuation of the radar wave. By means of tomographic measurements before and during the saline injection and by developing a differential tomogram for the fracture zone, the water conducting parts of the fracture zone can be determined /Andersson et al 1989/.

6.3 Televiewer logging

Determination of fracture orientation in boreholes can be done by several measuring methods, all of which have advantages and disadvantages. Some methods orient the drill core by marking it during drilling. Other methods, such as borehole televiewer and borehole TV, measure the fractures at the borehole wall.

The borehole televiewer is an investigation tool that uses acoustic signals to detect the structure of the borehole wall, enabling the fracture orientation in the borehole to be measured. In the televiewer probe an acoustic source rotates perpendicular to the borehole axis, scanning the borehole wall while slowly moving along the borehole, see Figure 6.11. The amplitude of the reflected

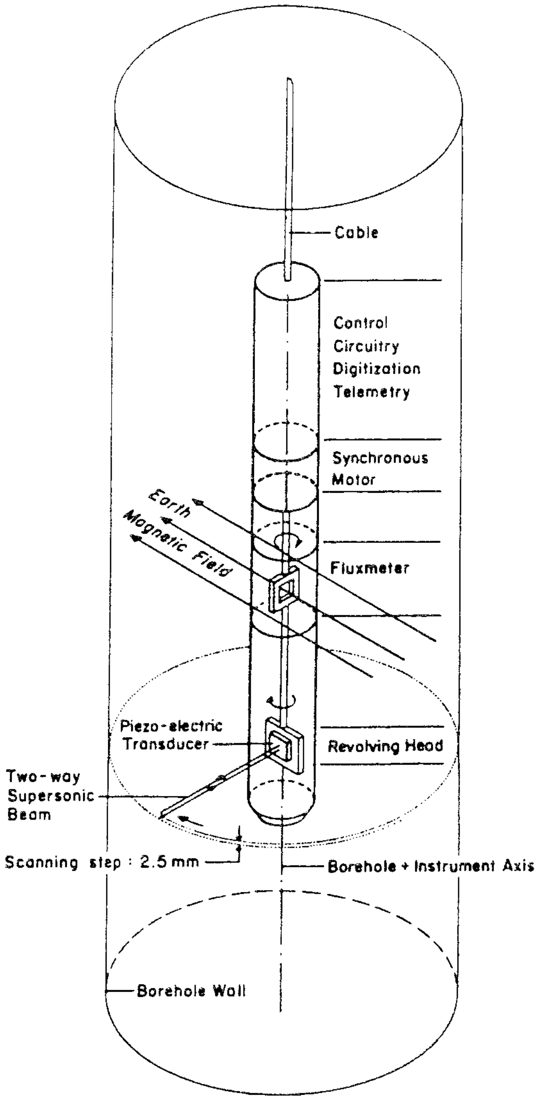


Figure 6.11 The principle of an acoustic televiewer logging probe.

acoustic signal provides information on discontinuities on the borehole wall, such as fractures, which reduce the amplitude. The probe also includes an orientation device to orient the survey. The measurements are displayed on a screen or paper print-out as an image of the borehole wall. The image is split vertically, preferably along the north axis in vertical boreholes. On the image a fracture is represented as a sinusoidal curve. The dip and dip angle (in relation to the borehole direction) are easily determined from the direction and peak-to-peak amplitude of the curve, see Figure 6.12.

For high quality results from a televiewer survey the tool must be exactly centred in the borehole.

During the pre-investigation phase of the Äspö Hard Rock Laboratory project two cored boreholes were televiewer-logged, one of which was 76 mm and the other 56 mm in diameter /Fridh and Stråhle, 1989/. The survey was performed by means of two different instruments, with specifications as follows:

The WBK SABIS tool used in the 56 mm borehole

- Outside diameter: 46 mm
- Rotation rate: 3 per second
  - 128 short pulses per revolution
- Flux gate magnetometer
- Down-hole microprocessor
  - 12 bit A/D for amplitude and orientation
- Cable length: 5 000 m
  - Transmission speed to surface recorder: 64 kbits per second

The WBK system TV 3 televiewer, used in the 76 mm borehole

- Outside diameter
  - small-diameter hole tool: 60 mm
  - standard tool: 88 mm
- Rotation rate: 12 per second
- Acoustic beam focusing technique
- For absolute orientation an additional orientation tool must be run simultaneously

The mean logging velocity for the SABIS tool was 0.7 m/min for a 500 m logging interval in the 56 mm borehole. The surveying speed for the WBK TV 3 tool in the 56 mm borehole was approximately the same.

The recording unit communicates with the borehole tool, receiving data and simultaneously reformatting for output to a grey-scale recorder and to a color image display system, and finally storing the data on tape.

Further processing of data is done in a VAX computer.

The results from the acoustic televiewer data were used in combination with the core logging data. Drill cores which core logging had given relative orientations along sections were given true orientations by determination of the direction of certain distinct fractures along the section with the televiewer.

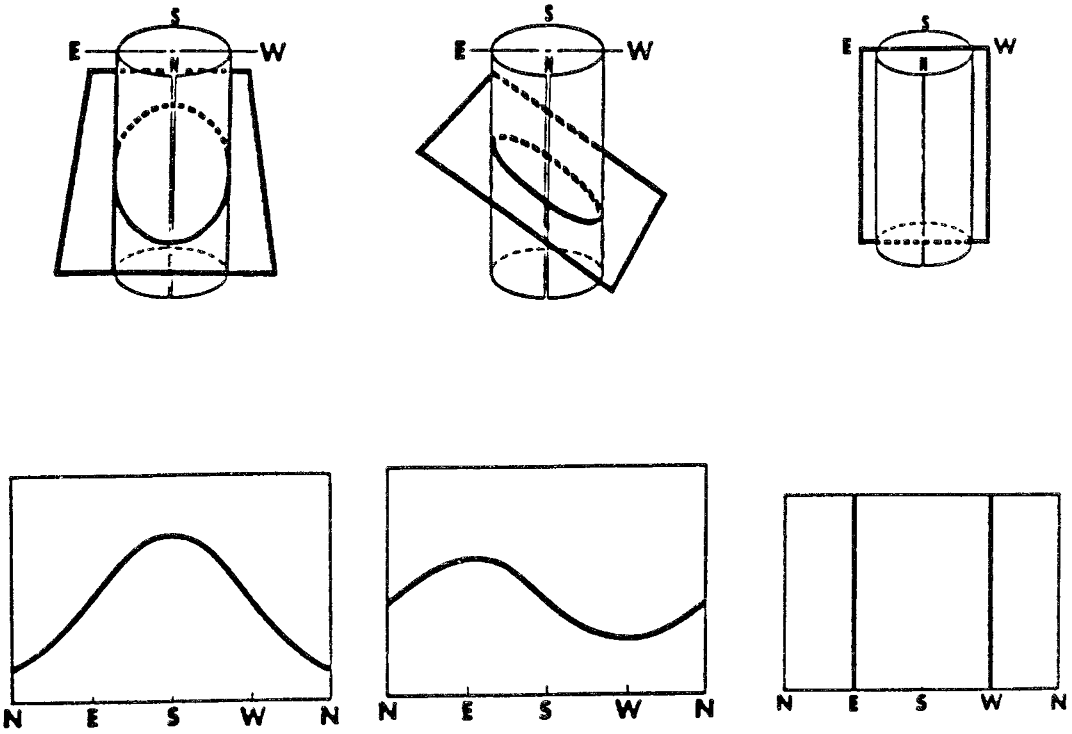


Figure 6.12 Illustration of how fractures or structures running in different directions will be registered on a televiewer image.

6.4. Borehole TV

Like the Televiewer method, the borehole TV is often used for orienting fractures in the borehole. However, TV logging of a borehole can be used for other purposes as well, such as inspection of the borehole condition and during fishing operations if equipment has been lost in the hole. One advantage of borehole TV is that it provides a real image of the borehole and the borehole wall from which other features such as cavities, minerals etc can be detected. On the other hand, disadvantages such as sensitivity to dirty water in the borehole and relatively time consuming interpretation of fracture orientation reduce the usefulness of the TV method as an orientation tool.

There are many types of borehole TV systems, monochrome or colour, with different kinds of optics, wide angle lenses or use of prismas or mirrors, for different hole diameters and borehole depths. There is also a point scanning system and systems that present a 0-360° image of the borehole wall on the screen. The great advantage of such a system is that interpretation of fracture orientations is easy to perform. However, these borehole TV cameras have diameters larger than 56 mm and cannot be used in most of the boreholes in the Äspö HRL project.

Borehole TV inspections have been carried out in a few of the cored boreholes at Äspö /Stråhle 1989/. Two different borehole TV systems have been used, Rees borehole TV and a new borehole TV developed for SKB.

Rees borehole TV

The Rees borehole TV system can be used in 56 mm boreholes down to a depth of 500 m. The principal technical specifications are:

* Monochrome videocone camera
  - optics: wide angle lens, 11 mm, f 2.8-16
  - rotating mirror
  - remote focusing from surface
  - remote iris control from surface
  - remote lighting control from surface

* 41 mm diameter

* Cable bundle: coax and electrical wires
  - electrical video signal to surface

* Maximum depth 500 m

ABEM Borehole TV

In order to make TV logging possible in deeper boreholes, a new borehole TV system has been developed by ABEM, on behalf of SKB. The principal technical specifications of the system are, see Figure 6.13:

* Monochrome CCD camera
  - optics: wide angle lens, 48 mm, f max 1.8
  - fix focus
  - automatic iris control

* 51 mm diameter

* Cable bundle: optical fibre and electrical wires
  - opto-video signal to surface

* Maximum depth 1000 m

In order to orient the video image of the borehole it is necessary to know the orientation of the camera probe in the borehole. Therefore an orientation device is mounted in front of the camera lens. The orientation device includes a compass for use in vertical or near vertical boreholes and a waterfilled ring with an airbubble for indicating the rotation of the probe in inclined boreholes.

Interpretation of fracture orientation is done from the video screen. The work is rather time-consuming and is normally not used to orient all fractures. However, when relative orientation of fractures has been performed from the drill cores, along a certain length of core, only a few fractures have to be oriented from the TV image in order to provide a true orientation of that specific core section.

6.5 Vertical Seismic Profiling (VSP)

6.5.1 General

For rock characterization, several kinds of acoustic or seismic methods can be used at different stages of a site investigation programme. The general principle of acoustic methods is that the propagation of a seismic wave is a function of the elastic properties of the media. Anomalies of elasticity in a rock mass normally indicate an increased degree of fracturing. Acoustic methods determinate the travel velocity of a seismic wave, but the degree of attenuation of the wave amplitude is also used in some of the methods.

Examples of acoustic methods are surface methods such as refraction and reflection seismics, as described in section 3.3.6. Several borehole methods also employ the acoustic principle, such as sonic logging (section 6.1.2), televiewer (section 6.3) and tube wave, the latter not used in the Project and therefore not described in this report.

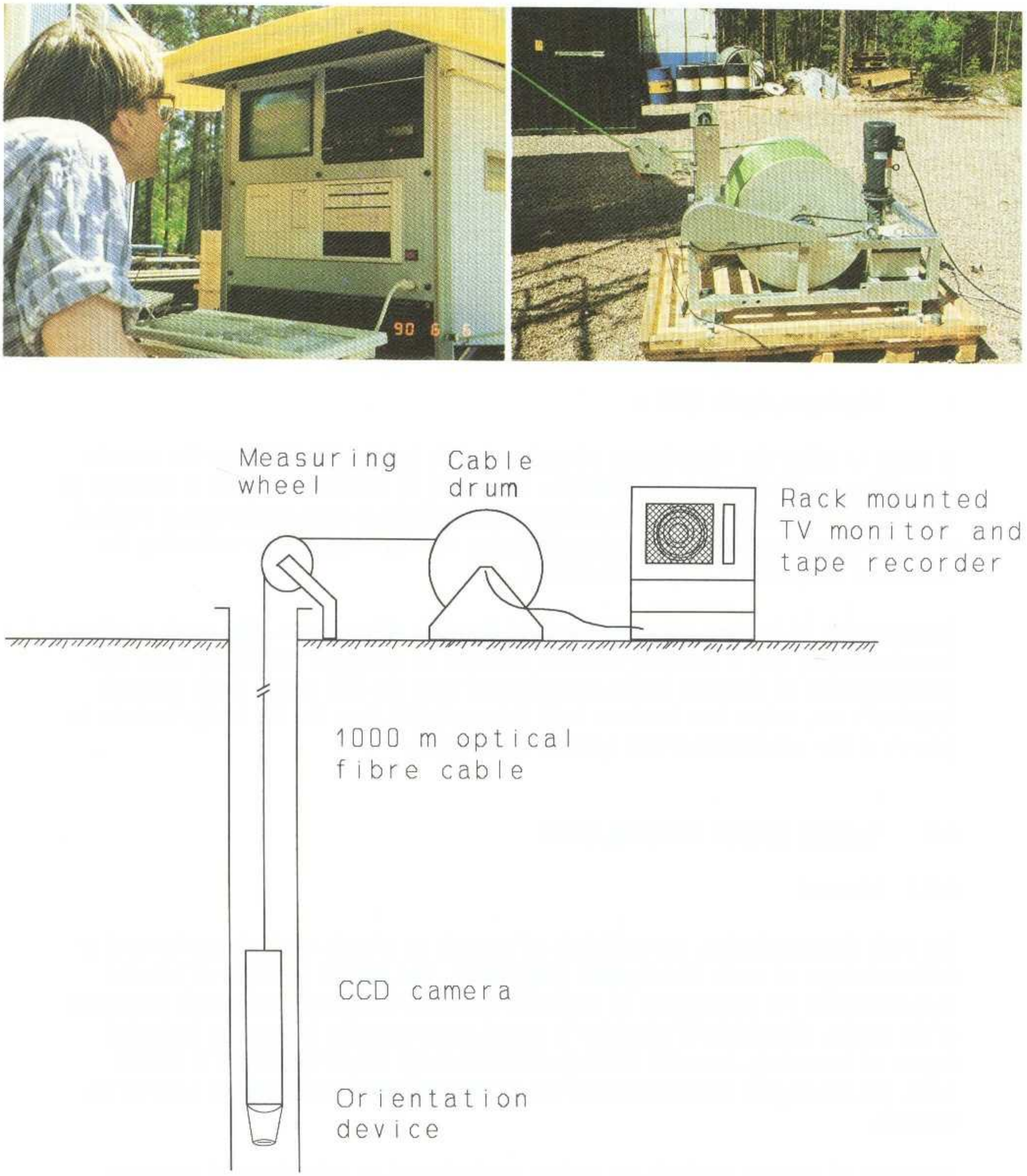


Figure 6.13 The ABEM borehole TV system.

However, the actual borehole seismic methods such as crosshole seismic and Vertical Seismic Profiling (VSP) are very important methods for characterizing structures in the rock mass far from a borehole or between boreholes.

Crosshole seismics can, like the previously described borehole radar method, be carried out as reflection measurements or as tomographic measurements. The VSP method was originally developed for use in combination with surface reflection seismics, in order to calibrate the identified seismic reflectors with results from seismic measurements in vertical boreholes penetrating the same reflectors. The method was mainly used to identify more or less horizontal layers in sedimentary rock.

The VSP method has now been further refined for use in crystalline rocks where more irregular structures are the normal case.

The only seismic borehole method used in the Äspö Hard Rock Laboratory project, is the VSP method. The VSP survey was carried out with the Vibrometric seismic system.

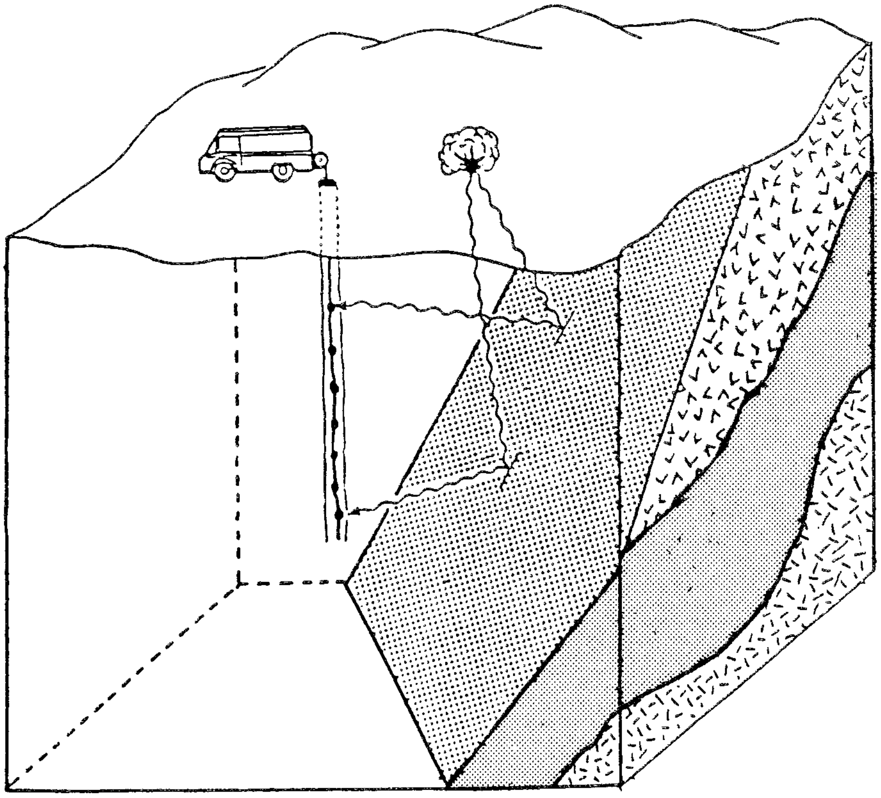


Figure 6.14 Schematic set-up of a VSP investigation.

6.5.2 The VSP method

The principle of Vertical Seismic Profiling is to emit seismic waves at the ground surface and record the waves when they arrive at a chain of detectors (geophones or hydrophones) in the borehole, see Figure 6.14. Different kinds of seismic waves will be recorded, P-wave, S-wave and Tube-wave, direct waves as well as waves which have been reflected against a fracture zone, a rock type boundary or other type of seismic reflector.

In the Äspö case, the VSP survey was carried out using five seismic source points distributed around the borehole /Cosma et al, 1990/. For each shot-point (an explosive charge was used as the source), at distances some ten meters from the borehole, a seismic profile along the borehole was plotted. As the detector chain included 10 geophones with five metres separation, each shot resulted in a record covering 50 m of the borehole. For a complete VSP profile a couple of records must be taken, lowering the geophone chain after each shot. The explosive charge used in the 1-2 m deep shot-point holes was thirty to sixty grams of dynamite.

The data acquisition and processing unit used was a multichannel A/D conversion module operated by a microcomputer, prepared for field operation conditions. Some technical specifications are summarized below:

* A/D resolution: 12 bits

* Channels (max.): 32

* Max. sampling speed (32 channels)
- 62.5 samples per microsecond

* Triggering: inductive coupling between detonation circuit and trigger circuit

* Stacking: when signal/noise ratio is poor

* Data storage: hard disc and cassette back-up

* CRT-monitor: displays seismograms after each shot

* Preliminary processing for data quality check performed in the field

Processing

In order to evaluate a data set of VSP records a number of processing steps will be carried out. The first step, preconditioning, includes filtering of the signals in order to exclude most of the Tube waves. Further processing will suppress the direct P waves from the seismogram.

An exclusive processing technique, Image Space Processing, is used to enhance the reflected signal and to estimate the strength and position of the reflector, see Figure 6.15. It is not possible to independently determine both the dip and the strike of a reflector from one single seismogram. The purpose of using several shotpoints resulting in individual seismograms around a borehole is to obtain 3-dimensional directions of the seismic reflectors. However, the 3-D interpretation uses a large volume of data, which are handled with a special 3-D modelling program, which is an extension of Image Space Processing.

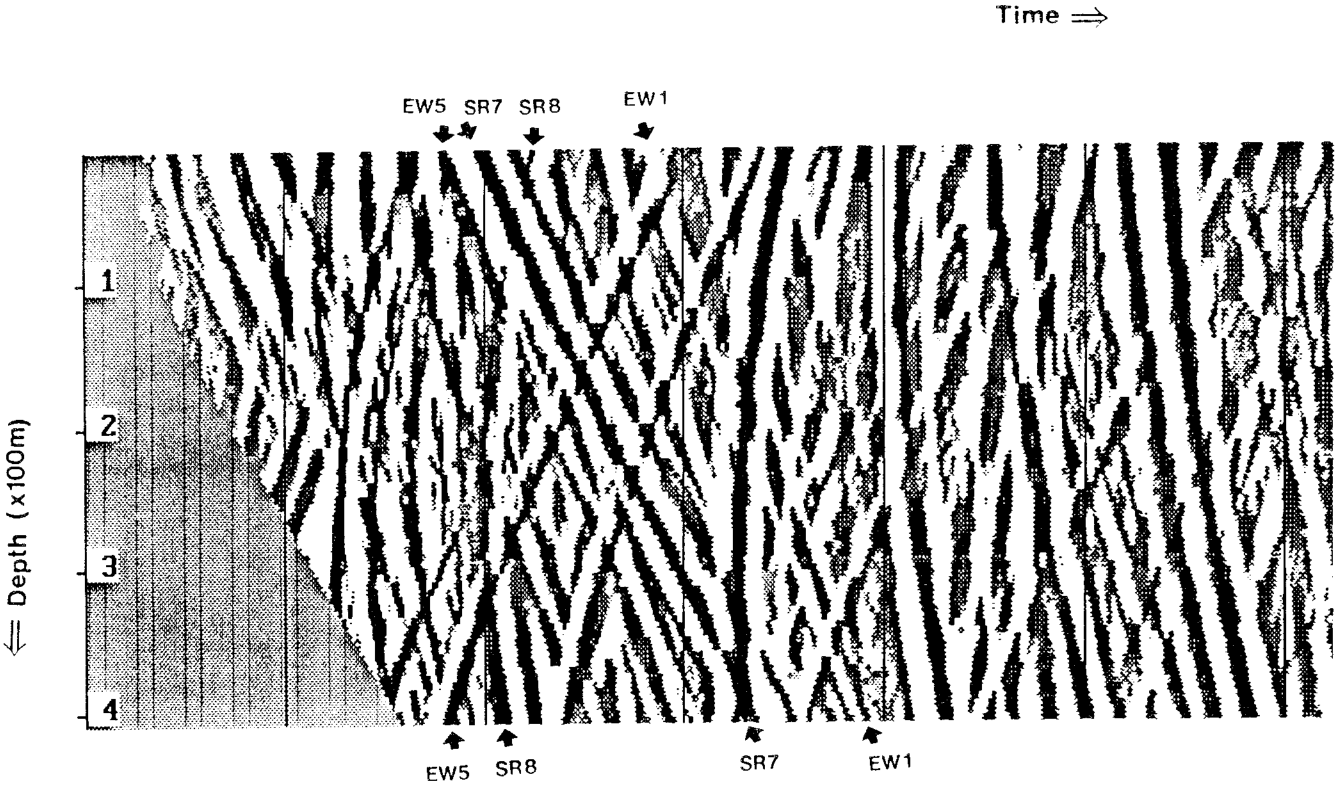


Figure 6.15 VSP-profile in KAS07 after data filtering and processing.

7. BOREHOLE HYDROLOGICAL INVESTIGATIONS

An extensive geohydrological testing program has been carried out within the Äspö Hard Rock Laboratory project. Different types of borehole investigations were performed at different stages of the Project. During the pre-investigation phase a number of single borehole tests were used for the determination of hydraulic parameters such as the hydraulic conductivity, se Figure 7.1, while interference tests have been used as an important tool for the characterization of large volumes of rock and for the identification of geometry and character of hydraulic conductive structures, see Figure 7.2.

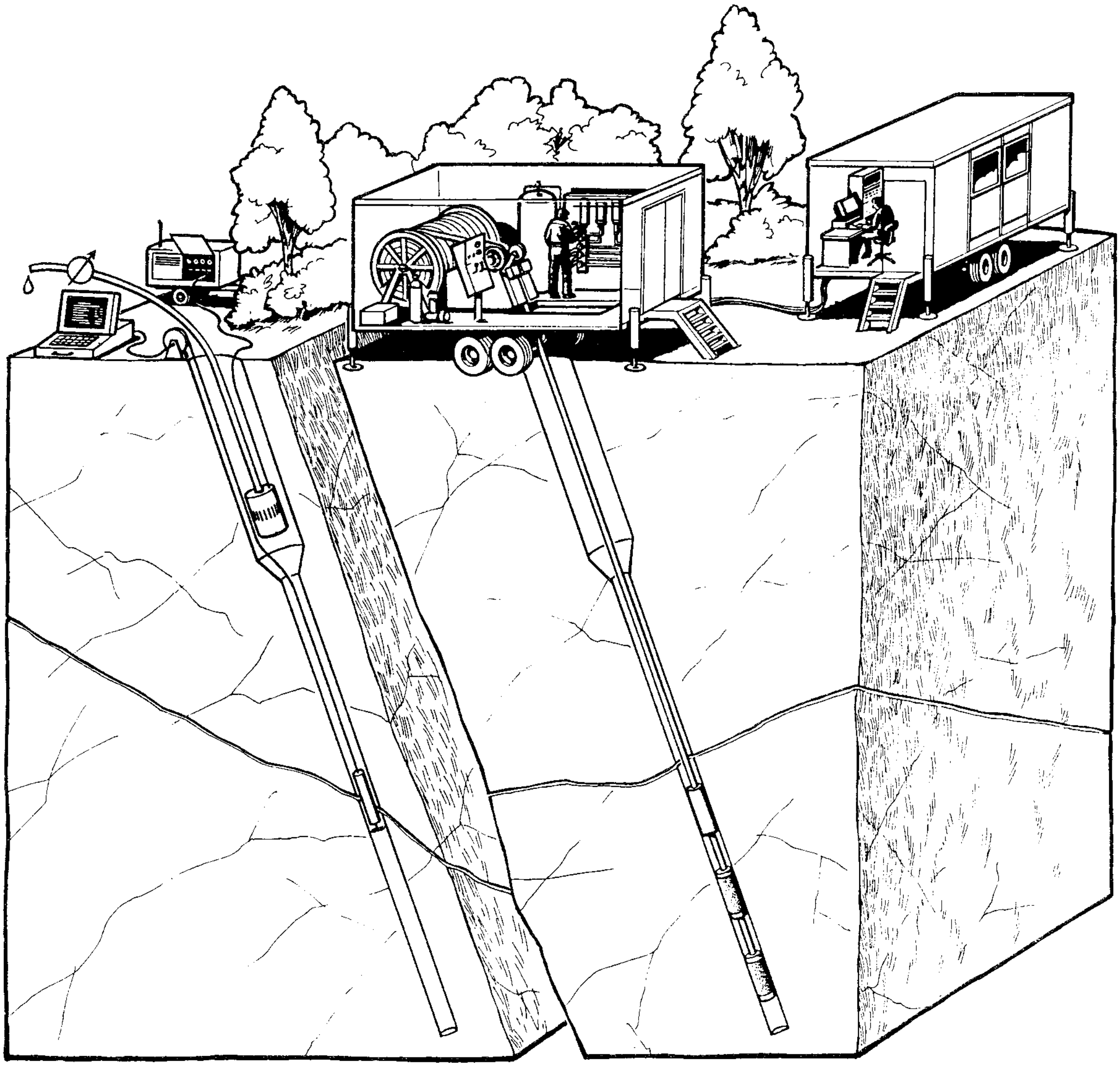


Figure 7.1 Illustration of flow-meter logging and hydraulic injection test, as single-hole hydraulic measuring methods.

This chapter will describe the methodology and instruments which have been used for the following hydrological measurements:

* Hydraulic test during drilling
* Pumping test
* Flow meter logging
* Hydraulic injection test
* Interference pumping test
* Long-term Pumping Test
* Dilution measurement
* Tracer test.

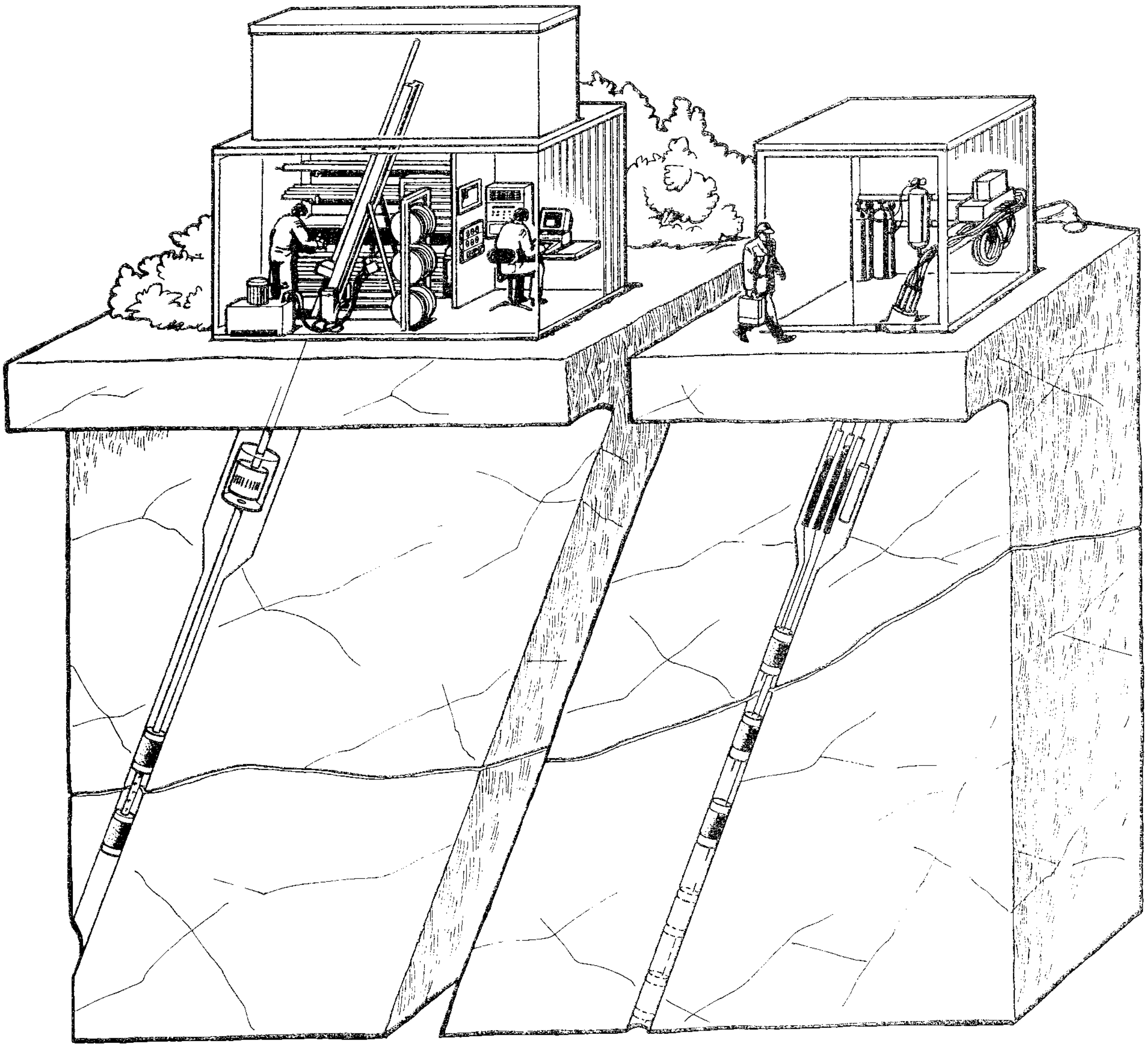


Figure 7.2 Interference pumping test, as an illustration of cross-hole hydraulic tests.

Techniques for monitoring groundwater pressures are separately described in chapter 8.

A huge ammount of data are collected during the hydrological investigations. Raw data are compiled and reported for each borehole /Borehole Reports/, from which hydrological parameters have been determined /Nilsson, 1987/, /Rhén, 1989/, /Nilsson, 1989/, /Nilsson, 1990/, /Rhén, 1990/, /Rhén 1991/.

7.1 Hydraulic testing during drilling

In an extensive drilling and investigation campaign, measuring data collected at an early stage are of great value for the further detailed planning and implementation of the project. For such a flexible programme the chain of measuring - data processing - interpretation - feedback into programme, must be rapid and strictly controlled in order to make use of these kinds of data. A successful project of this kind also requires an efficient project organization in order not to get bogged down in the decision making procedure. Measurement during drilling is an example of such a useful tool which was routinely empoyed in the Äspö Hard Rock Laboratory Project. Hydraulic tests during drilling were conducted in percussion drilled holes as well as in cored holes. Early data from these measurements were used not only as preliminary data, but also in the final interpretation of whether hydraulic parameters are representative for the characterization of the formation on the 100 m scale.

The hydraulic tests during drilling were carried out as air-lift pumping tests, with subsequent measurements of the recovery of the groundwater level /Rhén, 1991/. The air-lift pumping was done during a period of a few hours with approximately constant flow rate. After pumping was stopped, recovery was recorded as a function of time over a period of a few hours. The tests were normally performed in 100 m intervals of the borehole during interruptions in the drilling. The specific methodology used in percussion drilled holes and cored holes is described below. When other nearby boreholes were available for water level observations, such measurements were made according to methodology as described in chapter 8.

7.1.1 Methodology in percussion-drilled holes

For the percussion-drilled holes there is no need for any special arrangements to carry out the air-lift pumping, since airflow is normally used to discharge the cuttings and water from the borehole while drilling. After drilling of a certain borehole length, air-flushing continues for a while. After air-lift pumping is finished, the groundwater level in the hole is manually recorded during the recovery period by means of soundings, see Figure 4.2. In the percussion- drilled boreholes holes in the Äspö HRL Project, which are normally 100-150 m deep (in some cases 200 m), two tests were usually performed, one at half the drilling depth and the other one when the drilling was finished.

7.1.2 Methodology in cored holes

In the cored holes the first hydraulic test was performed after reaming-up to 155 mm diameter of the uppermost 100 m of the telescope-type borehole (described in section 4.2.2) had been carried out. This test is similar to the test performed during drilling in the percussion drilled holes described above.

In the deeper parts of the telescope-type borehole, the hydraulic tests were performed during interruptions about every 100 m of drilling length. The borehole interval drilled since the previous interruption was then tested using a borehole tool consisting of a packer and a down-hole valve, lowered down on the drill string. The packer was inflated with water by pressurizing the drill string. The test section was hydraulically connected to the water column in the drill string by means of the downhole valve, operated by slight movement of the drill string. Air tubing lowered 60-80 m into the drill string and then connected to an air compressor was used to conduct air-lift pumping from the drill string and hence also from the packed-off section, see Figure 7.3. The water level was recorded by means of manual sounding in a separate stand pipe, also lowered into the drill string. Readings were made before start of air-lift pumping (giving static pressure level in the section), during pumping and finally during the recovery period after the end of pumping, see Figure 7.4.

The length of the pumping period was normally determined by the time needed for water sampling, performed in conjunction with the pumping. The criterion was that at least the volume of water contained in the drill pipe and in the test section must be discharged before a water sample was accepted as being representative for the test section. Normally, the pumping took 6 hours and the entire test cycle 12 hours.

7.2 Pumping test

Pumping tests in cored holes

Immediately after the drilling of a core borehole was completed, a pumping test was performed. There are at least two reasons for this pumping:

- cleaning out the borehole
- hydraulic testing of the entire borehole.

Moreover, pumping is necessary for flow-meter logging along the borehole, as described in section 7.3.

A pumping test was carried out over a period of two days in order to clean out the borehole and the surrounding formation (especially the waterbearing fractures and fracture zones penetrated by the borehole) from any remaining drilling water and cuttings, and to obtain hydraulic data for calculating the total transmissivity of the borehole.

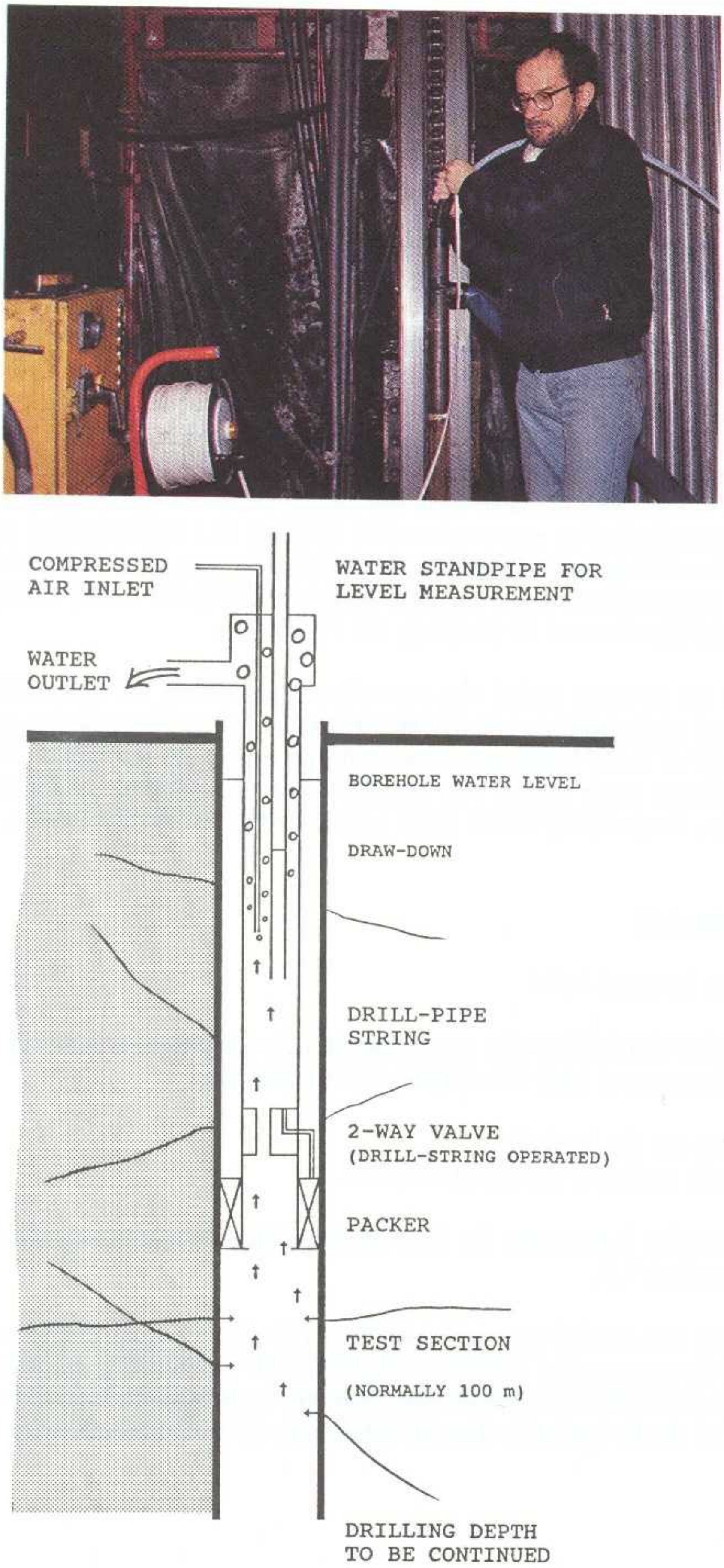


Figure 7.3 *Air-lift pumping carried out in conjunction with core drilling.*

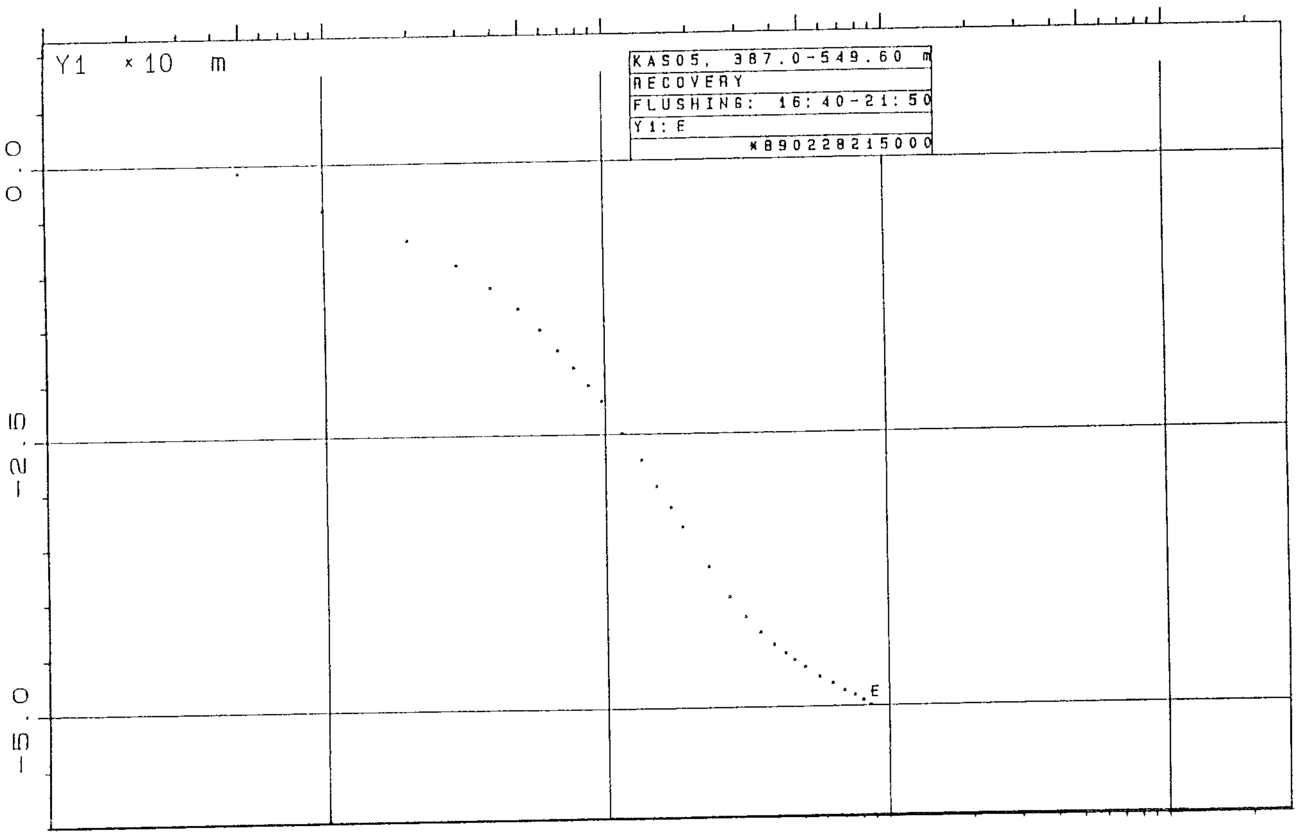


Figure 7.4 *Graph showing pressure recovery after air-lift pumping in a cored borehole.*

Due to the telescope-type borehole design it was possible to perform this test as a conventional pumping test. An electrical submersible pump was used and positioned at a depth of approximately 70-90 m in the borehole. The water level was measured with a pressure transducer in the borehole and recorded on a data logger, see Figure 7.5. In order to obtain good cleaning of the borehole, a high pumping rate (large draw-down) was desired. The flow rate was kept constant during the pumping period. After the pumping was completed, the recovery of the water level in the borehole was also recorded /Rhén, 1991/.

In a few of the boreholes, where the water capacity was extraordinary high, these pumping tests was carried out by means of airlift pumping.

This type of pumping test is regarded as a single hole hydraulic test, in contrast to the interference pumping test and Long-term Pumping Test (described in sections 7.5 and 7.6, respectively), which are carried out as interference tests. However, when surrounding boreholes were available, and especially when these boreholes were packed-off with packers and equipped with monitoring instruments (see section 8.2), groundwater head changes in these sections were recorded in order to obtain supplementary information from the pumping test.

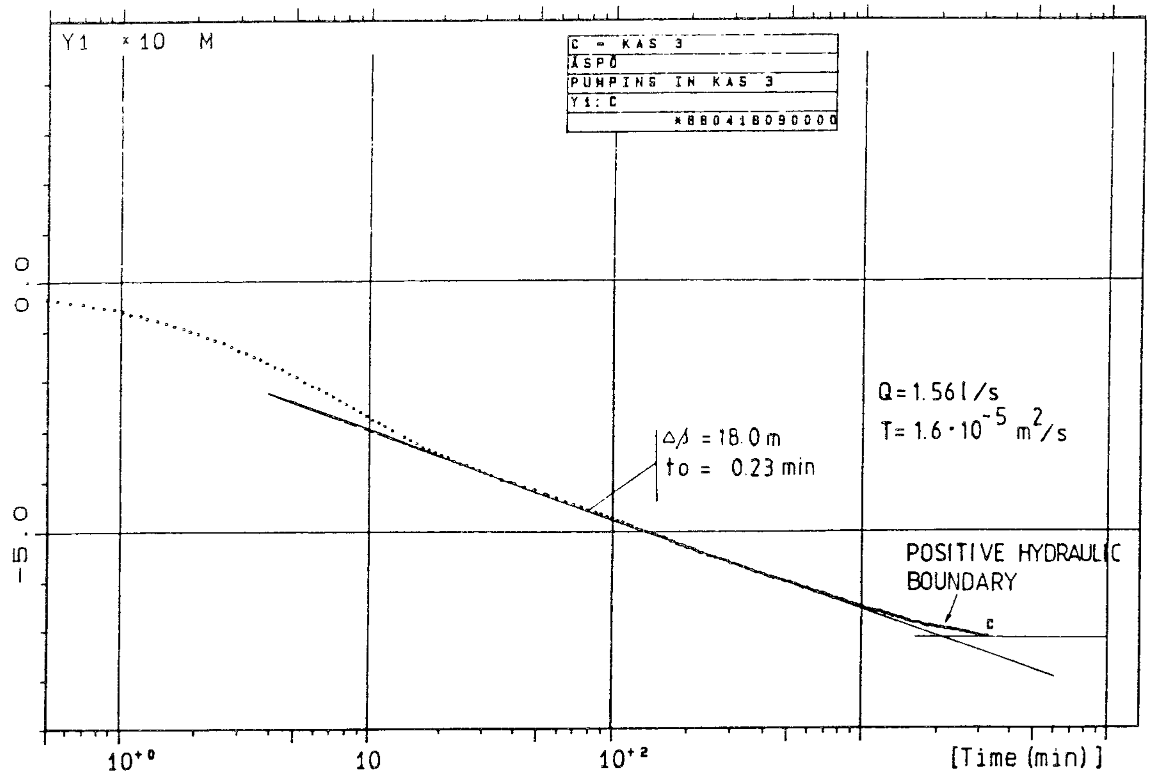


Figure 7.5 *Recordings of groundwater level during a pumping test, and straight-line interpretation of transmissivity from semi-logarithmic graph.*

Pumping tests in percussion-drilled holes

During the beginning of the siting stage, pumping tests were performed in percussion drilled boreholes at the three candidate sites Äspö, Ävrö and Laxemar. These pumping tests were conducted with methods as for the cored holes, however always as interference tests /Nilsson, 1987/.

7.3 Flow-meter logging

Flow-meter logging is a borehole logging method which was originally used to determine the vertical flow along a borehole in order to detect inflowing and outflowing sections. The method presupposes a significant difference between the groundwater heads in the aquifers penetrated by the borehole. These conditions are normally not fulfilled in fractured crystalline rocks in areas with ordinary topography, unless very dominant groundwater conductors are present or when local depressions in the groundwater formations have been artificially created (mining, underground excavation, etc).

However, in conjunction with pumping tests in boreholes, flow-meter logging has been found to be a very useful, time-effective investigation method for hydraulic characterization of a borehole. This method has therefore been used in most of the cored boreholes in the Äspö HRL project, in conjunction with the pumping tests described in section 7.2. The aim was to provide early quantitative (and valuable) information on the distribution of hydraulic conductive sections, i e prominent fractures and fracture zones, along the borehole. Flow-meter logging was carried out when steady-state or semi steady-state conditions had been reached during the pumping test.

The measurement principle is that a flow-meter probe is lowered down the borehole, from below the pump and down to the bottom of the hole, to measure the vertical flow velocity along the borehole, as illustrated in Figure 7.6. Normally measurements are made every meter, but more closely-spaced measurements are recommended over major inflow sections. Two different flow-meters have been used in the Äspö HRL project, the MLS flow-meter probe and the UCM flow-meter probe, see Figure 7.7.

In the MLS flow-meter, the rotational speed of a propeller is measured by means of a pulse counter. The rotational speed is then converted to vertical flow velocity in the borehole. The measuring range for flow velocity is 0.015 m/s to >0.7 m/s and the resolution is 0.003 m/s. These values correspond to vertical flows of 2.2 l/min, 103 l/min and 0.5 l/min, respectively, for a 56 mm borehole. The probe is connected to the logging cable of the geophysical logging equipment, described in section 6.1.1.

In order to increase the resolution of the flow measurements ABEM has recently developed a new flow-meter probe on behalf of SKB. In this flow-meter, the direction and magnitude of the water flow affects the travel time of acoustic waves (the Doppler effect). The measuring range and resolution of the UCM flow-meter probe is 0.001 m/s to 3 m/s and 0.001 m/s, respectively. These flow velocity values correspond to flow rates of 0.15 l/min, 450 l/min and 0.15 l/min, respectively, in a 56 mm borehole. The acoustic flow-meter probe also measures fluid resistivity in order to identify whether the inflowing water is saline or fresh at the different sections. It also measures the temperature of the borehole water.

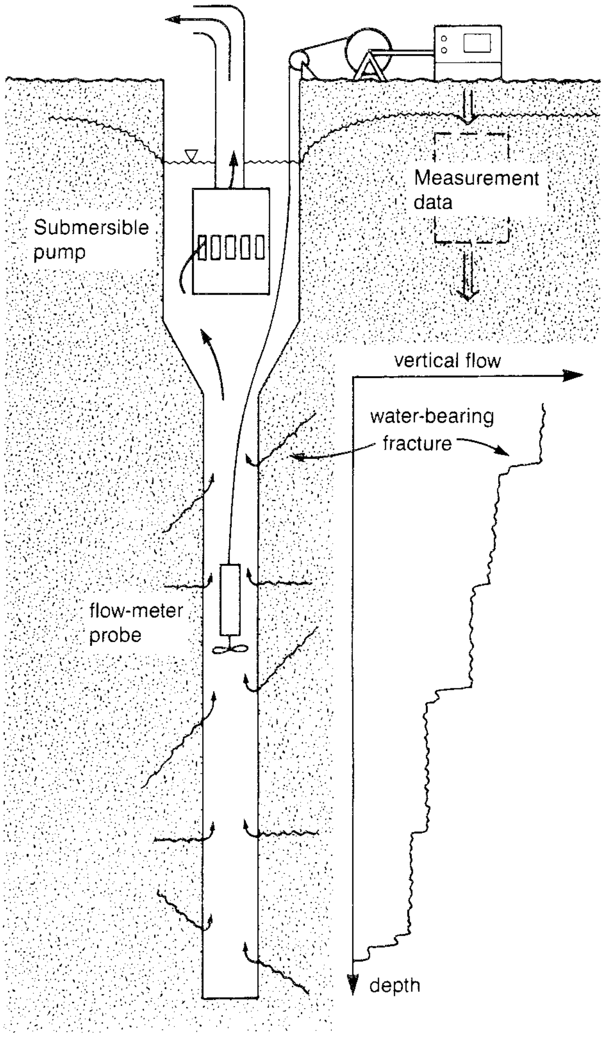


Figure 7.6 The measurement principle of flow-meter logging during pumping.

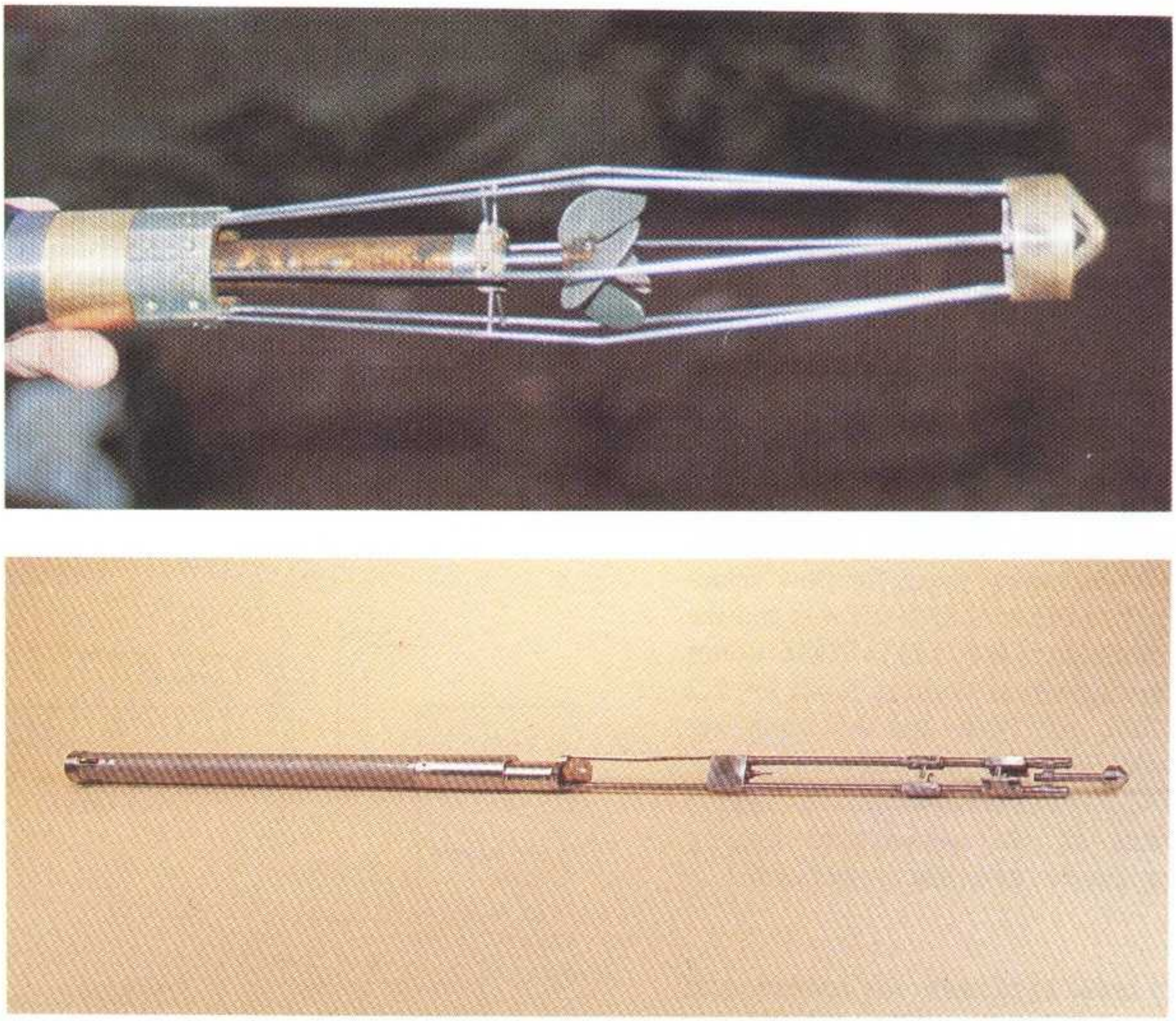


Figure 7.7 The two different flow-meter probes used in the project; the MLS spinner probe (upper) and the UCM acoustic probe (lower).

The flow-meter recordings result in a cumulative inflow profile along the borehole, providing a qualitative information on the hydraulic conditions for water conductors along the borehole /Rhén, 1991/, see Figure 7.8. This information is very valuable when dividing the borehole into monitoring sections, see chapter 8. By starting with the calculated hydraulic parameters, i e transmissivity, from the pumping test, and substracting the amount representing the uppermost 100 m of the telescope-type borehole (obtained from 100 m tests during drilling), transmissivity values for the most conductive inflow sections can also be calculated.

The resolution of the method depends on the resolution of the equipment used, the borehole diameter and the pumping rate. In 56 mm boreholes, intervals with transmissivity greater than 10^{-7} m^2/s or 2×10^{-8} m^2/s can be detected with the MLS and UCM flow-meter probes, respectively.

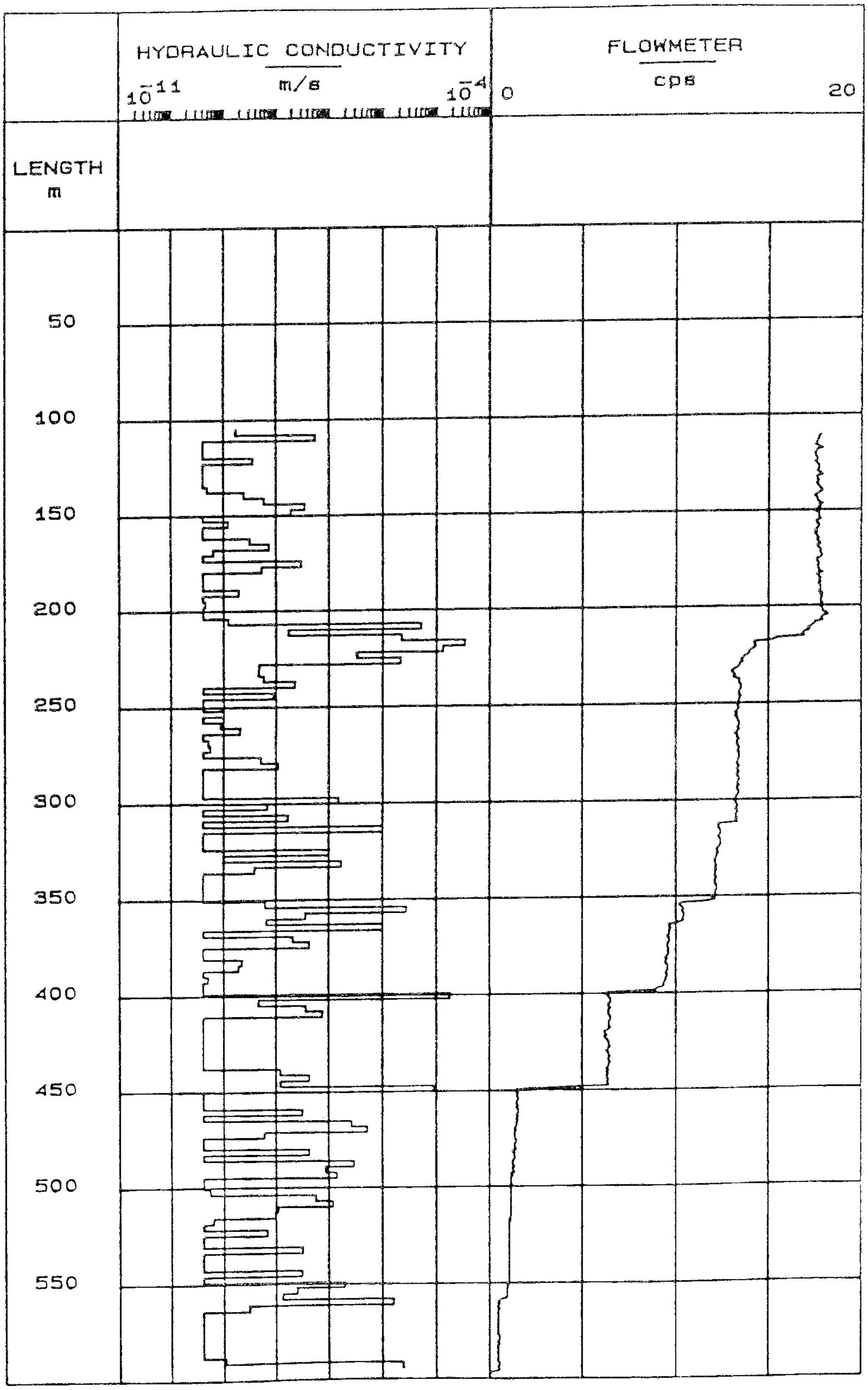


Figure 7.8 *Cumulative inflow profile along the KAS06 borehole, measured by flowmeter logging (right) and hydraulic conductivity log, measured by injection tests in 3 m sections (left).*

7.4 Hydraulic injection test

Hydraulic injection tests were performed in most of the cored boreholes. The measurements were carried out along the entire borehole (excluding the uppermost 100 m reamed-up part of the borehole), in 3 m test sections, using of a straddle-packer borehole tool. The test methodology used in the Äspö HRL project was normally 10 minutes of water injection, followed by another 10 minutes of pressure fall-off recordings (recovery), see Figure 7.9. In order to maintain as stable conditions as possible as regards background pressure and equipment performance, the injection was preceded by 15 minutes of packer inflation and pressure stabilization. Altogether, approximately 1200 injection tests were performed in the Äspö HRL Project /Nilsson, 1989/, /Nilsson, 1990/, /Rhén, 1991/. Some of the boreholes were also measured in 30 m section lengths with an injection test duration of 2 hours and 2 hours pressure fall-off.

7.4.1 Equipment for hydraulic injection test

Two types of equipment have been used for the hydraulic injection tests, the Umbilical Hose System and the Pipe String Equipment. The Umbilical Hose System is specially designed for this type of test, which means that the measurements are fully automated as regards control and data recording. The Pipe String Equipment is more manually operated, while data acquisition is computerized. This system is less specialized for injection tests, and can also be used for other type of borehole measurements, such as the pumping tests from packed-off sections, described in section 7.5. Both systems are designed for operation in all seasons, even at temperatures below -20 °C.

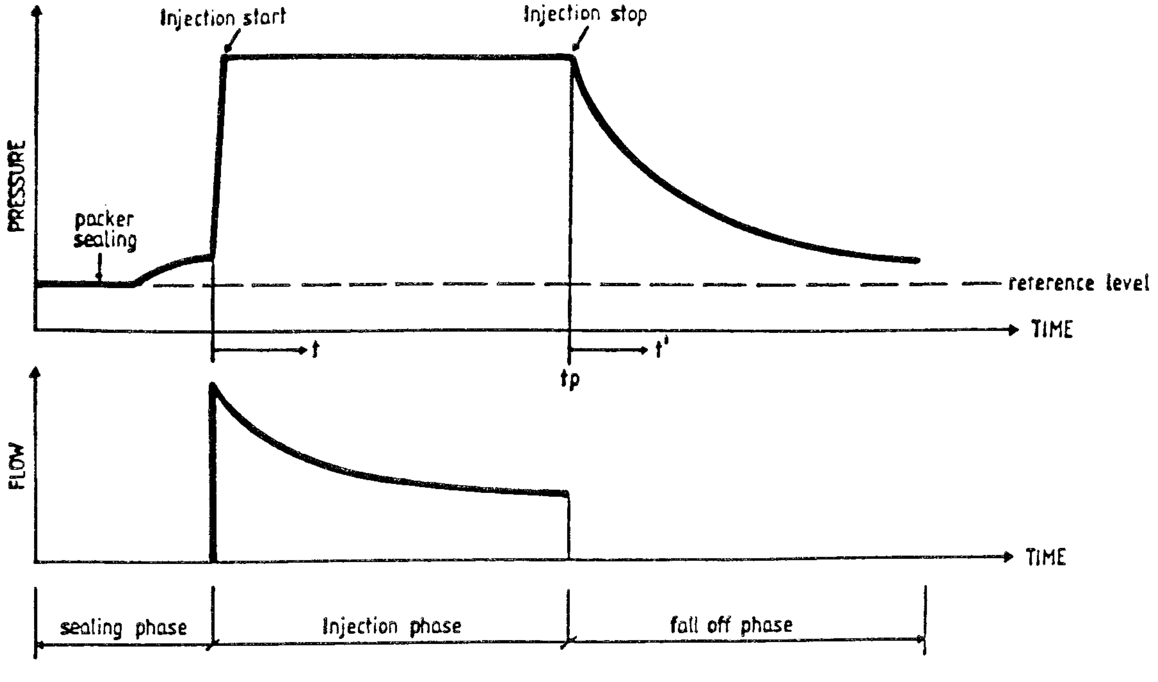


Figure 7.9 The test sequence of a hydraulic injection test.

The Umbilical Hose System

The Umbilical Hose System is described in detail in Almén et al /1986/. Only a brief technical description of the system is given in this report.

The Umbilical Hose System was developed by IPA-Konsult, on behalf of SKB, in order to carry out large numbers of measurements during the Study Site investigation period 1977-1986. Efficient and correct performance called for computerized operation of the measurements. All components of the Umbilical Hose System are mounted on two mobile units, the measurement trailer and the recording trailer, which makes it easy to relocate the system, see Figures 7.10 and 9.4.

The borehole tool with packers, pressure transducers, temperature sensors, down-hole valves and a microprocessor communicate with the surface via a multihose, which is also the carrier of the tool. The multihose, or umbilical hose, contains all water lines, pressure tubing and signal cables needed for operation of the borehole tool. This design makes all movements in the borehole very easy to perform. The measurement trailer contains the umbilical hose with reel and hoisting equipment, the systems for water

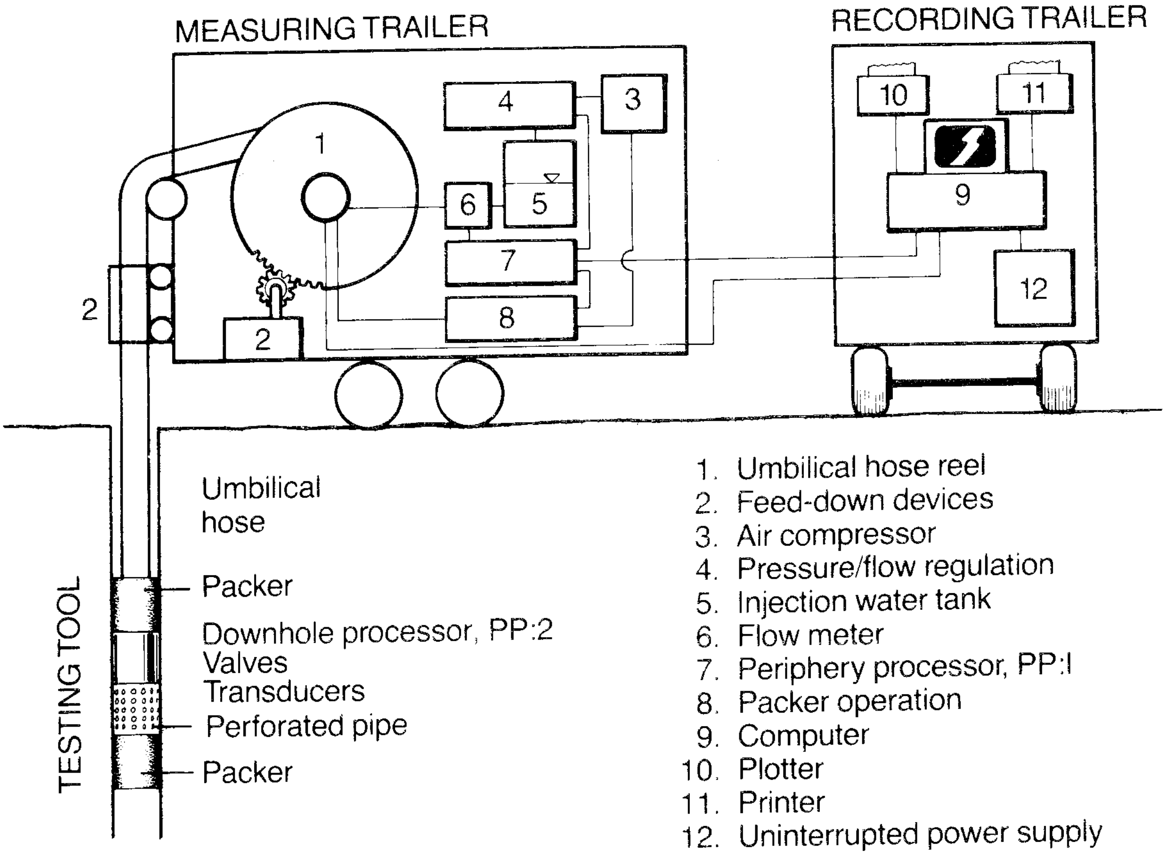


Figure 7.10 Schematic illustration of the Umbilical Hose System.

Figure 7.11 Interior of the measuring trailer of the Umbilical Hose System, and the down-hole electronics.

injection and packer operation, flow meters and other measuring sensors, etc, see Figure 7.11. The recording trailer is equipped with computer, data communication device, printer and plotter. The main technical features for the system are as follows:

* Rubber packers, for borehole diameters 56mm, 76mm, 4", 6", etc
  - hydraulically inflatable by means of pressurized nitrogen or air
  - 1.0 m sealing length

* Downhole testing tool including
  - electronic probe: microprocessor, A/D, communication circuits
  - test and relief valves: electrically operated
  - pressure transducers: Druck PTX 160/D, accuracy < 0.1%
  - temperature sensors

* Flow meters: type (accuracy)
  - Micro motion: 0-0.1 l/min (0.4% of rate ± zero stability 9×10^{-5} l/min)
  - Minimag: 0.09-7 l/min (1.0% of rate ± zero stability 0.1% FSO)

* Computer system: DEC 350/380

* Umbilical hose: including hydraulic hoses and signal cable for operating the downhole equipment, OD = 48 mm
  - hoisting speed approx. 18 m/min

* Depth capacity: 1000 m.

* Dimensions: length / width / height / weight
  - Measurement trailer: 7.1m / 2.5m / 3.4m / 9000 kg
  - Recording trailer: 6.8m / 2.5m / 3.1m / 1500 kg

The Pipe String Equipment

The Pipe String Equipment is also described in detail in Almén et al /1986/. The technical description in that report is still valid, with the addition that the equipment now is mounted in a container, a modification which has greatly simplified relocation of the equipment. Moreover, a test pumping unit has been developed for use with the Pipe String Equipment, see Figure 7.12. Only a brief description of the equipment is provided in this report.

In the Pipe String Equipment, designed by SGAB on behalf of SKB, all parts such as hoisting rig, systems for water injection and packer operation, measuring sensors, etc are mounted or stored in a container. The borehole tool consist of a straddle packer, a pressure transducer and a downhole shut-in valve. The tool communicates with the surface via a pipe string, pressure lines and a signal cable. The water injection flow is manually regulated via valves on a control panel. All surface electronics, the computer and the plotter are housed in an operator's room inside the container. The main technical features of the system are as follows:

* Rubber packers, for borehole diameters 56mm, 76mm, 4", 6", etc
  - hydraulically inflatable by means of pressurized nitrogen or air
  - 1.0 m sealing length

* Downhole pressure transducers (including temp. sensors)
  - Druck PTX 160/D, accuracy <0.1 %

* Flow meters: type (accuracy)
  - Micro motion 0-1 l/min (0.4% of rate ± 9×10^{-5} l/min)
  - Minimag 0-7 l min (1.0% of full scale or rate)

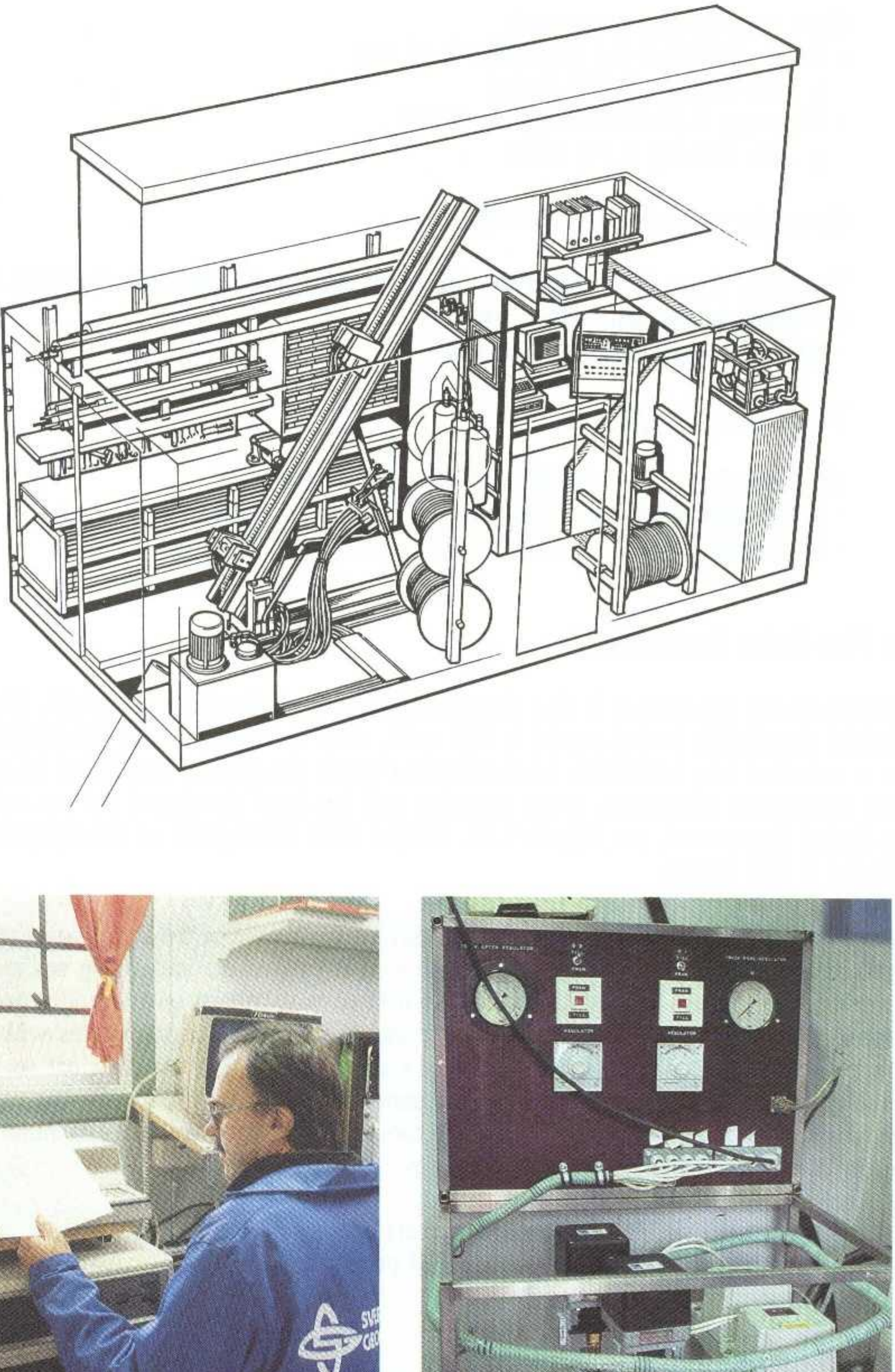


Figure 7.12 Schematic illustration of the Pipe String Equipment with photos from the operator's room and the flow meter and flow regulator unit used for pumping tests.

- * Computer system: DEC 350/380
- * Signal cable: six conductors and shield.
- * Hydraulic hoses for packer and valve operation: ID 1/4"
- * Pipe string: OD/ID = 33/21 mm, 3 m length
  - aluminum with stainless steel couplings
- * Hoisting rig: electrically powered, hydraulic operation
  - lifting capacity 3200 kg,
  - hoisting speed 18 m/min (1-2 m/min including pipe jointing)
- * Depth capacity: 1000 m.
- * Container: length/width/height 6.0 m/ 3.0 m/ 2.7 m
- * Total weight: 9000 kg

7.4.2 Injection test methodology

After being lowered to the test section in the borehole, the straddle-packer tool is expanded by water pressure from the surface. An open relief port prevents excess pressure in the test section caused by the packer inflation. After a certain duration the relief port closes and the pressure in the test section stabilizes. The water line (hose or pipe for the two test systems) is pressurized, after which water injection is started by the opening of a down-hole test valve. Injection is then maintained at a constant pressure, normally 200 kPa above the static pressure, and kept constant during the injection period by flow regulation. The injection is then stopped by closing of the test valve and recording of the pressure fall-off (recovery) is started, see Figure 7.9. The data acquisition systems in both measuring systems continuously record the section pressure and the flow rate. Besides these parameters, groundwater level, packer pressure, barometric pressure and temperature are also monitored.

A large number of graphs of all recorded parameters, pressures, flow-rates, temperatures, etc are drawn by the computer. Some graphs are used to check the equipment and test performance while others are used to identify flow characteristics (spherical, radial or linear flow) and determine hydraulic parameters, mainly hydraulic conductivity, from the injection and the recovery phases of the test. Below, standard graphs are marked with *, while optional graphs are marked with +.

Set of A - graphs: showing all measured parameters, all plotted against absolute time:

* absolute section pressure
* injection pressure
* injection flow-rate
\+ temperature in test section
\+ temperature in injection water

* packer inflation pressure
\+ groundwater level
\+ barometric pressure
\+ temperature at surface

Set of B - graphs: designed for interpretation of hydraulic parameters from the injection phase:

* P - log t
* 1/Q - log t
+ 1/Q - $\sqrt{t}$, t
+ 1/Q - $\sqrt{t}$, t
+ Q - $1/\sqrt{t}$, t
* log (Q) - log t
* log (1/Q) - log t

Set of C - graphs: designed for interpretation of hydraulic parameters from the fall-off (recovery) phase:

+ P - log (dt/(t_p+dt)), dt
* P - log (dte), dt
+ P - $\sqrt{dte}$, dt
+ P - $\sqrt{dte}$, dt
+ P - $\sqrt{t_{pp}+dt} - \sqrt{dt}$, dt
+ P - $1/\sqrt{dt} - 1/\sqrt{t_{pp}+dt}$, dt
+ log dP_p - log dt
* log dP_p - log (dte), dt

Nomenclature for B and C graphs:

P = pressure (test section)
Q = flow rate
t = injection test time
dt = fall-off test time
t_p = total injection time
t_{pp} = corrected t_p ($t_{pp} = V_{tot}/Q_p$)
V_{tot} = total injected water volume
Q_p = flow rate at end of injection
dP_p = differential pressure in relation to pressure at end of injection
dte = t_{pp} x dt / (t_{pp} + dt)

7.5 Interference pumping test

By "interference pumping tests" in the Äspö Hard Rock Laboratory project is meant pumping tests in packed-off borehole sections with monitoring of pressure responses in observation sections in surrounding boreholes, as illustrated in Figure 7.2.

For the interference pumping tests, a special test pumping device is used with the Pipe String Equipment described in section 7.4.1. This pumping method from packed-off sections in 56 mm boreholes has been possible due to the telescope-type borehole design, see Figure 7.13. The same type of straddle packer tool and pipe string are used as for the hydraulic injection tests, see Figure 7.12. Pumping from the pipe string is performed by connecting an electrical submersible pump, mounted in a housing, to the upper part of the pipe. The equipment is assembled so that the pumping device is located at a depth of some 90 m, in the upper, reamed-up part of the borehole.

In the Äspö HRL project a number of hydraulic transmissive zones were selected for investigations. A controlled pumping test from the packed-off section was performed during a period of three days, followed by one day of recovery /Rhén, 1989/ and /Rhén, 1990/. The pumping rate was automatically controlled and kept constant by a flow regulator in the range of $8x10^{-6}$ to $8x10^{-4}$ m^3/s. In addition to pressure recording in the test section, pressures were also measured above and below the straddle packer tool. Using the same computer software as for the injection tests, a number of plots for the pumping test were prepared during and after the test, see Figure 7.14.

The pressure responses in a large number of observation holes were measured in order to collect information for the 3-dimensional analysis of the geometry and character of the hydraulic conductors. The observation holes were equipped with a multipacker system in order to subdivide the main hydraulic conductors in the holes. The pressure levels in the sealed-off sections were recorded with pressure transducers and data loggers. Specifications of equipments used in the observation holes are given in chapter 8.

The test method is a valuable hydraulic investigation method for 3-dimensional characterization of a rock formation. In the pre-investigation phase of the Äspö HRL Project, 14 interference pumping tests were performed from hydraulically conductive intervals, identified via single-hole hydraulic methods. 13 tests were performed in cored holes while one test was done in a percussion-drilled hole.

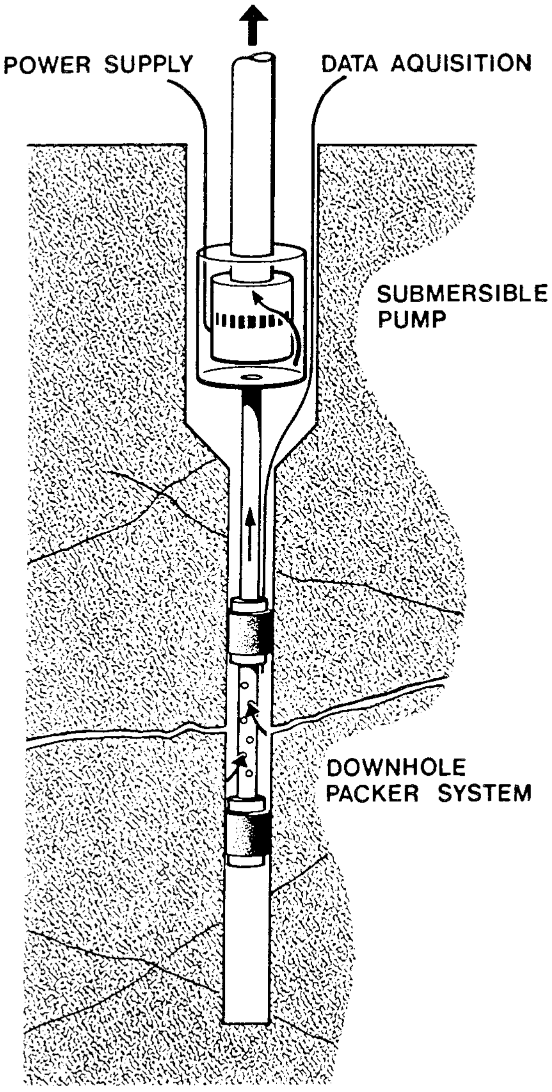


Figure 7.13 Schematic illustration of downhole equipment for interference pumping.

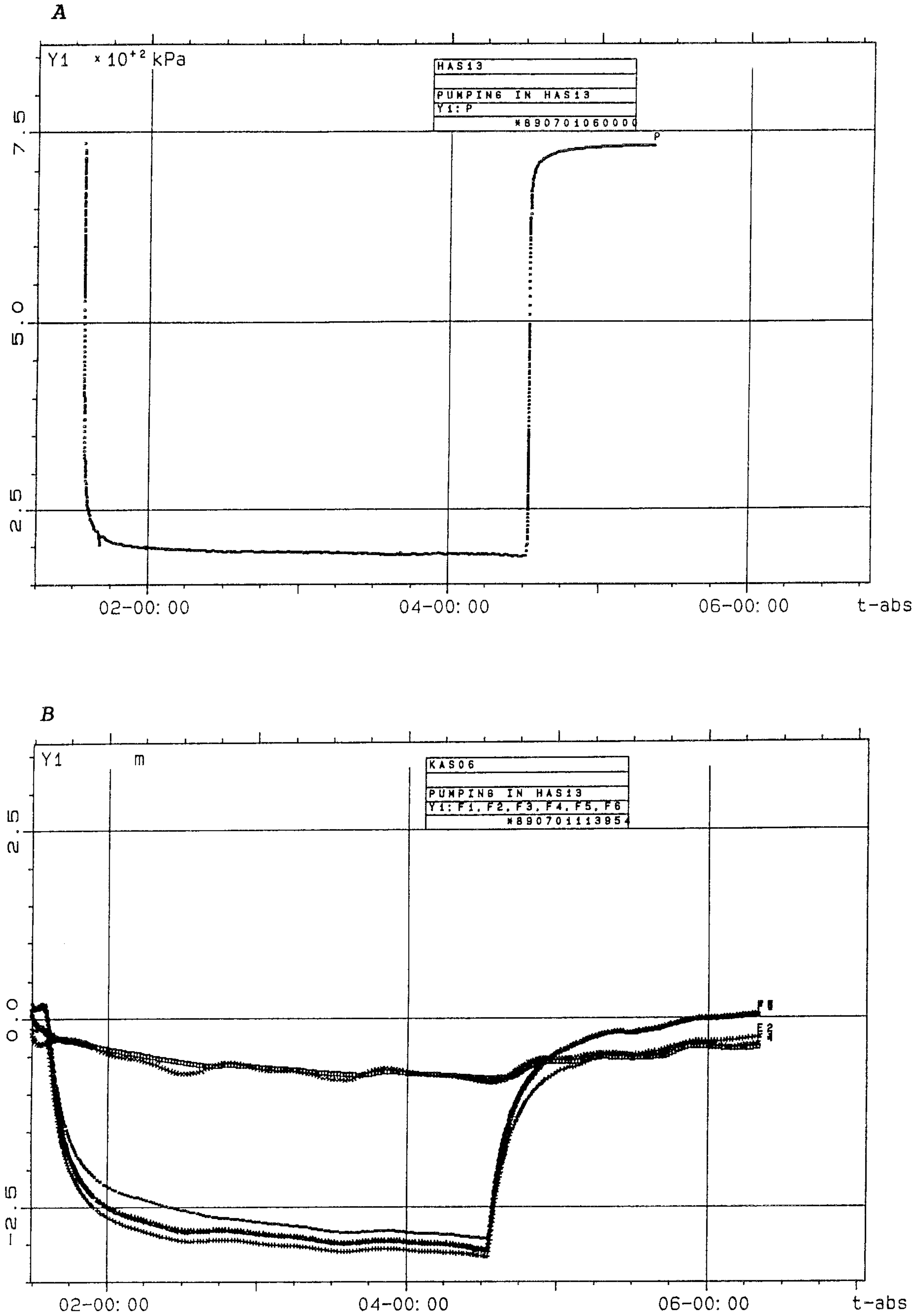


Figure 7.14 *Graphs from an interference pumping test*
A. pressure recording in the pumping hole
B. pressure responses in six packed-off sections of an observation hole

7.6 Long-term Pumping Test

Two Long-term Pumping Tests (LPT) were carried out during the pre-investigation phase of the Äspö Hard Rock Laboratory Project. The aim of a LPT is to induce a large-scale and long-duration hydraulic disturbance of the groundwater reservoir. In the Äspö HRL project the Long-term Pumping Test was conducted in the later stages of the pre-investigation phase. The purpose of the LPT was to validate an early conceptual model, obtain input data for refining the model and calibrate the numerical model calculations for predicting the influence of the underground excavation on the hydraulic situation, i e inflow to the tunnel and groundwater pressure response in monitored boreholes. The Long-term Pumping tests had a duration of approximately two months of pumping followed by one month of recovery. In conjunction with the latter test a tracer test was performed, see section 7.8.

The pumping was conducted in one of the telescope-type boreholes in the central part of the investigation site. Unlike the interference pumping tests (see section 7.5) the LPT was done from an open borehole, without packers and with a suitably sized electric submersible pump installed at a depth of about 90 m in the large-diameter part of the hole. The LPT pumping was carried out with a constant flow rate, which was automatically regulated as for the interference pumping test. Flow rate and pressure draw-down in the pumping hole were recorded with the data acquisition system of the Pipe String Equipment. The draw-down in all surrounding observation sections were monitored as well, as described in chapter 8.

Besides hydraulic head, fluid conductivity was recorded in two sections of the cored boreholes. During the pumping phase some of the prominent hydraulically conductive sections were selected for dilution tests, measuring groundwater flow through the test section. The dilution tests were carried out as described in sections 7.7 and 8.4 (methods and equipment, respectively). Dilution tests during pumping provide additional information about the flow distribution in the hydraulic conductors that are in contact with the pumping borehole.

Measured data from the Long-term Pumping Tests were processed according to routines developed for the interference pumping tests. A large number of graphs for the pumping period and the recovery are prepared for the pump hole and the observation boreholes, see Figure 7.15. The first LPT is reported by Rhén /1990/, while the second LPT, which were carried out in conjunction with the tracer test, has not yet been finally reported.

7.7 Dilution measurement

Tracer dilution in boreholes is a measuring method used to determine groundwater flow in an aquifer or hydraulically conductive fracture. The method can be carried out either under undisturbed conditions, for determination of natural groundwater flow, or under disturbed conditions, as during pumping tests, in order to collect additional information about flow conditions, as mentioned in section 7.6.

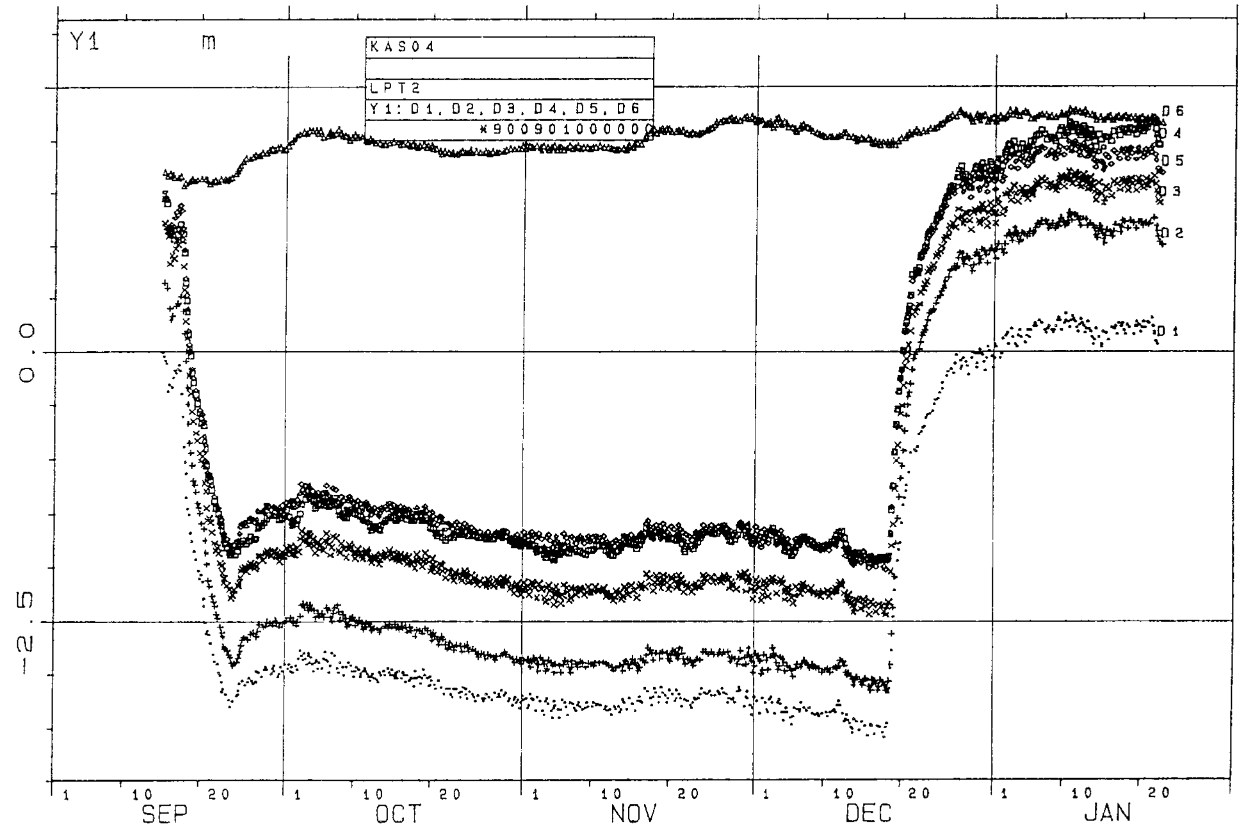


Figure 7.15 Recording of pressure responses in six monitored sections in borehole KAS04 during LPT in borehole KAS06.

The principle of the dilution method is to introduce a tracer into an isolated borehole section, and then measure the dilution of the tracer concentration as a function of time. The dilution is proportional to the water exchange rate in the isolated section, which is due to the groundwater flow through the packed-off section. Depending on the purpose of the measurement and the technical conditions of the borehole, dilution measurements can be performed with two different types of equipment: the borehole point dilution probe and the surface sampling dilution equipment.

In the Äspö Hard Rock Laboratory project, a special version of the surface sampling dilution equipment was designed for use in multipacker installed boreholes. The basic borehole installation of this equipment is described separately in section 8.4, see Figure 8.4. The technique includes circulation of formation water from the isolated section via a small tubing up to the surface, through a tracer test unit and then back again to the test section, see Figures 7.16 and 8.12. In the tracer test unit a tracer is introduced into the circulation water, and samples are regularly taken from the circulating water to measure the dilution rate. Tracer addition in the circulation system is done by a metering pump, providing constant concentration in the water until all circulation water has passed once through the tracer unit. 10-15 ml samples are taken every two to eight hours with an automatic sampler. Dilution measurements normally run for 5-10 days, depending on the groundwater flow.

Dilution measurements for determination of the natural groundwater flow were performed in most of the Äspö HRL cored boreholes. During the Long-term Pumping Tests, dilution measurements under disturbed groundwater flow conditions were also performed as well /Ittner et al, 1991/.

Different kinds of tracers can been used, colored tracers being the most common. In the Äspö HRL Project, uranine (sodium fluorescein) was used for dilution tests, under both natural and disturbed conditions. Altogehter 45 dilution measurements were performed in 22 borehole sections.

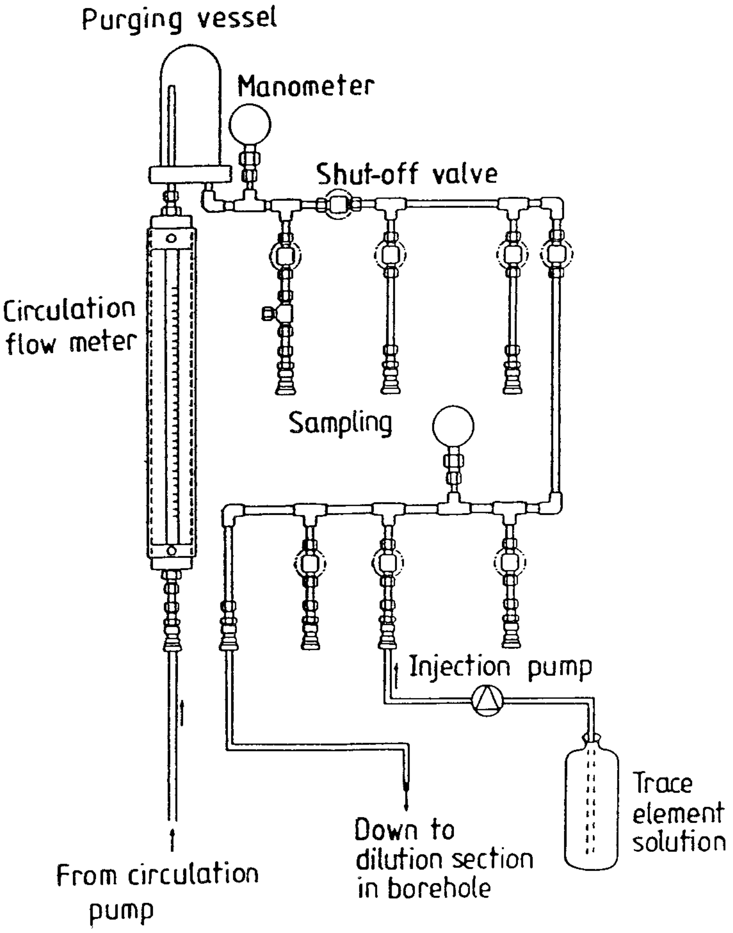


Figure 7.16 Schematic illustration of the tracer test unit, for tracer injection into the circulation system and water sampling.

7.8 Tracer test

While hydraulic tests, and interference tests in particular yield information on the hydraulic behaviour of a groundwater reservoir, i e the pressure response in the network of pores and fractures in a crystalline rock formation, a tracer test provides information on the transport properties of the formation, i e porosity and geometry of the groundwater flow paths. Two types of tracer tests are commonly used, the radially converging tracer experiment and the dipole tracer test.

At the end of the pre-investigation phase of the Äspö HRL Project a large-scale tracer test was conducted in conjunction with the second Long-term Pumping Test. The test was carried out as a radially converging tracer experiment, with tracers introduced in some of the packer-isolated sections in the observation boreholes, and pumping performed from a central positioned borehole. The method and equipment used for the hydraulic part of the test are described in section 7.6.

Four different types of tracers, of which three were radioactive, were injected into separate borehole sections in the observation boreholes by means of the water circulation system specially designed for these sections, as described in section 8.4:

* Uranine * Iodine (I-131)
* Indium (In-114) * Rhenium (Re-186)

In the tracer injection section the dilution of tracer was recorded as well, using the technique described in section 7.7 /Ittner et al, 1991/.

There are at least two advantages to using radioactive tracers under these conditions. One of them is that radioactive tracers are easy to detect, and a second advantage is that the tracers, which remain in the formation after the test is finished, will decay after a period of time. Hence, they will not create any background noise if the same tracers are used later on in the same formation.

The tracers in the water pumped up from the hole were detected by means of on-site recording and analysis of collected water samples, see Figure 7.17. In order to detect where the different tracers were entering the pumping borehole, water samples were periodically taken by means of a multi-level water sampling device lowered down in the borehole. Approximately 12 samples were collected simultaneously from 8 levels where the borehole penetrates water conducting fractures, previously determined by hydraulic injection tests and/or flow meter logging. The sampling frequency was one set of samples per day.

An attempt was also made to detect the entrance of tracers into the borehole by measuring along the borehole with a spectral-gamma log, from below the pump and down to the bottom of the hole. However, even though the technique worked well, the tracer concentration in the borehole was too low for the spectral-gamma probe which was used. As evaluation is still in progress the tracer experiment has not yet been finally reported.

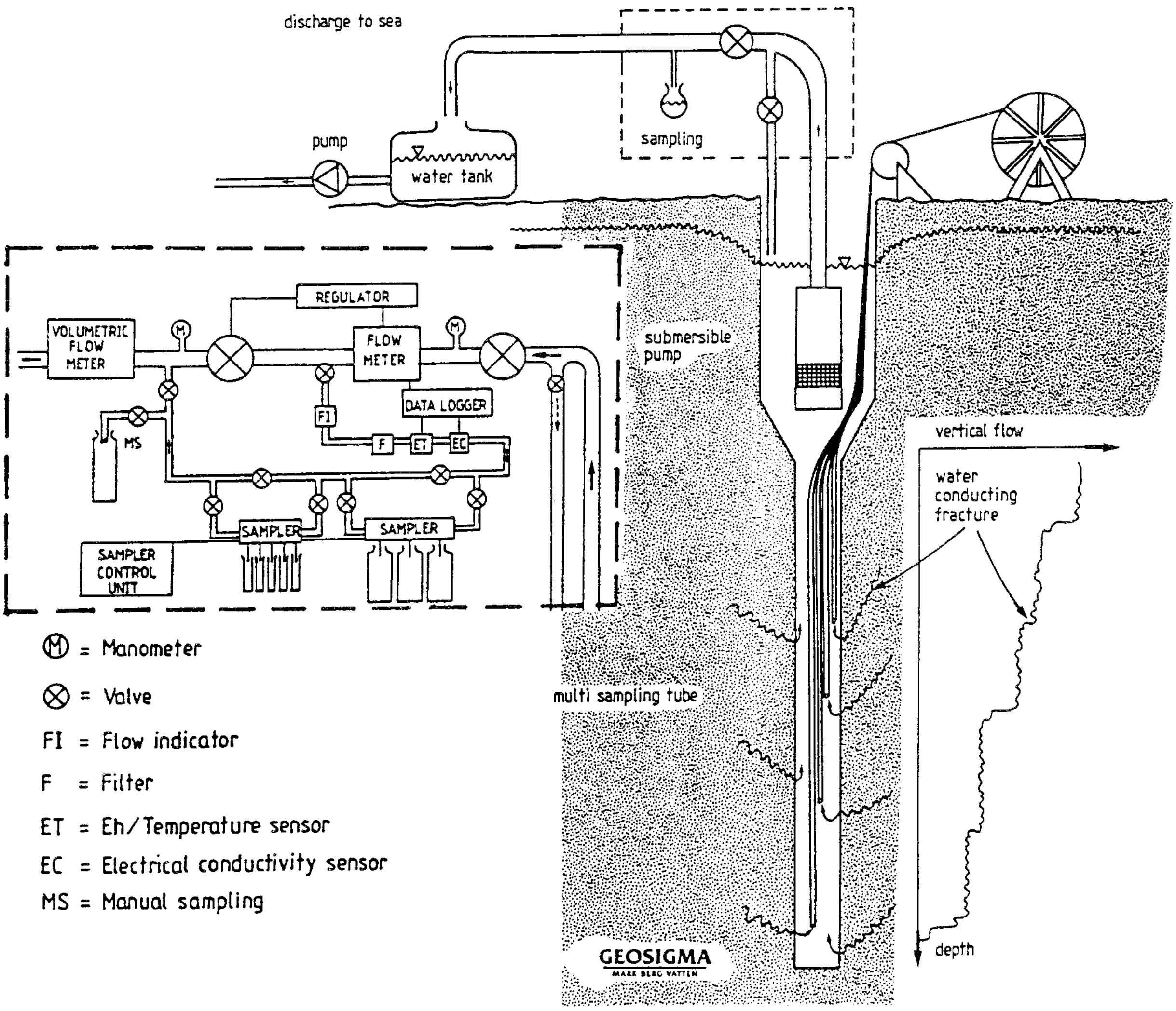


Figure 7.17 Equipment set-up for tracer test carried out in conjunction with Long-term Pumping Test, with on-site recording and analysis of tracers in the pumping water, and in-situ sampling of water at inflowing sections of the borehole (identified from flow-meter logging) by means of a multi-level sampling device.

8. GROUNDWATER MONITORING

The goal of the monitoring programme in the Äspö HRL Project is that recording of groundwater should start as soon as possible after the initial measurements in a borehole have been completed. Monitoring shall then continue for the entire pre-investigation phase, with the exception of periods when other activities occupy the borehole, see Figure 8.1. Monitoring shall subsequently continue during the construction phase.

The equipment and method used for long-term monitoring of groundwater during the pre-investigation phase are described in this chapter. The discussion is dominated by the equipment used in the cored telescope-type boreholes, since the installation in these holes are the most complex. The equipment is presented in four sections describing the multi-packer system, fluid conductivity recording and the water circulation system, followed by two sections discussing the methodologies for monitoring groundwater levels and groundwater chemistry.

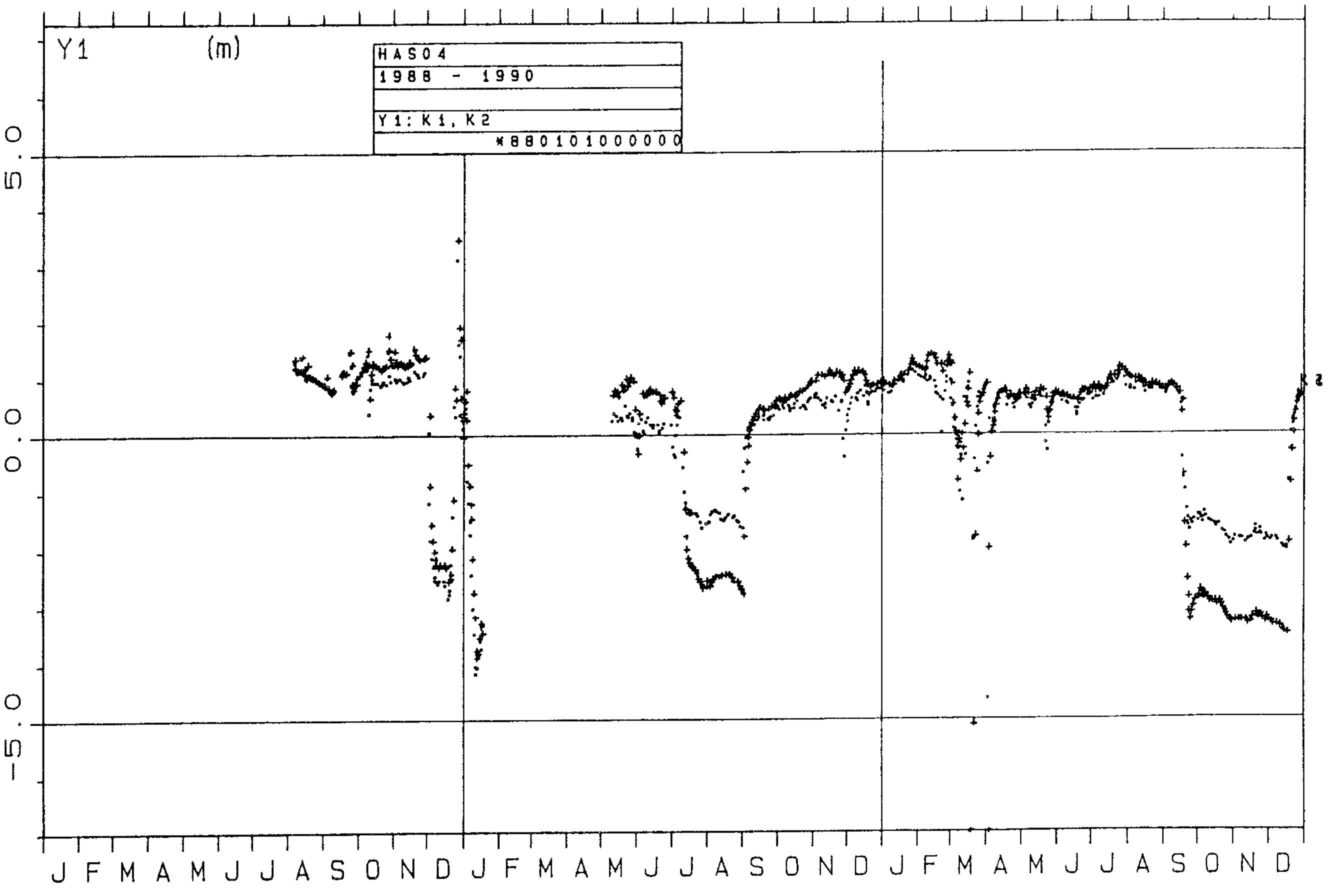


Figure 8.1 Three years monitoring of a borehole during the pre-investigation phase.

Most of the system will also be used continuously during the construction phase. However, some parts will be slightly modified, based on experience gained during the pre-investigation phase and in response to changed conditions. All dataloggers are, for example, planned to be connected to a host computer in order to obtain on-line monitoring of all measuring points from the site office. The monitoring system will also be expanded to include monitoring points in the tunnel.

8.1 Multi-packer system in boreholes

8.1.1 Cored holes

The multi-packer system in the telescope-type boreholes in the Äspö Hard Rock Laboratory project includes packers, rod string and pressure tubings. The multi-packer system, or base installation, is intended to be installed permanently, in order to maintain undisturbed conditions in the isolated borehole sections, preventing hydraulic as well as hydrochemical short circuits between the different sections, for as long periods as possible, even though the system is also designed for easy relocation. The multi-packer system therefore facilitates multidisciplinary measurements such as:

* groundwater level monitoring (sections 8.2 and 8.5)
* groundwater sampling (sections 8.4 and 8.7)
* fluid conductivity recording (section 8.3)
* dilution measurements (section 8.4 and 7.7)
* tracer injection (section 8.4 and 7.8)

Packers with up to nine internal pressure transmission lines and one signal cable have been designed for installation in the boreholes, resulting in a multipacker borehole system. In most of the boreholes six sections are sealed off, including the uppermost section. Two of the sections have been selected to be equipped with water circulation system, which also permits tracer injection or dilution measurement to be carried out without changing the packer system, see section 8.4.

Individual pressure tubes, one for each recorded section (two for the circulation sections), are installed from the section up to the surface. Including a signal cable for fluid conductivity measurements in two of the isolated sections, a total of eight transmission lines are occupied through the uppermost packer. At the uppermost reamed-up part of the borehole, the pressure tubes are connected to water level stand-pipes, see Figure 8.2. The water level in these stand-pipes, representing the groundwater pressure head in the isolated borehole section, can be recorded by means of either manual soundings or dataloggers and pressure transducers.

The borehole equipment is mounted on and carried by a string of aluminum rods. The rod string is capable of carrying a load of 2500 kilograms, which approximately corresponds to a multipacker system 3500 m in length in water-filled vertical boreholes. The multipacker system is installed in the borehole using a mobile, hydraulically operated hoisting rig, powered by electricity or diesel, see Figure 8.3. The lifting capacity of the rig is 4000 kilograms.

Some technical specifications on the multi-packer system for telescope-type boreholes are presented below:

- packers
  - 53 mm or 72 mm: 1 m sealing length of rubber
  - inflated by water pressure, regulated from surface by nitrogen gas
  - up to nine pressure transmissions, 4 or 6 mm ID

- pressure tubes
  - 6/4 mm: for piezometric recordings and packer inflation
  - 8/6 mm: for water circulation

- fluid conductivity sensors: 2 sections

- signal cable
  - 4 mm
  - 4 conductors

- rod string
  - 20 mm OD, 2 000 mm length
  - aluminum with stainless steel couplings

- water stand-pipes
  - 28/22 mm, OD/ID for water level measurements
  - 63/55 mm, OD/ID for water circulation

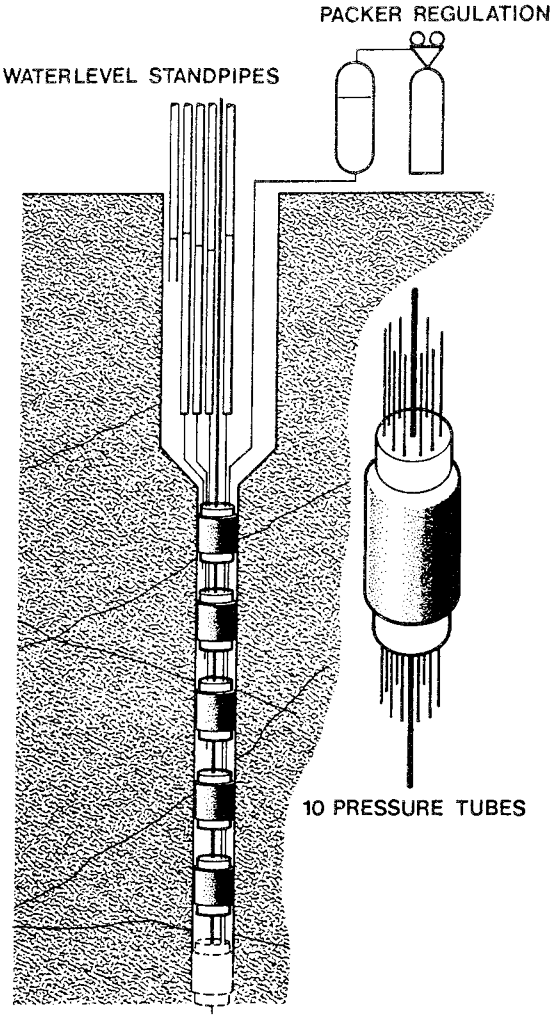


Figure 8.2 *Multi-packer system in a telescope-type borehole.*

8.1.2 Percussion-drilled holes

The base installations in the shallow percussion-drilled holes are in principle the same as for the telescope boreholes. The main differences are as follows:

- normally only 1-2 measuring sections, due to shallow borehole depth

- no water circulation section

- no fluid conductivity recording

- packer diameter 92 mm

8.2 Groundwater level recording system

The multipacker system for telescope-type boreholes permits measurements of groundwater pressure heads, or piezometric heads, in the isolated borehole sections to be

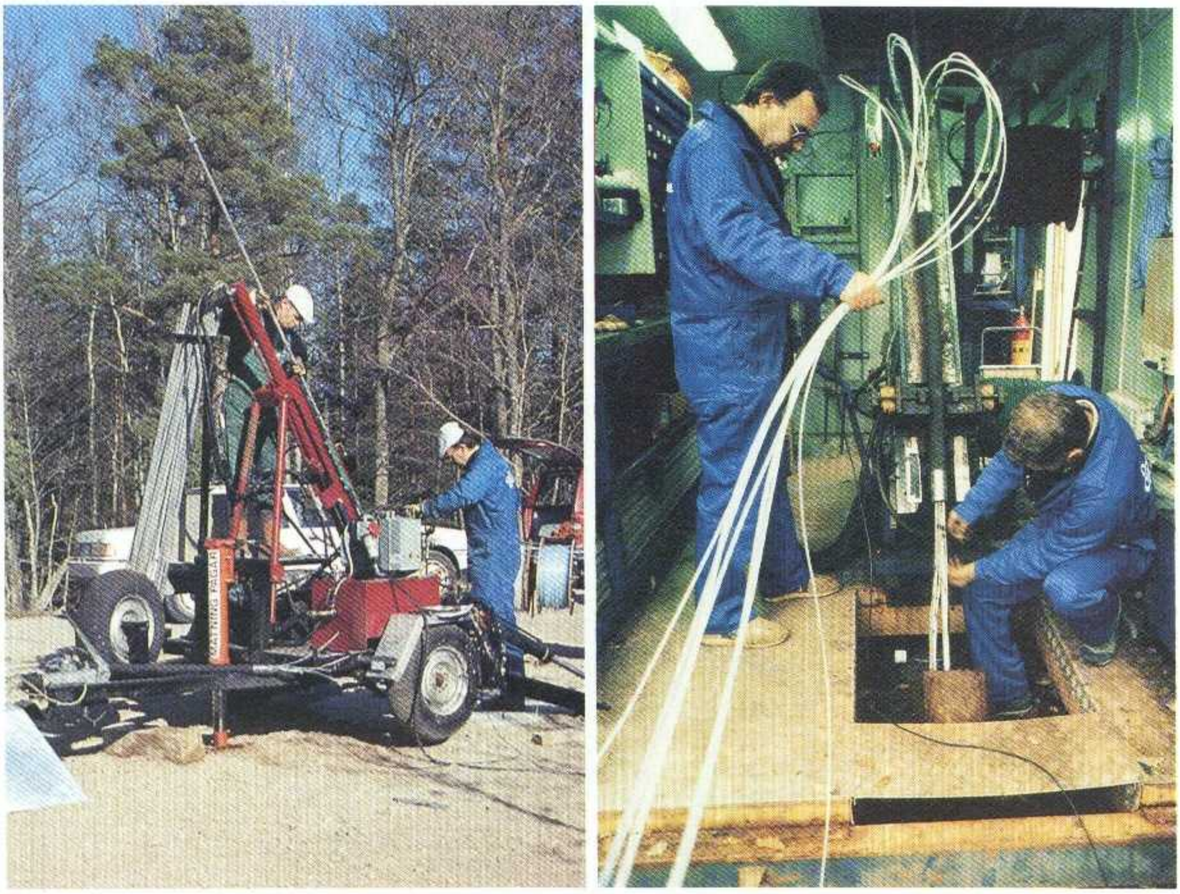


Figure 8.3 *Installation of multi-packer system in a telescope-type borehole, using mobile hoisting rig (left) or the Pipe String hoisting rig (right).*

made by means of either manual sounding or an automatic recording system. For long-term monitoring an automatic recording system will be the most cost effective, see Figure 8.4

The principle of recording pressure levels in water stand-pipes connected to the isolated sections instead of recording pressure down in the isolated sections has the following advantages:

- a low measurement range of the pressure transducers can be used, providing better resolution and accuracy in recordings of water levels and level changes
- easy installation of the transducers, easy replacement of failed transducers
- easy calibration and checking of the transducers, see Figure 8.5

To translate pressure readings to absolute pressures in the isolated section, the density of the water in the pressure tubes and the borehole deviation must be known. These data are available as the borehole deviation is known from earlier measurements. The density of water in the tubes was determined by means of air-lift pumping from the tubes, carried out when the equipment had been lowered down to the right position and

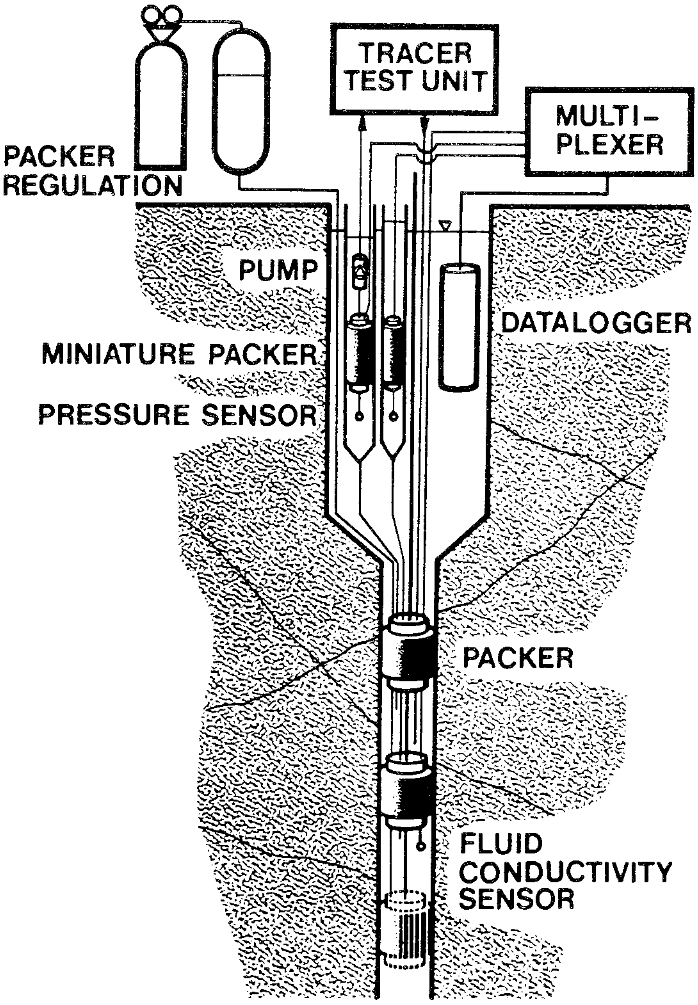


Figure 8.4 *Schematic set-up of groundwater level recording system for telescope-type boreholes (showing only two of normally six recorded sections) with the Borre datalogger. The figure also shows the water circulation equipment (for one section) and the tracer test unit.*

the packers had been inflated, see Figure 8.6. The entire pressure tubes was then filled with formation water of known density. Redetermination of the density can be performed when desired.

In the telescope-type boreholes in the Äspö HRL project, the water levels in each water stand-pipe have been recorded with pressure transducers, lowered down to approximately 30 m below the static water level. Especially during pumping tests or similar artificial disturbances of the groundwater magazine, a delayed response in the water stand-pipe can occur, caused by the relatively large volumes in the stand-pipes compared with the long and narrow pressure tubes. In order to get rid of this well-bore effect, specially designed miniature-packers were designed and installed in the stand-pipes, see Figure 8.7.

For the data recordings, three different types of data loggers are used, Borre MDL, Piezomac II and Grund.

Figure 8.5 *Top of monitoring hole, showing bundles of pressure tubings, signal cables etc. Calibration of pressure recording system by means of sounding in the stand-pipes.*

Figure 8.6 *Airlift pumping of stand-pipes, for water sampling and determination of the density of the water column.*

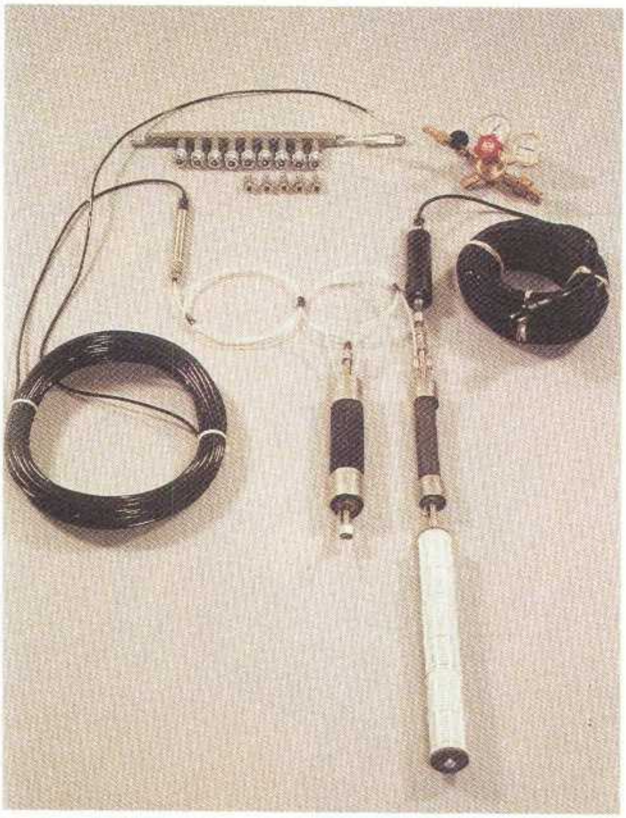


Figure 8.7 *Miniature packers and transducer for installation in a stand-pipe. The pump and filter for circulation sections are also shown (right).*

Borre MDL

The Borre MDL is a datalogger system designed for borehole applications, by IPA Instrument. The logger version used in the Äspö HRL project has 13 input channels and has mostly been used for the telescope-type holes. In most cases six pressure transducers, a fluid conductivity sensor and a temperature sensor are connected. The logger is composed of two units, one surface located box with multiplexer and power supply (battery or mains transformer), see Figure 8.8. The other unit is a borehole probe including microprocessor, A/D converter and memory, preferably installed below the groundwater level, where temperature fluctuations are minimal. The measuring software is very flexible with regard to sampling interval etc.

Once started by means of a laptop computer temporarily connected to the logger, the Borre MDL operates for a long period of time according to the measuring programme which was initiated. Before the memory is full the same laptop is connected to the datalogger for data retrieval. The datafile is then carried to the field office and further transferred to a desktop computer for transforming, calibration and presentation of data.

Some technical specifications of the Borre MDL are as follows:

* Number of channels: 13

* Dimension of borehole probe
  - length/diameter: 0.5 m / 54 mm

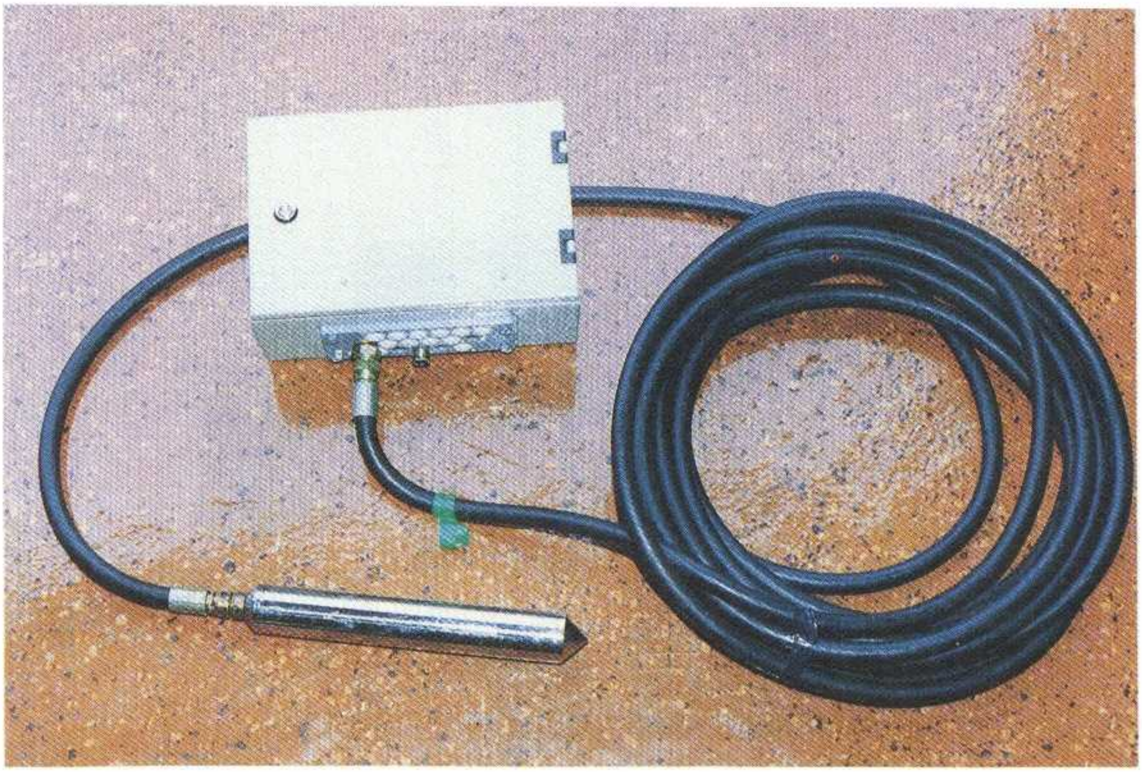


Figure 8.8 BORRE MDL datalogger system.

- * Resolution: 15 bit and sign, corresponds to about 3 microV for a measuring range of + 0.1 V

- * Memory capacity: 64 kByte (approx. 32000 measurements)

The pressure transducers used are Druck PDCR 830 or Druck PTX 160/D, gauge type with an appropriate measuring range, normally 3.5 bar.

Piezomac II

The Piezomac II is another type of datalogger system used in the Project, developed by SGAB, on behalf of SKB. There are two versions of the Piezomac II data logger, Piezomac II A and Piezomac II D. The Piezomac II A is used for recording groundwater levels if there are groups of two or more boreholes, and if the distances from the pressure transducers in the boreholes to the datalogger are less than approximately 1000 m. In these cases Druck PTX 160/D pressure transmitters with a 4-20 mA signal are used.

The Piezomac II D is used in a conventionally drilled core boreholes situated at the Ävrö reference site. Recordings of several sections in the borehole are made with a down-hole multi-pressure probe operated by the Piezomac II D, see Figure 8.9. A multi-port valve enables measurements to be made of up to five sections with a single

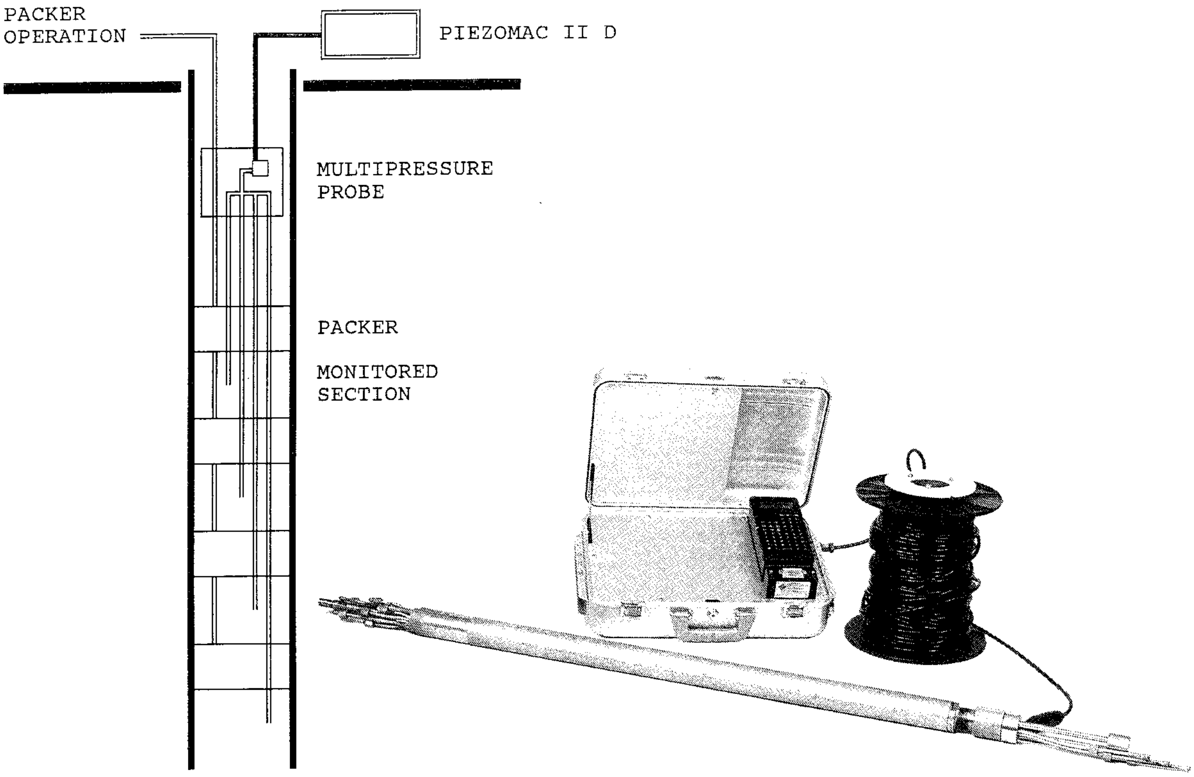


Figure 8.9 The Piezomac II D recording system

pressure transducer, Druck PTX 120/WL. This version of the Piezomac II is in detail described in Almén et al /1986/. This description is also valid for the most part for the Piezomac II A.

The measurement software and methodology for initiating the measurement and data transfer are quite similar to those for the Borre MDL. Some technical specifications of the Piezomac II A are as follows:

* Number of analogue channels, Piezomac II A: 24

* Number of digital channels, Piezomac II D: 8

* Resolution: 14 bit and sign

* Memory capacity: 220 kByte (approximately 40 000 measurements)

Grund

A third datalogger is used in the Project, the Grund datalogger, developed by IPA-Konsult on behalf of SKB. Grund is a one-channel logger with an internal pressure transducer, A/D converter, memory, battery etc, assembled in a borehole probe for installation below the groundwater level /Almén et al, 1986/. As with the above mentioned dataloggers a laptop computer is used to set the measuring parameters, to start the measurements and to transfer the collected data to the office.

Some technical specifications for the Grund logger are as follows:

* Number of channels: 1
* Resolution: 12 bits and sign, corresponding to 25 microV for a measuring range of +/- 0.1 V
* Event logging (storage only when data changes more than present value)
* Memory capacity: 2096 measurements
* Battery capacity (internal): several months of measurements

Transient protection system

The measuring system is designed with protection against external influences on the transducer and data signal caused by earth currents generated by thunderstorms etc. This is most important when long signal cables are used between boreholes. The first step was to use sensors with current signals. The next step was to install a number of Åskar, a combined transient and lightning protection device developed by ABEM, in the measuring system, see Figure 8.10. Åskar will cut off transients in the signals and protect the electronics in the system. When measuring equipment is connected to the power network, protection devices are used to stabilize the voltage.

8.3 Fluid conductivity recording

The groundwater at the Äspö site is saline below a depth of some 100 m. Fluid conductivity is measured during the geophysical logging campaign (borehole resistivity log) and on water samples collected within the hydrochemical measuring programme. During heavy withdrawals of water from the formation the saline/fresh water interface may change. This will probably occur during the tunnel excavation period but may also occur during pumping tests. Therefore, two of the isolated sections in each telescope-type borehole are fitted with fluid conductivity sensors, see Figure 8.11. As described in section 8.1.1 the sensors and signal cables were installed with the multi-packer system, see Figure 8.4.

At the ground surface, the signal from the sensors is converted to conductivity values, which are displayed on the instrument. One of the two measured sections is recorded on the datalogger.

As the borehole sensors are a part of the multi-packer installation, calibration of the sensors is difficult. However, the sensors are calibrated and checked prior to installation. In conjunction with installation, the fluid conductivity is also measured on samples taken from the air-lift pumping in the pressure tubes, as also mentioned in section 8.2. Separate test pumpings from the isolated sections can also be done at any time, when this does not interfere with other ongoing measurements.

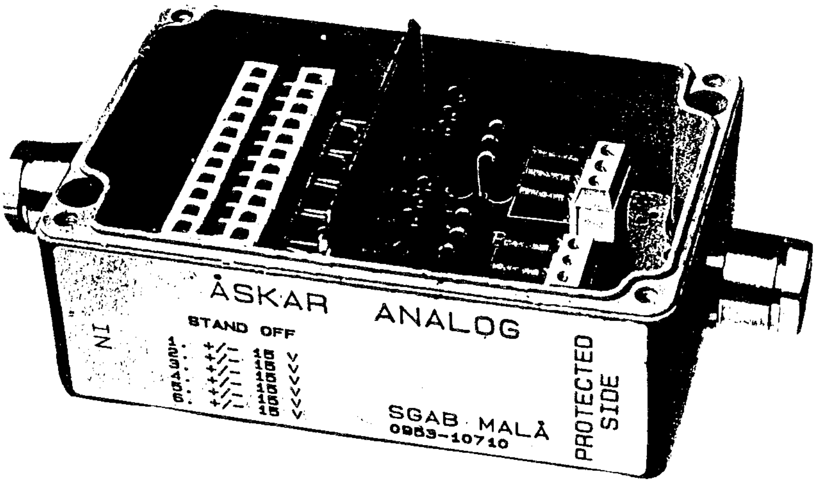


Figure 8.10 The Åskar transient and lightning protection system connected to signal transmission cables.

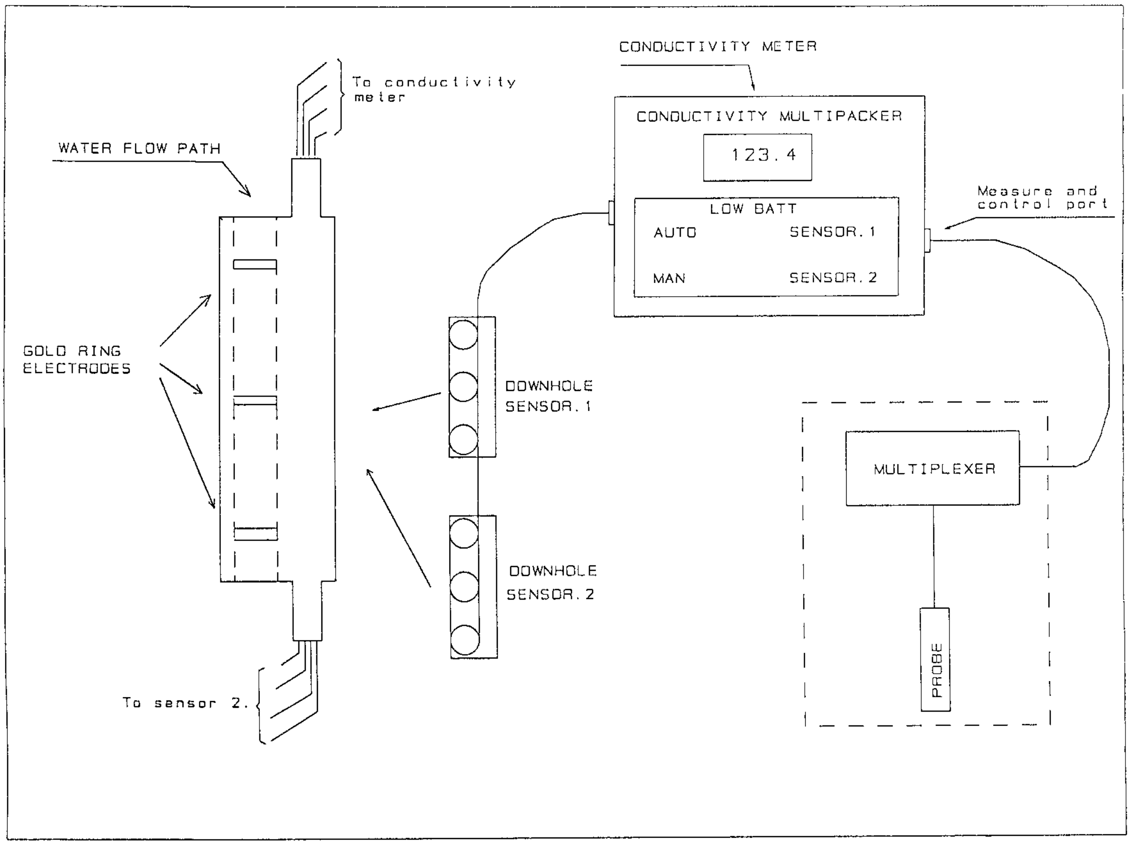


Figure 8.11 Fluid conductivity measuring system

8.4 Water circulation system

As discussed earlier, two of the packed-off sections in the telescope-type boreholes are equipped for water circulation up to the surface in order to make tracer tests and dilution measurements possible. Installations for this purpose include a second pressure tube and a somewhat larger stand-pipe, in addition to the packers and tubes used for piezometric monitoring. A special water circulation system is used to carry out tracer tests and dilution measurements. This system consists of a filter, a miniature submersible pump, a miniature packer and a pressure transducer, which are lowered down in the stand-pipe to replace the miniature packer and pressure transducer used for the pressure head monitoring, see Figure 8.7.

During circulation, the water is pumped up to the surface, into a tracer test unit and then back to the borehole section through the second tube into the borehole section, see Figure 8.4. The tracer test unit consists of a flowmeter, valves and time relay for collecting water samples, see Figures 7.16 and 8.12. The injection of tracers into the circulation system is done by a metering pump in order to achieve a constant concentration. The measuring methodology for dilution measurements and tracer tests was previously described in sections 7.7 and 7.8, respectively.

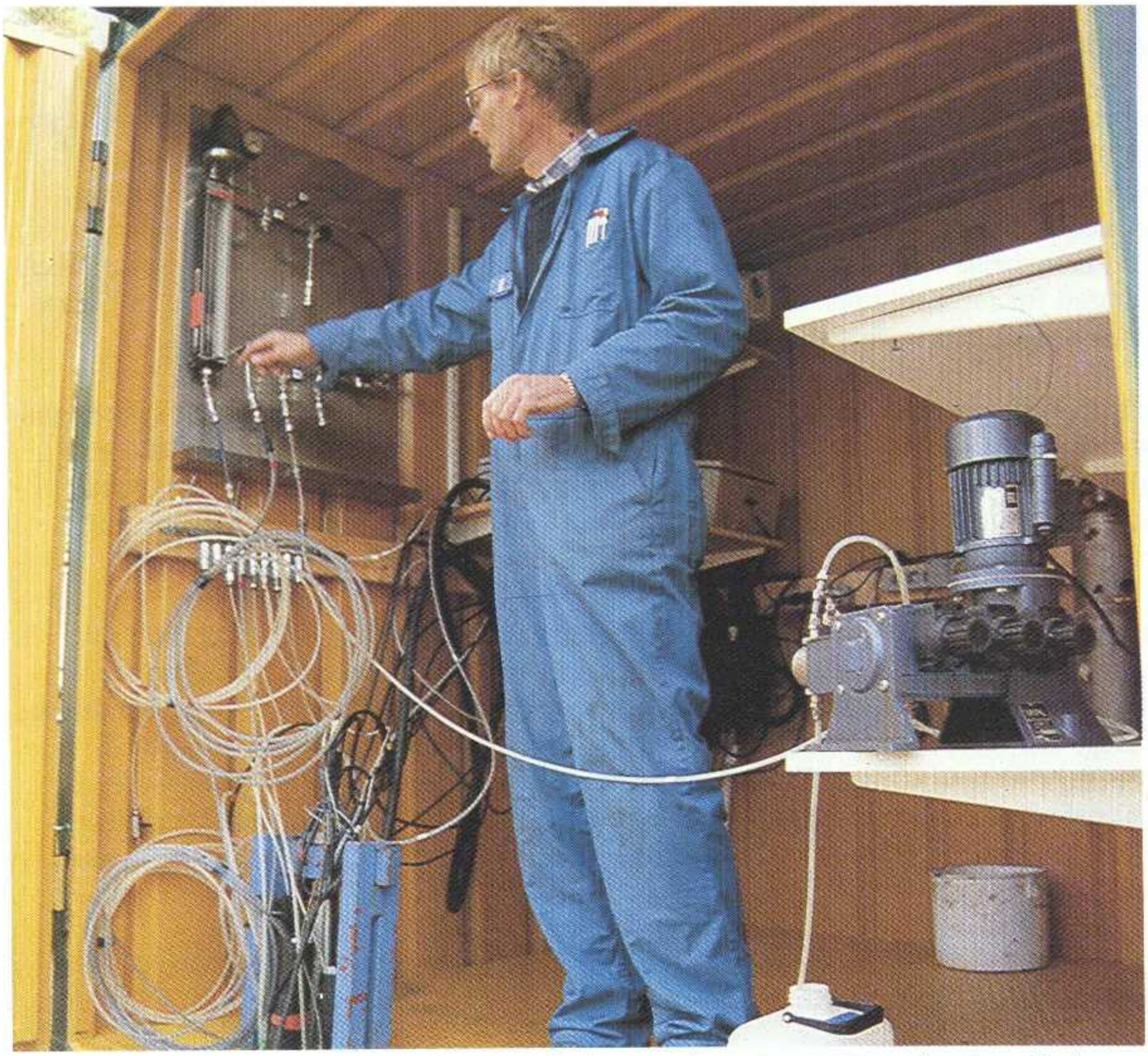


Figure 8.12 Tracer injection in a circulation section of a multi-packer installed borehole

8.5 Groundwater level monitoring program

A great number of activities will be performed during the forthcoming phases of the Äspö Hard Rock Laboratory project, of which the excavation of the underground facility will be the most important in terms of effects on the investigated formation. The excavation will act like a gigantic pumping test, with transient conditions as regards geometry of the source (continuous excavation) and water inflow. Of prime interest will be the influence on the groundwater situation, i e groundwater pressure distribution around the excavation, especially as a function of time during the construction period. A secondary effect will be changes in groundwater chemistry where the interface between saline and fresh water moves. Besides the geological character of the rock formation, changes in hydrological and hydrochemical conditions have been predicted and will be validated against real observations /Gustafsson et al, 1991/, /Rhén et al, 1991/.

During the course of the pre-investigation phase an attempt has been made to monitor the above-mentioned parameters for as long an unbroken period as possible in order to collect background data before the excavation starts, especially on groundwater pressures. Monitoring will continue during the construction phase in order to check predictions and to collect data for a more detailed understanding of the behaviour of the groundwater system.

A basic monitoring programme for groundwater heads was set up for the pre-investigation phase of the Äspö HRL project. The boreholes are divided into sections determined by the results of the investigations conducted earlier in the borehole sections, isolated and separated by means of packers (described in section 8.1). Groundwater head monitoring is also done as a part of interference tests, where the monitoring data are used for recording pressure responses in observation holes, as illustrated in Figure 7.2 and discussed in sections 7.5 and 7.6.

142 borehole sections are being monitored, 118 via the automatic recording system and 24 manually. The monitoring programme was defined as regards measuring intensity, calibration frequency and intervals for data processing. The intervals are somewhat different for different boreholes, and for some boreholes the programme has been changed on occasion.

In boreholes monitored with automatic recording systems, which is the case for all cored holes and most major part of the percussion drilled holes, the recording frequency was one measurement every four hours. For some percussion-drilled boreholes at Äspö the recording interval was two hours. In borehole sections where manual soundings were used the measurement frequency was one measurement per week. In connection with other activities on the site, such as the above mentioned interference tests when the boreholes act as observation holes, a higher recording frequency was used.

On-site calibration of the recording system, i.e. the datalogger and transducers in the boreholes, was done every month, see Figure 8.5.

The collected data were normally transferred from the field datalogger to the office for processing every second month, see Figure 8.13.

Figure 8.13 Data transfer from a Borre datalogger to the site office, via a laptop computer.

At the office the collected raw data were calibrated, quality controlled and converted to suitable units, see Figure 8.14. Time series graphs of groundwater levels and fluid conductivity were plotted, all sections of a borehole normally being displayed in one graph. Condensed graphs were plotted based on one measured value per day, see Figure 8.15. Data results were reported in periodical and annual reports /Nyberg et al, 1991/.

The monitoring records of groundwater levels are also stored in the SKB database GEOTAB: Calibrated raw data are stored on magnetic tapes, while condensed data files of daily values are stored on active disks.

8.6 Monitoring of other hydrological parameters

In addition to groundwater levels, other hydrological and meteorological data were monitored or calculated on a long-term basis, such as temperature, precipitation, potential evaporation, sea level and earth tide. These data were mostly collected from external base recording stations in the vicinity. Also these data records are reported in the annual groundwater level report /Nyberg et al, 1991/, see Figures 8.16 and 8.17.

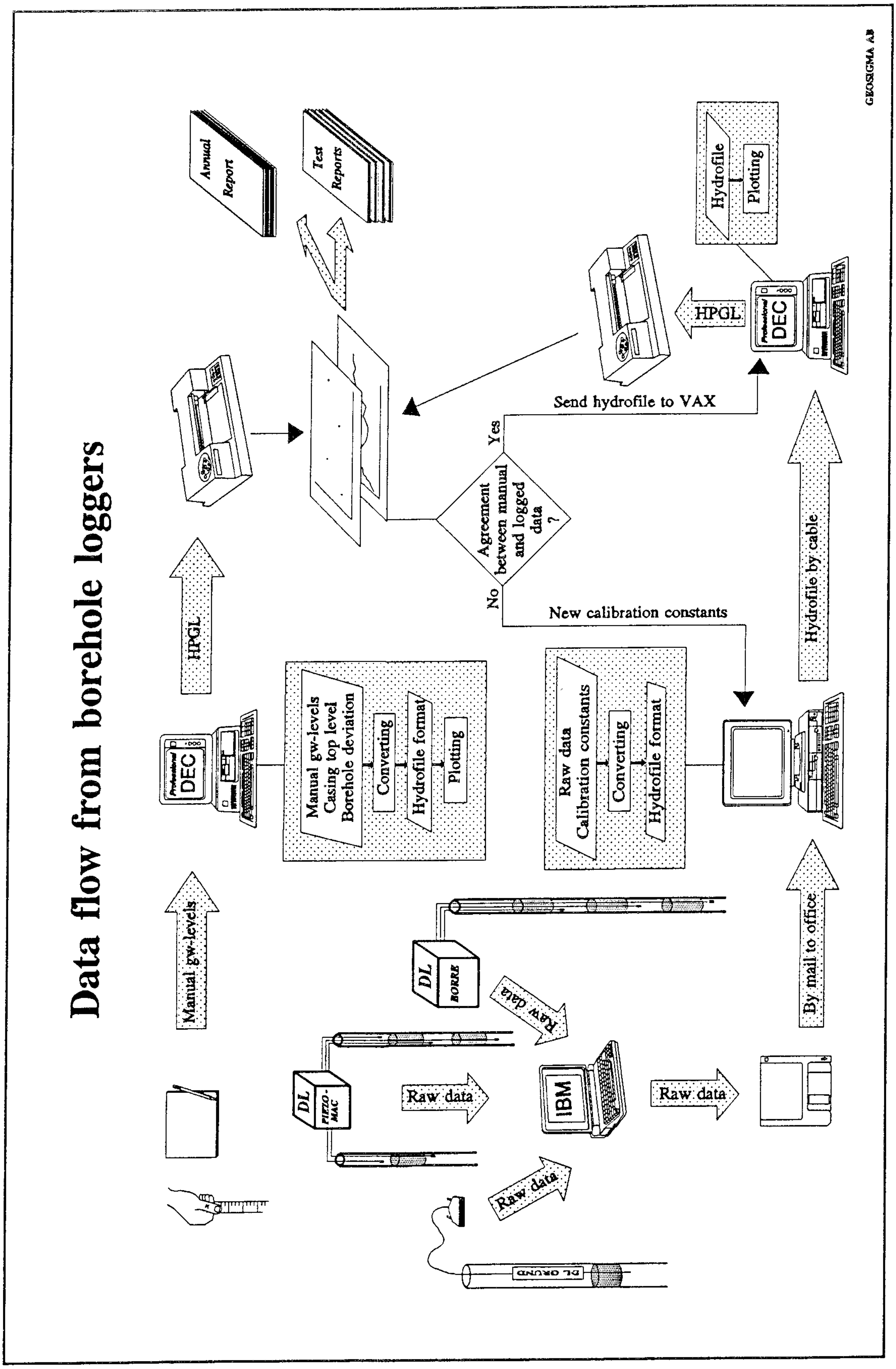


Figure 8.14 Diagram showing the data processing steps for groundwater monitoring.

8.7 Monitoring of ground water chemistry

Long-term monitoring of groundwater chemistry is carried out as well. The monitoring involves in-situ recording of fluid conductivity and groundwater sampling. The purpose of the chemical monitoring is to record changes in groundwater composition. In the case of borehole sections equipped with water circulation system, as described in section 8.4, samples are easily collected by means of running the miniature pump, see Figures 8.4 and 8.7. For other sections, equipped only with one pressure tube up to the surface and the smaller type of water stand-pipe, air-lift pumping from the water stand-pipes has to be performed, see Figure 8.6. This procedure is more time-consuming and does not give the same quality of the samples as from the circulating sections.

The programme for recording of fluid conductivity follows the same frequency as groundwater level monitoring during the pre-investigation phase, and probably during the construction phase as well. Sampling from monitored holes has been carried out during the pre-investigation phase on special occasions, such as during dilution and tracer tests and for determining the water density in the tubes, as mentioned in section 8.2.

A sampling programme will be defined for the construction phase, whereby approximately one sample will be taken every month for the "circulating" sections and every sixth months for the other sections.

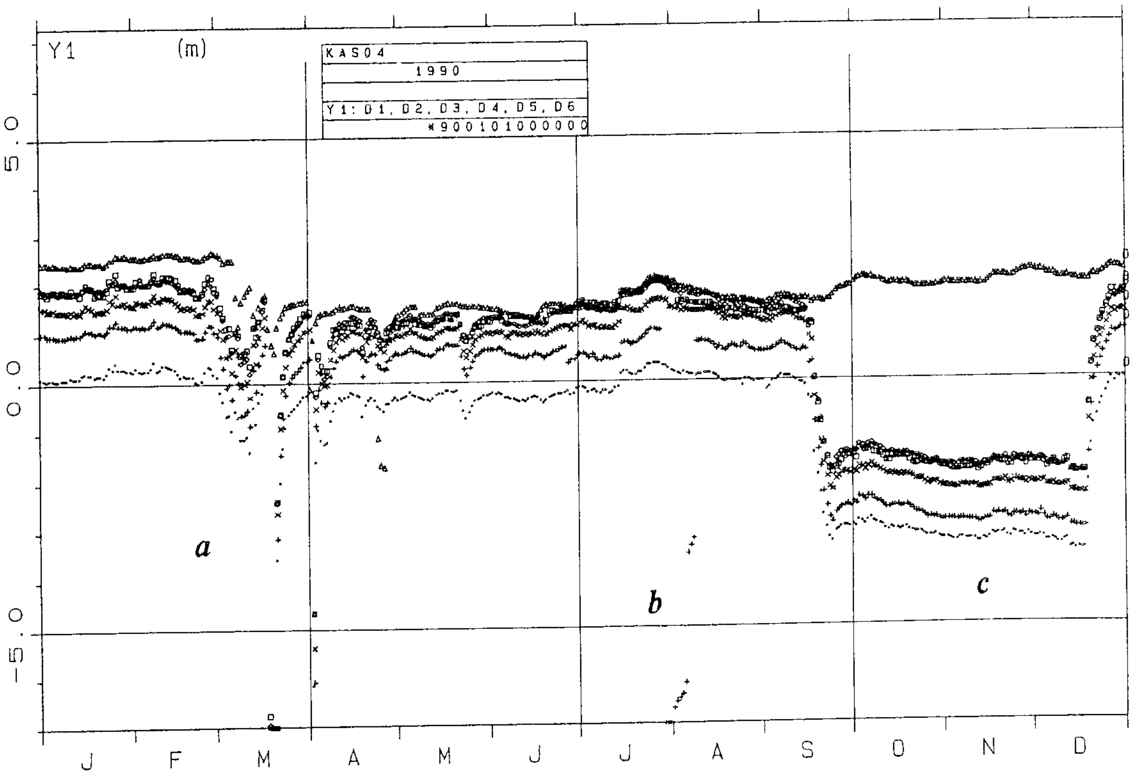


Figure 8.15 One year's recording of six monitored sections in borehole KAS04. Disturbing activities observed in the recordings are:

a. drilling of boreholes in the vicinity

b. dilution measurements in one section

c. draw-down caused by Long-term Pumping Test

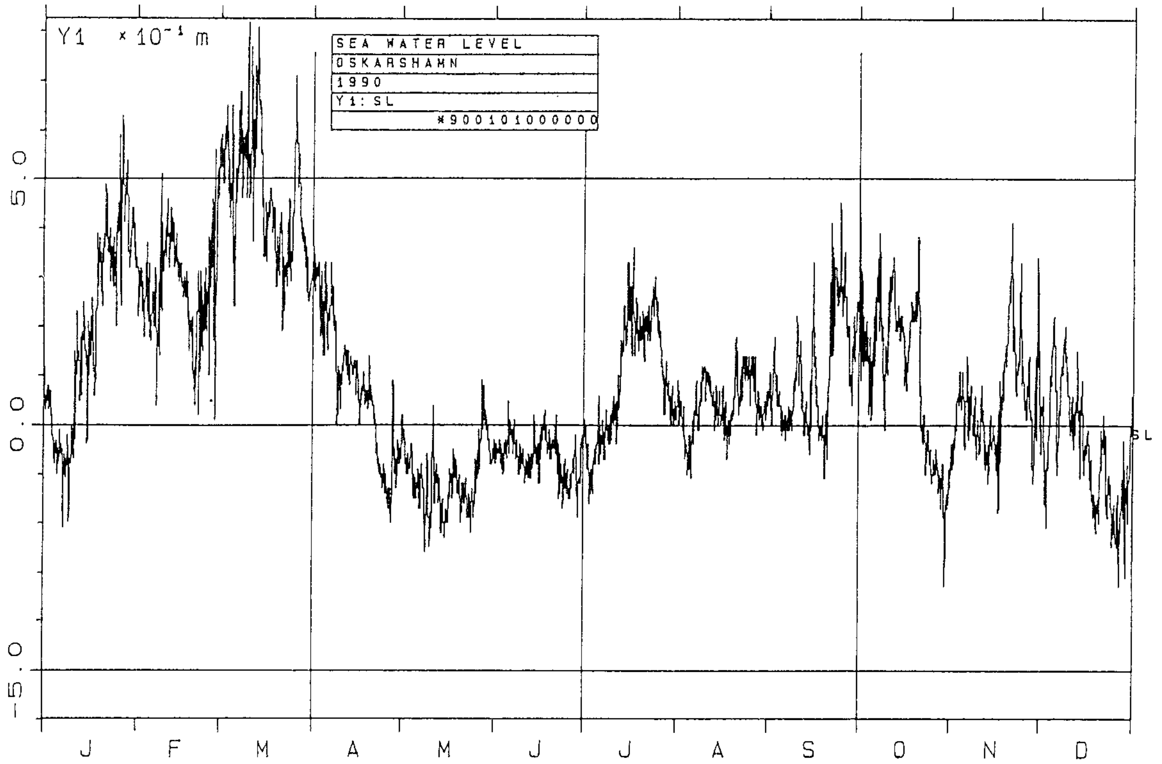


Figure 8.16 Graph of sea water level recording.

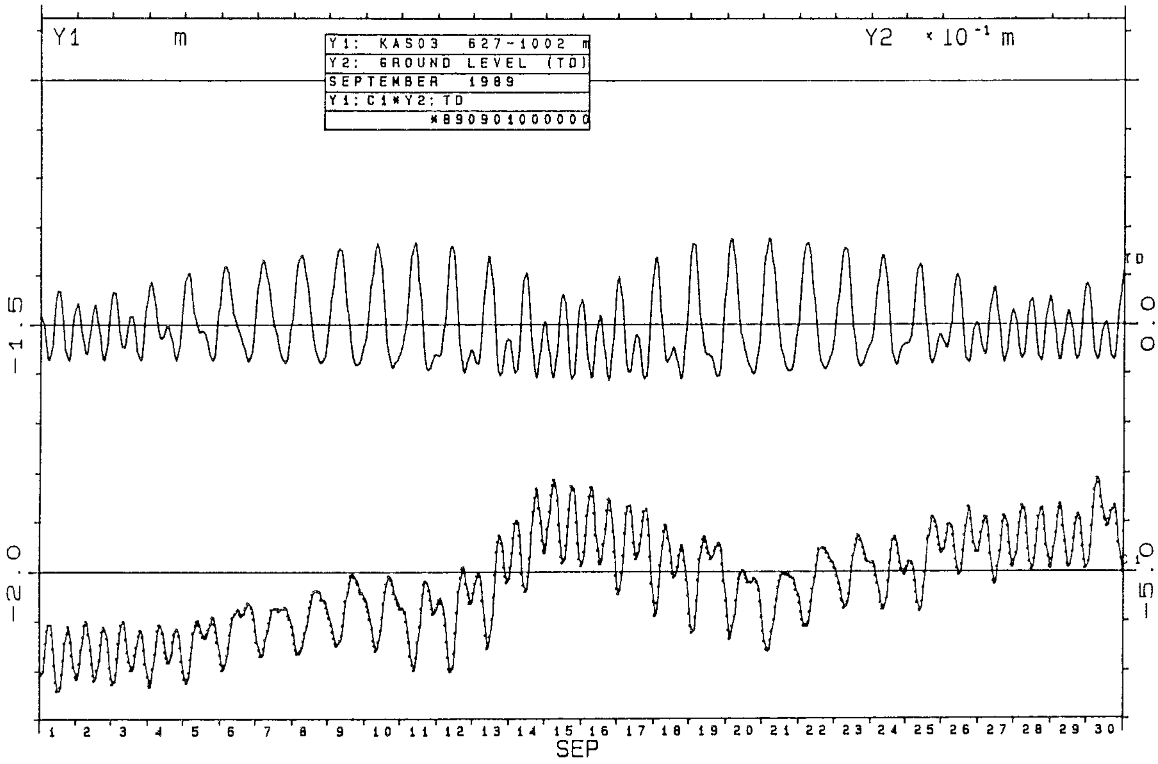


Figure 8.17 Tidal effects. The lower curve shows the observed groundwater fluctuations. The upper curve illustrates the earth tide, ground surface fluctuations, plotted from model calculations.

9. HYDROCHEMICAL INVESTIGATIONS

Hydrochemical investigation of a rock formation is important not only for characterizating the chemistry of the groundwater and understanding of its chemical interactions with minerals and waste elements. It is also a valuable tool for the characterization of the groundwater flow system and for an overall understanding of the groundwater hydrology in the formation, see Figure 9.1. In this chapter the groundwater sampling and analysis methodology used in the Pre-investigation phase of the Äspö Hard Rock Laboratory project are briefly described. In order to collect an appropriate amount of hydrochemical information, different types of samples have been taken at different stages of the investigations, and in conjunction with other measurements.

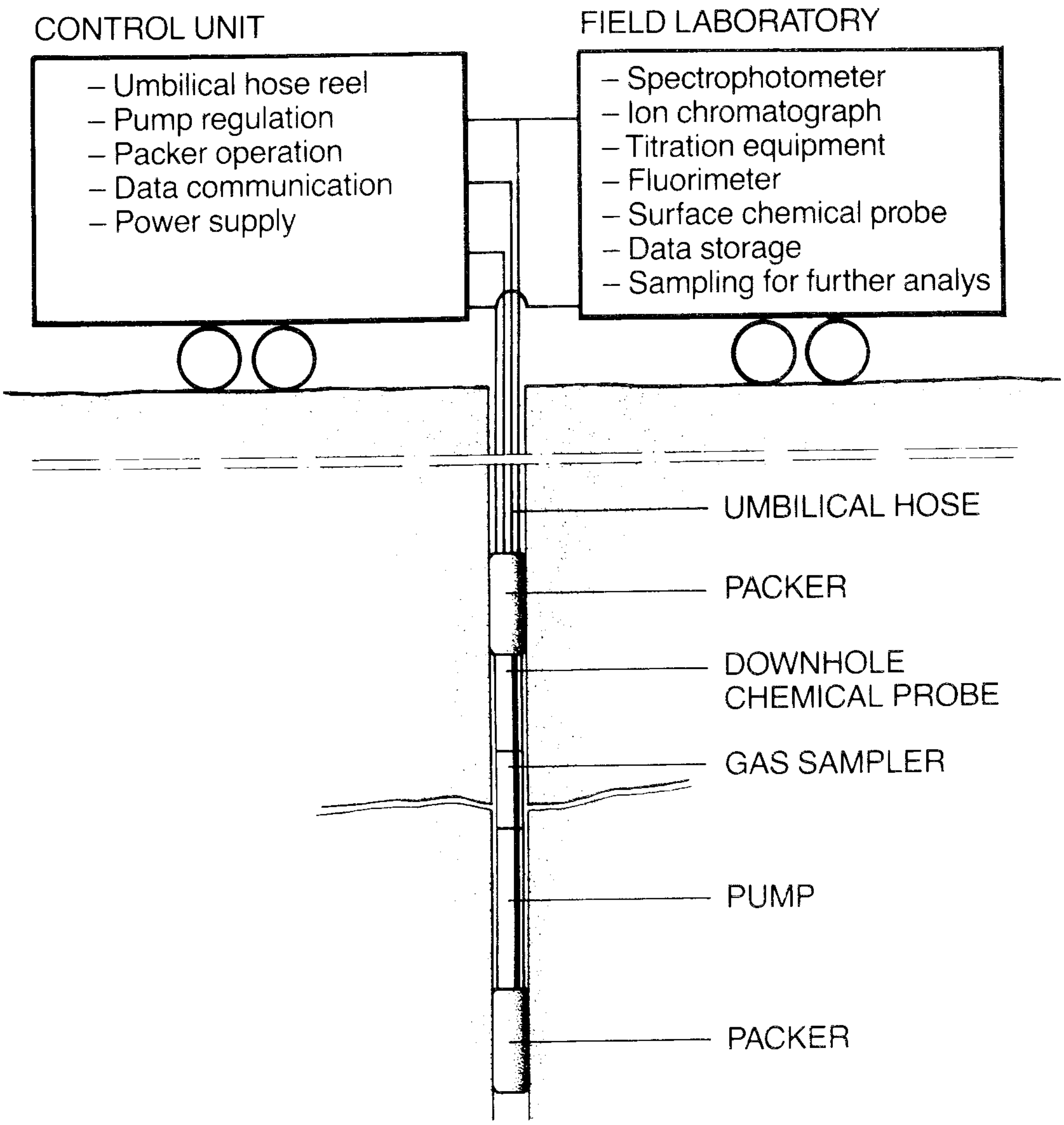


Figure 9.1 Illustration of advanced groundwater chemical investigations with the SKB mobile field laboratory.

9.1 Sampling during drilling

Drilling is the first activity in a borehole investigation programme. In addition to producing a hole to be used for later borehole investigations, drilling is of great value both for obtaining hydrological knowledge (as described in section 7.1) and for hydrochemical characterization to collect preliminary data already during the drilling activity. As regards hydrochemical conditions in particular, the drilling can disturb the groundwater by introducing drilling water into the formation. However, this effect has been reduced in the case of the core holes by means of the telescope-type drilling technique, see section 4.2.

9.1.1 Sampling during percussion drilling

In conjunction with the drilling of percussion boreholes in the Äspö HRL project, hydraulic tests were performed during an interruption in the drilling and after the drilling was finished, which means that tests were carried out at depths of approximately 50-75 m and 100-150 m, respectively (the actual depth depending on the total borehole depth). The testing technique used was air-lift pumping, as described in section 7.1.1, from which water samples were collected. These samples were normally used for analysis of the main chemical components.

9.1.2 Sampling during core drilling

Groundwater samples were collected during drilling of cored holes in conjunction with the hydraulic tests after each 100 m of drilling of the telescope-type boreholes, which is described in section 7.1.2. During air-lift pumping from the 100 m sealed-off section, water samples were taken both in the beginning and also after a certain pumping time when at least one volume of the entire borehole section and the drill pipe had been exchanged. The collected water has been analysed for to the following parameters /Laaksoharju and Nilsson, 1989/:

- drilling water content
- density
- potassium
- magnesium
- chloride
- silicon
- electrical conductivity
- sodium
- calcium
- bicarbonate
- sulphate
- pH

9.2 Sampling from percussion-drilled holes

Although groundwater samples from the deeper cored holes provides the most complete and correct information about the groundwater chemistry, sampling from percussion-drilled holes is important as a complement to the characterization of large rock volumes. Especially during early stages of a site investigation programme, when only percussion-drilled holes are available, these samples can be used for preliminary characterization.

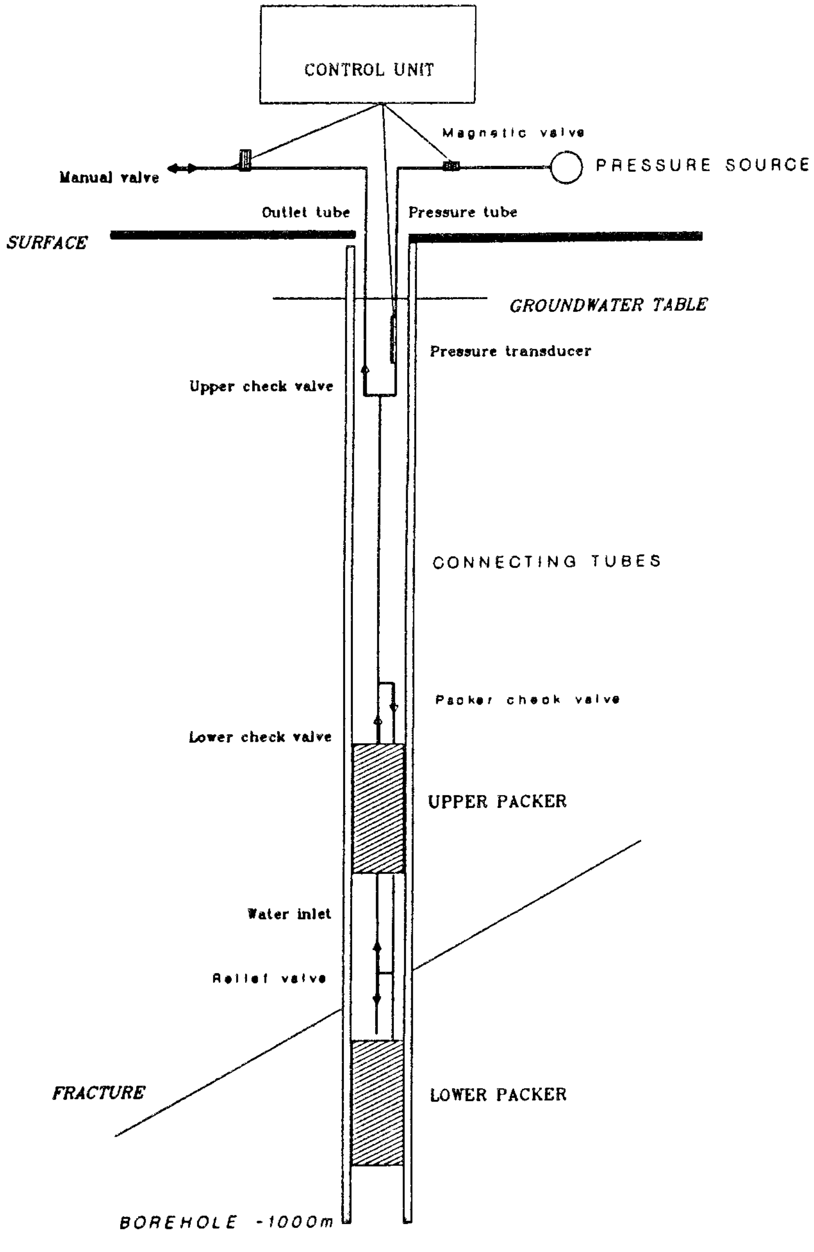


Figure 9.2 Schematic set-up of the light-weight sampling equipment used in percussion-drilled holes.

In the early stage of the pre-investigation phase of the Äspö HRL project, when only percussion holes were drilled, samples were taken from packed-off sections of these boreholes /Laaksoharju, 1988/. A light-weight sampling outfit was used for this purpose, see Figure 9.2. This equipment consists to a large extent of standard components and can easily be modified for different borehole diameters /Laaksoharju et al, 1991/.

The main down-hole component of the sampling equipment is the straddle-packer, which is operated from surface via a single tube, used both for packer inflation and for pumping up the water to the surface. This double function is possible due to the use of a pressure/manually-operated downhole changeover valve. When inflated, the changeover valve opens a connection between the tube and the section, so the equipment is set to the pumping mode.

Along the uppermost part of the single tube a second tube runs parallel to the first. Pumping is carried out by pulsing compressed air in one of the tubes. Via check valves at certain points in the system, water will then enter the tube from the isolated section, flow up and out at the surface.

The pulsation is automatically maintained by a control unit, by means of which the duration of each pump cycle can be adjusted. Pumping capacity is dependent on the depth to the pumped section, the length of the double tube and the water capacity of the formation, but will normally be in the range of 1-10 l/min.

9.3 Sampling during pumping tests

In conjunction with most of the pumping tests conducted in the Äspö HRL project - pumping tests after drilling, interference pumping test and Long-term Pumping Tests - groundwater samples were taken from the pumped water. Just as these hydraulic tests were conducted at different stages of the investigation process and for different purposes, the aim of water collection was also different for these cases.

Sampling during the first open hole pumping test, as described in section 7.2, provides an overall composition of the formation water, directly after drilling is completed. Measurements of the concentration of uranine in the water samples reflect the proportion of drilling water still remaining in the formation water, and how it decreases during the pumping period. Collected water from these pumping tests is normally analyzed with regard to the following parameters /Nilsson A-C, 1989/:

* drilling water content
* density
* potassium
* magnesium
* chloride
* silicon
* electrical conductivity
* sodium
* calcium
* bicarbonate
* sulphate
* pH

Interference pumping tests were carried out from a selected number of hydraulic conductors (normally fracture zones) in the telescope-type boreholes. The hydraulic conductivity of these sections is in the range of 10^{-6}-10^{-4} m/s, and the pumpings were carried out over a period of three days (see also section 7.5). As a large amount of water is pumped up during these tests the samples provide a good measure of the groundwater composition in these groundwater conductors.

During the interference pumping tests a small amount of the pumping water was led through a separate flow line into a surface chemical probe, the Chemmac surface probe, see Figure 9.3. The Chemmac surface probe contains electrodes for measuring Eh, pH, pS, O_2 and electrical conductivity. The surface chemical probe is a part of the mobile chemistry laboratory, which is described in section 9.4.

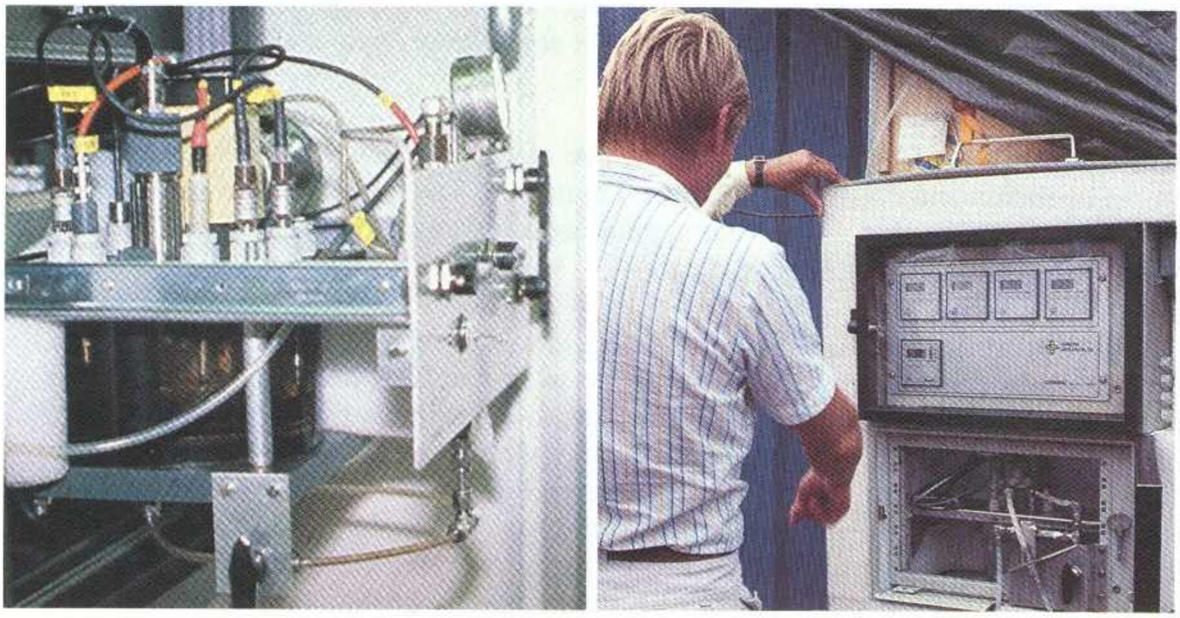


Figure 9.3 *Water flow from pumping are passing through the Chemmac Surface Probe of the mobile field laboratory (left), or the Chemmac Field Analyser (right), for recording Eh, pH, electrical conductivity and O^2.*

When the mobile field laboratory was not available another separate hydrochemical cell (the Chemmac field analyser) was used, which is similar to the Chemac surface probe in the mobile field laboratory.

Long-term Pumping Tests were carried out on two occasions during the pre-investigation phase of the Project, as described in section 7.6. These pumpings were carried out from an open hole in the central part of the investigation site for periods of two and three months, respectively. The groundwater collected during these tests is a mixture of formation water from several hydraulic units, fracture zones and from the rock matrix. No particular groundwater chemical analyses were made during the Long-term Pumping Tests, but water samples were taken for tracer analysis during the second test LPT, as was described in section 7.8.

9.4 Investigations with the mobile field laboratory

The measuring and analysis procedure is of great importance for high quality characterization of the groundwater. Some components of the groundwater have to be analysed as early as possible or measured in-situ. This is especially true of groundwater from relatively low-conductivity rock formations, where the pumping rate is normally very low and therefore also time-consuming. The characterization of very sensitive parameters such as pH, and Eh and the redox-sensitive components such as iron and manganese ion, sulphide and oxygen compounds is particularly improved by such early analysis.

The mobile field laboratory - developed in cooperation by the Royal Institute of Technology, IPA-konsult and Swedish Geological Co, on behalf of SKB - takes these factors into consideration, see Figure 9.1 /Wikberg et al, 1987/. In the Äspö HRL Project, investigations have been performed with this equipment in a large number of sections, most of them with hydraulic conductivities in the range of 10^{-8}-10^{-6} m/s. As the equipment is presented in detail in Almén et al /1986/, only a short description is given here.

The equipment is installed in two trailers, one of which contains the downhole tool, pump operation and hoisting system, see Figure 9.4. The other trailer contains a chemical laboratory and a computer system for communication with the down-hole probe and for recording chemical data.

The system works as follows: the down-hole tool including a straddle packer, pump, chemical probe and gas sampler is connected to an umbilical hose, similar to the one used for hydraulic injection tests, and lowered to a maximum depth of 1000 m in a 56 mm borehole. Pumping is then conducted from the packed-off borehole section by a downhole piston pump. The pump is hydraulically operated by water pressure from the surface. The maximum pumping capacity is 120 ml per minute, which means that relatively long pumping periods are needed before uncontaminated formation water has reached the surface. In other sections the water capacity of the formation is the limitation for the pumping rate.

Figure 9.4 *The two trailers of the mobile field laboratory, similar as the trailers of the Umbilical Hose System.*

At the sampling level the water is pumped through a downhole chemical probe, the Chemmac down-hole probe, see Figure 9.5. The probe contains electrodes for measuring the following parameters

* pH: pressure compensated glass electrode

* Eh:
 - gold electrode
 - platinum electrode
 - glassy carbon electrode (not always used)

* pS: solid Ag/Ag_2S electrode (not always used)

* reference electrode: Ag/AgCl double junction, gel-filled electrode

* temperature

* pressure

The probe also contains electronics for power supply, multiplexing and amplifying the signals, A/D conversion and serial data communication with the computer at the surface.

After passing through the Chemmac downhole probe the water passes through the umbilical hose up to another flow-through cell (Chemmac surface probe), which is situated in the chemical laboratory trailer, see Figures 9.3 and 9.6. The surface chemical probe is similar to the downhole probe. Besides the parameters measured in the downhole probe, electrical conductivity and dissolved oxygen are also measured in the surface probe.

Then the water passes through a 0.45 micron in-line filter in the uninterrupted flow line from the borehole section to the sampling point in the chemical laboratory. Water samples are taken both for direct analysis in the mobile laboratory and for supplementary analysis at other laboratories.

The field laboratory is equipped with the following instruments for chemical analysis of constituents, see Figure 9.7:

* ion chromotograph
* fluorimeter
* spectrophotometer
* titration equipment

The carbon-14 method is used for age determination of the groundwater. The amount of carbon-14 needed (from carbon in carbonate) for the analysis is expelled as carbon dioxide from some 130 l of water sample, acidified with HCL. The CO_2 is then trapped in a one litre wash-bottle and sent to an isotope laboratory.

In addition to the use of high-qualitaty instruments, high accuracy in the chemical analyses is dependent on having the right internal environment in the laboratory. A constant temperature is maintained and the air is kept clean by electrostatic filters in the ventilation system.

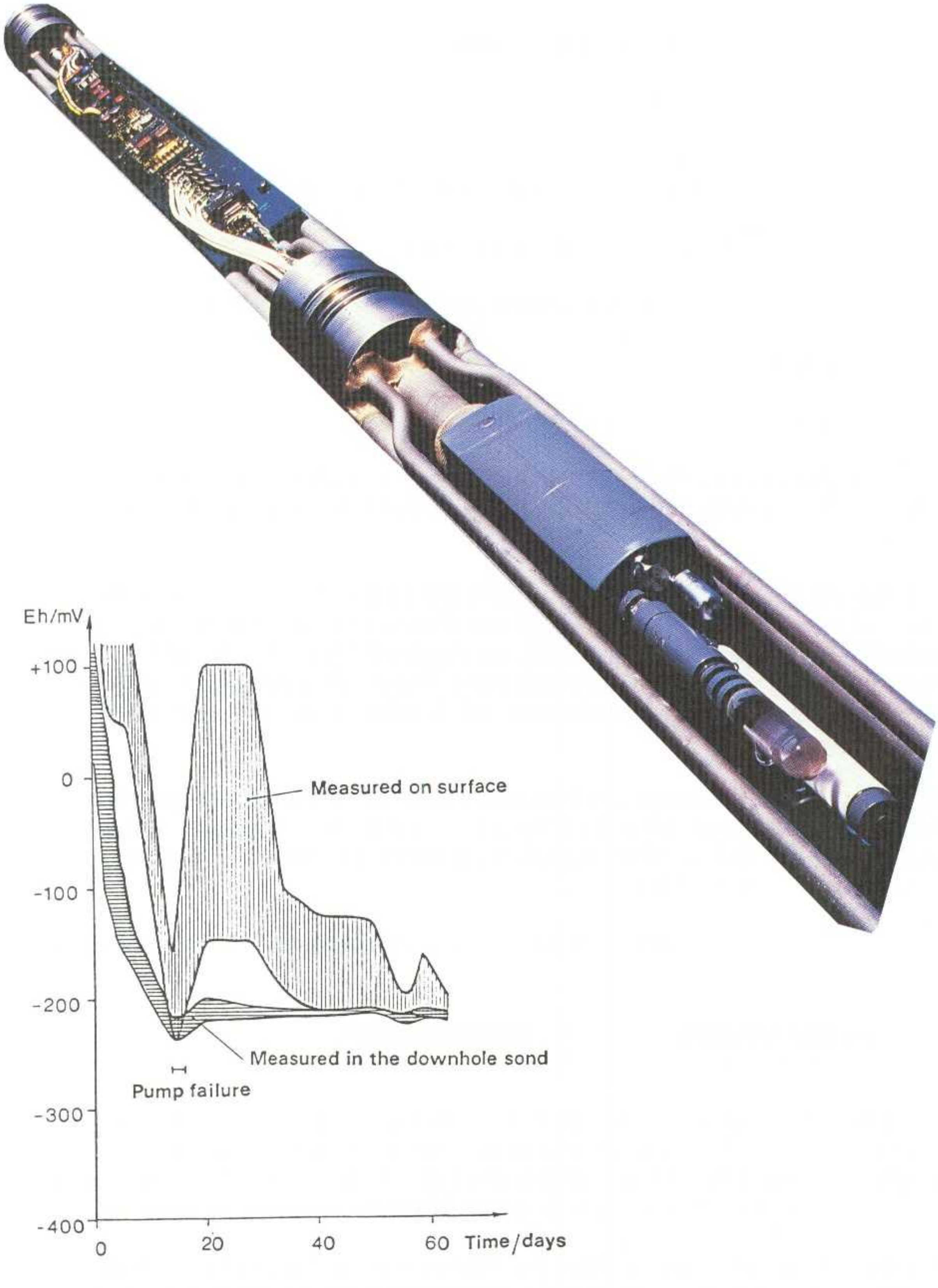


Figure 9.5 *The Chemmac Down-hole Probe, and graph illustrating down-hole and surface recording of Eh.*

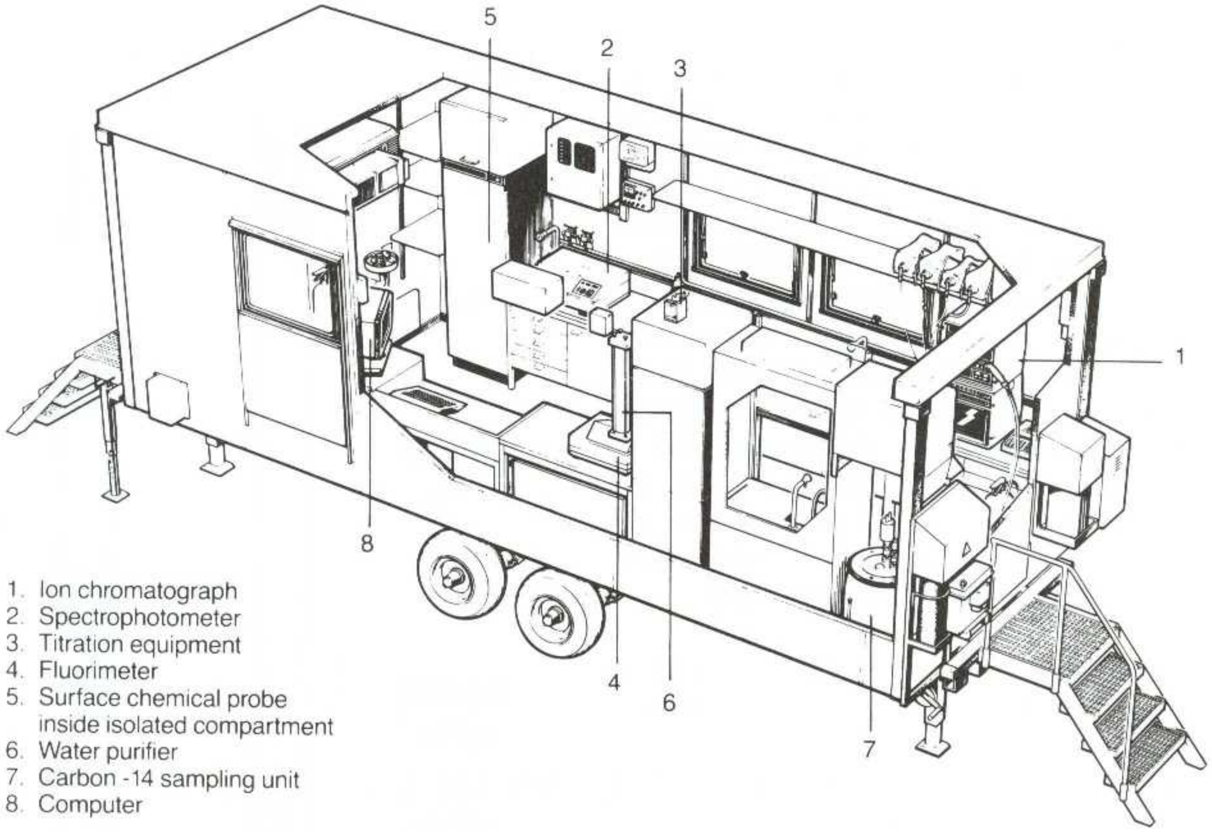


Figure 9.6 Principle layout of the chemical laboratory trailer.

Figure 9.7 Water chemical analyses in the mobile laboratory.

In-situ water sampler

As an integrated part of the borehole tool, a special water sampler (also called "gas sampler") is used for quantitative analyses of gases dissolved in the groundwater, see Figure 9.8. When the field measurements indicate good quality of the pumped water, stable conditions and low concentration of drilling water (uranine), the sampler is activated. After reclosing, the stainless sampling cylinder keeps the water sample isolated under natural pressure conditions during transport to a laboratory. In the laboratory the water is transferred to a vacuum chamber so that all gases dissolved in the water are released and can subsequently be analysed in a gas chromotograph.

On each sampling occasion two samples were taken, one for the gas analysis described above and one for microbe analysis. The microbe samples were taken for identification of possible microbiological activity in deep groundwater.

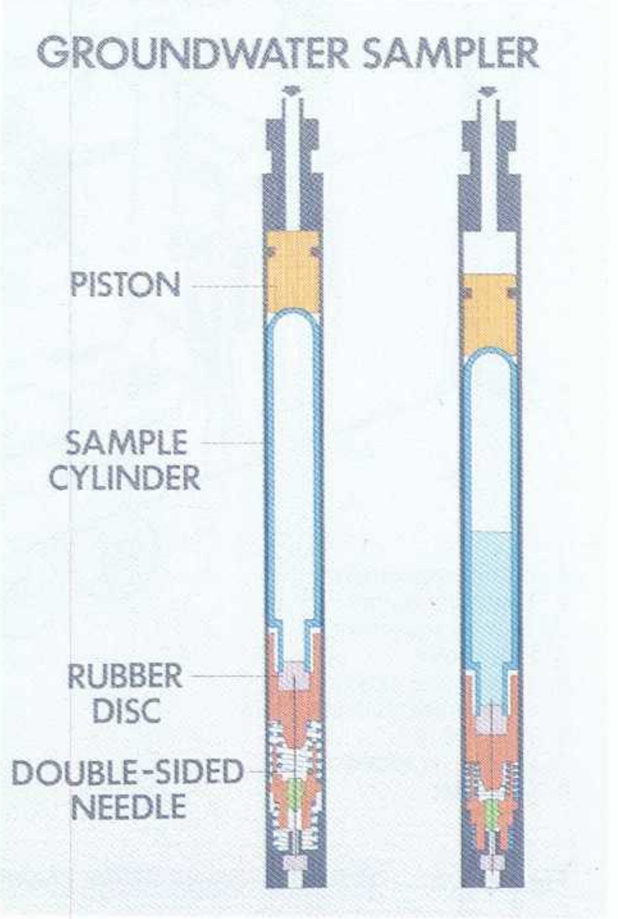


Figure 9.8 The principle function of the in-situ water sampler.

The mobile field laboratory is normally used to measure and analyse the following parameters and constituents in groundwater pumped out from an isolated borehole section:

* downhole probe: pH, Eh, (pS), temperature, pressure

* surface probe: pH, Eh, (pS), $p0_2$, electrical conductivity, temperature

* analysis in field laboratory
  - drilling water content: uranine
  - dissolved elements: Na, K, Ca, Mg, HCO_3, Cl, SO_4, SiO_2, Fe^{2+}, Fe^{Tot}, HS-, Mn^{2+}

* analysis at other laboratories
  - dissolved elements: U, Ra, Rn, Th, trace elements
  - filter residues: Ca, Fe, Al, Si, S
  - isotopes: ^{2}H, ^{3}H, ^{13}C, ^{14}C, $^{18}0$, $^{238}U/^{234}U$
  - organics: TOC

* Gases: N_2, H_2, 0_2, CH_4, He

10. ROCK STRESS MEASUREMENTS

Knowledge of stress situation in the rock is of importance for understanding groundwater flow behaviour in fractures and fracture zones. Rock stresses, directions and magnitudes are also taken into account in the planning and design of the underground structures, as this may affect the stability of the underground facility. Two different methods for rock stress measurements in deep boreholes are available and have been used in some of the Äspö Hard Rock Laboratory boreholes; the hydraulic fracturing method and the overcoring method.

10.1 Hydraulic fracturing method

The principle of the hydraulic fracturing method is to induce a new fracture in the borehole by means of high water pressure. The magnitudes of the stresses are determined from the pressure-time records obtained when inducing and pressurizing a fracture in the borehole wall. The direction of the stresses are obtained from orientated imprints of the induced fractures.

The equipment layout for carrying out hydraulic fracturing is shown in Figure 10.1. Water is pumped down to the borehole section, which is isolated with packers by means of a high pressure pump. In order to raising and lowering in the boreholes and regulating and measuring the water injection, a complete hydraulic fracturing system has been designed by the Luleå University of Technology, with funding from SKB /Bjarnasson and Torikka, 1989/. All components are built together and mounted on a truck. The equipment is easily hoisted by means of a multihose, which includes not only pressure tubes for water injection and packer inflation, but also electrical cables for signal transmission from the downhole pressure transducer. Packers and water flow/pressure are controlled independently on a control panel.

The capacity of the three-cylinder piston pump is 15 l/min at a pressure of 100 MPa. Pressure on the surface as well as down-hole and flow rates are continuously monitored and plotted on both analogue and digital data acquisition systems.

The direction of the induced fracture is measured by means of an impression packer tool, also including a compass and a single-shot camera. The impression packer tool is operated via the multihose. As an alternative for determining the fracture direction, a borehole TV can be used.

The testing procedure for a hydraulic fracturing test is as follows, see also Figure 10.1:

1. Lowering of packer system to test section and inflation of packers.
2. Pressurization of the isolated borehole section until fracturing of the borehole wall is recorded.
3. Cyclic reopening of the induced fracture.
4. Deflation of packers and hoisting of packer system.
5. Lowering of orientation device to the measuring section.
6. Inflation of impression packer and actuation of camera.

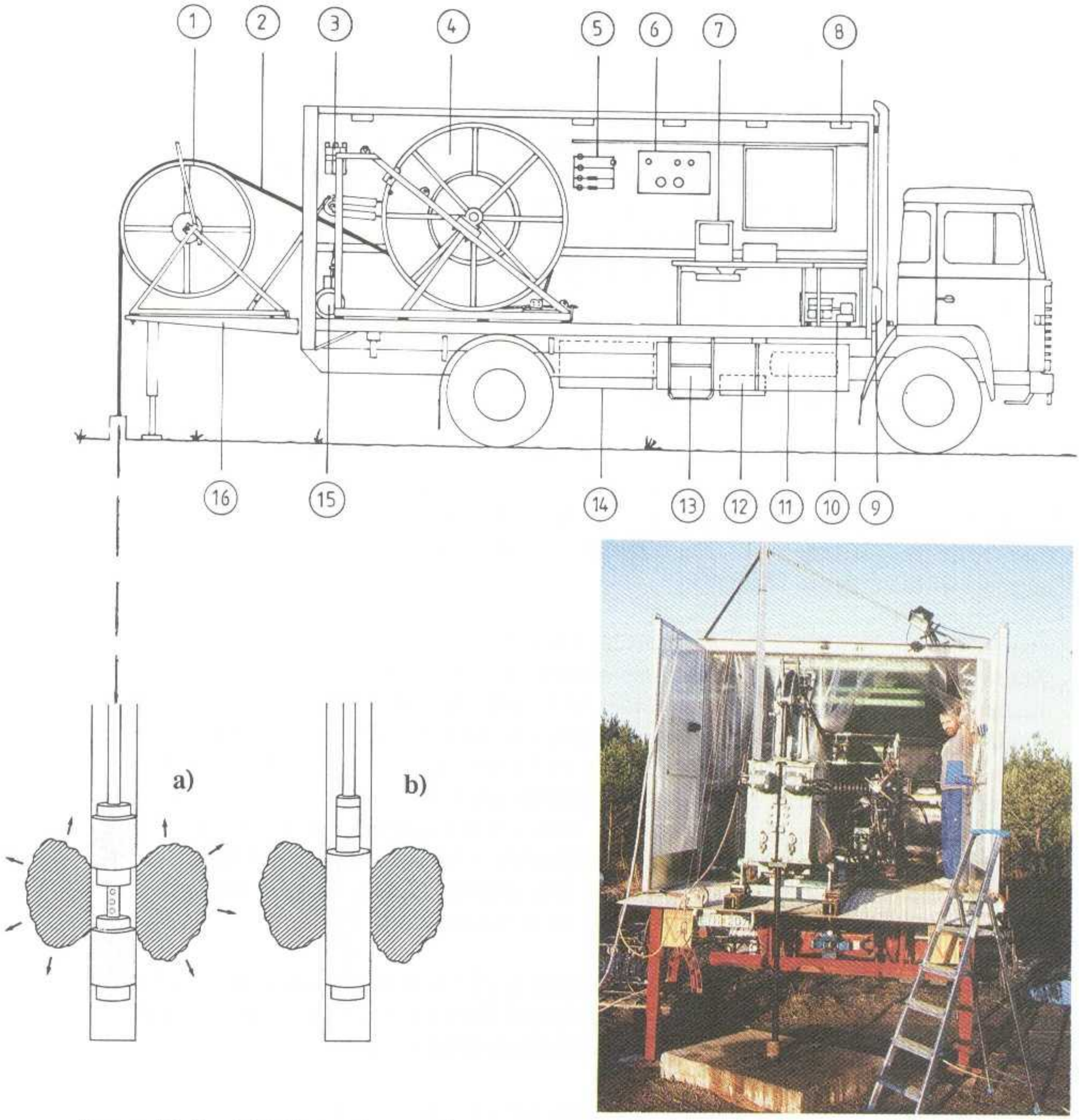


Figure 10.1 *Mobile equipment for rock stress measurements by means of hydrofracturing. Packer configuration during a) fracturing and b) fracture orientation.*

- *1 Guidewheel for multihose*
- *2 Multihose*
- *3 Control unit of the hydraulic system*
- *4 Drum for multihose*
- *5 Flow meters*
- *6 Manifold for control of fracturing flow and packer pressure*
- *7 Data acquisition system*
- *8 Working lights*
- *9 Cabin heater*
- *10 High pressure water pump*
- *11 Compressed air tubes*
- *12 Hydraulic pump*
- *13 Diesel fuel tanks*
- *14 Hydraulic tank*
- *15 Winch*
- *16 Working platform, adjustable height and inclination.*

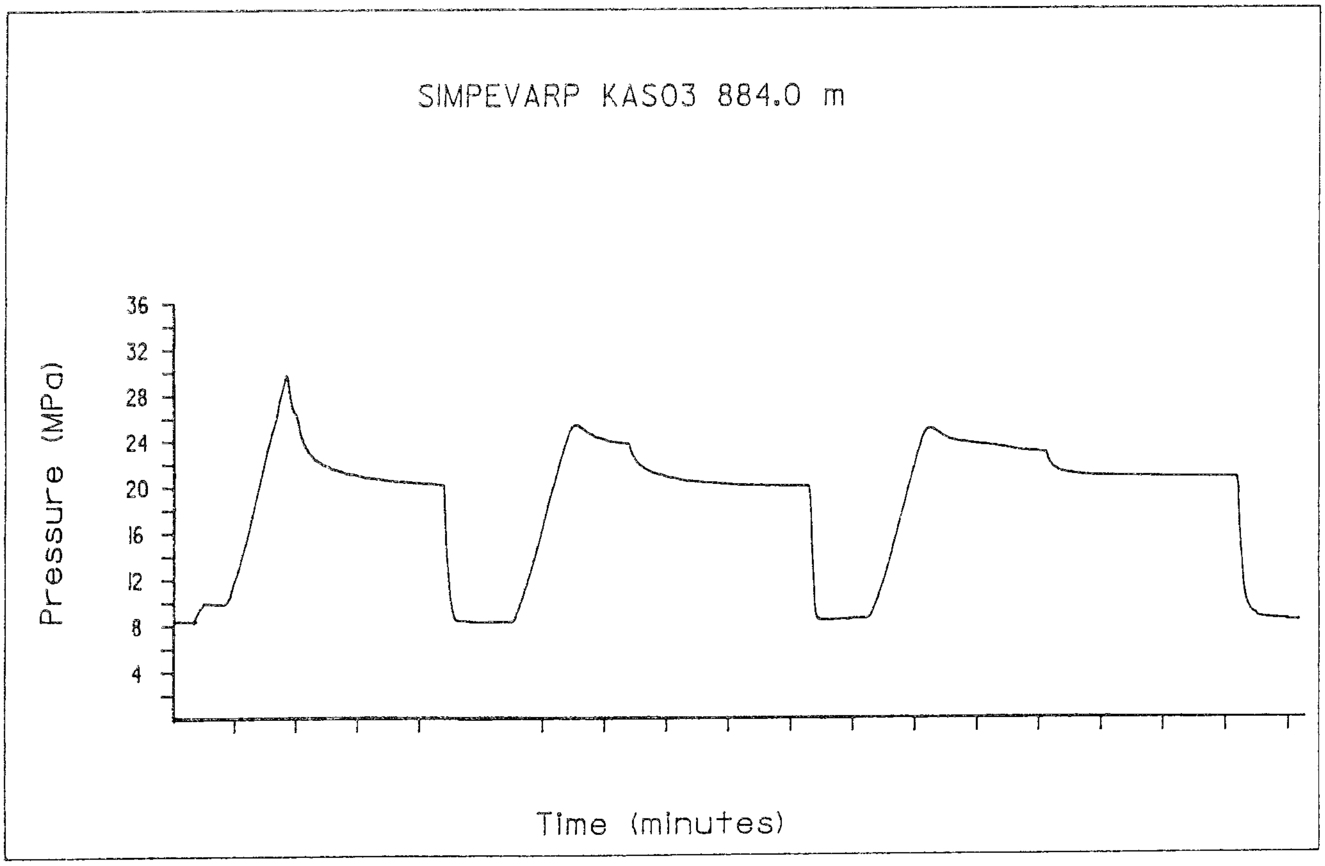


Figure 10.2 Example of recordings from hydraulic fracturing for rock stress measurements in the Äspö borehole KAS03.

7. Deflation of packer and hoisting to surface.
8. Detection of fracture mark on the impression packer and development of camera film.
9. Determination of rock stress magnitudes and direction by analyses of pressure records and orientation data from 3 and 6 above.

The rock stresses are calculated from the pressure-time record, Figure 10.2, by determining the pressure at which the fracture initiates (breakdown pressure) and the pressure corresponding to the equilibrium between the fluid pressure in the fracture and the stress acting normal to the hydrofracture plane. From these parameters and the tensile strength of the rock, it is then possible to calculate the stresses in the plane perpendicular to the borehole axis. The method is preferably used in vertical boreholes as one of the principal stresses is assumed to be parallel to the borehole axis. In such a case, the method allows the maximum and minimum horizontal stress to be determined, whereas the vertical stress is normally assumed to be equal to the weight of the overburden.

The hydraulic fracturing method has been used in two boreholes in the Äspö Hard Rock Laboratory project /Bjarnasson et al, 1991/. The rock stresses were determined at 38 points, down to a maximum depth of 970 m.

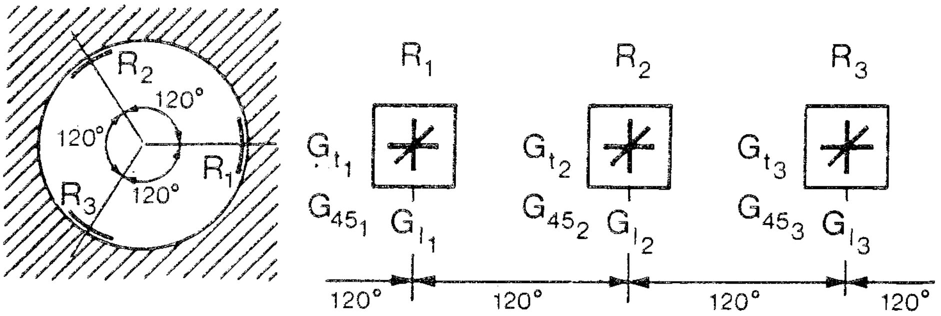


Figure 10.3 *Arrangement of the strain gauges in the small borehole according to Leeman and Hayes (from Hiltscher et al /1979/)*
a. *Arrangement of the rosettes R_1, R_2 and R_3 in the borehole*
b. *Position of the nine gauges G, seen from outside.*

10.2 Overcoring method

The overcoring method for in-situ rock stress measurements is based on strain gauge registrations of the stress release (core deformation) caused by overcoring. The 3-D state of stress is measured at each chosen measuring point. The measurements are performed in conjunction with the drilling of the borehole. With equipment developed by the Swedish State Power Board, measurements can be carried out in deep boreholes with a minimum diameter of 76 mm, yielding a core diameter of 62 mm.

The equipment is designed for rock stress measurements according to the Leeman-Hiltscher method /Hallbjörn et al, 1989/. Three strain gauge rosettes are cemented to the wall of a small pilot hole, see Figure 10.3. The natural rock stresses will be released in the resulting tabular core when the pilot hole with installed strain gauges is overcored. Based on the measurements of strains in the nine strain gauges before and after the overcoring, the triaxial stress situation can be determined.

In order to increase the accuracy of the measurements the probe has been further improved by incorporating a borehole datalogger. The strain gauges are monitored continuously during the overcoring process with this "computer probe".

The rock stress measurements by means of the described overcoring method are carried out according to the following procedure, see also Figure 10.4.

1. A borehole with a diameter of 76 mm or more is drilled down to the depth of the measurement.
2. A small (36 mm) pilot hole is drilled at the bottom of the larger borehole. The pilot hole is centred very precisely and cored to a length of approximately 400 mm.
3. The core from the pilot hole is inspected for determination of a suitable measuring point.
4. Glue is mixed an poured into the glue pot of the probe. The probe with strain gauges, electronics and datalogger, glue and cementing mechanics is lowered down to the measuring position, with a wire rope.

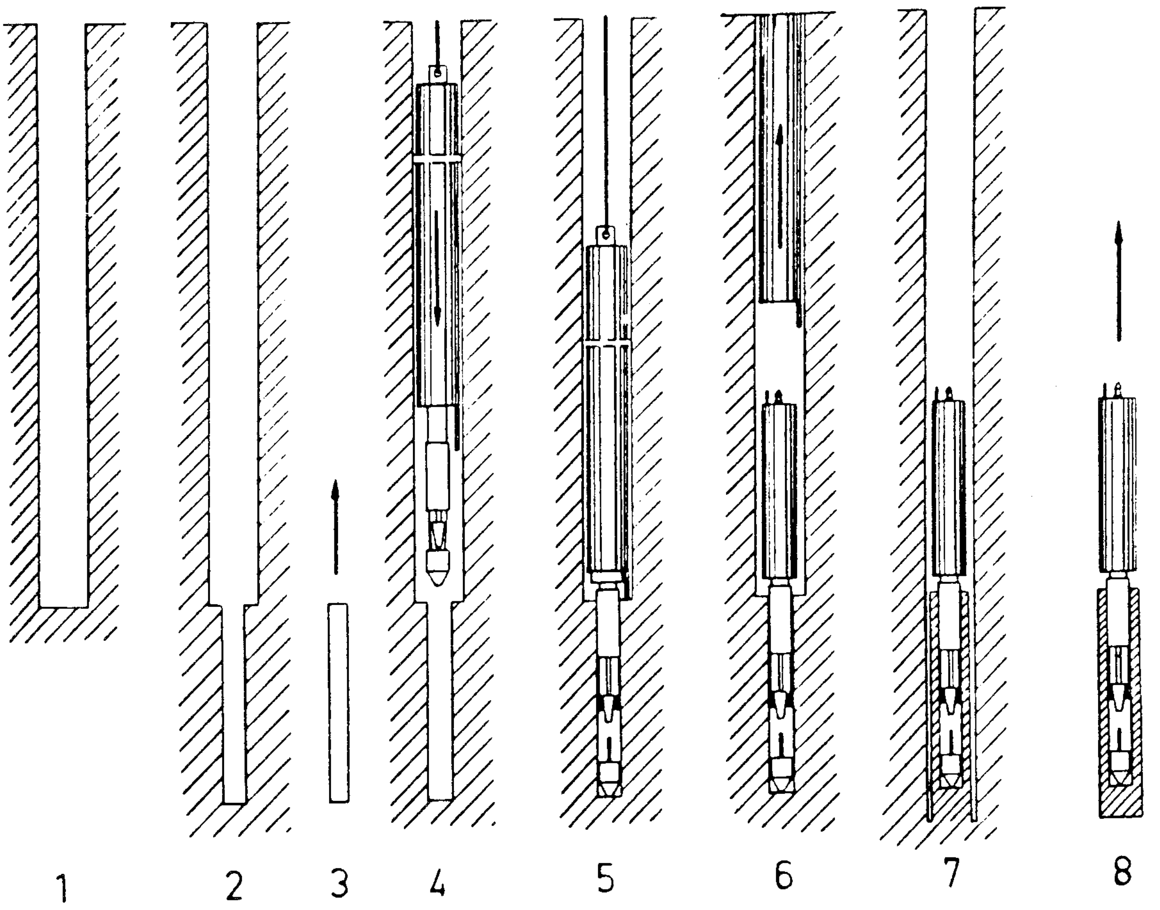


Figure 10.4 Operations in borehole for overcoring measurements

1 76-mm borehole
2 36-mm pilot borehole
3 small core
4 lowering the probe
5 cementing gauges to the small borehole wall under pressure from the cone
6 hoisting the adapter
7 overcoring, giving a core of 62 mm
8 hollow core pulled off and hoisted. Data transferred to the computer

5. The strain gauge rosettes are glued onto the pilot hole wall. When the glue has hardened, the first measurement is made.
6. The probe carrier with cementing mechanism is hoisted, leaving the data recording devices in the hole.
7. Overcoring is done with a 76 mm diameter core bit. Stress release is recorded by the strain gauges on the downhole data logger, see Figure 10.5.
8. The hollow core and the recording equipment are hoisted. The values are transferred from the borehole data logger to a computer for interpretation of magnitudes and directions of the three principal stresses.

The equipment is designed to conduct measurements in vertical or inclined boreholes down to 1 000 m. However, the difficulties increase with increased depth, the cementing of strain gauges being the most critical. So far the method with the computer probe has been successfully used down to 450 m depth, and to 670 m with the cable equipment probe (before development of the computer probe).

The overcoring method has been used in one borehole in the Äspö Hard Rock Laboratory. 3-D rock stress situation was determined at two levels of the borehole, 195 m and 355 m /Bjarnason et al, 1989/.

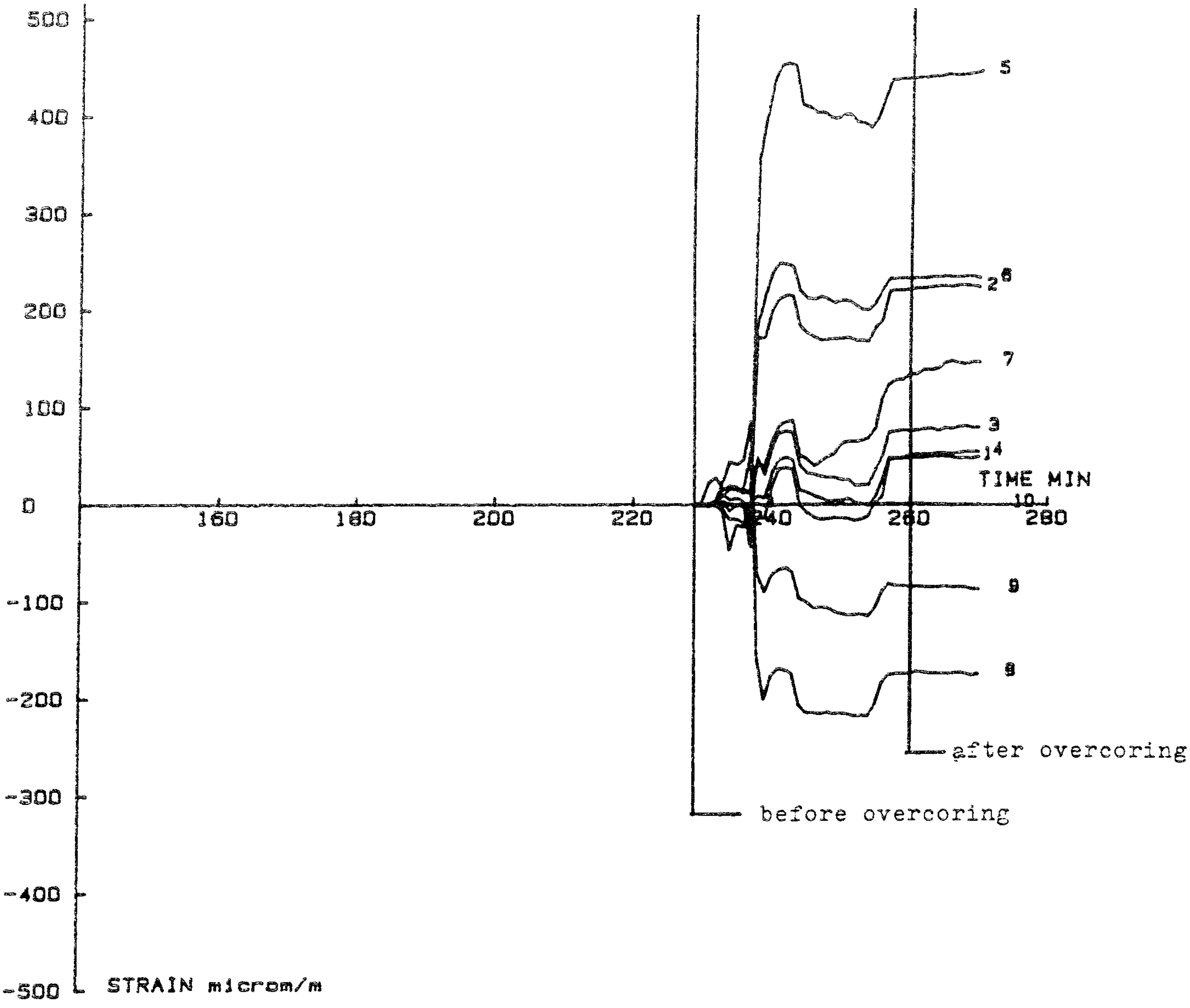


Figure 10.5 Illustration of continuously recording of the strain gauges during overcoring in borehole KAS05.

11. DATA STORAGE

During the course of a site investigation programme, a large amount of data are collected, refined, interpreted etc at different steps of data flow chains. The final results of a data flow chain, such as calculated or determined parameters, can be used as input data for further processing in additional data flow chains, as in the case of multivariate analysis and numerical modelling. It is very important that each step in the data processing chain be well documented and that data storage be well organized.

For the proper handling of all collected and interpreted data from the Study Site investigations performed by SKB during the period 1977-1986, as well as other geoscientific research projects carried out by SKB, a computerised database has been developed, the GEOTAB database. Data from most of the pre-investigations of the Äspö Hard Rock Laboratory are stored in the GEOTAB database, which will be described very briefly in this chapter.

11.1 The GEOTAB database

The development of the GEOTAB was initiated in 1986 and the first data were stored in 1987 . GEOTAB is built around a relational database system from Mimer Information System, with application programs developed for SKB by Ergodata /Eriksson et al, 1991/.

All data in GEOTAB are stored in tables. In order to make retrieval from the tables easier, they are organized in a structure where data from different geoscientific fields are grouped together under subjects, see Figure 11.1. Each subject is subdivided into methods, each method including data from one type of measurement or calculation, see Figure 11.2.

There are two types of tables. One is called flyleaf and describes what kind of data are stored in the method and how data have been collected and processed. The other type of table is the real data table containing columns of data.

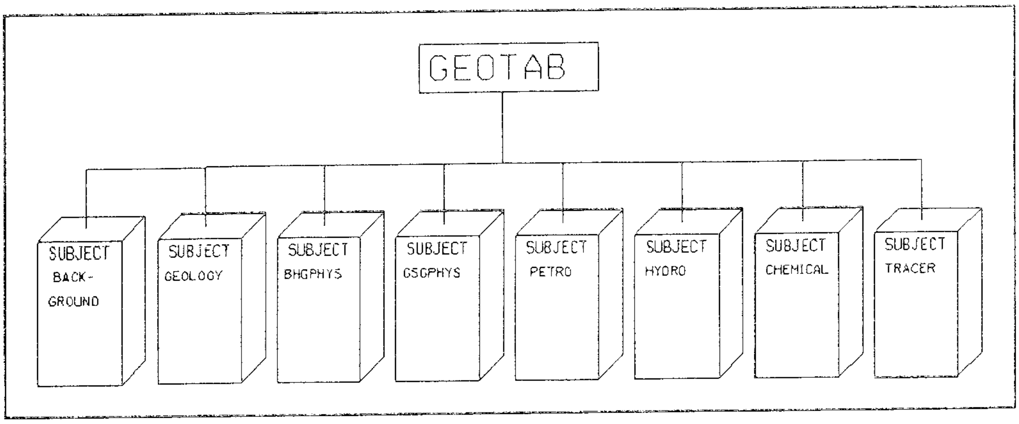


Figure 11.1 The structure of the GEOTAB database.

The GEOTAB structure contains the following subjects, see also Figure 11.1:

* BACKGROUND	Background data: provides information on the (BGR) locations of the areas studied, borehole positions and also some drilling information.
* GEOLOGY	Geological data: provides information on geological surface and borehole investigations, at present six methods containing data and one method containing lexicon data.
* GSGPHYS	Ground surface geophysical data: provides information on all geophysical investigations performed at the ground surface
* BHGPHYS	Geophysical borehole logging data: provides information on geophysical investigations carried out in the boreholes.
* PETRO	Petrophysical measurements: provides information on physical properties, obtained from laboratory measurements of rock samples from the surface and from drill cores.
* HYDRO	Hydrogeological data: provides information on all hydrological investigations. The subject is at present divided into fifteen methods, of which eleven are related to investigations performed, while the other four methods comprise data that have been calculated on the basis of results from the other methods.
* CHEMICAL	Chemical characterization of deep groundwater: provides information on the groundwater characterization methodology and results of measurements, analysis and calculations from analytical data.

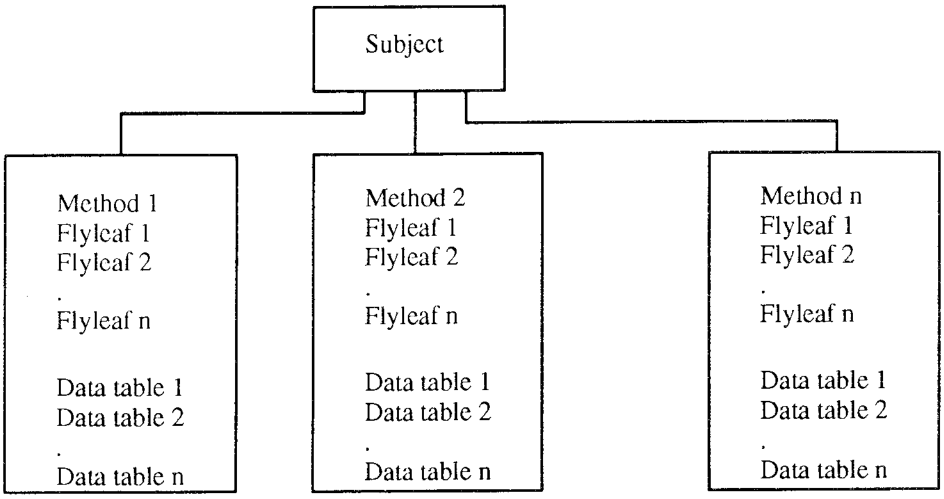


Figure 11.2 The structure of a subject in the GEOTAB; a group of methods, each method containing flyleafs (description of the method) and data tables.

* TRACER	Tracer tests: provides information from different kinds of tracer experiments.
* DOC	Documentation and reports: provides information on documentation and reports.

The GEOTAB structure is not static but will be added to with supplementary tables, methods and/or subjects when new investigation and interpretation techniques are introduced.

GEOTAB is run on a VAX computer. GEOTAB can be accessed via the SKB computer network - which also includes a CONVEX (used for numerical calculations), SUN computers and PCs - from SKB offices, universities and consulting companies contracted for SKB geoscientific research, see Figure 11.3. Via this network, GEOTAB is not only used for final storage of data, but also as a source for different kinds of postprocessing. The data requested by the researcher can be converted into different file formats, such as ASCII, dBase III+, HPGL, MIO, NCSS, Symphony etc.

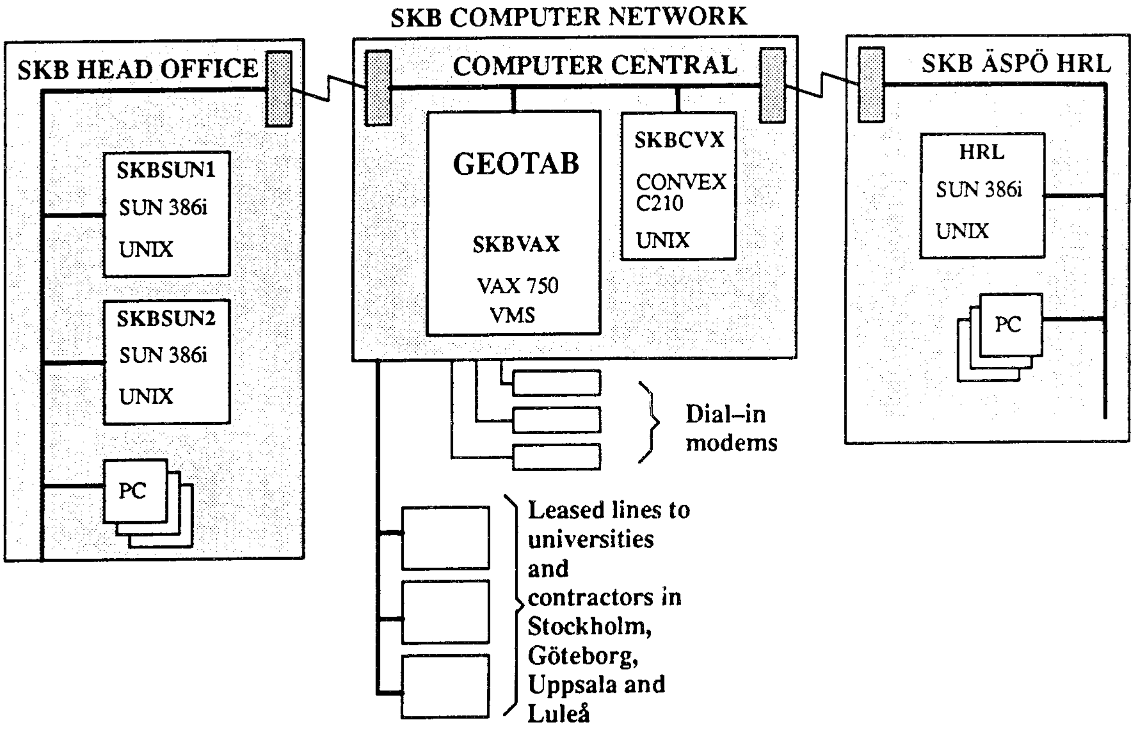


Figure 11.3 *The SKB computer network. (The lokal network at Äspö HRL came into operation in 1991).*

11.2 Data storage in the GEOTAB

Almost all geoscientific data collected or determined within the SKB research programme are available through the GEOTAB database. The data from most measurements or calculations are stored on an active disc. Raw data are more commonly stored on magnetic tapes and can be transferred to the computer on request. Other kinds of data cannot be transferred to the GEOTAB data media, such as geological maps, special kinds of measurements like radar etc. However, also these methods are defined in GEOTAB and described in flyleaves with references to where the actual data are stored (external computer systems, drawing archives, reports etc).

The idea is to store the data in GEOTAB as soon as possible after measurements, calculations or other kind of data processing. However, all data must have undergone quality control before being entered into the GEOTAB, and checked after being entered, before they are approved for further use. The entire data flow chain, from the raw data collection to the data storage, must be well documented, see Figure 11.4.

The following section briefly describes how data from measurements are stored in GEOTAB. The description follows the GEOTAB structure of subjects, see section 11.1.

Background data (BGR)

This subject contains information on the

- investigation site: name of reference maps, description of fix points and coordinates, grid-net used etc.

- boreholes: borehole name, coordinates, drilling method, diameter, length, deviation, events etc. All these data are stored on an active disc.

For detailed information on this subject, refer to Eriksson and Sehlstedt /1991/, see Figure 11.5.

Geological data (GEOLOGY)

This subject includes:

- geochemical analysis of rock samples taken from the surface as well as from drill cores, stored on an active disc.

- core logging data, most of them collected by the Petro Core system, from which data files are transferred to GEOTAB and stored on an active disc.

- fracture data from the surface, collected from outcrops, are stored as fracture frequency along sampling lines, stored on an active disc.

For detailed information on this subject, refer to Sehlstedt and Stark /1991/.

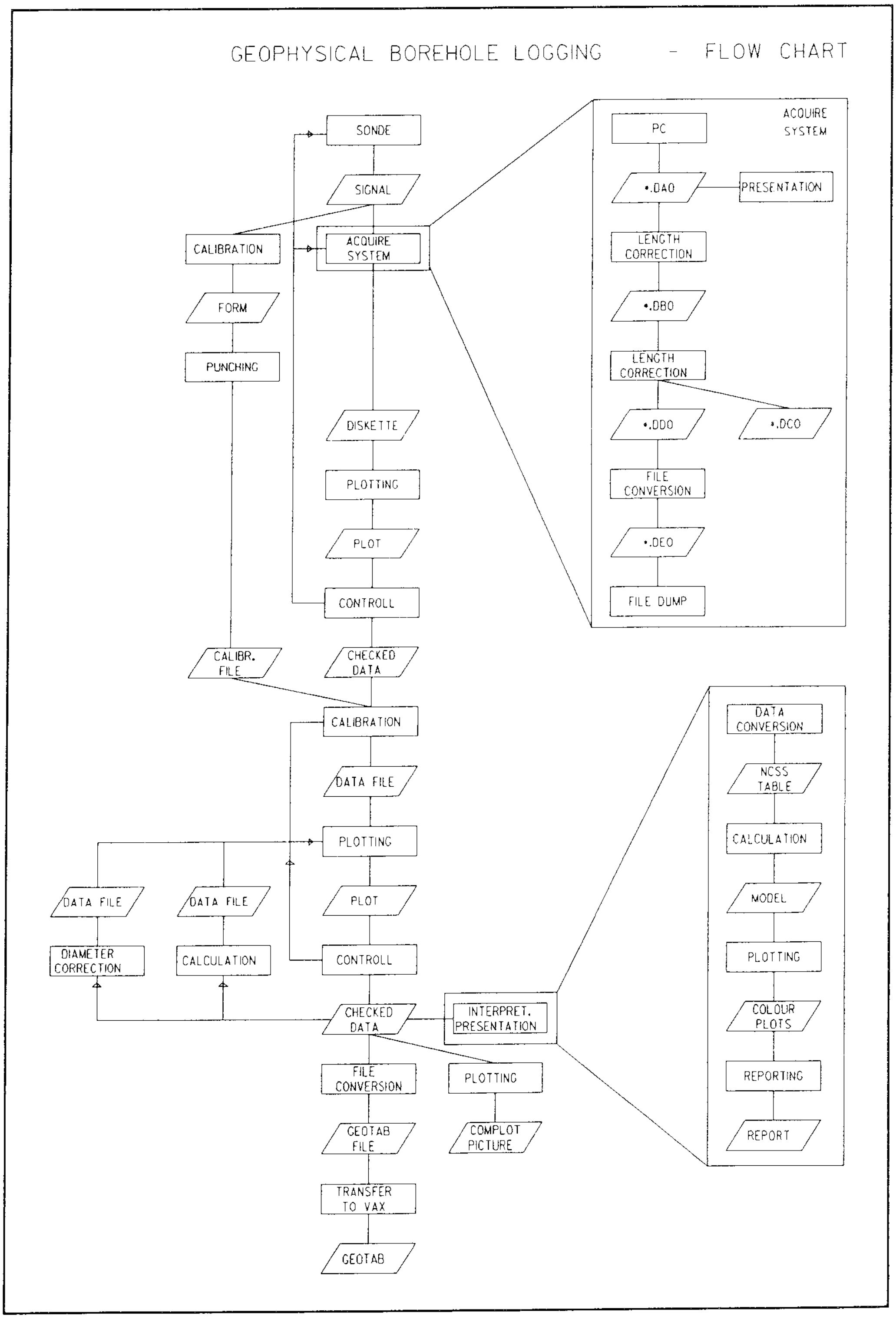


Figure 11.4 Data flow chart for geohpysical borehole logging.

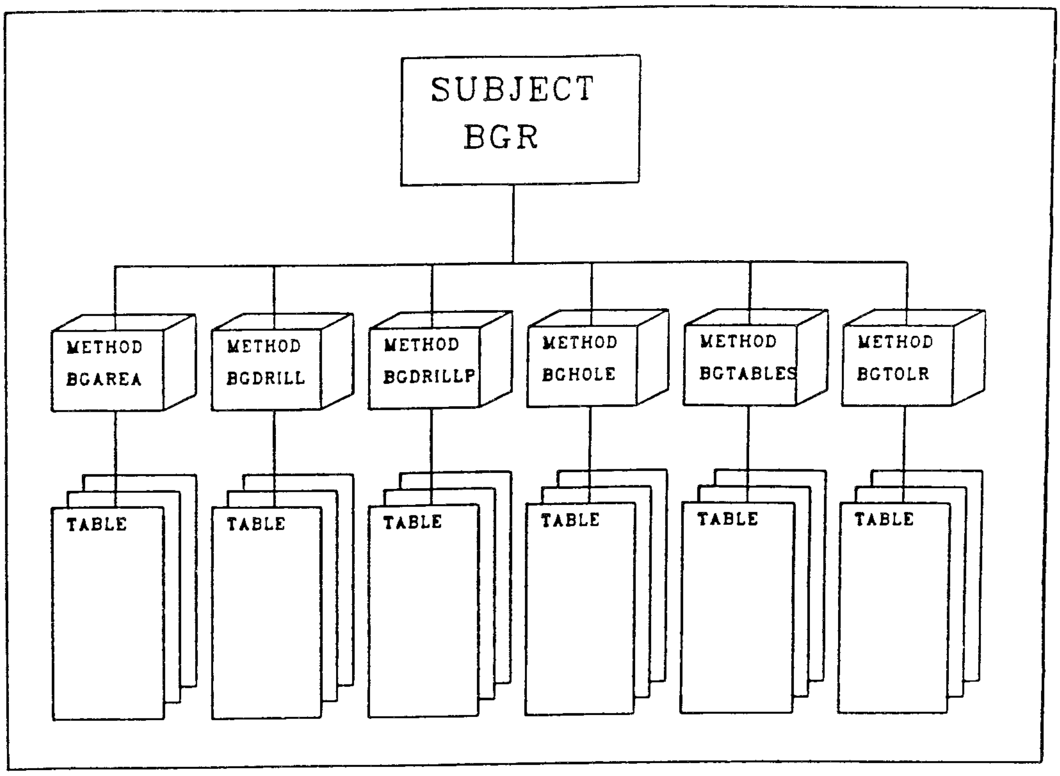


Figure 11.5 The structure of BACKGROUND (BGR) as an example of a GEOTAB method.

Ground surface geophysical data (GSGPHYS)

Data from the different ground surface geophysical measurements according to section 3.4 are stored under this subject. Calibrated data from each individual measuring point, collected along separate profiles or in grid nets, are stored on an active disc.

For detailed information on this subject, refer to Sehlstedt /1991/.

Geophysical borehole logging data (BHGPHYS)

All borehole geophysical logging data are stored or referred to under this subject. Regarding geophysical borehole logging, see section 6.1.2. Each individual measured and calibrated data point collected along the boreholes is stored on an active disc. Regarding borehole radar, VSP, televiewer and borehole-TV, the measurements are described in flyleaf tables with reference to where the data are stored.

For detailed information on this subject, refer to Sehlstedt /1991/.

Petrophysical measurements (PETRO)

Results from laboratory testing of physical properties of rock samples, taken from surface and from drill cores are stored under this subject. The parameter values are stored on an active disc.

For detailed information on this subject, refer to Sehlstedt /1991/.

Hydrogeological data (HYDRO)

This subject includes data from many different types of measurements. These measurements can be divided in two groups:

- hydrological tests
- monitoring data

In the case of hydrological tests, such as hydraulic injection tests, pumping tests, etc, measured datasets are normally used to plot graphs or as a basis for evaluation of hydrogeological parameters. As a huge quantity of measured data are collected, these data are stored on magnetic tapes. The evaluated hydrogeological parameters are stored on an active disc. In case of one method, flow-meter logging, the measured data along the borehole are stored on an active disc.

Typical monitoring data are groundwater heads, collected in time series in order to record changes with time. Here as well a large quantity of measurements are collected and stored on magnetic tapes. For storage on an active disc, some kind of data reduction is normally necessary, for example only one value per day is used or a daily mean value is calculated.

For detailed information on this subject, refer to Gerlach and Gentzschein /1991/.

Chemical characterization of groundwater (CHEMICAL)

This subject contains all results from chemical analysis of groundwater samples, as well as chemical parameters recorded by the in-situ and surface hydrochemical cells. All data are stored on an active disc.

For detailed information on this subject, refer to Laurent et al /1991/.

Tracer tests (TRACER)

Results from different kind of tracer experiments are stored under this subject. As with the hydrogeological data, the measured data are normally stored on magnetic tapes, while evaluated parameters and other results are stored on an active disc.

For detailed information on this subject, refer to Andersson and Gerlach /1991/.

At present some ten millions of data values are available on-line in GEOTAB, which is equivalent to 300 Mbytes. Some additional 400 Mbytes are stored on magnetic tapes. Most of the data pertain to Study Site investigations. At present most of the data from the pre-investigation phase of the Äspö HRL project have been stored.

12. REFERENCES

Ahlbom K, Carlsson L, Olsson O. 1983. Final disposal of spent nuclear fuel - geological, hydrogeological and geophysical methods for site characterization.
SKB TR 83-43

Almén K-E, Hansson K, Johansson B-E, Nilsson G, Andersson O, Wikberg P, Åhagen H. 1983. Final disposal of spent nuclear fuel - equipment for site characterization.
SKB TR 83-44

Almén K-E, Andersson O, Fridh B, Johansson B-E, Sehlstedt M, Gustafsson E, Hansson K, Olsson O, Nilsson G, Axelsen K, Wikberg P. 1986. Site investigation. Equipment for geological, geophysical, hydrogeological and hydrochemical characterization.
SKB TR 86-16

Andersson P, Andersson P, Gustafsson E, Olsson O. 1989. Investigation of flow distribution in a fracture zone at the Stripa mine, using the radar method, results and interpretation.
SKB TR 89-33

Andersson P, Gerlach M. 1991. Description of tracer data in SKB's database GEOTAB. Version 1.
SKB TR 91-05

Barmen G, Dahlin T. 1989. Ground level geophysical measurements on the islands of Äspö and Hålö in October 1989.
SKB PR 25-89-22

Barmen G, Stanfors R. 1988. Ground level geophysical measurements on the island of Äspö.
SKB PR 25-88-16

Bjarnason B, Klasson H, Leijon B, Strindell L, Öhman T. 1989. Rock stress measurements in boreholes KAS02, KAS03 and KAS05 on Äspö.
SKB PR 25-89-17

Bjarnason B, Torikka, A. 1989. Field instrumentation for hydrofracturing stress measurements.
SKB TR 89-17

Borehole Reports. 1988-1990. Individual borehole reports on raw data from measurements (in Swedish).
SKB Hard Rock Laboratory.

Bäckblom G, Gustafson G, Stanfors R, Wikberg P. 1991. Site Characterization for the Swedish Hard Rock Laboratory in Proceedings from a symposium on Validation of Geosphere Flow and Transport Models GEOVAL -90 Stockholm May 14-17 1990. OCED/NEA.

Carlsten S, Olsson O, Sehlstedt, Stenberg L. 1986. Radar measurements performed at the Klipperås study site.
SKB TR 87-01

Carlsten S. 1989. Results from borehole radar measurements in KAS05, KAS06, KAS07 and KAS08 at Äspö. Interpretation of fracture zones by including radar measurements from KAS02 and KAS04.
SKB PR 25-89-10

Carlsten S. 1990. Borehole radar measurements at Äspö boreholes KAS09, KAS10, KAS11, KAS12, KAS13 and KAS14.
SKB PR 25-90-05

Cosma C, Heikkinen P, Keskinen J, Korhonen R. 1990. VSP-survey including 3-d interpretation on Äspö, Sweden, borehole KAS07.
SKB PR 25-90-07

Ericsson L O. 1988. Fracture mapping study on Äspö island. Findings of directional data.
SKB PR 25-88-10

Eriksson E, Johansson B, Gerlach M, Magnusson S, Sehlstedt S, Stark T. 1991. GEOTAB Overview.
SKB TR 91-xx (in print)

Eriksson E, Sehlstedt S. 1991. Description of background data in the SKB database GEOTAB. Version 2.
SKB TR 91-06

Falk L. 1991. Development of tunnel radar antennas.
SKB TR 91-43

Fridh B, Stråhle A. 1989. Orientation of selected drillcore sections from the boreholes KAS05 and KAS06 Äspö, Sweden. A televiewer investigation in small diameter boreholes.
SKB PR 25-89-08

Gentzschein B. 1986. Geophysical investigations at the Klipperås study site.
SKB TR 86-08

Gentzschein B, Nilsson G, Stenberg L. 1987. Preliminary investigations of fracture zones at Ävrö - Results of investigations performed July 1986 - May 1987
SKB PR 25-87-16

Gerlach M, Gentzschein B. 1991. Description of hydrogeological data in the SKB database GEOTAB. Version 2.
SKB TR 91-07

Gustafsson G, Liedholm M, Rhén I, Stanfors R, Wikberg P. 1991. Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation.
SKB TR 91-23

Gustafsson G, Stanfors R, Wikberg P. 1988. Swedish hard rock laboratory first evaluation of preinvestigations 1986-87 and target area characterization.
SKB TR 88-16

Gustafsson G, Stanfors R, Wikberg P. 1989. Swedish Hard Rock Laboratory Evaluation of 1988 year preinvestigations and description of the target area, the island Äspö.
SKB TR 89-16

Hallbjörn L, Ingevald K, Martna J, Strindell L. 1989. A new automatic probe for the measurement of triaxial rock stresses in deep bore-holes. Paper presented at Rock Mechanics Meeting in Stockholm January 26, 1989.
BeFo 1989.

Hiltscher R, Martna J, Strindell L. 1979. The measurement of triaxial rock stresses in deep boreholes. Proceedings of the Fourth International Congress on Rock Mechanics. Montreaux 1979.

Hobb W H. 1912. Earth features and their meaning. Macmillan Co, New York.

Ittner T, Gustafsson E, Andersson P, Eriksson C-O. 1991. Groundwater flow measurements at Äspö with the dilution method.
SKB PR 25-91-18

Juhlin C. 1990. Evaluation of reprocessed seismic refraction data from Äspö.
SKB PR 25-90-02

KBS-3. 1983. Final storage of nuclear fuel - KBS-3.
SKBF/KBS

Kornfält K-A, Wikman H. 1987. Description to the map of solid rocks around Simpevarp.
SKB PR 25-87-02

Kornfält K-A, Wikman H. 1988. The rocks of the Äspö island. Decription to the detailed maps of solid rocks including maps of 3 uncovered trenches.
SKB PR 25-88-12

Laurent S. 1986. Analysis of groundwater from deep boreholes in Klipperås.
SKB TR 86-17

Laurent S, Magnusson S, Nilsson A-C. 1991. Description of chemical data in SKB's database GEOTAB.
SKB TR 91-xx (in print)

Laaksoharju M. 1988. Shallow groundwater chemistry at Laxemar, Äspö and Ävrö.
SKB PR 25-88-04

Laaksoharju M, Ahonen L, Blomqvist R. 1991. Leight-weight double packer equipment for water sampling and hydraulic measurements in deep drill holes.
SKB AR 91-29

Laaksoharju M, Nilsson A-C. 1989. Models of groundwater composition and of hydraulic conditons based on chemometrical and chemical analysis of deep groundwater on Äspö and Laxemar.
SKB PR 25-89-04

Munier R, Riad L, Tullborg E-L, Wikman H, Kornfält, K-A. 1988. Detailed investigation of drillcores KAS02, KAS03 and KAS04 on Äspö island and KLX01 at Laxemar.
SKB PR 25-88-11

Nilsson L. 1987. Hydraulic tests at Ävrö and Äspö.
SKB PR 25-87-11

Nilsson L. 1989. Hydraulic tests at Äspö and Laxemar. Evaluation.
SKB PR 25-88-14

Nilsson L. 1990. Hydraulic tests at Äspö KAS05-KAS08, HAS13-HAS17. Evaluation.
SKB PR 25-89-20

Nilsson A-C. 1989. Chemical characterization of deep groundwater on Äspö.
SKB PR 25-89-14

Nisca D. 1987. Aerogeophysical interpretation
SKB PR 25-87-04

Nisca D. 1987. Aeromagnetic interpretation 6G Vimmerby, 6H Kråkelund NW. SW.
SKB PR 25-87-23

Nisca D. 1988. Geophysical laboratory measurements on core samples from KLX01, Laxemar and KAS02, Äspö.
SKB PR 25-88-06

Nisca D, Triumf C-A. 1989. Detailed geomagnetic and geoelectric mapping of Äspö.
SKB PR 25-89-01

Niva B, Gabriel B. 1988. Borehole radar measurements at Äspö and Laxemar. Boreholes KAS02, KAS03, KAS04, KLX01, HAS02, HAS03 and HAV07.
SKB PR 25-88-03

Nyberg G, Jönsson S, Ekman L. 1991. Groundwater level program. Report for the period 1987-1989.
SKB PR 25-90-18

Nylund B. 1987. Regional gravity survey of the Simpevarp area.
SKB PR 25-87-20

Olkiewicz A, Stejskal V. 1986. Geological and tectonic description of the Klipperås study site.
SKB TR 86-06

Olsson O, Andersson P, Carlsten S, Falk L, Niva B, Sandberg E. 1989. Fracture characterization in crystalline rock by borehole radar.
ABEM AB, Sweden

Olsson O, Falk L, Forslund O, Lundmark L. 1987. Crosshole Investigations - Results from Borehole Radar Investigations.
Stripa TR 87-11

Ploug C, Klitten K. 1988. Seismical and geoelectrical test survey on Ävrö, Sweden.
SKB PR 25-87-14

Ploug C, Klitten K. 1989. Shallow reflection seismic profiles from Äspö, Sweden.
SKB PR 25-89-02

Rhén I. 1989. Transient interference tests on Äspö 1988. Evaluation.
SKB PR 25-88-13

Rhén I. 1990. Transient interference tests on Äspö 1989 in KAS06, HAS13 and KAS07. Evaluation.
SKB PR 25-90-09

Rhén I. 1991. Hydraulic test on Äspö, Bockholmen and Laxemar 1990 in KAS09, KAS11-14, HAS18-20, KBH01-02 and KLX01. Evaluation.
SKB PR 25-91-01

Rhén I, Gustafson G, Gustafsson E, Svensson U, Wikberg P. 1991. Predictions prior to excavation of the Äspö Hard Rock Laboratory.
SKB PR 25-91-02

Rydström H, Gereben L. 1989. Seismic refraction survey on Äspö and Hålö.
SKB PR 25-89-18

Rydström H, Gereben L. 1989. Regional geological study seismic refraction survey.
SKB PR 25-89-23

Sandberg E, Forslund O, Olsson O. 1989. Ground surface radar measurements at Äspö.
SKB PR 25-89-12

Sehlstedt S. 1991. Description of geophysical data in SKB's database GEOTAB. Version 2.
SKB TR 91-02

Sehlstedt S, Stark T. 1991. Description of geological data in SKB's database GEOTAB. Version 2.
SKB TR 91-01

Sehlstedt S, Stenberg L. 1986. Geophysical investigations at the Klipperås study site.
SKB TR 86-07

Sehlstedt S, Stråhle A. 1989. Geological core mapping and geophysical borehole logging in the boreholes KAS05-KAS08 at Äspö.
SKB PR 25-89-09

Sehlstedt S, Triumf C-A. 1988. Interpretation of geophysical logging data from KAS02-KAS04 and HAS08-HAS12 at Äspö and KLX01 at Laxemar.
SKB PR 25-88-15

Sehlstedt S, Stråhle A, Triumf C-A. 1990. Geological core mapping and geophysical borehole logging in the boreholes KBH02, KAS09, KAS11-KAS14 and HAS18-HAS20 at Äspö.
SKB PR 25-90-06

SKB, R&D-Programme 89. 1989. Handling and final disposal of nuclear fuel. Programme for research development and other measures.
SKB

SKB. 1989. Underground Rock Laboratory. Background report to R&D-Programme 89.
SKB.

Stanfors R. 1988. Geological Borehole Description KAS02, KAS03, KAS04, KLX01.
SKB PR 25-88-18

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

Stenberg L. 1987. Underground research laboratory. Geophysical profile measurements.
SKB PR 25-87-01

Stenberg L, Sehlstedt S. 1989. Geophysical profile measurements on interpreted regional aeromagnetic lineaments in the Simpevarp area.
SKB PR 25-89-13

Stråhle A. 1989. Drillcore investigation in the Simpevarp area, boreholes KAS02, KAS03, KAS04 and KLX01.
SKB PR 25-88-07

Sundin S. 1988. Seismic refraction investigation at Äspö.
SKB PR 25-87-15

Tiren S A, Beckholmen M, Isaksson H. 1987. Structural analysis of digital terrain models, Simpevarp area, south-eastern Sweden. Method study EBBA II.
SKB PR 25-87-21

Triumf C-A, Sehlstedt S. 1989. Magnetic measurements over Borholmsfjärden between Äspö and Hålö.
SKB PR 25-89-19

Tullborg E-L. 1989. Fracture fillings in the drillcores KAS05-KAS08 from Äspö, Southeastern Sweden.
SKB PR 25-89-16

Tullborg E-L, Wallin B, Landström O. 1991. Hydrogeochemical studies of fracture minerals from water conducting fractures and deep groundwaters at Äspö.
SKB PR 25-90-01

Wikberg P, Axelsen K, Fredlund F. 1987. Deep groundwater chemistry.
SKB TR 87-07

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

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

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

Technical Reports

List of SKB Technical Reports 1991

TR 91-01
Description of geological data in SKB's database GEOTAB
Version 2
Stefan Sehlstedt, Tomas Stark
SGAB, Luleå
January 1991

TR 91-02
Description of geophysical data in SKB database GEOTAB
Version 2
Stefan Sehlstedt
SGAB, Luleå
January 1991

TR 91-03
1. The application of PIE techniques to the study of the corrosion of spent oxide fuel in deep-rock ground waters
2. Spent fuel degradation
R S Forsyth
Studsvik Nuclear
January 1991

TR 91-04
Plutonium solubilities
I Puigdomènech[1], J Bruno[2]
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