SKB

TECHNICAL REPORT

97-03

ÄSPÖ HRL – Geoscientific evaluation 1997/2

Results from pre-investigations and detailed site characterization

Summary report

Ingvar Rhén (ed.)[1], Göran Bäckbom (ed.)[2],
Gunnar Gustafson[3], Roy Stanfors[4], Peter Wikberg[2]

1 VBB Viak, Göteborg
2 SKB, Stockholm
3 VBB Viak/CTH, Göteborg
4 RS Consulting, Lund

May 1997

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO

P.O.BOX 5864 S-102 40 STOCKHOLM SWEDEN
PHONE +46 8 665 28 00
FAX +46 8 661 57 19

ÄSPÖ HRL - GEOSCIENTIFIC EVALUATION 1997/2

RESULTS FROM PRE-INVESTIGATIONS AND DETAILED SITE CHARACTERIZATION. SUMMARY REPORT

Ingvar Rhén (ed.)[1], *Göran Bäckblom (ed.)*[2],
Gunnar Gustafson[3], *Roy Stanfors*[4], *Peter Wikberg*[2]

1 **VBB Viak, Göteborg**
2 **SKB, Stockholm**
3 **VBB Viak/CTH, Göteborg**
4 **RS Consulting, Lund**

May 1997

Information on SKB technical reports from1977-1978 (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), 1990 (TR 90-46), 1991 (TR 91-64), 1992 (TR 92-46), 1993 (TR 93-34), 1994 (TR 94-33) , 1995 (TR 95-37) and 1996 (TR 96-25) is available through SKB.

ÄSPÖ HRL

GEOSCIENTIFIC EVALUATION 1997/2

Results from pre-investigations and detailed site characterization
Summary report

Ingvar Rhén (ed), VBB Viak, Göteborg
Göran Bäckblom (ed), SKB
Gunnar Gustafson, VBBViak/CTH, Göteborg
Roy Stanfors, RS Consulting, Lund
Peter Wikberg, SKB, Stockholm

May 1997

Keywords: site characterization, model, geology, geophysics, rock mechanics, hydrochemistry, hydrogeology, transport of solutes, Äspö, experiences.

FOREWORD

The booklet *Äspö Hard Rock Laboratory - 10 years of research*, available from the SKB, provides the reader with a popular review of the achievements This report is No. 2 of six Technical Reports summarizing the pre-investigation and construction phase of the Äspö Hard Rock Laboratory.

The reports are:

1 Stanfors R, Erlström M, Markström I.
Äspö HRL - Geoscientific evaluation 1997/1.
Overview of site characterization 1986-1995
SKB TR 97-02.

2 Rhén I (ed), Bäckblom (ed), Gustafson G, Stanfors R, Wikberg P.
Äspö HRL - Geoscientific evaluation 1997/2.
Results from pre-investigations and detailed site characterization.
Summary report.
SKB TR 97-03.

3 Stanfors R, Olsson P, Stille H .
Äspö HRL - Geoscientific evaluation 1997/3.
Results from pre-investigations and detailed site characterization.
Comparison of predictions and observations.
Geology and Mechanical stability.
SKB TR 97-04.

4 Rhén I, Gustafson G, Wikberg P.
Äspö HRL - Geoscientific evaluation 1997/4.
Results from pre-investigations and detailed site characterization.
Comparison of predictions and observations.
Hydrogeology, Groundwater chemistry and Transport of solutes.
SKB TR 97-05.

5 Rhén I (ed), Gustafson G, Stanfors R, Wikberg P.
Äspö HRL - Geoscientific evaluation 1997/5.
Models based on site characterization 1986-1995.
SKB TR 97-06.

6 Almén K-E (ed), Olsson P, Rhén I, Stanfors R, Wikberg P.
Äspö Hard Rock Laboratory.
Feasibility and usefulness of site investigation methods.
Experience from the pre-investigation phase.
SKB TR 94-24.

The background and objectives of the project are presented in a background report to the SKB R&D Programme 1989 (Hard Rock Laboratory), which contains a detailed description of the HRL project.

The purpose of this report, No. 2, is to present the evaluation of the concepts and methods used during the pre-investigation and construction phases of the Äspö HRL. An overview of all the investigations performed is summarized in *Report 1*. The detailed evaluation of the pre-investigation and detailed site characterization is presented in *Reports 3-5*. *Report 6* outlines the usefulness and feasibility of pre-investigation methods.

May 1997

Ingvar Rhén Göran Bäckblom Gunnar Gustafson

Roy Stanfors Peter Wikberg

ABSTRACT

The geoscientific and other work at Äspö Hard Rock Laboratory provides an important scientific and technical basis for implementing and operating a future deep repository in Sweden.

A major milestone has now been reached with the completion of the pre-investigation and construction phases at Äspö HRL. The comprehensive research conducted has enabled valuable development and verification of site characterization methods applied from the ground surface, boreholes and underground excavations. The present data base at the Äspö HRL is one of the most comprehensive data bases in the world for crystalline rock properties, containing data from a large number of investigation methods from the surface down to 1700 metres below ground level.

Site characterization in conjunction with construction work at Äspö has basically confirmed the pre-construction models. The work at Äspö has shown that such pre-construction models can be obtained for the key features and properties of fractured crystalline rock through the application of 'standard methodology of good quality' for measurements, data analyses, modelling and evaluation. The site characterization at Äspö has been a realistic 'dress-rehearsal' that is invaluable for planning and execution of surface and underground characterization of sites for the deep repository for spent nuclear fuel in Sweden.

Site investigations at Äspö have contributed significantly to the development and improvement of instruments, investigation techniques and evaluation methods. This has provided a solid basis for future site studies. Areas have been identified where further development of techniques and methods would be useful.

ABSTRACT (in Swedish)

De geovetenskapliga och andra forskningsinsatser vid Äspölaboratoriet är en viktig del i SKB:s program att för att förbereda anläggandet av ett djupförvar för använt kärnbränsle i Sverige.

En viktig milstolpe är nu nådd, när förundersöknings- och anläggningsskedet är avslutat för Äspölaboratoriet. Den omfattande forskning som genomförts har visat på tillförlitligheten hos data och modeller som kan erhållas vid en platsundersökning. Metodik har utvecklats för undersökningar från ytan, från borrhål och från tunnlar. Databasen från den kristallina berggrunden i Äspöområdet är en de mest omfattande i världen och innehåller data från ett stort antal undersökningsmetoder från markytan ner till 1700 m djup.

Detaljundersökningarna som genomfördes i samband med anläggandet av Äspölaboratoriet har i huvudsak bekräftat de modeller som upprättades med ytundersökningar som grund. Arbetet vid Äspö har visat att modeller för strukturer och egenskaper i klistallin berggrund kan erhållas med tillgänglig teknik och metodik för mätningar, analys av data, modellering och utvärdering. Undersökningarna vid Äspö har varit en ovärderlig generalrepetition av plats- och detaljundersökningar för ett djupförvar av använt kärnbränsle i Sverige.

Undersökningarna vid Äspö har medfört avsevärd utveckling och förbättring av instrument och metoder för datainsamling och utvärdering, vilket ger en stabil grund för kommande platsundersökningar, liksom en bas för att genomföra fortsatta förbättringar inom angelägna områden.

CONTENTS

EXECUTIVE SUMMARY

INTRODUCTION

Background

The Äspö Hard Rock Laboratory (Äspö HRL) provides an important scientific and technical basis for the work of siting, design, construction and operation of a future deep geological repository in Sweden for spent nuclear fuel and other long-lived waste. The need for such an underground laboratory was identified at an early stage in the Swedish programme for final disposal of nuclear waste. The Äspö HRL was built to provide an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to the depth planned for a future deep repository for spent nuclear fuel.

The goals of pre-construction and construction phase characterization 1986 - 1995 were to :

- *demonstrate that investigations at the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level,*
- *refine and verify the methods and the technology needed for characterization of the rock on the detailed site investigations.*

The aim was also that the site investigations should give some experience in order to:

- *refine and test on a large scale at repository depth methods and models for describing groundwater flow and transport of solutes in rock.*
- *provide access to rock where methods and technology can be refined and tested so that high quality can be guaranteed in the design, construction and operation of the final repository.*

Characterization of the rock conditions at the Äspö site began in 1986. The first four years were devoted to investigations from ground surface and in boreholes drilled from the surface. Models of rock conditions at depth were developed on the basis of these investigations. The models were evaluated and further detailed during the following five years (1990 - 1995) when the laboratory was constructed. The laboratory tunnels and shafts extend down to a depth of 450 metres below ground level. Data collected in the 3.6 km long tunnel, in surrounding monitored boreholes and in boreholes drilled from the tunnel throughout the construction phase were evaluated and compared with predictions based on the pre-construction models.

A major milestone has now been reached with the completion of the pre-investigation and construction phases encompassing the years 1986 - 1995. This report summarizes the main findings from the pre-investigation and construction phase of the Äspö Hard Rock Laboratory, focussing on the reliability of site characterization methodology.

Approach to site characterization

The Äspö Project was structured to facilitate testing of the reliability of site characterization methodology. This included:

- iterative updating to allow for increasing the details of models and possible re-interpretation of previous data sets.
- multi-disciplinary and integrated approach to data collection and interpretation.
- selection of key issues for site characterization for study and subsequent sub-structuring in subjects and geometric scales, (*Figure 1).*

The Äspö key issues for site characterizations were:

- Geology,
- Mechanical stability,
- Groundwater flow,
- Groundwater chemistry,
- Transport of solutes.

The most important safety-related function of the bedrock is to protect the engineered barriers and to provide:

- long-term, stable and suitable chemical environment,
- low groundwater flow,
- mechanical stability.

Such conditions favour longevity of the engineered barriers and the host rock's function as a barrier to radio-nuclide migration.

A basic requirement for modelling of the mechanical stability, the groundwater flow, the chemical conditions and the transport of solutes is a good geological-structural model of the site. However, since the basic principle of the SKB deep repository is based on the isolation of the radioactive substances, the factors contributing to isolation are of greater importance than those favourable to sorption, slow transport in bedrock and dilution in the far-field (see *RD&D Programme 95 for SKB).* The selected key issues for the site characterization at Äspö (*Figure 1),* are thus relevant in relation to the safety related requirements.

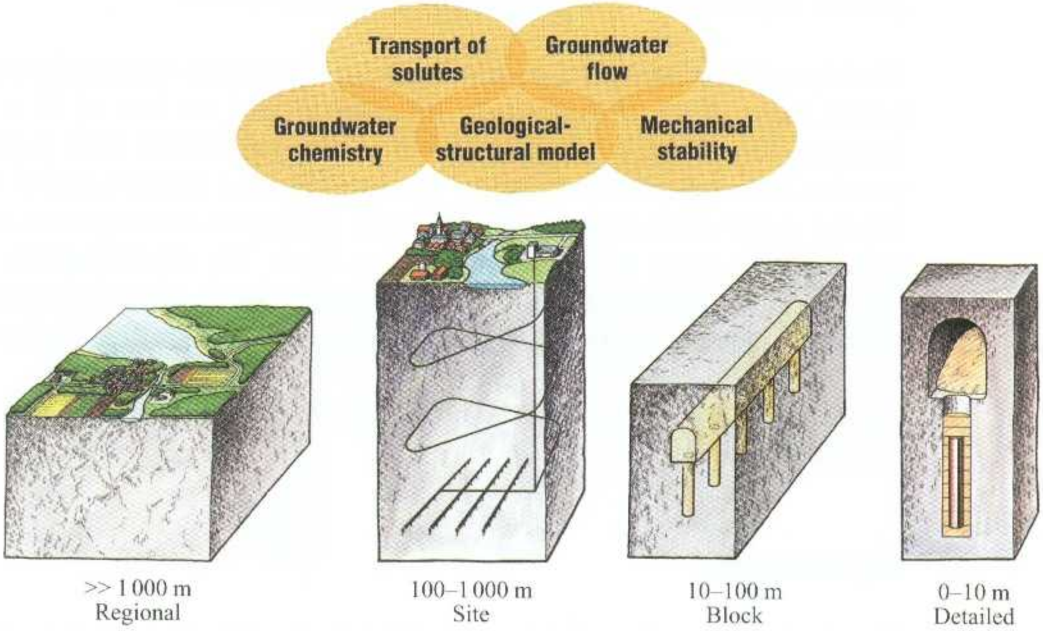


Figure 1. *Analyses and modelling have been made on different geometrical scales with respect to a number of key issues (Geological-structural model, Mechanical stability, Groundwater flow, Groundwater chemistry and Transport of solutes) for site characterization.*

Out of the five key issues, most work during 1986-1995 was devoted to the issues Geology, Groundwater flow and Groundwater chemistry. Mechanical stability addressed issues relating to excavation stability during construction of the laboratory. Transport of solutes included investigations of fracture connectivity, transient flow of natural isotopes and assessment of flow porosity. The main findings for each key issue are presented below.

GEOLOGY

A basic requirement for meeting the needs of repository engineering and performance assessment is development of a good geological-structural model of the site. This has been achieved in the quite complex geological environment at Äspö.

The geological-structural model is the simplified description of the lithology and fracturing. The simplification of the geological medium to a structural model is one of the most crucial issues in site characterization as this simplification provides the basis for design and modelling work for the other four site characterization key issues. A description of the lithology and main tectonic structures is needed to provide a framework for all modelling work concerning mechanical stability, groundwater flow and groundwater chemistry.

At Äspö the lithology has been classified into the rock types Småland (Ävrö) granite, Äspö diorite, fine-grained granite and greenstone.

There is a special need for a good description of the main structural pattern in a rock mass. Basic elements in a structural model are first of all a good interpretation of the major discontinuities (fracture zones) with respect to position, orientation and character. The identification and description of the fracture zones which are important hydraulic conductors and important for the rock stability were of special interest at Äspö. The discontinuities were classified into major fracture zones (width > 5 metres), minor fracture zones (width < 5 metres), single water conducting fractures and small-scale fractures.

Some main findings concerning the geological-structural models are summarized here.

Regional model

The bedrock in the Äspö area belong to the vast region of the Transscandinavian Granite-Porphyry Belt.

A number of massifs of basic rocks elongated E-W were indicated by positive magnetic and gravity anomalies. Fine-grained irregular bodies and xenoliths of greenstone (old volcanites) were found as remnants within the granite mass.

Some circular/semi-circular structures in the area investigated are interpreted as granite diapirs. They are all represented by a more or less round, non-magnetic patterns and negative Bouger gravity anomalies. The Götemar and Uthammar anorogenic granites are two of these structures which were interpreted as true diapirs.

Fine-grained greyish-red granite is common in the whole area. On and near Äspö, which was mapped in detail, the fine-grained granite occurs both in smaller massifs and as dikes in the older rock.

Information from geological and geophysical investigations support a tectonic picture dominated by an almost orthogonal system of major discontinuities trending N-S and E-W and the NW and NE trending system. These discontinuities exceed more than 10 km in length *(Figure 2)*.

Lithological model of Äspö

The lithological situation at Äspö is complex. It was possible to predict the general distribution and relative amount of the main rock types *(Figure 3)*, but as expected it was not possible to predict deterministically the location of rock types occurring as narrow irregular dikes, such as fine-grained granite and greenstone.

Estimates of lithological composition were also made for blocks of 50 m and 5 m size, respectively, and these predictions were in fair agreement with observations during the construction phase.

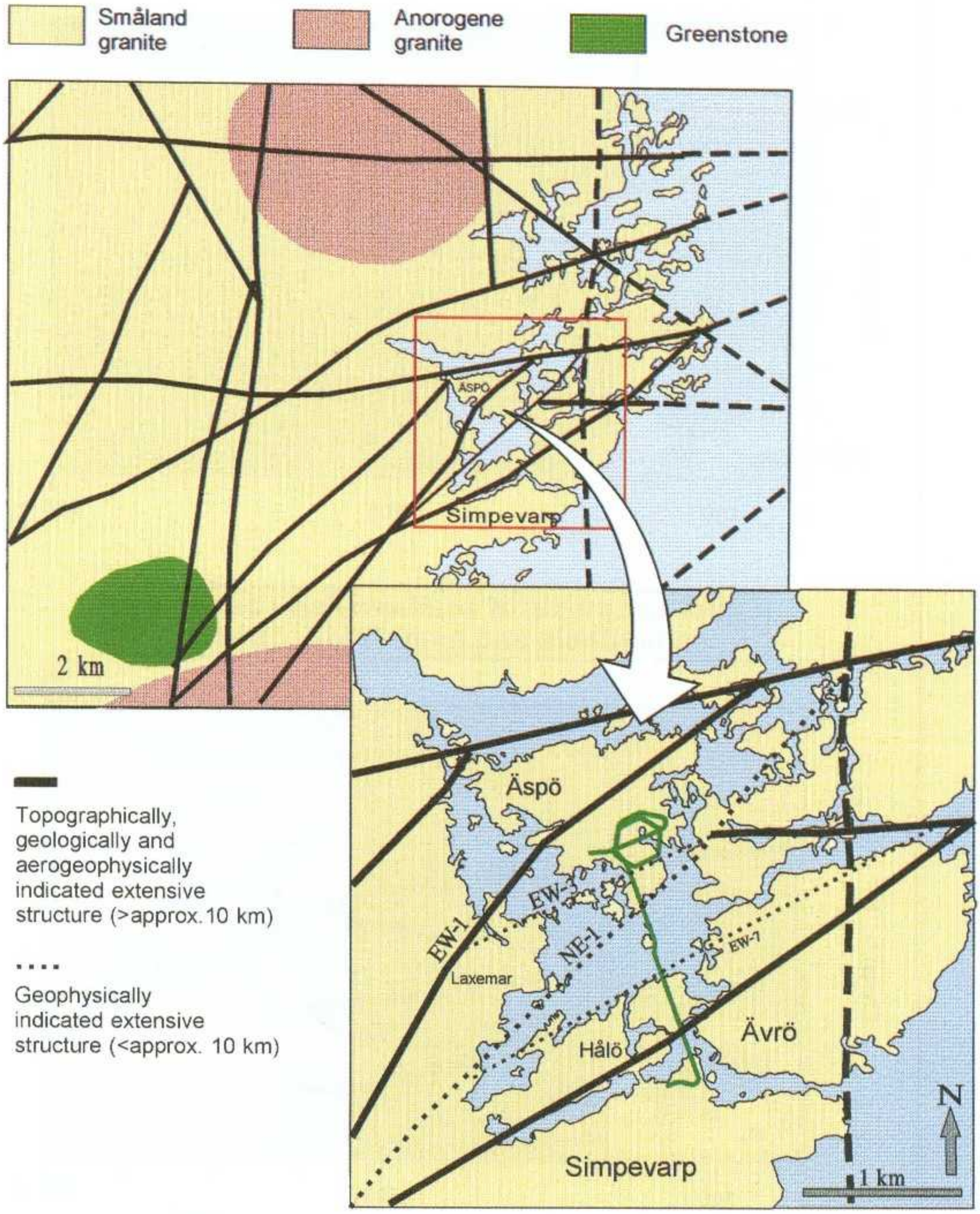


Figure 2. *Regional model of discontinuities in the Äspö environs.*

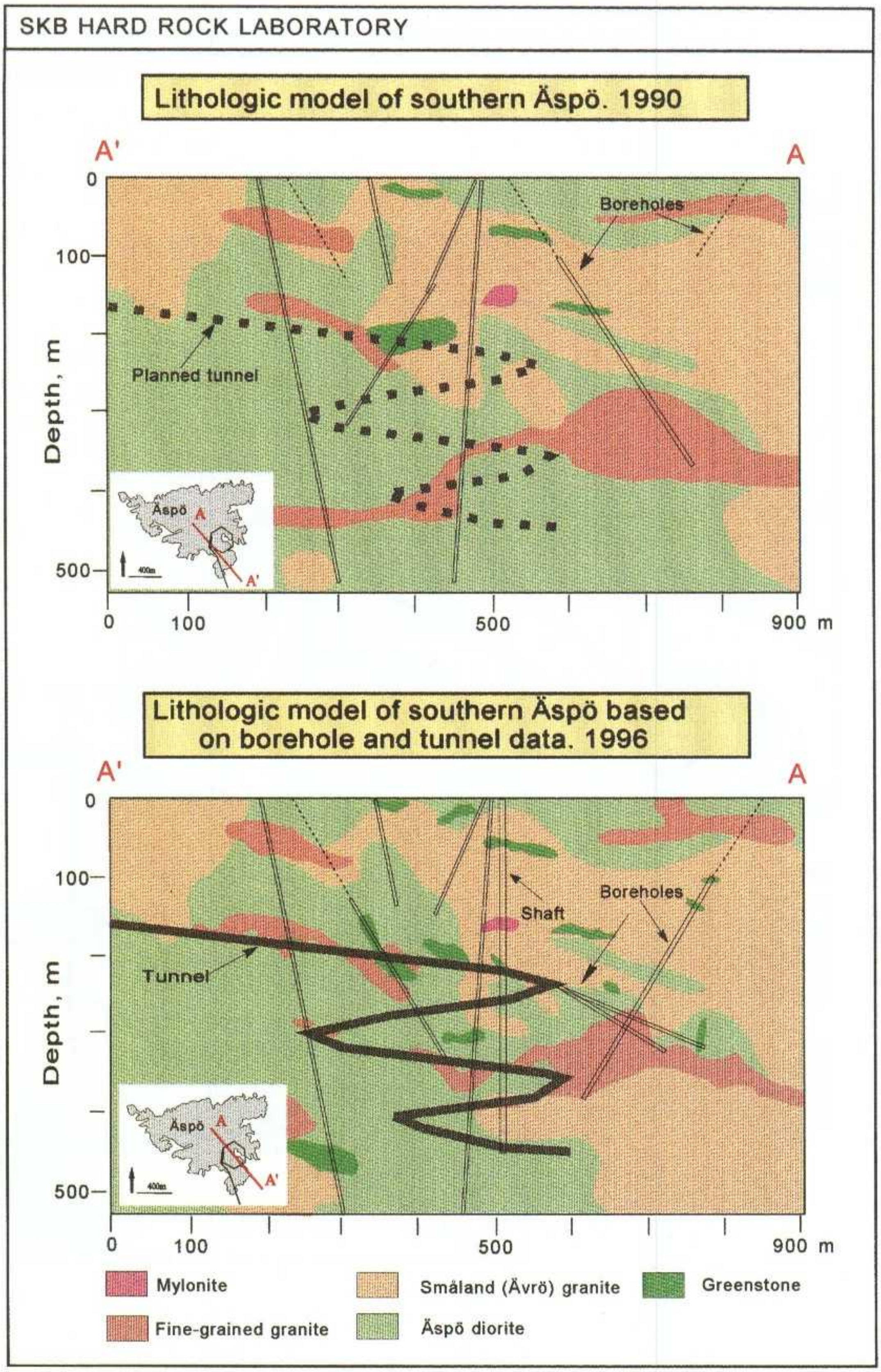


Figure 3. *Comparison of lithological model prior to construction and after construction. The prediction, Model 90 (top) is based on surface mapping and cored boreholes. Model 96 (bottom) is based on Model 90 data, tunnel mapping and supplementary boreholes from the tunnel.*

Structural model of Äspö

The existence of several major fracture zones was predicted and their existence has been confirmed. No further major zones were found during construction in the target volume for the investigations. A nomenclature for fracture zones and the reliability of their 'existence' in the predictions (certain, probable, possible) was adopted. One major subhorizontal zone classified as 'possible' has not been found. Subhorizontal structures found in the tunnel were narrower and less hydraulically important than predicted.

The dip and strike of the hydraulically most important fracture zone NE-1 was predicted and the actual measurements showed small deviations (see *Figure 4)*. The geometry of the major fracture zone NE-2 is complicated. Parts of the zone dip north, other parts dip south. As the zone was considered to be of minor importance, hydraulically and mechanically, few investigations were made to determine its exact geometry. The measurements show that the zone dips 70-80° south instead of 75° north as predicted.

The comparison between predictions and tunnel data shows that most of the predictions for major subvertical fracture zones (> 5 m wide) were reliable both with respect to existence, geometry *(Figure 4)* and geological character.

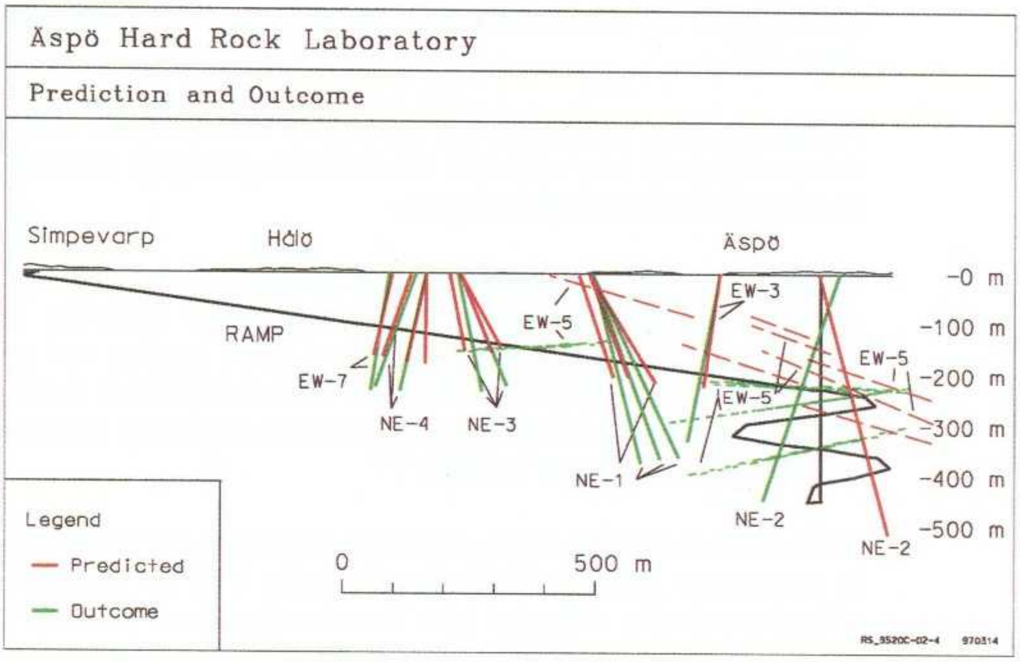


Figure 4. *Prediction and outcome for major fracture zones. The picture illustrates predicted (red) and observed (green) positions and dips in the tunnel.*

Äspö is intersected by a number of narrow, steeply dipping transmissive fractures or minor fracture zones (fracture swarms) trending WNW-NNW. The existence of minor fracture zones was predicted and their existence has been confirmed. The existence and frequency of these zones (fracture swarms) were recognized during the pre-investigation phase but it was not possible to predict deterministically their locations at depth.

The reliability of predictions of minor fracture zones (< 5 m wide) was good with respect to existence and hydraulic character. Their extent and properties at depth were described in a stochastic sense. The detailed investigations from the tunnels provided information on the location of these minor features where they intersect tunnels and boreholes and an improved statistical base on their frequency, orientation and properties. *Figure 5* shows a comparison of the structural model with discontinuities prior to construction and after updating based on all data 1986 - 1995.

Predictions of small-scale fracturing in six 50 m blocks along the tunnel show that the orientation of the main fracture sets were mostly in fair agreement with observations during the construction phase as well as nature of fracture infillings. Estimated fracture length and fracture spacing on tunnel/walls were in poor agreement with observations during the construction phase.

Methods

In general the site investigation methods used were adequate for relevant modelling of the most important parameters needed for construction of the Äspö HRL.

Aerogeophysical investigations, gravimetric measurement and lineament interpretation are very useful for the structural-geological modelling work of major structures on a regional scale.

Geological mapping and detailed ground geophysical profiling (electrical and seismic refraction investigations) indicated minor structures in the site description stage. Borehole investigations (core logging and geophysical logging) provided important data for the characterization of the rock mass at depth. Determination of fracture zone (fracture) orientation was performed by use of borehole radar and borehole TV.

Reflection seismic indications did not correspond to any subhorizontal zones of importance down to 500 m depth. Today both the borehole radar and reflection seismics technique have been developed and probably give better possibilities of detecting subhorizontal fracture zones compared to a few years ago.

There is a need for further development of drilling methodology. It is generally very difficult to penetrate sections of crushed and clay-altered rock using small bits without grouting. To be able to characterize the most fractured parts of a zone a triple-bar coring technique must be used.

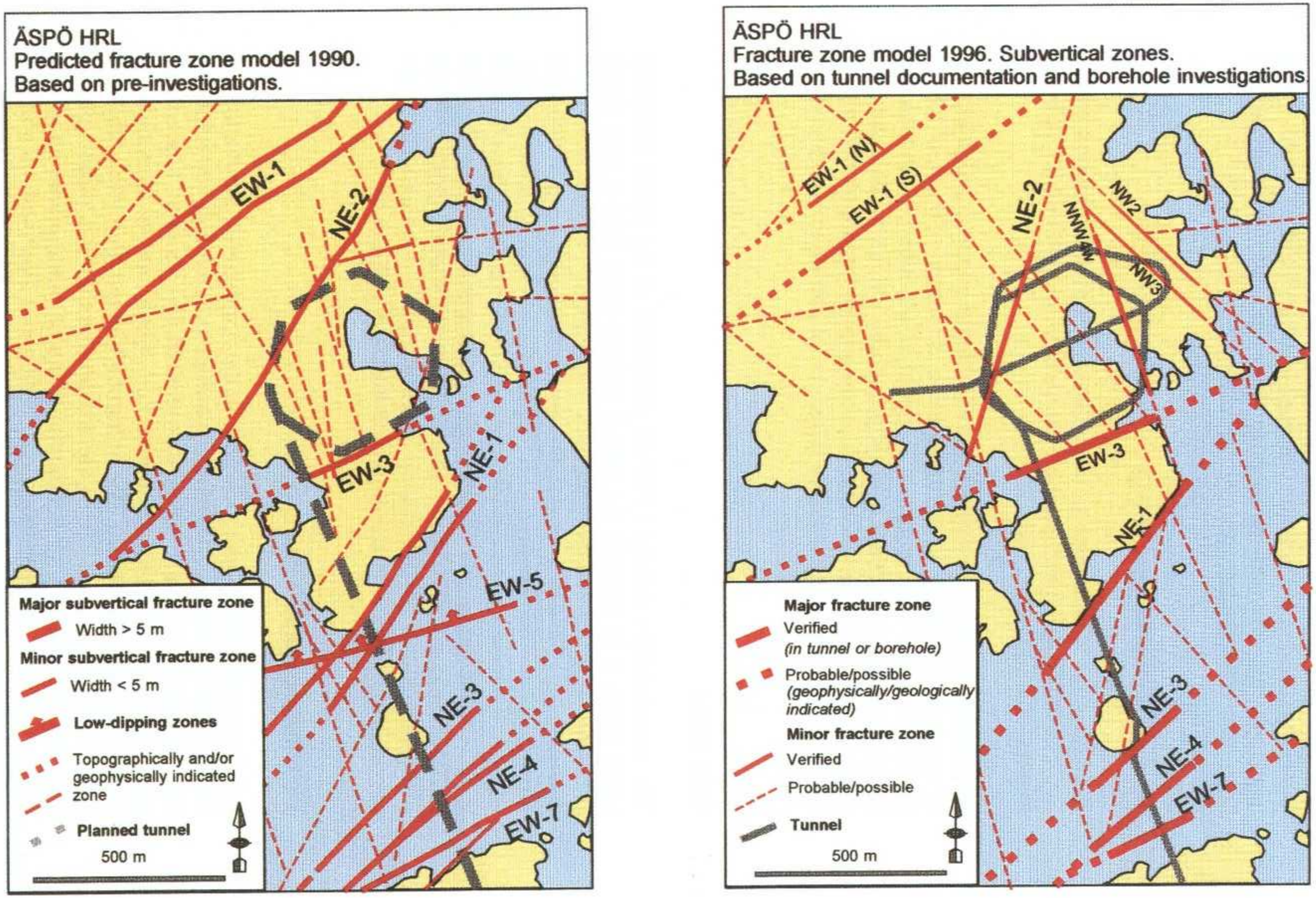


Figure 5. *Structural model of the Äspö area, with predicted main structures at ground level, prior to construction (left) and after construction (right).*

Fracture orientation in boreholes was not very successful due to the methods available. Development of digital down-the-hole TV equipment is now a preferred method to verify features mapped in the core with an image of their undisturbed intercept with the borehole. BIP images are also helpful tools in controlling core orientation during mapping.

MECHANICAL STABILITY

Rock stress and rock strength are important properties in the engineering of a repository. At Äspö studies were mostly made to find and evaluate potential problems for the construction.

No indications of rock burst were found and thus the overall expert judgement of mechanical stability at Äspö proved to be correct. The basis for the judgement relied very much on empirical observations in Sweden and elsewhere. The scientific basis for these judgements is limited due to scarce and scattered data, and model and parameter uncertainty. Models for excavation stability have not been thoroughly tested due to the limited stress levels at Äspö.

Rock stress

The measurements indicate a NW-SE orientation of the largest horizontal stress, which is in line with the overall regional stress field at great depth. Different stress measurement methods were used in surface and tunnel boreholes. This could be an explanation for higher stresses being measured in the tunnel than from the surface investigations. The mean K_o-value (= σ_H/σ_v, where σ_H is the maximum horizontal stress and σ_v the calculated stress from the weight of the overburden) from underground measurements is 2.9. The predicted range was K_o = 1.6-1.9. Due to the limited number of data points in a few boreholes it is possible that the predicted range did not sufficiently take into account the natural variability of the stress field (*Figure 6*).

Excavation stability

For the classification of the rock mass in the Äspö tunnel, the Rock Mass Rating (RMR) system was applied. Experience from the Äspö tunnel shows that the rock mass quality is very dependent on the rock type. Fine-grained granite, which is often fractured, exhibits both significantly lower mean RMR values and larger variations. The difference between greenstone, Småland (Ävrö) granite and Äspö diorite are smaller and they also exhibit smaller variations. The predicted RMR values for the tunnel mostly exhibit acceptable correspondence to the observations made in the tunnel. Poor rock was predicted at 8% while the outcome was 4%. The reliability of the excavation stability assessment is very much dependent on the reliability of the geological structural model.

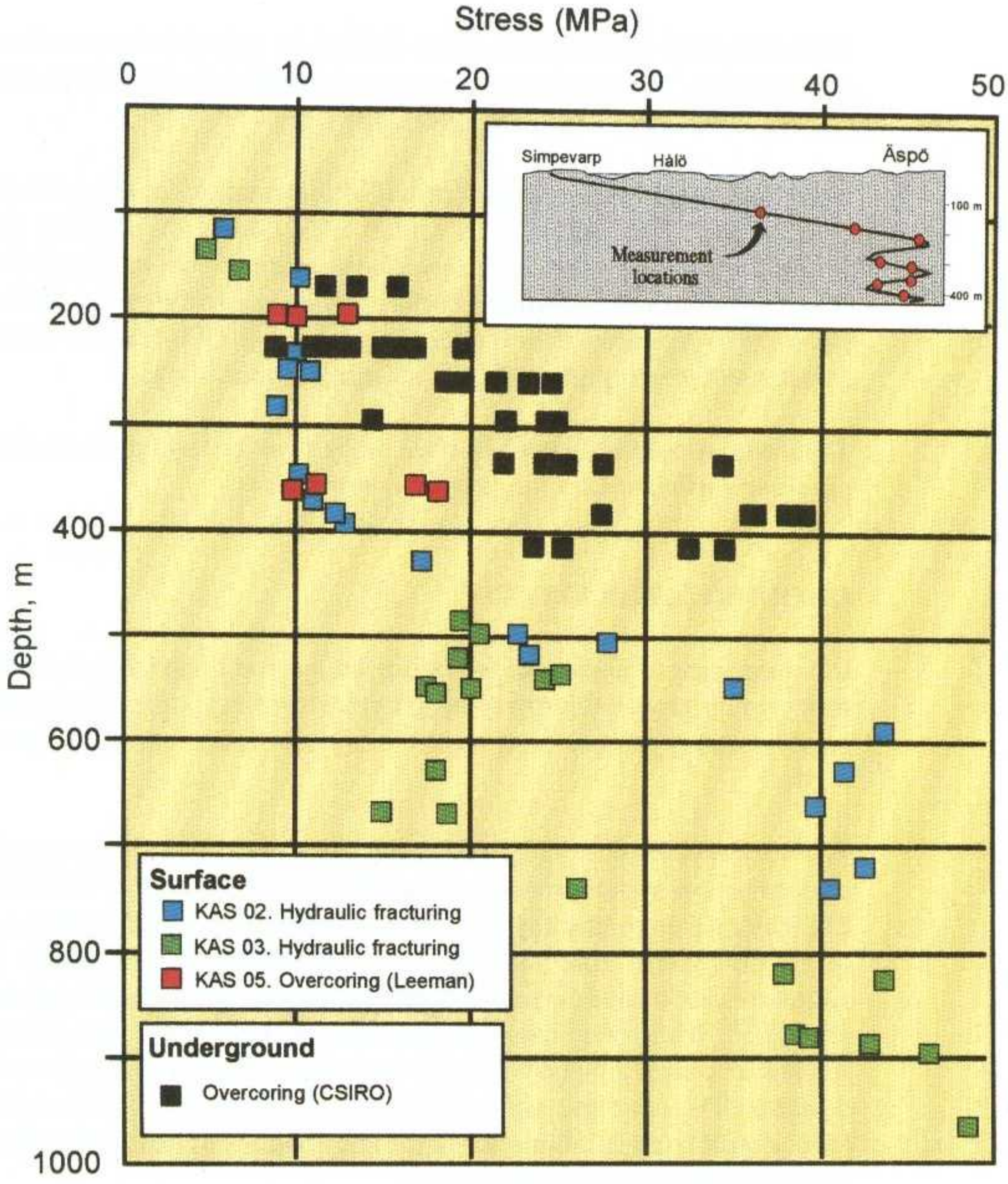


Figure 6. *Graph showing the maximum horizontal stress as a function of depth. Stresses measured and interpreted prior to construction are shown with blue, green and red squares and after construction with black squares. Measurement locations after construction are shown in the small figure above.*

Methods

During the site investigation, stress measurements were made in three surface boreholes. Hydraulic fracturing was used in two boreholes and the overcoring method in one borehole. Concurrent with the excavation overcoring measurements were made in boreholes drilled from the ramp with the main objective of evaluating the predictions made prior to excavation.

The big range of maximum horizontal stress data has to be analysed more.

The mechanical characteristics were defined by uniaxial compressive tests on core samples. The specimens were prepared before testing and the tests were carried out in a press with very great stiffness.

Core drilling and core mapping provided information for characterization of rock quality. The holes were drilled in different orientations to obtain information on different fracture sets, e.g. steep or subhorizontal. The cores were logged to provide further information on the distribution on different rock types and to determine their fracture frequencies (RQD), fracture distance and fracture surface properties (JRC, JCS and fracture fillings).

The methods used (except for surface properties) for testing were relevant and provided sufficient data for construction purposes.

GROUNDWATER FLOW

It is important to determine the existence, geometry and properties of major water conducting features in order to be able to select a repository volume that provides and supports protection of the engineered barriers and isolation of the waste.

The work at Äspö shows that the major factors of importance for modelling the stationary flow system were identified and characterized prior to construction. The major water-conducting features (*hydraulic conductor domains,* consisting of major fracture zones and some of the minor fracture zones (fracture swarms)) were treated deterministically with respect to existence, geometry and properties. The rock mass between the fracture zones was treated as a stochastic continuum and divided into subvolumes *(hydraulic rock mass domains).* The assignment of hydraulic properties to the rock mass was reliable, even if problems exist concerning understanding of scale dependency and anisotropy of hydraulic conductivity.

Numerical codes for groundwater flow have been developed considerably during the course of the project. A number of numerical modelling efforts were made and these show that the effects of salinity on the overall groundwater flow and draw-down can be modelled successfully.

Some main findings concerning the groundwater flow model are summarized below.

Major fracture zones, minor fracture zones (fracture swarms)

At Äspö all major fracture zones near or intersecting the tunnel were identified, see *Figure 7.* Most of them, but not all, were found to be highly or relatively highly transmissive ($T > 10^{-5}$ m^2/s), *(see Figure 8).* The transmissivity can be predicted if there are a few boreholes that intersect a major hydraulically conductive feature where hydraulic tests have been performed in these boreholes.

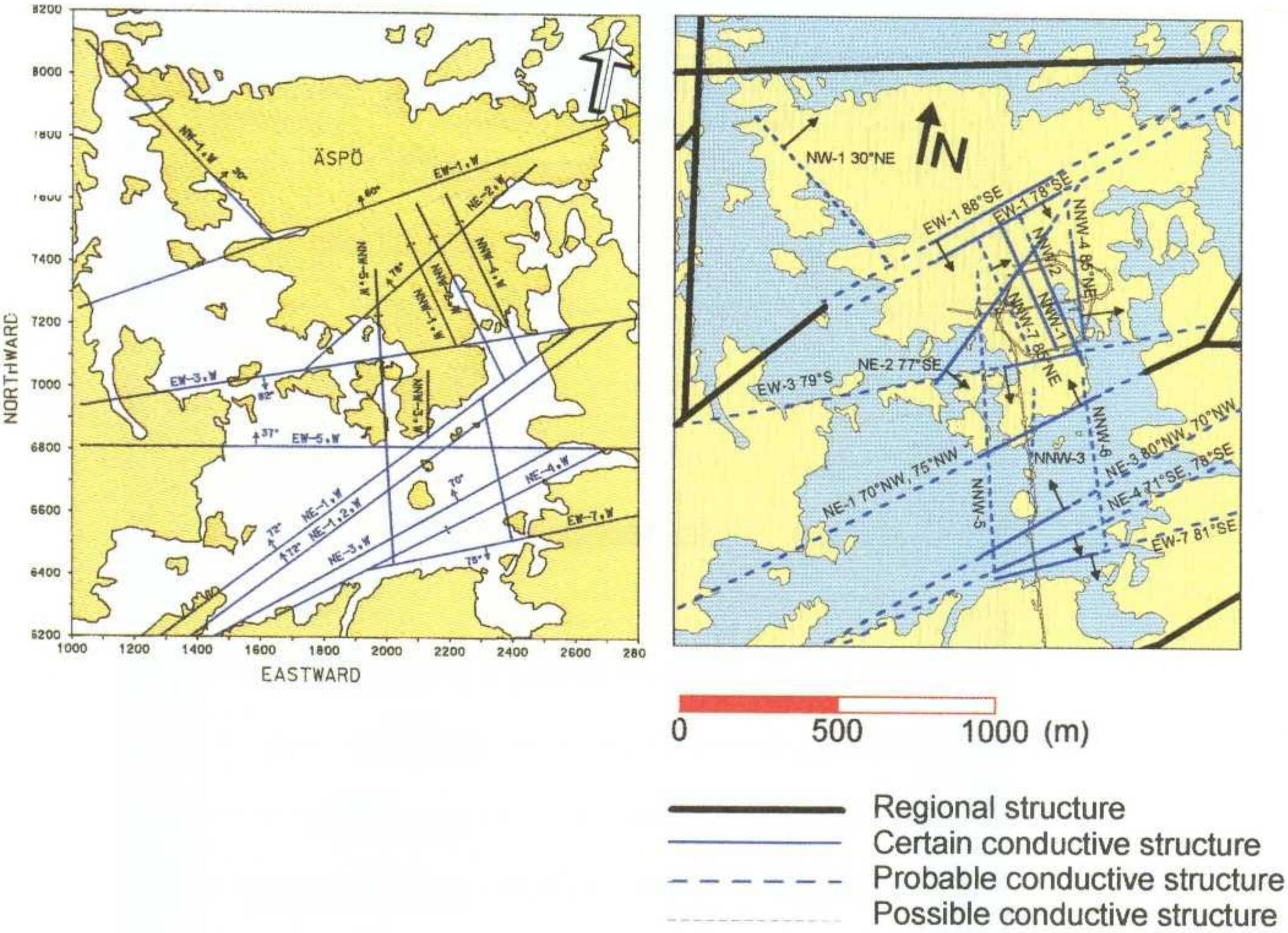


Figure 7. Left: Model 1990 of hydraulic conductors from the pre-investigation phase - site scale. Right: 1996 model of hydraulic conductors - site scale.

It was also shown that some minor fracture zones (fracture swarms) are highly water conducting and that it is difficult to describe their position and extent precisely in space. However, the evaluation showed that an approximate position and extent in the bedrock could be defined. Thus, these features were also represented deterministically in the numerical model.

The rock mass between fracture zones

Conductivity of the rock

A stochastic continuum model was used for groundwater flow simulations and the flow capacity of the rock was based on what was called 'effective hydraulic conductivity'.

The hydraulic properties of the rock mass below Äspö island were found to be approximately as predicted in spite of uncertainties, for example, regarding

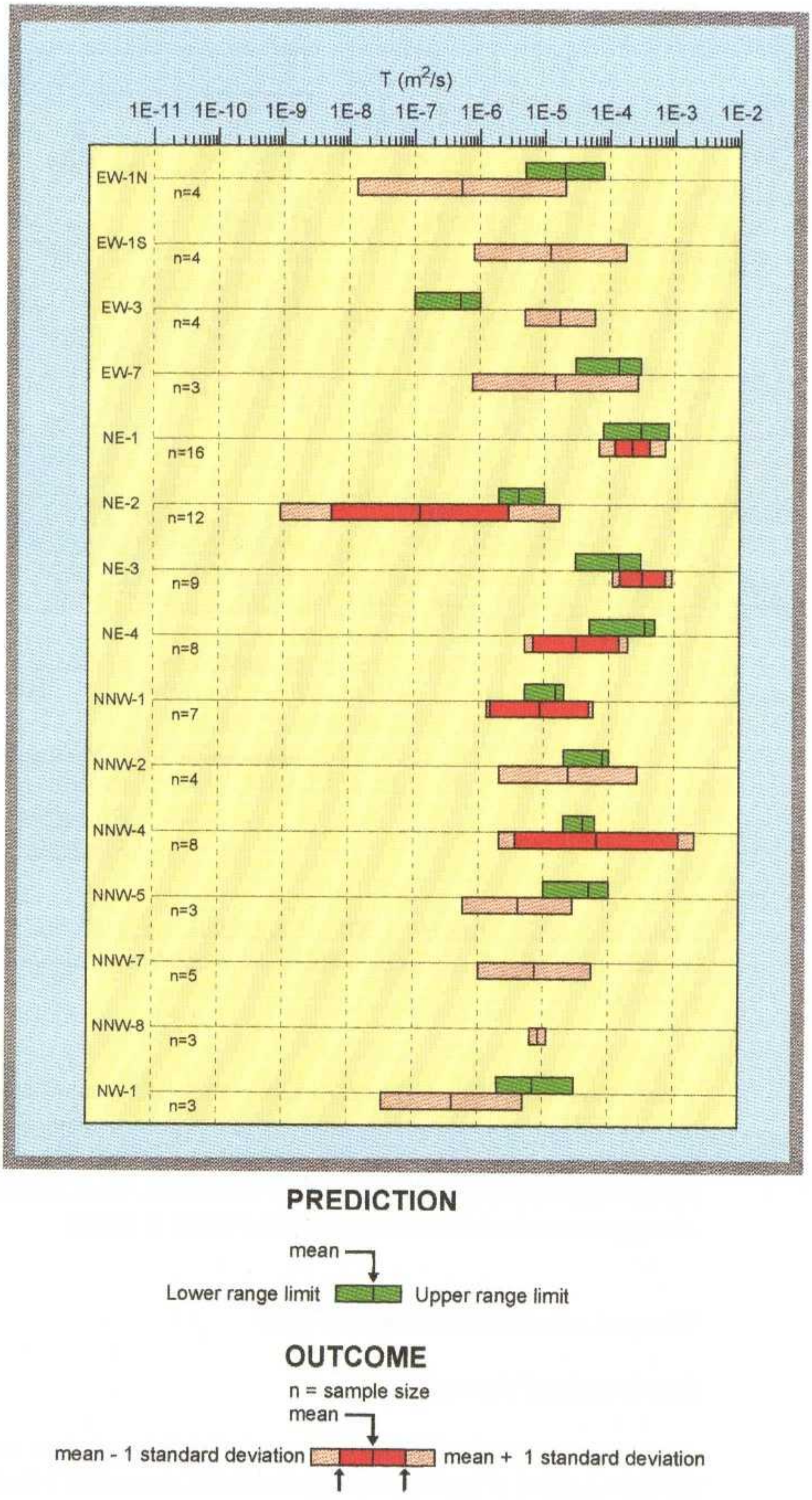


Figure 8. *Transmissivity of water-bearing zones. EW-1S, NNW-7, 8 are new water-bearing zones in Model 96 and NW-1 was re-evaluated, and these were not included in the predictions. (mean = arithmetic mean of* $Log_{10}(T)$*, standard deviation = Standard deviation of* $Log_{10}(T)$*, n = sample size).*

scale dependency, flow regime interpretation and anisotropy. The prediction for tunnel section 700-1475 m, below the Baltic Sea, was, however, not within the predicted range. As very few tests were performed below the Baltic Sea, data from Äspö was extrapolated to this area, but as tunnel section 700-1475 m is dominated by very transmissive and wide fracture zones the hydraulic conditions are quite different from Äspö island. Extrapolation of results to rock volumes outside the investigated volume should be made with caution if the geological characteristics can be expected to be different from the investigated volume.

Anisotropy

The hydraulic tests performed in a large number of probe holes drilled along the tunnel spiral during the construction showed that anisotropic conditions are present, with the largest conductivity within a sector being WNW to N-S. Subvertical fractures striking WNW-NW and approximately N-S are the dominant water conductive fracture sets and the WNW-NW set has the highest fracture frequency of all sets. This coincides also with the present main horizontal stress with direction about NW-SE.

If the rock mass is hydraulically anisotropic the evaluated properties will, to some extent, be dependent on the borehole direction. It is therefore important to obtain some indication of anisotropy early in an investigation programme for planning the main part of the investigations and also for the evaluation of data.

Scale dependency - correlation model

The mean hydraulic conductivity measured from a borehole section or entire borehole depends on the length of each test interval in the borehole, the test time and the heterogeneous nature of the rock mass. It has been shown mathematically that in a stochastic continuum the mean (effective value) of the hydraulic conductivity is dependent on the size of the volume, which is in agreement with the results from the Äspö HRL. However, some uncertainties remain as to how to produce reliable scale relationships and hydraulic descriptions of the rock mass.

So far no spatial correlation model for hydraulic conductivity has been used in the groundwater flow simulations. An important reason is that the nugget effect (the discontinuity at the origin in a variogram model) of the variogram models has been approximately 60% of the total variance. Because of this a generated hydraulic conductivity field becomes essentially stochastic without any major correlation. However, efforts should be made to try to find a methodology to define a reasonably good spatial correlation model than can include the effect of an anisotropy and scale dependency. There are also conceptual uncertainties in evaluation of hydraulic tests. New methodologies can improve the understanding of flow in the fractures, but conceptual models of the fracture system will also to some extent govern the type of parameters evaluated and also the way in which evaluated data should be used in groundwater flow models.

Groundwater flow model

In general, three-dimensional groundwater flow modelling of Äspö on the site scale, consisting of a stochastic continuum model with the major water-bearing zones as deterministic features, provided a good representation of the real system. The groundwater flow can be fairly well modelled for a site, in terms of water pressures in the rock mass with the assigned properties of the rock, if the flow rates at a pumped borehole or into the tunnel are known. Flow into a tunnel is difficult to predict as the amount and effect of the grouting rather than the hydraulic properties of the rock control the water flow.

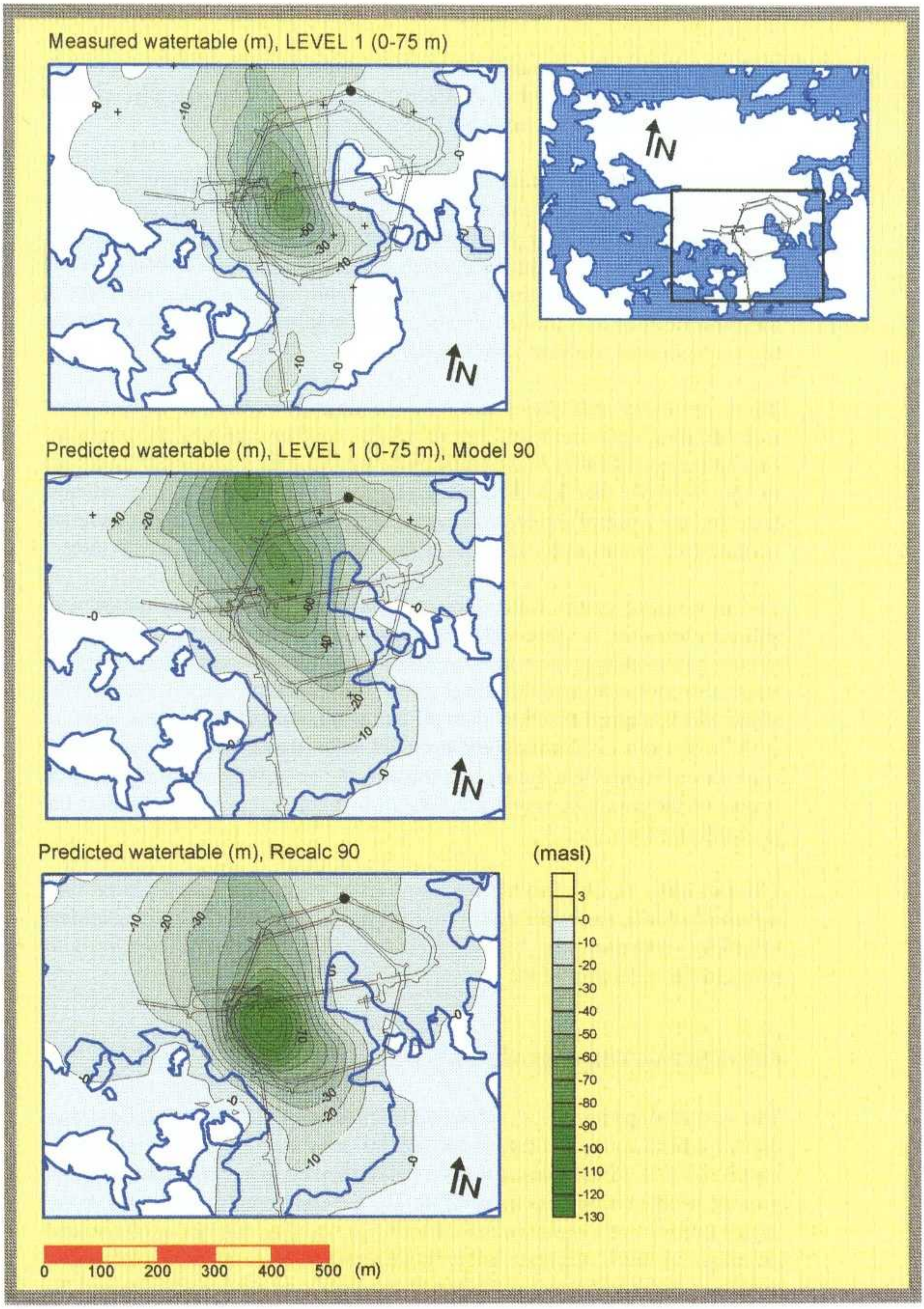
Figure 9 shows some calculations of drawdown during construction. It is the major water conductors and inflow to the facility that govern the overall pattern. However, close to the shaft there are differences due to a local water conducting feature penetrating the shaft that was not accounted for in *Model 90* (modelling performed in 1990 before construction of the tunnel was started). Recalculation of *Model 90* with the measured inflow (*Recalc 90*) to the tunnel shows good agreement with the measured heads. (Only minor adjustment of the transmissivities of the hydraulic conductor domains were made by calibration of the *Model 90*. The recharge rate was a calibrated parameter.)

The Äspö International Task Force on Modelling of Groundwater Flow and Transport of Solutes was formed in 1992. Besides SKB, modelling teams from ANDRA, CRIEPI, PNC, Posiva and Nirex have modelled a long-term pumping and tracer test (called LPT-2) and the drawdown caused by the Äspö HRL following somewhat different approaches. The major conclusion is that the general behaviour of the groundwater flow can be fairly well reproduced with all approaches based on the available data. However, the tasks have also illuminated needs for model developments and input data to the models. The modelling exercises were also fruitful as they gave the modelling teams the opportunity to discuss modelling concepts and to test the capability to handle large data sets.

Methods

The hydraulic test-methods used are in general considered to be sufficient for the models made. Minor problems are that the results are to some extent dependent of the equipment used and thus method developments during a project can possibly affect the results to some extent. It is also difficult to obtain reliable results from low conductivity sections of a borehole because of the elasticity of the equipment and also because of pressure oscillations.

It is important to perform transient hydraulic tests at different scales systematically in the boreholes both for scale relationships but also for flexibility in interpreting how to divide the rock mass into hydraulic conductor domains and



Measured watertable (m), LEVEL 1 (0-75 m)

Predicted watertable (m), LEVEL 1 (0-75 m), Model 90

Predicted watertable (m), Recalc 90

Figure 9. *Measured and calculated drawdown during construction. The black bullet shows the position of the tunnel face, the + shows the positions of the borehole sections for the measured water level. The water table is shown with the tunnel face at chainage 2875 metres (400 metres below the surface) for measured data (top) and Model 90 (middle) and for Recalc 90 (bottom). Recalc 90 is equivalent to Model 90, but with the measured inflow rate and a new deterministic water-bearing zone intersecting the shaft.*

hydraulic rock mass domains. It is also important to perform larger-scale interference tests both for defining hydraulic conductor domains and for calibrating and testing numerical groundwater models.

Flow-meter logging is a fast and useful method for finding major hydraulic conducting features in a borehole and to obtain a rough estimate of their transmissivities. However, in boreholes where there is a high transmissivity feature high up in the borehole and water with high salinity at the bottom of the borehole, flow-meter logging may give erroneous results in the lower part of the borehole. The possibilities of defining low-transmissivity features with the test methodology used are also limited.

There are several difficulties in estimating the proper fluxes in the rock mass from dilution measurements. The technique can be improved, but there are conceptual uncertainties of the coupling between the flow in the rock mass and in the borehole that are difficult to resolve. The dilution measurements, however, are a useful and feasible way of finding out whether or not there are hydraulic communication in terms of flows and not just pressure responses.

The monitoring of the water pressures is judged to have been made with sufficient intensity in space and time. However, it would have been preferable to have had somewhat more measurements of the natural conditions. Due to the large drawdowns close to the tunnel spiral some borehole sections close to the tunnel spiral stopped functioning as the equipment for monitoring the pressure in the boreholes was not designed for these large drawdowns that occurred. It is, however, judged that these two problems did not have a major detrimental impact on the possibilities of evaluating the hydraulic properties and testing the groundwater flow models.

The estimates of the absolute pressures along the boreholes at natural (undisturbed) conditions were useful for the interpretation of the water chemical sampling. However, the measurement technique should be improved to increase the reliability of the pressure measurements.

GROUNDWATER CHEMISTRY

The work at Äspö has given a broad understanding of the (chemical) processes that have been active in the past and are currently active in the Äspö groundwater and rock mass. These processes are expected to be typical of a coastal granitic rock environment in Sweden. The processes considered to have the largest impact on the groundwater chemistry are mixing, calcite dissolution and precipitation, redox reactions and biological processes. In addition to these fast processes, the long-term groundwater/rock interaction has largely affected the groundwater chemistry and produced a brine with a total salinity of nearly 100 g/l.

Mixing

Mixing of water from different sources is considered to be the main reason for the observed hydrochemical situation. A good overview of the distribution of the major constituents (main ions) in the water-conducting fractures was achieved already during the pre-investigation phase. Based on the spatial distribution and different extrapolation methods it was possible to predict the composition of groundwater to be sampled in the tunnel.

Methods and models have been developed for identifying the different sources of groundwater at the Äspö site and the way in which groundwater at specific locations in the rock mass can be described as a mixture of water from these sources.

There are two main causes for the mixing observed. One is the disturbance caused by the borehole by short-circuiting the different water-conducting fracture systems, the other one is the mixing which has taken place in the past due to varying hydraulic driving forces which have diverted the groundwater flow in different paths. In the evaluation work, the mixing caused by the borehole is considered to be a disturbance which is taken into account and corrected for. The remaining mixing proportions of different water types are then described as the result of varying groundwater flow conditions. The present hydrochemistry model of Äspö accounts for the conditions prevailing since the latest glaciation. The knowledge of the past also constitutes a basis for describing the future evolution of the hydrochemistry of Äspö.

Groundwater/rock interaction

Calcite saturation

Calcite dissolution and precipitation are among the few reactions between solid phases and dissolved components that are rapid. The calcite system affects the groundwater flow conditions in the rock mass indirectly, due to dissolution and precipitation, at different locations in the rock mass. Existing flow paths might be sealed whereas new flow paths might be opened. In addition to the groundwater composition these reactions are also affected by variations in temperature and pressure.

During the pre-investigations most of the sampled waters were slightly supersaturated with respect to calcite. The subsequent evaluation of data collected in the tunnel shows that the water sampled from tunnel boreholes was also supersaturated, as expected. Despite the small amount of supersaturation the groundwater is considered to be in equilibrium with respect to calcite.

Redox conditions and biological activity

It has been clearly demonstrated that the groundwaters at depths greater than 100 m are reducing, and that the dissolved oxygen in the infiltrating surface water is consumed by bacteria. It has also been found that bacteria are important for establishing high dissolved iron and bicarbonate concentrations and that bacterial reduction of iron (III) minerals and sulphate add to the reducing capacity of the groundwater.

In addition to the inorganic reactions between oxygen and minerals, the effective oxygen consumption by bacteria strengthens the general opinion that anoxic (oxygen free) conditions could always be expected in the deep groundwater, also during the operational phase of a deep repository.

Because of the effects of the biological processes the observed bicarbonate, sulphate and iron concentrations were different from those predicted. This was especially noticeable in the tunnel sections located below the sea, where the water percolating through the seabed sediments transported large quantities of organic matter into the rock. Bacteria have increased the iron concentration up to 4 mg/l and the bicarbonate content up to 500 to 1000 mg/l.

The observed biological processes are:

- oxygen consumption by oxidation of organic matter
- reduction of iron (III) minerals through oxidation of organic matter
- reduction of sulphate by oxidation of organic matter

The biological processes are important in the uppermost part of the rock but not necessarily throughout the entire area. It is mainly below the sea that the biological processes have been excessive due to a large supply of organic matter from the seabed sediments.

Modelling

In *Model 90*, at the end of the pre-investigations, groundwater was classified into four different water types (see *Figure 10)* based on linear principal component analyses of the constituents of the groundwater as collected from the boreholes prior to construction. Tools for analysis and modelling have been developed considerably since then. *Model 96* is based on all data collected during 1986 - 1995 and classifies the water according to its origin. For each 'origin' specific water constituents are identified in order to define 'end-members' in *Model 96.* At Äspö all end-members are not present but instead 'reference waters' and their interrelated mixing proportions are calculated: saline water, meteoric water, glacial water, altered marine water and Baltic sea water. Even if the results, as shown in *Figure 10,* may show resemblance it must be understood that while *Model 90* is based on multivariate statistics only, Model 96 is the combination of statistics *and* a better understanding of the processes behind the observations.

Salinity is one of the chemical conditions which illustrates the chemistry of the groundwater. *Figure 11* shows the comparison between the salinity distribution of the groundwater before and after tunnel construction.

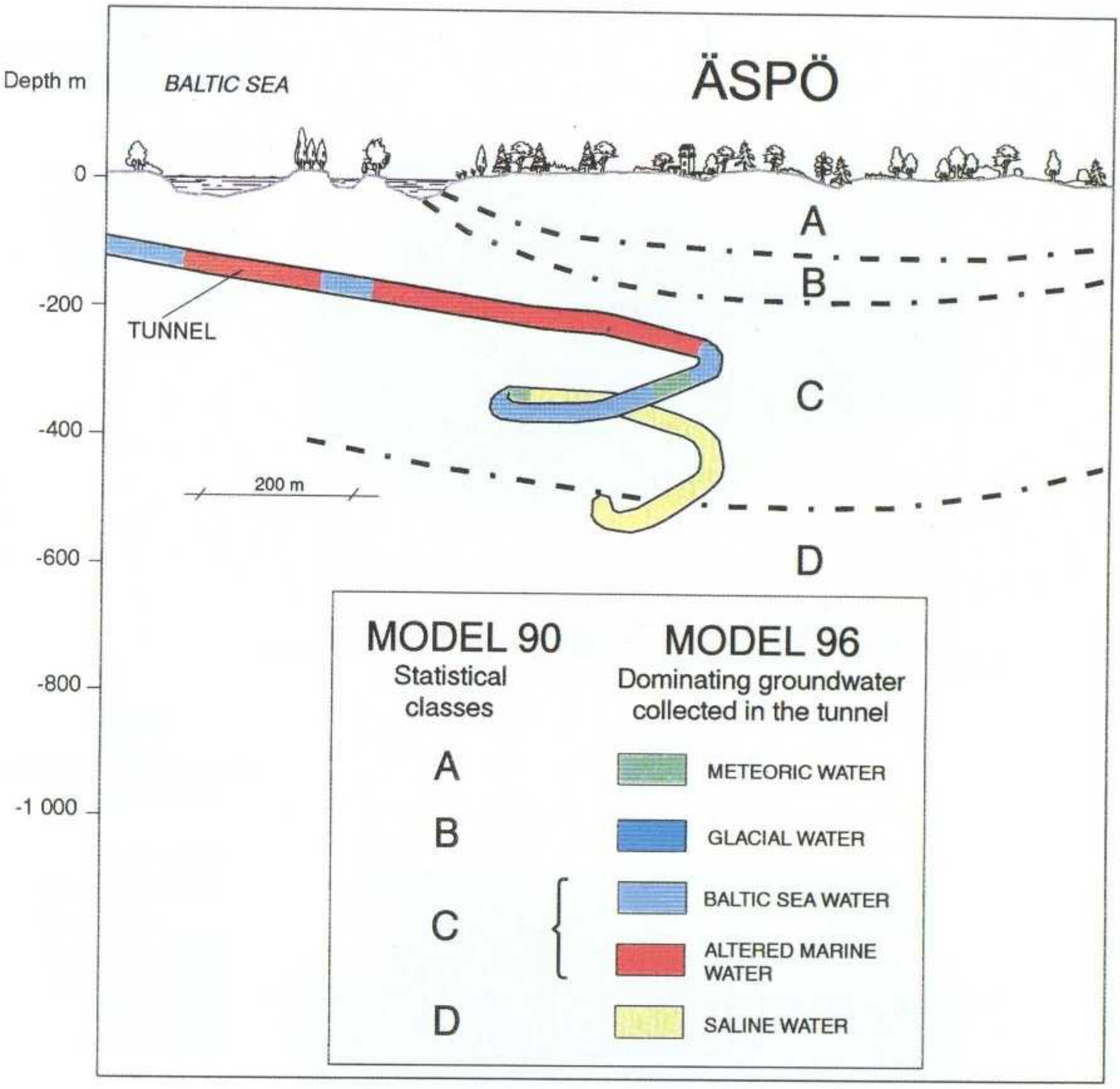


Figure 10. *Classification of groundwaters according to Model 90 and Model 96. Model 96 is based on the combination of statistics and interpretation of water type origin and their mixing proportions. Model 90 is based on multivariate statistics only. A corresponds to meteoric water, B to glacial water, C to Baltic sea water and altered marine water and, finally, D to saline water.*

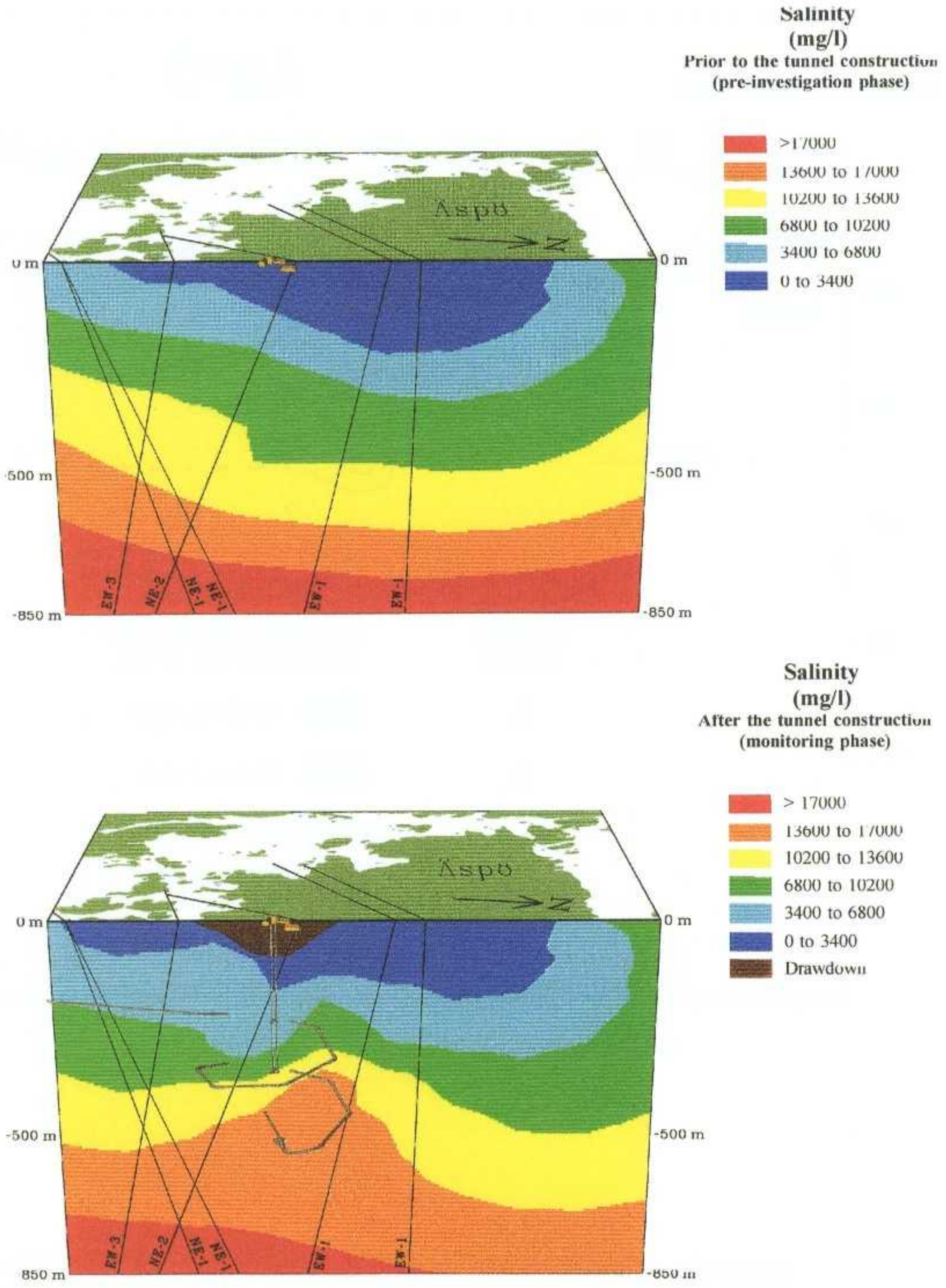


Figure 11. *Salinity of the groundwater at Äspö before (Model 90) and after (Model 96) tunnel excavation. The interpolated data are based on observations in 6 deep boreholes for Model 90 and 20 probing holes along the tunnel for Model 96.*

The initial predictions of groundwater chemistry to be observed during tunnel construction were based on *Model 90* and a combination of expert judgement and principal component analyses. However, the range was only estimated by expert judgement. It seems now that the estimated ranges presented as 'predictions' were too narrow. The ranges took into account the measurement uncertainty, but not the natural variability of input data. However, further analyses and re-modelling of pre-construction data using different mathematical methods took into account the natural variability. The range of variation was calculated on the basis of the variation in input data and the same variation was expected for the observations. These more correct methods show that most of the observations fall within the predicted ranges for all constituents except sulphate and bicarbonate. In some cases the range of the variation is so wide that it could be questioned whether the prediction is meaningful or not. Therefore, it can be concluded that predictions in exact locations should not be made.

Methods

Most important for investigating the chemical composition of the groundwater in major fracture zones has been the chemical characterization of the groundwater using a mobile field laboratory with the down-hole Eh and pH measuring devices. The second most useful method is the sampling during the hydraulic interference pumping tests. A third useful method is the sampling in percussion boreholes. The sampling during drilling was not useful due to uncertainty in the quality and representativity of the water. However, the method for sampling during drilling can be improved so that useful data on the groundwater origin and distribution can be obtained.

Much of the approach used at Äspö could be adopted for future site investigation programmes, provided it is adjusted to the specific conditions at the site. Hydrochemical characterization should preferably be made using water from major fracture zones and other water conducting features. Sampling of water conducting sections should be undertaken at an early stage in the drilling phase. This was tried at Äspö, but the results were of limited value, since the amounts of drilling water which remained in the samples were too large, primarily, due to the large length of the sampled sections. A better sampling procedure has now been developed to characterize the initial undisturbed situation.

TRANSPORT OF SOLUTES

Studies of the transport of solutes have focussed on two large experiments, that give relevant insights into this subject - the long-term pumping and tracer test LPT-2 conducted in 1990-1991 and the study of the flow of saline water during the tunnel excavation.

A few attempts were made during the pre-investigation and construction phases to estimate the flow porosity of the rock mass. For example, prior to construction a combined long-term pumping and tracer test (LPT-2) was conducted to test the hydraulic connectivity of hydraulic conductors and to derive estimates on flow porosity. During the construction period some efforts were directed to the use of other types of natural tracers as well to derive transport parameters for non-sorbing transport. However, more tests need to be performed to obtain data on the flow porosity and other transport parameters.

Prior to construction, scoping calculations were made to assess the change of salinity in the groundwater as a consequence of the drawdown caused by construction of the facility. When the flow paths in some major zones (from the surface, the sea and deep down in the rock) are compared with the water chemical composition of the water flowing into the tunnel and the water found in the Baltic Sea, the calculated results are in fair agreement with the measured values.

Models

Interpretation of the LPT-2 test and subsequent evaluation of the groundwater flow models has been a task for The Äspö International Task Force on Modelling of Groundwater flow and Transport of Solutes. Eleven different groups performed modelling using different conceptual and numerical approaches for simulating flow and transport in fractured rocks. Evaluation has shown that all models represented the measured LPT-2 data set well with respect to drawdown. In general, the data supplied for Äspö, including the geological structural model, provided a good representation of the real system. However, a few consistent errors in the modelling results from the teams provide valuable information for the model of the Äspö site.

If calibration of transport parameters is performed, reasonable agreement between models and experiment are obtained for the tracer tests of LPT-2. The general tendency was that modelled travel times for the tracers were too short. No ‘unique’ best solution was derived with respect to the transport parameters which means that the tests could not distinguish between the concepts applied. Tracer tests conducted in fracture zones, e.g. NE-1, during construction were useful to define hydraulic connectivity and estimate approximate values of flow porosity over a scale of about 100 m.

Salinity

Based on the pre-construction *Model 90* and assessing the impact of excavation response on the flow field, changes in salinities were modelled. Under undisturbed, natural, conditions the maximum depth of the freshwater layer was predicted to some 200 m and the measurements indicate a maximum depth of about 250 m (see *Figure 12)*. Observations in boreholes from the surface show that water with a salinity of 17000 mg/l under undisturbed, natural, conditions was found at a depth of about 700-800 m. A salinity of 8000-10000 mg/l under undisturbed, natural, conditions was found at a depth of 400-500 m.

After excavation of the tunnel, water in short boreholes drilled from the tunnel at a depth of about 360 m showed a salinity of about 17000 mg/l. Minor changes in the salinity were observed in boreholes at some distance from the tunnel. The predictions made using the numerical model also indicated an upconing of saline water (see *Figure 13)*. The sections in *Figures 12 and 13* showing the measured values are based on interpolation of the measured values from Baltic Sea water, meteoric water (on land), 29 borehole observations during the pre-investigations and 37 borehole observations during construction. The measured values are concentrated in the central part of the figures and mainly above 600 m depth. Outside this region the interpolated values should be concidered uncertain. The numerical model, *Model 90*, was a stationary simulation.

Natural tracers

The proportions of different water types, (reference waters, such as glacial, deep saline, Baltic Sea and meteoric) were evaluated from samples collected in the main hydraulic conductors on several occasions during construction. The results can be used to assess the hydraulic connectivity and flow direction in the zones as the proportions of the reference waters change with time in the zones. The conclusions from the data are that fracture zones NE-4, NE-3, NE-1 and NNW-4 are connected to the Baltic Sea. Fracture zone NE-2 has good contact with the deep saline water. Gradually there is a complete mixing situation in the fracture zones, and it is quite clear that the flow directions are changing during the construction phase.

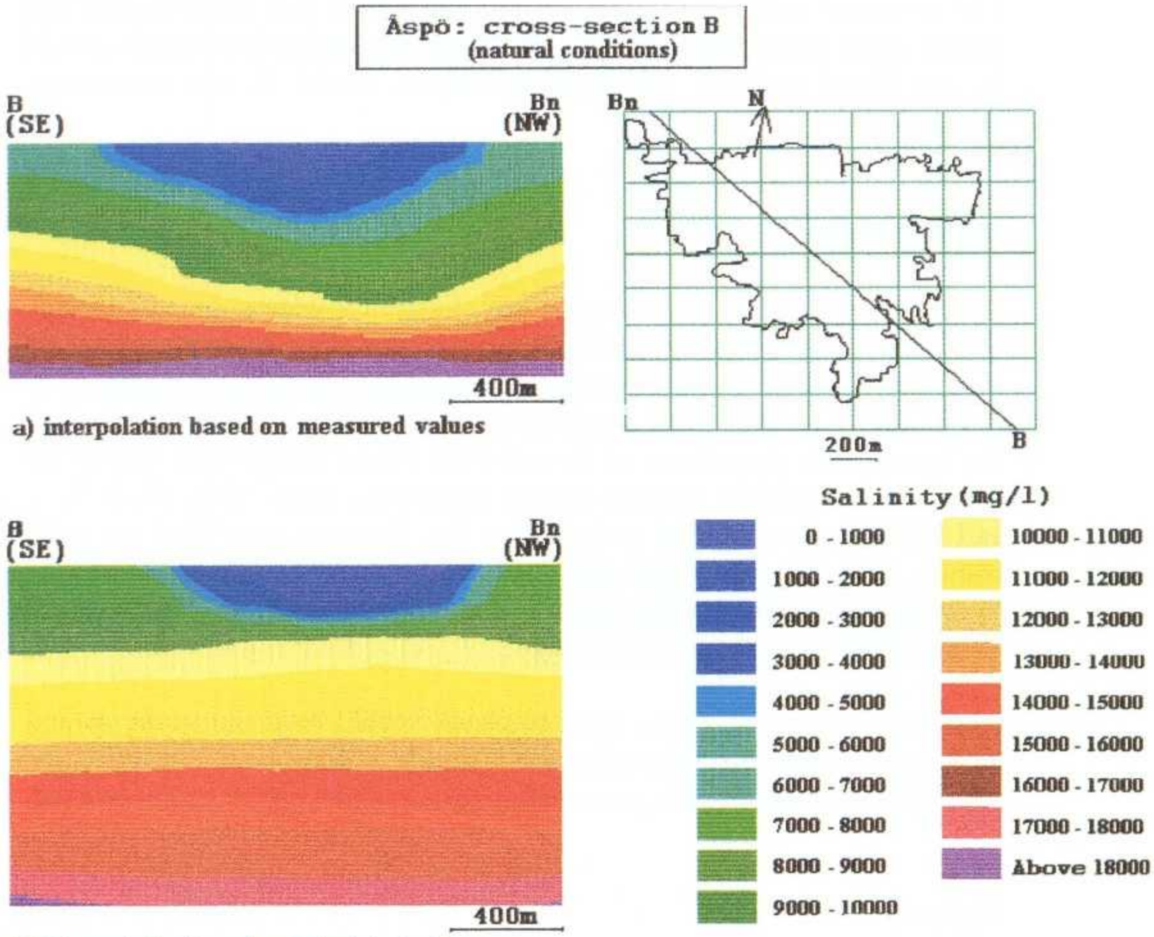
In future site investigations, more emphasis should be given to the natural tracers as a means of understanding the hydraulic connectivity. The technique developed for evaluating the groundwater types and proportions can be utilized.

Methods

It is important to have a sampling strategy that gives a reasonable number of points in space where time series are established for natural conditions and for the construction phase of the important chemical constituents. This forms the basis for evaluation and simulation of flow paths and flow times on a large scale. It is also important to measure the flow rates into the tunnel sections during construction and the chemical composition of the water flowing into the tunnel sections.

Large-scale tracer tests are to some extent difficult to perform and interpret but are useful to obtain information on large-scale connectivity. Test methods and methodology for evaluation have to be better developed to obtain relevant transport parameters. Work of this kind has already started at the Äspö HRL.

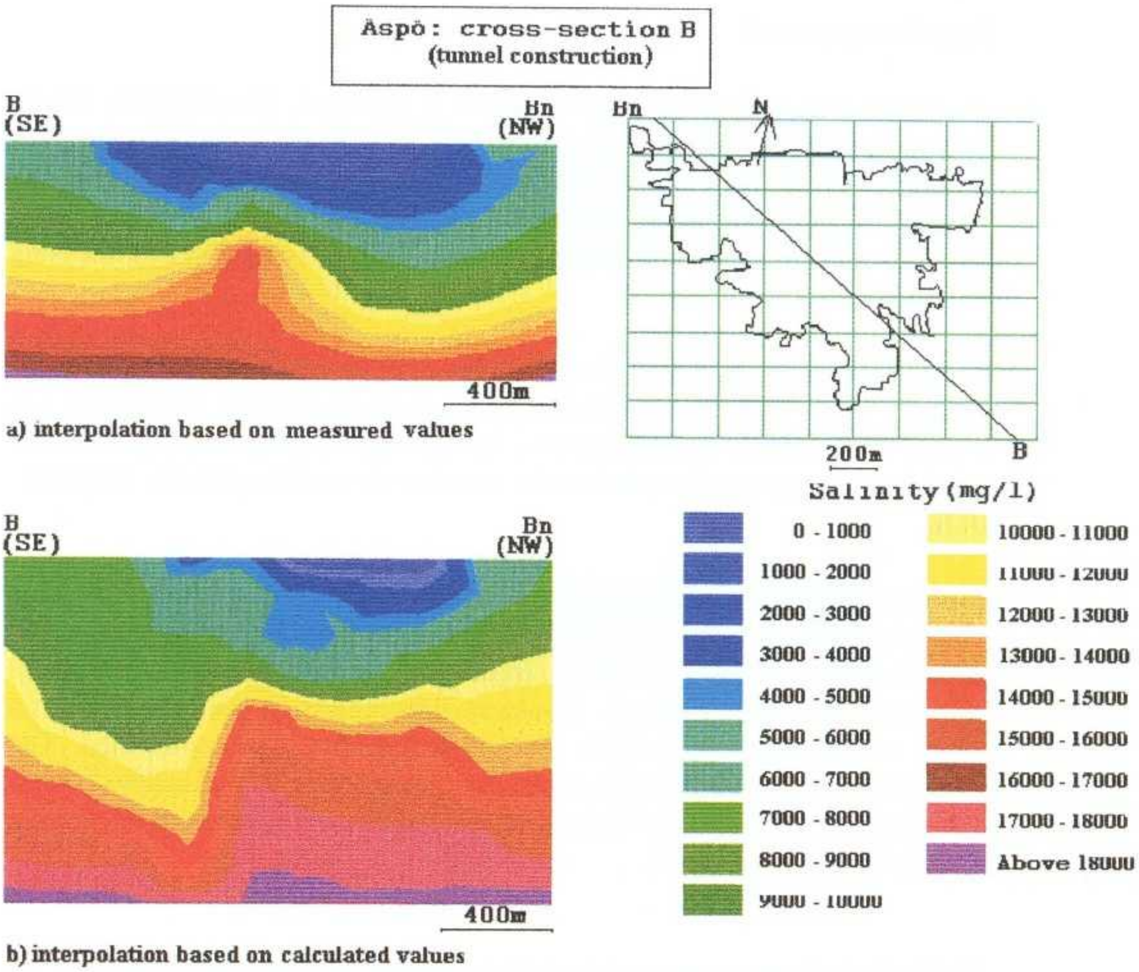
A few deep boreholes for sampling of groundwater and hydraulic tests are also needed to support the modelling of transport of solutes, and also groundwater flow and groundwater chemistry.



a) interpolation based on measured values

b) interpolation based on calculated values

Figure 12. *Salinity shown for a vertical section through Äspö from NW to SE. Ambient conditions. Numerical simulations (bottom) shown down to a depth of 1250 m. Measured values (top) based on interpolation, shown down to a depth of 850 m = the deepest measurement point. Salinity in mg/l.*



a) interpolation based on measured values

b) interpolation based on calculated values

Figure 13. *Salinity shown for a vertical section through Äspö from NW to SE. After construction. Numerical simulations (bottom) shown down to a depth of 1250 m. Measured values (top) based on interpolation, shown down to a depth of 850 m = the deepest measurement point. Salinity in mg/l.*

EVALUATION OF SITE CHARACTERIZATION METHODOLOGY

Iterative approach

An iterative approach to site investigation is preferred. The iterations should encompass all the activities, not only the data collection, but also analysis, modelling and evaluation of results compared with the goals set for the site characterization. The iterations should continue until there is confidence that the known uncertainties are acceptable for design, construction and licensing of a repository.

Clear goals for the characterization are important as they give the basis for the scope of work. Site characterization produces a huge amount of data and it is a great advantage to have access to a flexible data management system with good three-dimensional capabilities to visualize data and to perform interpretations.

The prediction/outcome approach used to evaluate model reliability has some obvious advantages. It is a good tool, useful for planning, transparency and documentation, which simplifies evaluation of model and also the usefulness and feasibility of the methods. However, data collection can be focused too much on pre-determined spots for which data have been predicted. The comparison of the predicted parameter with outcome can also lead to several explanations and therefore there is also a need to scrutinize the underlying assumptions and processes.

Multi-disciplinary approach to data collection and interpretation

Inter-disciplinary work was performed throughout the investigations to ensure model consistency. To facilitate integration, only four principal investigators with broad responsibilities were involved in the science management. Important definitions, classifications and main issues were defined in the beginning of the site investigation. It is important to have definitions and classification systems defined as good as possible at the outset of a site investigation.

Data collection

The direction, depth and inclination of boreholes, were decided in consensus. It was also more or less taken for granted that tests for several disciplines should be conducted in the same boreholes, to avoid ‘the geologist’s hole’, ‘the chemist’s hole’ etc. The advantage is that several types of observations are collected for the same rock volume, permitting joint-interpretation of geology, rock stress, hydrogeology and groundwater chemistry. The design of boreholes and the test sequence were planned in consensus, maximizing the information that could be obtained from each hole. Pumping tests for hydrogeology were planned to allow for sampling of the hydrochemistry as well. With the experience from the Äspö site characterization the sequence of testing would have been different, allowing for more undisturbed groundwater chemistry sampling.

Modelling

In the early phase of the investigations, all data collected were used to support the development of a reliable geological-structural model. The geological and geophysical data were compared with hydraulic responses and the chemistry of the groundwater to determine the model of the major fracture zones. The lithological model was used as base for division of hydraulic domains as well. Groundwater salinity data were used to check the groundwater flow model and the groundwater flow model was also used for understanding and checking the mixing models of groundwater chemistry. Rock stress measurements are also useful for comparing the principal direction of the hydraulic conductivity tensor with the rock stress tensor. There is a strong and direct coupling between the geological model and the rock mass classification used to assess excavation stability.

The use of each borehole for geological, geohydraulical and groundwater chemical observations also simplified joint-interpretative work when model updating was done. It is thought that the value of common boreholes overrides the possible disadvantages of making inter-disciplinary tests in the common holes.

Modelling on different scales

Äspö models were made on different scales (see *Figure 1*). The *Regional scale model* shall provide information useful for selecting potential sites for the repository. It shall also provide enough data for setting up groundwater flow and groundwater chemistry models in a large scale. These models are needed for the general understanding and evaluation of the present and past processes and have to be used to assess the boundary conditions for the site model.

Fairly limited investigations were performed during the pre-investigation phase but the data were sufficient to select the site for the laboratory but were later found to be insufficient for the understanding and modelling of the regional area with respect to groundwater flow and groundwater chemistry. Supplementary investigations during the construction phase of the laboratory (drilling of one very deep borehole and some ground geophysics investigations traversing a few fracture zones) gave a better insight into processes and properties within the regional model. However, it is likely that the investigations within a regional area have to be somewhat more extensive than those for the Äspö HRL to obtain better confidence of the boundary conditions (mainly hydraulic and groundwater chemical) but also on the properties of the rock mass in a regional context.

Site-scale models will be used to find out whether there is a large enough rock volume to host the repository. The investigations at Äspö were adequate in this respect - in this case to host the Äspö HRL. They provide confidence that major fracture zones and their geometry can be known, based on pre-construction investigations. Site-scale models are both useful and feasible.

Block-scale models were stochastic for subjects like rock composition, number of rock boundaries, single open fractures, etc. Sampling of populations to test these predictions was then conducted in 6 predetermined blocks located along the tunnel. This approach may be questionable as it might have been better - due to the natural variability at the site - to sample over larger volumes to compare parameter populations prior to and after construction. The block-scale assessment is of course useful for the near-field performance assessment. However as a 'prediction' exercise the results on the block scale at Äspö were usually outside the range for pre-located blocks along the tunnel, basically due to the lithological heterogeneity. Thus, for a repository it is of value that the site be fairly homogeneous to simplify confidence-building for the near-field models. Block-scale models should not be made for specific locations but should be stochastic in nature. Tools for such models have been developed and tested at Äspö.

Limited work was done for *Detailed-scale models*. The observations are considered to be more in line with the predictions than on the block scale due to the homogeneity of the detailed-scale models compared with that of the block-scale models. The detailed blocks represented a representative 'standard unit' of each major rock type at Äspö.

For future work models on different scales are useful. Their feasibility could, however, be improved by collecting samples over larger volumes rather than at pre-determined located blocks.

Äspö key issues for site characterization and their relation to SKB siting factors

The key issues selected at Äspö for site characterization are highly relevant as these are part of the siting factors defined at SKB.

The Äspö work provided further evidence that the chemistry of the groundwater at depth has been stable for long periods of time. The efforts undertaken also shed more light on the previous history of the groundwater and understanding of the chemical and biological properties that control the composition of the groundwater. Evidence at Äspö added to previous general knowledge that groundwater at depth is reducing. Understanding of the biological processes in the rock has taken a major step forward and these findings show that biological processes contribute to the reducing conditions in the rock.

Low groundwater flow is important. The investigations at Äspö show that, using appropriate methodology, it is possible to obtain confidence in the hydrological properties at a site being capable of being established in a timely manner, even in a complex geological environment as at Äspö.

The question of the long-term mechanical stability is mainly treated within the general SKB Geoscience Programme. The study of mechanical stability at Äspö has been devoted to understanding whether mechanical instability will occur during construction. The expert judgements on these matter have been correct, which can mainly be attributed to general experience in Sweden that mechanical stability prevails in 'good rock'.

INTERNATIONAL PARTICIPATION

The work at Äspö Hard Rock Laboratory has been of great interest internationally and several international organisations are participating in the work. Participating organizations during the period 1990-1996 were:

Atomic Energy of Canada Limited (AECL), Canada
Power Reactor & Nuclear Fuel Development Corporation (PNC) Japan
Central Research Institute of Electric Power Industry (CRIEPI), Japan
Agence Nationale pour la Gestion des Dechets Radioactifs (ANDRA), France
Posiva Oy, Finland
United Kingdom Nirex Limited
United States Department of Energy (USDOE), USA
Nationale Genossenschaft für die Lagerung von Radioaktiver Abfälle (Nagra), Switzerland
Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), Germany
Swedish Nuclear Fuel and Waste Management Co (SKB), Sweden (host organization)

The international co-operation promotes quality, efficient use of resources and scientific, technical and public confidence building.

In practice, much of the efforts by the organizations have been directed to refinement of models for groundwater flow and radionuclide transport. The existing and planned data base at Äspö was used to evaluate different approaches in modelling.

CONCLUDING REMARKS

Site characterization in conjunction with construction work at Äspö has basically confirmed the pre-construction models. However, the models have become more detailed after the construction period.

The work at Äspö has shown that such pre-construction models can be obtained for the studied key issues through the application of 'standard methodology of good quality' for measurements, data analyses, modelling and evaluation.

Considering the stage goals the characterization should *demonstrate that investigations at ground surface and in boreholes provide sufficient data on* *essential safety-related properties of the rock at repository level.* The work at Äspö has demonstrated that relevant safety-related data can be obtained. The data set is not complete, but has permitted safety analyses of a simulated repository at Äspö by the Swedish Nuclear Inspectorate and SKB (in progress).

The results and experience from Äspö are partly general in nature and partly site-specific and they should be relevant for planned site characterization in the Swedish bedrock. If these findings are transferred to other types of bedrock and target depths appropriate modifications of the characterization and modelling programme could be required.

In site characterization for a deep repository, methods should only be used that have been shown to be useful and feasible in practice. Should new methods be considered in the site investigations for the deep repository the Äspö facility will provide excellent conditions for testing prior to application at a real site.

The methods and technology needed for characterization of the rock in the detailed site investigations have been tested and developed. Valuable experience of construction-testing integration have also been obtained. On-going R&D work will supplement present knowledge.

The site characterization at Äspö has been used to *refine and test on a large scale at repository depth methods and models for describing groundwater flow and the transport of solutes in rock.* The joint international work in the Äspö Task Force on Modelling of Groundwater flow and Transport of Solutes has demonstrated many different approaches to modelling that seem useful.

Design and construction of the Äspö Hard Rock Laboratory, incorporating both drill-and-blast excavation and mechanical excavation using a tunnel boring machine, have *provided access to rock where methods and technology can be refined and tested so that high quality can be guaranteed in the design, construction and operation of the final repository.* On-going-experiments at the Äspö HRL, such as the planned Prototype Repository will be valuable to transfer general scientific knowledge into engineering practice. For example development of grouting theory will be useful for the future repository. Valuable work was performed by the project and developments will continue.

Finally, the site characterization at Äspö has been a realistic 'dress-rehearsal' that will be useful for planning and executing surface and underground site characterization for the deep repository for spent fuel in Sweden.

1 INTRODUCTION

1.1 THE ROLE OF THE ÄSPÖ HARD ROCK LABORATORY IN THE SWEDISH WASTE MANAGEMENT PROGRAMME

The Äspö Hard Rock Laboratory (Äspö HRL) provides an important scientific and technical basis for the programme of siting, designing, constructing and operating a future deep geological repository in Sweden. The need for such an underground laboratory was identified at an early stage in the Swedish programme. The Äspö HRL was built to provide an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to the depth planned for a future deep repository for spent nuclear fuel.

Geological investigations in the region around Äspö were started in 1986. The *pre-investigation phase*, 1986-1990, involved siting the Äspö HRL and Äspö was selected as the site for the laboratory in 1988. The natural conditions in the bedrock were described and predictions made with respect to the hydrogeological and other conditions that would be observed during the construction phase. Planning for the construction and operating phases was also carried out.

Construction of the underground facility started in October 1990 with the laboratory being completed in the summer of 1995. During the *construction phase*, 1990-1995, extensive investigations, tests and experiments were carried out at the same time as the civil engineering activities. The focus of the experimental work was mainly to check the reliability of interpretations based on the pre-investigations and to broaden and detail the data base of the Äspö site. The first part of the tunnel was excavated using the drill-and-blast technique. The last 400 metres were excavated by a Tunnel Boring Machine (TBM) with a diameter of 5 metres. The total length of the tunnel is 3600 m. The underground excavations are connected to the Äspö Research Village, containing offices, stores, hoist and a ventilation building, by a hoist shaft and two ventilation shafts (*Figures 1-1, 1-2, 1-3).*

A major milestone has now been reached with the completion of the pre-investigation and construction phases.

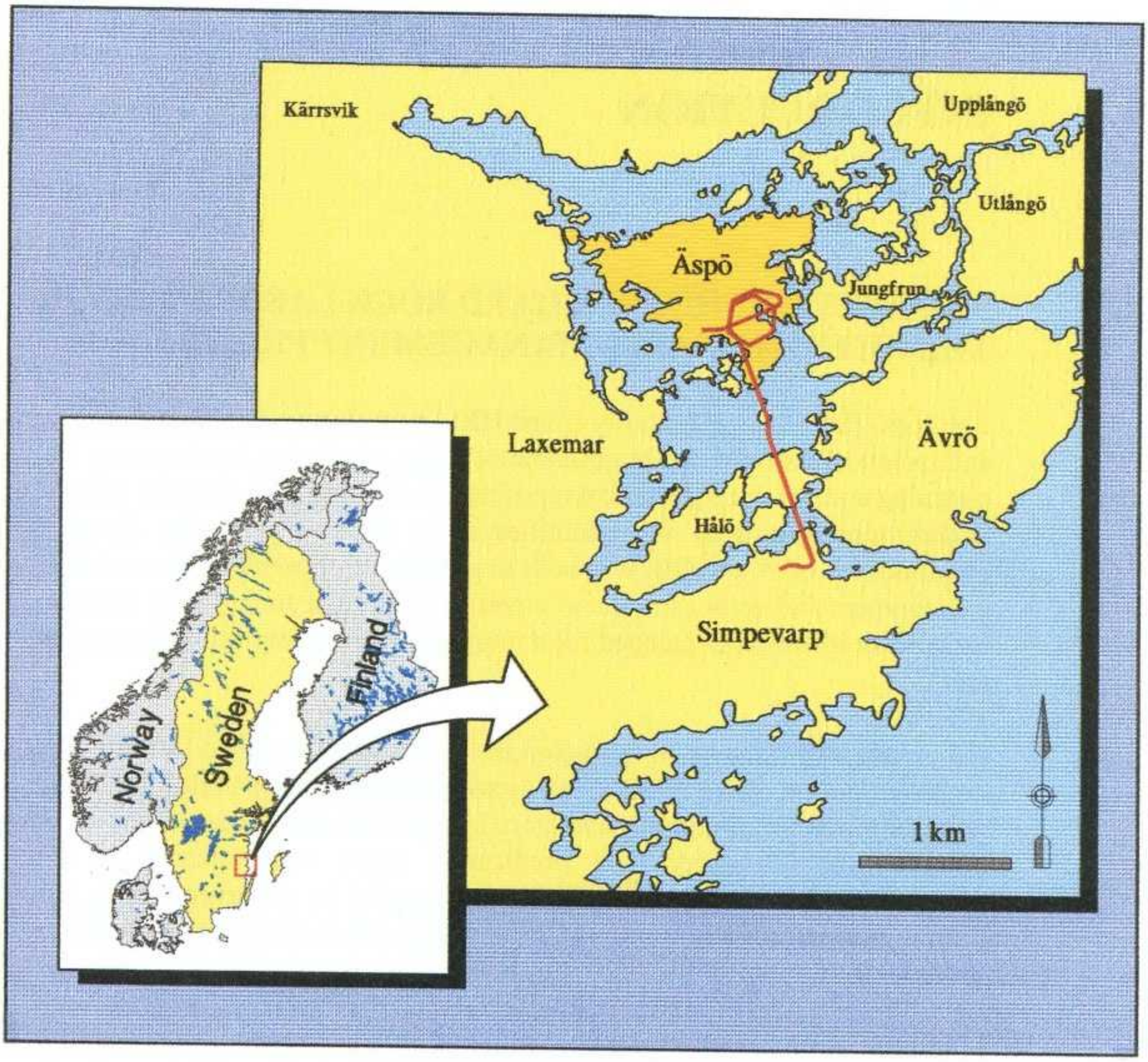


Figure 1-1. *Location of the Äspö Hard Rock Laboratory.*

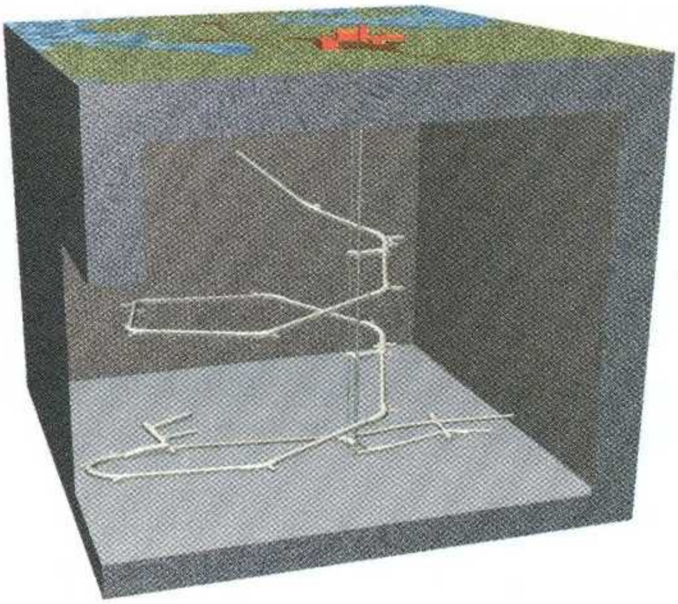


Figure 1-2. *General layout of the Äspö HRL. The total length of the tunnel is 3600 m. The first part of the tunnel was excavated using the drill-and-blast technique. The last 400 metres were excavated using a Tunnel Boring Machine (TBM) with a diameter of 5 metres. The underground excavations are connected to the Äspö Research Village, containing offices, stores, hoist and ventilation building, by a hoist shaft and two ventilation shafts.*

Figure 1-3. *Bird's-eye view of the Äspö Research Village.*

The research work at Äspö, 1986-1995, has focussed on the reliability of site characterization methods. It is important to understand this aspect of site characterization as the results from the investigations will be used to:

- show whether a site has suitable geological properties for a deep repository,
- provide data and knowledge concerning the host bedrock so that a preliminary emplacement of the repository in a suitable rock volume can be done as a basis for a constructability analysis,
- provide the necessary data for a preliminary safety assessment, which in Sweden shall serve as support for an application under the Management of Natural Resources Act (NRL) and the Nuclear Activity Act (KTL) to carry out detailed site characterization,
- provide data for the planning of detailed site characterization that will take place during excavation from surface down to the repository level.

The geoscientific site investigation programme which will be conducted by SKB at a potential repository site will be based on the experience gained from earlier investigations at study sites around Sweden, as well as at Stripa and Äspö, and will also draw on the experience from site characterization studies, in particular in Canada and Finland. Site investigations at Äspö contributed significantly to the development and improvement of instruments, investigation techniques and evaluation methods. This has provided a solid basis for future site studies as well as identification of areas where further development of techniques and methods has been justified.

1.2 APPROACH TO SITE CHARACTERIZATION AT THE ÄSPÖ HARD ROCK LABORATORY

The site investigations for the Äspö Hard Rock Laboratory prior to construction of the facility were planned to meet two requirements.

The first requirement set by the SKB was to test the ability to obtain a thorough *understanding* of the rock conditions based on investigations of surface and investigations in and between boreholes drilled from the surface. By *understanding* we here mean to obtain sufficient knowledge *to show how things are, but also to show how things cannot be /Bäckblom et al, 1991/.* The requirement led at that time to the development of a v*alidation process.*

The second requirement was to conduct the investigations necessary to *design the underground facility* so that it could be constructed with the technology available at present without major problems down to a depth of 500 metres. The facility should also be designed to meet the needs for research, development and demonstration studies in the operating phase.

The goals of pre-construction and construction phase characterization were to */SKB, 1989/*:

- *demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.*

- *refine and verify that the methods and technology needed for characterization of the rock in the detailed site investigations.*

The aim was also that the site investigations should give some experience on the third and fourth stage goal:

- *refine and test on a large scale at repository depth methods and models for describing groundwater flow and transport of solutes in rock.*

- *provide access to rock where methods and technology can be refined and tested so that high quality can be guaranteed in the design, construction and operation of the final repository.*

The two requirements *understanding* and *design of the facility* called for a careful focussing and structuring of the work. Several decisions were made to meet these requirements (cf. *Section 2.2).*

The results from the investigations performed during the pre-investigation and construction phases of the Äspö HRL have been presented in a large number of Progress Reports, International Co-operation Reports and Technical Reports (see *Bibliography).* An overview of the final reporting of the pre-investigation and construction phases of the Äspö HRL is shown in *Figure 1-4.* The booklet *Äspö Hard Rock Laboratory - 10 years of research*, available from the SKB, provides the reader with a popular review of the achievements. The overview of investigation methods used 1986-1995 is presented in *Stanfors et al /1997a/.* The detailed evaluation of the results from the pre-investigation phase is reported in *Stanfors et al /1997/* and *Rhén et al /1997a/.* Updated models of Äspö based on site characterization 1986-1995 are reported in *Rhén et al /1997b/.*The feasibility and usefulness of site investigation methods are described in *Almén et al, /1994/.*

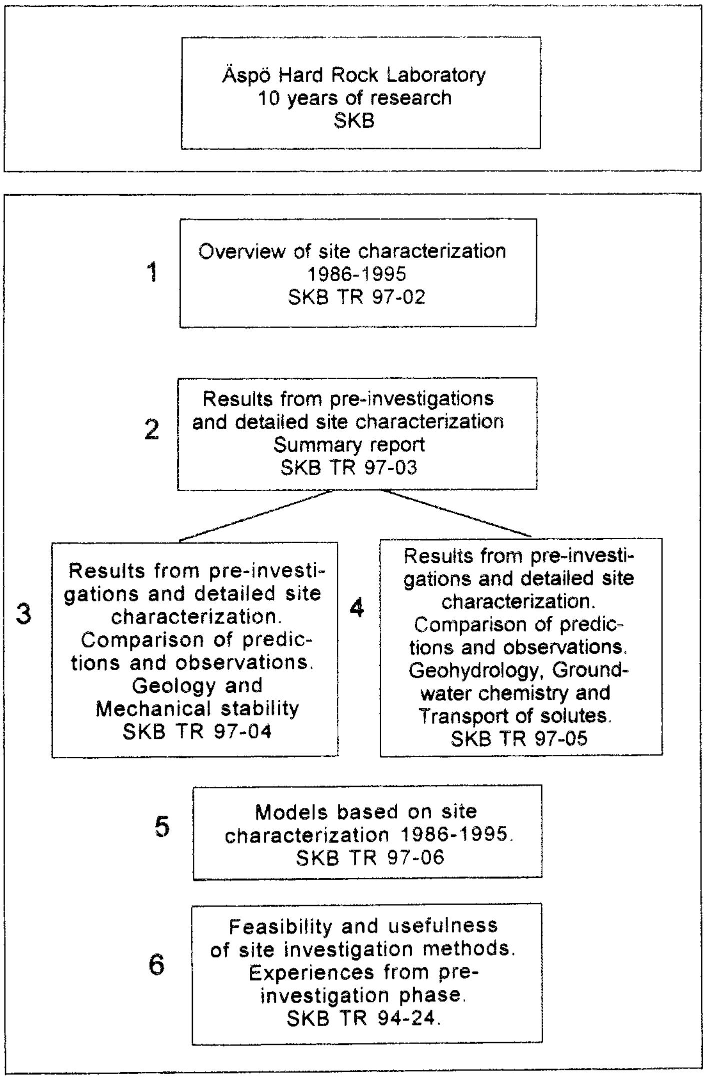


Figure 1-4. *An overview of the final reporting of the pre-investigation and construction phases of the Äspö HRL. 'Äspö Hard Rock Laboratory, 10 years of research' is an overview booklet of the entire project. The more detailed reporting is contained in the Technical Reports (TR) shown above.*

1.3 OUTLINE OF THIS REPORT

The purpose of this report is to summarize the findings concerning the reliability of the site investigation methodology. This is achieved by examining models based on pre-investigation results and comparing them with the derived results from the detailed characterization conducted in conjunction with the construction of the underground laboratory.

Chapter 2 explains the concept of key issues. Based on definitions of essential model elements, some general features of the Äspö models are discussed. The strategy used for testing the models and an introduction to current models of the Äspö site is then presented. Finally issues of relevance for repository studies that are not addressed in the scope of works are identified as an introduction to *Chapters 3,4,5,6,7.*

Chapter 3 to *Chapter 7* present the summarized evaluation of models for each key issue. *Chapter 3* deals with evaluation of geological models and the following chapters with mechanical stability, groundwater flow, groundwater chemistry and the transport of solutes. Each chapter contains comparison of models prior to construction and models made based on the complete data sets collected 1986-1995. Evaluations of characterization methods and summarizing conclusions are presented.

Chapter 8 presents general evaluations of the site characterization methodology applied at Äspö, and *Chapter 9* the concluding remarks.

The reader may have to consult background technical reports or general material in order to obtain maximum benefit of the report. The list of references and publications in the Bibliography may provide guidance in this respect.

2 STRATEGY FOR MODEL TESTS

2.1 INTRODUCTION

This chapter provides the reader with the necessary context to understand the approach to testing the reliability of models. This testing encompasses both general tests of the concepts used and the ability to collect enough data of good enough quality to defend the derived models.

The chapter starts with a definition of key issues and general approach to modelling in *Section 2.2* and model elements in *Section 2.3.* The approach taken for investigations of processes, geometrical framework, material properties and boundary conditions and the approach for testing the reliability of models are explained in *Section 2.4.* An overview of the models derived for the Äspö island is presented in *Section 2.5.* The chapter ends with stating the issues of relevance for a repository that will not be dealt with in this report.

2.2 SELECTION OF KEY ISSUES AND GENERAL MODELLING APPROACH

The two planning requirements *understanding* and *design of the facility* required careful focussing and structuring of the work. Several decisions were made to meet these requirements. These included the following:

- Selection of key issues and subsequent sub-structuring in subjects.
- Conceptual models of the rock made to several geometrical scales.
- Multi-disciplinary and integrated approach to data collection and co-interpretation.
- Iterative updating to allow for detailing and possible re-interpretation of previous models.

Figure 2-1 shows a sketch of the key issues (Geological-structural model, Groundwater flow, Groundwater chemistry, Mechanical stability and Transport of solutes) and geometrical scales adopted. The rationale for the structuring is described in *Bäckblom et al /1991 b/.*

Out of the five key issues, most work was devoted to the issues Geological-structural model, Groundwater flow and Groundwater chemistry. Mechanical stability mostly addressed questions relating to short-term issues. Long-term mechanical stability is a part of the SKB's general RD&D (Research, Development and Demonstration) programme. Transport of solutes has included investigations of fracture connectivity, transient flow of natural isotopes and assessment of flow porosity. The retention properties of rock are now a major issue in the Äspö Operating Phase.

Chapter 3 to *Chapter 7* reports on the overall evaluation of reliability of models at Äspö for each key issue as shown in *Figure 2-1*. More details are provided in *Stanfors et al /1997/* and *Rhén et al /1997a/*.

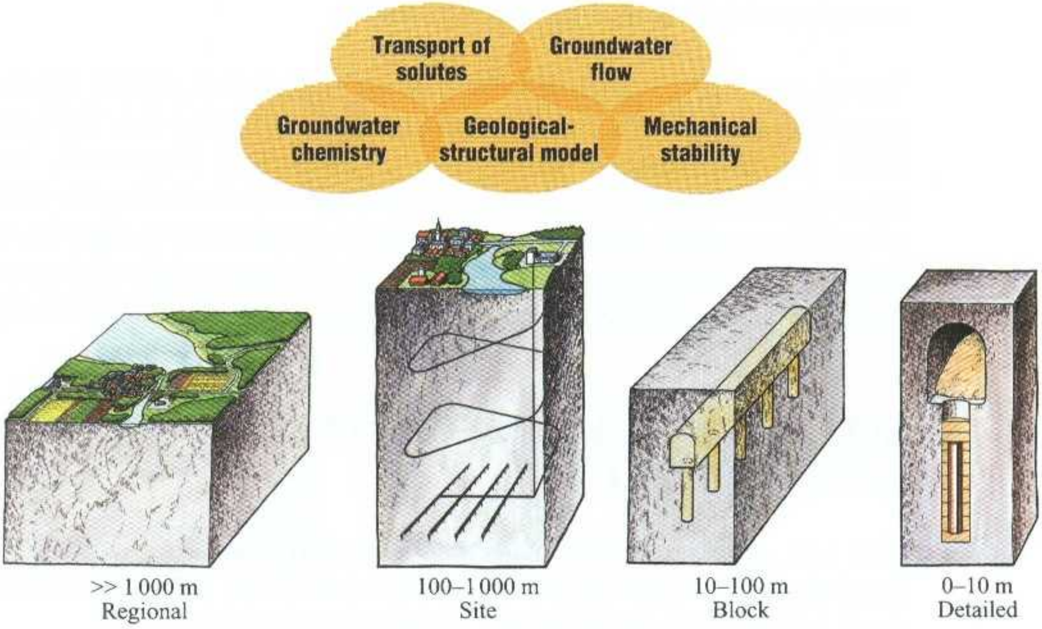


Figure 2-1. *Analyses and modelling were developed for different geometrical scales with respect to a number of key issues (Geological-structural model, Groundwater flow, Groundwater chemistry, Mechanical stability and Transport of solutes).*

2.3 DEFINITION OF MODEL ELEMENTS

During the course of the project we found it difficult to make overviews showing all models used and the concepts on which they were based. There were also imprecise definitions of what should be included in model descriptions. Thus, we developed a structure for describing models */Olsson et al, 1994/*. The basic structure of a model is presented in four groups, *Table 2-1* and application for each key issue is presented in *Chapters 3* to *7*.

Table 2-1. Format for a condensed description of models in the Äspö HRL project /After *Olsson et al, 1994*/.

MODEL NAME

Model scope or purpose
Specification of the intended use of the model

Process description
Specification of the process accounted for in the model,
definition of constitutive equations

CONCEPTS	DATA
Geometrical framework and parameters	
Dimensionality and/or symmetry of model. Specification of what the geometrical (structural) units of the model are and the associated geometrical parameters (the ones fixed implicitly in the model and the variable parameters).	Specification of the size of the modelled volume. Specification of the source of data for geometrical parameters (or geometrical structure). Specification of the size of the geometrical units and resolution.
Material properties	
Specification of the material parameters contained in the model (it should be possible to derive them from the process and geometrical units).	Specification of the source of data for material parameters (could often be the output from some other model). Specification of the value of material parameters.
Spatial assignment method	
Specification of the principles for the way in which material (and if applicable geometrical) parameters are assigned throughout the modelled volume.	Specification of the source of data for model, material and geometrical parameters as well as stochastic parameters. Specification of the result of the spatial assignment.
Boundary conditions	
Specifications of (the type of) boundary conditions for the modelled volume.	Specification of the source of data on boundary and initial conditions. Specification of the boundary and initial conditions.

Numerical or mathematical tool
Computer code used.

Output parameters
Specification of the computed parameters and possibly derived parameters
of interest.

First of all the *geometric framework* and its related parameters must be defined. Secondly, the types of *material property* to be assigned to the domains defined by the geometric framework have to be described. Thirdly, the *spatial assignment method* of the material properties within a domain has to be described. Finally the *boundary conditions* have to be defined. Now, for a real case, *data* will be needed for the four conceptual elements. If needed a *numerical* or *mathematical tool* that handles the processes, features should be chosen. And, finally, there is a need to select *output parameters* that satisfy the *purpose* of the model.

For the Äspö models we tried as much as possible to connect models for groundwater flow, groundwater chemistry, rock mechanics, transport of solutes to the basic geological-structural framework. *Figures 2-2 and 2-3* show the basic conceptual geological-structural framework and the conceptual framework for other models as well.

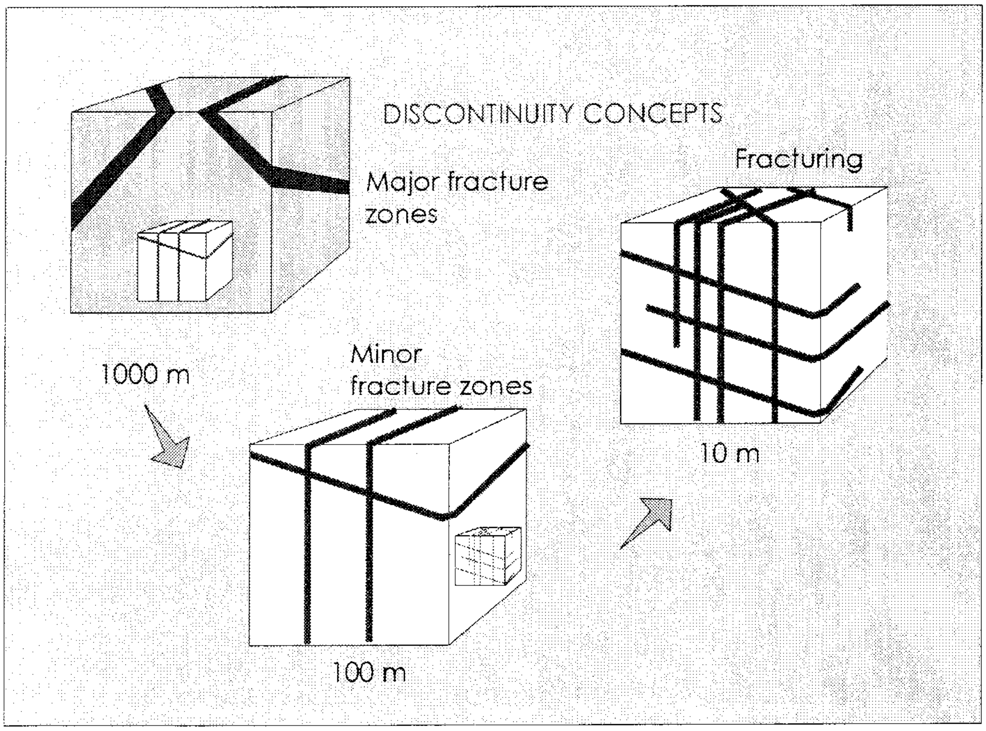


Figure 2-2. *The picture shows that discontinuities are divided into major (width > 5 m) and minor (width < 5 m) fracture zones. Major zones are deterministic with respect to existence, geometry and properties. Minor zones are deterministic with respect to existence, but exact location is not pin-pointed, thus, geometry is treated stochastically. Small-scale discontinuities, fracturing, are treated as stochastic with respect to location, orientation, length, etc.*

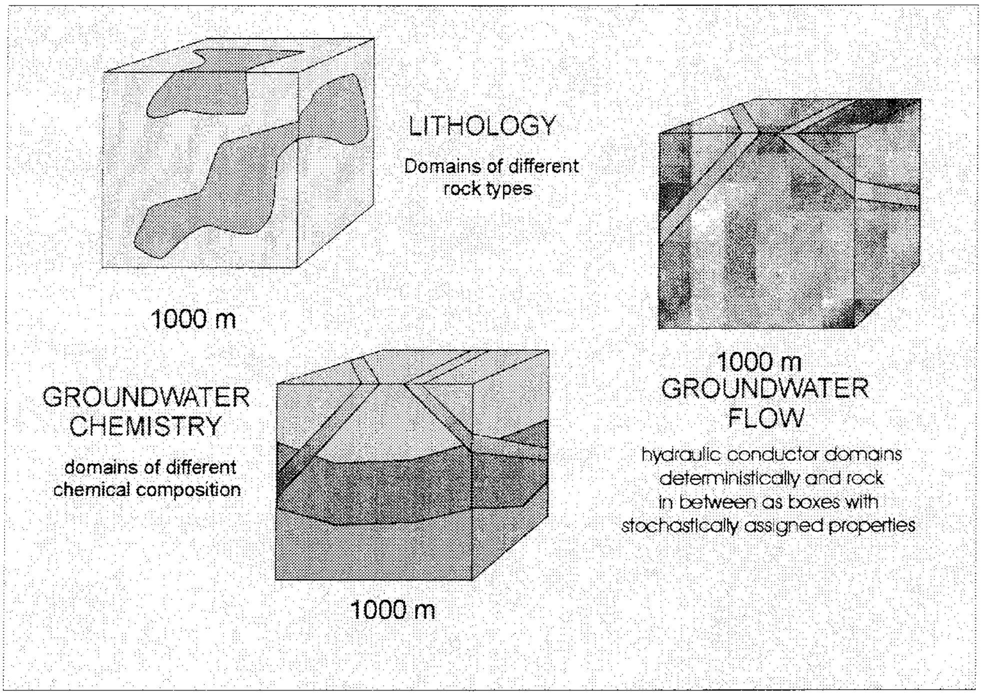


Figure 2-3. *Lithology and different groundwaters are divided into domains. Major and minor fracture zones are treated as hydraulic conductors with deterministic transmissivities. The rock mass between zones is treated as a stochastic continuum with random assignment of conductivities based on measured values.*

2.4 APPROACH TO TEST OF MODELS

One objective (see *Chapter 1*), was to test the ability to obtain a thorough *understanding* of the rock conditions based on investigations of the surface and investigations in and between boreholes from the surface. By *understanding* we here mean to obtain sufficient knowledge *to show how things are, but also to show how things cannot be.*

Based on the quite loose requirement of *understanding,* data were collected in the field. These data were analysed and abstracted into models set up for subjects to different scales, as shown in *Figure 2-1.* The models were, if possible, calibrated against independent tests. Then the calibrated models were used to predict outcome as expected from data collected in the excavated tunnel and in the surrounding boreholes. The idea was then to check predictions and outcomes as a mean of assessing the ability to *understand* the rock (see *Figure 2-4).*

The test of *understanding* is now restricted to testing a set of pre-described models based on certain concepts. The scrutiny of the prediction-outcome match is a part of the validation process adopted early in the project */Bäckblom et al, 1991a/.* It comprises three basic elements:

- A systematic comparison of prediction and outcome.
- A careful scrutiny of the underlying structures and processes.
- A (subjective) judgement of whether the prediction is good enough.

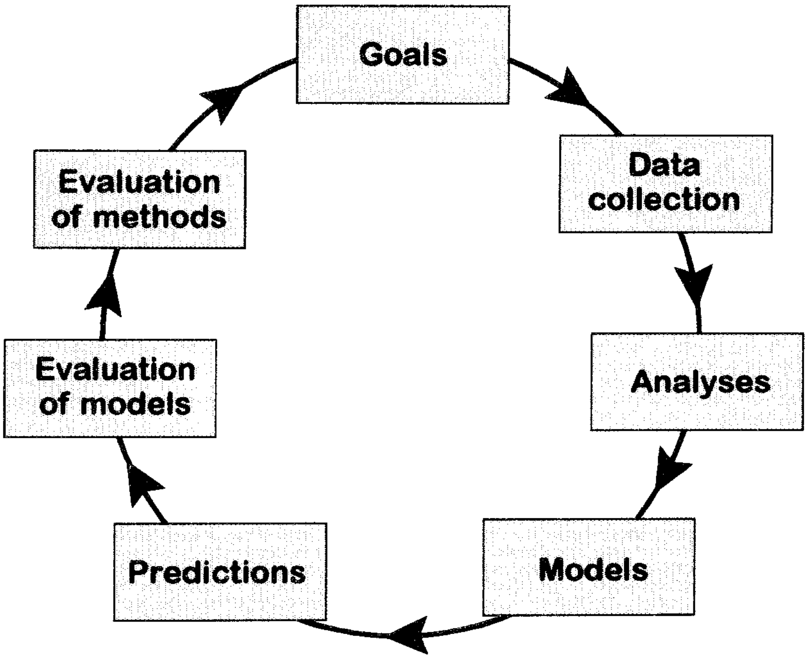


Figure 2-4. *Approach to verification of the pre-investigation methods. An iterative approach was taken to data collection, interpretation, modelling and evaluation.*

Thus, our approach to test *understanding* and in a more restricted sense - to test models - is to check and evaluate how an updated model agrees with earlier versions of the same model. The agreement is used to assess the robustness and correctness of previous forecasts and the appropriateness of the methods.

The predictions made at the Äspö HRL are all based on concepts and data acquired prior to construction of the facility. The site investigations performed for the Äspö HRL were conceptualized according to key issues and to different geometrical scales */Wikberg et al, 1991/,* and based on these models several hundred predictions were set up */Gustafson et al, 1991/.* All these predictions have now been checked during construction of the laboratory to test the appropriateness of earlier work (*Figure 2-5).*

As stated in the introduction to this report, one of the requirements of the site investigations was also to obtain sufficient understanding to design the facility down to a depth of 500 m. A simple test strategy of adequate understanding of the rock conditions is to track unexpected layout changes or changes in the construction specifications due to unexpected rock conditions.

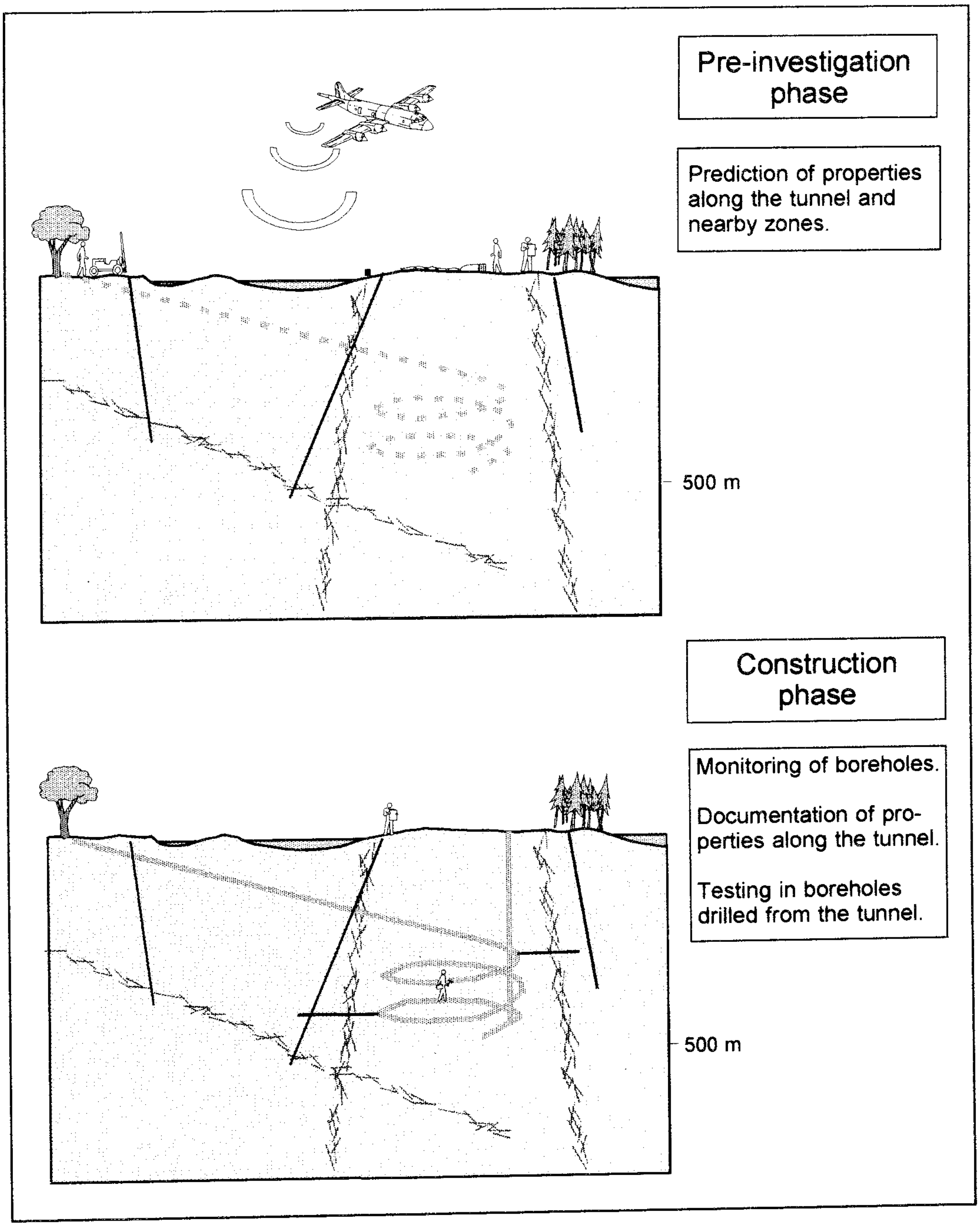


Figure 2-5. Data and models were initially set up based on pre-investigation data. Additional data collected in the tunnel and in monitoring boreholes were used to update previous models. The difference between the models was used to assess the reliability of models and methods applied from surface investigations.

2.5 OUTLINE OF MODELS DERIVED FOR ÄSPÖ ISLAND

The reader is first introduced to current models of the Äspö site based on the investigations from the period 1986-1995. Detailed presentations of the models for different scales (regional scale >> 1000 m, site scale 100 - 1000 m, block scale 10 -100 m and the detailed scale 0-10 m) are provided in *Rhén et al /1997b/*. These models are generally referred to as *Model 96* in this report. The models based on the pre-investigation data presented in *Wikberg et al /1991/* are generally referred to as *Model 90*. In this section an overview of *Model 96* for geology is presented on a regional scale and on a site scale for geology, rock mechanics, hydrogeology and groundwater chemistry.

2.5.1 Regional models of geology

Lithological model

The dominant rocks in the Äspö area belong to the 1700-1800 million year-old vast region of Småland-Värmland intrusions (or Trans-Scandinavian Granite-Porphyry Belt).

A number of massifs of basic rocks elongated E-W were indicated by positive magnetic and gravity anomalies. Fine-grained irregular bodies and xenoliths of greenstone (old volcanites) were found as remnants within the granite mass.

Some circular/semi-circular structures in the area investigated are interpreted as granite diapirs. They are all represented by a more or less round, non-magnetic pattern and negative Bouger gravity anomalies. The Götemar and Uthammar anorogenic granites are two of these structures which were interpreted as true diapirs (see *Figure 2-6, 'Anorogene granite'*).

Fine-grained greyish-red granite is common in the whole area. On and near Äspö, which was mapped in detail, the fine-grained granite occurs both in smaller massifs and as dikes in the older rock.

Structural model - Major discontinuities (major fracture zones)

Information from all geological and geophysical investigations supports a regional structural pattern dominated by one almost orthogonal system of major structures trending N-S and E-W and one system trending NW and NE and extending more than 10 km (*Figure 2-6*). They often coincide with some hundred-metre-wide low-magnetic zones with a central more intense fracture zone up to some tens of metres wide. The major discontinuities close to Äspö are shown in *Figure 2-6*.

The structures trending E-W are mostly vertical or with a moderately low dip. A major structure trending NE-SW across the island of Äspö, is indicated by mylonites in outcrops and boreholes. According to a general interpretation most of the structures trending NE-SW are older than the systems trending N-S and E-W. Most of the structures trending N-S are probably younger than the ones trending E-W.

The depth of most of the major structures is estimated to be at least 1500 m to several kilometres.

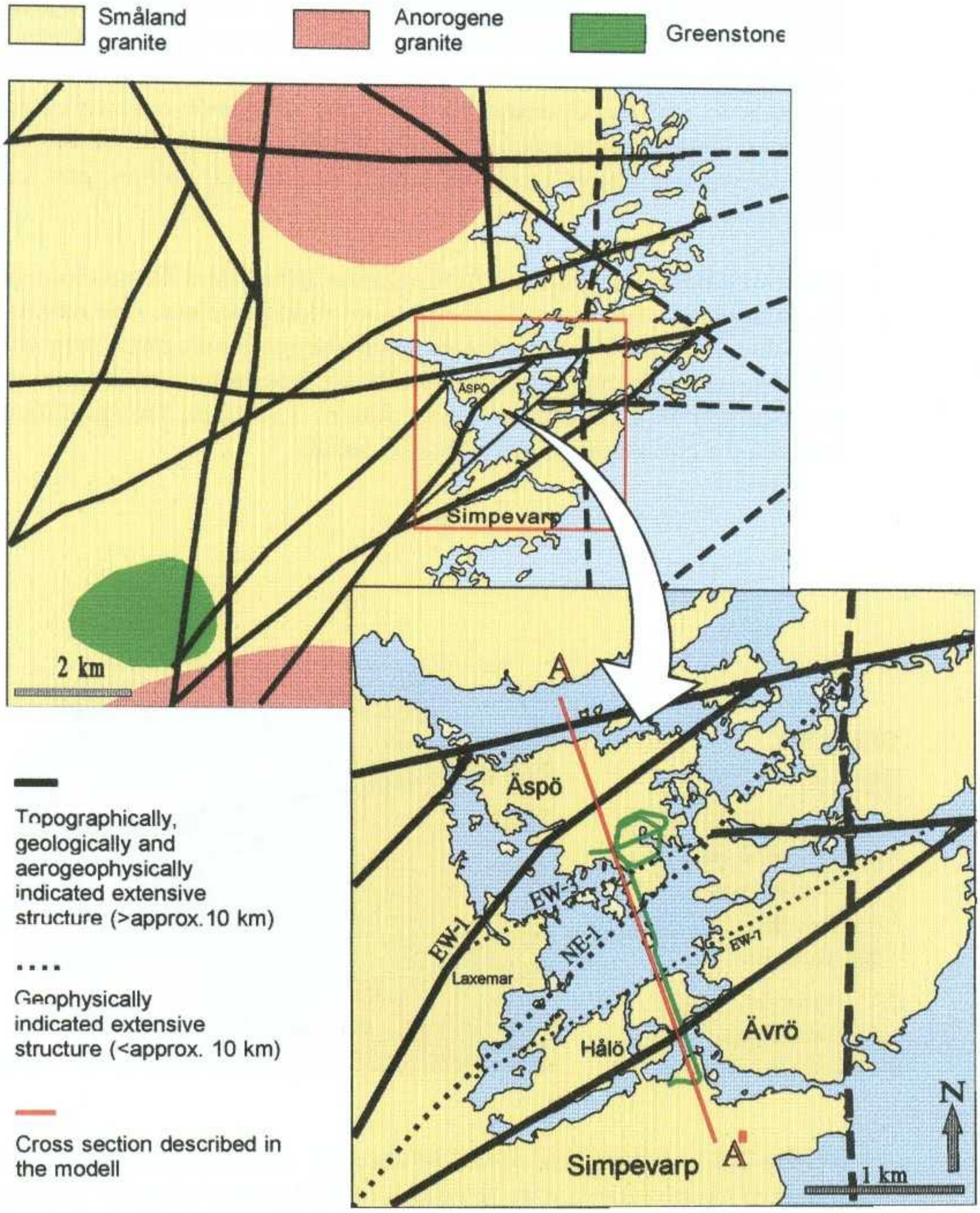


Figure 2-6. Overview of the regional structural framework in the Äspö area. A-A´: vertical section in Figures 2-7, 2-8 and 2-9. Äspö diorite and Småland (Ävrö) granite are two varieties of 'Småland granite'.

2.5.2 Models on a site scale

Lithological model

Four main rock types - Äspö diorite, Småland (Ävrö) granite, greenstone and fine-grained granite make up most of the rock mass in the Äspö tunnel area (see *Figure 2-7*). Äspö diorite and Småland (Ävrö) granite are two varieties of 'Småland granite'. Rocks belonging to the *Äspö diorite group* (granodiorite, quartz monzonite and quartz diorite) are by far the most common within the Äspö area, both on the surface and in the tunnel. The rocks are usually grey to reddish grey, medium-grained, and contain more or less scattered, large crystals of potassium feldspar. Granodiorites and quartz monzonites are most common, but there are also some tonalities and quartz diorites included in this group. Age determination gave a well defined age of 1804 ± 3 million years for the Äspö diorite.

Macroscopically, the *Småland (Ävrö) granite* differs from the previous group in its brighter, sometimes distinctly more reddish colour. The amount of potassium feldspar phenocrysts is lower and the crystals are much more irregularly distributed. In many places the Småland (Ävrö) granite can be seen to cut the Äspö diorite, which implies that the former is younger. The age difference between the two groups is probably very small.

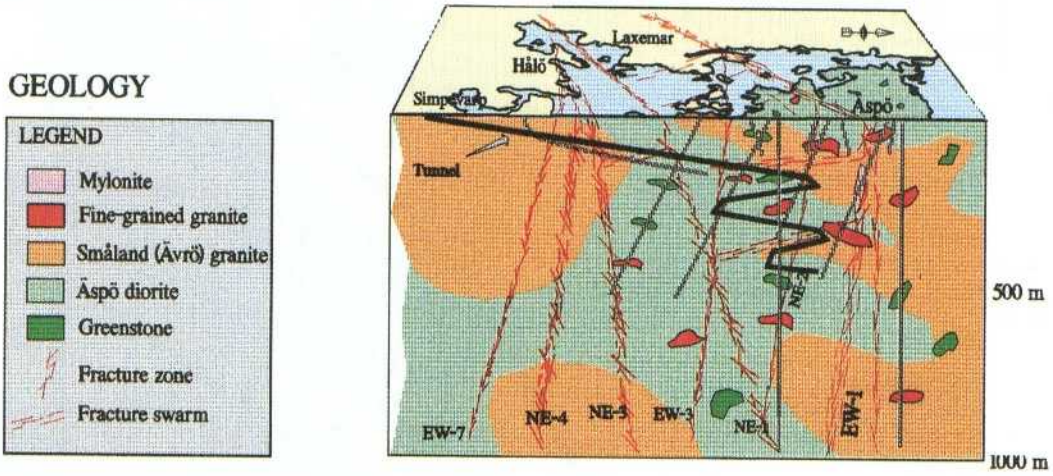


Figure 2-7. Lithological Model 96 showing domains of Äspö diorite and Småland (Ävrö) granite with inclusions of fine-grained granites, greenstone and mylonite The structural model shows major fracture zones (width > 5 m) and fracture swarms. Cored boreholes near the vertical section A-A´ are coloured grey. EW-7 etc is the fracture zone ID. Vertical section A-A´ shown in Figure 2-6.

The *greenstones* - fine-grained and medium to coarse-grained greenstone (diorites to gabbros) are easily distinguished from the granitoid rocks by their very dark, greenish or greyish black colour. As a rule they occur as minor inclusions or irregular, often elongated bodies within the granitoids and dioritoids following the common E-W foliation trend within the area. Except for the smallest inclusions, the greenstones are often intensely penetrated by fine-grained granitic material. Most of the greenstone has the character of inclusions but dikes are also mapped mostly trending EW to the NE.

Fine-grained granites occur rather frequently, both on the surface of the island of Äspö and its surroundings, as well as in the tunnel. From the surface mapping it is clear that most of these granites occur as dikes and irregular veins. The dike character is sometimes not very clear because of strong deformation in the fine-grained granites, which has obscured contacts. All the rock mass is veined by fine-grained granite but the number of veins in the Småland (Ävrö) granite in the tunnel is sparse compared with the number of veins and dikes in the Äspö diorite. Most of the dikes of fine-grained granite trending NE confirm the idea that the fine-grained granite is closely related to the Småland (Ävrö) granite which is obviously younger than the Äspö diorite.

The brittle deformation has caused a joint pattern in the fine-grained granites, often characterized by many short joints, closely spaced, which divide the rock into small blocks. This is quite different from the pattern in the medium to coarse-grained granitoids where joints are much more widely spaced. No significant difference has been found between the joint patterns on the surface and in the tunnel.

The distribution of the four main rock types at depth is quite similar except for the upper level, 0-100 m, along the first part of the tunnel where the Småland (Ävrö) granite occurs more frequently than the Äspö diorite and in the lower level, 400-460 m, where mainly Äspö diorite has been mapped. The Småland (Ävrö) granite - which is exposed on Ävrö, south of Äspö, and on southern Äspö probably extends northwards, folded beneath the Äspö diorite.

Structural model

The structural model describes the geometrical distribution and character of discontinuities in the rock volume. *Discontinuity* is the general term for any mechanical feature in a rock mass having zero or low tensile strength. It is the collective term for fractures, weak schistosity planes, weakness (fracture) zones and faults. During pre-investigation and tunnel mapping of the Äspö HRL discontinuities were divided into *fracture zones (major*, width > 5 m and *minor*, width < 5 m) and small-scale *fracturing* in the rock mass between fracture zones.

An almost vertical, penetrating foliation trending NE-ENE is the most dominant structural element in the 1700-1800 million year old Äspö granitoids and seems to be the oldest sign of the ductile deformation related to the sub-horizontal NNW-SSE compression.

The first brittle faults probably developed in the region in response to the emplacement of younger granites. These faults and older ductile zones were reactivated several times. Fracture zones on Äspö have a wide range of orientations and styles and most of them reactivate older structures.

Several *major fracture zones* were located in the Äspö environs (see *Figure 2-7).* These fracture zones are described in detail in *Rhén et al /1997b/.* Some of them are described briefly below: Three of the *major fracture zones* on Äspö are named NE-1, EW-3 and EW-1 (see *Figure 2-7*).

All three branches of the NE-1 fracture zone are connected to a rather complex rock mass with Äspö diorite, fine-grained granite and greenstone. The two southernmost branches, trending NE and dipping NW, can be described as highly fractured and more or less water-bearing. The northern branch, which is approximately 30 m wide in the tunnel, is the most intense part of NE-1 and highly water-bearing.

The fracture zone EW-3 was very well indicated topographically, and geophysically (magnetic, seismic and electric) and in core boreholes KAS06 and KAS07 during the pre-investigations and estimated to be approximately 10 m wide. In the tunnel EW-3 was found to be approximately 14 m wide and consisted of a 2-3 m wide crushed central section connected to a contact between Äspö diorite and fine-grained granite.

The fracture zone EW-1 was indicated at an early stage by the airborne geophysical survey and the lineament interpretation and can be regarded as the northern part of the about 200-300 m wide low-magnetic zone (Äspö shear zone), trending NE, which divides Äspö into two main blocks.

Studies of the surface geology revealed the presence of three *gentle thrusts* on Äspö striking E-W and dipping N, all of which appeared to be associated with early gently dipping gneiss zones and fault scarps. Interpretations based on seismic reflections also suggested the presence of gently dipping fracture zones at depth. However, only two narrow fracture zones, gently dipping S, were found in the tunnel.

A great number of *minor fracture zones* striking approximately NNW-NNE were mapped on outcrops in Äspö. More or less extensive, they seem to branch out in an en-échelon pattern across the island. Only a few of them are topographically significant but normally too narrow to be geologically unambiguously indicated. All these minor fracture zones were described under the designation 'NNW-system'. The different sub-zones, expected to be 0.1-5 m wide, were predicted for the 'NNW system' to be 'possible-probable' and their predicted positions in the tunnel very approximate.

Thorough analyses were made of the *small-scale fracturing* in the rock mass at Äspö. The data base consists of more than ten thousand fracture observations. Most fractures mapped at the Äspö HRL (all fractures >1 m in the tunnel except fractures in 'fracture zones') fall into four clusters. Three are steep and strike NS, NNW and WNW; a fourth cluster is subhorizontal. Most of the mapped fractures containing water are arranged in a single intense cluster of steep fractures striking WNW. Fractures containing water generally have coatings enriched in epidote, quartz and Fe-oxides. Fractures with injected grout are steep, strike WNW and are generally longer than other fractures. Repeated and sequential reactivation of the same faults was demonstrated by superposition of different mineral coatings. Fractures trace lengths are log-normally distributed in all rock types and fracture trace lengths do not vary with the rock type.

Primary rock stresses and assessment of excavation stability

During the site investigation phase, stress measurements were made in surface boreholes, employing both hydraulic fracturing and overcoring. Concurrent with the excavation of the tunnel, overcoring measurements were made in a series of 12-18 m long, near-horizontal boreholes drilled from suitable locations along the ramp.

The measurements show a dominating NW-SE orientation of the maximum horizontal stress (σ_H). The measurements made in the tunnel showed the presence of a considerably higher stress level than was anticipated, based on the measurements made in the deep surface boreholes. The estimated mean K_0-value, (K_0 is the ratio between the maximum horizontal stress (σ_H) and the theoretical vertical stress (σ_V)) for all boreholes is 2.9, with the average for individual boreholes ranging between 1.7 and 4.0. The values of single measurements in the individual boreholes varied between 1.5 and 4.0.

No rock burst was observed during the tunnelling operation. Occasional cracking was heard after excavation and some tendency to spalling was noted.

Hydraulic conductor domains

The geometry of the hydraulic conductor domains is mainly defined by the major fracture zones described above. The minor fracture zones in the 'NNW-system' are also important conductors. A few hydraulic conductor domains were also added to the model in order to explain some of the responses obtained in the interference tests. A simplified model of the hydraulic conductor domains was made by fitting planes to the observations at the surface and in the boreholes, see *Figure 2-8*.

The evaluated transmissivities are generally in the range 10^{-6}-10^{-4} m^2/s with a median of about 10^{-5} m^2/s. The greatest transmissivities for these larger features are for the hydraulic conductor domains below the Baltic Sea and for the minor fracture zone NNW-4. The largest transmissivity is approximately $4 \cdot 10^{-4}$ m^2/s for hydraulic conductor domain NE-1.

Hydraulic rock mass domains

For the southern part of Äspö, bounded by the southern part of EW-1 and to the fracture zone EW-3, the following results were derived:

The tests on the test scales 3, 30 and 100 m do not indicate a decreasing hydraulic conductivity in the 0 - 500 m depth interval. Below the 600 m depth the hydraulic conductivity decreases on southern Äspö, but the result is only based on one vertical borehole. If the data from the 1700 m deep cored borehole KLX02 are included in the analysis the hydraulic conductivity seem to decrease below a depth of 600 m below sea level.

The mapped water-bearing fractures and the fractures filled with grout in the tunnel (from the pre-grouting ahead of the tunnel face) are dominated by a subvertical fracture set striking WNW. This fracture set also has the highest frequency of all fracture sets. Hydraulic tests in probe holes drilled along the tunnel during excavation indicate that subvertical fractures striking approximately WNW and N-S are more transmissive than the others. Occasionally single water conducting fractures in the hydraulic rock mass domains can be very transmissive and cause high flow rates into drilled boreholes.

Hydrological setting of the Äspö area

The land surface of Äspö is slightly undulating, with a maximum height of about 14 m, giving small drainage basins with some peatlands and sediments in the topographic lows. There are no perennial streams on the island. The surface water is drained to the sea by the peatlands, sediments or directly to the sea. The annual mean precipitation and temperature of the area are about 550 mm/year, and 6.5°C respectively. The annual sea level fluctuations are generally within ±0.5 m.

The water table elevation above the mean sea level is about 30% of the elevation of the topography above mean sea level, within a few hundred metres from the coast line. During the construction of the tunnel the elevation of the water table decreased, mainly on southern Äspö. The minimum water table elevation in 1995 was about 100 m below sea level.

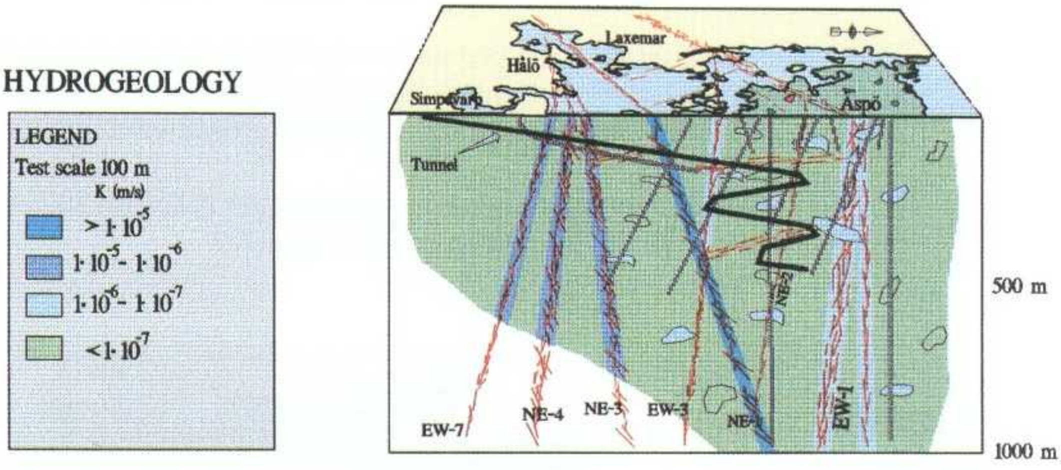


Figure 2-8. *Hydrogeological Model 96 showing the hydraulic conductivity of the major fracture zones and a typical range of hydraulic conductivity for the rock mass between the fracture zones. Widths of zones shown in figure are only approximate. Cored boreholes near the vertical section A-A´ are coloured grey. Inclusions of fine-grained granites, greenstone and mylonite are indicated in the figure (see Figure 2-7 for details concerning the lithology). Vertical section A-A´ is shown in Figure 2-6.*

Groundwater chemical model

In the pre-investigation phase, on a semi-regional scale, data were obtained from shallow, 100 m deep, percussion-drilled boreholes at Äspö, Laxemar and Ävrö.

Site-scale investigations included samples from sections isolated by packers in the deep core-drilled boreholes on Äspö. Most of the sampling was done in the first three cored boreholes which penetrated the northern and southern parts of the island and intersected the Äspö shear zone.

On the average there is a linear increase in salinity with depth, with an increase of 1000 mg/l for each 100 m. However, despite the linear increase in salinity, different water types can be distinguished. Glacial meltwater can be identified due to its very low oxygen-18 value. Modern and old Baltic Sea water and meteoric freshwater are also distinguished on the basis of their ratios of major components. At depths of more than 500 m at Äspö island the water is not affected by the different stages of the Baltic Sea evolution since the last glaciation.

The sampled groundwater is in general reducing at depths exceeding a few tens of metres. However, in exceptional cases oxidizing conditions may prevail down to 100 m. Oxygen-rich surface water rapidly becomes anoxic as it percolates into the rock due to microbial activity.

It was found that bacteria are important for establishing high concentrations of dissolved iron and bicarbonate and that bacterial reduction of iron (III) minerals and sulphate increase the reducing capacity of the groundwater.

Due to the water inflow to the tunnel, the groundwater chemistry has changed from the initial undisturbed conditions, see *Figure 2-9*.

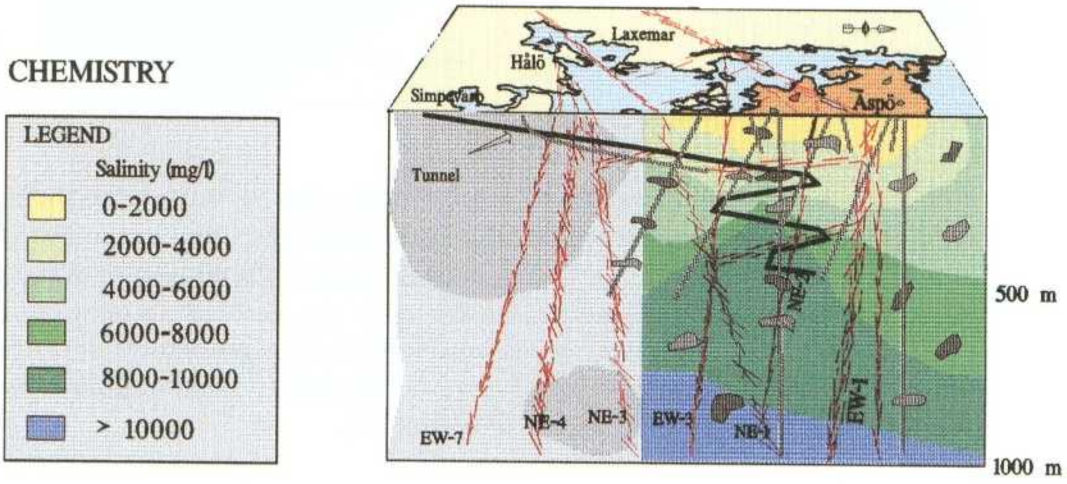


Figure 2-9*. The hydro-chemical model 1996 shows the distribution of saline water in the Äspö area based on 3D interpolation of observations in borehole sections, the Baltic sea and the composition of the recharge on Äspö. Cored boreholes near the vertical section A-A´ are coloured grey. Inclusions of fine-grained granites, greenstone and mylonite are indicated in the figure (see Figure 2-7 for details concerning the lithology). Vertical section A-A´ is shown in Figure 2-6.*

2.6 ISSUES OF RELEVANCE FOR REPOSITORY STUDIES THAT ARE NOT ADDRESSED IN THE REPORTS

Some technical/scientific subjects of relevance for a repository were not included in the scope of work. With respect to fulfilling the stage goal of *demonstrating that investigations at ground level and in boreholes provide sufficient data on essential safety-related properties of the rock at the repository level* it must be understood that the site investigations did not embrace, or only partially contained:

- Seismo-tectonics and consequences of future events like earthquakes, glaciation and other similar topics. These issues are a part of SKB's general Geoscience Programme. These are generic and cannot be expected to be resolved within a site characterization program.

- Thermo-mechanical properties were not investigated to any significant extent.

- Incomplete work was done to find procedures for selecting suitable near-field rock, including near-field models for rock mechanics.

- Regional groundwater flow and evolution with time. Partial findings were obtained and continuation is planned as a part of the SKB's general Geoscience Programme.

- Evolution of groundwater chemistry and kinetics of chemistry. Partial findings were collected and continuation is planned as a part of the SKB's general Hydro-chemistry Programme.

- Radionuclide migration. Partial findings were obtained and continuation is planned as a part of the Äspö HRL Operating Phase.

3 EVALUATION OF GEOLOGICAL MODELS

3.1 INTRODUCTION

The purpose of the geological models of Äspö is to provide a condensed description of the geological features as they exist today. The models are based on a number of assumptions related to geological evolution such as tectonics and intrusions in general and the major geological events of southeastern Sweden in particular. The geological models can be used to gain an understanding of observations and the underlying systems and for predictions.

The geological models of Äspö consist of a lithological description and a description of the discontinuities (fractures and fracture zones) (see *Figure 3-1)*. Based on the intended use of the models we have to define the concepts needed for the modelling work. *Table 3-1* provides a condensed description of the geological concepts, separated into four groups. For a more detailed presentation, see *Rhén et al /1997/.*

A description of the lithology and main tectonic structures is needed to provide a framework for all modelling work concerning mechanical stability, groundwater flow and groundwater chemistry. One of the main tasks is to describe the distribution of the main lithological domains and identify their importance with respect to brittleness and hydraulic conductivity, for instance.

There is a special need for a good description of the main structural patterns in a rock mass. Basic elements in a structural model are first of all a good interpretation of the major discontinuities (fracture zones) as regards position, orientation and character. The identification and description of the fracture zones which are important hydraulic conductors and from the rock stability point of view were of special interest at Äspö.

The geological concepts have as a rule been found to be relevant. The definition, however, of 'fracture zone', mainly according to fracture frequency compared with the surrounding rock and the subdivision of the zones into 'major' and 'minor' according to 'width', caused some practical problems during documentation and evaluation of data obtained in the tunnel. It seems to be more appropriate to describe all discontinuities with respect to geometry and character without classification at an early stage of pre-investigation.

In order to develop the geological models a number of pre-investigation methods were used.

Table 3-1. Condensed description of the geological concepts used within the Äspö HRL Project.

GEOLOGICAL MODEL OF THE ÄSPÖ SITE

Scope
Description of the lithology and tectonic structure to provide a framework for other models of the site.

Process description
Geological development of southeastern Sweden in terms of tectonization, post- and anorogenic intrusives, faulting, and fracturing.

CONCEPTS

Geometrical framework and parameters
3D box with
Lithological domains: Granitic rocks with lenses and xenoliths of minor rock types (summarized location of domains)
Discontinuities: Essentially subvertical fracture zones, possibly also some low-dipping (location, extent, orientation, width)

Material properties
Lithological domains: fracture density, composition (descriptive)
Discontinuities: character (tensional/shear, classification; major/minor, fracture density)

Spatial assignment method
Lithological domains: averaging, probabilistic with trends
Discontinuities: deterministic (probability classification)

Boundary conditions
Stationary

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

An extensive drilling programme including measurements in the boreholes was carried out. Geophysical logging and borehole radar were systematically utilised. TV logging, televiewer and Vertical Seismic Profiling were used in a few boreholes. Detailed geophysical ground surface measurements were performed which included VLF, resistivity, magnetic, radiometric, seismic refraction and reflection (limited use) Detailed geological mapping of surface bedrock was carried out as well. The pre-investigation methodology for

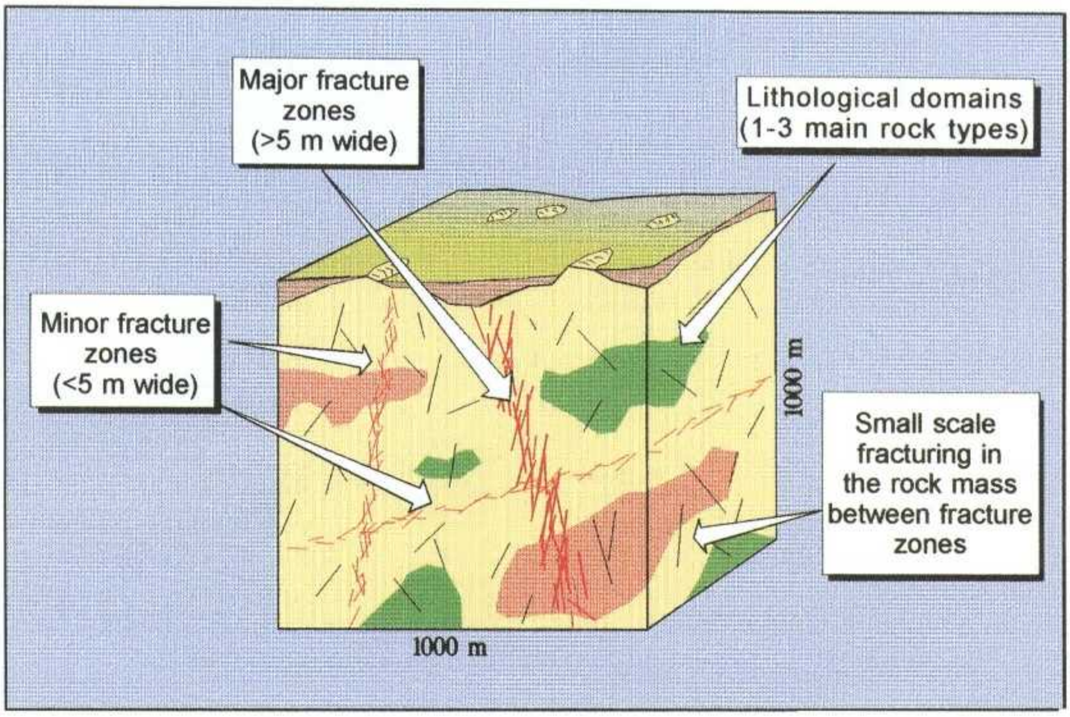


Figure 3-1. *Schematic description of two main components of the geological description. One is for the description of lithology and one for the description of discontinuities (fracture zones and fractures).*

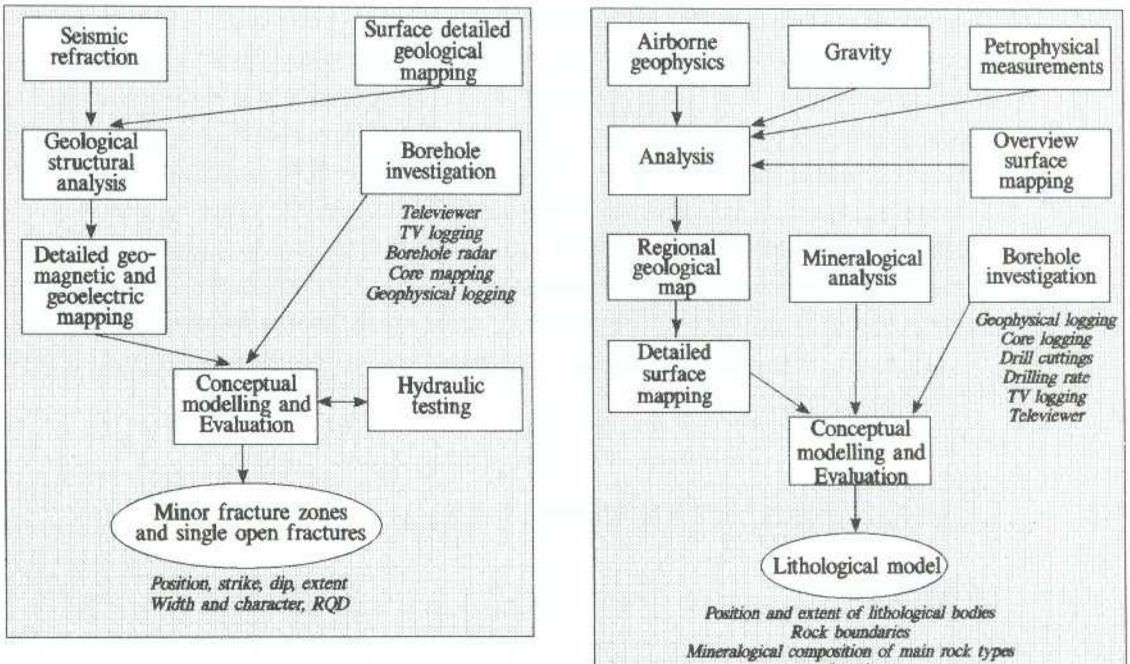


Figure 3-2. *Pre-investigation methodology. Left: Structural-geological characterization. Minor fracture zones. Right: Lithological characterization.*

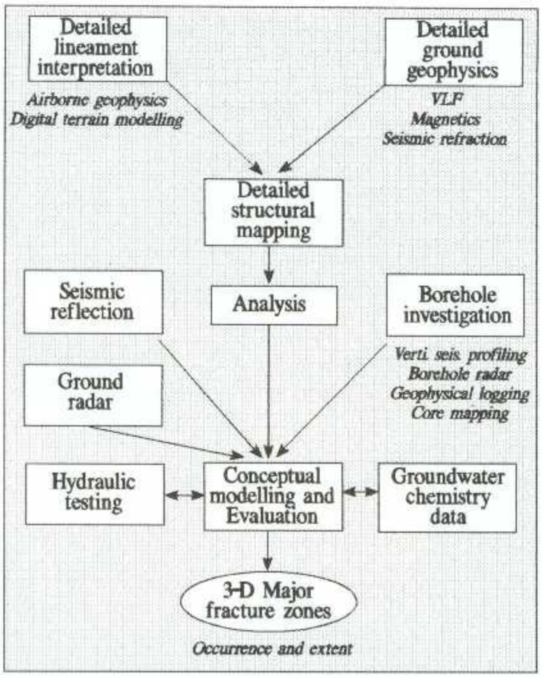


Figure 3-3. *Pre-investigation methodology. Structural-geological characterization. Major fracture zones.*

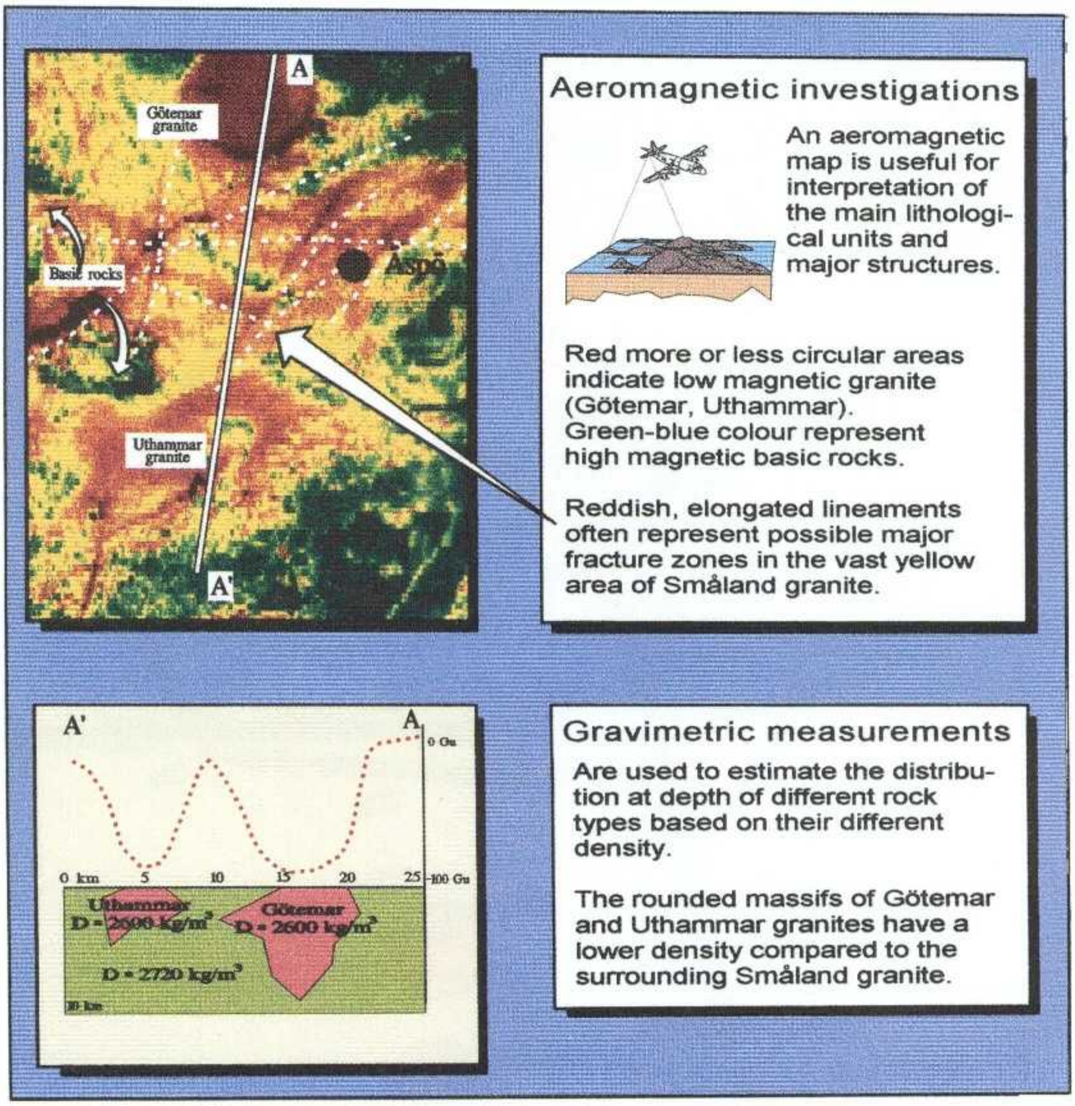
characterization of lithology and major fracture zones is presented in *Figures 3-2* and *3-3*.

In the tunnel rock type distributions and fracture data were assessed in connection with the general geological mapping performed after each new round excavated. An overview of geological documentation is illustrated on 150 m sections. Drill core samples from the tunnel walls were analysed as regards density and porosity of rock matrix. Rock types were checked by means of microscopic modal analyses. Fracture minerals were sampled and to some extent examined by means of XRD analyses (especially clay minerals). Core drillings provided supplementary information especially regarding fracture zone characteristics and grout spread in fractures by means of TV-inspection using a Pearpoint flexiprobe system. Radar measurements and geophysical logging in boreholes were also performed for supplementary structural characterization.

3.2 GEOMETRICAL FRAMEWORK

Lithology

The geological model uses two main concepts, such as lithological domains and discontinuities, both of which were very useful for describing the geological-structural model, especially on the regional scale. A lithological domain is a three dimensional volume of the rock mass which is approximately statistically homogeneous with respect to rock type. In the region, the Götemar granitic diapir represents one domain with one main rock type (Götemar granite) which is easily identified using aero-magnetics and gravity measurements on a regional scale (*Figure 3-4*).



Aeromagnetic investigations

An aeromagnetic map is useful for interpretation of the main lithological units and major structures.

Red more or less circular areas indicate low magnetic granite (Götemar, Uthammar). Green-blue colour represent high magnetic basic rocks.

Reddish, elongated lineaments often represent possible major fracture zones in the vast yellow area of Småland granite.

Gravimetric measurements

Are used to estimate the distribution at depth of different rock types based on their different density.

The rounded massifs of Götemar and Uthammar granites have a lower density compared to the surrounding Småland granite.

Figure 3-4. *Interpretation of geophysical pre-investigations on a regional scale.*

Minor inclusions, dikes and lenses of minor rock types such as greenstone and fine-grained granite at Äspö are normally too limited in extent to be described as separate domains.

The very irregular distribution of rock types like the fine-grained granite and greenstone makes it almost impossible to describe the position and extent of the minor rock units. It was possible on the site scale to make a rough estimate of the site scale distribution and mutual proportions of the two granitic rock types - Småland (Ävrö) granite and Äspö diorite, but the gradual transition boundaries between these rocks are difficult to predict. These two granitic rock types proved to be very similar as regards most rock mechanics parameters but somewhat different with respect to hydraulic conductivity. The complex lithology of Äspö is demonstrated in *Figure 3-5*, which shows tunnel mapping data.

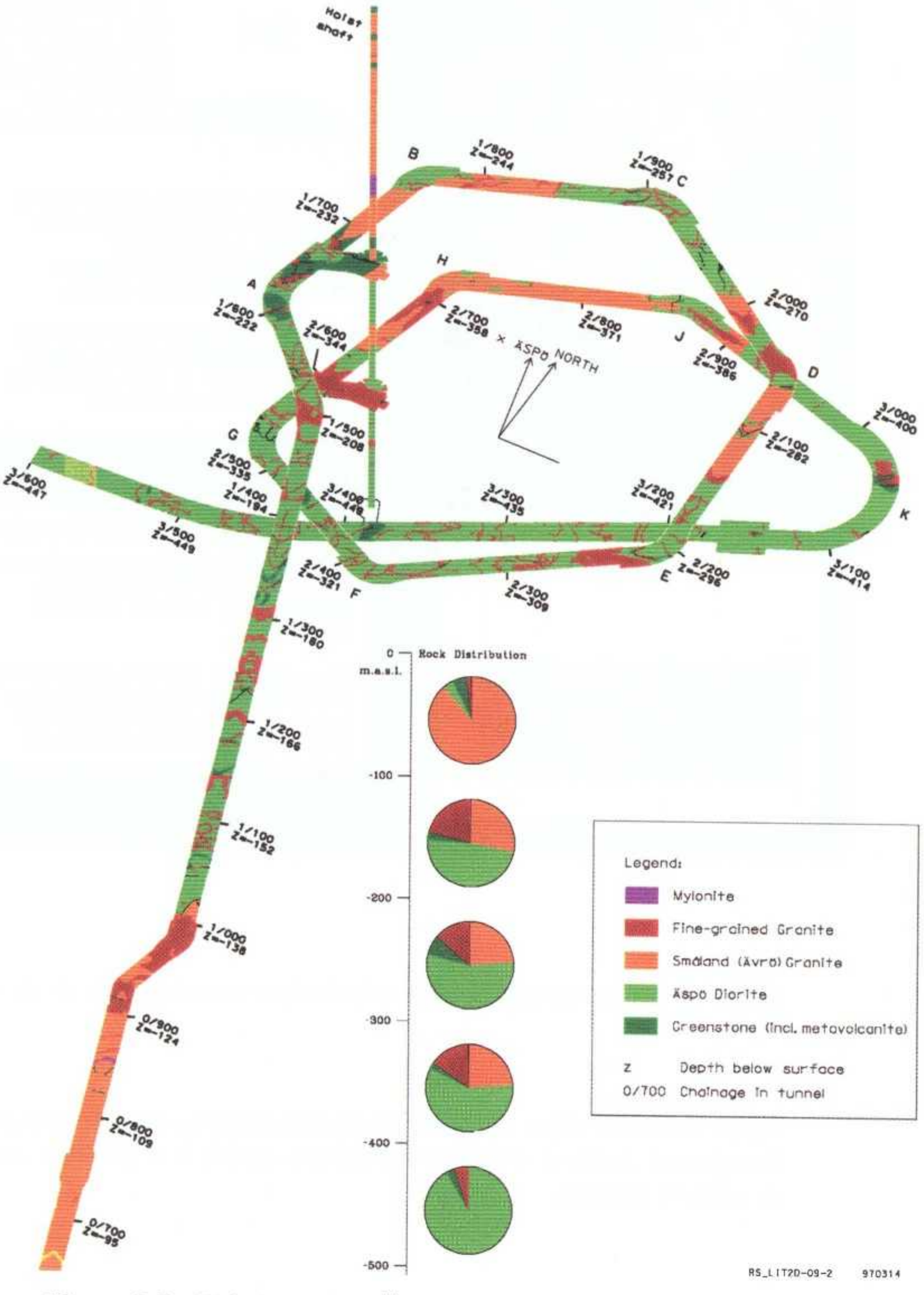


Figure 3-5. *Lithology of the Äspö tunnel.*

Discontinuities

The existence and extent of major fracture zones are normally revealed at an early stage of the pre-investigation phase using airborne geophysics and lineament interpretation. More detailed information on dip and character requires investigations in the form of ground-based geophysics and drilling *(Figure 3-6).*

Due to the winding and irregular extent of most fracture zones, especially their width is difficult to predict within a small range based solely on one or two boreholes *(Figure 3-7).* The irregular extent of the fracture zones is probably caused by the lithological complexity (greenstone xenoliths and winding dikes and schlieren of fine-grained granite) as well as ductile precursors in the form of mylonite and foliated gneissic bands in the rock mass.

A summarized comparison between prediction and outcome for a number of major fracture zones in the access tunnel is presented in *Table 3-2.* The fairly good agreement between prediction and outcome for most of the fracture zones is mainly due to information from a cored borehole KBH02 drilled almost parallel to the planned tunnel during the pre-investigation phase. The error in predicting the orientation of NE-2 *(Figure 3-8)* can be explained by the fact that only one cored borehole was drilled through the zone. The reason for the lack of more boreholes was that NE-2 was estimated to be of minor hydraulic importance.

Fracture zone EW-5 was assumed to trend ENE and dip gently (20-30°) to NNW, mainly based on observations of gentle thrusts and fault scarps on Äspö and east of southern Äspö. The zone was predicted to comprise a series of more or less parallel fractures of hydraulic importance. Two metre-wide, well-defined and gently dipping fracture zones were found in the tunnel. One intersects the tunnel at chainage 220 m, striking NW and dipping 25°S. The second one appears at chainage 1744 m down to 1850 m, trending NE with a dip 32°SE *(Figure 3-9).*

There are also normally variations along a fracture zone with respect to transmissivity and rock mechanics characteristics but core drilling data and interference testing in at least two boreholes complemented by ground geophysical data mostly contribute to a reliable description of the average character of a fracture zone.

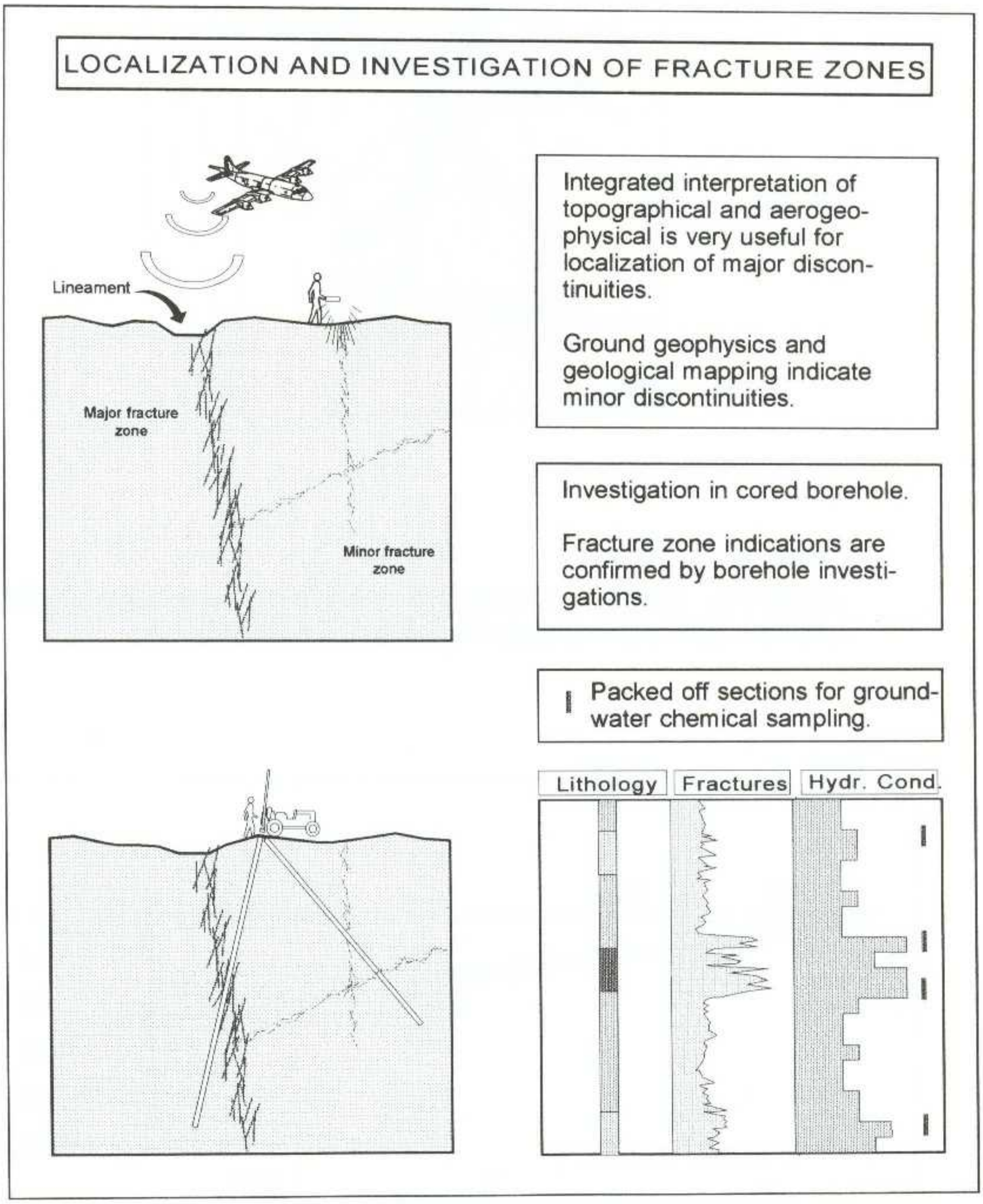
A number of minor fracture zones - indicated at the surface by mapping and ground geophysics - were predicted to intersect the tunnel volume trending NNW-NNE. On the site scale no exact position of a particular minor zone was predicted - only the frequency and main orientation of the minor zones. A comparison between prediction and outcome is presented in *Figures 3-10, 3-11, 3-12.* Notice that these figures only show zones which, according to definition, are mapped as 'minor fracture zones' (more than 10 cm but less than

Table 3-2. Summarized comparison between prediction and outcome */Stanfors et al, 1997/*
Major fracture zones.

Prediction **(based on pre-investigation data)**					**Outcome** **(mainly based on tunnel observations)**			
Fracture zone	**Position (centre of zone)**	**Strike**	**Dip**	**Width (m)**	**Position (centre of zone)**	**Strike**	**Dip**	**Width (m)**
EW-7	773 m(±20)*	N70°E	65°S(±10)*	10(±5)*	787 m	N75°E	75°S	10
NE-4	830 m(±20)*	N45°E	65°S(±5)*	50(±10)**	828 m	N50°E	60°S	41
NE-3	988 m(±20)*	N45°E	70°N(±5)**	60(±10)**	992 m	N60°E	75°N	49
NE-1	1285 m(±20)*	N45°E	65°N(±5)**	45(±5)**	1284 m	N50-55°E	70-75°N	61
EW-3	1427 m(±20)*	N70°E	85°S(±5)**	10(±5)**	1414 m	N80°E	75-80°	14
NE-2***	1740 m(±30)*	N45°E	75°N(±5)**	15(±5)*	1602 m 1844 m 2480 m	N15-36°E	70-80°S	1-6
EW-5	see *Figure 3-9*				see *Figure 3-9*			

* Confidence level 60 %
** Confidence level 75 %
*** NE-2 was not predicted to cross the tunnel spiral - only touch the tunnel at approx. 1740 m.

fractures'. They are presented and discussed in more detail in *Chapter 5 (Figure 5-20).* Except for the water-bearing zone NNW-4W it is not possible to find persistent 'minor fracture zones' at tunnel level. One reason for this may be the tendency for most fracture zones to be narrower at depth than what could be expected from surface indications in the form of fractured and weathered rock.



LOCALIZATION AND INVESTIGATION OF FRACTURE ZONES

Integrated interpretation of topographical and aerogeophysical is very useful for localization of major discontinuities.

Ground geophysics and geological mapping indicate minor discontinuities.

Investigation in cored borehole.

Fracture zone indications are confirmed by borehole investigations.

▮ Packed off sections for groundwater chemical sampling.

Figure 3-6. *Strategy for localization and investigation of fracture zones.*

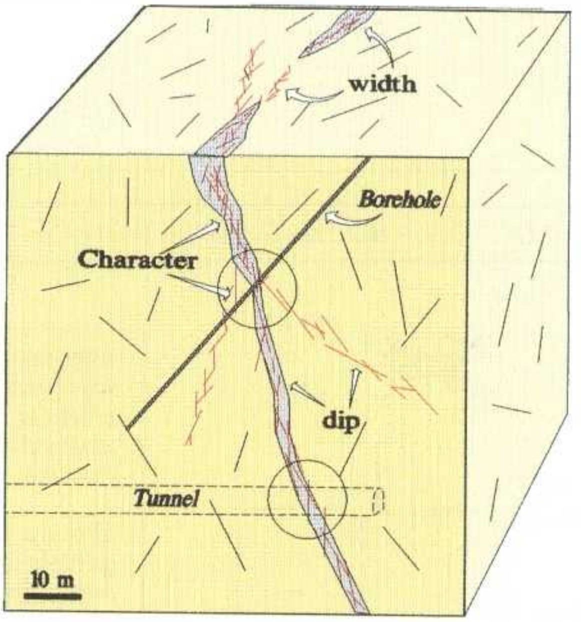


Figure 3-7. *The figure illustrates that modelling fracture zones as planes of constant width and orientation is a gross over-simplification.*

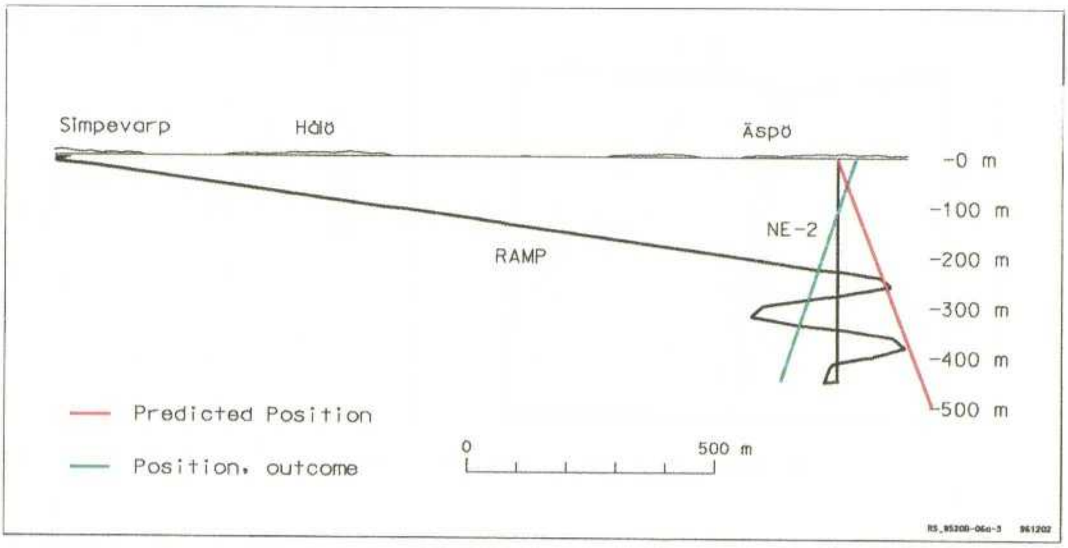


Figure 3-8. *Fracture zone NE-2. Prediction - outcome.*

In the tunnel steeply dipping single fractures (fracture swarms) and some decimetre-wide fracture zones trending WNW to NE form a complex structural pattern. The WNW-NW trending structures are normally the most frequent and hydraulically important *(Figure 3-13).* In summary, the position of minor fracture zones may be located at the surface but the prediction of their extent and position at depth is very uncertain using the methods and techniques employed on the project. However, in the statistical sense the frequency and character of the minor fracture zones are in general agreement with the predictions.

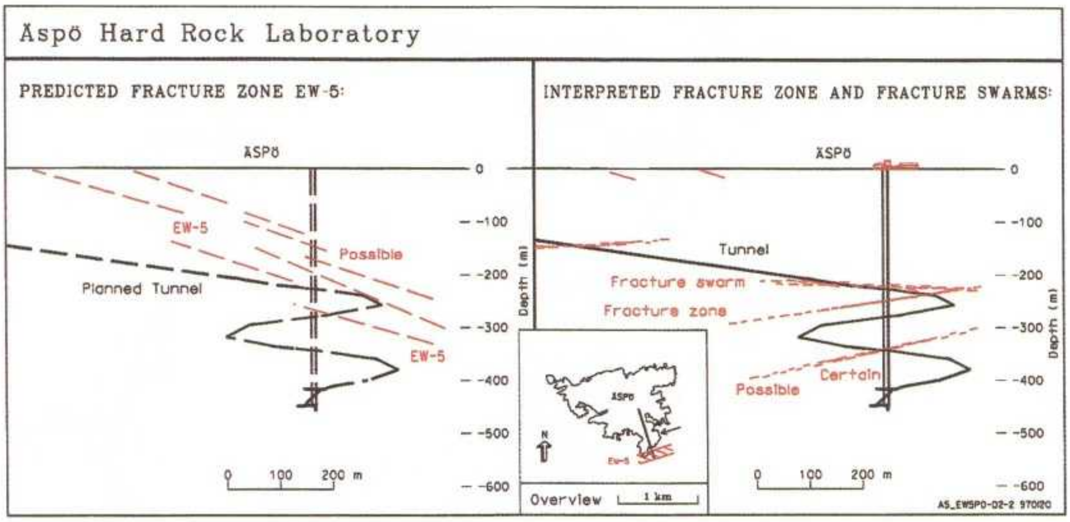


Figure 3-9. *Fracture zone EW-5. Prediction - outcome.*

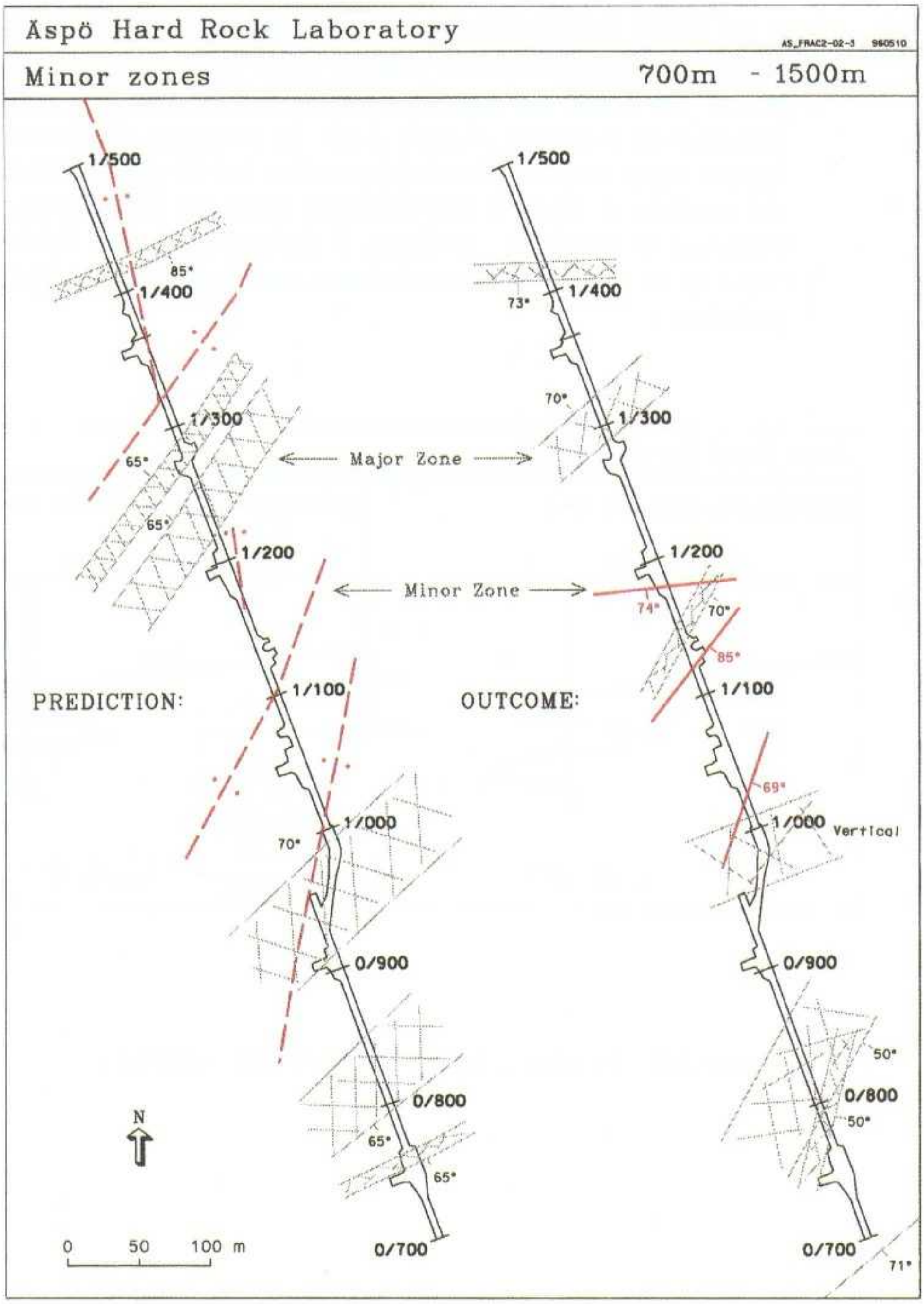


Figure 3-10. Comparison between the minor fracture zone prediction (based on pre-investigation data) and the outcome (based on tunnel data). Chainage 700-1500 m. /Stanfors et al, 1997/. Note, that features mapped as 'fractures' (less than 10 cm wide) are not presented in Figure 3-10 (see Figure 5-20 for larger mapped water-bearing fractures).

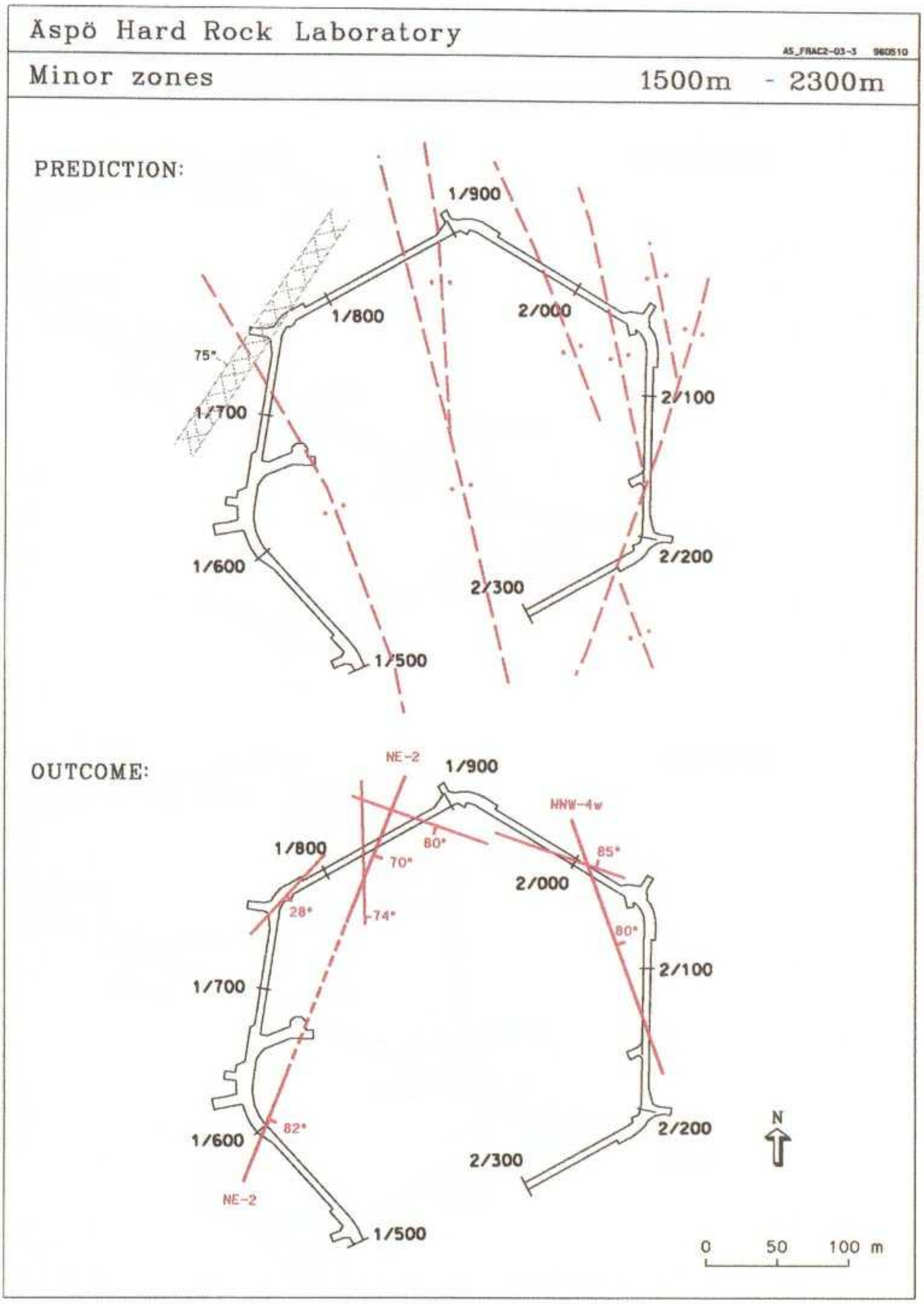


Figure 3-11. Comparison between the minor fracture zone prediction (based on pre-investigation data) and the outcome (based on tunnel data). Chainage 1500-2300 m. /Stanfors et al, 1997/. Note, that features mapped as 'fractures' (less than 10 cm wide) are not presented in Figure 3-11 (see Figure 5-20 for larger mapped water-bearing fractures).

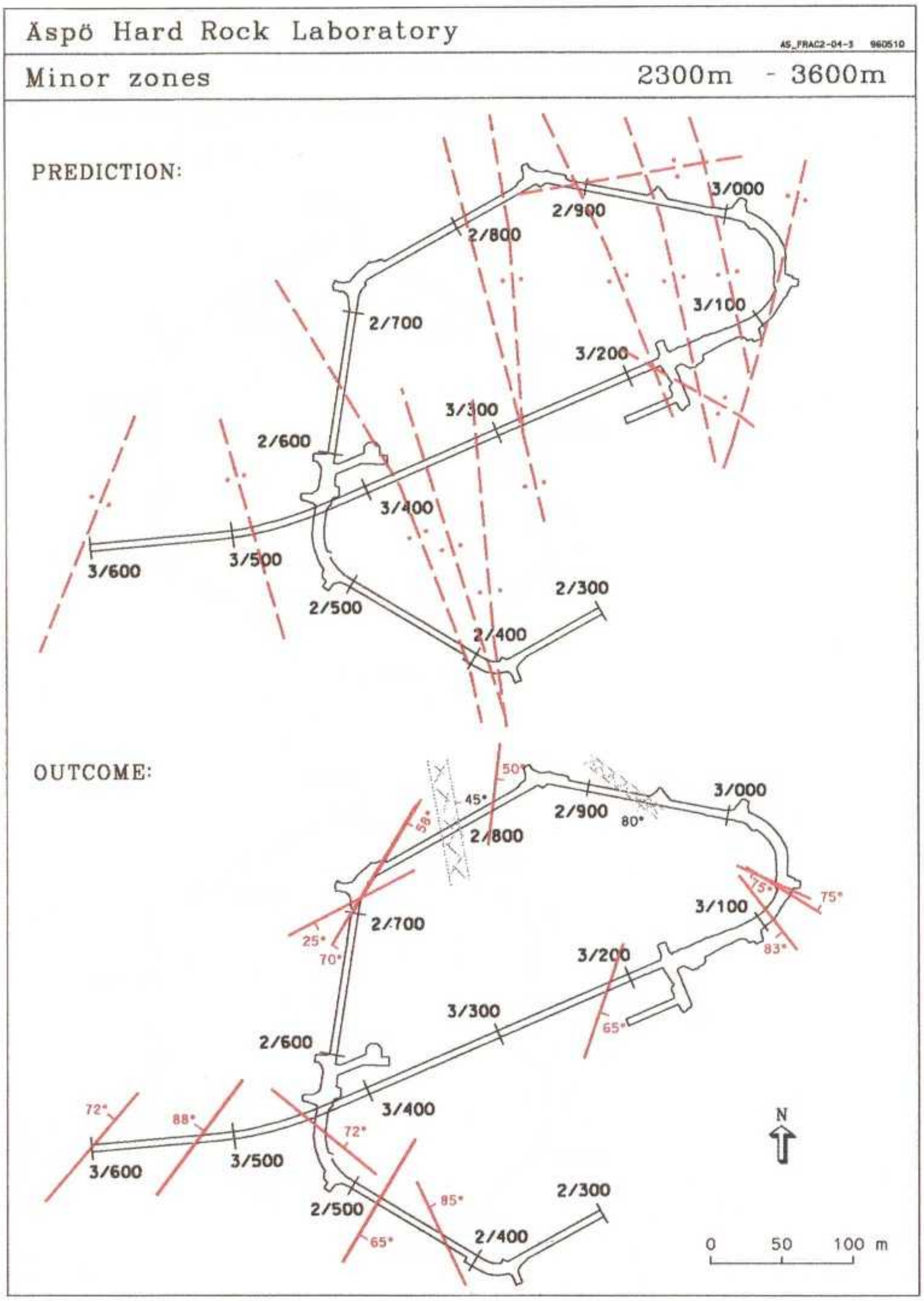


Figure 3-12. Comparison between the minor fracture zone prediction (based on pre-investigation data) and the outcome (based on tunnel data). Chainage 2300-3600 m. /Stanfors et al, 1997/. Note, that features mapped as 'fractures' (less than 10 cm wide) are not presented in Figure 3-12 (see Figure 5-20 for larger mapped water-bearing fractures).

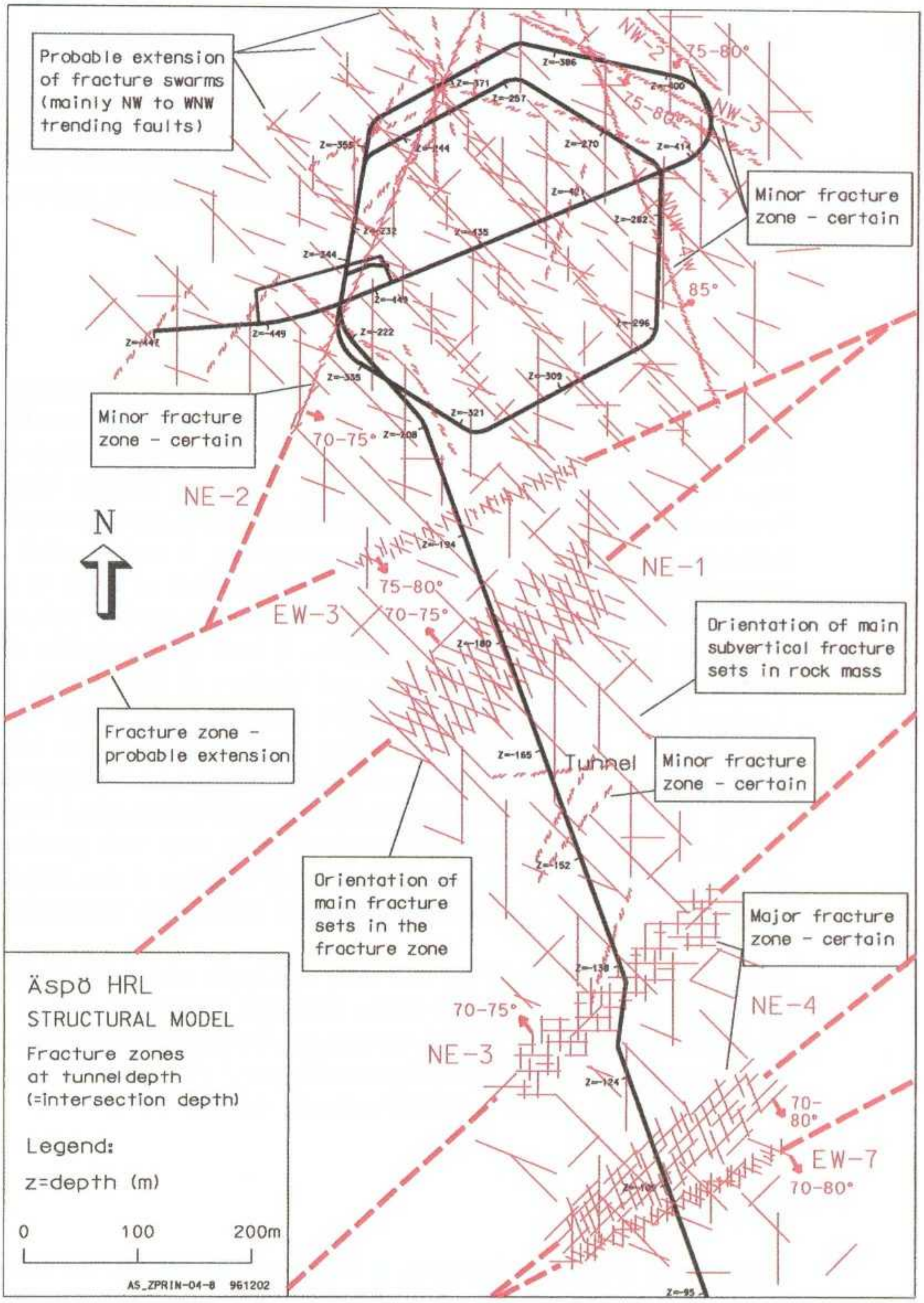


Figure 3-13. *Structural model of the rock mass surrounding the Äspö tunnel. The model represents the position and estimated extent of fracture zones (swarms) at tunnel level. The orientation of the main subvertical fracture sets in major fracture zones and the intact rock mass is based on tunnel mapping data. 'Fracture swarms' comprise concentrations of subparallel, often water-bearing faults. Fracture lengths shown are just relative. Actual mean fracture lengths are much shorter.*

3.3 MATERIAL PROPERTIES

The description of the material properties comprises alteration, porosity, density and a modal mineralogical description of the main rock types. The description of small-scale fracturing in different lithologic domains concerned the number of fracture sets, orientation, spacing and length of fractures and fracture infilling materials.

Lithology

Four main rock types - Äspö diorite, Småland (Ävrö) granite, greenstone and fine-grained granite make up most of the rock mass in the Äspö tunnel area. During the early investigations of the bedrock the dominant rock type in the Äspö area was mapped as 'Småland granite'. The most frequent variety of 'Småland granite' is medium-grained, porphyritic and ranges in composition between granite-granodiorite and quartz monzonite. A variety called Ävrö granite, being more like a real granite in composition, is found in minor amounts on the southern part of Äspö. Later, there was a need for a classification system based more on core logging data. A limit was fixed at the silicate density 2.65-2.70 g/cm^3 between the acid varieties of what is now called 'Småland (Ävrö) granite' (including Ävrö granite) and the more basic and heavier variety called 'Äspö diorite'. This classification was also followed during mapping in the tunnel and was found to be useful from the hydrogeological point of view. Data from geological surface mapping and boreholes were sufficient for mineralogical descriptions of the three main granitic rock types, but not so good for greenstone due to a big variation in the composition of many different rock types included under the designation 'greenstone'.

Rock type characteristics of the four main rock types were made to describe what were considered typical 5 m-blocks within the investigated volume. Each block described one of the four main rock types, Småland (Ävrö granite), Äspö diorite, greenstone and fine-grained granite *(Figure 3-14)*. An overview of the ability to predict a specific parameter is shown in *Table 3-3*.

Discontinuities

Predictions of small-scale fracturing, in six 50 m-blocks and for the four main rock types on a detailed scale in the rock mass were based on surface fracture mapping and analysis of fracturing in cored boreholes.

The orientations of the main fracture sets were mostly within the predicted range. The main fracture infillings were predicted on both the 50 m and 5 m scale but the fracture length and fracture spacing cannot be modelled with reasonable accuracy for a specific rock volume at depth. Examples in *Figures 3-15* and *3-16* and in *Table 3-3*.

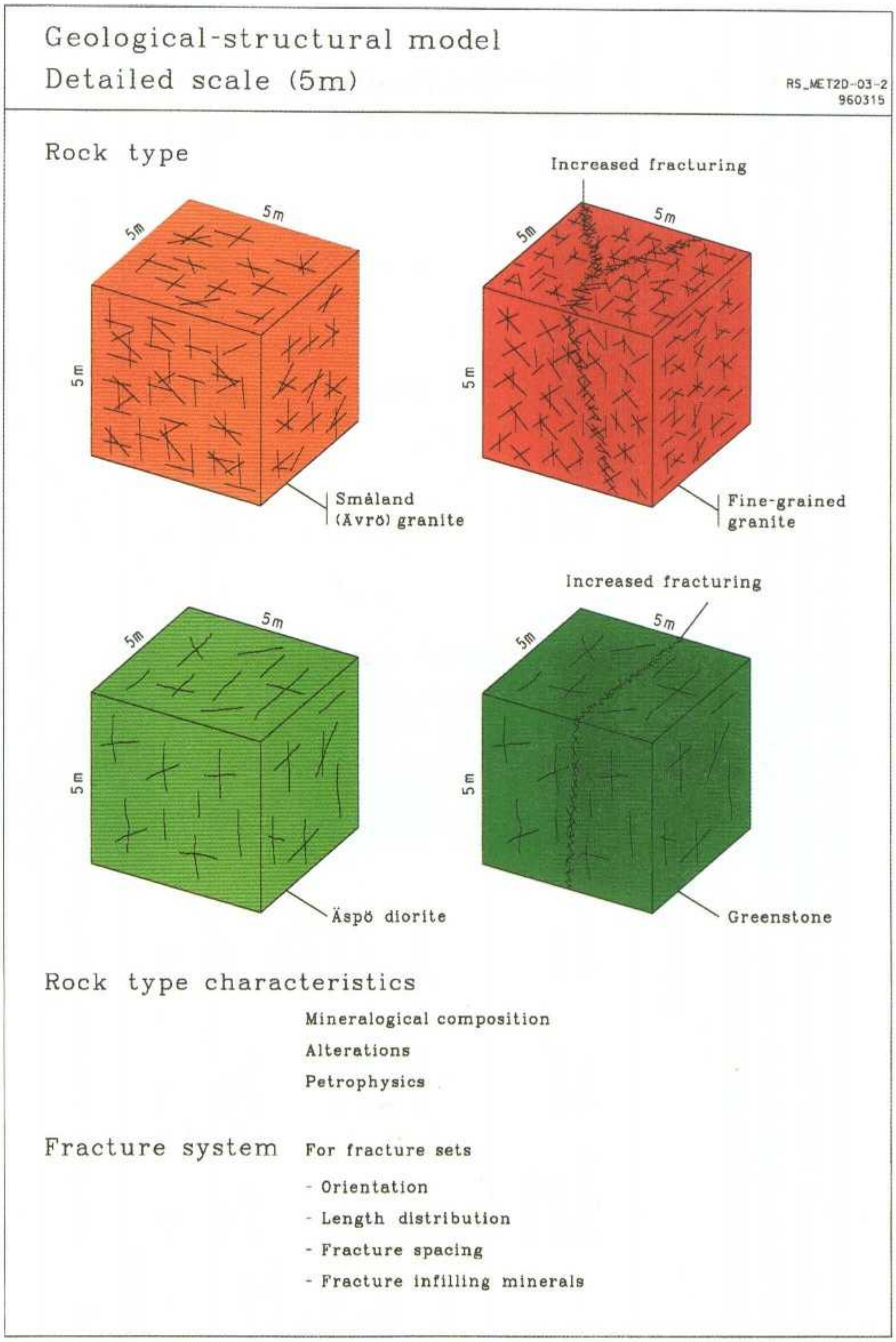


Figure 3-14. *Overview of the subject rock type characteristics of the lithological models (for the four main rock types), addressed on the detailed scale.*

Table 3-3. Lithological models on the (5-m) detailed scale. Comparison between the prediction and outcome for four (5-m) blocks. /*Stanfors et al, 1997*/. The generic 5-m blocks were made in order to describe what are considered to be typical 5-m blocks within the investigated rock volume. Each block described one of the four main rock types Småland (Ävrö granite), Äspö diorite, greenstone and fine-grained granite.

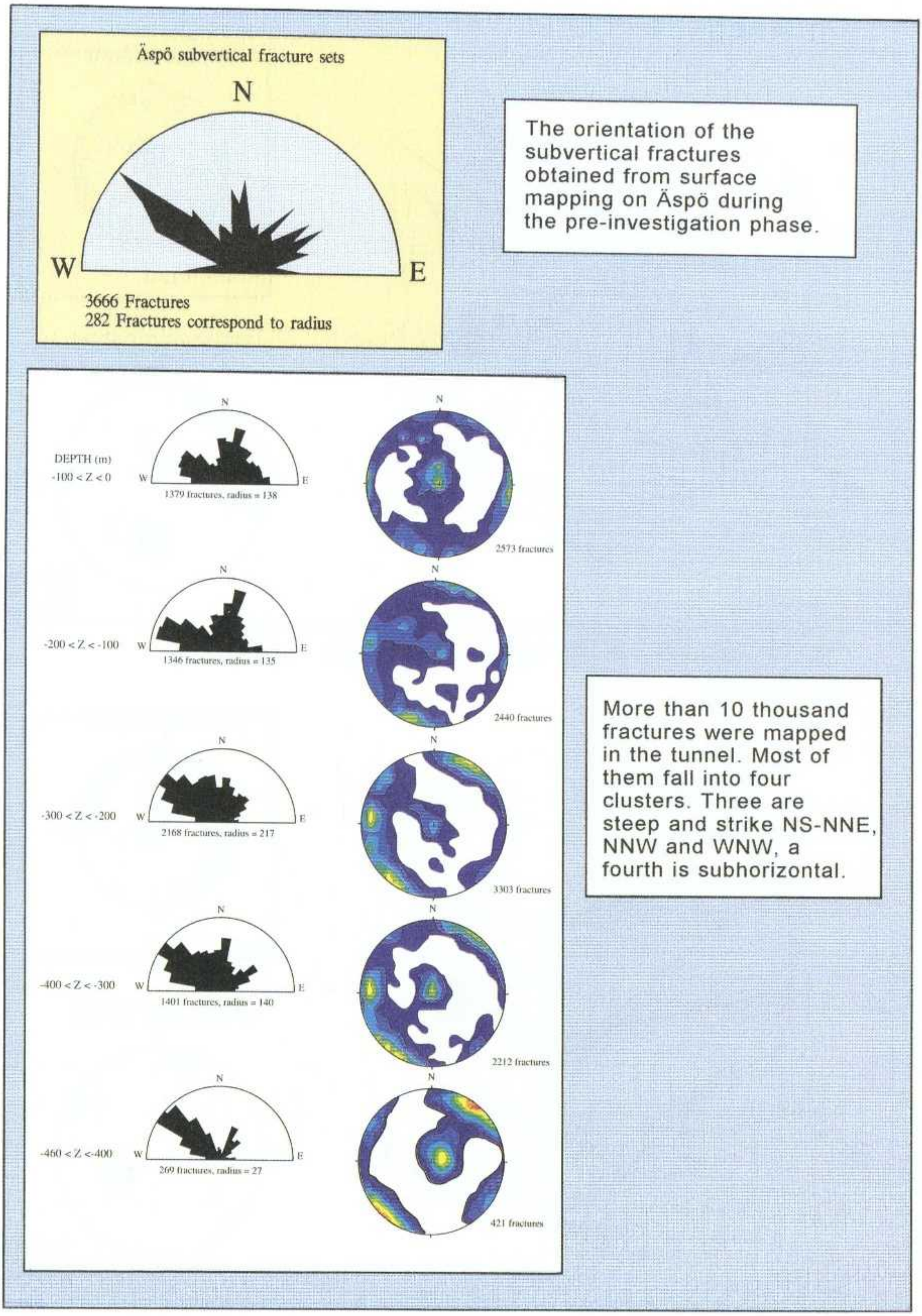
	PREDICTION				OUTCOME			
Subject	**Småland (Ävrö) granite**	**Äspö diorite**	**Green-stone**	**Fine-grained granite**	**Småland (Ävrö) granite**	**Äspö diorite**	**Green-stone**	**Fine-grained granite**
Mineral components (%)								
Quartz	20(±3)	15(±5)	5(±3)	30(±5)	26	12	4	27
Alkali-feldspar	25(±5)	15(±5)	-	40(±5)	26	17	-	36
Plagioclase	40(±5)	40(±5)	50(±5)	23(±5)	37	47	7	20
Biotite/Muscovite	10(±3)	20(±5)	20(±5)	7(±2)**	5	12	33	17
Amphibole	-	-	20(±5)	-	-	-	54	-
Epidote/pyroxene	-		5(±3)	-	-	-	2	-
Minor minerals	5(±2)	10(±3)	-	-	6	12	-	-
Total	100	100	100	100	100	100	100	100
Alteration (IUGS-classification)	1-2	1-2	1-2	1-2	2	2	2	1
Density (g/cm^3)	2.62(±0.03)	2.70(±0.05)	2.80(±0.05)	2.56(±0.02)	2.64	2.75	2.96***	2.67
Porosity (%)*	0.24(±0.02)	0.32(±0.02)	0.16(±0.02)	0.30(±0.01)	0.29	0.42	0.17	0.26

* Total porosity of matrix.

** Biotite, epidote and minor minerals.

*** "Greenstone" includes different basic rocks (dacite-gabbro) with different densities.

The confidence level (60% for mineral components and 90% for density/porosity) is based mainly on expert judgement.



The orientation of the subvertical fractures obtained from surface mapping on Äspö during the pre-investigation phase.

More than 10 thousand fractures were mapped in the tunnel. Most of them fall into four clusters. Three are steep and strike NS-NNE, NNW and WNW, a fourth is subhorizontal.

Figure 3-15. *Orientation of the main fracture sets on the surface of Äspö island (upper) and in the Äspö tunnel (lower).*

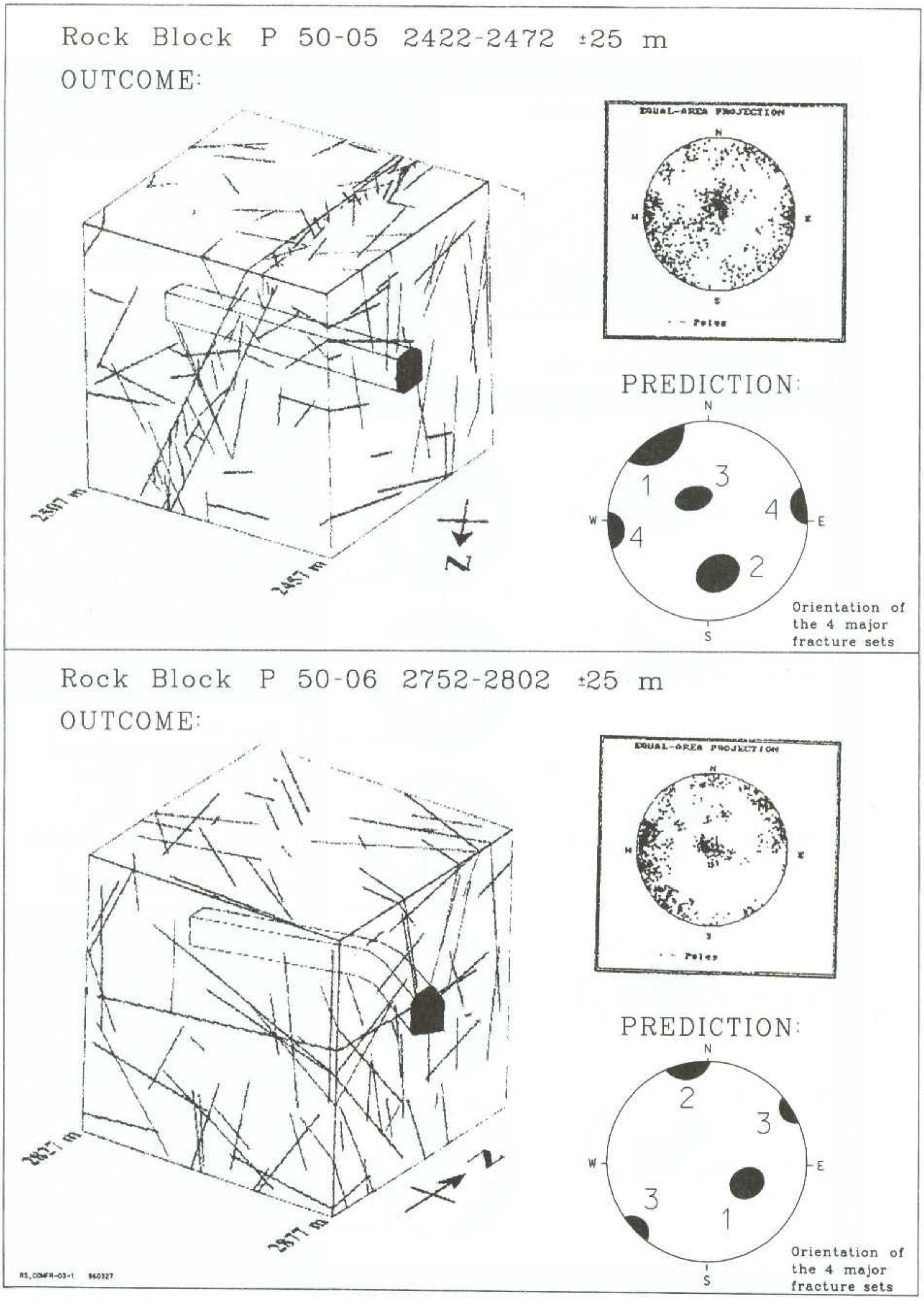


Figure 3-16. *Structural models on the (50-m) block scale. small-scale fracturing. Fracture network model for rock blocks P50-05 and P50-06 based on tunnel data, shown in the pole-diagrams above the predicted diagrams. /Stanfors et al, 1997/.*

Data available from cored boreholes are often sufficient for characterization of the major discontinuities from the aspect of kinematic indicators such as shear bands, mylonites and gouge, but not good enough for determination of fracture orientation within a discontinuity.

3.4 SPATIAL ASSIGNMENT METHOD

Lithology

The description of the distribution of major and especially minor lithological elements (fine-grained granite and greenstone lenses) is very scale dependent. Data from surface mapping and boreholes was found to be sufficient for average calculation giving reasonably accurate estimates of the amount of the different rock types on the site scale *(Figure 3-17)*. A deterministic distribution of a lithological domain on the block scale, however, is only valid for a very restricted area close to a borehole.

The lithological model seems to reflect our knowledge of the actual rock volume as a very complex rock mass *(Figure 3-5)* in an acceptable way but it is not possible to model the exact position of a lithological element with good accuracy *(Figure 3-18)*.

A probability model for the lithology at Äspö was produced from the ground surface to 800 metres below sea level by application of a Bayesian Markov Geostatistical Model */Rosén and Gustafson, 1995, 1996/*. The model was based on the surface bedrock map, surface boreholes, access tunnel boreholes, and access and TBM-tunnel mapping data. The Bayesian convincement maps show how the certainty of the lithologies decreases away from the borehole observations and at greater depth. It shows where further observations are needed to increase the certainty of the results, if required.

Discontinuities

Major fracture zones can normally be deterministically modelled based on geophysics and borehole data, while minor fracture zones should be described in a stochastic model on the site scale. This, of course, also applies to small-scale fracturing in the rock mass.

3.5 EVALUATION OF SITE INVESTIGATION METHODS

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

A summary of judgement of usefulness of different investigation methods for the pre-investigation phase of Äspö HRL is shown in *Tables 3-4* to *3-6*.

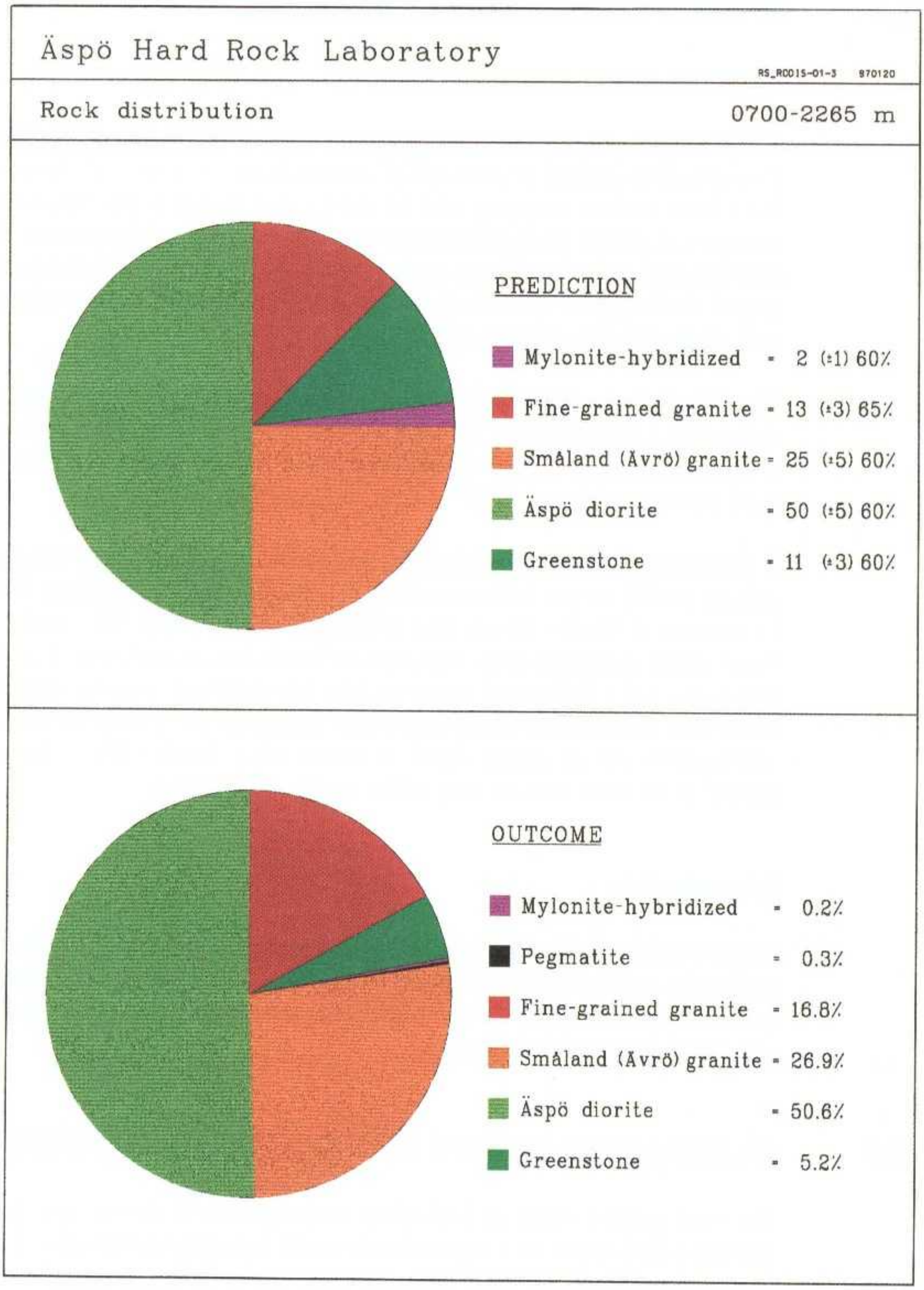


Figure 3-17. *Comparison between the prediction and outcome on the (500 m) site scale. Lithological model.*

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

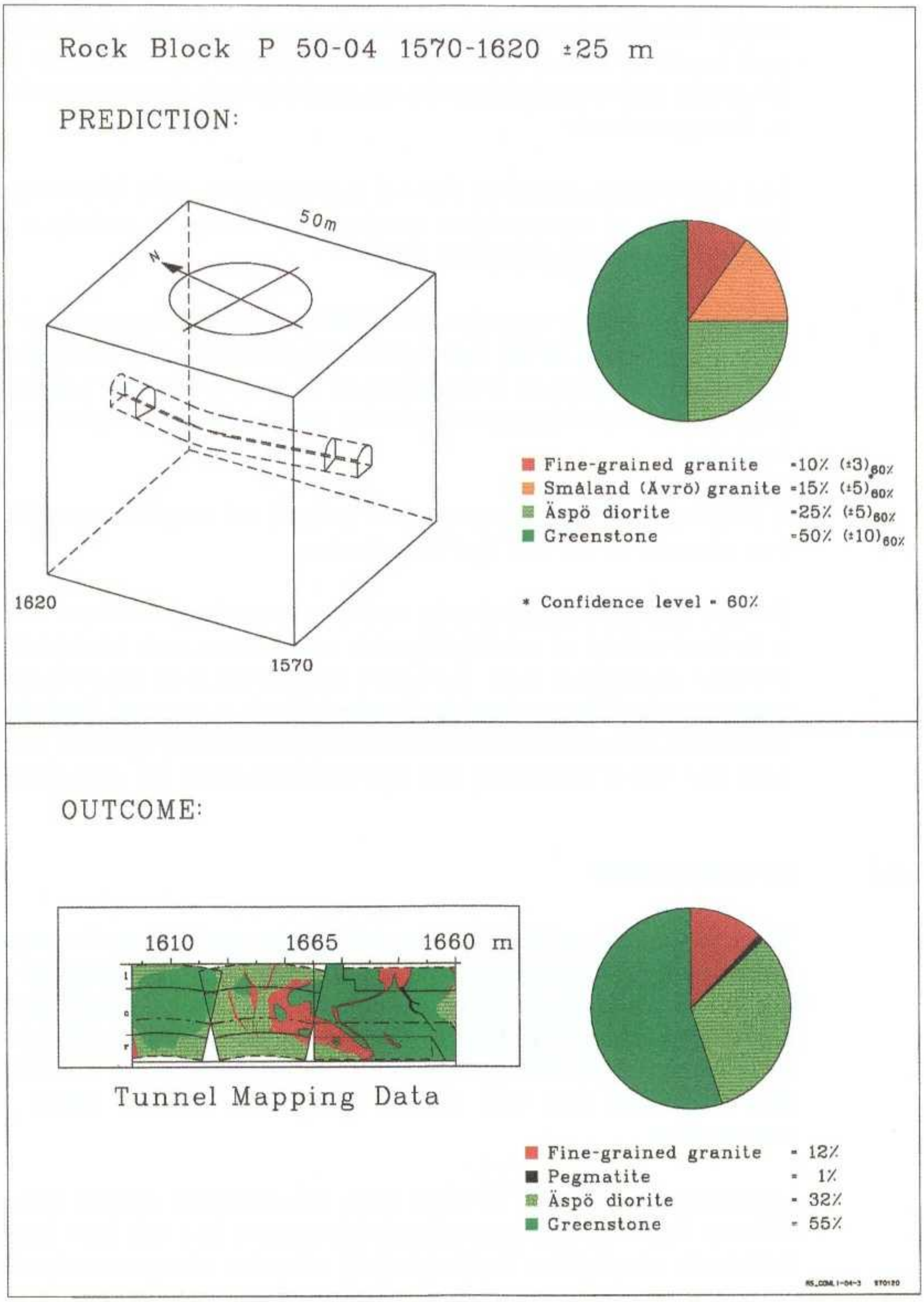


Figure 3-18. *Comparison between the prediction and outcome on the (50-m site scale. Lithological model. P50-04.*

3.5.1 Lithological model

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

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

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

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

Detailed geological mapping at the surface combined with drill-core analysis is the best method of investigating rock composition, rock boundaries and mylonites on the block scale. The density borehole log gives good information concerning the difference between Småland (Ävrö) granite and Äspö diorite. Microscopic examination of thin sections supplemented by chemical analysis is the best way of performing rock type characterization and classification.

3.5.2 Structural model

The aero-magnetic method was very useful on the regional scale for mapping possible major fracture zones in which oxidation of magnetite to non-magnetic minerals can cause magnetic minima. Aero-magnetic and Very Low Frequency measurements seem to be far superior to the EM measurements for interpreting possible fracture zones. It is important, however, to check the aero-geophysical data with ground investigation methods before final interpretation.

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

The reflectors indicated using the seismic reflection method could only in part be correlated with zones with increased frequency of low-dipping fractures in drill cores. The correlation seems to be greatest for reflectors at great depths, judging from borehole indications. The two gently dipping fracture zones mapped in the tunnel are probably too narrow to be indicated by use of seismic reflection.

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

Ground radar measurement data gave some interesting correlations with borehole radar reflections from structures/rock contacts, but further development is needed before this method can be regarded as a useful complement to seismic reflection.

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

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

The results from the caliper log, and the electric logs were of the greatest interest in detecting fractures and fracture zones. Fracture frequency, but not fracture length, could be estimated by use of these logs combined with core mapping. It seems, however, to be rather unnecessary to use three different electric logs which give largely identical results, so in most of the geophysical logging surveys, only the single-point resistance log was used.

The TV logging and Televiewer methods used for absolute orientation of fractures in core boreholes were accompanied by many problems.

Analysis of structural mapping, combined with lineament data and geophysical data, is very important in final location and characterization of major fracture zones.

It is generally very difficult to penetrate and characterize sections of crushed and clay-altered rock in fracture zones using normal small drill bits without grouting. In such cases the triple barrel coring technique seems to be most useful.

Table 3-4. Judgement of the usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL. Lithology and rock properties /Almén et al, 1994/.

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

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

Table 3-5. Judgement of the usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL. Major fracture zones /Almén et al, 1994/.

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

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

Table 3-6. Judgement of the usefulness of different investigation methods for the pre-investigation phase of the Äspö HRL. Minor fracture zones. /Almén et al, 1994/.

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

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

3.6 OVERALL EVALUATION AND CONCLUSIONS CONCERNING GEOLOGICAL MODELS

A summarized evaluation, based on data from comparisons between prediction */Gustafson et al, 1991/* and outcome */Stanfors et al, 1997/,* is presented in *Tables 3-7* and *3-8*. Our ability to predict a certain subject (parameter) is shown by the amount of outcome results inside the predicted range. Results outside the predicted results are discussed as regards the reason for the deviation. The sign + represents the most common parameter result (>50%).

3.6.1 Lithology

A lithological description comprise an overall distribution of the main rock units on a regional scale, while *'Rock composition'*, *'Rock boundaries'*, and *'Rock type characteristics'* refer to a more detailed description of small-scale petrographic variation on the block and detailed scales. *'Rock type characteristics'* refer to the mineralogical composition and petrophysics of the four most frequent rock types in the Äspö area: Småland (Ävrö) granite, Äspö diorite, fine-grained granite and greenstone.

Airborne geophysics (magnetic and electromagnetic) provide valuable information on the distribution of the major rock types on the regional site scale, especially with respect to big basic intrusions and diapirs of younger granite. Gravity data confirmed the depth extent of diapiric granites and bodies of basic rocks. Data from surface mapping contributed to a good understanding of the two-dimensional extent of the main rock types. In order to get a three-dimensional lithological model borehole, investigations were performed, comprising core mapping and geophysical logging.

The reliability of the predictions of the relative amount of the main rock units is rather good mostly due to well exposed bedrock and borehole data (core and geophysical logging) *(Figure 3-17)*.

The very irregular distribution of rock types like the fine-grained granite and the greenstone makes it almost impossible to describe the position and extent of the minor rock units. Borehole data give only representative information for a small volume close to the borehole. In a complex rock mass such at Äspö therefore dikes and veins of greenstone and fine-grained granite are very hard to model on the block scale *(Figure 3-18)*.

Table 3-7. **Comparison between prediction and outcome** */Stanfors et al, 1997/.* **The '+' sign represents the most common parameter results.**

Subject	Site scale		Block scale		Detailed scale		Comments
	Within predicted	Outside range	Within predicted	Outside range	Within predicted	Outside range	
Lithology							
Rock types	+						
Position of different rock types				+			Very difficult to predict in a complex lithology.
Rock boundaries (No/100 m)	+		+				
Rock composition (%)	+			+			
Major fracture zones							
Geometry							
Position in tunnel	+						Prediction of the more exact orientation and width uncertain due to the winding extent and variation in thickness along most fracture zones.
Strike	+ *						
Dip	+						
Width	+						
Properties							
Character		+					
Minor fracture zones							
Geometry							
Position in tunnel		+					The more exact location and width at depth of the minor fracture zones were not predicted.
Strike	+						
Dip	+	+ **					
Width	+	+ **					

* Verification based only on tunnel observations.

** Subhorizontal fracture zones.

The predictions generally comprise both point estimates and a confidence interval at a certain confidence level. These point estimates and confidence intervals are obtained both from sample properties and expert judgement. Rather than obtaining a very wide interval for a confidence level, the level of confidence is in these cases lowered to 60% for most geological parameters, which indicates an estimated low level of certainty*/Gustafson et al, 1991/.*

Table 3-8. Comparison between prediction and outcome */Stanfors et al, 1997/.* **The '+' sign represents the most common parameter results.**

Subject	Site scale		Block scale		Detailed scale		Comments
	Within predicted	Outside range	Within predicted	Outside range	Within predicted	Outside range	
Rock type characteristics							
Mineralogical composition			+		+		Mean values of a great number of core samples normally give reliable predictions for most of these parameters.
Alteration			+		+		
Density			+		+		
Porosity				+		+	
Small-scale fracturing							
Number of fracture sets			+		+		Surface and borehole data mostly give reliable predictions of the number of fracture sets and fracture infilling. Changes in orientation at depth, spacing and fracture length are more difficult to predict based solely on borehole data.
Orientation			+		+		
Spacing				+		+	
Length				+		+	
Fracture infilling minerals			+		+		

The predictions generally comprise both point estimates and a confidence interval at a certain confidence level. These point estimates and confidence intervals are obtained both from sample properties and expert judgement. Rather than obtaining a very wide interval for a confidence level. The level of confidence is in these cases dropped to 60% for most geological parameters, which indicates an estimated low level of certainty. */Gustafson et el, 1991/*

On the detailed scale the prediction of the mineralogical composition of the four main rock types *(Figure 3-14)* was based on numerous microscopical analyses of core samples from the Äspö area. The petrophysical parameters density and porosity were based on geophysical logging data. There is rather good agreement between the prediction and outcome regarding alteration and the major minerals - less good concerning biotite and minor minerals. The outcome data are normally based on 2-3 microscopical analyses and the density and porosity are based on 10-12 analyses per a number of 50 m rock blocks along the tunnel *(Table 3-3)*.

The mineralogical composition data should also be compared with the mean composition of the four relevant rock types in the whole Simpevarp area *(Table 3-9)*. It is important to note that the designation 'greenstone' was used to cover all basic rocks such as fine-grained metavolcanics to the rocks of dioritic-gabbroid composition.

Table 3-9. Main composition of main rock types in the whole Simpevarp area based on microscopical analyses. (n = Sample size).

Minerals	**Småland (Ävrö) granite** (n=41) (%)	**Äspö diorite** (n=87) (%)	**Fine-grained granite** (n=41) (%)	**Greenstone** (n=23) (%)
Quartz	25.8	14.0	30.6	3.5
K-feldspar	25.5	13.0	38.6	0.8
Plagioclase	37.1	44.7	20.8	35.4
Biotite	5.2	14.5	-	14.0
Epidote	-	-	-	6.0
Pyroxene/Amphibole	-	-	-	35.7
Minor minerals	6.4	13.8	10.0	4.6
Total	100	100	100	100

3.6.2 Discontinuities

On the site scale is possible to localize sub-vertical major fracture zones (>5 metres wide) during the pre-investigation phase at shallow depths. However, it is very difficult to predict more exactly the position, width and character at increasing depth. The error in predicting the position of a major fracture zone at depth is mainly due to the uncertainty of the dip *(Figure 3-7)*.

There is generally good agreement between the prediction and observations concerning the main orientation of sub-vertical fracture zones and their importance for construction. An exception, however, was fracture zone NE-2 which was predicted to be major zone and dip to the NW, outwards from the tunnel spiral but underground the zone was demonstrated to be a minor fracture zone dipping to the SE. The predicted dip was estimated mainly on the basis of one cored borehole. Underground the undulating character of NE-2 was confirmed by various measurements in the tunnel.

There is not always a clear correlation between distinct geophysical indications and the real importance of a fracture zone. For example, the topographically and geophysically very distinct regional zone EW-1 - which divides Äspö into two blocks - is of fairly low transmissivity and mostly of rather good mechanical strength for construction purposes. Zone NE-1, however, which was crossed by the tunnel, proved to be very difficult to excavate due to very high transmissivity and low mechanical strength. This zone was rather faintly indicated geophysically during the regional stage of pre-investigations, partly because it is located under the sea.

A number of minor, mostly steeply dipping, fracture zones were predicted to intersect the tunnel volume trending NNW-NNE. On the 500-m site scale, however, no exact position of a particular zone was predicted - only the frequency and main orientation of the zones. The different zones in the 'NNW' system were predicted to be 'possible-probable' and their predicted position in the tunnel very approximate. The widths were expected to be 0.1-5 m *(Figure 3-10* to *3-12).* The character of the zones were not predicted due to lack of relevant data.

Only structures that display indicators, such as slickensides, mylonitic fabrics or faults, were mapped in the tunnel as minor fracture zones. Most of them are generally not wider than 1 m. Most consist of a single or up to a handful of faults that generally contain gouge. The host rock is generally mylonitized shear faults. The nature of fracturing in sheets of fine-grained granite make such structures difficult to differentiate from fracture zones. However, fracture zones are here defined as broken volumes of rock that also display kinematic/tectonic indicators which discriminate most sheets of fine-grained granite.

The predicted water-bearing zone NNW-4W is an example of a minor fracture zone which is indicated in the tunnel by two intersections, at 2020 m and 2120 m and 2914 m *(Figure 3-13).* Except for NNW-4W it is not possible to find persistent 'minor fracture zones' in the tunnel according to the definition given in the prediction based on surface indications. One reason for this may be the tendency of most fracture zones to be narrower at depth than what could be expected from surface indications in the form of fractured and weathered rock.

Combined results from tunnel mapping and drilling show the characteristic pattern of the 'NNW structures'. They mostly occur in a complex pattern of steeply dipping fractures (fracture swarms) and some decimetre-wide 'fracture zones' trending WNW to NE. Many of the narrow fracture zones are connected to veins or dikes of fine-grained granite. It seems possible to correlate a few fracture zone indications in the tunnel to observations in boreholes crossing the central part of the spiral and forming a hydraulically active pattern trending WNW-NNW *(Figure 3-13).* The character of many of these structures as 'fracture zones' is not very evident. They should rather be described as a 10-

30 m wide swarm of mostly subvertical conductive fractures trending WNW-N where the WNW trending fractures are normally the most frequent and hydraulically important.

On the 50-m scale minor fracture zones are penetrated by the access tunnel in rock blocks 50-01 and 50-02. (Predictions were made for six 50 m rock blocks along the tunnel.) In rock block 50-01 – where the prediction/outcome discrepancy is most evident – three minor fracture zones were predicted, based on cored borehole KBH02. In the tunnel the increased fracturing is found to occur more or less continuously over an approximately 40-m long section.

In rock block P50-04, at 1570-1620 m in the spiral tunnel three minor fracture zones were predicted, based on the cored boreholes. In the rock block only one minor fracture zone was found.

Three(±1) minor fracture zones were predicted for each of the blocks P50-05 (at 2422-2472 m) and P50-06 (at 2752-2802 m) but only one zone was mapped in each block.

The discrepancy between the prediction and outcome regarding minor fracture zones shows that it is almost impossible to predict the exact position of a specific minor fracture zone based solely on surface data and information from a single borehole in or close to an actual rock block. The main orientation, however, of the 'NNW fracture zone system' and its water-bearing character was in fair accordance with the prediction.

Predictions, in the 50-m blocks, of small-scale fracturing were based on surface fracture mapping and analysis of fracturing in cored boreholes.

As there was no core orientation in borehole KBH02, penetrating P50-01 to P50-03, the prediction of the main fracture set orientation in these blocks was based solely on data from surface mapping. The best agreement with predictions seems to be for the approximately N-S and E-W fracture set orientations, which could be explained by the dominating character of these fracture sets in the whole area.

The prediction of the main fracture set for the rock blocks P50-04 to P50-06 was based mainly on data from TV orientation in cored borehole KAS05. The best agreement with predictions seems to be for the approximately N-S and NW-SE fracture set orientations. Example in *Figure 3-16.*

As regards predictions of small-scale fracturing on the 5-m scale for typical examples of the four main rock types, there is good agreement between the prediction and outcome regarding 'fracture minerals' and 'main fracture orientation' (especially concerning the two dominant fracture sets striking approximately E-W and N-S) and less good regarding fracture spacing and fracture length *(Table 3-10).*

Table 3-10. Structural models on the (5-m) detailed scale. Comparison between prediction and outcome for four (5-m) blocks involving small-scale fracturing. */Stanfors et al, 1997/.*

	PREDICTION				OUTCOME			
Subject	**Småland (Ävrö) granite**	**Äspö diorite**	**Green-stone**	**Fine-grained granite**	**Småland (Ävrö) granite**	**Äspö diorite**	**Green-stone**	**Fine-grained granite**
Fracture length (>0.5 m)	1.2(±0.3)	1.2(±0.3)	1.2(±0.3)	0.8(±0.1)	1.6	2.1	1.9	0.7
Fracture spacing (>0.5 m)	1.0(±0.3)	1.0(±0.3)	1.0(±0.3)	0.5(±0.1)	0.6	0.5	1.5	0.5
Main fracture orientation								
Equal area projection (lower hemi-sphere)								
Fracture minerals	1. Cl,Ep,Ca,FeOH 2. Cl,Ca,FeOH 3. Cl,Ep,Ca 4. Cl,Ep,Ca	1. Cl,Ep,Ca,FeOH 2. Cl,Ca,FeOH 3. Cl,Ep,Ca 4. Cl,Ep,Ca	1. Cl,Ep,Ca,FeOH 2. Cl,Ca,FeOH 3. Cl,Ep,Ca 4. Cl,Ep,Ca	1. Cl,Ep,Ca,FeOH 2. Cl,Ca,FeOH 3. Cl,Ep,Ca 4. Cl,Ep,Ca	a. Cl,Ca,FeOH,Ep b. Cl,Ca,FeOH	a. Cl,Ca,FeOH b. Cl,Ep,Ca c. Cl,Ep,Ca	a. Cl,Ca b. Ca,Cl c. Ca,Cl,Cy,Ep d. Cl,Ca,Cy	a. Cl,FeOH,Ca b. Cl,Ep,Ca,FeOH

Cl = chlorite, Ca = calcite, Ep = epidote, FeOh = Fe-oxihydroxide, Cy = clay

The confidence level (60% for fracture length and spacing) is based mainly on expert judgement.

3.6.3 Conclusions

The following are the most important conclusions.

- Predictions of lithology on the regional scale are mostly very reliable as regards the distribution of major lithologic domains such as granite diapirs and big massifs of basic rock, where we had aero-geophysical data and well exposed bedrock.

- The main rock types is generally well predicted for most of the tunnel rock volume whereas the spatial distribution of minor rock types is very uncertain. Borehole data provides only representative information for a small volume close to the borehole. In a complex rock mass such as at Äspö therefore dikes and veins of fine-grained granite and greenstone for example cannot be predicted with respect to exact position at depth.

- The position and general properties of major fracture zones are accurately obtained from the surface and borehole investigations in particular for subvertical structures. The main structural pattern is normally revealed at an early stage of the pre-investigation phase using airborne geophysics and lineament interpretation (existence and extent of major structures). Accurate information on the dip and character of the structures was obtained from more detailed investigations in the form of ground-based geophysics and drilling (see *Figure 3-19*).

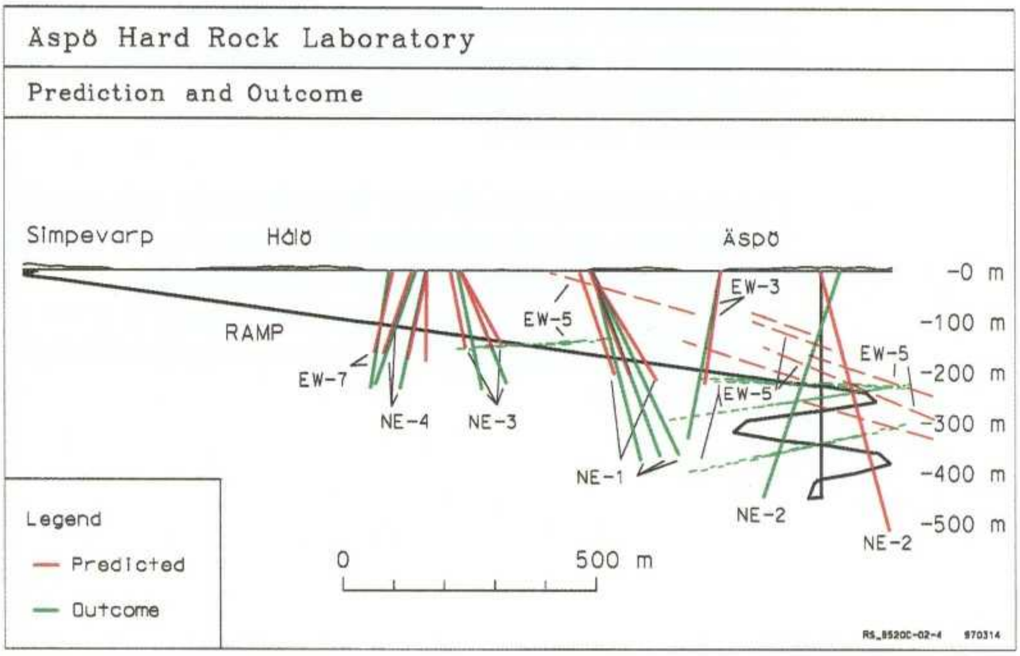


Figure 3-19. *Prediction and outcome of major fracture zones. The picture illustrates predicted (red) and observed (green) dips and positions in the tunnel of the major fracture zones.*

- To be able to determine the geometry of a certain fracture zone at depth it is very important to try to find some significant features and properties which can be used for identification of the zone in cored boreholes. Examples of such 'markers' are shear bands, mylonite, certain fracture minerals and gouge. Interference tests can be helpful for defining the geometry of a fracture zone.

- Suitable investigation methods, such as refraction seismics, core drilling, geophysical logging and radar in boreholes, have resulted in generally good agreement between the prediction and outcome where major subvertical fracture zone data are concerned, such as orientation and general character. An exception, however, was fracture zone NE-2, which was predicted to be 'major' and dip to the NW, outwards from the spiral but underground the zone has been demonstrated to be a 'minor' fracture zone dipping to the SE. The reason for the poor prediction was that only one cored borehole crossed the zone, which is winding and irregular.

- All the subhorizontal structures found in the tunnel were narrower and less hydraulically important than had been predicted, based mainly on geological field observations. There was no agreement - except as regards the existence - between prediction and outcome. Geophysical methods, which are suited to determination of geometry and more detailed characterization of narrow fracture zones at depth in crystalline rocks, were not available.

- The reliability of minor (local) discontinuities (less than 5 m wide) was good regarding their existence and hydraulic character but not so good as regards the extent and structural character at depth. It seems to be almost impossible to predict an individual minor zone in terms of exact position and orientation.

- The characteristics of small-scale fracturing in the rock mass between the fracture zones, such as orientation of the main fracture sets and fracture infillings were mainly concordant with the predictions *(Figure 3-7)*. Spacing was almost within the predicted range. It is not possible to estimate fracture length from borehole investigations at depth.

4 EVALUATION OF MECHANICAL STABILITY

4.1 INTRODUCTION

Mechanical stability is a key issue when engineering a deep repository. The long-term aspect of mechanical stability is to design the repository so that potential movements caused by current and future stresses (due to temperature changes, earthquakes and glaciation) will not damage the canisters containing the waste. The short-term aspect is mechanical stability during construction and operation of the repository. The Äspö project has so far dealt mostly with the short-term aspect to assess that the excavated openings in the rock will be stable during construction and operation of the laboratory.

There is a need for good understanding of the geology, the stress field and mechanisms of deformation and potential failure to make reliable models for assessing short-term mechanical stability.

Primary stresses were measured using two different methods, hydraulic fracturing and overcoring. Rock mass quality assessments were made using the Rock Mass Rating (RMR) system */Bieniawski, 1989/.* The assessment is primarily based on the geological-structural model at Äspö. Several properties of intact rock and fractures were collected and tested in the laboratory prior to and during construction as depicted in *Figure 4-1.*

The pre-investigation methodology for defining the rock stress model and the rock quality according to the RMR system is shown in *Figure 4-2.*

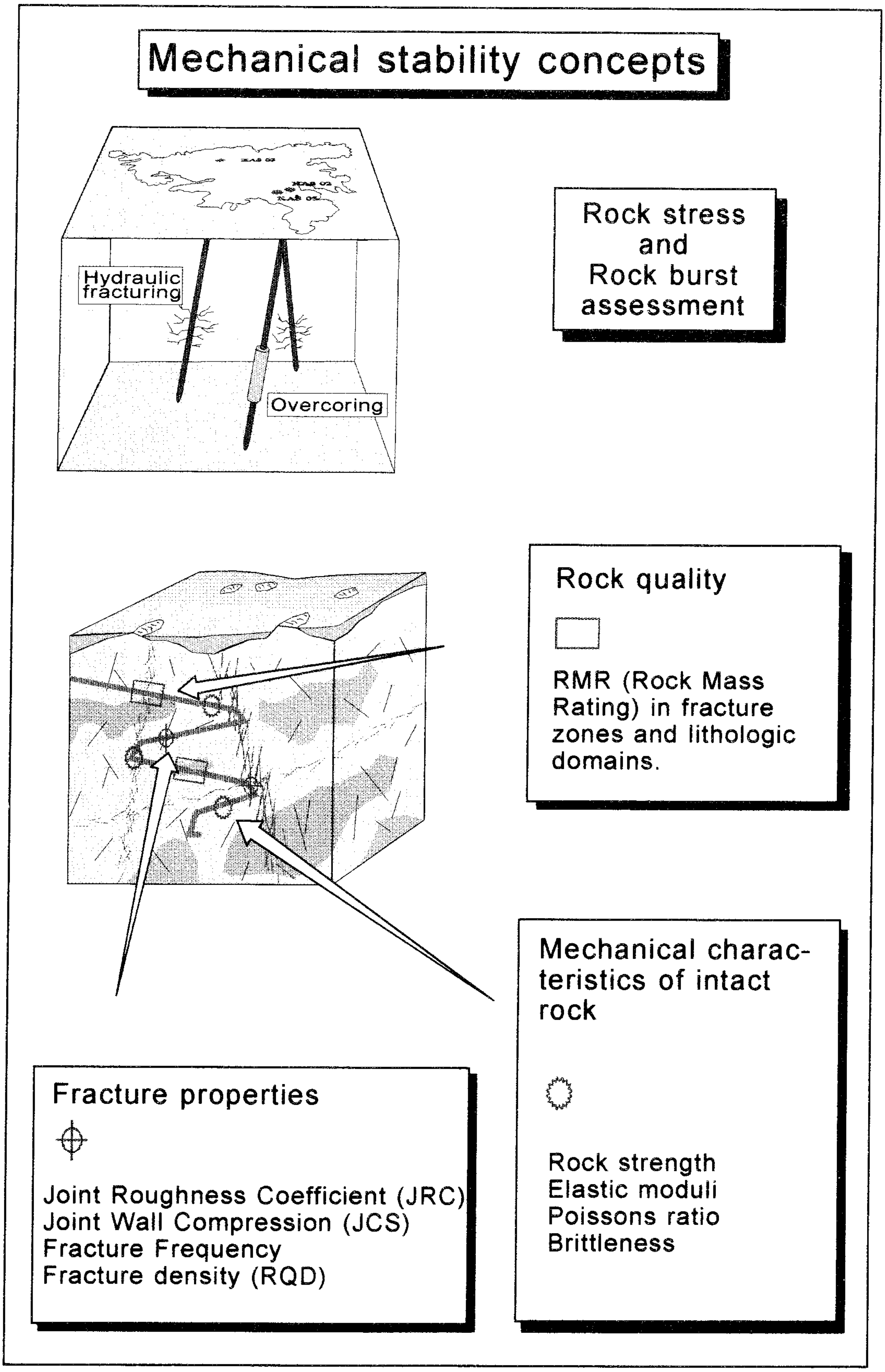


Figure 4-1. *Schematic description of the work of assessing the reliability of mechanical models. Primary stresses were assessed using two different measurement methods, hydraulic fracturing and overcoring. Rock quality assessments along the tunnel were made using the Rock Mass Rating (RMR) system. Several properties of intact rock and fractures were collected prior to and during construction.*

The overall concepts used to describe the issue of mechanical stability are shown in *Tables 4-1 to 4-3*. More details are provided in *Stanfors et al /1997/* and *Rhén et al /1997/*. The concepts used to assess stability comprise basically concepts for the state of stress, excavation stability and rock burst. These concepts are closely interrelated with the geological processes acting in the area, i.e. the strain history in southeastern Sweden in relation to faulting and fracturing and present stress conditions.

The primary rock stresses, *Table 4-1* are very much dependent on the local geology and measurements of rock stresses in general show great variation, cf *Chapter 4.2*. The Rock Mass Rating (RMR) system has been used to assess excavation stability, *Table 4-2*. Assessment of possible occurrence of rock burst relied on expert judgement, *Table 4-3*.

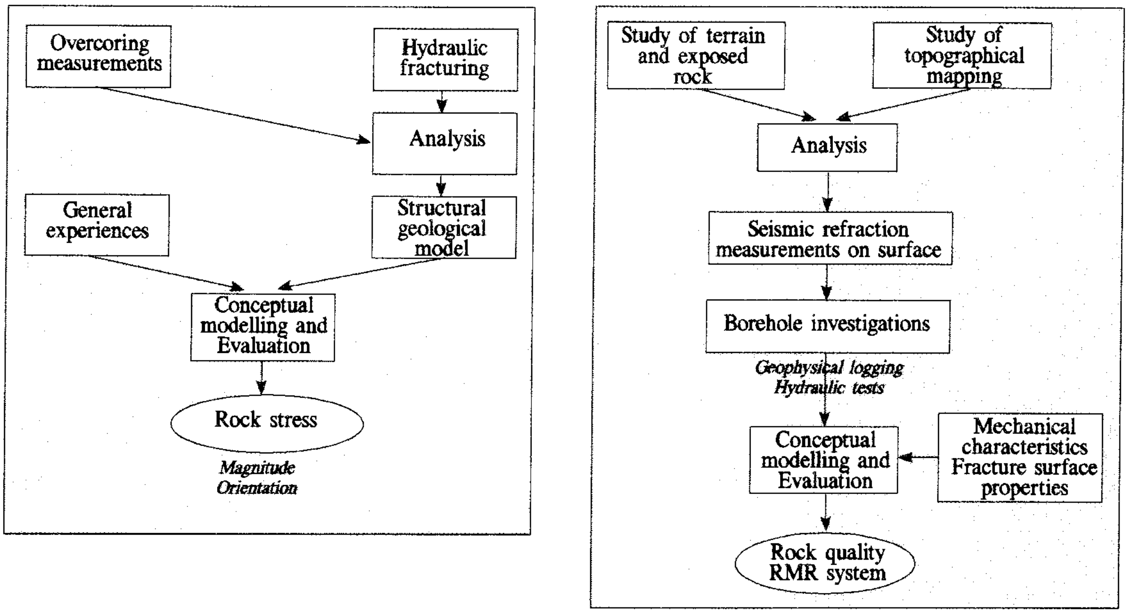


Figure 4-2. *Pre-investigation methodology. Left: Rock stress model. Right: Rock quality - RMR system.*

Table 4-1. Condensed description of the concepts for rock stress at the Äspö site within the Äspö HRL Project.

MODEL NAME
Rock stress

Model scope or purpose
State of stress.

Process description
State of stress: Calculation of a rock stress field assumes continuum, homogeneous, isotropic, linear elastic material based on measured strains (overcoring) or evaluation of measured pressure responses and the tensile strength of the rock (hydraulic fracturing)

CONCEPTS

Geometrical framework and parameters
Three-dimensional box for primary stresses at boundaries. Shape of opening for rock stresses close to excavation.

Material properties
Young's modulus, Poisson's ratio and tensile strength of the rock (hydraulic fracturing).

Spatial assignment method
Homogeneous and identical to primary stresses.

Boundary conditions
Primary stresses at measurement points and linear regression of stresses with depth.
Vertical stress calculated from the weight of overburden.

Numerical or mathematical tool
-

Output parameters
Rock stress.

Table 4-2. Condensed description of the concepts for excavation stability at the Äspö site within the Äspö HRL Project.

MODEL NAME
Excavation stability

Model scope or purpose
Assessment of potential non-elastic behaviour of rock, assessment of potential engineering problems.

Process description
Empirical-based expert system, like Rock Mass Rating:

CONCEPTS

Geometrical framework and parameters
Based on geological model (lithology, discontinuities) and empirical relations.

Material properties
RMR: (strength of intact rock material, drill core quality (RQD), spacing of discontinuities, condition of discontinuity, groundwater and strike and dip of discontinuities). Joint surface parameters for characteristic joint sets: (JRC, JCS, spacing, RQD).

Spatial assignment method
Grouping of RMR in five classes and deterministic determination of mean and range of RMR for the tunnel. Application of the Bayesian Markov geostatistical model to spatial assignment of RQDs was also tested

Boundary conditions
-

Numerical or mathematical tool
-

Output parameters
Potential for excavation instability, assessment of rock quality for engineering purposes.

Table 4-3. Condensed description of the concepts for rock burst at the Äspö site within the Äspö HRL Project.

MODEL NAME
Rock burst

Model scope or purpose
Assessment of potential non-elastic behaviour of rock, assessment of potential engineering problems.

Process description
Empirical-based expert system, supplemented by measurement of brittleness on cores.

CONCEPTS

Geometrical framework and parameters
Geological model, stresses and empirical relations.

Material properties
Empirical assessment based on values of rock stress and unconfined compressive strength. Brittleness based on comparison of energy used prior to failure and energy after failure as measured on an intact specimen in a stiff machine.

Spatial assignment method
-

Boundary conditions
Local stress field.

Numerical or mathematical tool
-

Output parameters
Assessment of potential for rock burst in each rock type, potential for excavation instability, assessment of rock quality for engineering purposes.

4.2 ROCK STRESS

The magnitudes of the principal rock stresses are important when making predictions of the excavation stability and the rock burst potential. Problems related to excavation stability normally also increase with increasing deviatoric rock stress magnitude. A detailed assessment of the stress field necessitates a detailed geological description and knowledge of deformation properties of rock types and discontinuities. A detailed model of the stress field cannot be made at an early stage of the investigations.

The predictions of the rock stress situation were based on rock stress measurements in three cored boreholes. Most of the measurements were made using hydraulic fracturing in cored boreholes KAS02 and KAS03. Some additional measurements were made by overcoring in cored borehole KAS05 (cf. *Figures 5.27* and *5-28* for borehole locations). The measurements indicated a NW-SE orientation of the largest horizontal stress component which is in line with the overall regional stress field at great depths in this part of the Baltic Shield as evaluated by fault-plane solutions of earthquakes */Muir Wood, 1993/*.

The ratio between the maximum horizontal stress σ_H and the theoretical vertical stress σ_V was estimated prior to excavation at about 1.6-1.9. According to the measurements made, this value was estimated to be typical for the depth interval between 300 m and 500 m below the surface.

In the tunnel, rock stress measurements were made in eleven boreholes. All measurements were made using the overcoring technique and CSIRO Hollow Inclusion cells. Measurements in the tunnel were made far from the tunnel opening (> 12 m) so the tunnel opening itself would not create a stress redistribution at the measuring points.

The measurements during construction proved a dominating NW-SE orientation, which corresponds to the prediction. The measurements made in the tunnel showed considerably higher stress levels than anticipated */Stille and Olsson, 1996/*. The mean Ko-value (σ_H/σ_V) for all boreholes, is 2.9 with the average for individual boreholes ranging between 1.7 and 4.0. Single measurements in the individual boreholes vary between 1.5 and 4.0. *Figure 4-3* shows the maximum horizontal stress for different depths and for different boreholes.

A more comprehensive analysis of the rock stress condition at Äspö and measurement methods is needed to provide a clear explanation of the significant difference between the rock stress magnitudes measured from the surface and from the tunnel.

4.3 EXCAVATION STABILITY

The RMR system was used for the classification of the rock mass in the Äspö tunnel. This system operates with six parameters to describe the rock mass and is simple to use when the classification is based on pre-investigation data. If any parameter is missing it is possible to estimate the value of the missing parameter using engineering judgement. The reliability of the framework is to a large extent connected to the reliability of the geological model.

Rock mass quality is estimated for the tunnel based on the lithological and discontinuity domains mentioned in *Section 3.2*. Experience from the Äspö tunnel proved that the rock mass quality is very dependent on the rock type. Fine-grained granite, which is often fractured, exhibits both significantly lower mean RMR values and larger variations. The differences between greenstone, Småland (Ävrö) granite and Äspö diorite are smaller and they also exhibit smaller variations. The predicted RMR values for the tunnel mostly exhibit acceptable correspondence to the observations made in the tunnel. Poor rock

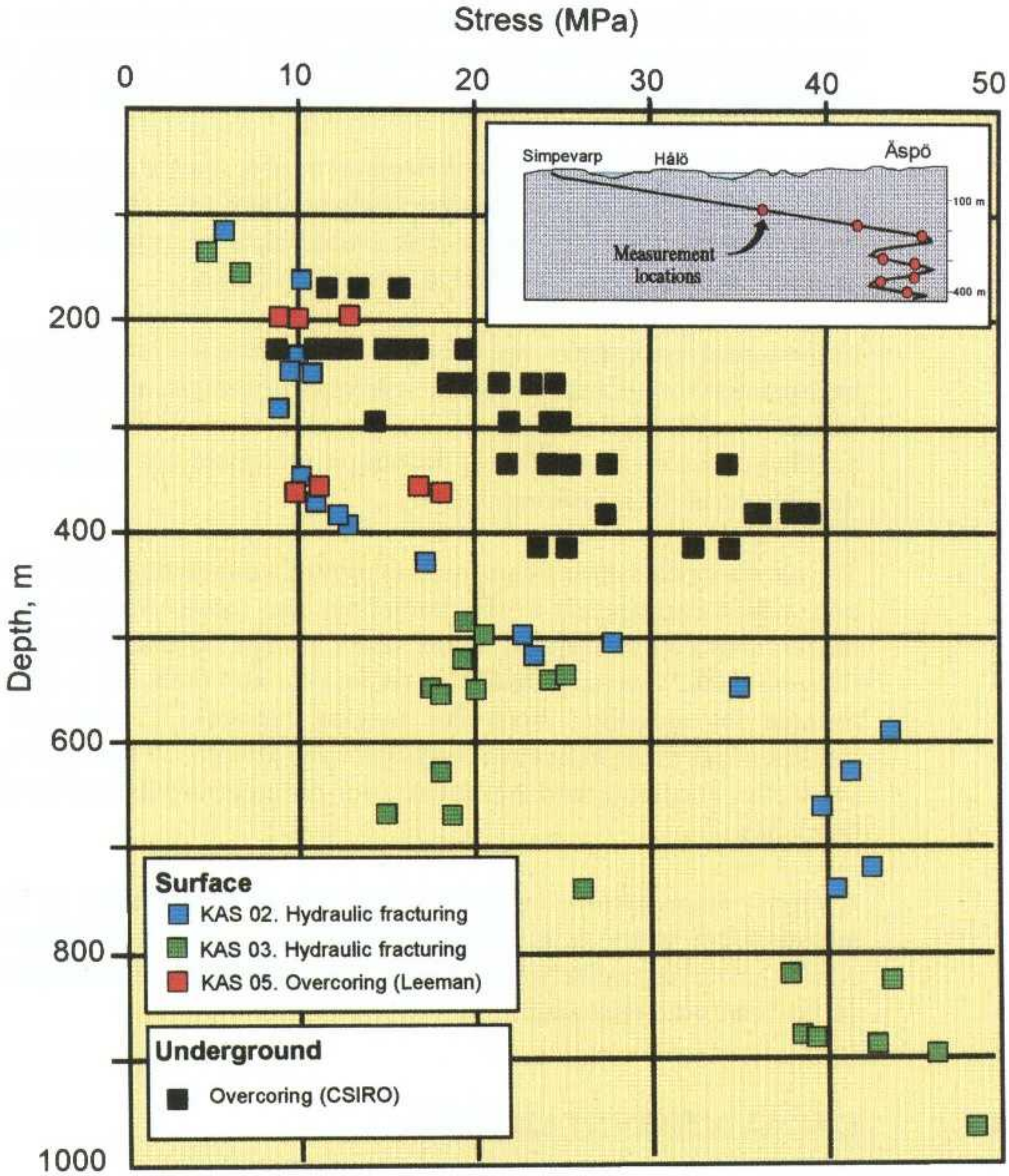


Figure 4-3. *Maximum horizontal stress as a function of depth below the surface. Two boreholes, KAS02 and KAS05, are only separated by a distance of 65 m. Different results with depth could be contributed to natural spatial variability of the stress field or to the different stress measurement methods used. Underground measurements exhibit a larger range for maximum horizontal stresses than the predicted range. The mean Ko-value (σ_H / σ_v) for all boreholes is 2.9, with the average for individual boreholes ranging between 1.7 and 4.0. Single measurements in the individual boreholes vary between 1.5 and 4.0. The estimated range of Ko was 1.6-1.9. σ_v is calculated as the weight of the overburden, regardless of the measured vertical stress.*

was predicted at 8% of the tunnel length while the outcome was 4% (*Table 4-4*).

While establishing a rock quality prediction, a rock classification system is commonly applied to core samples. General experience from using core samples is that the prediction will be somewhat conservative, i.e. lower RMR values were predicted than actually found in the tunnel. This can be due to a fracture length cut-off (0.5-1.0 m) in the tunnel which gives a higher RQD in the tunnel.

Table 4-4. Summary of predicted and observed RMR values along the tunnel */Stanfors et al, 1997/.*

Class	Rock Mass Rating-Value	Predicted distribution	Outcome distribution
Very good	RMR > 72	23%	28%
Good	RMR 60-72	50%	39%
Fair	RMR 40-60	19%	28%
Poor	RMR < 40	8%	4%

Predictions of the spatial variability of parameters used in the predictions were quite simplistic. Mean values and ranges were determined more or less by averaging collected data over lithological domains.

Later work */Rosén and Gustafson, 1996/* describing a Bayesian Markov geostatistical model for spatial assignment of parameters is an important development. The model has been applied to estimate spatial variability of lithology, RQD, hydraulic conductivity - for which the Äspö site was divided into cells measuring 20 · 20 · 20 metres and properties were assigned to each cell. The method is non-parametric, to be able to handle classified information with unknown statistical distributions. It also uses Bayesian statistics to formally handle professional judgements of the evaluation. Assignment of values to each cell can make use of data from the surface, boreholes and tunnel mapping. The methodology can be useful in future work in spatial assignment of, for example RMR.

4.4 ROCK BURST, ROCK TYPE PARAMETERS

Rock burst

Rock burst is thought to be a local phenomenon for depths considered for the Swedish repository (< 700 m). Very high stresses and very brittle rock behaviour could pose serious problems at repository depth.

Assessments were based on evaluation of measurement of brittleness and rock stress. During the excavation period cores were drilled in the tunnel and selected for laboratory testing. Similar testing was performed during the prediction phase. A total of ten tests were generally made for each parameter and rock type. The cores for each rock type were selected from 2-8 different boreholes, mainly located in the first part of the tunnel, section 745-1675 m. Less indications of rock burst, like spalling, were observed than expected, even if the stress range is higher than expected, as interpreted from the CSIRO measurements. On the other hand, measurements of rock type parameters performed during excavation show higher values compared to measurements performed prior to excavations (cf. below).

Rock type parameters

Laboratory testing of cores comprised unconfined compressive strength, Young's modulus, Poisson's ratio and an estimate of the degree of brittleness. A few results from testing of joints were also presented.

Prior to construction four samples were tested for each main rock type, in all 16 samples */Stille and Olsson, 1989/.* Only a few samples were collected for testing based on the assessment that no major mechanical problems were expected. In spite of the few data collected, a prediction exercise was performed. The difference between the result from the pre-investigation phase and the excavation phase is mostly significant, */Stanfors et al, 1997/.* The significant deviations are possibly explained by the small number of tests performed compared with the large natural variations in the rock mass, *Table 4-5.*

Predicted ranges did not account for the limited number of samples and several parameters were thus, with hindsight, assigned too small a range compared with the observations made in the tunnel. With few samples wider ranges should be assigned for new sites exhibiting similar rock variability.

4.5 ROCK SUPPORT, GROUTING

Three fundamental cases of stability problems can arise:

- The 'normal case' with good rock, some loose blocks, but otherwise good stability.
- Passage of significant zones of weakness, which comprises a special case.
- Good rock, but over-stressing and spalling/rock-burst occurs, which comprises another special case

Based on the RMR classification along the tunnel, demands on rock support (shotcrete, bolts) were made. It was not possible to identify a relationship between the rock quality or rock type and the frequency of rock bolts, except for the zones. 55% of all bolting and 77% of all shotcreting were performed in conjunction with fracture zones. Shotcreting was performed predominantly where the RMR value was less than 60. However there are many areas in the tunnel with RMR less than 60 that not have been shotcreted. Thus, the amount of reinforcement has been overestimated in the pre-construction estimates.

Developments in grouting theory and practice were achieved during the construction phase */Gustafson and Stille, 1996/* based on data collected during grouting at Äspö. A total of 150 series of grouting were conducted. Re-grouting at a given tunnel section was done 50 times out of the 150. 36 out of these re-grouting series were done in the major water-conductive fracture zone NE-1. The total grouted length of the tunnel is about 840 m, (27%). 44% of the grout volume was injected into major fracture zones (width > 5 m). The rest of the volume was injected into minor fracture zones (16%) and single fractures.

Table 4-5. Laboratory testing of mechanical parameters. From *Stille, Olsson, 1996*.

	Greenstone	**Fine-grained granite**	**Äspö diorite**	**Småland (Ävrö) granite**
Unconfined compressive strength (Mpa)	**(Mpa)**	**(Mpa)**	**(Mpa)**	**(Mpa)**
Prediction				
-mean	119	236	184	189
-range	103-168	152-336	164-217	147-260
No. of tests	4	4	4	4
Outcome				
-mean	207	258	171	255
-range	121-274	103-329	103-210	197-275
No. of tests	10	9	10	10
Young's modulus (GPa)	**(GPa)**	**(GPa)**	**(GPa)**	**(GPa)**
Prediction				
-mean	53	65	60	62
-range	32-74	59-70	54-65	62-63
No. of tests	4	4	4	4
Outcome				
-mean	78	77	73	74
-range	71-96	72-80	65-80	63-79
No. of tests	10	9	10	10
Poisson´s ratio	(-)	(-)	(-)	(-)
Prediction				
-mean	0.25	0.22	0.23	0.24
-range	0.24-0.26	0.20-0.22	0.20-0.25	0.24
No. of tests	4	4	4	4
Outcome				
-mean	0.24	0.23	0.24	0.23
-range	0.18-0.31	0.21-0.25	0.22-0.29	0.20-0.26
No. of tests	10	9	10	10
Brittleness				
Prediction				
-	more brittle	less brittle	brittle	brittle
No. of tests	4	4	4	4
Outcome				
-	brittle	more brittle	more brittle	more brittle
No. of tests	10	9	10	10

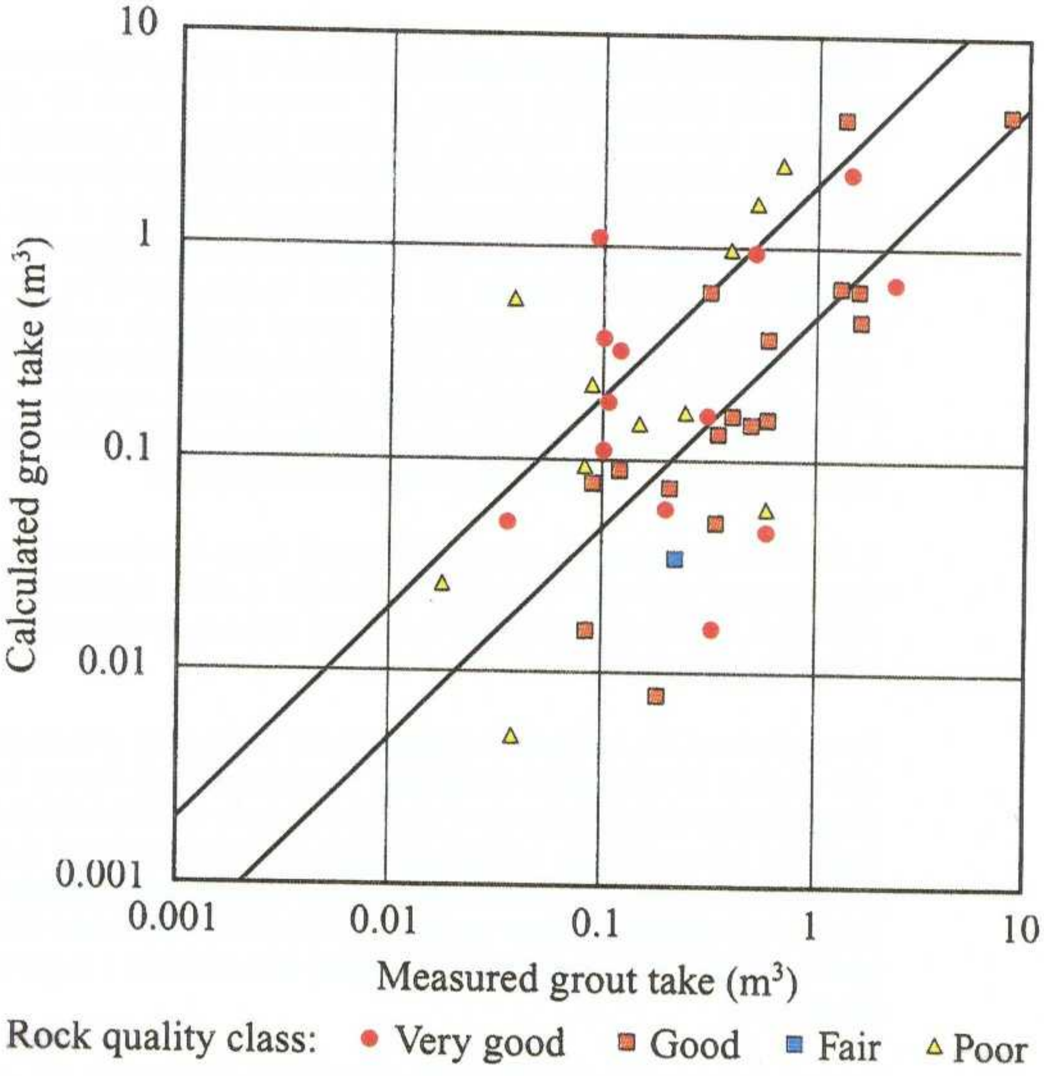


Figure 4-4. Models were developed to describe the spreading of grout. Based on the model the volume of injected grout (grout take) can be estimated if the grout properties, the hydraulic transmissivity of the grout holes and the injection gauge pressure during grouting are known /Gustafson and Stille, 1996/. Comparison between calculated and measured grout take for the Äspö tunnel. (The black diagonal lines indicate the area where the deviation from the 1:1 relationship is less than a factor 2).

Tunnels at great depth with high water pressure are exposed to increased risk of instability and special attention must be devoted to the design of the support in these conditions.

4.6 EVALUATION OF METHODS

In *Almén et al, 1994* feasibility and usefulness of site investigation methods, including models for mechanical stability were presented. Views are expressed on the usefulness of different methods for different subjects and scales.

Standard geological and hydrogeological practises are deemed very useful to assess rock quality. Rock stresses are measured at points by means of overcoring or hydraulic fracturing. The spatial variation of measured stresses is very high due to the presence of different lithologies and discontinuities of differing nature. A detailed description of the spatial variability of rock stresses is in practice impossible, but a high measurement density should increase the confidence in predicted ranges. On the site scale it should be possible to evaluate the general stress direction and general magnitude and range of the stresses. Large variation in results should be expected. Precise prediction of rock stresses on the detailed scale should only be expected very close to a point at which the stress has been measured. Further away, different methods for stress measurement are not likely to show identical results.

A more comprehensive analysis of the rock stress condition at Äspö and measurement methods is needed to provide a clear explanation of the significant difference between the rock stress magnitudes measured from the surface and from the tunnel.

Descriptions of the mechanical characteristics of the rock properties should also account for the spatial variability. The International Society for Rock Mechanics has developed a set of standard methods for measurement and at Äspö the same methods, instruments and staff were employed for testing throughout the project. However, too few data samples were collected during the pre-investigations to allow for a decent statistical analysis and subsequent predictive work should, with hindsight, have accounted for a larger range of parameters.

Fracture surface properties were collected prior to construction, but complete follow-up was not achieved during the construction phase.

4.7 OVERALL EVALUATION CONCERNING MECHANICAL STABILITY

A simplified overview of subjects, predictions and observed outcome are shown in *Table 4-7*. Further details are provided in *Stanfors et al /1997/* and *Rhén et al /1997/*.

The following are the most important conclusions:

- At Äspö experts judged that there would only occur some possible rock burst problems in greenstones. No indications of rock burst were collected and thus the overall expert judgement of the mechanical stability at Äspö proved to be correct. However, relevant data on which to base judgements are normally sparse and scattered due to large natural variability and model and parameter uncertainty. Models for excavation stability were not thoroughly tested due to the limited stress levels at Äspö.

Table 4-7. Overview of subjects, predictions and observed outcomes of relevance for the key issue of mechanical stability. Further details are given in *Stanfors et al /1997/*. The '+' sign represents the most common parameter results.

Subject	**Site scale**		**Block scale**		**Detailed scale**		**Comments**
	Within predicted range	**Outside predicted range**	**Within predicted range**	**Outside predicted range**	**Within predicted range**	**Outside predicted range**	
Rock quality (RMR)	+		+			+	
Primary stress		+		+		+	In order to make precise prediction of the rock stresses on the block and detailed scales further investigations of geological variations and measurement methods are needed .
Rock burst	+						
Mechanical characteristics (laboratory measurements)							
Rock strength					+		Predictions for greenstone and Småland (Ävrö granite) outside the range.
Elastic moduli						+	
Poisson's ratio					+		
Brittleness					+		
Fracture properties (laboratory measurements)							
JRC						+	Only a few measurements were made prior to construction and during the construction phase. Further improvements are required in the recommendations for applying JRC and JCS.
JCS						+	
Spacing						+	
RQD					+		

- The difference between the results from laboratory testing of rock type parameters in the pre-investigation phase and the excavation phase is significant. The outcome for several parameters were wider than the predicted range, thus not fully accounting for the natural variations in the rock. Further, the number of samples was small, thereby providing a low level of confidence for mean and variance values.

- The prediction of rock stress orientation corresponds well to the outcome. The relation between the maximum horizontal stress and the theoretical vertical stress, Ko, was predicted to be in the range of 1.7 while the outcome was 2.9. Average values for individual boreholes vary between 1.7 and 4.0. Single measurements in individual boreholes vary between 1.5 and 4.0.

- The difference between the predicted rock stress levels and the outcome can possibly be explained by geometric factors and geological variations. It is also probable that a large portion of the differences is due to the different methods used to make the measurements. Hydraulic fracturing results in lower maximum horizontal stress levels than the results of measurements made using the overcoring method.

- The prediction of rock quality for the tunnel, using the RMR system, show acceptable correspondence to the observations made in the tunnel. The rock quality is very dependent on the rock type. Fine-grained granite exhibits both larger variations and significantly lower mean RMR values than greenstone, Småland (Ävrö) granite and Äspö diorite.