Technical Report

TR-01-29

Site investigations

Investigation methods and general execution programme

Svensk Kärnbränslehantering AB

January 2001

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Preface

The work of gathering the material on which the siting of the deep repository for spent nuclear fuel is based is proceeding in two main stages: feasibility studies and site investigations. The feasibility study phase is currently being concluded, and in a recent publication entitled "Integrated account of method, site selection and programme prior to the site investigation phase", SKB presented the areas in which they wish to carry out site investigations. The goal of the site investigation phase is to obtain the permits required to site and build the deep repository. The results from the investigations, the design activities and the safety assessments that will be carried out for the investigated sites will constitute supporting material for SKB's permit application.

In a previous report, TR-00-20, SKB presented the main aspects of how investigation and evaluation of these sites will be conducted. The present report complements this report insofar as it provides a more extensive and detailed description of how the investigations of geosphere and biosphere on the sites can be carried out. This description includes specifying what will or can be measured if need be, what methods will be used, and how site-descriptive models will be set up. Both of these reports are generic, i.e. they describe how the activities during the site investigation phase can be carried out without direct adaptation to the sites to be investigated. When the contents and scope of the sub-steps of the various stages have been tailored to the different sites, however, it may be found that certain investigation steps must be added, while others described here are unnecessary and can therefore be omitted. The sequence of the different investigation steps may also need to be modified. What is essential is that the site-specific information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account after completed site investigation.

The work of preparing site-specific execution programmes, which will be adapted to the selected areas' specific conditions and special questions, is now commencing for each of the selected areas. These site-specific programmes, which will mainly deal with the initial investigations, will be presented during 2001, after which the aim is to be able to commence the site investigations at the beginning of 2002.

The present programme report with so-called discipline-specific programmes for site investigations has been prepared by a project group consisting of Roy Stanfors, Leif Stenberg, Ingvar Rhén, Mansueto Morosini, Rolf Christiansson, Anders Fredriksson, Peter Wikberg, Anna Säfvestad, Ann-Chatrin Nilsson, Anders Ström, Peter Andersson, Ulrik Kautsky, Tobias Lindborg, Lennart Ekman, Erik Thurner, Johan Andersson and the undersigned.

Karl-Erik Almén
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Summary

SKB plans to commence site investigations in 2002. A general investigation and evaluation programme has already been presented. The general programme stipulates goals for the site investigation phase and describes the coordination between the main activities investigation, design and safety assessment.

The present report is a broadening of the general programme and describes the execution of the investigations in so-called discipline-specific programmes for the disciplines *geology*, *rock mechanics*, *thermal properties*, *hydrogeology*, *hydrogeochemistry*, *transport properties of the rock* and *surface ecosystems*. It also describes various technical aspects of drilling, which comprises a significant portion of the investigations. The programmes are generic, i.e. not tailored to the specific conditions that will exist on a particular site. Based on this possible programme, site-specific programmes will then be prepared and adapted to the site-specific questions and conditions on the specific candidate area. When the contents and scope of the sub-steps of the various stages have been tailored to the different sites, it may be found that certain investigation steps must be added, while others described here are unnecessary and can therefore be omitted. The sequence of the different investigation steps may also need to be modified. What is essential is that the site-specific information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account after completed site investigation.

What is to be determined?

The general investigation and evaluation programme stipulates what parameters need to be determined to judge whether the requirements and preferences made on the rock are satisfied. Besides these parameters, additional parameters need to be determined in order to describe the surface ecosystems and to obtain a good understanding of the site. Additional information on ground conditions etc is needed to design the repository's surface facilities and to enable tunnels to be constructed outside of the actual repository site. The parameters that will be determined are shown in tables presented in the relevant discipline chapter in the report.

The main product of the investigations is a *site description*. This document presents an integrated description of the site (geosphere and biosphere) and its regional environs with respect to current state and naturally ongoing processes. The description presents all collected data and interpreted parameters that are of importance both for the overall scientific understanding of the site and for the analyses and assessments that are made of *design* and *safety assessment* with respect to the deep repository's layout and construction as well as its long-term performance and radiological safety.

Stages of the investigations

The site investigation phase is so great in scope in terms of time, space and content that it must be subdivided into stages to permit a rational execution of all investigations and analyses.

During the *initial site investigation* stage, each candidate area is investigated in order to:

- provide an initial basis for understanding of the rock and the surface ecosystems on a regional scale,
- provide a basis for choosing a site within the area for continued investigations, and
- with the aid of in-depth investigations in a limited number of boreholes on the site, collect information that makes it possible to determine whether the site is suitable for complete site investigations.

The initial investigations should also determine parameters that require undisturbed conditions and initiate monitoring of parameters where long time series are essential.

Provided that the initial site investigation shows that the site is still favourable, complete investigations are commenced. During the *complete site investigation* stage, the investigations are aimed at:

- completing the geoscientific characterization of the site and its environs so that, if the site is found to be suitable, design and safety assessment can produce the supporting material required for a siting application,
- compiling and presenting all information in site-specific databases and descriptive models of the site's geosphere and biosphere conditions.

The complete site investigation determines the parameters that are of importance for ascertaining whether the investigated site satisfies the fundamental requirements made on the rock and to what extent the site satisfies stipulated preferences.

Stepwise investigations and integration between disciplines

In order for the activities to produce the necessary information of sufficient precision, level of detail and accuracy, and with efficient utilization of resources, a logical and well-structured investigation programme is needed. The integration between disciplines is above all of crucial importance during execution in the field in order to make optimal use of boreholes, time and resources, as well as in devising the site-descriptive model.

For execution of the investigations, the main stages of initial and complete site investigation are therefore broken down into smaller steps. Stepwise execution provides better opportunities for a site-adapted investigation methodology and more effective feedback from evaluation. In general, each new step consists of confirming or rejecting the main results of the preceding step, answering questions that have come up and achieving the goals set for the particular stage. Each step builds further on the description that emerged from the preceding investigation step. In each step, all disciplines interact in the planning of the investigations and the evaluation of results.

Site-descriptive models

The results of completed measurements must be analyzed and interpreted in order to provide a description of the site that can be used for design and safety assessment. Primary investigation data are stored in SKB's database SICADA. The database's primary data mainly represent parameter values for single measurement points or limited measurement objects. Primary data are subjected to both discipline-specific and integrated analysis and interpretation in order to be able to subdivide the site into suitable geometric *units* and to assign discipline-specific properties to these geometric units. In this way a three-dimensional, primarily geoscientific, site-descriptive model (depiction) of rock and ground is built. The site-descriptive model is represented with the aid of both geographic information systems (GIS) and above all SKB's CAD-based computer tool, Rock Visualization System (RVS). RVS is also used as an active instrument in the interpretation of information, especially to be able to judge the relative locations of different deformation zones.

The main purpose in interpreting measurement data is to obtain values for the different parameters in the descriptive model. At the same time, an evaluation of the uncertainties in individual parameter values and an assessment of whether the geometric subdivision is reasonable are made. An important way to handle uncertainties and alternative interpretations is to arrive at alternative geometric subdivisions or alternative values of the models' parameters.

During the site investigation, a detailed descriptive model is devised, a *local model*, for the area within which the repository is expected to be placed, including accesses and the immediate environs. In addition to a description on a local scale, a description is also devised for a much larger area, a *regional model*, in order to provide boundary conditions and to put the local model in a larger context. The site-descriptive model is devised and updated stepwise as the site investigations proceed. New model versions are devised as new information becomes available.

Initial site investigation – choice of priority site within the candidate area

The investigations in the first sub-step of the initial site investigation are based on feasibility study results, initially cover the entire candidate area, and are concluded when a priority site within the candidate area has been chosen. A limited percussion drilling programme of 10–20 percussion boreholes is carried out to answer specific questions, such as e.g. to confirm and preliminarily characterize the regional and local fracture zones that have been identified with the aid of geological and geophysical investigations. The number of percussion boreholes given here is a preliminary estimate, like most other quantities in this general programme. More exact quantities can be given in the site-adapted execution programmes, but cannot be finalized until during actual execution.

In order to ensure undisturbed conditions, the characterization of the surface ecosystems must be commenced early and is therefore concentrated to the initial site investigation, even though follow-up measurements and monitoring are performed during later phases. The geological investigations are focused on creating a regional understanding as regards the extent and character of soil and rock types as well as major fracture zones. The hydrogeological investigations are mainly focused on a preliminary definition of the area that must be included in the regional hydrogeological model and are aimed at providing a general description within the regional area of the hydrogeological properties in the near-surface parts of the rock (regional fracture zones and near-surface rock mass) as well as a general description of the hydraulic boundary conditions and the natural variation of the groundwater level. The hydrogeochemical activities consist above all of investigating near-surface groundwaters, lakes and watercourses, sampling in percussion boreholes after drilling, and start of long-term monitoring of chemical parameters in selected sampling points.

No actual investigation activities are carried out within the disciplines of rock mechanics, thermal properties or transport properties of the rock. Available geological information is, however, evaluated and used for an initial model interpretation and as a basis for planning of continued investigation activities.

Initial investigations of the site

When the site has been selected, the investigations are focused on characterizing conditions at depth. Of primary importance is to identify any conditions at depth that cannot be accepted or are clearly unsuitable for the deep repository. A drilling and investigation programme comprising a few (2 to 3) deep cored boreholes and a few additional percussion boreholes is carried out. The first cored borehole is planned to be a so-called chemistry-prioritized borehole, to be drilled with special requirements on quality and purity. One to two cored boreholes are used for rock stress measurements.

The work within surface ecosystems is narrowed down from the previous regional scale to local data collection in the priority site within the candidate area. Measurement series and monitoring points that have been initiated regionally will continue in order to provide a picture of natural variation and annual cycles. A selection of monitoring points will serve as reference points for the investigations on the site.

The geological investigations focus on fractures and fracture zones. Above all, it is important to investigate whether any major gently-dipping fracture zone occurs at a depth unsuitable for the facility. The investigations in this phase focus on seismic reflection and interpreting the results from the first deep investigation boreholes.

The rock mechanical investigations will be focused on an overall picture of the initial rock stresses and the quality of the rock mass at the planned repository level within the chosen site. Rock stresses are measured in one or more of the cored boreholes. An initial assessment is made of whether there is a risk of serious stability problems at repository level. For the thermal programme, a check is made of possible unsuitable conditions such as high thermal gradient, high initial temperature at repository depth or inhomogeneous thermal properties, based on temperature measurements and rock composition of drill cores.

The initial hydrogeological investigations of the site are mainly aimed at providing a general picture of the water-bearing properties of the rock from the ground surface down to a depth of approximately 1,000 m (size and variability both spatially and in terms of properties). Another purpose is to improve the description of the boundary conditions by continuing and expanding the monitoring programme within the regional area. Different pumping and flow tests are performed in the drilled holes. The limited number of holes that are drilled during this phase do not permit a complete determination of the variation of hydraulic conductivity within the site, but provide some idea of conditions at depth.

The two-fold purpose of the hydrogeochemical characterization in the initial phase is, firstly, to obtain a good idea of the composition of the groundwater by means of a careful survey in a deep chemistry-prioritized cored borehole before the composition has disturbed by other sampling, and secondly to investigate whether the site has suitable hydrogeochemical properties by means of sampling in all boreholes.

The hydrogeochemical work is organized into the following main activities: sampling in all percussion boreholes after drilling, sampling during drilling of cored boreholes, hydrochemical logging in all cored boreholes, complete chemical characterization of at least one deep chemistry-prioritized cored borehole, and start of long-term monitoring of chemical parameters in new selected sampling points. Fracture-filling mineral investigations are initiated during the final phase of the initial site investigation.

The transport properties of the rock are estimated mainly on the basis of the hydrogeological and hydrogeochemical description, combined with generic, non-site-specific information. Furthermore, supplementary measurements of groundwater flow are performed in one of the first deep boreholes. In cases where mineralogy and/or groundwater chemistry differs significantly from the generic database, certain time-consuming laboratory investigations such as through diffusion measurements will be initiated.

Complete site investigations

The main purpose of complete site investigation is to carry out investigations on the site and in its regional environs in order to obtain sufficient background data to be able to finish design and safety assessment and thereby be able to determine the suitability of the site for the deep repository. The borehole programme is carried out in a number of sub-steps of 2 to 4 cored boreholes each. The investigations during these sub-steps will be similar but increasingly focused on the relevant repository depth to obtain detailed knowledge within the areas where design has placed conceivable deposition areas. Additional percussion boreholes will also be drilled.

Within surface ecosystems, the follow-up of seasonal variations started during the initial site investigation continues. Furthermore, the existing data on the area are supplemented with quantitative inventories of terrestrial and aquatic fauna and flora. Long-term monitoring continues.

The geological investigations will be dominated by borehole investigations and investigations of drill cores. Surveys and measurements on the ground surface also occur during the complete site investigation, although to a lesser extent than before and using fewer methods, mainly to supplement previous investigations and answer specific questions from previous investigation steps. The investigations will focus on the following principal properties of the rock: detailed knowledge of the properties and distribution of different rock types, greater knowledge of regional and local fracture zones crucial for the overall layout of the deep repository, and greater knowledge of the frequency and properties of minor fracture zones and fractures.

A rock mechanical survey (rock stress measurements, analyses of drill cores etc) of the rock mass in the central investigation area on the site is carried out in order to provide evidence for proving the feasibility of building the proposed deep repository. A thermal characterization of the rock mass within and around the repository is carried out. The descriptive thermal model is based on the lithological model that is devised within the geological programme.

The work within the hydrogeological programme is focused on describing the hydraulic conductivity of the rock based on the large number of different hydraulic tests that will be done in the boreholes. To obtain data for the boundary conditions within the regional area, the monitoring programme is continued and extended to include hydrological measurement stations (meteorology, runoff) and groundwater level measurements.

Within the hydrogeochemistry programme, further investigations of deep groundwaters in particular are conducted. Here it is essential to supplement, verify and increase the quantity of data in order to obtain as complete a picture of the groundwater situation as possible and to obtain a good basis for evaluations and modelling.

In order to determine the transport properties of the rock, laboratory measurements are performed on drill cores and rock material in order to determine sorption values and diffusivities. Certain in-situ tests and tracer tests are also planned. The description of the transport properties of the rock is based on a weighing-together of generic data, results from the various tests, and the hydrogeological and hydrogeochemical description of the rock.

Characterization methods

An integrated geological characterization of an area entails geometrically representing the topography, deformation zones, lithological boundaries, rock units and soil strata of the investigated area and describing them in an integrated model. A large number of methods are used to investigate the geology of the site. They can be described in general terms under the headings: geophysics, surface geology, soil geology, bedrock geology, borehole investigations and geodetic measurements.

Within the rock mechanical programme, the initial rock stresses are determined partly by means of direct measurement methods and partly by means of various downhole indications and with the guidance of a geological-structural model. The mechanical properties of the intact rock and the fractures are measured for the most part on recovered rock cores. The deformation properties and strength of the rock mass are estimated on the basis of the properties of the intact rock and the frequency, orientation and mechanical properties of the fractures.

The thermal properties of the rock (thermal conductivity and heat capacity) are determined primarily on the basis of mineral composition and by means of laboratory studies of recovered rock cores.

The hydrogeological characterization includes meteorological and hydrological investigations, hydraulic borehole investigations and monitoring. The emphasis lies on hydraulic borehole investigations such as pumping tests and flow logs. With these the hydraulic conductivity of the soil strata and the rock can be measured along the boreholes and between nearby boreholes (interference test).

The hydrogeochemical characterization includes investigations of surface waters and near-surface groundwaters, borehole investigations, long-term measurement/monitoring, and water and fracture-filling mineral analyses. Borehole investigations include investigations in percussion boreholes and in cored boreholes with regard to groundwater and fracture-filling minerals.

The determination of the transport properties of the rock is based on generic, non-site-specific data, combined with the hydrogeological and hydrogeochemical description of the rock. Laboratory measurements on drill cores and rock material are used to determine/verify sorption values and diffusivities. Diffusion tests and tracer tests in and between boreholes can be used to verify the reasonableness of estimated parameter values.

The discipline *surface ecosystems* includes both the living (biotic) environment, i.e. animals and plants, and their interactions with the non-living (abiotic) environment, e.g. climate and water. The characterization includes both hydrogeological and hydrogeochemical characterization of soil strata and surface waters and inventory/characterization of flora and fauna.

Content

1 Introduction

A site investigation is an important step in the process of siting a deep repository for spent nuclear fuel. SKB wants to conduct thorough investigations in three municipalities and arrive at detailed proposals of how a deep repository can be built and operated /SKB, 2000a/. SKB's goal is to commence site investigations in 2002. Extensive preparations are under way for this transition to the next phase in the siting process for the deep repository.

1.1 Background and purpose

One of the main tasks is to formulate a comprehensive and clear site investigation programme. By "site investigation programme" is meant here a chiefly geoscientific programme for investigation and evaluation of sites. The programme stipulates both what type of information is to be collected from a site and how it is to be used in evaluating the suitability of the site for the deep repository. The general investigation and evaluation programme has already been presented /SKB, 2000b/.

This report is a broadening of the general programme and describes investigation programmes and methods more exhaustively in so-called discipline-specific programmes. Both the general programme and this report are generic, i.e. not tailored to the specific conditions that will exist on a particular site.

The discipline-specific programmes constitute a basis for site-specific execution programmes. When the contents and scope of the sub-steps of the various stages have been tailored to the different sites, it may be found that certain investigation steps must be added, while others described here are unnecessary and can therefore be omitted. The sequence of the different investigation steps may also need to be modified. What is essential is that the site-specific information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account after completed site investigation.

An overview of the different programmes is shown in Figure 1-1. In addition to programme writing, work is also being pursued on development, testing and documentation of investigation methods, measuring instruments and analysis methods, along with preparation of an organization plan and quality procedures.

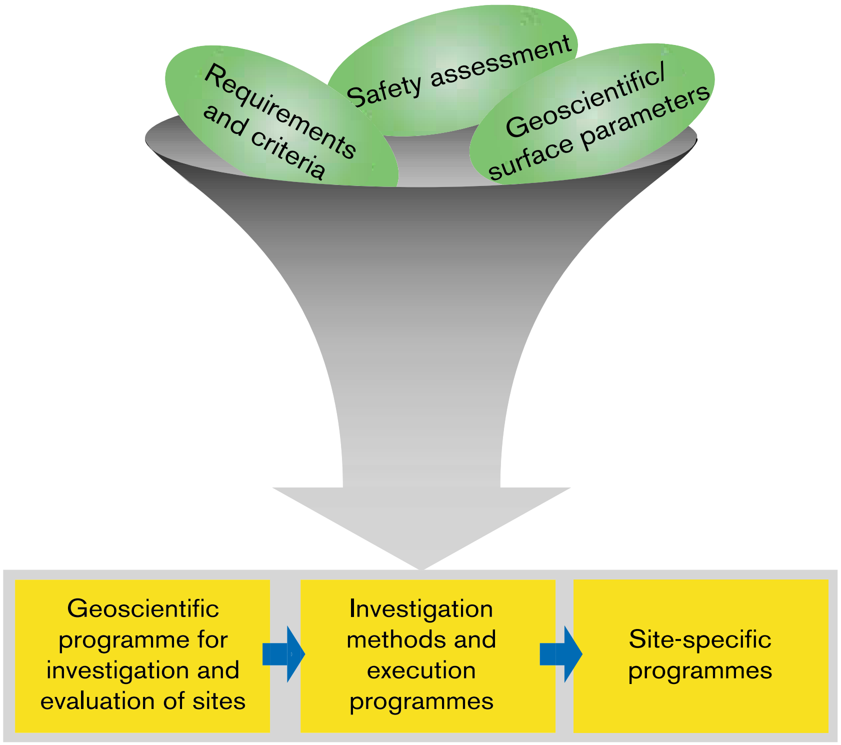


Figure 1-1. *Programme writing in steps leading up to the site investigations. Overview of important documents underlying the programme writing work. Investigation methods and execution programmes are presented in this report.*

1.2 Key issues

Preparation of the investigation programme is based on a number of key issues that need to be dealt with. The most important are to:

- design the programme so that the information needed on the site is actually collected,
- be able to describe the properties of the site in space and be able to judge the uncertainty in the description based on measurement results from the ground surface and from a limited number of boreholes,
- make sure that different disciplines are coordinated and build up a consistent description of geosphere and biosphere,
- identify whether there are measurements that must be carried out in a certain sequence, since certain measurement methods have a short-term impact on the site,
- make sure that the programme is of reasonable scope and focuses on the different information needs at different points in the decision-making process.

The overall handling of these issues is described in Chapter 2. The methodology reported there is then used consistently for the various disciplines included in the programme.

The need for geoscientific information is evident from the so-called parameter report /Andersson et al, 1996/. The need for information for surface ecosystems is described in /Lindborg and Kautsky, 2000/. The parameter report is largely based on experience from previous safety assessments of the KBS-3 method. The lists of geoscientific parameters are kept updated with any new knowledge that emerges. Besides the parameter report, the report on requirements and criteria /Andersson et al, 2000/ and the general programme /SKB, 2000b/ also constitute important reference documents for writing the programmes.

The parameter report presents and explains what is to be determined during a site investigation, the requirements and criteria report describes the geoscientific grounds on which it is possible to assess the suitability of a site, while the programmes for the site investigations present a strategy for execution and how it is to be carried out. Finally, the investigation methods comprise the toolbox.

1.3 Method development

The report describes investigation methods available today. Some method development will take place (see section 4.4 in /SKB, 2000b/). The methods available today are, however, judged to be fully adequate for characterizing investigated sites.

1.4 This report

Chapter 2 gives an account of the investigation programme's goals and strategy. Chapter 3, execution programme, provides an integrated account of what measurements, analyses and interpretations will be made during different phases of the stepwise execution of the site investigations. Chapters 4–10 describe, discipline by discipline, what is to be determined, how the rock and the site are described in a preferably geoscientific site-descriptive model, and what characterization methods may be used. Chapter 11 summarizes various practical aspects of drilling.

2 Programme overview

2.1 Goals and stages

Goals, stages and principal actors for the geoscientific work during the site investigation phase are described in the general investigation and evaluation programme /SKB, 2000b/. The present programme is based on these goals. The investigation programme has a discipline-specific structure for the disciplines *geology*, *rock mechanics*, *thermal properties*, *hydrogeology*, *hydrogeochemistry*, *transport properties of the rock* and *surface ecosystems*.

Figure 2-1 shows the activities planned by SKB during the site investigation phase. It is the principal technical activities *investigations*, *design* and *safety assessment* that carry out the investigations, evaluate the information and assemble the needed technical supporting documents in the form of site description, facility description and safety report.

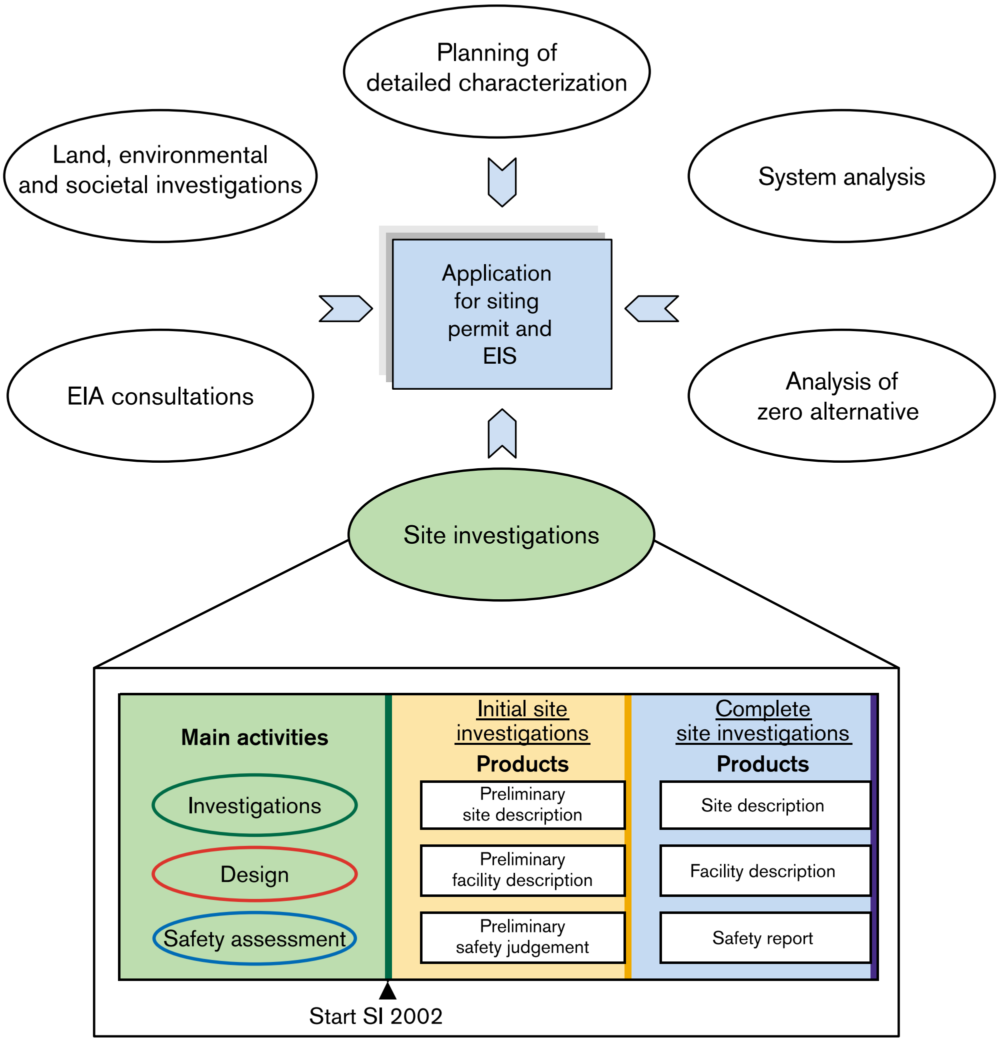


Figure 2-1. *Illustration of the activities and products which SKB expects during the site investigation phase (SI). The products are a part of the supporting documentation to be submitted together with the application for a siting permit for the deep repository. Activities are shown in the figure as ovals, while products are shown as rectangles.*

It should particularly be noted that the EIA (environmental impact assessment) consultations that take place to arrive at an EIS (environmental impact statement) comprise a separate activity and are not described in this report. The principal technical activities will, however, produce much of the essential documentation that will be needed in the EIS.

2.1.1 Goal of the site investigation phase

The goal of the site investigation phase is to obtain the permits that are required to site and build the deep repository. The geoscientific work during the site investigation phase is supposed to provide the broad knowledge base that is required to evaluate the suitability of investigated sites for a deep repository. The material must be comprehensive enough to

- show whether the selected site satisfies fundamental safety requirements and whether civil engineering prerequisites are met,
- permit comparisons with other investigated sites, and
- serve as a basis for adaptation of the deep repository to the properties and characteristics of the site with an acceptable impact on society and the environment.

The work is being carried out in consultation with municipalities, regulatory authorities and nearby residents.

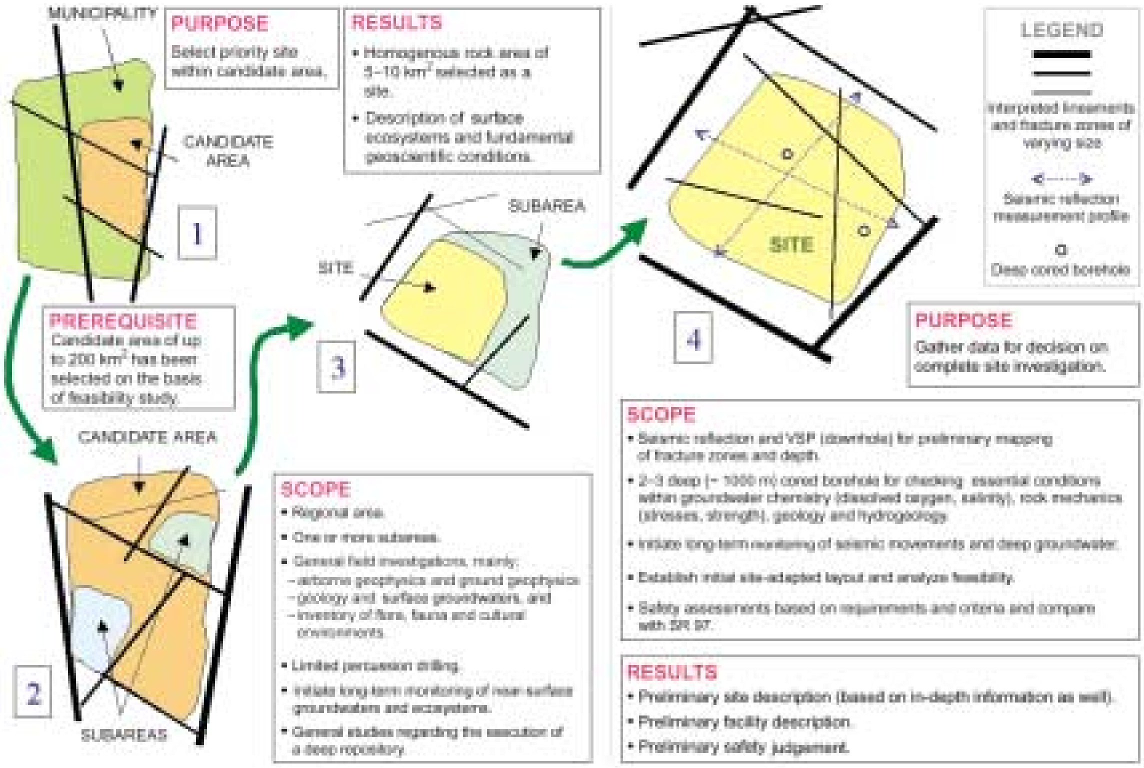
When investigations and other studies have been completed and the results analyzed, SKB will decide whether the necessary conditions have been fulfilled for submitting an application for a permit for siting of the deep repository on one of the sites. If so, the application will be submitted along with the environmental impact statements that have been prepared in consultation with all concerned parties. Permit and permissibility review will then take place under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act. If a permit is obtained, the detailed characterization phase will commence.

2.1.2 Stages

The site investigation phase is so great in scope in terms of time, space and content that it must be subdivided into stages to permit a rational execution of all investigations and analyses. Dividing the work into stages also better enables the investigation methods to be adapted to conditions on the site and permits more effective feedback from the evaluation. The site investigation is therefore divided into the stages *initial* and *complete* (more detailed) site investigation.

The main purpose of the initial stage is:

- to identify and select the site within a specified candidate area that is deemed to be most suitable for a deep repository and thereby also the part to which further investigations will be concentrated, and
- to determine, with limited efforts, whether the feasibility study's judgement of the suitability of the candidate area holds up in the light of in-depth data.



PURPOSE
Select priority site within candidate area.

RESULTS
- Homogenous rock area of 5–10 km² selected as a site.
- Description of surface ecosystems and fundamental geoscientific conditions.

PREREQUISITE
Candidate area of up to 200 km² has been selected on the basis of feasibility study.

SCOPE
- Regional area.
- One or more subareas.
- General field investigations, mainly:
  - airborne geophysics and ground geophysics
  - geology and surface groundwaters, and
  - inventory of flora, fauna and cultural environments.
- Limited percussion drilling.
- Initiate long-term monitoring of near-surface groundwaters and ecosystems.
- General studies regarding the execution of a deep repository.

PURPOSE
Gather data for decision on complete site investigation.

SCOPE
- Seismic reflection and VSP (downhole) for preliminary mapping of fracture zones and depth.
- 2–3 deep (~ 1000 m) cored borehole for checking essential conditions within groundwater chemistry (dissolved oxygen, salinity), rock mechanics (stresses, strength), geology and hydrogeology.
- Initiate long-term monitoring of seismic movements and deep groundwater.
- Establish initial site-adapted layout and analyze feasibility.
- Safety assessments based on requirements and criteria and compare with SR 97.

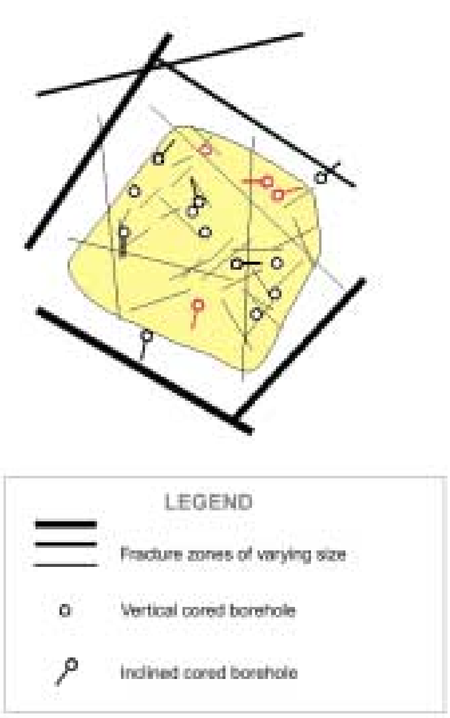
RESULTS
- Preliminary site description (based on in-depth information as well).
- Preliminary facility description.
- Preliminary safety judgement.

Figure 2-2. *Conceivable scope of, and activities during, an initial site investigation.*

By "site" is meant a prioritized part of a candidate area, i.e. the area required to accommodate a deep repository with good margin and its immediate environs, roughly 5–10 square kilometres. Figure 2-2 shows its conceivable scope.

If the overall assessment shows that the prospects for siting a deep repository on the investigated sites are still good, complete site investigations follow on these sites, see Figure 2-3. The purpose of the complete site investigations is to gather the material that is required to select a site and apply for a permit for siting of the deep repository. This means that knowledge of the rock and its properties needs to be increased so that:

- a scientific understanding of the site can be obtained as regards current conditions (states) and naturally ongoing processes,
- a site-adapted repository layout can be arrived at,
- an analysis of the feasibility and consequences of the construction project can be done, and
- a safety assessment can be carried out to determine whether long-term safety can be ensured on the site.



PURPOSE

Gather the necessary supporting data for selection of site and application for siting permit.

SCOPE

- Supplementary geological and geophysical ground surveys on the site and in the regional environs.
- Drilling programme (percussion and cored drilling) with measurements including:
  - – measurement and sampling during drilling,
  - – core mapping, BIP (Borehole Image Processing), geophysical measurements,
  - – flow logging, injection tests, pumping tests, cross-hole tests,
  - – dilution tests, groundwater sampling/analysis,
  - – in-situ rock stress measurements and laboratory analyses of rock samples.
- Continued long-term monitoring.
- Activities governed by site-specific conditions and arising questions (cf. red symbols in figure at left, i.e. ○ ⚲).
- Site-specific databases with quality-assured primary information.
- Site models on regional and local scale.
- Site-adapted deep repository facility and analysis of feasibility.
- Complete safety assessment carried out.
- Background information for EIA consultations and EIS document.

RESULTS

- Site description.
- Facility description.
- Safety report.

Figure 2-3. *Conceivable scope of, and activities during, a complete site investigation.*

2.1.3 Goals and products of the investigations

The activity of conducting field investigations and evaluating data is called *investigations*. When the site investigations are finished on a site, the activity *investigations* shall have:

- presented the necessary data on the site for a site-adapted layout of the deep repository and assessment of the deep repository's long-term radiological safety to be carried out,
- achieved fundamental geoscientific understanding, i.e. have analyzed the reliability and assessed the reasonableness of the assumptions made with respect to the current states of the site and naturally ongoing processes,
- identified objects that may require special environmental considerations during construction and operation of the deep repository.

Based on these general goals, it is decided what is to be investigated and how extensive the investigations are to be. To achieve the goal in the first point, it is necessary to determine the properties within the repository volume that are of importance for safety and rock construction, and especially the structures in the rock that are decisive for repository layout. Determination must furthermore be used to decide whether the favourable rock volume is large enough to accommodate a repository. However, the final design of the investigation programme must be adapted to the relevant (actual) sites.

The main product of the investigations is a *site description*. This document presents an integrated description of the site (geosphere and biosphere) and its regional environs with respect to current state and naturally ongoing processes. The description presents all collected data and interpreted parameters that are of importance both for the overall scientific understanding of the site and for the analyses and assessments that are made of *design* and *safety assessment* with respect to the deep repository's layout and construction as well as its long-term performance and radiological safety.

The investigations result in primary data (measurement values and directly calculated values) that are collected in a *database*. In order for the collected (measured) information to be used for design and safety assessment, and to enable the reliability of the information to be judged, it must be interpreted and presented in a (mainly geoscientific) *site-descriptive model*, Figure 2-4. The site-descriptive model consists of a description of the geometry and different properties of the site and comprises, together with databases, the backbone of the site description. After the initial site investigation, a *preliminary site description* is presented.

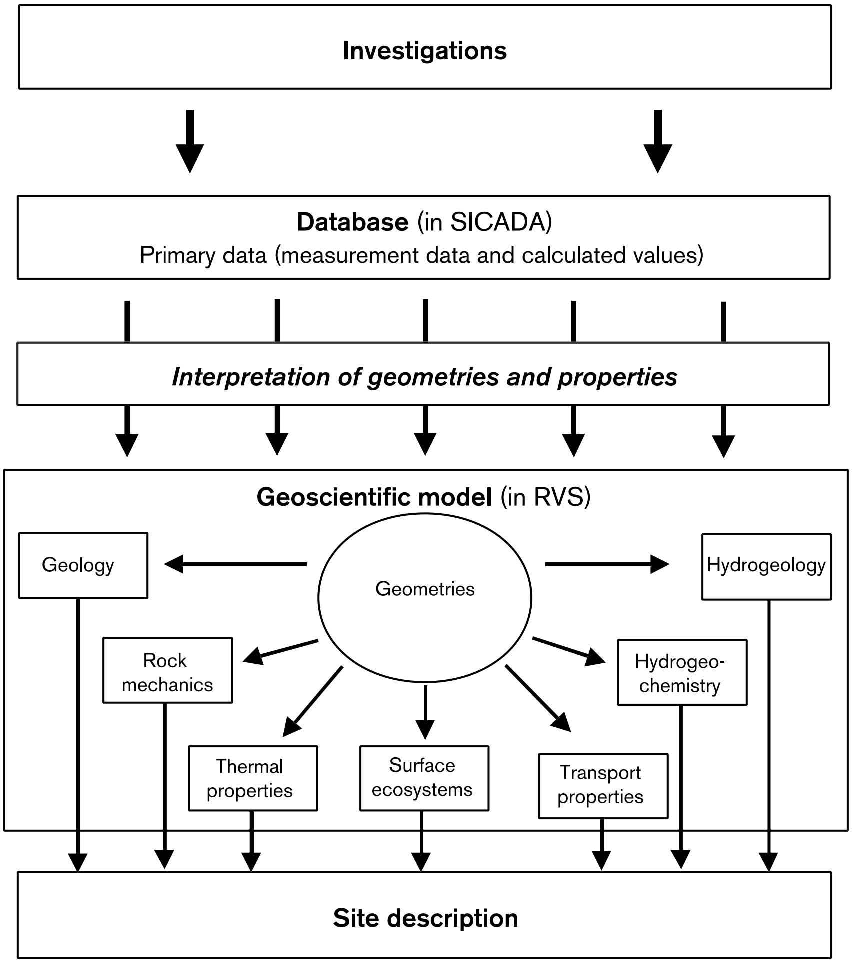


Figure 2-4. *The primary data from the investigations are collected in a database. Data are interpreted and presented in a site-descriptive model, which consists of a description of the geometry and different properties of the site.*

2.1.4 Related activities

The activities *safety assessment* and *design* are the primary beneficiaries of the resultant site descriptions. *Design* uses the site description to prepare a site-specific facility description with facility layout and assesses the prerequisites for and consequences of the civil engineering work. The *safety assessment* evaluates safety on the basis of specified site models and repository layout. Results of early analyses from design and safety assessment may also be used to guide the thrust of the continued investigation activities.

Design

By *design* is meant all the work of developing a facility description for a proposed siting, including layout above and below ground, plus definitions of constituent systems. When the site investigations are finished, the activity *design* shall have:

- presented one site-adapted deep repository facility among several analyzed and proven its feasibility,
- identified facility-specific technical risks, and
- developed detailed design premises for the detailed characterization phase.

The main product of design is a *facility description*, which presents layout proposals with associated construction analyses based on data reported from investigations. It also presents various premises for the different rock works to be carried out, such as requirements on rock reinforcement. A technical risk evaluation is carried out, by which is meant a description of uncertainties in calculations and the environmental impact of the civil engineering work. The facility description includes the choice of technology and repository layout, plus an establishment description.

The facility description, including plan for tunnel works during the detailed characterization, comprises one of the prerequisites for the preparation of draft documents for the rock and construction works. The description also comprises a basis for the preparation of programmes for layout-governing systems in the underground facility such as ventilation, rock drainage and electricity supply. The results of the site investigations are used in the design process to propose locations for the various facility sections, whereby the site-adapted layout of the deep repository is obtained.

The facility description is developed stepwise. When the initial site investigations have been completed, a *preliminary facility description* will be presented. Alternative layout sketches may be required to handle uncertainty in early versions of the site-descriptive model. After one or two sub-steps of the complete site investigation, a main layout is prepared for the repository and is later modified in subsequent steps to be finally included in the finished facility description. In each step, various analyses are performed whose results are used as a basis for the detailed control of the continued site investigation programme, as a basis for the safety assessment work and for the continued design work.

Safety assessment

By *safety assessment* is meant the analysis that is required for evaluation of the long-term safety of the proposed facility design on the site in question. When the site investigations are completed, the activity *safety assessment* shall have:

- evaluated the long-term radiological safety of the planned deep repository based on reported investigation results and prepared repository layout.

The methodology and results from the safety assessment SR 97 /SKB, 1999a/ form an important foundation for the work with safety assessments during the site investigations. The safety assessment can be said to consist of:

- a thorough description of the appearance or state of the repository system at an initial point in time, e.g. just after construction and closure,
- a survey of what changes the repository can be expected to undergo with time as a consequence of both internal processes and external forces, and
- an evaluation of the consequences of the changes for long-term safety.

The main product of the safety assessment is a *safety report*. The safety report presents analyses and assessments of whether long-term safety is ensured for the planned deep repository based on reported investigation results and the proposed repository layout. The safety assessment includes analyses of technical, hydraulic, mechanical and chemical processes around a deep repository as well as calculations of radionuclide transport.

Major safety reports are delivered on at least two occasions in the site investigation programme: once in the form of a *preliminary safety judgement* based on data from the initial site investigation, and once in the form of a *safety assessment* based on data from the complete site investigation. Furthermore, the preliminary judgements and analyses done within the framework of the safety assessment work are used in the planning of the continued investigations and the site-descriptive modelling. Safety-related aspects of layout proposals or more detailed questions regarding the geometric configuration of the repository are analyzed and assessed, providing background material for the continued design work.

2.1.5 Interaction between main activities

The integration between the main activities investigation, design and safety assessment is described in detail in /SKB, 2000a/ and will not be further described in this report. When investigations have gathered and interpreted new data for revised site-descriptive models, first the layout can be modified and then the safety assessment can be revised in the light of the new models with associated layout. In the design and safety assessment work, requests arise for new data or data with greater precision. Judgements made during the safety assessment work may further entail that the layout should be revised. The interdependence between the different principal activities requires coordination to ensure that the safety assessment and layout are based on consistent versions of site-descriptive models, unnecessary overlap of modelling work is avoided, questions or judgements that are made within one principal activity are actually answered or applied in the other activities, and the work is terminated when the goals of the various principal activities have been attained.

2.2 Focus of the investigations during different stages

The investigations are supposed to provide the information that is needed so that design and safety assessment can judge the suitability of the site and, if it is found suitable, whatever other material is needed for a siting application, see Figure 2-1. The overall goals of the investigations presented in section 2.1 are general and do not suffice to control the detailed course of the investigations during their stepwise execution.

2.2.1 Control of the investigation work

The investigation programme is divided into different disciplines. But the disciplines do not have any overall goals of their own. Within each discipline, the activities are controlled by the common aims of the investigations. The detailed control of each discipline is obtained by specifying the discipline's principal tasks and activities based on the common aims.

The progressive execution of the investigations involves to a great extent increasing the degree of detail and reducing the uncertainty in the site-descriptive models. It is important to be able to determine what degree of detail is necessary and what amount of uncertainty is acceptable in the data. This is done by stepwise cross-checking (see section 2.3.1) against the intentions of the programme, reliability assessments of the integrated model descriptions, and the needs of the beneficiaries.

The strategy is thus to jointly define for all the investigations precise aims for each investigation step and the principal tasks for each discipline that are related to these aims. On the other hand, the scope of the investigations cannot be defined in this programme, since both the site-specific conditions and the concrete needs of the beneficiaries must be allowed to control details in the execution of the programme.

2.2.2 What is to be determined?

SKB has conducted several studies – mainly the "Parameter report" /Andersson et al, 1996/ and the report on requirements and criteria /Andersson et al, 2000/ – to ascertain what site-specific information is needed to carry out safety assessment and design during the site investigation phase. The choice of parameters that need to be determined is based on SKB's long experience from rock investigations, including the Äspö Hard Rock Laboratory (HRL), and from various performance and safety assessments that have been conducted. The data need has in particular been cross-checked against experience and conclusions from SKB's most recent safety assessment, SR 97 /SKB, 1999a/. The need for information on surface ecosystems is described in /Lindborg and Kautsky, 2000/.

The general investigation and evaluation programme /section 4.1.1 in SKB, 2000b/ stipulates what parameters need to be determined to judge whether the requirements and preferences made on the rock are satisfied and to describe the surface ecosystems and otherwise achieve a good understanding of the site. Additional information on ground conditions etc is needed to design the repository's surface facilities and to enable tunnels to be constructed outside of the actual repository site. The parameters that will be determined are shown in tables presented in the relevant discipline chapter further on in this report.

The report on requirements and criteria /Andersson et al, 2000, section 10.1.3/ also stipulates criteria for conditions that can warrant discontinuation of a site investigation. The site is accepted only if the safety assessment is able to show that a safe repository can be built. During a site investigation, when measurement values have been obtained from repository depth but before the overall assessment has been carried out, criteria are used to check whether requirements and preferences may be satisfied. The criteria provide guidance on the outcome of the assessments and can therefore also be used to review a safety assessment.

2.2.3 Initial site investigation

During the initial site investigation stage, each candidate area is investigated in order to:

- provide an initial basis for understanding of the rock and the surface ecosystems on a regional scale,
- provide a basis for choosing a site within the area for continued investigations, and
- with the aid of in-depth investigations in a limited number of boreholes on the site, collect information that makes it possible to determine whether the site is suitable for complete site investigations.

The initial investigations should also determine parameters that require undisturbed conditions and initiate monitoring of parameters where long time series are essential.

The point of departure for the initial site investigations will vary a great deal, for example as regards the size of, and level of knowledge concerning, the designated candidate areas. The initial investigation programme for investigations will thereby differ between different candidate areas. At a size of up around a couple of hundred square kilometres, or where the level of geoscientific knowledge is low, it may for example be suitable to carry out the geographic area restriction by identifying and studying several potential sites or subareas.

In order to provide a basis for choosing a priority site within a given candidate area, the following must above all be determined during the initial site investigation:

- conditions that may suggest geological homogeneity and a suitable rock type,
- an initial judgement of the size of extensive deformation zones1), i.e. regional and local major fracture zones and extensive plastic shear zones,
- an absence of indications of unfavourable hydrogeochemical and hydrological conditions.

The initial site investigation includes various surface-covering investigations, a number of percussion boreholes and a few (2 to 3) deep cored boreholes. The preliminary site description, see Figure 2-3, which is to be produced from these results in turn comprises a basis for preliminary facility description and preliminary safety judgement. On the basis of these products, an overall assessment is made of whether the selected site is suitable for complete investigations.

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1) SKB uses the term "deformation zone" as a collective name for plastic shear zones and (brittle) fracture zones, see e.g. /Andersson et al, 2000/.

2.2.4 Complete site investigation

Provided that the initial site investigation shows that the site is still favourable, complete site investigations are commenced. During the complete site investigation stage, the investigations are aimed at:

- completing the geoscientific characterization of the site and its environs so that, if the site is found to be suitable, design and safety assessment can produce the supporting material required for a siting application,
- compiling and presenting all information in site-specific databases and descriptive models of the site's geosphere and biosphere conditions.

The complete site investigation determines the parameters that are of importance for ascertaining whether the investigated site satisfies the fundamental requirements made on the rock and to what extent the site satisfies stipulated preferences. The investigations are based on and supplement the knowledge of the site obtained during the initial investigation.

Main aspects regarding the structure of the investigation programme, especially execution of the drilling, during the complete site investigation are:

- The site shall be well-defined geographically and the site-descriptive models shall cover the entire volume (local model). Similarly, the depth boundary of the investigation area shall be well-defined.
- The regional model area should be geographically well-defined.
- Borehole positions and directions are chosen in order to locate and characterize individual fracture zones and to characterize different rock units. Different borehole directions and inclinations shall hereby be used to achieve statistical representativeness for parameters that may be directionally dependent (i.e. anisotropic), such as fracture frequency and hydraulic conductivity.
- The investigation boreholes are planned and executed to minimize disturbance of other ongoing investigations, in particular hydrochemical samplings and hydraulic tests. A couple of holes can be drilled simultaneously in order to provide drilling-free lulls for investigations.
- It is essential that measurement data be recorded, samples taken and tests performed during drilling. The drilling programme shall therefore contain an investigation part that satisfies the various disciplines' data needs.
- Which investigations will be conducted in finished boreholes depends on the main purpose of the borehole in question. Depending on the spatial variation of different parameters, the representativeness of individual measurement values, the desired degree of detail, data security etc, the scope of measurement will vary for different parameters. The needs of the beneficiaries (for geoscientific understanding, design and safety assessment) are coordinated to produce specific measurement programmes for each individual borehole.
- In order to obtain a uniform body of basic knowledge for all boreholes, a base programme will be carried out in all boreholes (although different for percussion and cored boreholes).
- Certain boreholes are prioritized for certain disciplines, but will of course also be used for other purposes.

- Previously initiated monitoring programmes on the ground surface and in boreholes continue and are supplemented with new measurement points so that uninterrupted measurement series are obtained with suitable point density and measurement frequency.
- Previous documentation of surface ecosystems is supplemented with detailed studies to achieve an adequate description of conditions. The execution of the site investigations can thereby also be adapted to protect valuable landscape elements and biological diversity.

The scope of the investigations can only be determined site-specifically and in consultation with the primary beneficiaries: design and safety assessment. SKB estimates that the complete site investigation should comprise between 10 and 20 cored boreholes on each site, plus at least as many percussion boreholes. A rational execution of drilling and investigation require drilling and investigating a limited number of boreholes (2–4) in each campaign. The different investigation campaigns do not differ much from each other. New boreholes are drilled where the previous investigations show more information is needed.

2.3 Methodology

Investigation programme and methods are presented discipline-specifically for the disciplines *geology*, *rock mechanics*, *thermal properties*, *hydrogeology*, *hydrogeochemistry*, *transport properties* and *surface ecosystems*. In order for the activities to produce the necessary information of sufficient precision, level of detail and accuracy, and with efficient utilization of resources, a logical and well-structured investigation programme is needed:

- The investigations and the analyses of measurement data are performed in appropriate steps.
- Measurement data are analyzed and interpreted in order to arrive at a site-descriptive model on various scales.
- The scope and thrust of the investigations are determined by the needs and goals of the beneficiaries (mainly design and safety assessment).
- Integration between the different disciplines is necessary.
- Interaction with beneficiaries is a prerequisite.

The integration between disciplines is above all of crucial importance during execution in the field in order to make optimal use of boreholes, time and resources, as well as in devising the site-descriptive model (see below). The methodology that comprises the backbone of the programme is discussed in the following section.

2.3.1 Stepwise planning, execution and interpretation

The site investigations are divided into the two main stages *initial site investigations* and *complete site investigations*. The overall purpose of these two stages is described in section 2.1.2. The main thrust of these stages is presented in sections 2.2.3 and 2.2.4. For execution of the investigations, these main stages are broken down into smaller steps.

This subdivision into steps provides better opportunities for a site-adapted investigation methodology and more efficient feedback from evaluation. Generally speaking, each new step entails confirming or rejecting the main results of the preceding step, answering questions that have come up and achieving the goals set for the particular stage. Each step builds further on the description that emerged from the preceding investigation step. In each step, all disciplines interact in the planning of the investigations and the evaluation of results. The steps are divided into a number of operations (see also Figure 2-5):

- Planning of investigations.
- Investigations and data acquisition.
- Preparation of database with primary data.

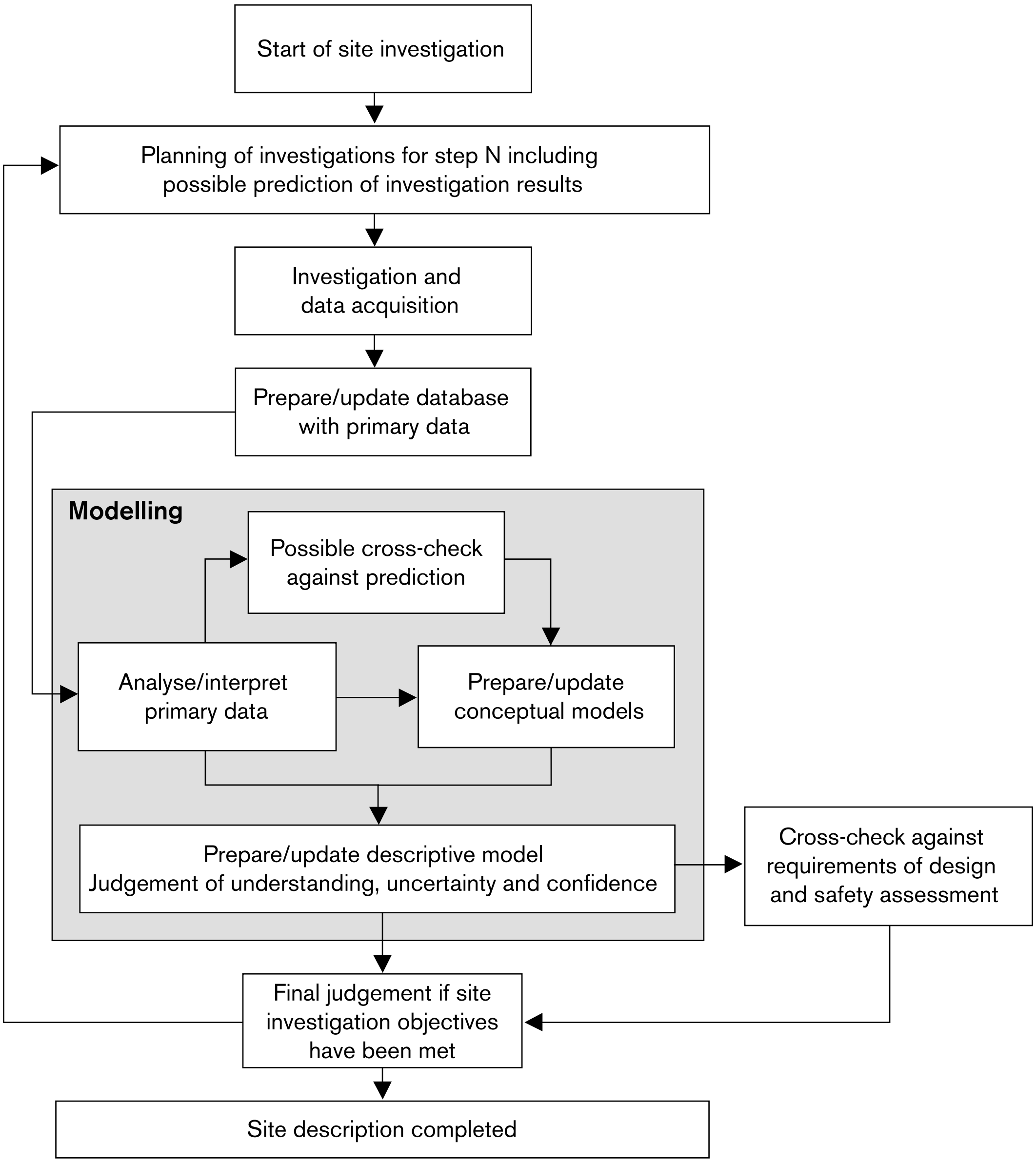

Figure 2-5. *The site investigation phase consists of several steps with planning, investigations, interpretation and cross-checking. The implications of the terms "conceptual model" and "descriptive model" are explained in section 2.3.2.*

- Where applicable: Verification of whether outcome of investigation step agrees with prediction made in advance.
- Formulation/updating of conceptual models (see 2.3.2).
- Interpretation of primary data and determination/updating of parameters in the site-descriptive model (see 2.3.2).
- Cross-check against safety assessment and design, and in certain steps submission of up-to-date model versions, and discussion of whether further knowledge is required.
- Predictions or judgements of what can be expected in the next investigation step are used as a basis for planning and for testing understanding.

Planning of the investigations is done in consultation between the disciplines in order to coordinate certain joint investigations and to minimize the risks for disturbance-sensitive investigations. Investigations, interpretations and analyses are then carried out discipline-by-discipline in most cases, but require integration with other disciplines.

Subdivision into stages and iterative investigation methodology have been applied by SKB in previous study site investigations and during the pre-investigation phase for the Äspö HRL, see e.g. /Rhén et al, 1997a/.

The primarily geoscientific site-descriptive model is devised and updated stepwise as the site investigations progress, Table 2-1. New model versions are devised as new information becomes available. Model versions produced during the initial site investigation are

Table 2-1. Different versions of the site-descriptive models that are produced during the site investigation.

Phase	Basis	Covers	Product/model
Prior to site investigation	Feasibility studies. Processing of existing data. Field checks.	Part of municipality and candidate area where site will be chosen.	General model, above all on regional scale (version 0).
Initial site investigation	General surveys from air, surface and short boreholes.	Candidate area and site (regional and local scale).	Choice of priority site within candidate area. Generall model (version 1.1).
	Investigations from surface and some deep boreholes.	Site (regional environs).	Preliminary model on local and regional scale (version 1.2). Preliminary site description.
Complete site investigation	Investigations in many deep boreholes and supplementary ground surveys.	Site. Regional environs.	Model on regional and local scale (version 2.1).
	More deep boreholes and supplementary ground surveys.	Site. Regional environs.	Revised model on regional and local scale (version 2.2).
	More supplementary surveys.	Site. Regional environs.	Finished model on regional and local scale (version 2.X). Site description.

called preliminary 1.1 and 1.2 in this report [2]. Model versions 2.1, 2.2 etc are thus produced during the complete site investigation. Note, however, that the number of model versions may be modified. Both fewer and more versions may be produced, depending on local conditions and how easy it is to interpret the studied site. This in turn influences the interaction with other actors. In order to handle uncertainties in data interpretation, particularly in the initial phases, alternative interpretations are also developed.

2.3.2 Site-descriptive models

The results of completed measurements must be analyzed and interpreted in order to provide a description of the site that can be used for design and safety assessment. Primary investigation data are stored in site-specific databases in SICADA. The database's primary data mainly represent parameter values for single measurement points or limited measurement objects.

Primary data are subjected to both discipline-specific and integrated analysis and interpretation in order to be able to subdivide the site into suitable geometric *units* and to assign discipline-specific properties to these geometric units. In this way a three-dimensional, primarily geoscientific, site-descriptive model (depiction) of rock and ground is built. The relationship between investigation database and site-descriptive model is illustrated in Figure 2-4.

The purpose of dividing the site-descriptive model into different geometric units is to be able to describe spatial variation in a manageable way. The geometric units are chosen so that the spatial variation is limited, or can be described with relatively simple statistical measures, within the unit. The extent of the units is essentially based on the interpreted *geometry for fracture zones and soil and rock type distribution*, but e.g. hydrogeological information can also be used to achieve an expedient geometric subdivision. For each geometric unit, the model describes *geological conditions*, *mechanical*, *thermal*, *hydraulic* and *hydrogeochemical properties* and properties of importance for *transport* of solutes in the groundwater in the rock. In addition, it describes the *surface ecosystems*. What needs to be included in the site-descriptive model and how detailed the description needs to be is mainly determined by the design activity's need to produce a facility description, the safety assessment activity's need to study the long-term evolution of the site, and the need to achieve and demonstrate geoscientific understanding.

The site-descriptive model comprises one of the main constituents of the site description. Table 2-2 describes in brief the principle of how SKB intends to build up and present the discipline-specific models included in this model.

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[2] Version numbering is preliminary with the format m.n where m=0 for versions based on feasibility study material, m=1 for versions produced during the initial site investigation and m=2 for versions produced during the complete site investigation, n indicates sequence number.

Table 2-2. Brief presentation of structure and content of discipline-specific models. The site-descriptive model consists mainly of geometric framework, parameters, data representation and boundary conditions (shaded area in table).

Name of model
Purpose of model Presentation of what the model will be used for.
Process description Explanation of which process is handled in the model; equations used in the process description are identified where applicable.
Constituents of model
Geometric framework Presentation of the dimensions of the model and the geometric boundaries of the model area. Specification of the model's (geometric) units, how they are generated and which geometric parameters are included in the background material.
Parameters Specification of which parameters are included in the model. Presentation of the origin of data and/or how values are determined.
Data representation Presentation of how parameter values have been distributed within the model's geometric units.
Boundary conditions Specification of type and geometry for boundary conditions as well as initial state and how they have been determined.
Numerical tools Presentation of mathematical formulas or computer programs that are used in process simulation.
Calculation results Presentation of the results that are obtained in numerical simulation/calculation.

Conceptual model

The general parts of the model, which describe its constituents, are called the *conceptual model*. The conceptual model describes the basic structure of the model and the constituent processes.

The conceptual model is determined with reference to what the model is to be used for, its purposes. Based on all conceivable processes, the conceptual model focuses on the processes that control the questions which the model aims to answer. The report *Processes in repository evolution* /SKB, 1999b/, which comprises a part of the safety assessment SR 97, gives a discipline-by-discipline account of what processes need to be described to assess the long-term evolution of the repository. The choice of constituent processes is moreover based on the model development and application done at the Äspö HRL /Olsson et al, 1994/.

Descriptive (quantitative) model

The descriptive (quantitative) model for each discipline stipulates values or statistical distributions for the parameters that are needed, based on the conceptual model, to describe the properties and initial state of the rock. The choice of parameters within each discipline is based on the conceptual model and the overviews performed in the "Parameter report" /Andersson et al, 1996/ and the report on requirements and criteria /Andersson et al, 2000/. These previous overviews have now been revised within each discipline and are reported for the relevant discipline (Chapters 4–10) in tables that follow the template in Table 2-3.

Table 2-3. Template table of constituent parameters and their use. The table also shows when the parameter is primarily determined. Many parameters are, however, preliminarily determined in early phases, and then subsequently continuously updated as new information becomes available. ISI and CSI belong to the site investigation phase (initial and complete site investigation, respectively) and are preceded by feasibility studies (FS) and followed by detailed characterization (DC).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	

The descriptive models are based on a common geometric framework, see Figure 2-4. The geometric model primarily describes the investigated area's topography, deformation zones, lithological boundaries, rock units, soil strata and watercourses. (The term "deformation zone" is used as a collective name for plastic shear zones and fracture zones, see /Andersson et al, 2000/.) For each part of the geometric model, the model gives values and initial state for each discipline for the relevant parameters within the discipline. Certain parameters are specified *statistically*, while *deterministic values* are assigned to others. The spatial resolution of the description (the "*scale*") can also vary between different areas and during different phases of the site investigation.

By "deterministic description" is meant that the parameter (property or geometric position) is given as a value or a function, while "statistical description" means that properties are described in statistical terms (e.g. fracture density and distribution of hydraulic conductivity in rock mass). Uncertainty can, particularly in early stages of the characterization, also be represented by utilizing different (alternative) conceptual or descriptive models simultaneously. On the other hand, inherently uncertain properties can be stipulated "deterministically", in the form of e.g. a mean value, if this degree of detail is sufficient for the beneficiaries' purposes. The degree of determinism in the description and the necessity of working with different alternatives is dependent on the available information density, but also on the degree of detail needed by the beneficiaries.

Since the models are constantly being refined (updated) based on a progressively growing body of data, strict version management is essential. This quality aspect necessitates the traceability of the data incorporated in each model version so that they can be recreated, e.g. for examination at a later time. This is discussed further in section 2.5.

Size of model area – different scales

The generalizations in a model that are necessary in order to get an overview or be relevant from a process perspective depend on what geometric resolution (scale) being described. During the site investigation, a detailed descriptive model is devised, a *local model*, for the area within which the repository is expected to be placed, including accesses and the immediate environs. In addition to a description on a local scale, a description is also devised for a much larger area, a *regional model*, in order to provide boundary conditions and to put the local model in a larger context. Each discipline-specific model is developed progressively from general regional to more detailed local descriptions during the stepwise execution of the site investigation.

The surface area of the deep repository (at repository depth) is ideally about 2 km^2. This area includes a fully built-out repository with approximately 4,000 canisters and 90% assumed utilization of possible canister positions and required central spaces. The surface facility and the descent to the deep repository are not included in this area since their area needs depend on whether a straight ramp, a spiral ramp or a shaft will be used. The geometrically ideal case will not be achieved in reality, since the layout of the deep repository will be adapted to conditions in the bedrock (fracture zones, etc). The more deposition areas the deep repository is divided up into and the more irregular these geometries are, the greater total repository area will be required, since intervening unutilized "corridors" must also be included in the total "encompassing" area. In view of this, 2–4 km^2 can be used as a guide value for the underground portions of the repository area. The above-ground area includes a relatively small surface area which, in the straight ramp alternative, is located outside the actual repository area and also leads to a "ramp corridor" whose length and geometry are site-specifically dependent.

The local investigation and model area should be considerably larger than the repository area, above all because it is not otherwise possible to try alternative repository layouts and gradually arrive at the optimal placement and adaptation to rock conditions. The local model should therefore encompass a surface area of 5–10 km^2. The scope of the local model will also be determined in depth. In view of the fact that the deep repository will be located at a depth of approximately 500 m (which, depending on rock conditions, may mean between 400 and 700 m), and the bedrock should be characterized down to approximately 1.5 times the planned repository depth, the model (and thereby also the investigations) should extend down to approximately 1,000 m.

The geographic scope of the regional models depends on the local premises and is controlled by the need to achieve understanding of the conditions and processes that determine the conditions on the site. The regional model should encompass such a large area that the geoscientific conditions that can directly or indirectly influence the local conditions, or help in understanding the geoscientific processes in the repository area, are included. In practical terms, this may entail a surface area of a few hundred square kilometres.

Calculation tools – analytical and numerical calculation methods

The site-descriptive model is represented with the aid of both geographic information systems (GIS) and above all SKB's CAD-based computer tool, Rock Visualization System (RVS), together with underlying databases. RVS is based on a CAD program (Microstation®) and presents models in three dimensions. RVS, which is directly linked to SKB's database SICADA, is used as an active instrument in the interpretation of the database's primary data, especially for identification of deformation zones and their extent, i.e. for setting up the geometric backbone in the site-specific models. At present RVS is being refined so that interpreted properties for the geometric units can be booked and administered in a given discipline-oriented structure /Munier, Hermanson, 2001/. The application will include standard procedures for version management to provide traceability and consistency between different disciplines. It will also show which data underlie a given model version and who stands behind the interpretation made. Model version and other information on traceability is essential when site-descriptive models are used for design and safety assessment. Furthermore, conversion procedures are being developed so that the RVS model can be exported to the mathematical calculation tools described below.

The description is primarily devised to permit predictions of the future evolution of the repository within the safety assessment and for the various analyses that are done in design. To make predictions and analyses, mathematical calculation tools are used that may sometimes be simple analytical solutions and in other cases are more or less complex computer codes (numerical solutions). Calculations are also needed to devise the site-descriptive model.

The quantitative modelling tools do not need to include all the processes and parameters included in the conceptual model or match the spatial resolution in the site-descriptive model. The modelling tools can be designed to describe a few processes under special conditions. Since many processes interact and the dominant processes have varied during different periods, different modelling tools will have different predictive capacity in time and space.

The choice of computer codes is primarily a question for the beneficiaries (safety assessment and design), but must of course be adapted to the parameter description. Subsequent analyses within safety assessment or design may, however, change the degree of detail, exclude certain parameters, or choose values that e.g. exaggerate consequences, all depending on the purpose of these later analyses. Plans for these coming analyses or the choice of calculation tools suitable for these analyses are not further described here, but are dealt with in plans for safety assessment and design.

The description is complicated by the fact that several of the properties (parameters) of the rock, such as hydraulic conductivity, are determined by subjecting the rock to a disturbance, e.g. a pumping test. Mathematical model calculations are used to simulate the disturbance and the parameter values are adjusted (calibrated) so that the calculated impact agrees with the observations. Mathematical calculations can also be used to simulate the historical evolution of the site.

The calculation tools that will be used for interpretation of data and to analyze the evolution of the site are described under the relevant discipline. Other tools will be used in certain contexts and for certain purposes in safety assessment and design, as already mentioned. Where appropriate, however, an effort will be made to use the same calculation tools to carry out both geoscientific model simulations and the analyses included in safety assessment and design.

2.3.3 Positioning of boreholes

The different characterization methods are described under the relevant discipline chapter. But most of the investigation methods are conducted from boreholes, although various surface-covering investigations from the ground surface are also conducted. Essentially, two types of holes are drilled: relatively short (100 to 200 m) percussion boreholes and deep (700 to 1,000 m) cored boreholes, see Chapter 11. The positioning of boreholes and the sequence of different measurements in the holes are planned jointly by different concerned disciplines.

Information density

Ideally the information density should be evenly distributed within the local and the regional model areas. (The information density is naturally much lower within the regional area.) It is therefore appropriate to determine the local model's geographic area as early as possible during the site investigations, i.e. when a priority site has been chosen within an area. The regional model should also be given a set geographic demarcation. Some of the information for the regional model has been compiled in the feasibility studies, but additional field surveys will be conducted during the site investigations, both the initial and complete ones.

The degree of determinism in the model description is largely dependent on degree of detail, information density and uncertainty and should therefore increase as the investigations progress. However, it is essentially the beneficiaries' demanded degree of precision for a given investigation phase that should control the scope of the investigations. Neither design nor safety assessment require thoroughly deterministic knowledge of the properties of the rock after concluded complete site investigation. For many parameters, a statistical distribution is sufficient. Even a small number of boreholes provides good information on the site's major fracture zones and on the statistical distribution of rock properties. Additional boreholes provide information on minor fracture zones and more detailed knowledge of the spatial variation of the properties. When the uncertainties are sufficiently well-determined, there is no reason to drill more boreholes, even though this would provide limited additional information. Furthermore, for many parameters it is considerably easier to then increase the degree of detail in the subsequent detailed investigations under ground. Other parameters cannot be determined at all with boreholes from the ground surface, instead requiring measurements under ground.

It is not possible in advance to specify how many boreholes are needed to acquire sufficient knowledge. The scope of the investigations is dependent on how complex the site is and how the boreholes are positioned. A site with heterogeneous bedrock and with many irregularly occurring fracture zones needs a relatively greater number of boreholes than a site with homogeneous bedrock and more regular fracture zones. The scope of the investigations can therefore only be determined site-specifically and in consultation with the primary beneficiaries, design and safety assessment. However, SKB estimates that the complete site investigation may comprise between 10 and 20 deep cored boreholes, plus a number of less deep percussion boreholes.

Geometric distribution of boreholes

Despite extensive investigations, the information density in the site investigations will be relatively low. The geometric distribution of measurement points in the large rock volume will be uneven. The biggest difference naturally arises between the shallower parts where measurements can be made from the ground surface and the deeper parts where downhole measurements are needed. This difference is slightly less on sites with a thick soil cover, where the shallow rock also has to be investigated via short boreholes.

Generally speaking, however, the boreholes should be suitably distributed over the entire site, in terms of both geographic area and depth, with the goal of achieving the same geoscientific level of knowledge for the entire local model area, but with a greater degree of detail for the parts judged to be suitable as deposition areas. Boreholes can also be positioned to investigate purely construction-related questions, e.g. to provide data for locating possible access tunnels outside of the actual repository area.

Ideally, the information points should be as evenly distributed as possible. On the other hand, it may be necessary to increase the information density where the rock conditions exhibit greater variation than where conditions are more homogeneous. Obvious examples with great variation are the major fracture zones. Regional and local major fracture zones that are to be described deterministically thus require greater information density to be located, oriented and characterized.

Since most information from great depth is collected from boreholes, the location and orientation of the boreholes is crucial for the distribution of the measurement points. Without any knowledge of the rock volume whatsoever, a uniform geometric spread of both borehole positions and borehole directions would be ideal, the latter in order to identify the anisotropic properties of the rock volume on both a large and small scale. Another strategic extreme would be to position each borehole to check or verify indicated fracture zones. Since uncertainties always exist, there is then a risk of concentrating the information density to certain limited parts, while other large areas are underrepresented. The optimal strategy is to combine these two aspects with a fundamental even distribution of measurement points throughout the rock volume in combination with targeted investigations/boreholes to secure information on the most important properties of the bedrock.

The detailed planning of where new boreholes will be located takes place prior to each sub-step (see 2.3.1) and can thereby not be determined from the start. The need for further information density in different areas is taken into account. By simulating possible outcomes of the new investigations based on a current version of the descriptive model (premodelling, see section 2.3.4), future efforts can be optimized. An estimate of how much additional information would be obtained with new boreholes is thereby also made. If the additional information is judged to be marginal, this may be reason to terminate the drilling programme.

Borehole geometry in relation to the repository area and plugging

The investigations must naturally not degrade the long-term properties of the site. The boreholes constitute in themselves short-circuiting channels in the bedrock of relatively large size in relation to individual natural fractures. While this does not place any restriction on where the boreholes can be positioned, a couple of aspects of drilling must be taken into consideration:

- In planning drilling in the vicinity of the repository area, a respect distance should be observed between the deposition areas and boreholes. This may entail difficulties, since the location of the deposition area cannot be exactly determined until after borehole and other investigations, but must be done in the best possible manner. Correct *position measurement* of the boreholes is crucial for accurately defining this safety distance. In design that takes place during the later detailed characterization phase, it is possible to make sure that deposition areas are located with a suitable respect distance to boreholes.
- After concluded site investigations a site is chosen for detailed characterization. When this is also concluded, some of the boreholes in the repository area and its vicinity must be plugged with sealing material.
- Decisions on which boreholes should be plugged on repository closure and which should remain open for long-term monitoring are made at late stages of repository build-out or at the time of repository closure.

Deciding how to deal with short-circuiting boreholes lies well in the future, but should nevertheless be looked at during the planning work.

2.3.4 Interpretation and description of uncertainties

The results from the field investigations are mainly used to determine parameter values in the descriptive model. A parameter is always defined in reference to a given model, and strictly speaking all measurement entails a model interpretation. Furthermore, only a few parameters can be determined directly over the entire investigation area. Most common is that measurement data (primary data) must be interpreted and extrapolated to different parts of the model area (see section 2.3.2). The main purpose in interpreting measurement data is to obtain values for the different parameters in the descriptive model. At the same time, an evaluation of the uncertainties in individual parameter values and an assessment of whether the conceptual model is reasonable are made. The analysis is also used as a basis for planning further investigations. The various analyses are based to a varying degree on different model simulations.

Alternative models

In view of the spatial variation and the difficulty of determining in detail a reasonable geometric subdivision of the rock, it is essential not to commit to a single model alternative, especially at an early phase of characterization. An important way to handle uncertainties and alternative interpretations is to arrive at alternative geometric subdivisions or alternative values of the models' parameters and to analyze the consequences of the different alternatives.

Extrapolation to the entire volume

The measurement results from the investigations generally pertain to conditions within very limited areas, such as investigations of recovered drill cores, logged boreholes or water samples. In order to obtain parameter values in the entire rock volume, the results must be extrapolated. This is done on the basis of the assumed conceptual model, which in principle describes how the relevant quantity varies in space.

The extrapolation starts with the geometric units of the geometric model, or of the model alternatives. The basis for this subdivision is an analysis of the geometric information concerning locations and size of deformation zones, lithological boundaries, rock units, soil strata and watercourses. The endeavour within each unit can then be to specify a given parameter as a constant value, a mean value, or a statistical distribution. The degree of assumed spatial variation is based on previous experience regarding the relevant quantity and the purposes of the modelling. For example, a detailed resolution of the variation in hydraulic conductivity on a local scale is necessary in order to be able to determine the rock's retention properties reliably. Hydraulic conductivity is suitably described there as a stochastic continuum, see e.g. /Walker et al, 1997/, or as a discrete fracture network /Dershowitz et al, 1999/. For the regional description, which is usually done to determine boundary conditions, it is sufficient for most purposes to stipulate mean values for each unit.

After completed extrapolation it is necessary to ask the question as to whether the underlying models of the spatial variation are reasonable. This applies especially to the actual subdivision into geometric units. It is thereby valuable if model calculations can be carried out to simulate how the rock reacts to a major disturbance and then compare this with the actual outcome of the disturbance. An example of such a disturbance is the pressure responses that arise in conjunction with hydraulic interference tests between different borehole sections. A simulation may to some extent entail fine adjustment (calibration) of the parameter, but it also provides a check of the descriptive model, which may lead to adjustment of e.g. the geometric model of one or more zones.

Prediction of expected investigation results

Prior to each investigation step, a prediction should be made of the expected outcome of the coming investigations. The types of analyses and calculations needed to make such predictions vary between disciplines and investigation methods. Predictions with the existing geometric model may, for example, pertain to calculated positions where new boreholes will intersect different fracture zones and can therefore suitably be made with the RVS tool. Predictions of hydraulic interference tests may pertain to expected pressure responses in different measurement sections and can be made with a suitable groundwater simulation model.

The prediction can be used directly to optimize the investigation work, for example to decide where new boreholes should be positioned or what size of disturbance (e.g. pumping, choice of tracer) can be expected to produce a clear response. If there are alternative interpretations, it may be particularly interesting to see whether the new investigations are able to distinguish them.

The predictions are also valuable in evaluating the results when the new investigations have been completed. The reliability of the models is tested by checking new sets of measurement data for their agreement with predictions from current model versions and model alternatives. Certain model alternatives may be discarded and new ones created in this process. One alternative may prove to be more reasonable than others and thereby be regarded as the principal model. If the agreement is poor for all alternatives, the question must also be asked whether the conceptual model should be revised. However, it is important to retain possible alternatives to the principal model and to carry out variation analyses to test the sensitivity of the models (see also Figure 2-5).

Assessment of understanding – confidence in the models

The level of confidence in the safety assessment's predictions is highly dependent on the level of confidence in the models that are devised. This confidence needs to be described. The ambition is to make the models as reliable as possible, but since all models are simplified representations of reality, there will always be discrepancies between the model and reality. The uncertainties contained in models stem partly from the fact that processes may have been neglected or simplified and that certain parameters exhibit spatial variability, which can only be handled statistically, and partly from uncertainties due to measuring error, measuring accuracy, interpretation methodology, etc. Uncertainties due to measuring error or measuring accuracy are often small, however.

The uncertainty in the interpretation is assessed and quantified after each investigation step. The size of the statistical spread or the validity of many different interpretations based on the same measurement information indicates the degree of uncertainty. Another indication of confidence in the description is the extent to which measurement results from late investigation steps confirm predictions made in earlier steps. Good agreement between prediction and measurement result is a sign that the models are reasonable in the comparison in question, while poor agreement suggests the converse.

It is also essential that the models can credibly explain the current state of the site based on the natural processes that are changing this state. For example, the distribution of the composition of the groundwater on the site must be reasonable in relation to lithological composition, fracture mineralogy, groundwater flow and earlier climatic evolution with associated changes in hydrogeological and chemical boundary conditions. Even though such paleohydrogeological arguments cannot be used as formal evidence that models and parameters have been correctly chosen, they are essential in a qualitative chain of evidence for determining the reliability of the models.

Documentation of uncertainties

Uncertainties shall always be described, if possible quantified, and discussed in an appropriate fashion in connection with the reporting of results, and not just in the final report but also in all measurement and investigation steps. Such a report is furthermore associated with the quality assurance requirement of traceability (see 2.5). Reporting of results also includes evaluating the quality of the data, often by indicating or discussing uncertainties. In certain cases, alternative model interpretations are given. Furthermore, understanding and uncertainty are documented on the basis of observed field data, extrapolations in space and model simulations in the site description.

2.3.5 Coordination

The subdivision into disciplines comprises the base for the structure of the programme, for execution and for modelling and reporting. Integration and coordination between the disciplines is, however, a basic prerequisite for a successful execution. This is particularly true of the field investigations, as well as for the creation of site-descriptive models.

Surface ecosystems, geology, hydrogeology and hydrogeochemistry, as well as rock mechanics to some extent, are the disciplines that dominate the field investigations. Most measurable thermal parameters are obtained from the geological investigations. Measurement data that provide a basis for determining transport properties are mainly taken from hydrogeology and hydrogeochemistry, but certain specific investigations of transport properties are also included in the programme. Geophysics is included as a part of the geological programme.

Information (data and interpreted parameters) collected within other disciplines will also be needed for devising discipline-specific models. An inventory is therefore made for each discipline of data obtained from other programmes. A check is made to verify that different disciplines use consistent data, especially after the completion of each sub-step of the investigations.

2.4 Environmental impact

The general investigation and evaluation programme /SKB, 2000b, Chapter 2/ describes how the investigations will be noticed on the site, what impact the field work may have on the environment and how SKB intends to minimize any adverse environmental effects. Drilling activities have the greatest impact. Further disturbances could possibly arise due to e.g. occasional overflights, exposure of the rock surface, road construction and visiting activities. A more detailed description than the one given in /SKB, 2000b/ will be prepared when the investigation programmes are adapted to a given site. The programme for surface ecosystems (see Chapter 10) ensures that the necessary background data on environmental conditions are acquired and compiled so that this adaptation can be done.

2.5 Quality assurance

Quality assurance is dealt with in /SKB, 2000b/. The site-descriptive model is devised and updated stepwise as the site investigations progress. New versions are devised as new information becomes available and stored as quality-assured primary data in site-specific databases. Strict version management is applied in order to maintain traceability and consistency within and between different disciplines. It must also be clearly evident which measurement data underlie a given version.

3 Execution programme

3.1 Introduction

Based on the outline of the programme, this chapter presents a *possible execution programme* for the investigations, subdivided into initial site investigation and complete site investigation. Based on this possible programme, subsequent *site-specific programmes* will be prepared and adapted to the site-specific questions and conditions on the particular candidate site. When the contents and scope of the sub-steps of the various stages have been tailored to the different sites, it may be found that certain investigation steps must be added, while others described here are unnecessary and can therefore be omitted. The sequence of the different investigation steps may also need to be modified. What is essential is that the site-specific information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account after completed site investigation.

The initial site investigation is carried out in two sub-steps, of which the first is aimed at obtaining data as a basis for selecting a priority site within the candidate area (section 3.2) and the second is aimed at obtaining information from a limited number of in-depth investigations to make it possible to judge whether the site is suitable for further investigations (section 3.3). The complete site investigation is also carried out in sub-steps, but the steps are very similar to each other and are therefore described in a single section (section 3.4).

The chapter describes what measurements are planned and the data required for producing different versions of the site-descriptive model. However, the chapter does not provide any more detailed description of the methods for field investigation, analysis, interpretation and modelling. This information is provided in the different discipline-specific chapters (4–10). This chapter also deals with which parameters are to be determined.

3.2 Initial site investigation – choice of priority site within the candidate area

The investigations in the first sub-step of the initial site investigation are based on feasibility study results, initially cover the entire candidate site, and are concluded when a priority site within the candidate area has been chosen. With reference to the integrated overview in Figure 3-1, discipline-specific execution programmes are given below.

The contents and scope of the initial site investigations are, as pointed out several times previously, very site-specifically dependent. It is therefore not possible to define any absolute boundaries for what is included in any one sub-step, but it has been an ambition to link the scope as clearly as possible to the two main purposes of initial site investigations. As indicated in Figure 3-1, the step of focusing the investigations on a site may also include studies of one or more subareas. On the other hand, if a chosen candidate area is so small that it virtually corresponds to what is called a site in Figure 3-1, no choice of site need be made. In that case, no investigations need be conducted aimed directly at this choice, which means that the site investigations in principle begin with the sub-step “investigations on the site”.

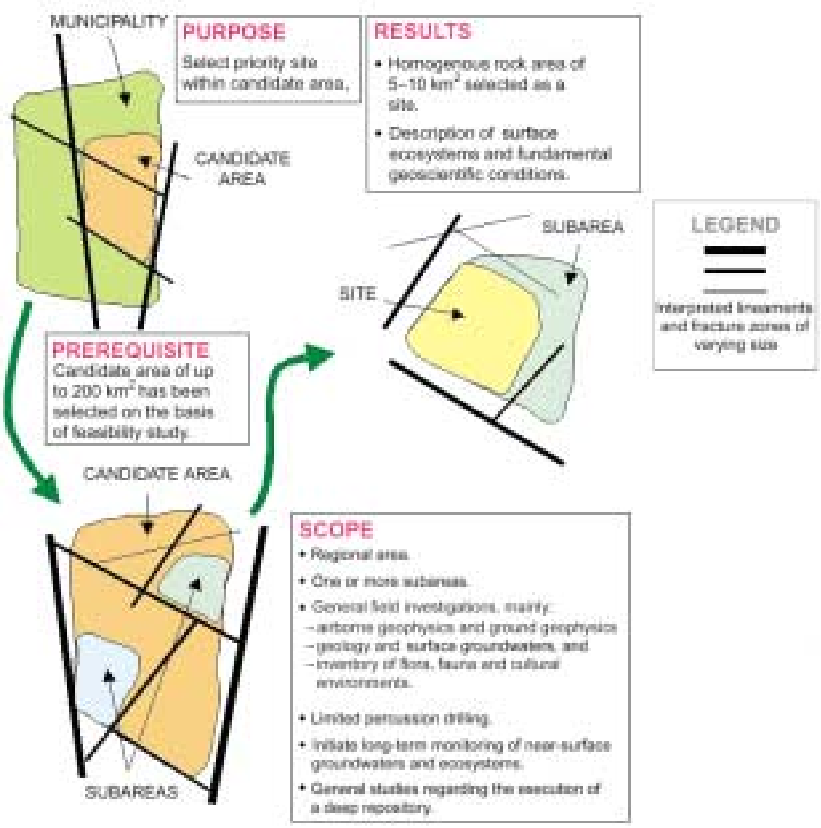

Figure 3-1. *The first sub-step of the initial site investigation is aimed at selecting a priority site within the candidate area.*

Investigations in the regional environs are examples of work that can be done on various occasions during both initial and complete site investigation. What is essential is that the regional information is collected when it is needed and that it is ultimately sufficient for the site-descriptive account after completed site investigation.

The concrete site-specific preparations for the site investigations are commenced when SKB has presented its choice of areas for site investigations. These preparations result in site-specific programmes for execution of the investigations. In order to design these programmes, the results of the relevant feasibility study will be combined where needed with any other available material on the candidate sites. In conjunction with this compilation, site-descriptive models are prepared in accordance with the structure that will subsequently be used in the continued investigations. This model, version 0, will comprise the basis for the site-specific programmes and subsequently for updating to later model versions. The ambition is that this version will already be an integrated site-descriptive model, based on a jointly prepared geometric framework, as described in section 2.3.2. Even if the model is devised as a 3D model with the aid of the computer tool RVS, it will of course be based above all on information from the surface. This means that there is great uncertainty in the description at greater depth. Furthermore, the descriptions for the different disciplines are very different.

An important basis for the detailed planning of the execution of the investigations is the compilation and inventory of natural and cultural values within the area. This includes both known ancient monuments and nature-protected sites such as valuable landscape environments. The compilation results in an availability map that provides guidance in how the investigations can be adapted to these environments so that negative impact can be minimized. For each activity that may entail disturbance (such as drilling, road-building etc), a cross-check shall be made against this availability map, see also 3.2.1, 3.3.1 and 3.4.1.

Provided that the first sub-step for choice of site is carried out, the results from these steps will be summarized in an update of the site-descriptive model (in this report preliminarily designated version 1.1).

3.2.1 Surface ecosystems

The characterization of the surface ecosystems is begun early and therefore concentrated to the initial site investigation, although follow-up measurements (monitoring) are performed during later phases. Table 10-1 in Chapter 10 shows when different data should be determined. It is not necessary that all the measurements described below be performed before other measurements are made.

Compilation of existing information

As far as surface ecosystems are concerned, a relatively extensive collection of data is taking place in national and regional monitoring programmes, the national forest valuation survey, and various research projects. A compilation has been made of some nationally available data, including climate data /Lindell et al, 1999/, statistics /Haldorson, 2000/ biological parameters /Kyläkorpi et al, 2000/ and other parameters /Blomqvist et al, 2000/.

When the candidate areas for site investigation have been selected, compilation of existing information in the relevant areas begins, with an emphasis on data from existing vegetation mappings, aerial photo interpretations and satellite imagery. The compilation is presented in map form and analyzed in GIS to identify areas that do not require special consideration or protective measures. These biotope and vegetation maps comprise a good basis so that initial investigations can be performed with the least possible environmental disturbance and with the necessary adaptation to the natural environment. Areas are also identified – mainly in the aquatic environment, but also in the terrestrial environment – where long, undisrupted measurement series should be commenced. The material also provides an idea of which parameters must be collected in this programme and are not covered by other work.

The historical values of the area, including both archaeological sites and valuable cultural environments, should also be documented in this compilation (availability map), even if they do not fall within the discipline.

Field inventories

The general biotope and vegetation maps serve as a basis for decisions on where more thorough field checks and inventories must be carried out. The purpose is to obtain more knowledge concerning areas that require special consideration with regard to environmental impact, e.g. special key habitats and breeding grounds. Ancient monuments and cultural environments are also inventoried, adding greater detail to the availability map for the site investigation. Any invasive measures such as roadbuilding and drilling should be planned based on the denser information. If areas classified for special consideration will be affected, further inventories are carried out to ensure that any environmental impact can be minimized and documented. By "environmental impact" is meant here in particular the impact of a deep repository, but also the possible impact of the relevant investigations. In other areas, a simpler field check is made before invasive measures are taken.

The map also comprises a part of the starting point for the data acquisition that is required to describe the most important functions in the ecosystem with respect to radionuclide transport, which is needed for the safety assessment, and to prepare EISs for description of the possible future environmental impact of a deep repository. This data acquisition continues throughout the site investigation.

The points selected for long-term monitoring should be inventoried early in the field to provide sufficient background data. This is particularly true of watercourses and lakes.

Long-term monitoring

After field check and evaluation, long-term monitoring of hydrochemistry, hydrology, and fauna and flora can begin. These long-term measurements provide an understanding of the area's natural evolution over an extended period of time and will continue if the site is selected for the deep repository. Long time series provide a good basis for documenting undisturbed conditions and for gaining an understanding of seasonal variations in the area, provided they begin before the disturbance occurs. The site investigations are only expected to have a very limited environmental impact, however, and only on special objects. Environmental impact should therefore be documented above all prior to the construction and operation of a deep repository. Changes in the environment are monitored both on the site in question and in a nearby reference area, away from any possible impact. This is done throughout the site investigation phase and will thereby provide several years' time series before detailed characterization starts. Some of the measuring stations are temporary and will be abandoned when the area is left.

Analysis, interpretation and modelling

The results of the initial compilations, field investigations and long-term measurements will be presented as versions 1.1, Figure 3-2.

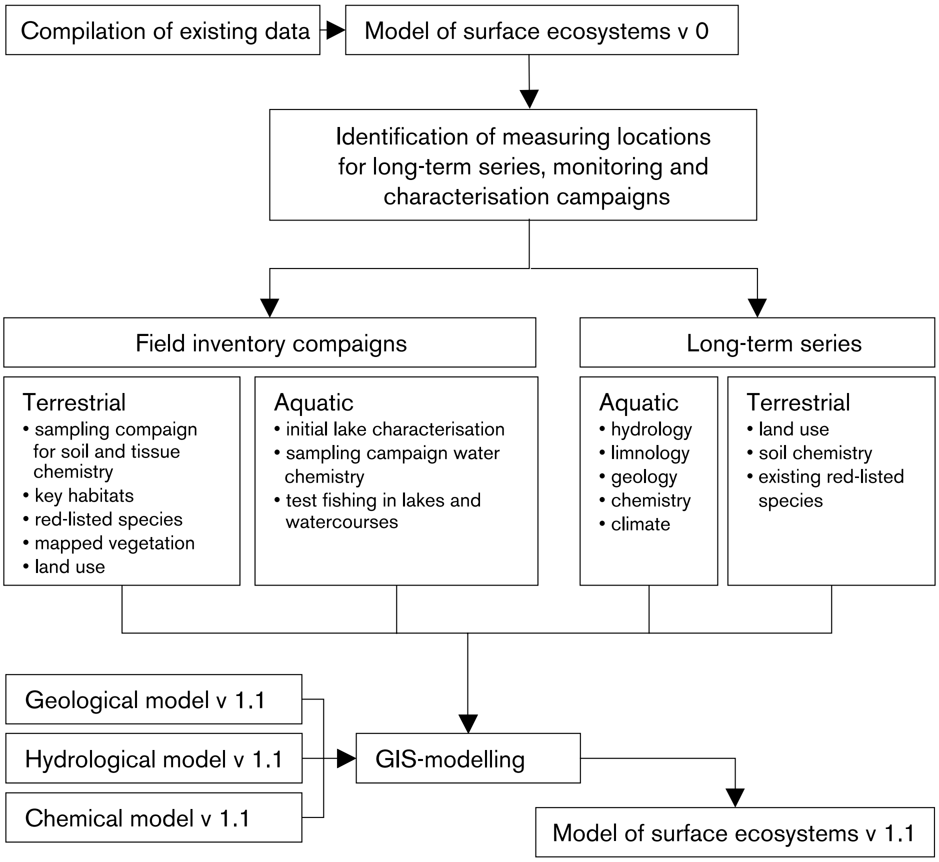

Figure 3-2. *Flow plan and information needs for the first model (version 1.1[3]) of the surface ecosystems that is devised in the first step of the initial site investigation.*

3.2.2 Drilling programme

Drilling is of limited scope in the first sub-step of initial site investigations compared with later phases. A limited percussion drilling programme comprising 10–20 percussion boreholes (usually graded and with a maximum vertical depth of about 150–200 m) is carried out, if necessary, to answer specific questions, such as for example to confirm and preliminarily characterize the regional and local fracture zones identified by means of geological and geophysical investigations (see section 3.2.2). The boreholes primarily enable the inclination and hydraulic properties of the fracture zones to be determined (Figure 3-3). Choice of drilling sites and investigations are mainly coordinated between the programmes for geology, rock mechanics, hydrogeology and hydrogeochemistry.

Soil drilling and soil sampling as well as installation of groundwater pipes are carried out for characterization of soil strata. The scope of these activities is dependent on the extent and variability of the soil strata. To the extent the investigation area contains lakes and/or sea areas, sediment drilling and/or sampling is done. These drilling activities are integrated with the programmes for surface ecosystems, geology, hydrogeology and hydrogeochemistry. Drilling programme and drilling methods are described exhaustively in Chapter 11.

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[3] Version numbering is preliminary with the format m.n where m=0 for versions based on feasibility study material, m=1 for versions produced during the initial site investigation and m=2 for versions produced during the complete site investigation. n indicates sequence number.

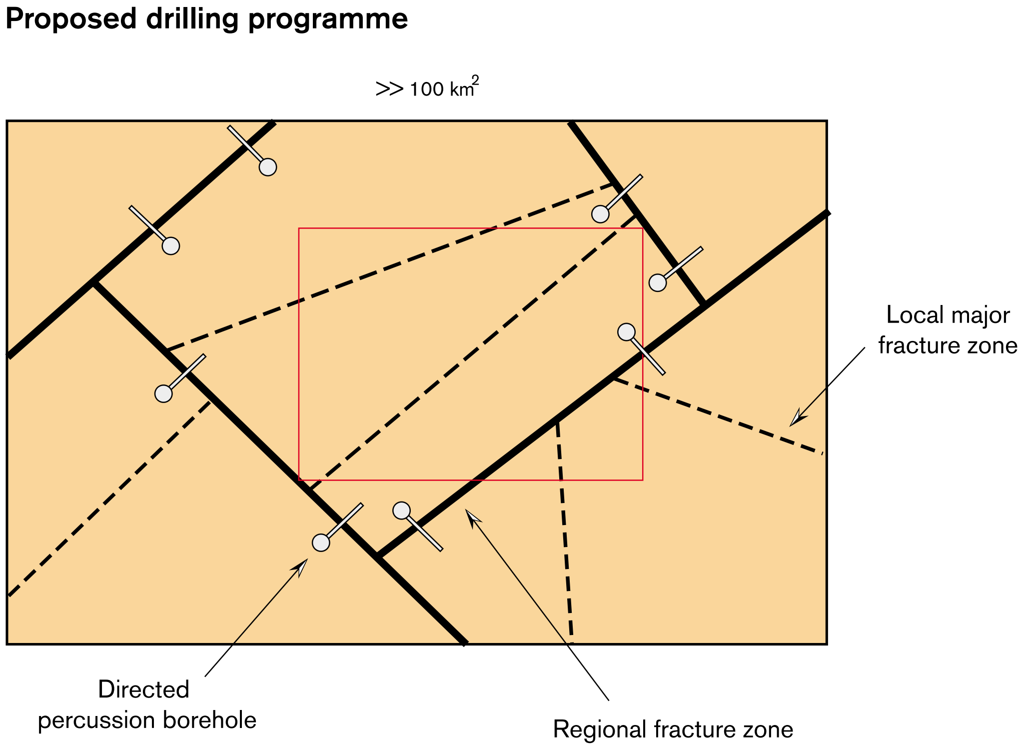


Figure 3-3. *A drilling and investigation programme which preliminarily comprises 10–20 percussion boreholes is conducted at the beginning of the initial site investigation.*

3.2.3 Geology

The site-specific planning is predicated on a compilation of existing feasibility study material. At the beginning of the initial site investigation, efforts are focused on obtaining good knowledge of regional and local major fracture zones, and finding rock areas with a relatively homogeneous lithological composition. The investigations include *geological mapping* (geological field studies, airborne geophysics, geophysical ground surveys, investigations of rock type samples, possibly also seismic reflection) and *lineament interpretation* from various types of map material supplemented with information from percussion boreholes. In addition, *long-term monitoring* of conditions requiring long time series is initiated. Some of the investigations may be performed even before the actual site investigation is begun, if this is deemed suitable for various reasons. The geology programme's models, parameters and measurement methods are presented in Chapter 4.

Geological mapping

The initial field studies are dominated by rock and soil type mapping as well as geophysical surveys. Rock type mapping includes studies of rock outcrops, road cuts and quarries and carries further the geological field checks that have been done during the feasibility studies. It provides information on rock types and their distribution as well as structures in the rock mass (folding, foliation, fractures, etc) and deformation zones (plastic shear zones and fracture zones). General knowledge of the frequency, orientation and length of fractures is important already at an early stage. In conjunction with rock type mapping, radioactive radiation and magnetic susceptibility are measured with handheld instruments (see section 4.3.3).

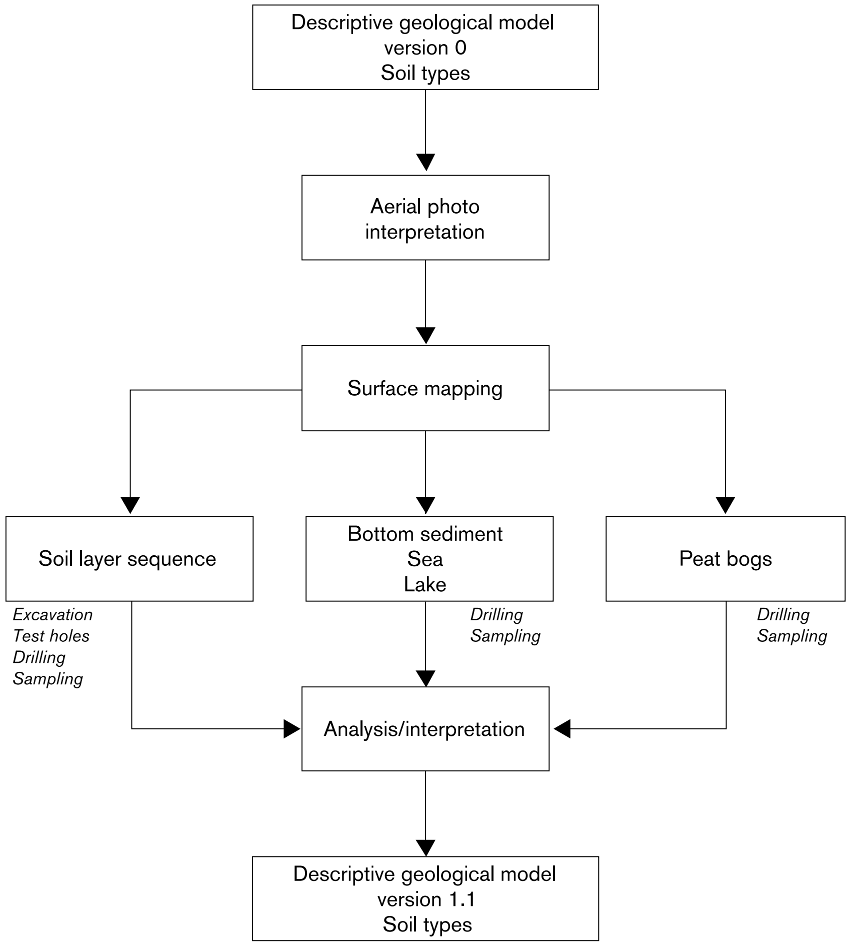


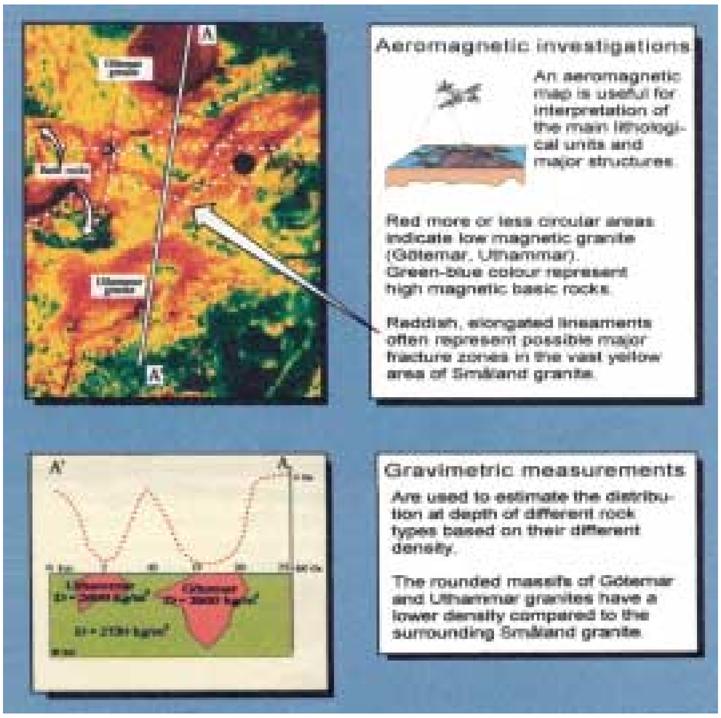
Figure 3-4. *Flow plan for characterization and description of soil types (Quaternary deposits). Soil type characterization is carried out on suitable occasions during the site investigations, which means that the flow plan is not unique for any particular phase.*

Soil type mapping includes both determination of the extent and character of the soil types on the surface and studies of soil layer sequence and soil depth with the aid of excavated test holes and soil drilling, see Figure 3-4. A rough soil mapping can be performed in conjunction with field inventory of soil types. In conjunction with soil type mapping it is important to observe any indications of postglacial faults, see further sections 4.1.1 and 4.3.3.

Geophysical surveys

Which geophysical surveys are to be performed depends on the contents of the material from the feasibility study.

If necessary, already available airborne geophysical base surveys will be supplemented by airborne surveys with a helicopter-borne system over the entire candidate area with regional environs. Magnetic and to some extent radiometric methods are used for description of rock types, while magnetic and electromagnetic (EM) methods are used for identification of regional and local major fracture zones, Figure 3-5. Since positioning is carried out by means of GPS, dense profiles can be measured. A dense airborne



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.

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 3-5. *An airborne geophysical magnetic survey and a gravimetric measurement profile on the ground surface for regional description /from Rhén et al, 1997a/.*

survey with helicopter system is expected to take the place of equivalent geophysical measurements on the ground, which require a fragmented stake system for accurate positioning. Airborne measurements will be performed as early as possible, since they serve as a base for further characterization.

Examples of geophysical ground surveys that may be used are gravimetry, by means of which major rock units of varying density (e.g. granite bodies or greenstones) can be identified, and resistivity and IP (Induced Polarization) measurement, by means of which the bulk resistivity and IP effect of different rock units can be determined. The latter are used to study the occurrence of metallic mineralizations (greisen formations) in the investigation area. For crystalline rock, bulk resistivity is determined above all by the fracture frequency in the rock.

In order to support analysis and interpretation of geophysical results and geological mapping, rock type samples are taken from the investigation area. These samples are sent to laboratories for determination of petrophysical parameters such as density, porosity and susceptibility.

Seismic reflection measurements may be performed at this stage, suitably in the form of intersecting profiles a few kilometres in length, in order to identify any subhorizontal structures (fracture zones) of importance, see further sections 3.3.2 and 4.3.2.

The geophysical measurements, together with geological mapping, provide material for compilation of a regional bedrock map (geological model of rock types), Figure 3-6.

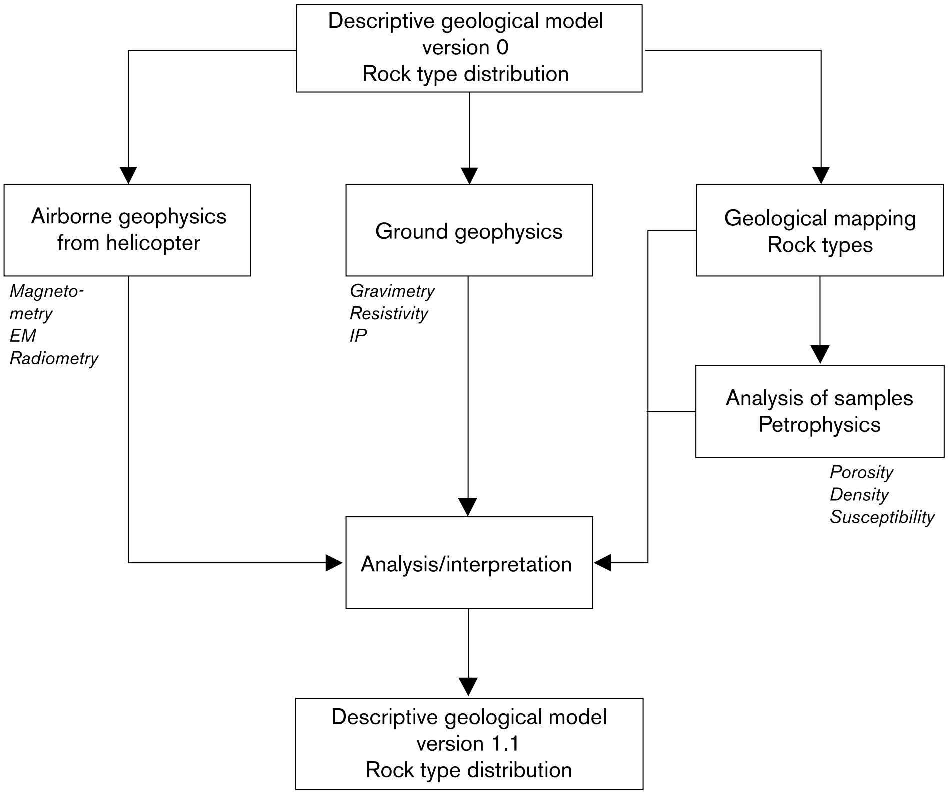


Figure 3-6. *Flow plan for characterization and description of rock types, preferably on a regional scale, during the first step of initial site investigation.*

Lineament interpretation – identification of regional fracture zones

If detailed aerial photography is lacking, an airborne photography survey is performed from an altitude of 500–1,000 m. Rectified aerial photos comprise a good basis for both interpretation of lineaments and compilation of base map material with suitable horizontal and vertical resolution.

Lineament interpretation is used for identification of the area's regional and local major fracture zones and is done on the basis of e.g. geophysical maps, topographical maps/ images and satellite images, see section 4.3.3. Identified lineaments are checked in the field by means of ground geophysics, percussion drilling or excavation. Surveys with magnetometer, slingram or resistivity and seismic refraction are preferably performed along transverse profiles over presumed regional or local major fracture zones to establish their occurrence more precisely and determine their position and width.

Interpreted regional fracture zones within the area are checked if needed by percussion drilling to answer specific questions, such as to confirm the existence of fracture zones and determine their inclination and hydraulic properties. Figure 3-7 shows the flow plan for investigation of the area's structures. Excavation straight across major fracture zones can be resorted to in order to ascertain the character of fracture zones. Any indications of postglacial movements in rock and soil strata are also investigated in this context.

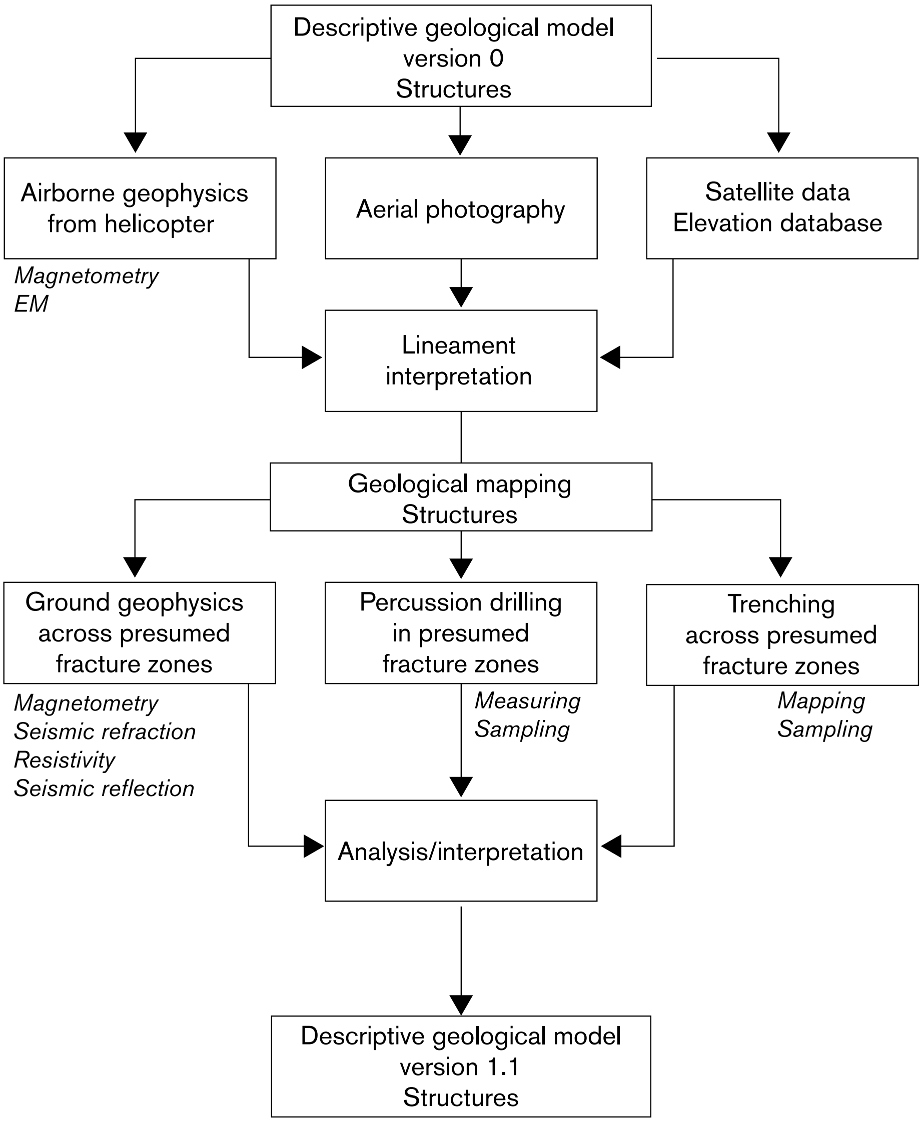


Figure 3-7. *Flow plan for characterization and description of structures, preferably on a regional scale, during the first step of initial site investigation.*

Long-term monitoring

Monitoring programmes for parameters that should be long-term monitored are started early. It may, for example, be suitable as a complement to Sweden's existing regional seismic networks to establish early on a local seismic network that also permits registration of small earthquakes in order to obtain a relatively long time series and thereby gain a better understanding of the causes of seismic events in the area. The seismic network thereby makes it possible to build up a geoscientific understanding of the mechanical stability of the site. Deformation measurement with GPS technology for monitoring creep movements in the bedrock is another method involving recurrent measurements over a long time. Precision networks for these measurements are mainly established over regional fracture zones, see section 4.3.2.

Analysis, interpretation and modelling

The first geological model (version 0) was devised as a basis for writing the site-specific programme. When the investigations are commenced, updating of the descriptive geological model is also begun and then proceeds in parallel throughout the site investigation. Initially the models contain no details and feature lots of generic data, which are gradually replaced by site-specific information and higher detail resolution and certainty. The first versions are thus founded chiefly on existing feasibility study information and results of surface measurements.

The work is mainly done on a regional scale, with a focus on identifying regional and local major fracture zones at the surface. Interpreted fracture zones, rock types and soil types on the surface are entered in RVS; possible extent in depth is illustrated as an example (see further discussion in section 4.2.3). The description along the depth axis contains great uncertainties in this model version, for understandable reasons since it is mainly based on observations and measurements on the surface. The uncertainties are documented. The interpretation methodology is described at length in section 4.2.3.

The geological terminology is also established in this phase. This includes, for example, deciding how rock types are to be classified and designated in the area, in other words arriving at a site-specific application of general nomenclature rules. The same goes for the local use of designations of deformation zones (see otherwise Table 4-2 in Chapter 4).

3.2.4 Rock mechanics

It is not possible to characterize the mechanical properties of the rock on the basis of the limited investigations conducted within the rock mechanics programme in the initial phase. However, existing generic knowledge can be refined with respect to the rock types existing in the area in question. These data are used to set up the first truly descriptive rock mechanics model, Figure 3-8. This model is based on version 0, which was devised already on the basis of the compilation prior to the site investigation. The models, parameters and methods of the rock mechanical programme are presented in Chapter 5.

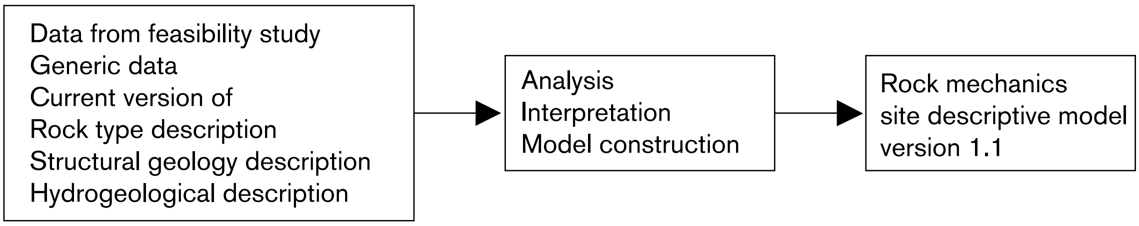


Figure 3-8. *Flow plan for preparing the first rock mechanical description during the initial site investigation.*

3.2.5 Thermal properties

It is not possible to characterize the thermal properties of the rock by means of the limited measures performed during the initial investigations, which consist only of temperature logging in the percussion boreholes drilled in this phase. On the other hand, the existing generic knowledge for the various thermal properties can be refined with respect to the area in question and in particular the rock types existing in this area. The models, parameters and methods of the thermal programme are presented in Chapter 6.

3.2.6 Hydrogeology

The hydrogeological investigations are initially focused on the regional area. The investigations provide a partial basis for selecting the priority site within the candidate area, but are mainly focused on a preliminary definition of the area that should be included in the regional hydrogeological model. This provides essential background material for planning of further investigations. The investigations aim at providing a general description within the regional area of the hydrogeological properties in the near-surface parts of the rock (regional fracture zones and near-surface rock mass) as well as a general description of the hydraulic boundary conditions and the natural variation of the groundwater level. These latter data are obtained by establishing hydrological measurement stations (meteorology, runoff) and commencing groundwater level measurements for monitoring. The hydrogeological investigations in this initial step consist of mapping in the field and of downhole investigations in percussion boreholes. The models, parameters and methods of the hydrogeological programme are presented in Chapter 7.

Data compilations

The site-specific planning of a site investigation is predicated on a review of the feasibility study material and an augmentation of this material by compilation of other existing material not already included in the feasibility study. The following data are relevant:

- material from hydrogeological investigations, mainly within the regional area,
- data from the well archive for the region,
- extent of watercourses and any measurements of runoff in the watercourses,
- meteorological data for the region, and
- interpretation of drainage basins.

Based on feasibility study material and new compilations of existing material, version 0 of the descriptive hydrogeological model is devised. The model will be essentially two-dimensional. This model serves as a basis for the actual site investigations.

Hydrogeological mapping

Hydrogeological mapping is performed at the same time as geological mapping and consists of mapping of springs, streams, discharge areas, dam projects, drainage schemes and land use. Existing wells are inventoried with respect to production data (capacity, need coverage, drawdown). Important background material for the hydrogeological model is the Quaternary geology and the bedrock geology (interpretation of lineaments, fracture orientation, fracture roughness, fracture lengths, orientation of mapped surfaces on rock outcrops and road cuts) within the regional area.

Drilling and excavation in the soil strata is documented geologically (see section 3.2.2) and soil samples are taken for grain size analysis. In pipes placed in the soil layers, groundwater levels are measured and in some cases simple hydraulic tests are performed. In certain cases, wells may be drilled or dug and pumping tests performed in them. If there are boreholes located nearby, possible pressure responses are measured in them during the pumping tests. The groundwater level in some of the wells and in observation pipes placed in the soil layers will be recorded continuously in the same way as in the boreholes in rock, see below. Here as well, it is essential to start early in order to get a long time series of the natural variation of the groundwater level in the soil strata.

Capacity tests are performed in a selection of inventoried existing wells (both drilled and dug) and boreholes, after which groundwater levels are measured approximately 6 times/ year.

If there is no suitable meteorological station in the area, at least one should be established. It may also be necessary to establish one or more measurement stations for flows in some of the major watercourses in the area.

Hydraulic tests in percussion boreholes

Data from the well archive and other hydrogeological investigations within the regional area provide a basis for estimating the hydraulic conductivity of the rock mass in the near-surface rock, but cannot be directly used to determine water conductivity at depth. Hydrogeological properties at moderate depth can be assessed on the basis of hydrogeological investigations in the 100–200 m long percussion boreholes drilled in this phase, see section 7.3.

In order to determine hydraulic conductivity, pumping tests are performed for every 100 m section during or after concluded drilling of percussion boreholes. If there are boreholes nearby, possible pressure responses should also be measured in them during the pumping tests. After drilling, each borehole is flow-logged, whereby drawdown and recovery are also measured. Afterwards it is determined whether, and if so how, the borehole should be packed-off for monitoring of groundwater pressure and recurrent water sampling.

Analysis, interpretation and modelling

When the results of the actual investigations begin to become available, version 1.1 of the hydrogeological portion of the site-descriptive model begins to be devised. The hydraulic tests, other mappings and measurements in the field are evaluated, and it is judged whether the conceptual models can be applied to the area or whether they must be modified. If the conceptual models are modified, evaluations may need to be revised. All data is thereafter processed based on the structure of the conceptual model and the jointly devised geometric model. As a result of the analysis, spatially distributed properties are obtained. Figures 3-9, 3-10 and 3-11 illustrate the working methodology for how the constituent parts of the hydrogeology model are devised and what background material is needed from other discipline-specific programmes. (The interpretation methodology is described more thoroughly in section 7.2.3.)

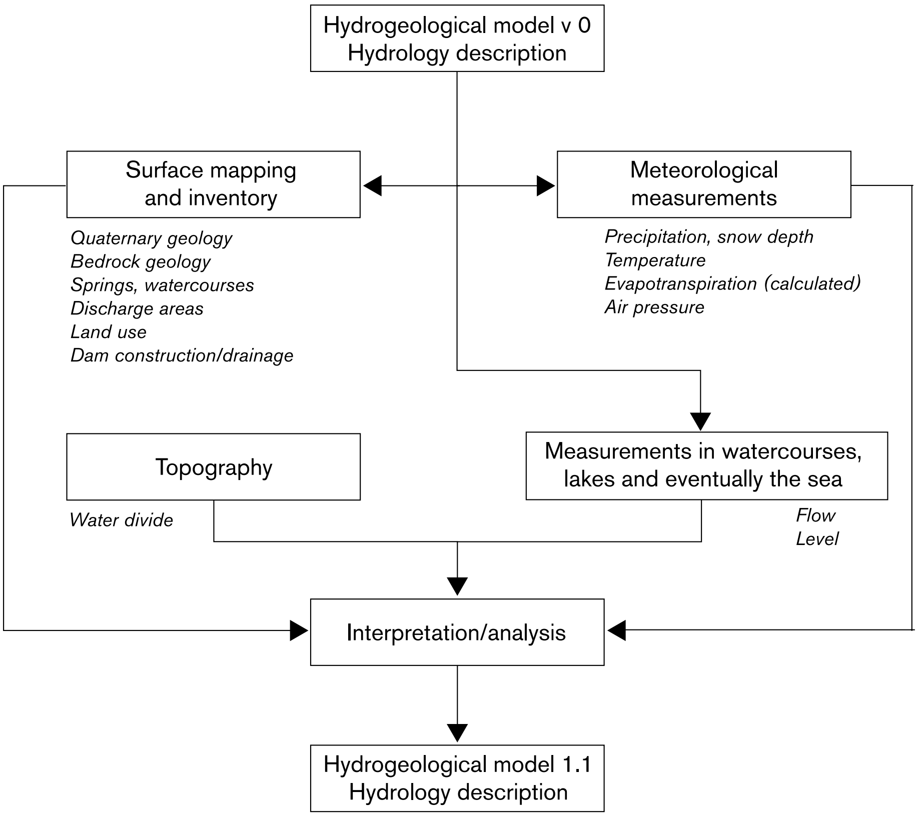


***Figure 3-9.** Flow plan for preparing the first description of the hydrology in the hydrogeological model during the initial site investigation.*

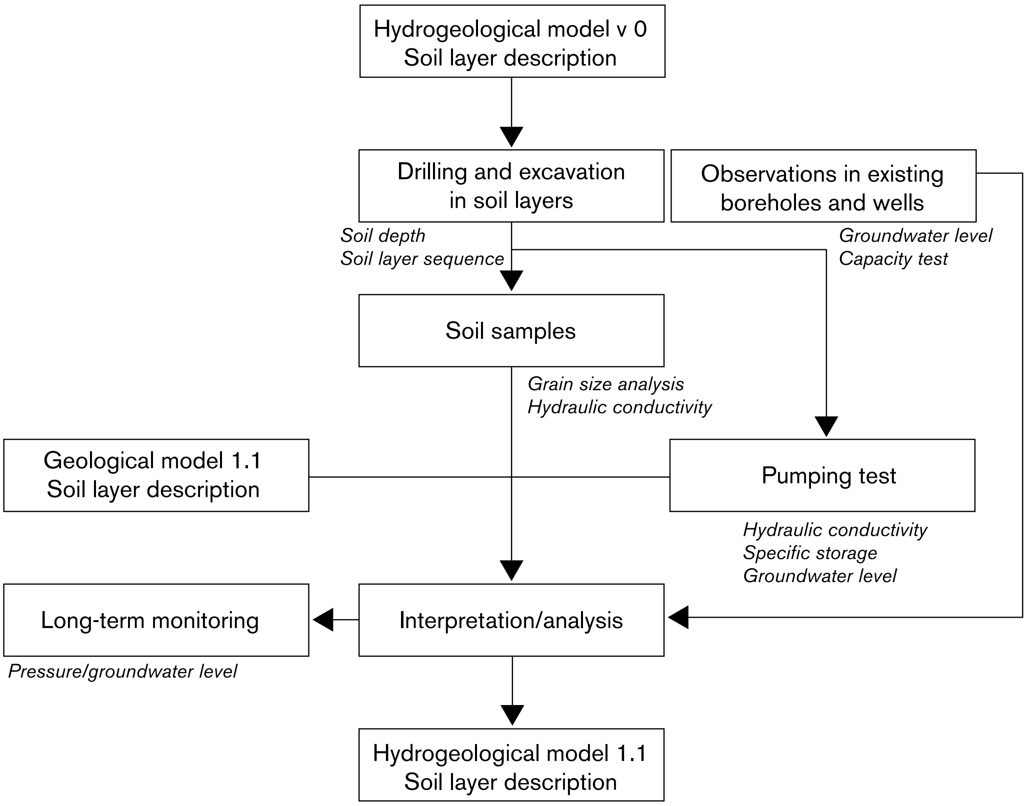


***Figure 3-10.** Flow plan for preparing the first description of the soil layers in the hydrogeological model during the initial site investigation.*

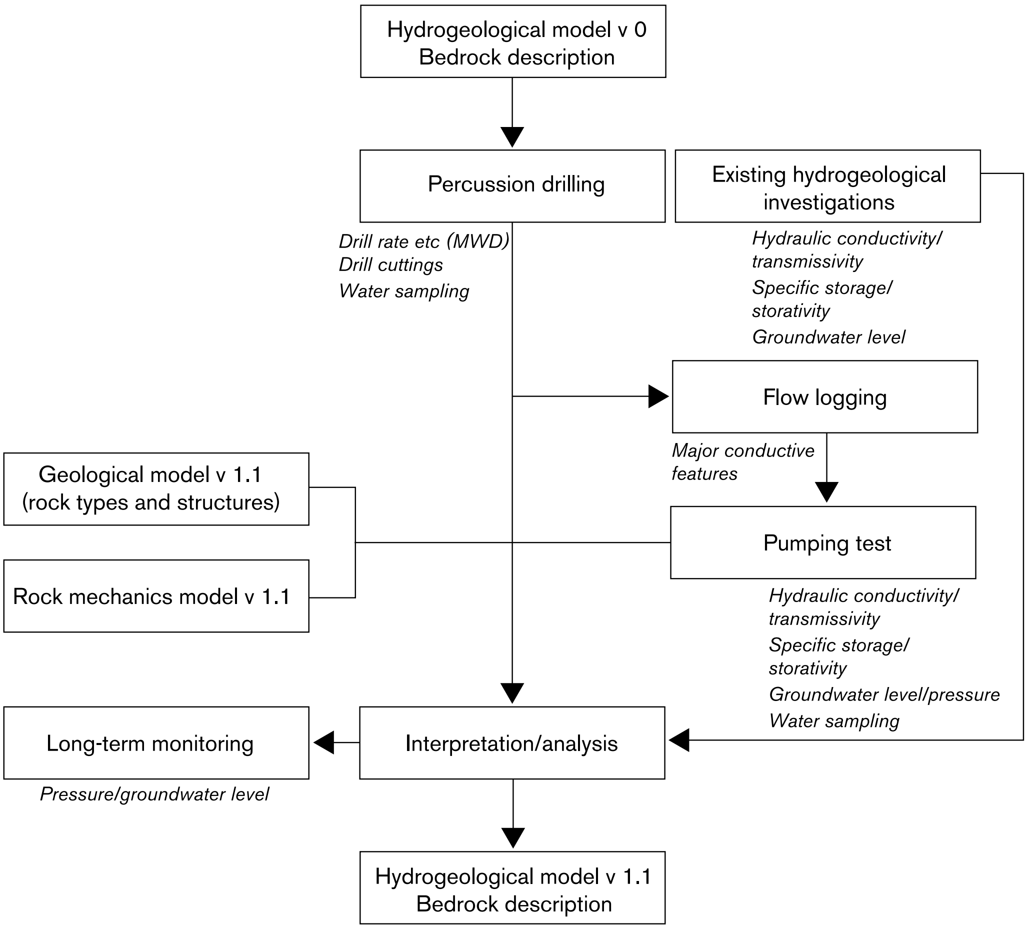


Figure 3-11. *Flow plan for preparing the first description of the rock in the hydrogeological model during the initial site investigation.*

Version 1.1 of the model description is prepared for the most part on a regional scale and is based chiefly on two-dimensional information.

- The hydrological description includes discharge basins, runoff data, meteorological data, as well as interpreted recharge and discharge areas. Description of groundwater recharge and the natural variation of the groundwater level is also included.
- The subdivision of the soil layers into hydraulic units is based on the Quaternary geological mapping.
- For the rock, transmissivity is determined roughly for the near-surface portions of major fracture zones and hydraulic conductivity is determined on a relatively rough level of spatial detail (approximately 100 m scale) for the near-surface portions of the rock down to approximately 100 m.

Based on the resultant description, calculations of the groundwater flow on a regional scale are also performed with a suitable calculation model. The purpose of the calculations is to obtain an overview of the large-scale flow pattern in order to determine recharge and discharge areas and to study how different boundary conditions influence the calculated flow. The calculation does not have to be completely set up before the choice of the site, but it does when the initial site investigation is finished.

3.2.7 Hydrogeochemistry

With reference to the goals of the investigations during initial site investigation prior to the choice of priority site within the candidate area, the hydrogeochemical work can be organized into the following main activities:

- Investigation of near-surface groundwaters, lakes and watercourses.
- Sampling in percussion boreholes after drilling, where applicable.
- Start of long-term monitoring of chemical parameters in selected sampling points.
- Preparation of model version 1.1, mainly with description of the near-surface conditions and presentation of some depth information from individual shallow boreholes.

The first characterization of surface waters, near-surface groundwaters and groundwaters found in percussion boreholes down to a depth of about 200 metres is done during the first step of the initial site investigations. The results are used to provide a general description of the hydrological systems in the area and to confirm hydrologically identified recharge and discharge areas. An overview of the sampling objects included in the initial site investigation as well as sampling occasions and scope of analysis for the object in question is given in Table 3-1. The models, parameters and methods of the hydrogeochemical programme are presented in Chapter 8.

Table 3-1. Sampling objects, sampling occasions and scope of analysis in the initial site investigation. The table also includes the samplings after selection of the site.

Sampling object	Comprehensive chemical analysis	Natural variations	Analysis class*
Surface waters			
Precipitation**	X	6–20 times/yr	3 (a, b)***
Lakes	X	12–20 times/yr	5 (c, f, g, h)***/ 3 (a, b)***
Watercourses	X	12–20 times/yr	5 (c, f, g, h)***/ 3 (a, b)***
Sea water**	X	12–20 times/yr	5 (c, f, g, h)***/ 3 (a, b)***
Pore water in sediments (lakes, sea)**	X	4 times/yr	5 (h)****
Springs**	X	6 times/yr	5 (c, f, g, h)***
Near-surface groundwaters			
Wells	X	6 times/yr	3 (a, b)***
Soil pipes**	X	6 times/yr	5 (c, f, g, h)***
Groundwaters			
Percussion boreholes**	X	6 times/yr	3 (a, b, c, d)/ 5 (c, d, f, g, h)
Cored boreholes** (chemistry priority)			
– during drilling	X	–	3 (a, b, c, d)
– hydrochemical logging	X	–	3 (a, b, c, d)
– complete chemical characterization	X	–	4 (e)/ 5 (c, d, f, g, h, I, j, k, l)
– long-term monitoring	–	–	5 (c, d, f, g, h)

* The analysis classes are defined in Table 8-4, Chapter 8.

** Typical waters that can comprise important input data in mixing calculations, see section 8.2.

*** Also includes options from the discipline *surface ecosystems*, such as nutrients, heavy metals and radionuclides.

Water sampling in the field

In an initial phase, before the area is overly affected by drilling activities, a comprehensive analysis of surface waters and near-surface groundwaters is begun in close cooperation with the discipline *surface ecosystems*. The scope is dependent on the availability and type of sampling objects in the area. The choice of sampling points is made on the basis of indications of recharge and discharge areas and to get a spread over the entire area and cover different types of sampling objects.

The samplings are performed in the form of a first coordinated sampling campaign which is then repeated regularly during a two-year period in a small number of selected sampling points. The purpose is to obtain as clear an overall picture of the surface water system in the area as possible, including with regard to the size of the natural variations during e.g. an annual cycle. The chemical composition of surface waters and near-surface groundwaters can be expected to vary widely depending on weather conditions and time of year, and it is important to get an idea of the size of the variations. From the viewpoint of the discipline *surface ecosystems*, it is also necessary to know when the variations occur and what controls them.

Yet another form of recurrent follow-up is long-term monitoring of the water composition in a number of selected observation points. The programme for long-term monitoring will continue during the complete site investigation and also extend into the detailed characterization phase. An ambition is to obtain long time series, but sampling points will be eliminated or added during the course of the investigations.

In conjunction with or after the more near-surface samplings and as the drilling programme gets underway, samplings in percussion boreholes begin. The execution of water samplings in the field is described in general terms in point form with reasons for scope of analysis. For a more detailed description of characterization methods, the reader is referred to section 8.3.

- Precipitation in the form of rain and snow is collected during different seasons over a two-year period. The composition of the precipitation is important from modelling aspects and should therefore be characterized exhaustively, but since many concentrations are very low and below the detection limit, a limited analysis programme as per class 3 is carried out.
- In the first comprehensive sampling of lake water, sea water, springs and watercourses, the samples are taken at many points on the same occasion and the scope of the analysis is as complete as possible. Thereafter, on repeated sampling occasions and based on earlier results, the number of sampling points can be reduced. All components are not analyzed on every occasion. Table 3-1 gives the maximum and minimum scope.
- Sampling of sediment plugs in lakes and sea is carried out with several discipline-specific programmes (including geology and surface ecosystems) as stakeholders. For hydrogeochemistry, it is the sediment pore water that is interesting, and the scope of the analysis should as far as possible correspond to class 5, since pore water composition is important from modelling aspects. The number of sampling points depends on their availability, but can be limited to 5 per candidate area. Natural variations in pore water composition are examined in one or two of the points by repeating the samplings.

- Samples are taken from wells during the survey campaign. Some of the wells are selected for inclusion in the repeated sampling (approximately six times per year over the course of two years) in order to determine natural variations. The selection takes into account anthropogenic sources of contamination such as road salt, fertilized fields and barns. All private wells in the area are included in a programme for long-term monitoring of drinking water quality. Analysis class 3 is warranted by the fact that these waters are expected to be impacted by human activities and chemistry data thereby has limited use in modelling.
- Water samples from soil pipes are expected to provide a good picture of near-surface groundwater systems compared with samples from existing wells. A relatively large number are positioned to provide a good spread over the area and to investigate recharge and discharge areas. Furthermore, different land types (forest, meadow, bog, etc) should be covered. The first survey includes all soil pipes. After that a number of soil pipes are selected for repeated sampling over the course of two years. Some of the soil pipes will be included in the long-term monitoring programme.

Sampling is performed immediately after drilling in all percussion boreholes in order to provide a picture of as undisturbed conditions as possible. For practical reasons the scope of the analysis is limited to class 3. Another reason for this limitation is that the water may have been contaminated by oxygen in conjunction with drilling. Repeated sampling, as per analysis class 5, is performed in a few selected boreholes, six times per year during a two-year period. This sampling is done to identify natural variations, if possible, and takes place in conjunction with other sampling of surface waters and near-surface groundwaters. Long-term monitoring takes place in selected boreholes (approx. 5) as per analysis class 5.

The samples from the various sampling objects are analyzed in accordance with one of SKB's chemistry classes /SKB, 1998/, see Table 8-4, Chapter 8.

Analysis, interpretation and modelling

The results from samplings and analyses are interpreted and compiled in a hydrogeochemical model, version 1.1, and are included in the background material for choice of priority site within the candidate area, see Figure 3-12.

The samplings and analyses that have been carried out with respect to near-surface conditions are interpreted to provide a spatial presentation of the distribution of the chemical components. The results are used to identify and/or confirm the recharge and discharge areas and to identify the occurrence of different typical waters. If possible, the effects of chemical reactions and biological processes will also be examined.

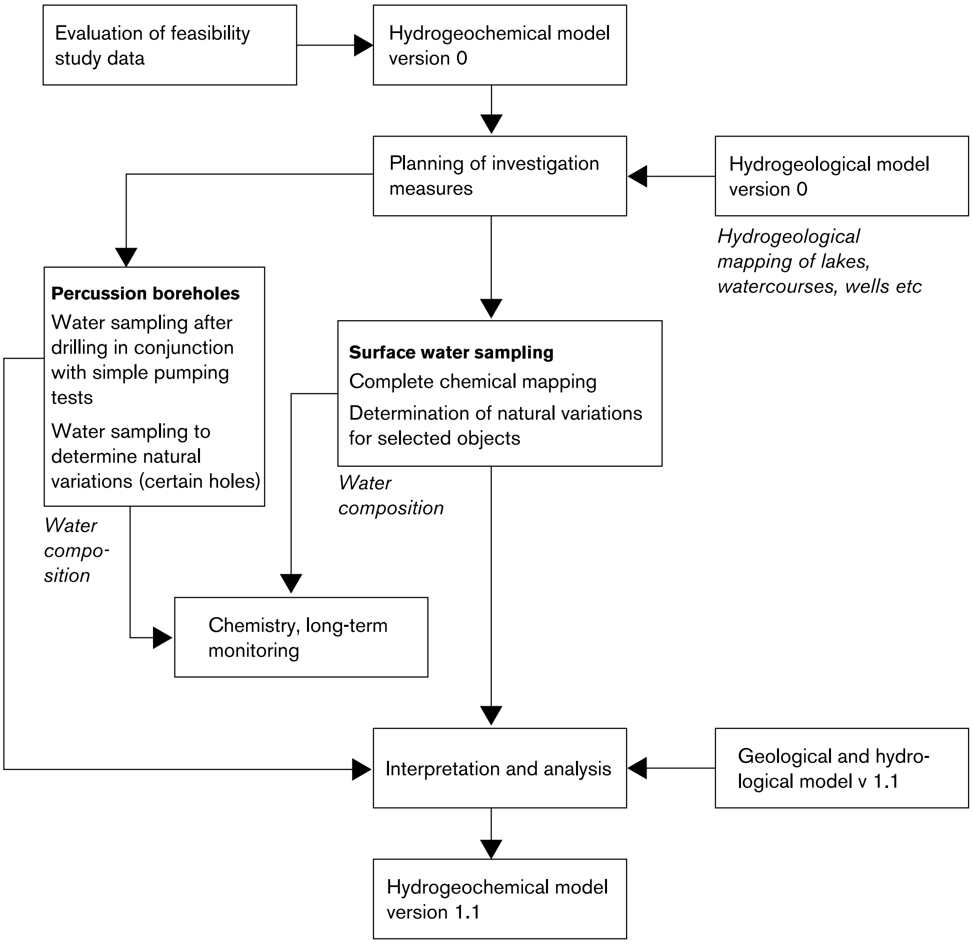


Figure 3-12. *Flow plan and information needs for the first hydrogeochemical model that is devised in the first step of the initial site investigation.*

3.2.8 Transport properties of the rock

The initial site investigations include a limited number of investigations within the transport programme. No new measurements are performed during the initial sub-step. Geological and hydrochemical investigations, such as rock type determination and water sampling, provide material for links to available generic databases for diffusion and sorption parameters that can be used for initial estimates of site-specific transport parameters. Parameters, models and methods used by the programme for transport properties are presented in Chapter 9.

Interpretation/modelling

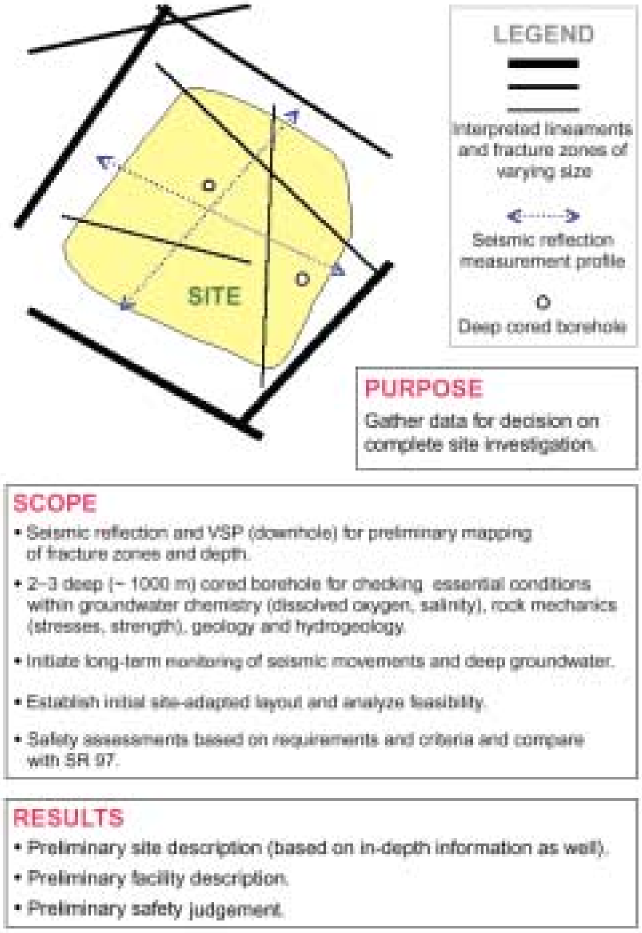
It is not meaningful to carry out transport modelling in the early phase before a priority site has been chosen with the limited data that are then available. In other words, no transport model version 1.1 will be devised. In this phase, however, estimates of transport parameters will be made based on generic data from similar bedrock conditions.

3.3 Initial investigations of the site

By no later that when the priority site within the candidate area has been chosen, the investigations will be focused on characterizing the conditions at depth. However, it should be pointed out that there are no technical obstacles to drilling deep cored boreholes even before all the investigation steps described in section 3.2 have been carried out.

Initial and limited investigations of the site are carried out in order to improve established models, especially at depth, and determine whether the site is suitable for further investigations. Of primary importance is to identify any conditions at depth that cannot be accepted or are clearly unsuitable for the deep repository.

Based on the integrated overview in Figure 3-13, discipline-specific execution programmes are given below. The investigations in this phase are based, for each investigated site, on the site-descriptive model, version 1.1, and will result, after completion of the phase, in a site-descriptive model, version 1.2, and a preliminary site description.



PURPOSE

Gather data for decision on complete site investigation.

SCOPE

- Seismic reflection and VSP (downhole) for preliminary mapping of fracture zones and depth.
- 2–3 deep (~ 1000 m) cored borehole for checking essential conditions within groundwater chemistry (dissolved oxygen, salinity), rock mechanics (stresses, strength), geology and hydrogeology.
- Initiate long-term monitoring of seismic movements and deep groundwater.
- Establish initial site-adapted layout and analyze feasibility.
- Safety assessments based on requirements and criteria and compare with SR 97.

RESULTS

- Preliminary site description (based on in-depth information as well).
- Preliminary facility description.
- Preliminary safety judgement.

***Figure 3-13.** The first real in-depth investigations are conducted in the second sub-step of initial site investigation.*

3.3.1 Near-surface ecosystems

The work is concentrated from the previously mainly regional scale to a local data collection on the site. Measurement series and monitoring points that have been initiated regionally will continue until the natural variation and annual cycles have been understood, or serve as reference points for the investigations on the site.

The land use and biotope maps are supplemented with more detailed vegetation maps. Depending on area conditions, the characterizations of lakes, watercourses and marine basins already initiated are continued with regard to chemistry, morphology, hydrology and biota. Based on the existing data compilation and the previously commenced field investigations, GIS modelling will be carried out to produce land-use maps, biotope boundaries, deposit models and surface hydrology. The previously produced availability map (see section 3.2.1) is updated and adapted to the site in order to further safeguard the site's natural and cultural values. The site-descriptive model of the near-surface ecosystems is updated to version 1.2 (Figure 3-14).

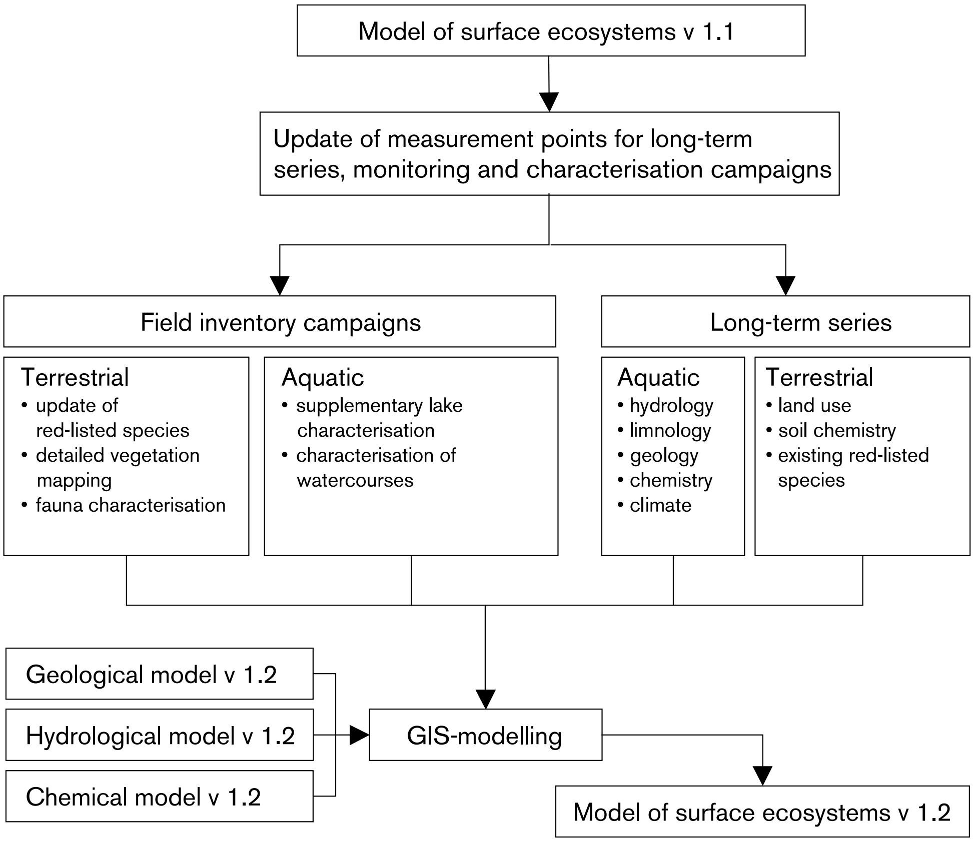


Figure 3-14. *Flow plan and information needs during the initial site investigation in order to update the model that describes the site's surface ecosystems.*

3.3.2 Drilling programme

In the first real investigation boreholes to great depth, it is essential to primarily investigate parameters that require undisturbed conditions and conditions at depth that could directly disqualify the site. A drilling and investigation programme including a few (preliminarily two to three) deep cored boreholes is therefore conducted with these primary purposes, Figure 3-15.

Two of the cored boreholes are planned to be about 1,000 m deep and nearly vertical, while any additional holes will primarily reach down below projected repository depth. The investigations are coordinated with needs from various disciplines. Special account must be taken of the needs within hydrogeochemistry and rock mechanics. The first cored borehole is planned to be a so-called chemistry-prioritized borehole, to be drilled with special requirements on quality and purity, see Chapter 11. One to two cored boreholes are used for rock stress measurements.

A complete hydrogeochemical characterization is done in chemistry-prioritized boreholes. Several of the hydrogeochemical parameters are sensitive to disturbance, which means it is important that the samples be taken early and that special measures be taken in the investigation hole and for cleaning of equipment to be used in the borehole. All boreholes are furthermore checked for salinity and the presence of dissolved oxygen, since both of these parameters are suitability indicators for the siting of the deep repository. These measurements do not require a special chemistry-prioritized hole.

SKB's concept for flushing water management during drilling is applied to all cored holes. The concept is intended to minimize contamination of the rock's fracture system and groundwater with flushing water and drill cuttings and to permit documentation of the contamination that is unavoidable, see section 11.3.2.

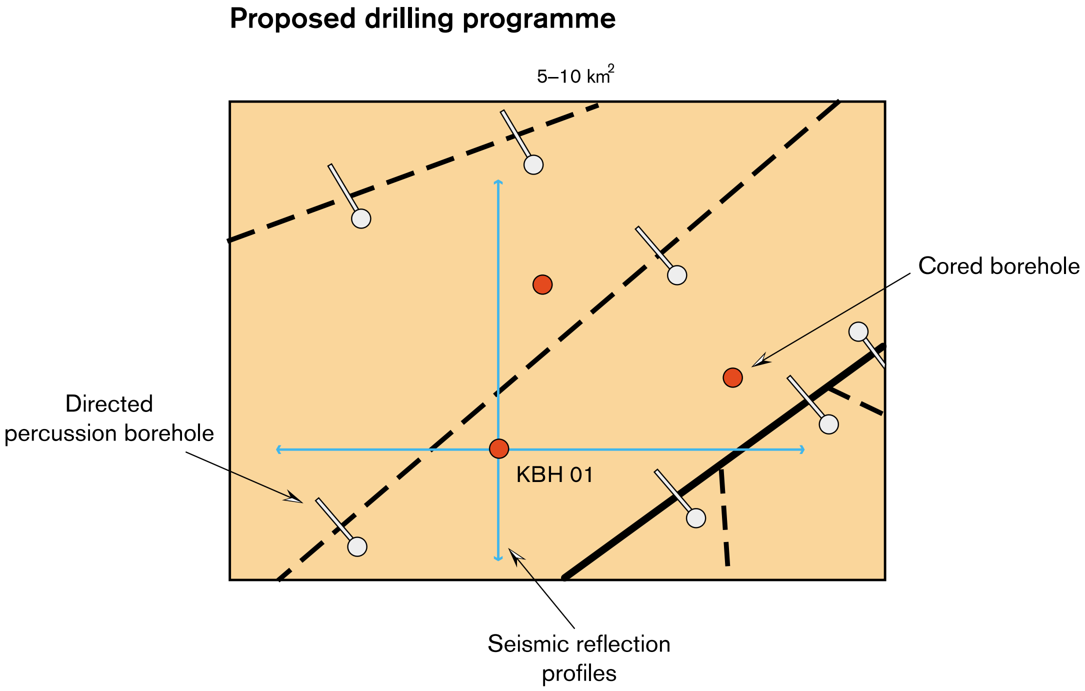


Figure 3-15. In the initial site investigation, 2 to 3 (preliminarily) cored boreholes are drilled. At least one of these is drilled vertically down to a depth of approximately 1,000 m.

The cored boreholes are executed using the telescopic drilling method, see section 11.2.3, whereby the uppermost 100 metres of the borehole has a larger diameter. This section is percussion-drilled either directly or included in percussion drilling after predrilling with core retrieval. The first alternative is used above all for chemistry-prioritized boreholes, and in order to obtain core specimens from this section of the bedrock as well (for geological characterization and for sampling of fracture-filling minerals), a 100 m cored hole can be drilled near the main cored hole.

Moreover, a limited number of percussion boreholes (preliminarily 5–10) with a maximum depth of 200 m are drilled within the site to confirm and preliminarily characterize local major fracture zones and regional fracture zones.

Selection of drilling sites and drilling directions is coordinated to meet the needs of geology, rock mechanics, hydrogeology and hydrogeochemistry in particular. At least one of the cored boreholes should be positioned in such a way in relation to completed or upcoming seismic reflection measurements that it can be utilized for VSP measurements, see 3.3.3.

The surveying of soil layers and (where applicable) lake and sea sediments continues within the programme for surface ecosystems, now more focused on the site, which may entail drilling of additional soil boreholes, including soil sampling, recovery of sediment plugs and installation of groundwater pipes. As in the previous phase, these drilling activities are integrated with the programmes for geology, hydrogeology and hydrogeochemistry, which utilize collected data for programme-specific purposes. In connection with soil drilling, the top surface of the rock is sampled, in the form of either cuttings or core sampling or using a specialized method for sampling of rock chips, see section 11.2.1.

3.3.3 Geology

Fractures and fracture zones occur in all sizes and may be the phenomenon that most typically requires greatly increased investigation efforts as demands on knowledge of the bedrock increase. It is only when the investigation is concentrated to a site that it actually becomes possible to map the fracture zones in the rock with depth. Above all, it is important to investigate whether any major gently-dipping fracture zone occurs at a depth unsuitable for the facility, since such zones greatly restrict the available rock volume and can even make the site unsuitable for the deep repository. Rock types and their distribution with depth are not critical in the same way, unless workable minerals are encountered, but since the first cored boreholes are drilled in this phase, the first direct information on rock types and their distribution at repository depth is now obtained.

The investigations in this phase are focused on seismic reflection and interpreting the results from the first deep investigation boreholes. If seismic reflection measurements have already been performed before the site was chosen, supplementary measurements can now be performed.

Geological mapping of rock and soil types

Field mapping of soil types is carried out. Sampling in the form of digging and soil drilling is performed in order to study the sequence of soil strata and the character of the soils. The scope of the soil description is determined by what has been done in previous steps and by what is required in this step. Other mapping of soils can be carried out during complete site investigation.

The distribution of the rock types on the surface is determined by mapping. Sampling and analysis are carried out for determination of rock type. Even if only a few boreholes are drilled to great depth, the drill core and downhole investigations provide a relatively good picture of existing rock types and their distribution, as well as other geological-structural conditions. Figure 3-16 summarizes how the investigation is conducted in this phase in order to update the site-descriptive model with regard to rock types. See section 4.3. for a description of the methods referred to in the figure.

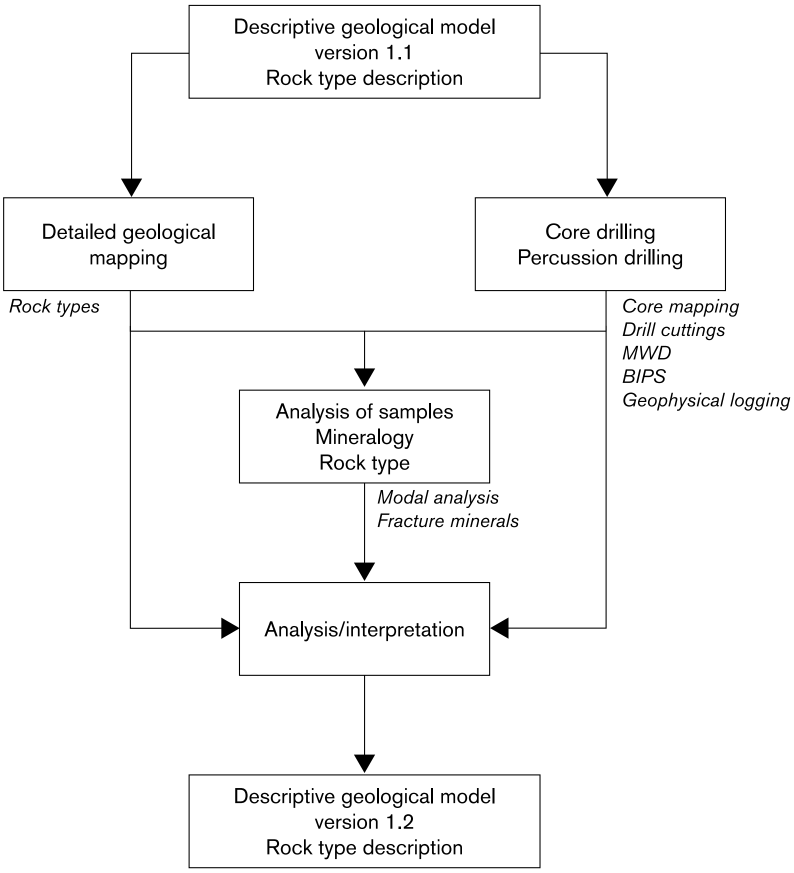


Figure 3-16. *Flow plan for characterization and modelling of rock types during the first step of initial site investigation on the site.*

Fracture zones and fractures

The geological-structural characterization is aimed at preliminarily identifying fracture zones that affect the overall repository layout. This means that it is primarily the regional and local major fracture zones that should be identified. It is thereby also important to look for indications of possible gently-dipping major fracture zones, since they cannot easily be identified from the early surface mapping. The fracture zones that can be expected to be of less importance for the repository layout (mainly local minor fracture zones and fractures) are more roughly determined in this step. A flow plan for preparation of model version 1.2 for geological structures during the initial site investigation is shown in Figure 3-17.

With the guidance of the site-descriptive model from the previous phase, strategic locations are planned for a (supplementary) seismic reflection measurement programme. (Seismic reflection may possibly be commenced even earlier, see 3.2.2.) Seismic reflection is carried out as one of the first investigations in this phase and is performed preliminarily along intersecting profiles, each a few kilometres in length.

Data for identification and interpretation of fracture zones are taken from geological and geophysical measurements (see sections 4.3.5 and 4.3.6) in the cored boreholes, possibly augmented by drilling of shorter percussion boreholes specially intended for determining the dip of ground-exiting fracture zones. One of the deep cored boreholes should be located near the point of intersection of the seismic reflection profiles. VSP (Vertical Seismic Profiling) is planned to be done in this hole, which should be nearly vertical and approximately 1,000 m deep. Co-interpretation of VSP and seismic reflection offers good possibilities for characterizing the presence of major fracture zones in a relatively large rock volume.

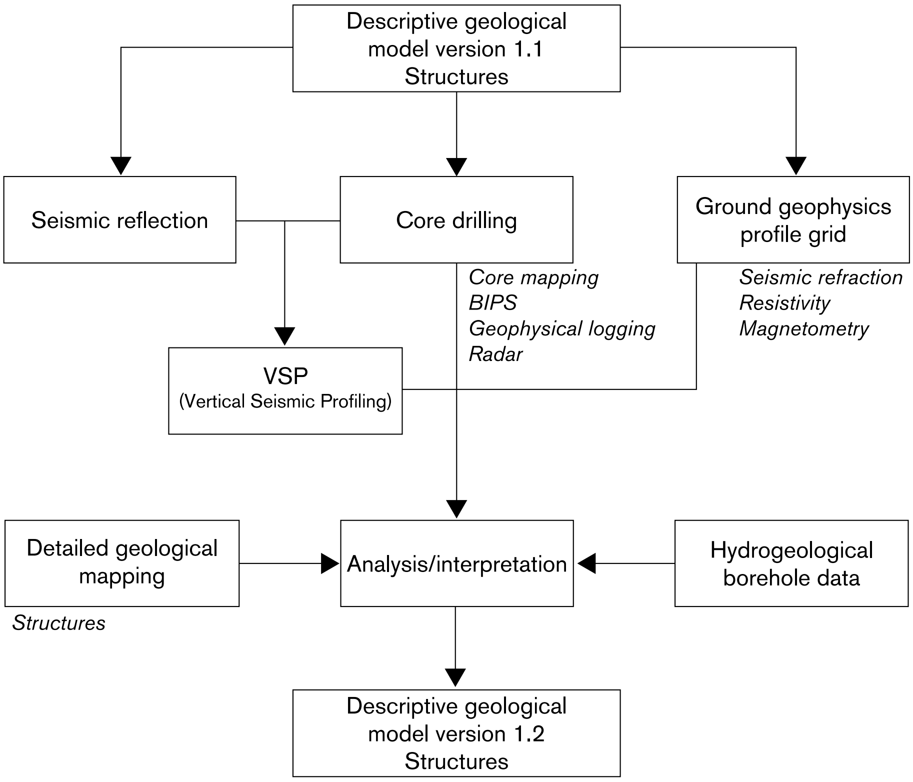


Figure 3-17. *Flow plan for identification of fracture zones and preparation of geological-structural description during the initial site investigation on the site.*

Geophysical profile measurements, mainly magnetic and electromagnetic or electrical methods arranged in so-called profile mats with e.g. six profiles with a profile spacing of 50 m, should be carried out to augment the geological-structural characterization. Electrical resistivity methods (CVES = Continuous Vertical Electrical Soundings) and transient electromagnetic soundings (TEM) can be used to obtain an indication of resistivity changes with depth, which may be due to major gently-dipping fracture zones with a relatively high fracture frequency, or to interfaces with more saline groundwater. If the results can be calibrated by sampling in a cored borehole, it is possible that e.g. the extent of the saline groundwater over a larger area be determined.

Analysis, interpretation and modelling

The geological models are updated (batchwise) as new investigation results are received and are progressively transformed into the local model scale, but the regional models will continue to be kept updated as well. The earlier model versions are based above all on surface data, even though it is presented in three dimensions by means of RVS, where the geometries at greater depth consist for the most part of vertical projections or educated judgements. As investigations proceed toward greater depth, the three-dimensional model becomes more reality-based, even though the limited in-depth investigations in this phase provide only meagre data.

The integrated site-descriptive model is based on a common geometric framework, where the site is divided into different geometric units, see section 4.2.3. The geological site description entails interpretation and analysis of geological data, representing boreholes and surface data, to identify geometric units so that each geometric unit can be given geological properties for the geological site description.

The locations of the geometric observations of possible fracture zones is entered in RVS. In order to determine the locations of the fracture zones, an attempt is made in interpretation to tie these different observations together into different coherent zones. Interpretations and uncertainties are described in the site-descriptive document. An initial base interpretation of the location of regional and local major fracture zones on the site is also reported in RVS. Alternative locations, or completely alternative interpretations, can also be presented, depending on a judgement of the magnitude of the uncertainties. Varying and uncertain parameters are described statistically. Model documents and different RVS representations comprise the geological model (version 1.2) after completed initial site investigation.

Besides description of the current conditions on the site, the geological site description also includes describing the geological-tectonic evolution of the site.

3.3.4 Rock mechanics

The actual rock mechanical characterization is not started until deep cored boreholes are available. The investigations will be focused on obtaining an overall picture of the initial rock stresses and the quality of the rock mass at the planned repository level within the chosen site. An initial assessment is made in this sub-step of whether there is a risk of serious stability problems at repository level. See section 5.3 in Chapter 5 for a method description.

Rock stresses

Rock stress measurements are carried out by means of the overcoring method down to about 500 m and by means of hydraulic fracturing down to about 700 m. The measurements (both methods) start at a depth of about 200 m. Hydraulic fracturing is done after the hydrogeological characterization of the borehole.

The measurements are done at 2–3 levels in order to get an idea of fracture growth with depth. The aim is that one or two holes will be used and that both methods will be used. The holes should be positioned relatively centrally in potentially interesting blocks of intact rock so that the measurement results will not be disturbed by any local disturbances in the stress field near the boundaries of the blocks. In order for hydraulic fracturing to be performed, the boreholes should not deviate more than 30° from the vertical.

The boreholes are mapped with respect to possible instability. If breakouts are observed, this reveals high rock stresses.

In order to get a picture of the orientation and variation of the regional stress field, the downhole measurements should be augmented by surface rock stress measurements in rock outcrops by means of overcoring within a large area.

Characterization of rock cores

In addition to collection of geological parameters, the drill core is mapped with respect to:

- the quality of the rock mass by mapping of the drill core in accordance with the various rock classification systems (see section 5.3.4), and
- core discing, which reveals high rock stresses.

Various tests are performed in the laboratory on retrieved drill cores, such as:

- Uniaxial and triaxial compression tests for determination of the deformation and strength properties of the intact rock.
- Determination of the propagation velocity of the P-wave, which can be used to judge whether retrieved drill cores have been damaged by microfractures. (The use of full-wave sonic (FWS) logging, which gives both P- and S-wave velocity, is being considered within the geological programme. FWS can then be an important complement to these laboratory measurements on cores and provide a virtually continuous velocity profile along the borehole.)

The tests are utilized to identify any property variations with depth or between rock types.

Information from rock cuts and outcrops

The following information from the geological mapping of rock cuts and outcrops will be used:

- Orientation of fractures and fracture zones.
- Fracture length.
- Fracture roughness (on small and large scale).

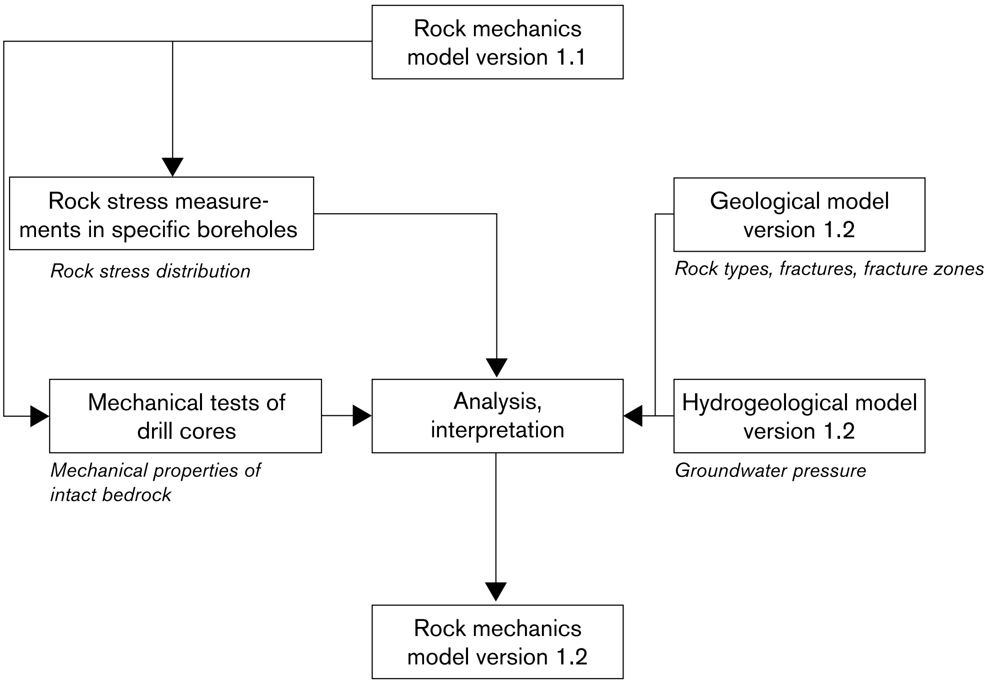


Figure 3-18. *Flow plan for updating the descriptive rock mechanics model in the initial site investigation on the site.*

Analysis, interpretation and modelling

Primary data obtained from the investigations are stored in SICADA, and based on these data the rock mechanics site descriptive model is updated to version 1.2, Figure 3-18, which comprises a part of the overall preliminary site description, see further section 5.2.3.

3.3.5 Thermal properties

The main thrust of the initial site investigations in this phase is to identify wherever possible any unsuitable conditions such as high thermal gradient, high initial temperature at repository depth or highly heterogeneous thermal properties. In this phase the investigations will be focused on the following activities:

- Logging of temperature in boreholes.
- Determination of density, porosity, chemical and mineralogical composition, thermal conductivity and heat capacity on cores from the first cored borehole.

Analysis, interpretation and modelling

Primary data obtained from the investigations are stored in SICADA, and based on these data the rock mechanical model is updated to version 1.2, which comprises a part of the overall preliminary site description.

3.3.6 Hydrogeology

The initial site investigations of the site are aimed at providing a general picture and first estimate of the water-bearing properties of the rock from the ground surface down to a depth of approximately 1,000 m (size and variability both spatially and in terms of properties). Another purpose is to improve the description of the boundary conditions by continuing and expanding the monitoring programme within the regional area. The limited number of holes that are drilled during this phase do not permit a complete determination of the variation of hydraulic conductivity within the site, but provide some idea of conditions at depth.

Hydraulic borehole tests

Investigations are performed in the manner described in section 3.2.6 in the percussion boreholes that are drilled. An extensive investigation programme is performed in the cored boreholes.

During core drilling, pumping tests should be performed for every 100 m section in the rock. Furthermore, a pumping test should be conducted whenever water samples are taken during drilling. The absolute pressure should also be measured in sections along the borehole. After drilling the cored borehole should be pumped and flow-logged (see section 7.3) to provide information on the more hydraulically conductive sections of the borehole. The information is used for interpretation of the rock's structures and as a basis for where water sampling and packering should be performed in the hole. The pumping test is performed as an interference test if there is reason to believe that pressure responses can be measured in nearby boreholes. Data from the geology programme (BIPS logging and geophysical logging) are a sufficient basis for the hydrogeological evaluation of the borehole.

Hydraulic tests should therefore be carried out systematically along the entire cored borehole (although only after the completed chemistry campaign in chemistry-prioritized holes). These tests are performed before hydraulic fracturing is done to determine rock stresses, see section 3.3.4. The tests can be performed as injection tests with a (preliminary) section length of 20 m, or as differential flow logging, see section 7.3.3. Moreover, injection tests with a (preliminary) section length of 5 m are carried out in a couple of boreholes within the depth interval 100–700 m. After the systematic testing of the borehole, a couple of pumping tests between packers can be considered, for example if the borehole penetrates regional or local major fracture zones of high hydraulic conductivity. Pumping time and recovery time are then estimated to be a few hours.

Groundwater flow measurements are performed below the natural gradient in a selection of short sections in a couple of cored boreholes. Data on the salinity distribution with depth, which are essential for the groundwater flow modelling, are obtained from the hydrogeochemistry programme.

Each cored borehole is subsequently packed-off and monitoring of groundwater pressure is begun. In order to provide time series of the natural variation, previously initiated monitoring of groundwater levels in wells, groundwater pressures in percussion boreholes and meteorological and hydrological parameters continues. During periods when neither hydrotests, nor drilling nor other hydraulically disturbing activities are going on, the natural (undisturbed) groundwater flow can be measured in the packed-off sections.

In the final phase of the initial site investigation, it is considered whether interference tests should also be performed during this phase. However, the basic principle is that such tests are not performed until during complete site investigation.

Hydrogeological mapping

The hydrogeological mapping may be augmented within the site in question. Important background information for the hydrogeological model is the Quaternary geology and the bedrock geology (interpretation of fracture zones, fracture orientation, fracture roughness, fracture lengths, truncation of fractures, orientation of mapped surfaces on rock outcrops and road cuts) within the site. Calculated principal stress directions in the rock mass provide part of the information needed to assess possible anisotropy in the rock mass.

Interpretation, analysis and modelling

The modelling work consists largely of analysis of results from flow logging, pumping tests and injection tests. The conceptual models are examined and modified if necessary. Spatially distributed properties are obtained as a result of the analysis. An assessment is made of whether anisotropic conditions prevail, since this influences the continued investigations. Figure 3-19 illustrates the working methodology for how the models are devised, essentially based on investigations and tests in percussion and cored boreholes. The lithological and hydrological model is updated according to Figures 3-9 and 3-10.

A three-dimensional local-scale description is prepared in version 1.2 for the hydrogeological model. The regional-scale description is updated.

- Hydrology and soil layers are described in the same way as in version 1.1, but with greater precision and revised principles for geometric subdivision. The hydraulic properties of the soil strata can now also be determined based on the results of different hydraulic tests.

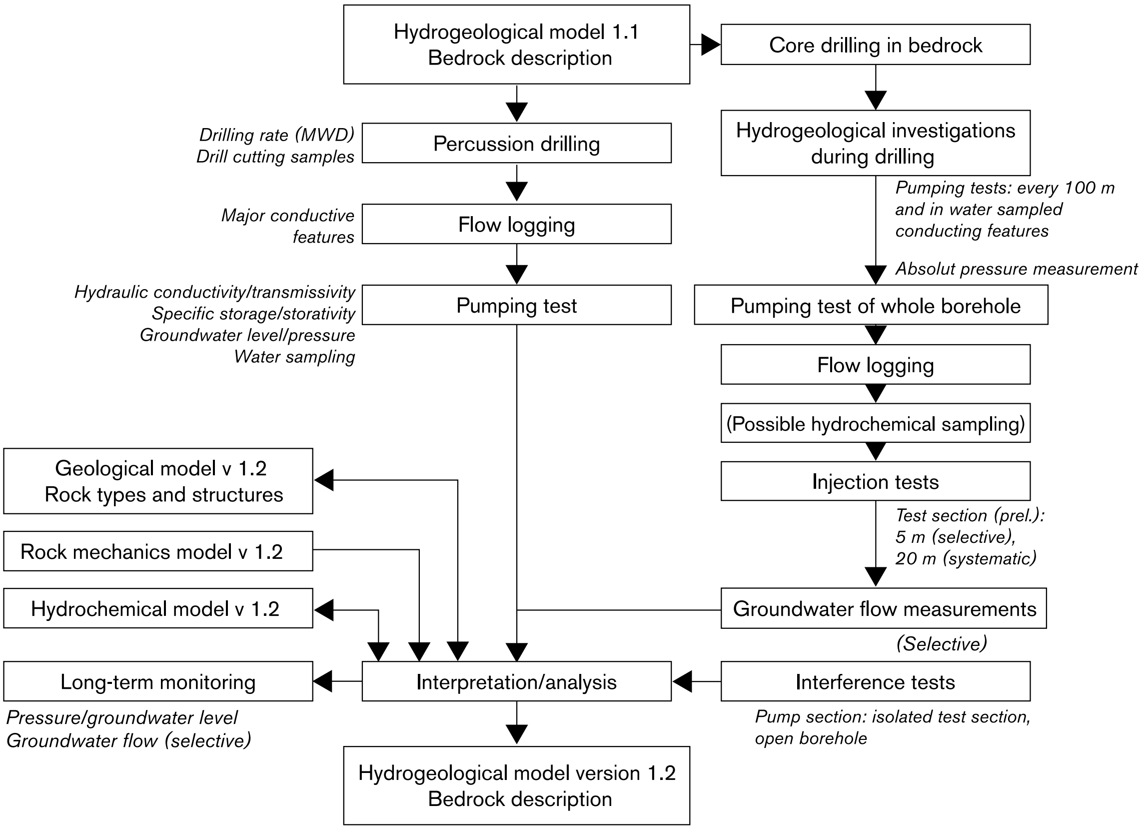


Figure 3-19. Flow plan for description of the rock in the hydrogeological model in the initial site investigation on the site.

- For the rock, transmissivity is roughly determined for the near-surface parts of major fracture zones and at greater depth for the areas where information is available from the deep boreholes. The distribution of the hydraulic conductivity in the parts of the rock that are not classified as fracture zones is indicated roughly and at different levels of detail ("scales"). The entire holes are described preliminarily, down to a depth of about 1,000 m, on scales of both 100 m and 20 m, and conductivity is also indicated on the 5 m scale in the depth range 100 m to 700 m. Furthermore, an assessment is made of whether the rock is hydraulically anisotropic, based on the geological and rock mechanical models and on results from injection tests and any interference tests performed. The scale is finally determined in connection with the formulation of the site-specific execution programmes. However, it is essential that all investigated sites be described in a uniform manner.

Prevailing groundwater flow is calculated on the local scale based on the descriptive model. The purpose of the calculations is to obtain an overview of the large-scale flow pattern in order to assess the recharge and discharge areas and to study how different boundary conditions influence the results. New calculations of the groundwater flow on the regional scale may also be done.

3.3.7 Hydrogeochemistry

The results from the hydrogeochemical characterization during the initial site investigation provide guidance for deciding whether to continue with the investigations. The salinity and redox status of the water at repository level are the crucial chemical parameters in this phase. No extensive calculations are required to clarify whether the site is acceptable for continued investigations. When the priority site has been chosen, the work is concentrated on this site. The hydrogeochemical work is organized into the following main activities:

- Sampling in all percussion boreholes after drilling.
- Sampling during drilling of cored boreholes.
- Hydrochemical logging in all cored boreholes.
- Complete chemical characterization of at least one deep chemistry-prioritized cored borehole.
- Start of long-term monitoring of chemical parameters in new selected sampling points.
- Fracture-filling mineral investigations are initiated during the final phase of the initial site investigation.
- Preparation of model versions 1.2, since the description of chemical conditions at depth is of great importance for determining whether the site still has good prospects of being suitable for the deep repository.

An overview of the sampling objects included in the initial site investigation as well as sampling occasions and scope of analysis for the different objects are given in Table 3-1 above.

Water sampling in the field

Water sampling in the field continues and is done using the same procedures as in the initial part of the initial site investigation, see section 3.2.7 above.

Work in cored boreholes

At least one of the cored boreholes during the initial site investigation, and probably the first one, will be chemistry-prioritized. This means that only a few, absolutely necessary investigations may be performed before "complete chemical characterization" of the borehole, and that high demands are made on purity and choice of materials during drilling (see Chapter 11). Sampling is done using several methods and on several occasions. The work is performed in the sequence described below, and the results of each step provide information for the next step.

- Water sampling during drilling will take place with a water sampler in the section. The advantage of this sampling is that the impact on the groundwater chemistry is judged to be less than on subsequent sampling occasions, since the borehole's short-circuiting effect has been acting for a shorter time. A disadvantage is that flushing water contamination of the samples may be high, and that the number of parameters that can be determined is limited. Sampling as per class 3 takes place when water-bearing fracture zones are penetrated and/or every 100 metres.
- BIPS taping, flow logging and geophysical logging of temperature and electrical conductivity are performed within the discipline-specific programmes for hydrogeology and geology prior to complete chemical characterization. Information from these methods is necessary for choosing water-bearing borehole sections for chemical characterization.
- A hydrochemical logging of the borehole is done shortly after concluded drilling using a hose sampler. Hydrochemical logging quickly provides a picture of the water composition in 50-m sections along the entire borehole and detects any concentration anomalies. The analyses are done as per class 3.
- Complete chemical characterization with a mobile field laboratory is commenced within a month of drilling. This sampling is conducted in water-bearing sections in the boreholes (hydraulic conductivity K between 10^{-6} m/s and 10^{-8} m/s) and the sections are distributed over the depth. A guideline is five sampled sections per borehole. The samples are analyzed as per classes 4 and 5.

The hydrochemical logging may be repeated to investigate possible changes in the water composition when the borehole has arrived at a steady state after drilling. The purpose is to identify internal circulation in the hole.

After complete characterization, at least two borehole sections in each borehole will be selected for continued regular sampling (once or twice a year), which represents the start of long-term monitoring of chemical parameters in these cored holes. Permanent downhole equipment must be installed in the boreholes for this purpose.

The samples from the various sampling objects are analyzed in accordance with one of SKB's chemistry classes /SKB, 1998/, see Table 8-4, Chapter 8.

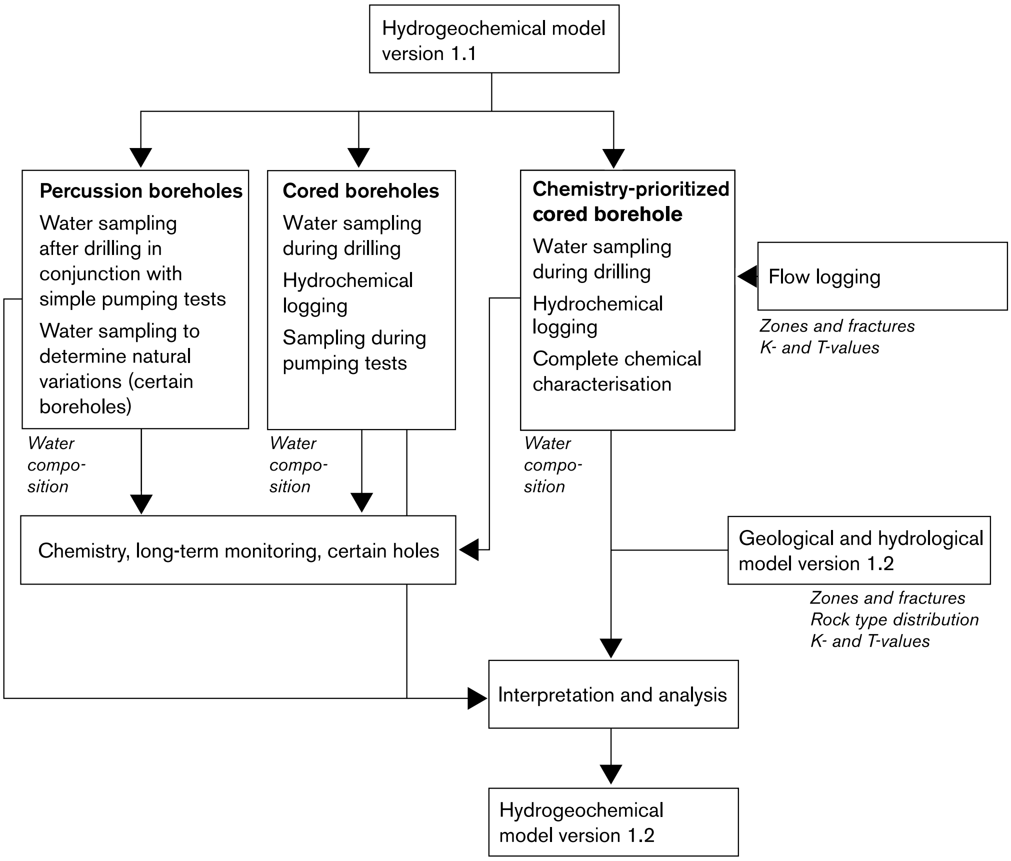


Figure 3-20. *Flow plan and information needs for the hydrogeochemical model that is devised in the initial site investigation on the site.*

Analysis, interpretation and modelling

The preceding version of the descriptive hydrogeochemical model (version 1.1) is updated on the basis of investigations, analyses and interpretations during this step to model version 1.2, see Figure 3-20. This in turn serves as a basis for the continued investigations during the complete site investigation.

3.3.8 Transport properties of the rock

Investigations

When the investigations have been focused on a site, drilling of a few deep boreholes takes place. This means that the regional groundwater model can be refined with data that are of great importance for the modelling of the transport properties of the rock. These are:

- Location, geometry, extent and connectivity of hydraulically conductive features.
- Frequency of hydraulically conductive features in the rock mass (conductive fracture frequency).
- Hydraulic conductivity in the rock mass.

- Groundwater flow (calculated and measured).
- Rock type distribution at great depth in the rock mass.
- Fracture-filling minerals and alteration.
- Hydrogeochemical conditions.

The methods and investigations that are used to determine these parameters are described for the most part in the geology, hydrogeology and hydrogeochemistry chapters. Determination of the groundwater flow and thereby also indirectly distribution of hydraulic conductivity and hydraulic boundary conditions are of great importance for being able to estimate the transport properties of the rock. Measurements of groundwater flow are thereby made in one of the first deep boreholes, in short sections (2 to 10 m) along the borehole in selected fractures or fracture zones. In cases where mineralogy and/or groundwater chemistry deviates significantly from the generic database, certain time-consuming laboratory investigations, such as through diffusion measurements, will be initiated.

Analysis, interpretation and modelling

No complete model of the transport properties of the rock on the site is made during the initial site investigation. However, based on the geological, hydrogeological and hydrogeochemical description, version 1.2, a first preliminary description is made – transport model version 1.2, see Figure 3-21. The model is mainly used for planning and design of upcoming field and modelling work. This very preliminary description of transport properties will be included in the overall preliminary site description that will be presented after the initial site investigation. Section 9.2.3 provides a more exhaustive description of how the modelling work will be carried out.

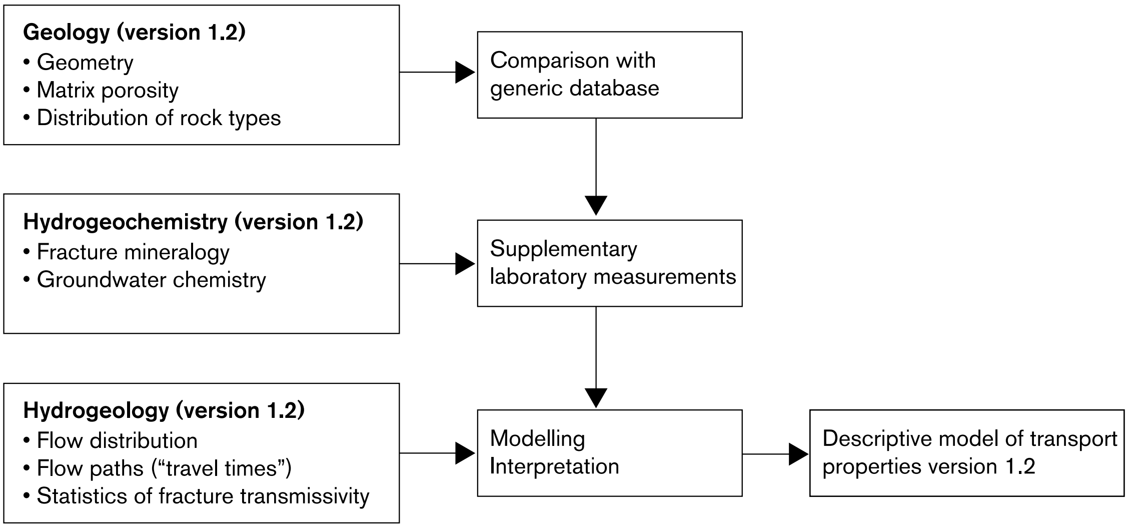
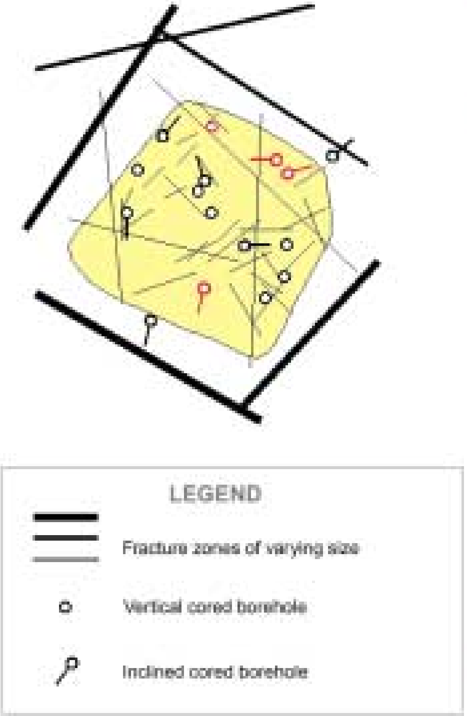


Figure 3-21. *Flow plan and information needs for the model of the transport properties of the rock that is devised during the initial site investigation on the site.*

3.4 Complete site investigation

The main purpose of complete site investigation is to carry out investigations on the site and in its regional environs in order to obtain sufficient background data to be able to finish design and safety assessment and thereby be able to determine the suitability of the site for the deep repository, see Figure 3-22. The investigations will be carried out in sub-steps, and since the investigations are dominated by drilling and borehole investigations it is above all practical aspects of these operations that control the subdivision into steps. This is further elaborated on in the drilling programme, section 3.4.2. The characterization of the particular site during complete site investigation is based on version 1.2 of the site-descriptive model. The site-descriptive model is updated to new versions (2.1, 2.2, etc) for each sub-step. After complete site investigation is finished, the final site account is compiled in a final report called site description.



PURPOSE

Gather the necessary supporting data for selection of site and application for siting permit.

SCOPE

- Supplementary geological and geophysical ground surveys on the site and in the regional environs.
- Drilling programme (percussion and cored drilling) with measurements including:
  - – measurement and sampling during drilling,
  - – core mapping, BIP (Borehole Image Processing), geophysical measurements,
  - – flow logging, injection tests, pumping tests, cross-hole tests,
  - – dilution tests, groundwater sampling/analysis,
  - – in-situ rock stress measurements and laboratory analyses of rock samples.
- Continued long-term monitoring.
- Activities governed by site-specific conditions and arising questions (cf. red symbols in figure at left, i.e. ○ ⚲).
- Site-specific databases with quality-assured primary information.
- Site models on regional and local scale.
- Site-adapted deep repository facility and analysis of feasibility.
- Complete safety assessment carried out.
- Background information for EIA consultations and EIS document.

RESULTS

- Site description.
- Facility description.
- Safety report.

Figure 3-22. The complete site investigation is dominated by deep boreholes and extensive downhole measurements.

3.4.1 Surface ecosystems

In addition to a continued follow-up of seasonal variations that was started during the initial site investigation, existing data are augmented by quantitative inventories of terrestrial and aquatic fauna and flora. This work consists of estimating the coverage of dominant vegetation types and fauna belts. A stratified quantitative sampling is carried out in each identified dominant zone to permit estimation of the total biomass. The quantitative samples are sorted and species determinations are made of the dominant taxa, along with biomass quantity estimates per m^2 expressed as carbon. Different methods are used, depending on the biotope (see Chapter 10). This quantitative material is used in the systems-ecological models that serve as a basis for the safety assessment, but is also supporting material for the EIS for the deep repository. The information is also essential for being able to make assessments of possible radiological effects on the environment.

During the complete site investigation, measurements should also be made of biological production, above all in lakes and mires but possibly also in the sea. The work is pursued as intensive campaigns during the different seasons of the year, where the oxygen and carbon dioxide curves are followed, along with nutrient turnover, for the different biotopes in the waters. On land, production estimates are carried out in the form of measurements of the growth of the vegetation at certain selected sites. Despite the fact that production estimates are important quantitative information in the systems-ecological models that are used in the safety assessment, few measurements have been made to date.

In conjunction with the hydrology programme, mappings and quantifications are carried out of the terrestrial and aquatic discharge areas in areas identified in the earlier studies. This provides background material for describing the processes and the turnover in the geosphere/biosphere interface. In conjunction with the geological programme, studies are made of sediments, peat bogs, agricultural land and deposits to describe and quantify the long-term evolution of the area as a basis for describing the future evolution of the area for the next 1,000 years.

The above work is cross-checked against the need for data and understanding for the systems-ecological models developed with the aid of earlier quantifications. The model that describes the site's surface ecosystems is updated, Figure 3-23, and forms a part of the integrated site description. As during the initial site investigation, the availability map is kept up-to-date to ensure that the site's environmental values are taken into account.

3.4.2 Drilling programme

The borehole programme is carried out in a number of sub-steps of 2 to 4 cored boreholes each. The investigations during these sub-steps will be similar but increasingly focused on the relevant repository depth to obtain detailed knowledge within the areas where design has placed possible deposition areas. Additional percussion boreholes will also be drilled.

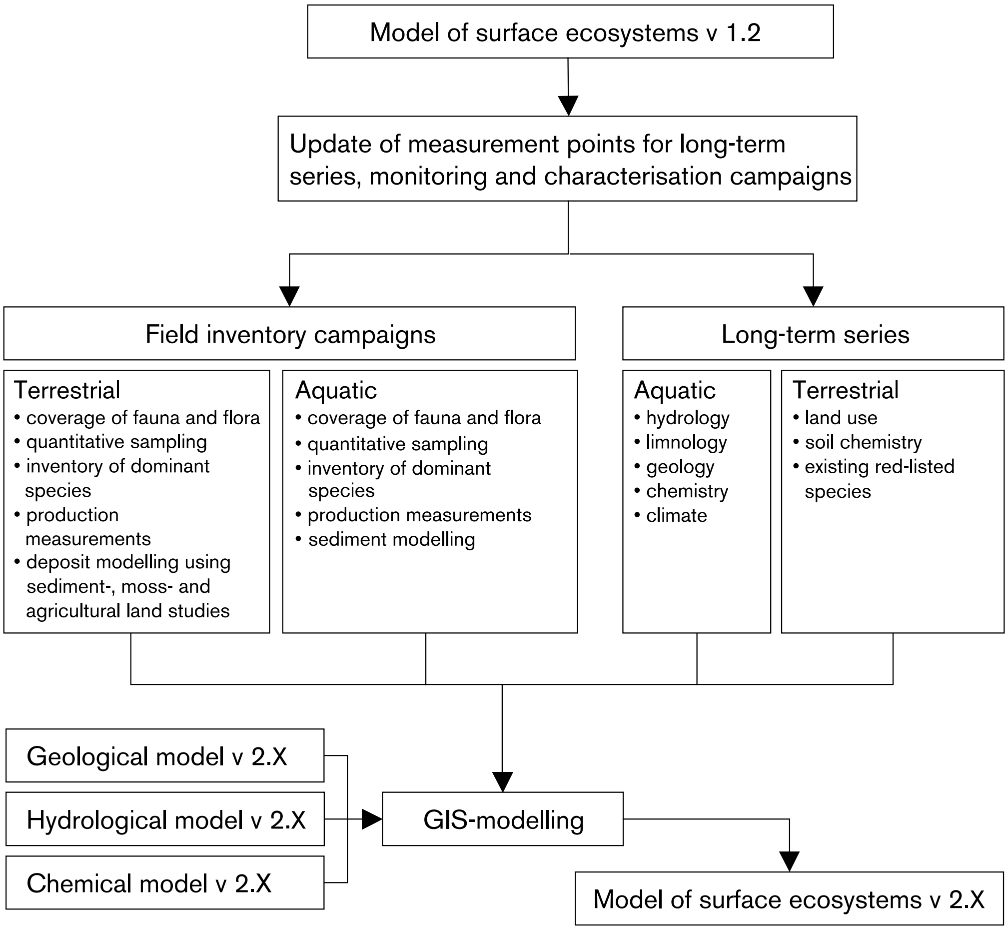


Figure 3-23. *Flow plan and information needs during the complete site investigation in order to update the model that describes the site's surface ecosystems.*

Principal factors regarding the execution of the drilling programme during the complete site investigation include the following:

- The exploratory boreholes shall be suitably distributed over the entire central investigation volume (geographic area and depth), with the objective of achieving the same level of geological knowledge (degree of detail and certainty) for the entire model volume, but with some increased detail for the parts that are of greater functional importance.
- Borehole positions and directions are chosen in order to locate and characterize individual fracture zones and to characterize different rock units. Different borehole directions and inclinations shall hereby be used to achieve statistical representativeness for parameters that may exhibit anisotropic conditions (different fracture directions, and other orientation-dependent parameters).
- At least a couple of the cored boreholes made during this phase shall be chemistry-prioritized.
- The cored boreholes are executed using the telescopic drilling method, see section 3.3.2 above and section 11.2.3.

The scope of the drilling programme in number of boreholes and the scope of the measurements cannot be specified in advance, owing to the fact that conditions on the site – such as soil cover and homogeneity of the rock – are of very great importance for this. As a guide, however, the drilling programme can be estimated to include 10–20 cored boreholes and 5–10 percussion boreholes, see Figure 3-24. One or more of the cored boreholes are located within the regional area in order to provide data as a basis for hydraulic and hydrogeochemical boundary and initial conditions, e.g. depth to saline water, in the regional model.

The characterization of the soils within the site that was begun in the initial investigation is completed. A number of additional soil boreholes are thereby made for sounding of the rock surface and determination of the soil layer sequence (including soil sampling). By the installation of casing pipe, some of the boreholes are preserved for subsequent water sampling, hydraulic tests and groundwater level measurements. The number of boreholes depends on the conditions on the site and on the scope of corresponding drilling work during the initial site investigation.

Mapping and sampling of lake and sea sediments is also completed in this phase.

The drilling programme and various technical conditions that have to be taken into account are discussed in Chapter 11, "Drilling programme".

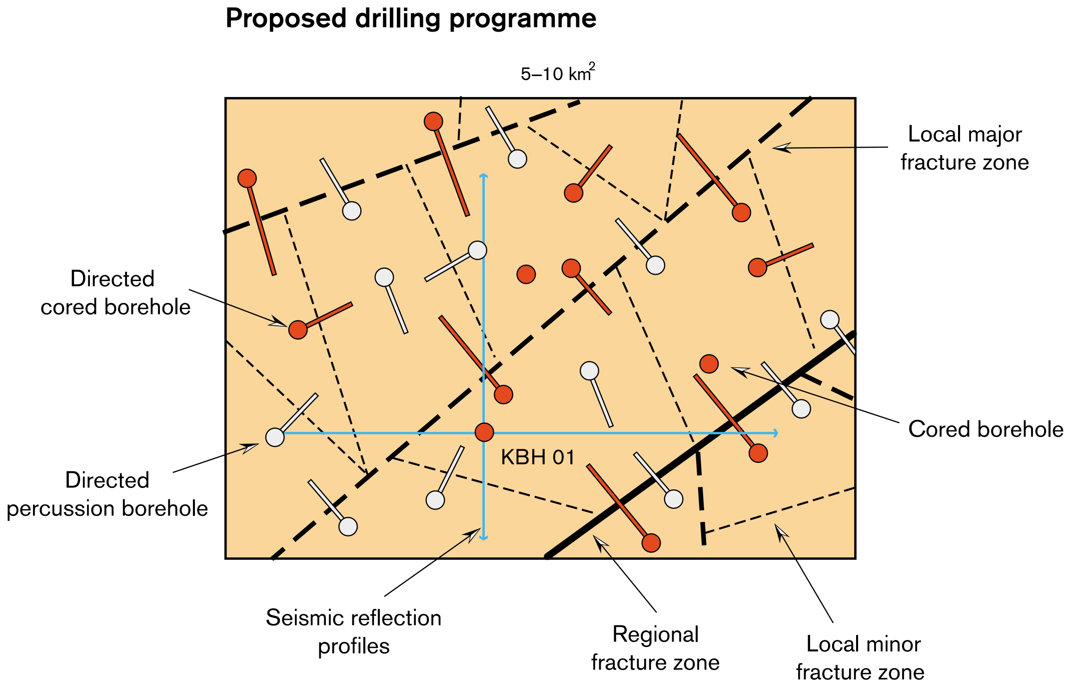

Proposed drilling programme

Figure 3-24. *During CSI, 10–20 cored boreholes and 5–10 percussion boreholes are drilled. The holes are intended for both identification and characterization of fracture zones and investigation of intervening rock.*

3.4.3 Geology

The main purpose of the complete site investigation is to verify and augment knowledge of the rock within the limited area chosen during the initial site investigation by means of borehole investigations and geological and geophysical investigations. The properties of the rock that will be of primary interest are:

- knowledge of the properties and distribution of different rock types,
- greater knowledge of regional and local fracture zones crucial for the overall layout of the deep repository, and
- greater knowledge of the frequency and properties of minor fracture zones and fractures.

The geological investigations will be dominated by drilling and downhole investigations (measurements and tests). Surveys and measurements on the ground surface also occur during the complete site investigation, although to a lesser extent than before and using fewer methods, mainly to supplement previous investigations and answer specific questions from previous investigation steps. The main purpose will be to add detail to the geological mapping and to carry out supplementary geophysical measurements. The regional environs will also probably be subject to supplementary investigations in this phase.

During the complete site investigation, knowledge of all occurring fracture zones that have been classified in consultation with design and safety assessment so that they are not permitted to occur within the repository volume, or can only be permitted between repository sections, are verified/modified and augmented. The geometry of each such fracture zone shall be described deterministically on the site. Detailed properties are characterized. Other fracture zones are described statistically, by which is meant that occurrence, geometric extent and properties are represented by statistical measures.

Investigations of boreholes and drill cores

Data collection during the complete site investigation will mainly be based on drilling and downhole investigations. The different investigation methods are described in section 4.3. The methods and their purposes are summarized only briefly here.

The borehole wall in the finished borehole is videotaped by means of the BIP (Borehole Image Processing) system. Geophysical logging (radiometric, electrical, magnetic, acoustical methods and temperature) and borehole radar are performed. Downhole seismic methods (VSP) are also used. See more detailed method descriptions in section 4.3.

The base for the geological mapping along the cored borehole consists of integrated mapping of the drill core and analysis of the videotape recording of the borehole wall. The combination of drill core and BIPS data have proved very useful for rock types and minor fracture zones and individual fractures. The methodology for the geological borehole mapping is based on taking the geometric components (lithological boundaries and the location and orientation of certain fractures) from the BIPS image, while rock type information and properties of rock surfaces (fracture-filling minerals, roughness, etc) are taken from the drill core. A BIPS-like picture of fractures is obtained with a televiewer, but the method is based on the acoustic properties of the fracture.

The geological characterization of the cored borehole is complemented by laboratory analyses of core specimens. Microscopic, chemical and petrophysical analyses are used for mineralogical analysis of rock types and fracture-filling minerals, chemical composition and determination of density, porosity, susceptibility, etc. In connection with percussion drilling, the colour of the water/cuttings mixture that comes up is checked and routine samples of this are taken for ocular inspection as well as laboratory analyses, if necessary.

The geophysical logs provide supplementary indirect information on the petrophysical properties of the rock, see Chapter 4. For example, the natural radioactivity of the bedrock is measured, which is determined above all by the fraction of radioactive isotopes of uranium, thorium and potassium and thus depends on the mineralogical composition of the rock. The method can therefore contribute towards distinguishing different rock types, which can sometimes be difficult with the naked eye. Among electrical methods, resistivity methods are used to reflect variations in the fracture content of the bedrock along the borehole, whereby individual fractures can be detected or average resistivity determined, depending on how the electrodes are arranged geometrically in the borehole and on the ground surface. Computer-based evaluation methods such as multivariate analysis of geophysical parameters have been tried. The geophysical logging results described above should be regarded as supplementary information for the mapping geologist and hydrogeologist.

Borehole radar is above all useful for locating and determining the orientation of local major and local minor fracture zones in an environment which in favourable cases extends to a radial distance of up to 100 m from the borehole. Seismic borehole methods (VSP) are often able to detect fracture zones at an even greater distance, but with poorer detail resolution. The methods complement each other in the determination of fracture zones, in part because of the aforementioned difference in range and resolution, but perhaps above all because the methods utilize different properties of the rock (electrical and acoustical, respectively) and are therefore advantageous under different conditions.

With SKB's integrated system for Geological Borehole Documentation (GBD) of individual boreholes based on the BIP system and the Boremap mapping system, and with interpretation support from geophysics and sample analyses, the results are presented in composite charts with the aid of a customized WellCAD system, see Figure 3-25. Any number of parameters can be presented, as well as statistically processed information.

Hard copy printouts of continuous BIP logging of an entire borehole also comprise a very useful basic documentation of the borehole. Together with the GBD results, this provides a good visual impression of the borehole which is of use in planning different kinds of subsequent downhole measurements.

Investigations on the ground surface

Even though the geological and geophysical investigations are dominated by downhole activities, supplementary geological and geophysical studies on the ground surface will also be performed. Depending on the proportion of exposed rock, surface-geological mapping can be carried out with a varying degree of difficulty. The rock surface is exposed for mapping along at least a couple of perpendicular swaths and one or two larger surfaces. Where soil cover is great, this should be at least partially compensated for by increased short-hole drilling for sampling of the rock. Moreover, the area's soil types, layer sequences and soil depths are characterized, as well as sediments on lake and sea bottoms, where applicable.

Figure 3-25. Example of presentation of geological borehole documentation (GBD) with the aid of WellCAD presentations.

Interpretation of data – updating of descriptive geological model

Principal rock types are represented deterministically in the geological model description, i.e. geometric extent and properties are determined for each rock type. Similarly, the geometry and properties of regional and local major fracture zones are described. The occurrence, percentage fraction and properties of subordinate rock types are presented as statistically distributed parameter values. Local minor fracture zones and fractures are described statistically. The RVS system will be an essential tool here to an even higher degree than in earlier phases, not least for the geological-structural model, as well as for the geometric repository model, for which the geological-structural model comprises the geoscientific foundation. The methodology for interpretation and reporting of uncertainties is described in section 4.2.3.

As during the initial site investigation, the descriptive geological model will be updated as new site-specific information is obtained, Figure 3-26. Several model alternatives should be developed in parallel so they can be tested and compared with each other. There is continuous integration between the disciplines with regard to both the detailed planning of the investigations and the modelling work. Major model cross-checks are done according to the division into sub-steps mentioned earlier. Feedback from the beneficiaries also improves these model versions.

In all investigation steps, data of importance to the area's geological evolutionary history are collected, e.g. the relative and absolute ages of the soils and rocks, and the relative ages of the structures. The results are described in a summarizing geological evolutionary model (see section 4.2).

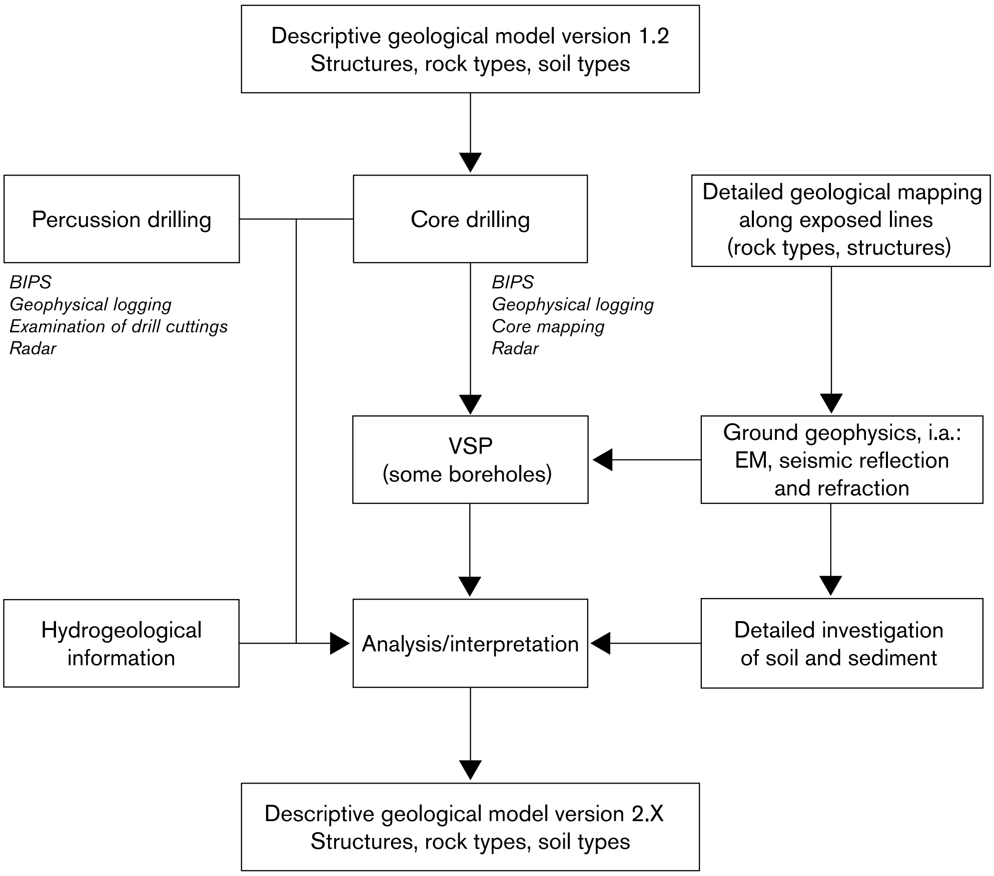


Figure 3-26. *Flow plan for investigation and updating of geological model for description of distribution of soil and rock types as well as structures in the bedrock during the complete site investigation.*

3.4.4 Rock mechanics

In connection with complete site investigation, a rock mechanical characterization of the rock mass in the central investigation area on the site is carried out to enable the feasibility of building the deep repository to be demonstrated. As even a distribution of boreholes in the large rock volume as possible should be striven for in order to provide input data to the descriptive rock mechanical model.

In-situ tests in boreholes

Rock stress measurements are carried out in a number of the boreholes using one or more of the following methods:

- Rock stress measurements by means of overcoring.
- Rock stress measurements by means of hydraulic fracturing, after hydrogeological and hydrogeochemical characterization.
- Rock stress measurements by means of HTPF (Hydraulic Testing of Pre-existing Fractures), if sufficiently many fracture groups have been encountered in the boreholes.

Furthermore, boreholes are mapped with respect to possible instability in the form of breakouts.

Mapping of drill cores

In addition to collection of geological parameters, the drill core is mapped with respect to:

- The quality of the rock mass – in accordance with various rock classification systems (see section 5.3.4).
- Core discing, which reveals high rock stresses.

Various tests are performed in the laboratory on retrieved drill cores, such as:

- Uniaxial and triaxial compression tests for determination of the deformation and strength properties of the intact rock.
- Determination of the propagation velocity of the P-wave.
- Mechanical properties of individual fractures, direct shear tests and characterization.
- Determination of possible clay-weathered products (minerals, swelling pressure).

Analysis, interpretation and modelling

Quality-assured primary data obtained from the investigations are stored in SICADA. Based on these data the rock mechanical model is updated after each sub-step (borehole campaign), see Figure 3-27. After completed site investigation, the final version of the rock mechanics model will comprise a part of the integrated site descriptive model. (See also section 5.2.3 in Chapter 5.)

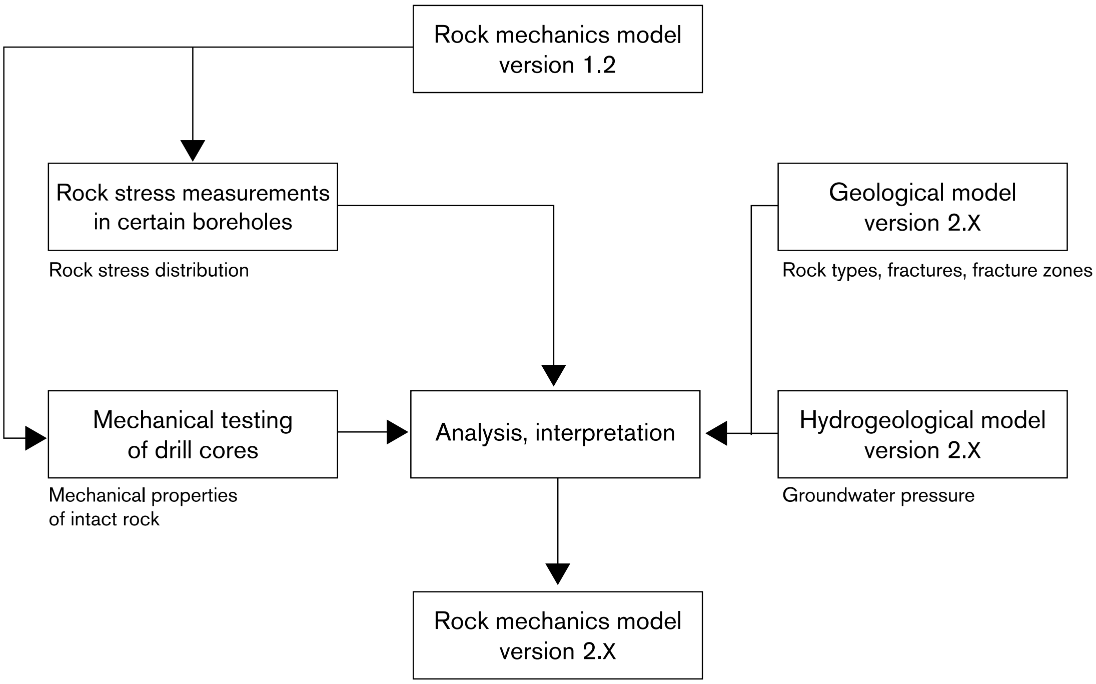


Figure 3-27. *Flow plan for updating the rock mechanics site descriptive model during the complete site investigation.*

3.4.5 Thermal properties

In connection with complete site investigation, a thermal characterization of the rock mass within and around the repository is carried out. A description of the initial thermal state and the thermal boundary conditions is prepared. The descriptive thermal model is based on the lithological model that is devised within the geological programme. A series of laboratory investigations is performed on drill cores taken from cored boreholes. Density, porosity, chemical and mineralogical composition, thermal conductivity and heat capacity are determined for the different rock types. (See section 5.3 for method descriptions.)

Samples for laboratory analysis are taken, evenly distributed within the area to enable the spatial distribution of the thermal properties to be determined. This analysis is also based on the lithological model devised within the geological programme and with the aid of generic knowledge concerning the thermal properties of the rock types.

The laboratory investigations will be able to be supplemented with thermal response tests in boreholes in order to determine/check the thermal properties of the rock mass in the field on a larger scale.

Quality-assured primary data obtained from the investigations are stored in SICADA. Based on these data the rock mechanical model is updated after each sub-step (borehole round). After completed site investigation, the final version of the rock mechanical model will comprise a part of the integrated site descriptive model.

3.4.6 Hydrogeology

The hydrogeological investigations are aimed at:

- achieving a hydrogeological understanding of the regional area and the site which is sufficient to comprise a basis for analysis of properties and boundary conditions,
- preparing hydrogeological descriptions on a regional and local scale that are sufficiently detailed to comprise a hydrogeological basis for evaluation in accordance with the needs that exist within safety assessment and design.

To obtain data for the boundary conditions within the regional area, the monitoring programme is continued and expanded, comprising hydrological measurement stations (meteorology, runoff) and groundwater level measurements, during the complete site investigation as well.

Hydraulic borehole tests

Hydrogeological investigations are conducted in all boreholes. In the percussion boreholes the investigations are conducted in the same way as during the initial site investigation, and in the cored boreholes essentially in the way described in section 3.3.6. One difference is that injection tests with short section length (preliminarily 5 m) are only carried out in some of the cored holes and only within the depth interval 300–700 m. All short-duration pumping tests, i.e. tests with a duration of a few hours, are conducted as interference tests if there is reason to believe that pressure responses can be measured in nearby boreholes.

Several interference tests with pumping for about 3 days and recovery for about 1 day are performed. Most of these tests are performed after each drilling campaign. When these interference tests are performed, it is of the utmost importance that activities not be under way which create pressure responses in the groundwater reservoir within the influence area of the test. Activities that can disturb include drilling, other hydrogeological tests, and water sampling. Pumping is done in packed-off sections in cored boreholes or in open cored or percussion boreholes. Pressure observations with suitable measurement intervals are performed preliminarily in borehole sections situated closer than approximately 1 km from the pumped borehole. Towards the end of the complete site investigation, one or two interference tests are performed with pumping for 3–6 months and recovery for about 1–2 months. One of these tests may be combined with a large-scale tracer test.

Hydrogeological mapping

In an early step within the phase, the hydrogeological mapping within the regional area and site is supplemented to provide a complete body of material for description of the soil layers. This also means that the Quaternary geological model is supplemented and made more detailed within the priority site and its immediate environs, above all within areas that can be expected to be recharge and discharge areas. The geological-structural mapping of exposed rock surfaces along lines and surfaces also provides valuable information on the brittle structures that are up to 10 metres or so in length.

Monitoring

Monitoring of groundwater pressure in all packered-off borehole sections and measurement of meteorological and hydrological parameters continues. As during initial site investigation, groundwater flow measurements in packered-off sections can be performed when there is no hydraulic disturbance (see also the programme for the transport properties of the rock, Chapter 9). Measurements of groundwater levels in previously selected wells and boreholes continues with the same frequency as before.

Interpretation, analysis and modelling

Quality-assured primary data obtained from the investigations are stored in SICADA. The analysis resembles the one performed during the second stage of the initial site investigation, see section 3.3.6, with the difference that the interference tests will be greater in number and better in quality. This provides a better basis for determining extent and hydraulic connections between fracture zones, especially regional and local major fracture zones. The description of the Quaternary geology within the site and the regional area is also updated in this phase.

The working methodology for devising different model versions of the description of the rock is similar to that applied during the initial investigation and is illustrated in Figure 3-28. The description of hydrology and of soil strata is updated in the same way as during the initial investigation (see Figures 3-9 and 3-10).

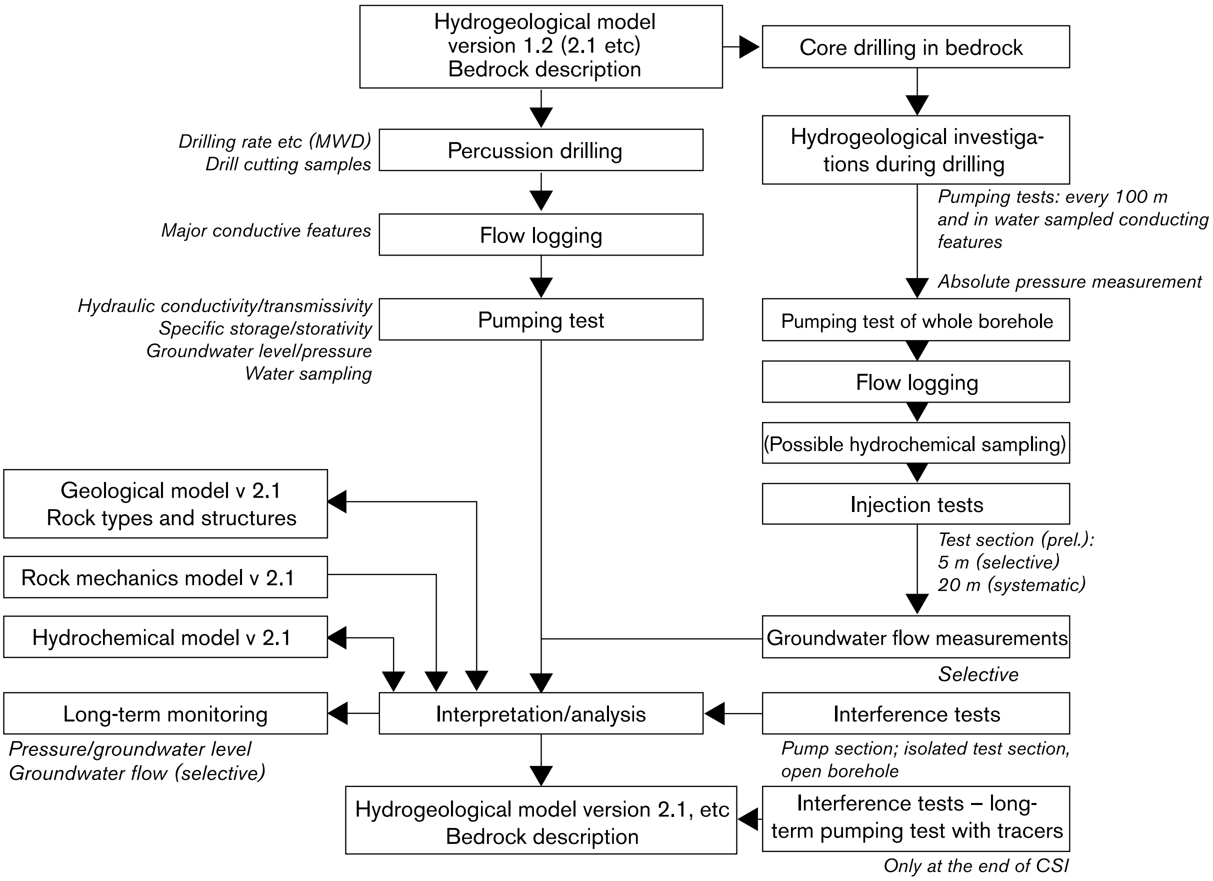


Figure 3-28. Flow plan for description of the rock in the different versions of the descriptive hydrogeological model during the complete site investigation.

The hydrogeological model is updated in different versions (2.1, 2.2 etc). The description is three-dimensional and is done on the local and regional scale. Hydrology and soil layers are described in the same way as in version 1.2, but with greater precision and revised principles for geometric subdivision.

The rock is described in the following manner, but with increased precision in later model versions (see also section 7.2.3):

- Most regional fracture zones and some local major fracture zones within the regional area are described in general terms with respect to transmissivity and location. Deeper parts of fracture zones are based on statistics from fracture zones within the area where there is knowledge of the rock at depth.
- All known local major fracture zones and regional fracture zones within the site are described with respect to transmissivity and location.
- Some of the local minor fracture zones within the site are described with respect to transmissivity and location.
- Local minor fracture zones and fractures are described statistically with respect to transmissivity, frequency (density) and spatial distribution. The degree of detail is higher at repository depth.
- Hydraulic conductivity on the 100 m scale is specified statistically within the site from the ground surface down to about 1,000 m and is specified roughly statistically within the regional area down to at least 1,000 m.
- Hydraulic conductivity on the 20 m scale (a suitable multiple of "canister scale" 4)[4], see below) is specified statistically within the site from the ground surface down to 1,000 m and roughly statistically within the regional area down to about 1,000 m.
- Hydraulic conductivity on the 5 m scale ("canister scale") is specified statistically within the site from a depth of 300 m down to about 700 m.
- Assessment of whether hydraulic anisotropic conditions prevail, based on the geological and rock mechanical models and the results of injection tests and interference tests.

The groundwater flow is calculated on both the local and regional scale, based on the descriptive model. One purpose of the calculations of the large-scale flow pattern is to determine the recharge and discharge areas within the regional area and the priority site, and to study how different boundary conditions influence the results. After complete site investigation, the final version of the hydrogeological model will comprise part of the integrated site description.

3.4.7 Hydrogeochemistry

Further investigations of deep groundwaters in particular are conducted during the complete site investigation. Here it is essential to supplement, verify and increase the quantity of data in order to obtain as complete a picture of the groundwater situation as possible and to obtain a good basis for evaluations and modelling. The results of these

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4) It is essential to determine the hydraulic conductivity with different resolutions in order to get an idea of its scale dependence. The chosen 20 m scale is appropriate for characterization of all boreholes and is therefore an important "base scale".

investigations will be used for analysis of the repository's long-term safety and the function of the engineered barriers.

An overview of the sampling objects included in the initial site investigation as well as sampling occasions and scope of analysis for the different objects are given in Table 3-2.

The four areas of activity within the complete site investigation – water sampling in the field and analyses, work in cored boreholes and evaluation/modelling – are described in the following sections.

Water sampling in the field

The investigation of natural variations in surface waters and near-surface groundwaters is expected to be completed, but targeted investigations of the surface waters from other aspects will be conducted during the complete site investigation, for example "production studies" in lakes or studies to discover whether deep groundwater penetrates up to the surface. Long-term monitoring continues during the complete site investigation, and new objects may be added. Any new percussion boreholes are sampled immediately after drilling in the same way as before.

Work in cored boreholes

The emphasis in the investigations during the complete site investigation is on a number of supplementary deep cored boreholes down to a depth of approximately 1,000 metres. One or a few of the cored holes will be chemistry-prioritized. The number of chemistry-prioritized boreholes depends on how many were already drilled during the initial site

Table 3-2. Sampling objects, sampling occasions and scope of analysis during complete site investigation (the analysis classes are shown in Table 8-4 in Chapter 8).

Sampling object	Comprehensive chemical analysis	Natural variations	Long-term monitoring	Analysis class*
Surface waters				
All	N/A	N/A	1–12 times/yr	5 (c, f, g, h)***/ 3 (a, b)***
Near-surface groundwaters				
Wells	N/A	N/A	1–2 times/yr	3 (a, b)***
Soil pipes**	N/A	N/A	1–2 times/yr	5 (c, f, g, h)***
Groundwaters				
Percussion boreholes**	N/A?	N/A	1–2 times/yr	5 (c, f, g, h)
Cored boreholes**				
– during drilling	X	–	–	3 (a, b, c, d)
– hydrochemical logging	X	–	–	3 (a, b, c, d)
– compl. chem. char.	X	–	–	4 (e)/ 5 (c, d, f, g, h, i, j, k, l)
– during pumping tests	X	–	–	4 (e)/ 5 (c, d, f, g, h, l)
– long-term monitoring	–	–	1–2 times/yr	5 (c, d, f, g, h)
– fracture-filling minerals	X	–	–	–

* The analysis classes are defined in Table 8-4, Chapter 8.

** Typical waters that can comprise important input data in mixing calculations, see section 8.2.

*** Also includes options from the discipline *surface ecosystems*, such as nutrients, heavy metals and radionuclides.

investigation. Sampling in chemistry-prioritized boreholes is done in the same way as previously described , see 3.3.7.

In non-chemistry-prioritized boreholes, the requirements on washing and sterilization of drilling equipment and other borehole equipment are not as stringent. Furthermore, the chemistry investigations in these boreholes will primarily be coordinated with the pumping tests conducted within the discipline *hydrogeology*. Investigations in non-chemistry-prioritized boreholes take place in the following sequence. The methods are described in greater detail in section 8.3.

- Water sampling during drilling is done using water samplers in the borehole section or another method. Sampling as per class 3 takes place when water-bearing fracture zones are penetrated and/or every 100 metres.
- Hydrochemical logging of the borehole is done using a hose sampler shortly after concluded drilling. The hydrochemical logging may be repeated in a later phase. Analysis as per class 3. The hydrogeochemical sampling should be checked by geophysical logging of salinity before and after chemical sampling in order to get an idea of the mixing caused by the sampling procedure and thereby the representativeness of the samples for a given borehole depth.
- Since the holes are not chemistry-prioritized, investigation steps within other disciplines can then precede further chemistry investigations.
- Sampling in conjunction with pumping tests will be the primary investigation step in non-chemistry-prioritized cored boreholes. During the pumping tests, approximately four water samples will be taken as per class 4/5 from each tested borehole section. At the same time, measurements will be made of the parameters pH, Eh, electrical conductivity and dissolved oxygen.
- Complete chemical characterization with a mobile field laboratory may also be done in non-chemistry-prioritized cored holes where it is necessary to supplement and verify data quantities. Execution is the same as in initial site investigation. Sampling and analysis as per classes 4 and 5. Bacterial sampling may be omitted in non-chemistry-prioritized boreholes due to the fact that sterilization and washing of borehole equipment has not been performed.
- Drill cores are studied with respect to frequency of different fracture-filling minerals as a function of depth and occurrence of water-bearing fractures. The core mapping performed within the geology programme is used as a basis for the study. Mineralogy, texture and chemical composition are studied and samples are taken for both chemical composition and isotope composition. Furthermore, fracture-filling mineral samples corresponding to the water-bearing fracture zones in the borehole are investigated. The section from a depth of 0 to 100 metres is studied in drill cores from nearby short cored boreholes drilled solely for this purpose, since the first part of the cored boreholes is percussion-drilled.
- After the chemistry campaign, at least two borehole sections in each borehole will be selected for continued regular sampling (once or twice a year). This represents the start of long-term monitoring of chemical parameters in these cored holes. Permanent downhole equipment must be installed in the boreholes for this purpose.

The samples from the sampling objects are analyzed in accordance with one of the different chemistry classes /SKB, 1998/, see Table 3-2, in the same way as described earlier. The results are used for modelling as described in section 8.2.3.

Analysis, interpretation and modelling

The results from sampling and analysis in the earliest drilled deep holes are used during the initial site investigation in a first interpretation to describe the depth dependence of the groundwater chemistry. Thereafter, with data from several boreholes, the results are interpolated to a three-dimensional distribution in the identified conductive features. Evaluation of conductive features, their occurrence and properties, must be carried out in coordination with geology and hydrogeology representatives. Flow plan and information needs are shown in Figure 3-29.

The history of the groundwater is investigated by determining the distributions of dissolved components and isotope ratios encountered in all sampled borehole sections. In order to perform this historical retrospect (paleohydrology), a conceptual picture of the historical groundwater flow is also required. With knowledge of the various typical waters that occur, mixing calculations can be carried out. The results of these calculations are compared in every point with measured values for each individual dissolved component. The difference between calculated and measured values (the mass balance) shows to what extent chemical and biological reactions have occurred. Calculations of chemical equilibria then continue, showing to what extent the hydrogeochemical system is stable or dynamic. The more of the chemically active minerals are in equilibrium with

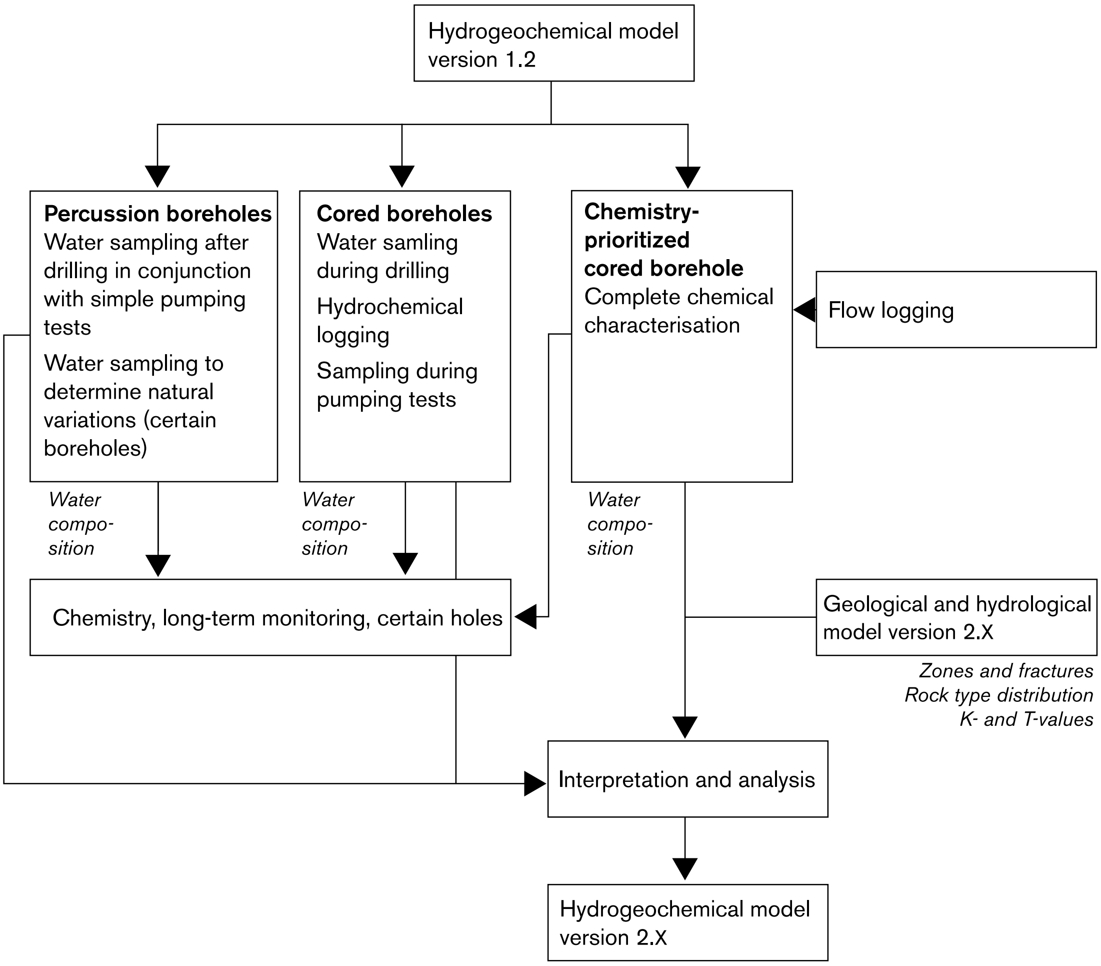


Figure 3-29. Flow plan and information needs in order to update the descriptive hydrogeochemical model during the complete site investigation.

dissolved constituents in the groundwater, the more stable is the system. This is of direct importance for the interpretation of the groundwater's turnover times and indirectly for flow rates as well.

In addition to an understanding of present-day and historical hydrogeochemical conditions, parameter values for the components listed in Table 8-2 in Chapter 8 are also needed in the safety assessment. The devised model is included as a hydrogeochemical part of the overall site description.

3.4.8 Transport properties of the rock

The complete site investigation is aimed at gathering material as a basis for conducting a safety assessment, which is why site-specific data for all transport parameters given in Table 9-3 in Chapter 9 have to be determined.

Investigations

The complete site investigation includes a number of cored boreholes drilled in several campaigns. A preliminary scope of laboratory measurements and field measurements for determination of site-specific transport parameters is presented in Tables 3-3 and 3-4. (Information from several other disciplines is also needed to determine transport parameters, see Table 9-3 in Chapter 9.)

The laboratory measurements are supplemented with mineralogical analysis of selected rock samples and hydrogeochemical sampling. These analyses are coordinated with the geology and hydrogeochemistry programmes.

Groundwater flow measurements are conducted by logging (see Table 3-4), but also at a later stage, after instrumentation, by dilution measurements in fixed sections for the purpose of determining the influence of activities during the site investigation (long-term monitoring).

Table 3-3. Compilation of laboratory measurements for determination of site-specific transport parameters during the complete site investigation. The methods are described in section 9.3.

Method	Parameters	Number of samples/fractions
Batch sorption measurement	Sorption coefficients	At least three from each rock type depending on homogeneity. Two fractions (fine+coarse). Samples from possible soil layer.
Through diffusion measurement	Matrix diffusivity, matrix porosity, sorption coefficients	At least three from each rock type plus a fracture surface, depending on homogeneity.
Gas diffusion measurements	Matrix diffusivity	See above
Porosity measurements; water saturation technique, ^{14}C-PMMA method	Matrix diffusivity, pore structure	Determined on nearby samples (or same sample) as sorption coefficients and diffusivity.

Table 3-4. Compilation of field measurements for determination of site-specific transport parameters during the complete site investigation. The methods are described in section 9.3.

Method	Parameters	Number of tests/sections
Groundwater flow measurement	Groundwater flow	Three boreholes, one measurement every 100 metres or so in individual fractures/fracture zones.
Single-hole tracer test (SWIW/push-pull)	Wet surface, dispersivity flow porosity, sorption parameters	Three boreholes. Several measurements per hole, includes injection of weakly sorbing substances.
Multi-hole tracer test	Verification of structural, model, dispersivity, flow porosity, travel time	One test in two nearby boreholes. These holes should also be tested by push-pull testing. At least one test in conjunction with long-term test pumping (LPT).
Single-hole tracer test (in-situ-sorption)	Sorption parameters	New method, scope and use under investigation.
Radon measurement	Wet surface (transport resistance	New method, scope and use under investigation.
Resistivity measurement	Matrix diffusivity	New method, scope and use under investigation.

The transport resistance is determined primarily on the basis of the hydrogeological and hydrogeochemical description. The description is supplemented with various field measurements (see section 9.3.2):

- In individual boreholes, geological information is combined with hydraulic tests, fine-scale differential flow logs and Borehole Image Processing (BIPS).
- In a flow path between two relatively closely spaced boreholes, tracer tests are carried out and evaluated where the injection and detection boreholes are investigated as described in the above point.

Matrix porosity and/or matrix diffusivity as well as sorption coefficients are determined by means of a single-hole test in the field (in-situ sorption test) if practically possible. A pilot study is currently planned within the TRUE project. The method has the advantage that it is performed under actual water pressures and chemical conditions in the rock, in contrast to laboratory tests.

The range of variation in "travel times" (dispersion, see Chapter 9) is determined on three scales: In individual fractures by single-hole tracer tests (also called SWIW or push-pull tests) and in individual structures by two-hole tests. In the latter, the same test is used to determine the wet surface and flow porosity. The large-scale dispersivity is determined in a combined interference and tracer test (LPT).

Analysis, interpretation and modelling

Besides these direct measurements within the transport programme, a number of measurements are performed within adjoining programmes that are of great importance for solute transport:

- Hydrochemical samplings, to supplement those performed during the initial site investigation, for hydrogeochemical characterization of flow paths and rock of low hydraulic conductivity at planned repository depth (see Chapter 8).
- Determination of hydraulic conductivity by means of water injection tests (see Chapter 7).
- Determination of conductive fracture frequency and flow distribution by means of fine-scale differential flow logging (see Chapter 7).

The results of the investigation are used to devise a descriptive model of the transport properties of the site. This comprises part of the overall site description, in accordance with Figure 3-30. Section 9.2.3 provides a more detailed description of the modelling work.

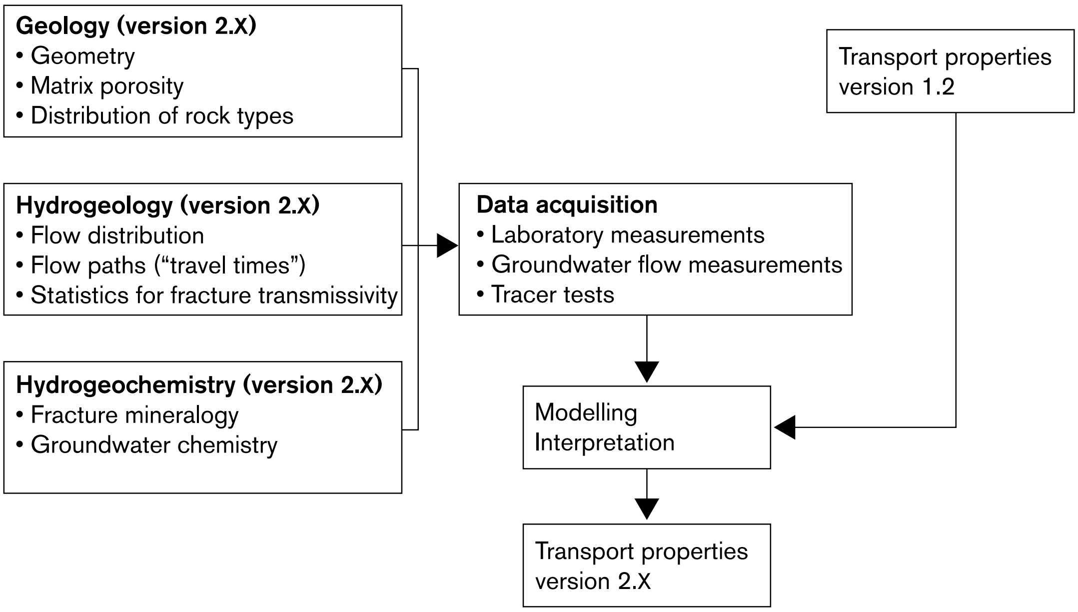


Figure 3-30. *Flow plan and information needs during the complete site investigation in order to update the descriptive model of the transport properties of the rock.*

3.5 Base programmes for investigations in different boreholes

During the site investigation, boreholes will be drilled during virtually all phases, as can be seen in the compilation in Table 3-5. Many parameters are recorded during drilling. In addition, certain tests, measurements or samplings are performed during the ongoing drilling activity. After concluded drilling, investigations are carried out according to one base programme for percussion boreholes and another base programme for cored boreholes. In most cored holes, the base programme is supplemented with additional investigations.

Early data collection provides several advantages. For certain parameters early sampling is compulsory, since delaying of the sampling can lead to contamination (e.g. groundwater samples) or because the measurement is dependent on the bottom of the borehole being at a certain level (e.g. rock stress measurements by means of overcoring). Early investigations can also be used as support for decisions to change the thrust of the investigations. Finally, an early data flow provides better opportunities for efficient analysis and evaluation of the investigation area, since a good understanding of the geoscientific conditions can be built up right from the start.

3.5.1 Recording of parameters during drilling

A number of drilling parameters and flushing water parameters will be recorded in the site investigations during ongoing drilling, see section 11.4. The drilling parameters (feed pressure, torque, drilling rate and extra flow) may be related to the material being drilled through or machine-related. Some parameters can be utilized for documenting different functions of the drilling equipment, and some data are fed back for optimization of the drilling process. Other recorded drilling parameters depend on the properties of the rock and therefore provide early information that can be used in different discipline-specific programmes. The flushing water parameters of interest are flow parameters (pressure and flow, which are recorded) and physical-chemical parameters (tracer concentration, oxygen concentration by sampling). The equivalent parameters are recorded in the return water, except oxygen concentration, while electrical conductivity may be considered.

Table 3-5. Compilation of which boreholes are drilled during the different phases of the site investigation and preliminary estimate of the number of boreholes.

SI phase	Type of borehole	Number of boreholes
Initial site investigation Choice of site	1) Percussion boreholes 2) Soil boreholes	1) Site-specific, up to 10–20 2) Site-specific, probably <100
Initial site investigation Preparatory investigation of site	1) Cored boreholes (long) 2) Percussion boreholes 3) Soil boreholes	1) Site-specific, approx. 2–3 2) Site-specific approx. 5–10 3) Site-specific, probably <50
Complete site investigation	1) Cored boreholes (long) 2) Percussion boreholes 3) Soil boreholes	1) Site-specific, 10–20 (in campaigns of 2–4) 2) Site-specific, approx. 5–10 3) Site-specific, probably <50

3.5.2 Tests during the drilling period

Tests during the drilling period require the drilling to be interrupted for a shorter or longer period of time and then resumed. Tests during drilling are conducted within the discipline-specific programmes for rock mechanics, hydrogeology and hydrogeochemistry. The testing programme during drilling differs between percussion and cored boreholes. The following programme is typical, but may be departed from for various reasons:

- In percussion boreholes, pumping tests are performed every 100 metres (often in the form of an interference test), see section 7.3.3. The drilling interruption can be limited to a few hours.
- In certain cored boreholes (not in the chemistry-prioritized ones), rock stress measurements are performed by overcoring, see section 5.3.1. The measurement work requires a drilling interruption of one or two days.
- In all cored boreholes, pumping tests are performed every 100 metres (when water samples are also taken), see section 7.3.3. The tests require a drilling interruption of a few hours to a day.
- In all cored boreholes, water samples are taken with a wireline probe (or similar equipment) on indication that a water-bearing fracture has been penetrated, see section 8.3.7. The drilling interruption can be estimated at a few hours, at most 24 hours.

3.5.3 Standardized downhole investigations after concluded drilling

Downhole investigations will be performed according to standardized programmes (called base programmes here) in all completed rock boreholes. The base programme is conducted immediately after drilling has been concluded for the purpose of providing a fundamental characterization of the formation based on uniform methodology. The base programme has a slightly different design in percussion boreholes compared to cored boreholes.

In *percussion boreholes*, the base programme includes the following steps:

- BIPS and borehole radar logging (see geology, section 4.3.6).
- Geophysical logging (see geology, section 4.3.6).
- Boremap mapping (see geology, section 4.3.5).
- Test pumping and flow logging (see hydrogeology, section 7.3.3).
- Water sampling (see hydrogeochemistry, section 8.3.6).
- Installation of groundwater monitoring equipment (see hydrogeology, section 7.3.4).

The base programme for *cored boreholes* consists of the following steps:

- BIPS and borehole radar logging (see geology, section 4.3.6).
- Geophysical logging (see geology, section 4.3.6).
- Hydrochemical logging (see hydrogeochemistry, section 8.3.8).
- Flow logging and pumping tests i different sections (see hydrogeology, section 7.3.3).

- Boremap mapping (see geology, section 4.3.5).
- Geological analyses of drill core specimens and drill cuttings. (For lithological and mineralogical analysis, see section 4.3.5. For rock mechanical analysis, see section 5.3.2. For thermal analysis, see section 6.3.2.)

3.5.4 Supplementary investigations in cored boreholes

After completion of the base programme, additional investigations are conducted, above all in the cored boreholes. Which measurements, tests or samplings are performed depends on the purpose of the borehole. For example, some cored boreholes are designated as being chemistry-prioritized. Some methods are only performed in occasional boreholes, while others are performed in most boreholes. The methods are described in the discipline-specific chapters and their use is described in the execution programme presented in previous sections. The methods in question are above all:

- Differential flow logging or hydraulic injection tests with a 20 m section length are performed in most boreholes (see hydrogeology, section 7.3.3).
- Hydraulic injection tests with a 5 m section length are performed in some boreholes, above all in the depth range 300–700 m (see hydrogeology, section 7.3.3).
- Groundwater flow measurements are performed in a limited number of boreholes (see transport properties, section 9.3.2, and hydrogeology, section 7.3.3).
- Complete hydrochemical characterization is performed in chemistry-prioritized boreholes (see hydrogeochemistry, section 8.3.9).
- Interference tests in the form of pumping tests are performed in a couple of boreholes per campaign (see hydrogeology, section 7.3.3).
- Rock stress measurements are performed by means of hydraulic fracturing in a limited number of boreholes, preferably the same borehole measured during drilling by means of overcoring (see rock mechanics, section 5.3.1).
- Vertical Seismic Profiling (VSP) is performed in some boreholes, suitably in connection with seismic reflection profiles (see geology, section 4.3.6).
- Tracer tests are performed in the form of both single-hole tests and multi-hole tests, with different durations and test designs (see transport properties, section 9.3.2).

3.6 Infrastructure on the investigated site

Once a priority site has been chosen within the candidate area, extensive investigations will be conducted on it during a period of several years. In order for the work to be conducted rationally, a certain base infrastructure must be in place. The most important elements of this infrastructure are:

- Logging roads to all cored boreholes, as well as to selected percussion boreholes.
- A level, gravelled area at each cored borehole and at selected percussion boreholes.

- Electricity (3-phase and 1-phase) at each cored borehole and at selected percussion boreholes, as well as at the investigation area's base camp, see below. A signal cable may also need to be run from the borehole to a centrally located logger along certain stretches.
- Base camp for office and analysis work, preferably consisting of a level area of sufficient size with offices, personnel quarters, demonstration hall and changing room for visitors, storeroom for drill cores and other specimens as well as for investigation instruments etc, holding area for vehicles and farm tanks, lavatory and toilet facilities, plus waste management facility.

A logging road to each cored borehole is necessary so that heavy and bulky drilling equipment can be transported up to the drilling site, and to facilitate the large number of investigations performed in each cored hole requiring a great deal of equipment and personnel to be transported and from the boreholes. The roads do not have to be wide, but must have good bearing capacity (for heavy trucks). Roads only have to be built to the percussion boreholes in exceptional cases, since percussion drilling equipment has good off-road mobility, and because the scope of downhole investigations in percussion boreholes is smaller than in cored boreholes.

The logging roads are built so that they do not cut off natural drainage pathways and otherwise conform to ground conditions and existing vegetation. It must be kept in mind that the roads require some maintenance during the investigation period, and that snow must be cleared during the wintertime. After concluded investigations and long-term monitoring, the roads can be removed or, if the landowner so desires, left in place to facilitate future timber haulage.

A gravelled apron of about 400 m^2 is required at each borehole to set up drilling equipment and accessories during the drilling phase and later to set up measuring equipment. A concrete slab is poured around the borehole's casing pipe in order to prevent surface water from leaking in along the casing pipe and for setting up a borehole container and measurement equipment directly above the borehole. After the slab is poured, surrounding land is filled up with gravel or crushed rock to even out the level difference between the slab and the surroundings. After concluded investigations, the apron can be left intact or be reduced in size, according to the landowner's wishes.

Electricity can be supplied to the boreholes in two ways. Firstly, a cable can be run from a suitable power transmission pole up to the cored borehole, where distribution boxes are installed with 3-phase and 1-phase outlets and with fuses of high enough amperage for the electrical equipment to be used. Secondly, diesel-powered generators can be used. The latter solution has many disadvantages, for example noise and exhaust gases, but may be necessary as either a temporary solution or where cables cannot be laid, or as a standby unit for power outages in the mains system.

The premises in the base camp consist primarily of mobile crew barracks and lockable steel freight containers. If the investigation site is situated near built-up areas, one or more buildings can instead be rented. The latter solution is preferable for reasons of comfort and because it facilitates communications with the outside world. A remote base camp will probably also require a fixed connection to SKB's computer network, which may require a relatively long (temporary) line to be run.

Field investigations are also performed in a larger, regional area. Some of the infrastructural facilities mentioned above are required in this larger area as well, e.g. road to and gravelled apron at cored boreholes. However, the majority of the investigations in the regional area consist of measurements from the air and on the ground, which require only marginal infrastructural resources. Most boreholes in this area are soil and percussion boreholes.

4 Geology

4.1 General

This chapter describes which geological conditions and properties will be determined and possible characterization methods. The chapter also describes how the measured information is interpreted in the geological model that comprises part of the site-descriptive model. The geological model is based on a geometric model which is the same for all disciplines. Furthermore, a description of the geological evolution of the area is prepared as a basis for an understanding of the geological conditions.

4.1.1 Introduction

The Swedish crystalline bedrock is made up of different rock types, of which gneiss and granite are the most common. A large portion of these rock types in eastern Sweden are approximately 1,750–1,900 million years old. Repeated tectonic movements in the bedrock have led to the formation of e.g. plastic shear zones, fracture zones and faults. These are referred to jointly as deformation zones. Plastic shear zones have been formed at relatively great depth (10–15 km) and under high temperature (300–400°C). Rock types that are deformed at a higher level in the earth's crust give rise to fractures, fracture zones and faults. Clusters of fractures along bands of differing length and width form fracture zones which divide the bedrock into larger or smaller blocks. The parts of the bedrock that are unaffected, or seemingly unaffected, by surrounding plastic shear zones are called tectonic lenses /Bergman et al, 1996; Bergman et al, 1998/.

An important task is to establish the extent and character of major (regional) fracture and shear zones to be avoided in the siting of the deep repository. Good knowledge is also required of the rock's fracture content and the frequency of local fracture zones in the rock between the regional fracture zones.

Knowledge of the extent and character of the soils (Quaternary deposits) is mainly of interest for hydrogeological and surface-ecological assessments, but certain disturbances in the layer sequence of the soils can be important indications of postglacial movements (faults) in underlying bedrock.

Good knowledge of the properties of the rock and the soil strata is of great importance for all geoscientific disciplines. Figure 4-1 provides an overview of some geological investigation methods and the properties in the bedrock that are to be described.

An integrated geological characterization of an area entails geometrically representing the topography, deformation zones, lithological boundaries, rock units and soil strata of the investigated area and describing them in an integrated model. A large number of methods are used to investigate the geology of the site. They can be described in general terms under the headings: geophysics, surface geology, soil geology, bedrock geology, borehole investigations and geodetic measurements /Stanfors et al, 1997/.

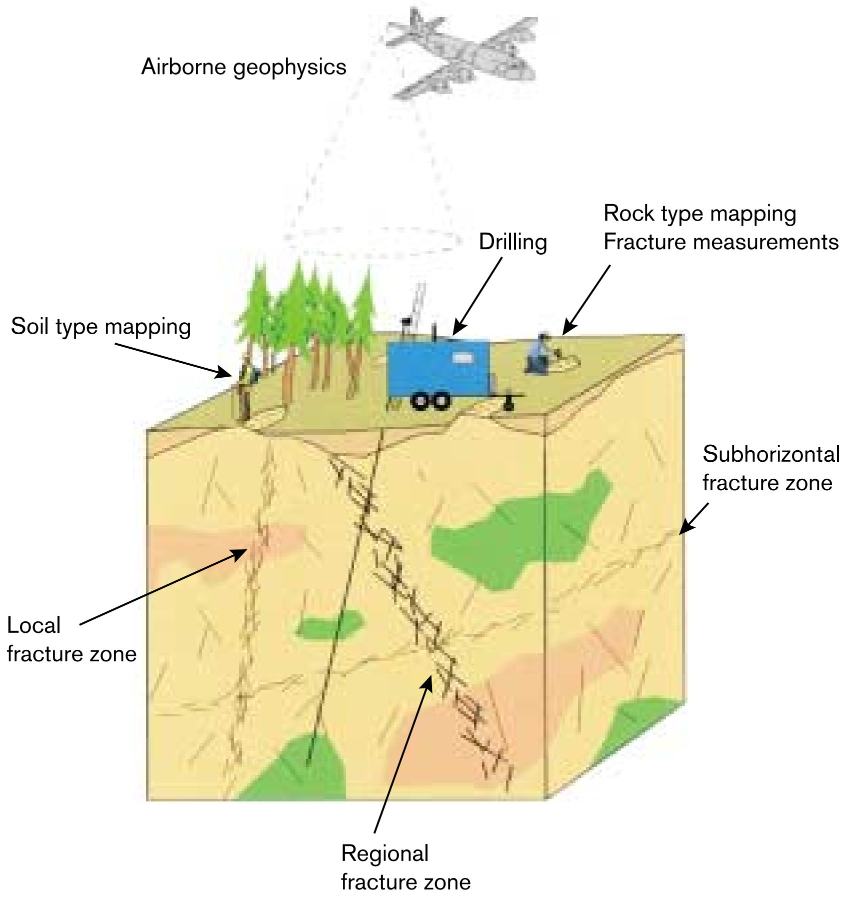


Figure 4-1. *Some geological investigation methods and properties that are to be described.*

Certain *geophysical* methods are used to measure the natural variations in physical properties that exist between different rock and soil types, while other methods are used to create disturbances and measure the generated responses. The results can thereby be used as a basis for geological, hydrogeological or rock mechanical interpretations.

The concept *surface geology* refers to all investigations of soil types and bedrock performed from the ground surface. A subdivision is made here into soil geology and bedrock geology. The studies of recent movements and deformations in the bedrock have been grouped together under the heading "neotectonics". *Soil geology* includes investigation and description of the area's soil types and, where applicable, sediments in lakes and seas. Investigation of indications of possible postglacial movements, such as disturbances in sedimentary layers, will be included as a separate task. *Bedrock geology* includes investigation and description of the area's rock types and structures in the bedrock based on mapping of exposed rock surfaces (outcrops).

Studies of neotectonics include investigation of possible indications of postglacial faults. Monitoring with a local seismic network for registration of microquakes and deformation measurements using GPS technology to check for possible movements in the bedrock provide the data needed to build up an understanding of the mechanical state of the site.

Even though e.g. seismic reflection, bulk resistivity and gravimetry indirectly provide valuable information on geological conditions at depth, it is via direct *downhole investigations* that the essential information on geological conditions down to a depth of at least around 1,000 m is acquired. Drilling is done either as core drilling, whereby drill cores are obtained, or as percussion drilling. The drill cores are mapped and investigated with regard to geological, geophysical and rock mechanical parameters. Borehole geophysics includes investigations of boreholes with various geophysical logs.

Geodesics includes setting-out and surveying of measurement points, measurement profiles and boreholes.

4.1.2 Discipline-specific goals

The requirements, preferences and criteria that have been identified for the discipline of geology are presented by /Andersson et al, 2000/. With reference to the general focus of the investigations, section 2.2, the geological work is mainly aimed at investigating:

- topographical forms and the extent of the soil layer, plus constituent mineral soils and their properties,
- the composition of the bedrock with regard to rock types and their extent and contact pattern, as well as the degree of complexity with regard to the number of rock types,
- the bedrock's deformation pattern with regard to both plastic structures (plastic shear zones) and brittle structures (fractures and fracture zones),
- the geological evolution of the area with the aid of geochronological studies, the genesis of the fracture-filling minerals and studies of movements along fracture surfaces.

The investigations serve as a basis for devising geological models which comprise a part of the site descriptions, which are in turn used for design and safety assessment. It is essential that the investigations and the descriptions be sufficiently detailed so that the suitability of the site can be judged. A more detailed presentation of which geological parameters are to be determined is given in section 4.2.2.

Focus during the initial site investigation

With reference to section 2.2.3, the geological work during the initial site investigation is focused on:

- investigation of geological homogeneity, suitable rock types and possible ore occurrence,
- investigation of the extent and character of fracture zones (mainly regional, local major and subhorizontal zones of crucial importance),
- investigation of any indications of postglacial faults.

In addition, long-term monitoring is initiated of parameters where it is essential to have long time series to get a useful database (seismic network and deformation measurements).

A first version of the geological description in the site-descriptive model is set up at an early stage. The description is updated after initial investigations are concluded.

Focus during the complete site investigation

During the complete site investigation, the geological characterization of the site is completed. The general task is described in section 2.2.4. As regards geology, the investigations are focused on:

- detailed investigation of the occurrence and extent of fracture zones and other structural features within the site, and otherwise providing deeper knowledge of geological conditions on the site.

The geological programme shall ensure good geometric representation of data for determination of the location and properties of rock types and structures by e.g. suitable setting-out of boreholes. The geological description in the site-descriptive model is updated on different occasions, coordinated with updating of the description obtained from other disciplines. The description is finalized when the site investigations are concluded.

4.1.3 Working methodology and coordination

Investigations and characterization are carried out stepwise (see section 2.3.1). Collaboration with other disciplines is essential. The work procedure is illustrated schematically in Figure 4-2.

The investigations are planned in consultation with other disciplines in order to coordinate certain common investigations and to minimize the risks to disturbance-sensitive investigations. There must be collaboration in the planning and setting-out of cored boreholes for rock stress measurements, early hydrogeochemical sampling and hydraulic tests. Planning must also take into consideration the fact that many investigation tasks are seasonally dependent (e.g. geological field investigations), while others (e.g. helicopter surveys) require special permits and preparatory setting-out in the terrain. Some investigations require long measurement series, e.g. seismic networks and deformation measurements.

Measurements, interpretations/analyses and verification/updating of the descriptive model are done discipline-by-discipline, but require integration with other disciplines. The discipline-specific programme for geology provides fundamental data and parameters that are essential for other disciplines. Results from interference tests and chemistry data provide valuable information for the geological modelling. Fracture-filling mineral studies will be coordinated with the hydrogeochemistry programme. This provides data for the rock type and geological-structural model and is of interest for rock mechanics.

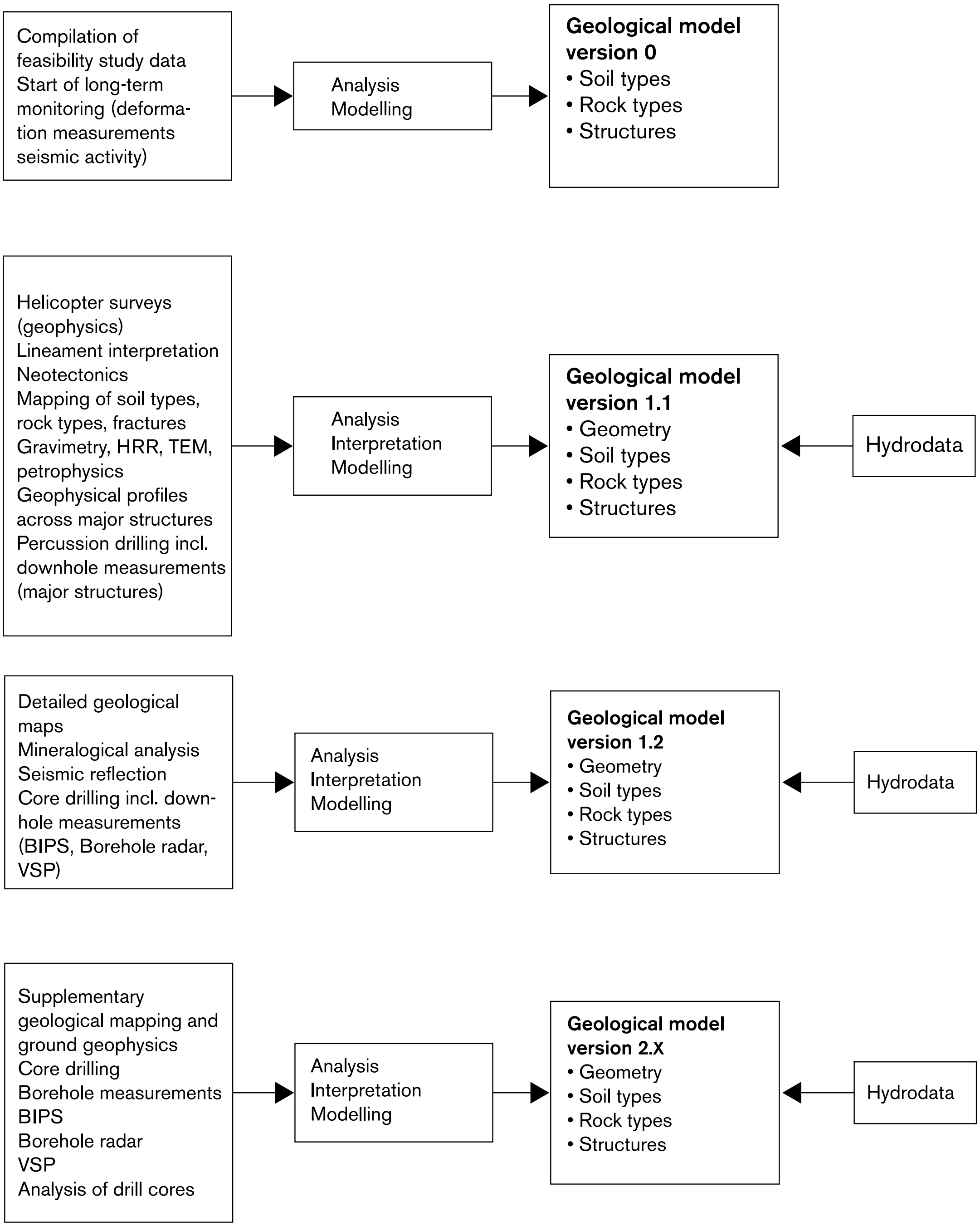


Figure 4-2. *Overall flow scheme showing how the geological and geometric model evolves and how it is dependent on information from other disciplines.*

4.2 Models and parameters

4.2.1 Structure of the models

The foundation of an integrated geological characterization consists in geometrically representing the topography, deformation zones, lithological boundaries, rock units and soil strata of the investigated area and describing them in a site-descriptive model. The site-descriptive model is set up on a regional and local scale. The model furthermore consists of several different parts (Figure 2-4 in Chapter 2).

A common geometric model is used for all disciplines. The geometric description of the bedrock will be primarily based on geological information, but the data set also includes information from the other disciplines' databases for interpretation of geometries. The geological description thus comprises a part of the site-descriptive model. Within geology, descriptions are prepared of soil type distribution, rock type distribution and structural geology. As a basis for understanding the different descriptions and how they are interrelated, a geological evolution model is also needed. An overall picture of the geological models is provided in Table 4-1 /Olsson et al, 1994/.

Table 4-1. Brief presentation of the geological parts of the site-descriptive model.

Geological description of the repository site

Purpose of model
To describe present-day soil types, rock types and rock mass structures for a given investigated volume as well as the geological evolution of the area.

Process description
Description of currently ongoing processes in the area in question, e.g. slow movements in the earth's crust.

Constituents of the model

Geometric framework
Coordinate-assigned soil/rock volume showing soil type distribution, rock type distribution, geometric distribution and orientation of plastic and brittle structures (fracture zones).

Parameters
Soil types – stratigraphy, structure, composition.
Rock types – mineral composition, texture, porosity, density, fracture distribution (fracture character, fracture-filling minerals).
Structures – character (plastic–brittle), fracture content, degree of alteration (fracture-filling minerals).
Relative age distribution.

Data representation
For soil types and rock types, a uniform distribution of data within the entire volume is striven for.
For regional and local major fracture zones, a deterministic determination of the geometry is striven for.
Local minor fracture zones and properties of the rock matrix are described stochastically.

Boundary conditions
Regional and local descriptions are mutually consistent.

Numerical tools
RVS

Calculation results
Properties and distribution of soil and rock types, plus location, width, orientation and properties of major fracture zones.

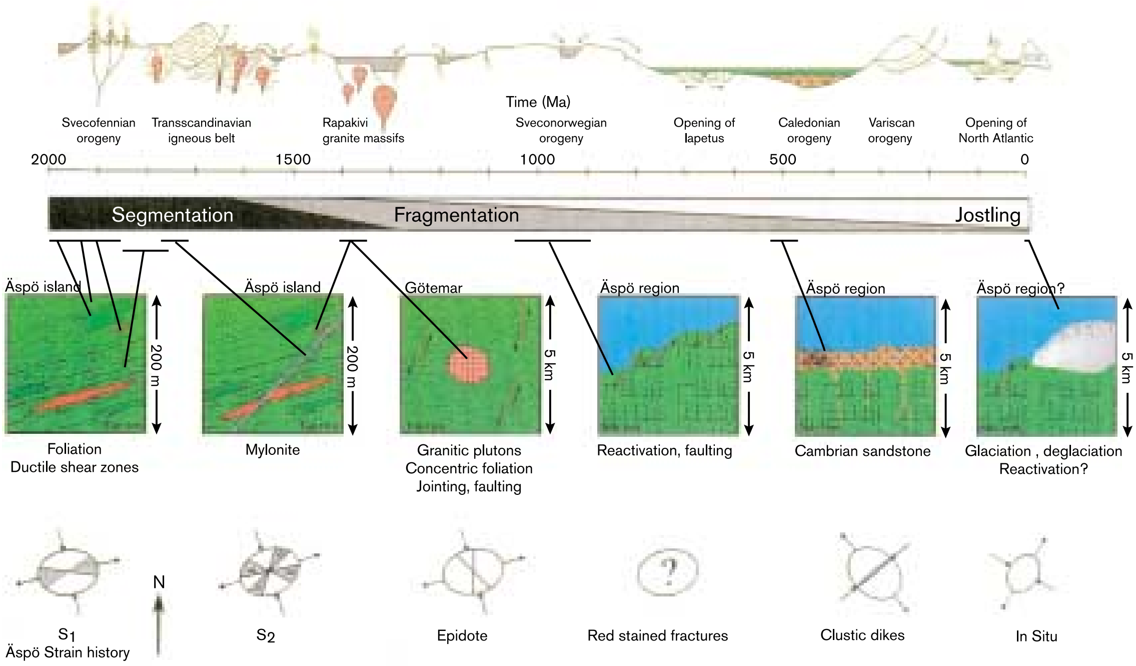


Figure 4-3. *Schematic illustration of a geological evolution model /from Rhén et al, 1997c/.*

Geological evolution model

The geological evolution model comprises the foundation for the geoscientific understanding of the geology of the site. The evolution model describes how and when rock types and structures were formed/altered. Geological evolution also includes Quaternary geological evolution. Dating, for example by means of isotope measurements, is an important source of information here. Examples of ongoing processes are slow movements in the bedrock resulting from continental drift (a few mm/y). Figure 4-3 shows an example of a geological evolution model /Rhén et al, 1997/.

Soil description

The soil description mainly includes the distribution, thickness and composition of different soil types and bottom sediments in seas and lakes. This description serves primarily as a basis for modelling of surface ecosystems and recipient conditions (biosphere modelling).

Rock type description

The rock type description includes the structure of the rock mass as regards the distribution of different rock types both spatially and in terms of percentage, plus a characterization of the different rock types. This description is primarily of importance in preparing the geological-structural and rock mechanical descriptions. The different rock types are also of importance for the geochemical understanding of the site.

Geological-structural description

The geological-structural description includes a description of the plastic structures in the rock, e.g. folding and foliation, and its various deformation zones. The deformation zones indicate that alterations or movements have taken place at some time during the geological history of the site. To obtain a consistent terminology that can be unambiguously understood by representatives of all disciplines, SKB uses the terms "plastic shear zones" and "fracture zones" to designate zones where the deformation has been plastic and brittle, respectively, see /Andersson et al, 2000/. The fracture zones are subdivided into the size classes *regional*, *local major*, *local minor* and *fractures*, see Table 4-2 and Figure 4-4.

The description is of direct importance for the rock mechanical and hydrogeological descriptions, as well as for general geological understanding. The geological-structural model is thereby of very great importance for the layout of the deep repository, since the principles that are used for positioning of the deep repository in the rock are based to a high degree on avoiding the regional and local major fracture zones.

Table 4-2. Classification and naming of fracture zones and ambition level for geometric description during site investigation /from Andersson et al, 2000/.

Name	Length	Width	Ambition for description
Regional fracture zones	> 10 km	> 100 m	Deterministic
Local major fracture zones	1–10 km	5–100 m	Deterministic (with uncertainties)
Local minor fracture zones	10 m–1 km	0.1–5 m	Statistical (some deterministic)
Fractures	< 10 m	< 0.1 m	Statistical

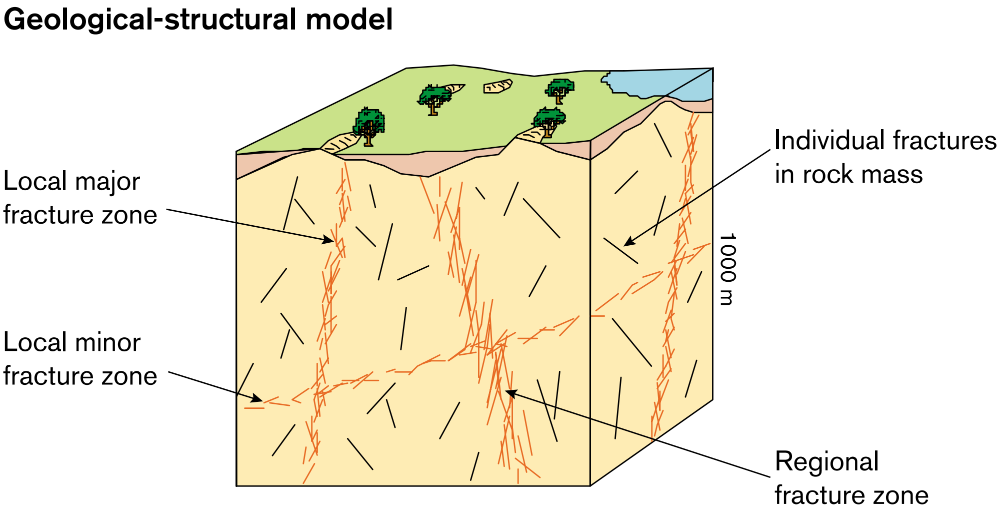


Figure 4-4. Fracture zones are classified according to size into regional, local major and local minor fracture zones. Individual fractures also occur in the rock.

4.2.2 Included parameters

In order to prepare the desired descriptions, information is needed on measured parameters. The descriptions are in turn based on determination/interpretation of a number of different parameters. The necessary parameters are shown in Table 4-3, which is based on the tables compiled for the parameter report /Andersson et al, 1996/, the revision that took place in connection with the work on requirements and criteria /Andersson et al, 2000/ and the production of the general investigation and evaluation programme /SKB, 2000b/.

Table 4-3. Compilation of geological parameters included in the geological description in the site-descriptive model. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Topography	– topography	x	x			Overview, geological-structural model, identification of structures.
Soil cover	– thickness of soil cover		x	x		Soil model (indirectly soil and environment, superficial hydrogeology, biosphere model).
	– soil distribution	x	x			
	– soil description		x			
	– soil type		x			
	– bottom sediment		x	x		
	– indication of neotectonics		x			Assessment of neotectonics.
Bedrock – rock types						
Occurring rock types	– rock type distribution (spatial and percentage)	x	x	x	x	Lithological model (used indirectly for rock mechanical, hydrogeological and geochemical understanding).
	– xenoliths			x	x	
	– dikes	x	x	x	x	
	– contacts		x	x		
	– age			x		
	– ore potential - industrial minerals	x	x			
Rock type description	– mineralogical composition		x	x	x	Lithological model (used indirectly for rock mechanical, hydrogeological and geochemical understanding).
	– grain size		x	x	x	
	– mineral orientation		x	x	x	
	– microfractures			x	x	
	– density		x	x		
	– porosity			x		
	– susceptibility, gamma radiation etc		x			
	– mineralogical alteration/ weathering		x	x	x	
Bedrock – structures						
Plastic structures	– folding (geometry)		x	x	x	Geological-structural model.
	– foliation		x	x		
	– lineation		x	x	x	
	– veining		x	x		
Shear zones	– age			x		
	– extent, properties	x	x	x	x	

Parameter group	Parameter	Determined primarily during FS	ISI	CSI	DC	Used for
Brittle structures						
Regional and local major fracture zones	– location	x	x	x		Geological-structural model. Repository design. Input data to hydrogeological model and rock mechanical model. Fracture-filling minerals etc input data to hydrogeochemical model.
	– orientation		x	x		
	– length	x	x	x		
	– width		x	x		
	– movements (size, direction)			x		
	– age			x		
	– properties (number of fracture sets, spacing, block size, fracture character, fracture filling (fracture mineral), weathering/alteration		x	x	x	
Local minor fracture zones (mainly data that permits stochastic description of parameters, but where discrete observations are reported)	– location/density		x	x	x	Input data to hydrogeological model and rock mechanical model (repository design). Fracture-filling minerals etc input data to hydrogeochemical model.
	– orientation			x	x	
	– length		x	x	x	
	– width			x	x	
	– movements (size, direction)			x	x	
	– age			x	x	
	– properties (number of fracture sets, spacing, block size, fracture character, fracture filling (fracture mineral), weathering/alteration			x	x	
Fractures – data for stochastic description	– density (different groups)		x	x	x	Input data to detailed hydrogeological model and detailed rock mechanical model. Indirect input data to nuclide transport model. Fracture-filling minerals etc input data to hydrogeochemical model.
	– orientation		x	x	x	
	– trace length		x	x	x	
	– contact pattern			x	x	
	– aperture width			x	x	
	– roughness			x	x	
	– weathering (alteration)			x	x	
	– fracture filling (fracture mineral)			x	x	
	– age			x	x	

4.2.3 Modelling tools and analyses

In a site investigation, a large quantity of data from different investigations is collected and interpreted. This information is used to write the different descriptions of the properties and conditions on the site.

Interpretation of data and extrapolation to space – "geological modelling"

The investigations result in primary data (measurement values and routinely calculated values) that are collected in a database (SICADA). Primary data are interpreted, both with respect to the geometric units in the bedrock (fracture zones, rock types, etc) and with respect to the various properties of the rock units in accordance with parameter tables for different disciplines, see Figure 2-4. It is hereby important to distinguish between primary data (stored in SICADA) and interpreted properties (presented in models).

In principle, interpretation entails that measurement results, representing measurement points of varying distribution and density on the ground surface or in boreholes, are analyzed by experts by means of e.g. interpolation, statistical processing etc so that specific properties (parameter values) can be assigned and distributed over the entire modelled rock volume. The interpretation methodology cannot be described with the same precision as routine measurements and calculations, since it also includes the discipline experts' judgements and evaluations of the primary information (see Figure 4-5). Uncertainties must be described, see e.g. /Saksa and Nummela, 1998/. Interpretation may be both method-specific and interdisciplinary, and it is important to clarify whether an interpretation is based on one method, several methods within a discipline, or is interdisciplinary.

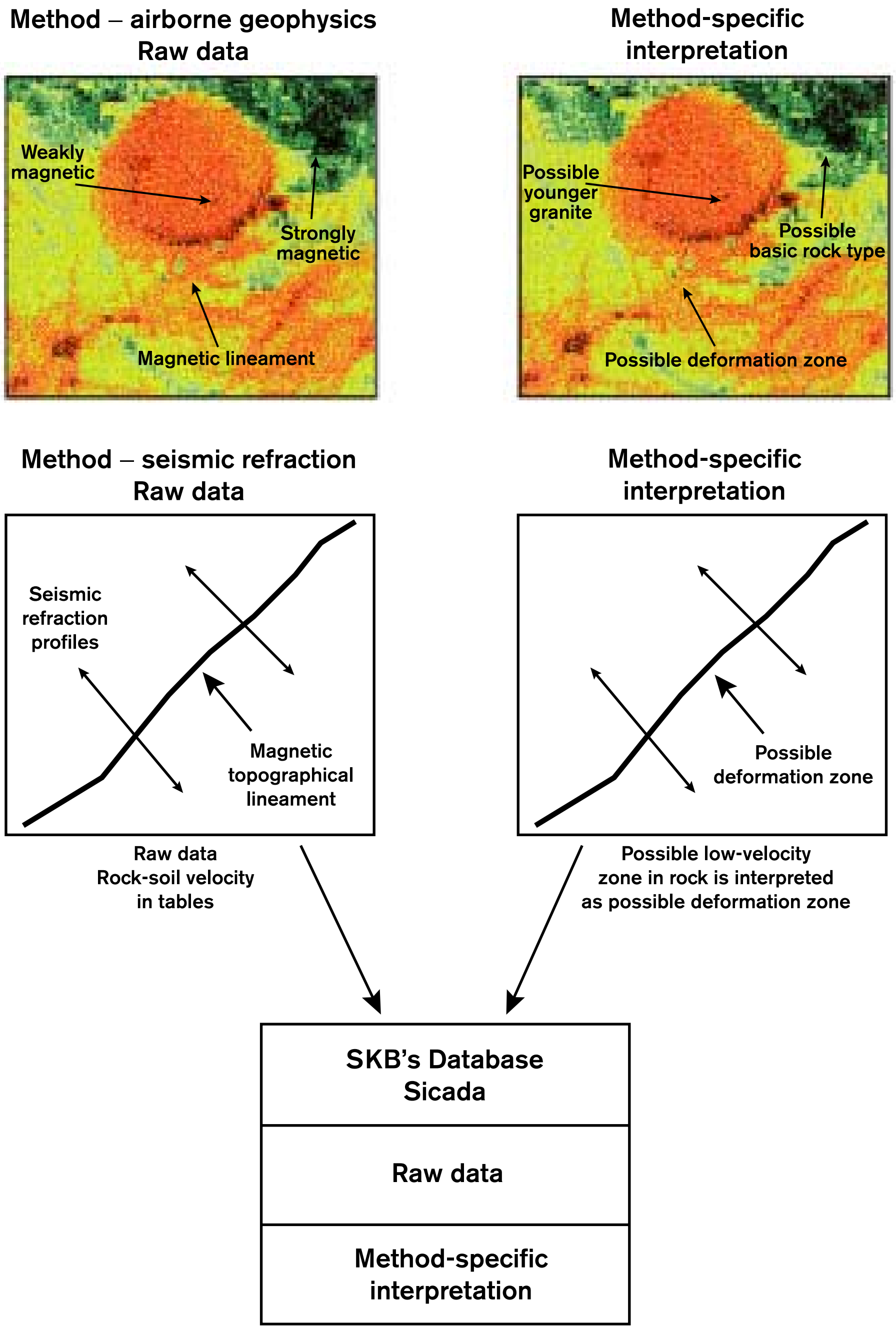


Figure 4-5. *Example of method-specific interpretation of raw data for two geophysical methods.*

For example, a gabbro body in a surrounding granite matrix can be interpreted as a disc or a lens of a certain assumed size. This can be done in the light of data from e.g. outcrop observations, geophysics (gravimetry) and cored boreholes. In a similar manner, a fracture zone can be interpreted in the light of surface observations in the form of a lineament (topographical, magnetic), outcrop observations (high fracture frequency) and geophysics, as regards extent on the surface and character (partially). Boreholes and seismic reflection provide data concerning extent (dip) and character at depth.

This interpretation is done according to a methodology developed by SKB around the 3D tool RVS, Figure 4-6. This method mainly involves initially devising a strict geometric description in which the rock is subdivided into geometric units. Then, as primary data are collected, the identified geometric units are described with geoscientific properties (interpreted data). The gradual construction of the models is version-managed and saved in a "model database". Particulars regarding which data the model is based on and who has performed the interpretation are also saved for each version (or alternative description).

At the beginning of the site investigation, very little data are available at depth. Early model versions therefore feature great uncertainty in the depth dimension. The location of fracture zones is based on interpreted lineaments on the surface. The assessment of the continuation of the fracture zones at depth or the presence of subhorizontal structures is highly uncertain. A description of relatively well-known conditions is first entered into RVS, above all the distribution of lineaments and rock types on the rock surface. The extent of the fracture zones at depth can also be exemplified in RVS for different assumed dips or frequency of subhorizontal fracture zones. In other words, there are several alternative interpretations in an early phase, even though only a few will be visualized.

As the investigations progress, more information is obtained from depth, for example in the form of seismic reflection data, borehole geophysics data and investigations of drill cores. Later on, information is also added from hydrogeological interference tests. The location of the geometric observations of possible fracture zones is entered into RVS. In order to determine the locations of the fracture zones, an attempt is made in interpretation to tie these different observations together into different coherent zones.

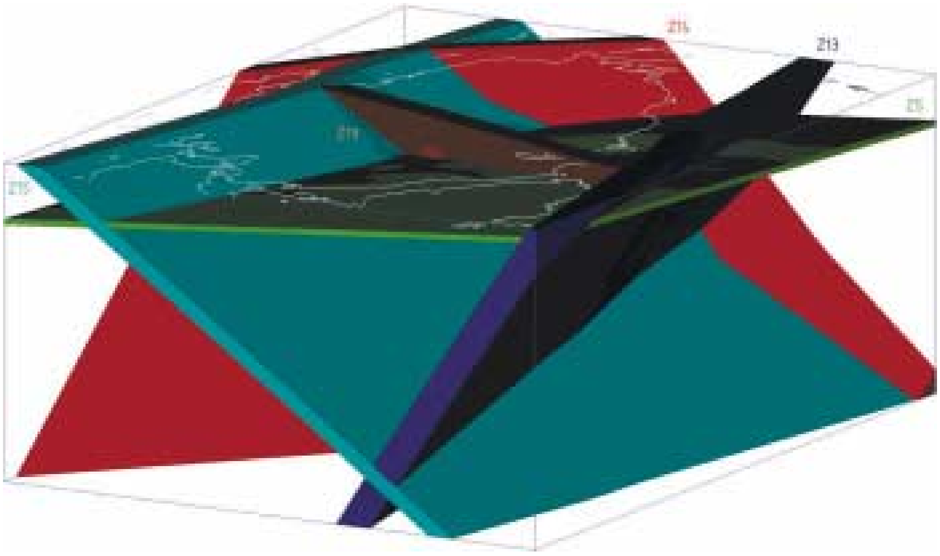


__Figure 4-6.__ Example of modelling (RVS) of the attribute "deformation zone".

The uncertainty in interpretation is dependent on, among other things, the density of observation points/areas, but also on how easily interpreted the observations are. Interpretation procedure and uncertainties are described for each model version in the site-descriptive document. Provided the uncertainties are not unreasonably great, a reasonable base interpretation of the location of regional and local major fracture zones is presented in RVS. Alternative locations, or completely alternative interpretations, can also be presented, depending on an assessment of the magnitude of the uncertainties. Local minor fracture zones and individual fractures are preferably described in statistical terms.

The geometric units do not initially contain any geological information (only coordinates), until they are marked with so-called object types. An object type can be regarded as a heading for a number of geological parameters. Examples of object types are deformation zone, and rock unit. In order for an object type to be included in the description, established parameters must have been determined with sufficient density and acceptable certainty with a view towards the methodology and prevailing geological conditions. For example, the object type "deformation zone" is described as a volume (disc) within which fracture zones or plastic shear zones are judged to occur. The deformation zone is assessed in the light of a number of parameters and the precision of the assessment is graded. The geometric units are then assigned parameter values interpreted from measurement results, or in some cases in early phases assigned on the basis of generic values.

4.3 Characterization methods

General accounts of various characterization methods that can be used for the geological description are given below.

4.3.1 Geodetic methods

By "geodetic methods" is meant the methods that are used in different ways for position measurement and setting-out of measurement profiles, measurement points, sampling points, boreholes, etc, Table 4-4. The geodetic methods provide geometric information that is necessary for all measurements.

As far as measurement points on the ground surface are concerned, traditional position measurement methods and GPS (Global Positioning System) will be used. The GPS method is constantly being developed with respect to accuracy and practical use, and is therefore expected to be used to an increasing extent. Position measurement with a theodolite will also be carried out.

Experience from the Äspö HRL shows that using local coordinate systems in parallel with a national system is not to be recommended. Instead, it is recommended that the national coordinate system (RT90 and RH70) will be used in preference.

Several commercial methods are available for measuring the direction and deviation of the boreholes. SKB usually uses the Maxibore system, which utilizes 3 reflector rings (one with a level) placed in sequence in 3 aluminium tubes. The position of the reflector rings is registered optically on a CCD (charge-coupled device). The displacement of the rings shows in which direction the borehole deviates. SKB is currently in the process of evaluating the performance and accuracy of different methods.

Table 4-4. Description of geodetic methods for setting-out and position measurement of points, boreholes etc.

Method	Parameter (information)	Comment
Geodetic methods **Coordinate systems**		
Base coordinate system RT90 national system should be used	**Positioning structure** X, Y, Z coordinates	Use of a standardized coordinate system is necessary.
Setting-out and position measurement		
Position measurement by means of traditional method or GPS	**Coordinate positions**	Known, commercial methodology where GPS in particular is constantly being developed.
• measurement profiles	X, Y, Z (RT90)	
• measurement points/ sampling points	X, Y, Z (RT90)	
• borehole	X, Y, Z (RT90) and direction	
Borehole measurement deviation measurement	**Positions along borehole**	Deviation measurement methods inadequately verified and will be reviewed. Own system for length calibration has been developed.
• length from drilling	borehole length	
• borehole deviation	X, Y, Z (RT90) against borehole length	
• length marking and calibration in borehole	Length-corrected measurement points	
Seismic and aseismic movements		
Observations and long time monitoring	**Indicator phenomena**	A deformation measurement programme (aseismic) is under way in Oskarshamn.
• geological/topographical observations in soil and rock	neotectonic indications (postglacial faults)	
• seismic observations/ monitoring	seismic activity (stability)	
• analysis of geodetic data	slow tectonic movements (aseismic) and block displacements	
• GPS network and precision levelling		
• land uplift data		
• deformation measurements		

As far as downhole investigations are concerned, length measurement exhibits poor accuracy in many cases, particularly as regards methods where measurement probes are carried by a wire or cable. This problem is being solved by SKB by development of a method where fixed lengths are marked in the borehole by cutting grooves in the borehole wall during drilling. The grooves are then used for calibration of the measurement probes' length measurement.

4.3.2 Measurement of rock movements

For deformation measurements to check for movements in the bedrock, precision measurements should be carried out using GPS technology /Muir-Wood, 1993; LaPointe et al, 1999/. The measurements should be concentrated to regional fracture zones and should enable movements (aseismic) on the order of 1 mm per year to be estimated with sufficient accuracy after 2–3 years measurements. For this purpose, 7–10 measurement steel screws are drilled into solid rock. Satellite antennae with a free field of vision down to 20° above the horizon are mounted on the steel screws. Antennae and receivers are deployed 2–3 times a year and measurements are made via satellites for 24–48 hours.

To monitor seismic events in the area and to get an idea of what deformation processes are going on, a seismic observation network is needed. The observation network should cover a large area. It must be possible to relate individual seismic events to seismic events in a larger region in order for them to be evaluated. The existing network along the coast of the Bay of Bothnia should therefore be extended southward towards Oskarshamn, and the network around the investigated sites should be densified. Approximately 14 new stations are required for an extension of the network from Gävle to Oskarshamn in order to achieve the desired detection level of magnitude (M) 0.5. To further increase the detection level around the investigated sites, a densification in the immediate vicinity by 2 stations is recommended. This is estimated to provide an increase in sensitivity to magnitude 0 and reasonable prospects for accurate depth determination in the areas in question.

4.3.3 Surface geophysical methods

Both the character of the bedrock and the occurrence of plastic and brittle structures, as well as overlying soil cover, can be investigated by means of surface geophysical methods, see Table 4-5. The surface geophysical methods described here include both airborne geophysics and ground geophysical surveys.

Airborne geophysics

The airborne geophysical methods used are magnetic, electromagnetic and radiometric methods. Most of Sweden is covered by surveys using these methods, although with varying investigation parameters. The airborne geophysical maps are used for an assessment of the occurrence of regional and local major fracture zones and various rock type volumes and their character.

Table 4-5. Description of geophysical methods for investigating soils and the superficial bedrock.

Method	Parameter (information)	Comment
Geophysical methods **Surface geophysical methods**		
Airborne geophysics (incl. helicopter)	**Airborne geophysical maps, interpretation basis for**	Documented methods. Survey from helicopter can be offered by Finland and Norway. Interpretation methodology should be optimized.
• magnetic methods	• regional and local structures, rock types	
• electromagnetic methods	• regional and local structures	
• radiometric methods	• rock types	
Ground geophysical survey (different scales)	**Geophysical maps, interpretation basis for**	Mainly documented methods. Further development of seismic methods is in progress. Studies for optimization of electrical (CVES) and EM methods should be carried out.
• gravimetry	• rock types	
• magnetic methods	• rock types, structures	
• resistivity (CVES)	• structures, (porosity)	
• electromagnetic methods (VLF, slingram)	• structures	
• transient electromagnetic sounding (TEM)	• structures, deep saline groundwater	
• seismic refraction	• structures	
• seismic reflection	• subhorizontal structures	
• ground-penetrating radar	• structures, soil depth	

Helicopter-borne surveys are performed over a slightly smaller area, and magnetic, electromagnetic and radiometric methods are used here as well. The magnetometer which is used is a sensitive proton magnetometer of the cesium type. The electromagnetic methods used employ a multi-frequency EM system with frequencies from approximately 1 kHz to more than 30 kHz. In the helicopter surveys, the sensors are placed in a special module (bird) carried below the helicopter at a height of about 40 m above the ground. The helicopter flies at an altitude of about 80 m. The airborne geophysical maps provide rock type information and information on the occurrence of regional and local fracture zones, as well as some information on the overburden (soil layer). The helicopter-borne system is preferably flown in one direction with a 50 m line spacing.

Ground geophysical survey

Gravimetric measurement mainly provides information on the extent of the different rock types at depth and some information on soil depths where they vary widely. Gravimetric methods are based on the fact that a weight suspended from a spring at different places or points is acted on by the earth's gravity. The device is extremely sensitive and can detect changes in the earth's gravity on the order of 10^{-6} m/s^2. The gravimetric measurements are conducted with a point density of around 1 point/km^2. In order to obtain valuable information on variations in the bedrock, corrections must be made for height above the geoid (or sea surface) and topography in the vicinity of the measurement point. This means that the height above sea level of the points must be determined by means of GPS or levelling.

Resistivity measurement (CVES = Continuous Vertical Electrical Sounding) measures the resistivity in rock volumes. Down to a depth of a few hundred metres, it provides some information on the occurrence of major fracture zones and the depth to saline groundwater. CVES entails deploying some 80 or so electrodes along a profile.
An electric current is passed between one pair of electrodes at a time and the electric potential is measured at the same time between another pair of electrodes. The control units then reconnects the electrodes and an electric current is passed between another pair of electrodes and the potential is once again measured between yet another pair. This is repeated until the entire array has been measured. The array is then moved to a new position and the measurements are repeated. The resistivity measurement is conducted along a couple of intersecting profiles over the areas of potential interest for the complete site investigation.

Transient electromagnetic sounding (TEM) provides the same information as CVES but to greater depth. In TEM, a measuring loop is placed out on the ground. An electromagnetic pulse containing a large number of frequencies is sent out. Eddy currents are induced in electrically conductive strata in the bedrock. The eddy currents give rise to a secondary field, which is measured in a receiver loop. The lower the frequency, the greater the depth information is obtained from. Information is also obtained from deep-lying saline water horizons.

By means of a ground geophysical survey along parallel profiles spaced at a distance varying between 10 and 50 m, the character and dip of regional and local fracture zones is studied in greater detail. The methods used in this case are magnetic, multi-frequency electromagnetic (HLEM = Horizontal Loop Electromagnetic), and multi-electrode resistivity measurement (CVES). Magnetic measurement involves use of a proton magnetometer. Protons in a container are made to spin or precess by means of a brief current pulse, and when the current is turned off the protons align themselves in the direction of the prevailing magnetic field. Normally a measurement accuracy of about 1 nT is obtained. In HLEM an electromagnetic field is generated by a portable transmitter coil. The transmitted field induces eddy currents in electrically conductive material in the bedrock. This gives rise to a new secondary electromagnetic field that can be measured in a portable receiver coil placed at a certain distance (about 60 m) from the transmitter coil. By carrying the coils along a profile and repeating the measurements at different points, information is obtained on conductive structures in the rock or in overlying soil layers above the rock surface. In HLEM, a large number of different frequencies are utilized to obtain information from different depths in soil layers and bedrock.

In conjunction with rock type mapping, radioactive radiation and magnetic susceptibility are measured with handheld instruments /Almén et al, 1994/.

Seismic refraction over large valleys and soil-covered areas provides information on the character and properties of regional and local major fracture zones. It also provides information on rock quality and soil depth. Seismic refraction employs a large number of sensors (geophones) arranged on the ground at intervals of 5–20 m. Explosive charges ranging from 50 grams up to 2–3 kg in extreme cases are placed at regular intervals both inside and outside the profile. These charges are exploded one at a time, generating a sound wave that is propagated down into the soil strata and into underlying bedrock. The sound wave is gradually refracted back to the ground surface where the sensors have been placed. If the bedrock contains fractured rock or rock of lower quality, the sound wave will be propagated more slowly. This is recorded by the ground-based geophones. In the same way, they record whether the soil layers increase in thickness, since the sound wave is propagated more slowly in soil.

Ground-penetrating radar provides information on soil layer sequences and soil depths down to approximately 15 m in glacial till and non-cohesive soils and detects superficial fractures if the soil cover is homogeneous and thin. The ability of the method to detect soil depths in clayey or silty (and saline) sediments and soils is highly limited. In ground-penetrating radar, an electromagnetic pulse of high frequency, 25 MHz up to 1 GHz, is transmitted as vertically down into the ground as possible. The electromagnetic wave is reflected by irregularities in the soil layers and structures in the rock. After reflection and attenuation of the wave, the received signal is registered in the receiver antenna placed in the same unit as the transmitter antenna. The ground-penetrating radar antenna can easily be pulled by one person by walking along a profile. Pulses are transmitted continuously and results are obtained directly on the screen in a portable computer (radargram). The ground-penetrating radar antenna can also be towed by a vehicle.

Seismic reflection investigations are carried out to discover large, gently-dipping fracture zones in the bedrock that may make the area unsuitable for the deep repository. The seismic reflection profiles are some km long. Just like seismic refraction, seismic reflection employs an array of ground-based geophones. The explosive charges are generally smaller, 25 g up to 1 kg, than those used in seismic refraction. The distance between the shot points is also much smaller, e.g. 10 m. The reflected sound waves are recorded, and the subsequent data processing refines the information from the reflected waves. Information is above all obtained from gently-dipping fracture zones, but also from fracture zones that dip up to 45° /Juhlin and Palm, 1997/.

4.3.4 Geological methods – surface methods

The geological methods will be used to investigate both bedrock and soil cover, see Table 4-6. Soil geology includes determination of the mineral soil types and their extent. As far as the bedrock is concerned, rock types, rock type distribution and structures are investigated.

Lineament interpretation

Lineament interpretation of digital elevation data, aerial photos and airborne geophysical maps is used to obtain information on large-scale lineaments that may comprise regional or local fracture zones. This image analysis is done at an early stage of the initial site investigations.

Soil mapping

Aerial photo interpretation is used in soil mapping for a general survey. This provides information on the overall extent of the soil cover. Field mapping is done of the different soil types. Sampling in the form of digging and soil drilling is performed in order to study the character of the soils. Soil probing is done to study the thickness of the soil cover. Trenches are dug in sediment areas below the highest coastline to look for possible signs of neotectonic movements. The character and properties of the soil comprise an interpretation basis for surface ecosystems (in particular peat mosses and organic soils) and groundwater recharge for the discipline of hydrogeology. The soil types are described with respect to extent, thickness, grain size distribution and their variations laterally and vertically, as well as mode of formation and stratigraphic conditions. This requires excavation and/or drilling with sampling. The goal is to devise a model for the properties and extent of the soils in three dimensions.

Table 4-6. Description of geological methods for investigating soil and bedrock.

Method	Parameter (information)	Comment
Geological methods **Surface geological methods**		
Image analysis/lineaments • aerial photo interpretation • analysis of digital elevation database	**Lineament map** • large-scale tectonic structures • regional and local structures	Documented methods
Soil mapping • aerial photo interpretation • field mapping • sampling • investigation of bottom sediments (lake, sea) • peat mosses • organic soils	**Soil map with description** • Quaternary deposits, soils • thickness of soil cover • identification of recipients • neotectonic indications • interpretation basis for surface ecosystems • interpretation basis for groundwater recharge	Documented methods Of interest for surface ecosystems
Bedrock mapping (different scales) • rock outcrops, rock cuts • exposed rock surfaces • sampling • soil/rock drilling with core sampling from rock surface	**Bedrock geology maps with description** • rock type distribution • rock type description • plastic structures • brittle structures • neotectonic indications	Documented methods

Bedrock mapping

Rock outcrops, rock cuts, rock quarries and cleared rock surfaces are surveyed for description of lithology and bedrock structure. Major plastic and brittle structures, e.g. regional and local major fracture zones, are mapped. The rock surface is sampled as a basis for petrographic and petrophysical determination.

4.3.5 Geological borehole investigation

Percussion boreholes

Lithological variations are investigated via percussion boreholes by studies of drill cuttings and MWD (Measurements While Drilling), see Table 4-7. A sample of drill cuttings is taken in a plastic bag every 0.5 m. The drill cuttings are subjected to visual examination for observation of colour variations as well as microscopic studies. The colour and quantity of the flushing water are also recorded. MWD entails recording of

Table 4-7. Description of geological methods for investigating the bedrock at depth.

Method	Parameter (information)	Comment
Geological methods **Geological borehole investigations**		
Percussion drilling – investigation of drill cuttings and MWD • visual examination • sampling for mineralogical analysis • MWD	**Basis for GBD** (see below) • lithological boundaries • fracture zones	Documented methods.
Core drilling – mapping of drill core with Boremap • based geometrically on BIPS logging (if done) • geological description of drill core • sampling of rock matrix and fracture-filling minerals for lab analyses (see below)	**Basis for GBD** (see below) • rock type distribution • rock type description • plastic structures • fracture location/orientation • properties of fracture surfaces	Integrated mapping from BIPS and drill core. Methodology developed by SKB.
Sample analyses • microscopic analysis • chemical analysis • petrophysical analysis • rock mechanical analysis • dating	**Analysis results** • mineral composition • chemical composition • density, porosity, susceptibility, etc • see rock mechanics • age	Documented methods.
Geological Borehole Documentation (GBD) • geological characterization along borehole • Boremap core mapping • examination of drill cuttings • MWD • interpretation support from geophysics • interpretation support from sample analyses • statistical processing	**Geological description along borehole** • rock type distribution • rock type description • plastic structures • fracture location/orientation • properties of fracture surfaces • statistical analysis of fractures • interpreted fracture zones	Based primarily on Boremap mapping and complements this by interpretation support from geophysics (possibly radar, seismic methods). Single-hole descriptions are presented with WellCAD.

drilling parameters during the drilling process, e.g. drilling rate, feed pressure and rotation pressure. After drilling, the percussion borehole is videotaped by BIPS as a basis for geological borehole documentation (GBD).

Cored boreholes

The drill core obtained from core drilling is mapped with Boremap. The method is based on the fact that the borehole has previously been examined by BIPS, see section 4.3.6, and the digital BIPS image is used as a basis for mapping the drill core. The methodology is based on the fact that the geometric components (lithological boundaries and location of certain fractures) are taken from the BIPS image, while lithological information and the properties of the fracture surfaces are taken from the drill core. In conjunction with drill core mapping, rock type and both plastic structures (e.g. indications of shear movements) and brittle structures (e.g. fractures), as well as their frequency, orientation and character, are determined. The absolute orientation of the fractures and fracture-filling minerals can be entered directly into the mapping database.

Rock samples are taken from the drill core, along with samples of fracture-filling minerals. These samples are analyzed microscopically (thin section) and by means of e.g. x-ray spectrography.

Sample analysis

During both field and drill core mapping, samples are taken of soil and rock types as well as fracture-filling minerals for laboratory analysis. The soils are primarily analyzed with respect to grain size distribution. Thin sections are prepared of the rock type samples and examined in a microscope for more exact lithological determination. Rocks and fracture-filling minerals are also analyzed by means of e.g. x-ray spectrography for determination of their chemical composition. For the geophysical interpretation, rock type samples are taken for analysis of petrophysical parameters such as density, porosity and magnetic susceptibility.

4.3.6 Borehole geophysical methods

Among borehole geophysical methods, caliper provides information on the geometry of the borehole, i.e. borehole diameters. Furthermore, a four-arm caliper can measure any ovality in the borehole, which may indicate anomalous rock stresses at great depth, Table 4-8.

Radiometric methods such as natural gamma, gamma-gamma and neutron-neutron provide information on lithological variations. The natural gamma probe uses an NaI crystal as a detector and measures variations in content of uranium, thorium and potassium. Variations in these elements reflect variations in lithology. The gamma-gamma (density) probe uses Cs-137 as a gamma-emitting preparation and an NaI crystal as a detector. The preparation emits gamma radiation, which is absorbed above all by dark and heavy minerals. Neutron-neutron uses a preparation that emits neutrons (Am-241). The emitted neutrons are slowed down and absorbed by water molecules (actually hydrogen atoms) and dark minerals. The neutron probe is thereby sensitive to increase porosity, but also to the presence of dark minerals (Fe silicates and Fe oxides).

Table 4-8. Description of geophysical methods for investigating the bedrock at depth.

Method	Parameter (information)	Comment
Borehole geophysical methods		
Borehole geophysical logging	**Interpretation support for GBD** (see geology)	Documented methods.
• caliper	• borehole status, geometry	Optimization of interpretation methodology.
• radiometric methods (natural gamma, neutron, gamma-gamma)	• lithological parameters	
• electrical methods (resistivity, single-point resistance, fluid resistivity)	• lithological parameters, structures, groundwater salinity, hydraulic conductors	A method study of focused resistivity using dual laterolog has been conducted in the KLX02 borehole in Laxemar.
• magnetic methods	• lithological parameters, structures	
• sonic (full-wave)	• lithological parameters, structures	Full-wave sonic provides rock mechanical information.
• temperature	• rock temperature, water-bearing fractures	
Borehole radar	**Interpretation support for GBD** (see geology)	The RAMAC equipment is undergoing further development
• reflection measurement	• structures (local major and local minor)	
• tomography	• same (within about 100 m from the borehole)	
Borehole seismic methods	**Interpretation support for GBD** (see geology)	Full-scale test performed in KLX02, Laxemar, for the purpose of testing co-interpretation with seismic reflection
• VSP (vertical Seismic Profiling) • reflection measurement • tomography	• structures (regional, local major and local minor), within up to 500 m from the borehole	
Borehole TV • BIPS	**Image of borehole wall** • basic background data for GBD (see geology) • lithology • fracture orientation • borehole status	Minor technical modifications are being made.

Electrical methods such as resistivity and single-point resistance provide information on fractures and fracture zones as well as the salinity of the borehole water. In normal resistivity, electric current is transmitted by an electrode in the probe and an electrode located on the ground surface. The potential electrode in the probe is located 1.6 m or 0.4 m from the current electrode, and the other potential electrode is placed on the ground surface. In single-point resistance, one and the same electrode is used as current and potential electrode both in the probe and up on the ground surface.

Sonic is an acoustic method that is sensitive to fractures in the rock. Sonic consists of an acoustic transmitter located in a probe that transmits a sound wave. The sound wave is propagated in the rock along the borehole and is recorded by two receivers spaced at 30 cm or 60 cm from each other. There is also a full-wave sonic that records both the P-wave and the S-wave. The method is useful within rock mechanics because it gives elastic parameters if the density is measured, e.g. by gamma-gamma or on rock samples. Rock of higher fracture content or lower quality gives rise to a lower velocity for the sound wave.

Magnetic susceptibility provides information on lithological variations and alteration. Magnetic susceptibility registers the magnetizability of the rock; the presence of magnetite in particular affects susceptibility. Magnetite occurs to a greater or lesser extent in most rock types.

Temperature measurements provide information on the temperature gradient and water flow in fracture zones. The temperature is measured with a thermistor located in a separate borehole probe or incorporated in other probes, for example a flow probe.

Borehole radar with reflection measurement provides information on the inclination of fracture zones in relation to the borehole axis. In borehole radar measurement, an electromagnetic pulse of high frequency (20 MHz up to 250 MHz) is transmitted into the rock. The radar wave is reflected by surfaces with anomalous electrical properties, such as fracture zones and dikes. The reflected waves are recorded by a receiver antenna. Borehole radar with directional antenna is used to calculate the absolute orientation of fracture zones, i.e. strike and dip. Then a receiver antenna with four separate receiver loops is used. Depending on the angle of the reflecting wave penetrating through the receiver loops, the orientation of the reflector can be determined.

VSP in boreholes can be used for co-interpretation with seismic reflection. VSP (Vertical Seismic Profiling) is based on generating a vibration or sound wave in the rock from a drilled hole or with a vibrator surface based on the rock surface and then using geophones (microphones) to record how this signal propagates in the bedrock. The sound waves are absorbed and reflected against surfaces in the rock with anomalous mechanical or elastical properties, such as fracture zones.

The videotape recording of the borehole wall by BIPS and the processing of this information together with the drill core is one of the most important data sources for geological borehole documentation (GBD). BIPS consists of a digital TV camera that tapes the borehole wall while the camera is lowered into the borehole. BIPS has a conical mirror in front of the camera and a compass needle that shows north or a plumb that shows the bottom edge of the borehole. The borehole wall is presented folded-out with e.g. the north line in the middle of the sheet. A fracture shows up as a darker sinus-shaped line across the image. The camera records in colour and has very good contrast and high resolution. Fractures more than approximately 1 mm in width are detected by current equipment, but the method may be improved.

5 Rock mechanics

5.1 General

This chapter describes which rock mechanical conditions and properties will be determined and possible characterization methods. The chapter also describes how the measured information is interpreted in the rock mechanics model that comprises part of the site-descriptive model.

5.1.1 Introduction

The mechanical properties of the rock affect both the isolating and retarding functions of the deep repository. The rock mechanical properties are also of great importance for how the repository will be configured and constructed.

The rock is a mechanical system that is normally in static equilibrium under the prevailing loads. Disturbances of this equilibrium may be caused by load changes, for example due to excavation of cavities in the rock, or to changes in mechanical properties. Instability leads to deformation of the rock mass and failures can occur if the strength is exceeded. Failures as such do not have to entail serious instability. Small deformations, without consequences for performance and safety, may be sufficient to restore equilibrium to the system.

The mechanical properties of the rock are dependent partly on the properties of the intact rock, and partly on the frequency and properties of fractures. Thus, the geometric distribution of fracture zones, fractures and rock types determine the mechanical properties of the rock mass and will thereby control where deformation and possible failures will occur. Displacements take place primarily along fractures and fracture zones. Furthermore, different rock types have different strengths and different deformation properties.

Mechanical disturbances will occur during different eras in the future of the repository and in different parts of the rock. The disturbances cause effects on different scales, such as deposition holes, tunnels, the entire tunnel system, and the rock volume surrounding the repository. The disturbances can cause both small- and large-scale changes. The importance of the disturbance also depends on the specific load case at which the disturbances occur. The rock properties that are of importance for the performance of the deep repository are therefore only meaningful when they are analyzed for a given tunnel layout in a given stress field.

The excavation of rock that takes place during the construction of the deep repository causes the largest relative change in mechanical equilibrium. This excavation leads to a redistribution of stresses and deformations around the tunnels. If the stress levels are high in relation to the strength of the rock, local failures may occur. This can occur rapidly in brittle rocks and is then known as “spalling”. A number of engineering-related requirements and preferences are therefore associated with repository construction.

The main question relating to long-term safety is whether changes in the geometry of the deposition holes could damage the buffer or canister and whether extensive movements along fractures and fracture zones or extensive formation of new fractures could degrade the retention properties of the rock. The load cases that need to be considered are primary changes in pore pressure during resaturation, the swelling pressure from the bentonite, thermal expansion of the rock, effects of earthquakes, and effects of extensive climatic change such as glaciations. Furthermore, it is necessary to take account of the fact that the mechanical properties of the rock can change with time, e.g. due to chemical weathering.

The state of stress in a rock mass depends in part on the weight of overlying masses and in part on the tectonic forces to which the studied rock volume is or has been subjected. In Swedish crystalline bedrock, horizontal stresses are normally greater than vertical stresses. The state of stress is a tensor, and is characterized by three mutually perpendicular principal directions, each of which corresponds to a principal stress. If all three principal stresses are equal, the state of stress is isotropic and the principal directions are indeterminate. If the principal stresses are unequal, the state of stress is anisotropic (deviatoric).

Within the rock mechanical programme, the initial rock stresses are determined by means of both direct measurement methods and various indications in boreholes, and on the basis of a geological-structural model. Nearness to fracture zones affects the state of stress in the rock mass. To analyze the distribution and direction of the stress field, numerical modelling will be carried out based on the geological-structural model.

Within the rock mechanical conceptual model, the rock is divided into intact rock (rock blocks) and discontinuities (mainly fractures and fracture zones). When the rock mass is loaded, the intact blocks are deformed and the discontinuities undergo shear movements, compression or expansion. The deformation properties and strength of the rock mass are thus dependent not only on the properties of the intact rock, but also on the frequency, orientation and mechanical properties of the fractures (joints). The deformation and strength properties of the rock mass are scale-dependent, see Figure 5-1. Provided that a studied rock volume is big enough to contain four or more fracture systems with similar properties, it can be represented as an isotropic material. The properties of such a rock volume can be estimated using a rock classification system. There are no general and simple relationships for rock masses with a small number of fracture systems (fewer than 3).

The deformation properties and strength of the individual fractures and the intact rock can be satisfactorily described by means of stress-strain relationships and failure criteria. Within the rock mechanical programme, the mechanical properties of the intact rock and the fractures are determined for the most part on recovered rock cores.

The rock mechanical properties are summarized in a rock mechanics site descriptive model where the rock mechanical properties of different parts (fracture zones, rock masses, fractures, intact rock) are described on different scales. Rock mechanical calculation models are used to analyze different mechanical processes both during construction and after repository closure. Rock mechanical calculation models may also be used for interpretation and evaluation of e.g. rock stress measurements. These models often consist of numerical calculation tools.

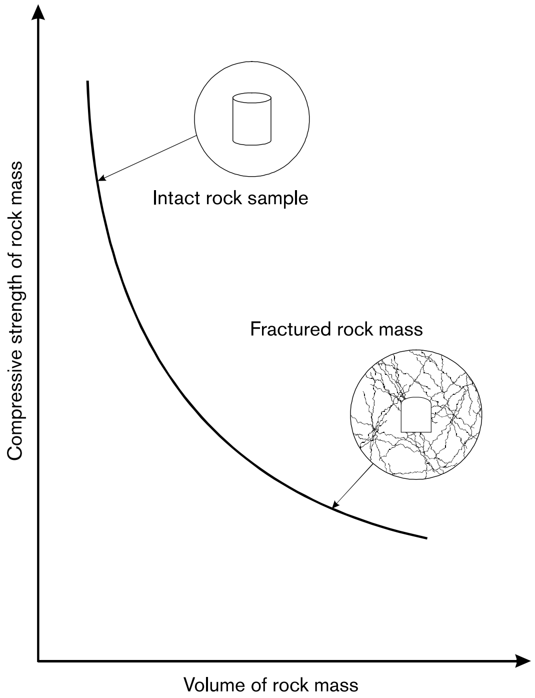


Figure 5-1. *Deformations and strength properties are scale-dependent.*

5.1.2 Discipline-specific goals

The requirements, preferences and criteria that have been identified for the discipline of rock mechanics are presented by /Andersson et al, 2000/. The rock mechanical programme is aimed at collecting data to answer these questions. The requirements and preferences can generally be satisfied by means of a suitable repository layout, choice of repository depth and choice of execution methods. For this, rock mechanical analyses are integrated with the design. With reference to the main goals of the geoscientific investigations (section 2.2), the rock mechanical work is mainly aimed at:

- determining whether the selected site is large enough to accommodate a repository,
- determine and assess the distribution of initial rock stresses within the site,
- identify the risk of extensive spalling problems or other rock breakout in deposition tunnels or holes,
- determine mechanical properties of fracture zones and individual fractures,
- determine mechanical properties of intact rock and various rock masses,
- identify possible problems where tunnels may pass fracture zones.

Focus during the initial site investigation

Information from boreholes is needed in order to characterize the mechanical properties of the rock. The choice of priority site within the candidate area is therefore controlled more by the geological-structural information. However, measurement results from the first boreholes within the site, especially the first cored borehole where stress measurement is performed, are of great importance for being able to judge whether the selected site is suitable for continued investigations. The investigations are focused on:

- initial measurement of initial rock stresses at the planned repository level,
- initial determination of the strength of the intact rock and the rock mass at the planned repository level,
- a first analysis of the risk of extensive spalling problems or other rock breakouts.

Based on this information, a preliminary rock mechanical description (model) is devised on the local and regional scales.

Focus during the complete site investigation

During the complete site investigation, additional measurements and characterization are carried out to be able, above all, to demonstrate the feasibility of building a deep repository on the site. The characterization is concentrated to the central investigation area, i.e. around and in the hypothetical repository. The investigations are focused on:

- determination of initial rock stresses and their distribution,
- determination of the mechanical properties of intact rock,
- determination of the mechanical properties of different rock masses,
- determination of the mechanical properties of individual fractures and fracture zones.

Based on this information, a rock mechanical description (model) is devised on the local and regional scales as a part of the overall site description.

5.1.3 Working methodology and coordination

The rock mechanical discipline includes investigation and description of the rock mechanical properties of the area in question. Generic data are used for the most part to describe the rock mechanical properties in an initial phase. The first rock mechanical investigations will be conducted when a priority site within the candidate area has been chosen.

Investigations and characterization are carried out stepwise (see section 2.3.1 and Figure 2-5 in Chapter 2). Some of the rock mechanical investigations (rock stress measurement with overcoring) will be carried out during drilling of cored boreholes. Positioning of boreholes, drilling and execution of investigations in boreholes that can disturb other measurements (e.g. hydraulic fracturing) require coordination with other disciplines, mainly geology, hydrogeology and hydrogeochemistry. This means, for example, that hydraulic fracturing is performed last in the borehole. Samples for rock mechanical laboratory investigations are taken out after the routine mapping of drill cores has been performed and the first geological-structural and rock type models have been devised. Figure 5-2 shows that information is also taken from other discipline-specific programmes, mainly geology.

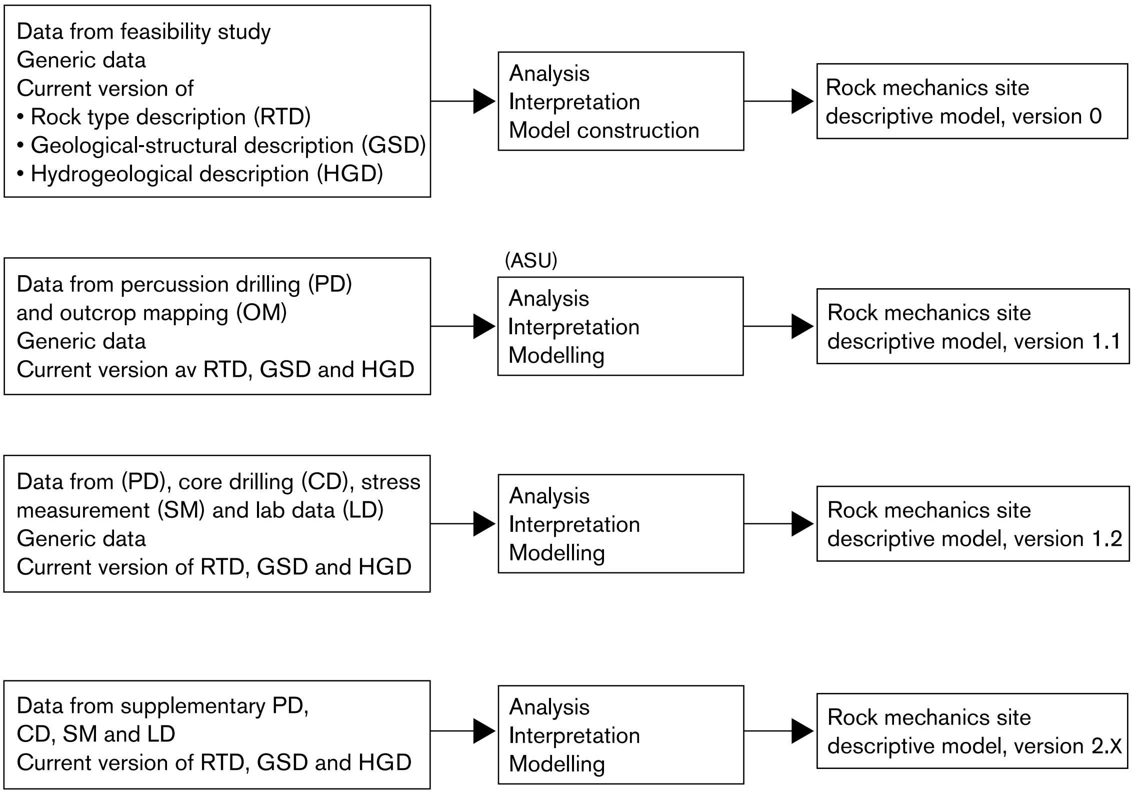


Figure 5-2. *Overview of working methodology and information needs for devising the descriptive rock mechanical model of the site and the regional area.*

Collaboration is required with adjoining disciplines – geology, thermal properties and hydrogeology – with regard to both the planning and execution of the investigations and co-evaluation and modelling. The discipline of geology provides the geometric premises for the structures and rock masses that are to be characterized within the discipline. There must also be coordination with geology and hydrogeology with regard to field studies and location of boreholes and with geology and hydrogeochemistry with regard to sampling of drill cores. Coordination with other disciplines must take place with regard to the order in which different investigations, in particular in boreholes, are carried out so that they do not disturb each other or make certain sampling impossible. /SKB, 2000b/ tells how the rock mechanical information is used within design and safety assessment.

5.2 Models and parameters

5.2.1 Structure of the models

The description of the rock mechanical conditions in the site-descriptive model includes the mechanical properties of the rock and their distribution on different scales. It also contains a description of the initial rock stresses and the distribution of the stress within the area. The geometric framework for this model consists of the geometric model, which is mainly based on the structure and lithological composition of the rock (see Chapter 4). An overall picture of the descriptive rock mechanical model is found in Table 5-1.

Table 5-1. Brief presentation of the rock mechanical model.

Descriptive rock mechanical model

Purpose of model
The parameters included in the model shall serve as a basis for design and safety assessment and the analyses performed in these steps. The model shall describe, for a given investigated volume, the initial stresses and the distribution of rock mechanical properties such as deformation and strength properties of the intact rock, of fractures and zones of weakness in the rock volume, and of the rock mass viewed as a unit consisting of intact rock and fractures. The model shall also describe the rock quality with regard to constructability.

Process description
Description of the processes that have given rise to the current distribution of rock stresses and properties in the area in question

Constituents of the model

Geometric framework
The base for the geometric framework consists of the lithological model and the geological-structural model that is set up within the discipline of geology, as well as the hydrogeological model that is developed within hydrogeology. With reference to the investigations conducted on the intact rock and the fractures, the geometric model can be further subdivided to get volume units with similar properties.

Parameters
Stresses: magnitude and direction of initial rock stresses, stresses in relation to tectonic structures.
Intact rock: deformation and strength properties, density, porosity, dynamic parameters, degree of weathering and degree of alteration.
Fractures: deformation and strength properties, statistical distribution of fracture geometries.
Rock mass: deformation and strength properties, seismic propagation velocity.
Rock classification system: as Q index, RMR, GSI, RMi.
See further Table 5-2.

Data representation
A uniform distribution of data is striven for within the volume in question. For the most part, however, constant parameter values and index values are associated with selected objects such as zones to represent and characterize the selected object in the rock volume. Statistical distribution is sought after for representation.

Boundary conditions
Initial rock stresses.

Numerical tools
RVS is used for interpretation and presentation of the constructed model. Numerical calculation models such as 3DEC are used to simulate the processes that have created the present-day distribution of rock stresses and properties.

Calculation results
Distribution of properties in accordance with the above parameter list plus distribution, magnitude and orientation of initial rock stresses within the area.

The information that is gathered within the rock mechanical discipline comprises input data to, above all, various rock mechanical calculation models, some for positioning of the repository and geometric configuration of its various parts, and some for studying long-term mechanical processes.

5.2.2 Included parameters

Table 5-2 summarizes which parameters are included in the mechanical description. As a rule, these parameters need to be interpreted from the results of the various investigations. The table is based on the tables compiled for the parameter report /Andersson et al, 1996/ and the revision that took place in connection with the work on requirements and criteria /Andersson et al, 2000/ and the work on the general investigation and evaluation programme /SKB, 2000b/. Information from several other disciplines, especially geology, is also required to prepare the rock mechanical description (see section 5.2.3).

Table 5-2. Compilation of rock mechanical parameters included in the rock mechanical model. The table also shows when the parameter is primarily determined.

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Fracture zones	– Geometry (see geology table)		x	x	x	To subdivide the rock into different rock masses in the descriptive rock mechanical model
Mechanical properties of fractures in different rock masses	– Deformation properties in normal direction			x	x	Discrete rock mechanical model, input data deformation properties of rock mass
	– Deformation properties in shear direction			x	x	
	– Shear strength JRC (joint roughness), JCS (joint compressive strength), ϕ_b (base friction), ϕ_r (post failure friction)			x	x	
Mechanical properties of intact rock in different rock masses	– (Young's) modulus of elasticity		x	x	x	Discrete rock mechanical model, input data deformation properties of rock mass
	– Poisson's ratio (ν)		x	x	x	
	– Strength (σ_c, m_i, s, a acc. to Hoek & Brown failure criterion)		x	x	x	
	– Tensile strength		x	x	x	
	– Indentation index			x	x	Assessment of drillability
Mechanical properties of different rock masses	– Young's modulus (of elasticity)			x	x	Rock mechanical model
	– Poisson's ratio (ν)			x	x	Rock mechanical model
	– Rock classification (RMR, Q) different systems		x	x	x	Determination of deformation and strength properties
	– Dynamic propagation velocity, pressure wave		x	x	x	Model for dynamic analysis
	– Dynamic propagation velocity, shear wave			x	x	Model for dynamic analysis
	– Strength (σ_{ci}, m_b, s, a acc. to Hoek & Brown failure criterion)			x	x	Rock mechanical model
Density and thermal properties	– Density		x	x	x	Rock mechanical model
	– Coeff. of thermal expansion		x	x	x	Rock mechanical model
Boundary conditions and supporting data	– In-situ stresses, magnitude and directions		x	x	x	Assessment of stability
	– Observed deformations and seismic activity	x	x			Rock mechanical model "Validation"

5.2.3 Model tools and planned analyses

Interpretation and extrapolation of data

The geometric framework consists of the geometric model, which is based for the most part on the structure and lithological composition of the rock (see Chapter 4). Each part of the geometric model is assigned mechanical properties and initial rock stresses, see Figure 2-4. The geometric distribution is based on the deformation zones and areas with different rock types that are given by the geological description (see Chapter 4). Section 5.3 gives a more detailed account of how the individual parameters are determined based on different investigation methods.

Interpretation of properties of intact rock and fractures: A uniform distribution of laboratory data is striven for within the volume in question. Statistical distribution is sought after for representation. For the most part, however, constant parameter values are associated with selected units such as zones and rock units to represent and characterize the selected unit in the rock volume. The classification will be based on the geological rock type description. A further subdivision may be done with reference to e.g. degree of weathering.

Interpretation of the properties of the rock mass: The properties of the rock mass will be evaluated based on a description of the geology and tectonics of the bedrock and a testing of the properties of included rock types and fractures. Several different approaches are possible. One empirical method entails evaluating the properties of the rock mass based on geological description and some classification system, empirical relationships and experience from similar areas. Another way is to describe the properties of the rock mass on the basis of theoretical principles based on measurement results. These principles are based on a measurement of the geometry of the fracture system, the fractures and the properties of the intact rock. A third way is to test the behaviour of the rock mass directly by means of in-situ testing and thereby determine its properties. This is done from underground chambers and will not be possible until the detailed characterization phase. Combinations of approaches may also be used. Due to the difficulties associated with the evaluation of the properties of the rock mass and thereby the uncertainty of the evaluation results, a comparative analysis of the results of different evaluation methods can reduce the uncertainty in the prediction of the properties of the rock mass. In-situ testing of the properties of the rock mass in conjunction with driving of the tunnels to the repository level gradually reduces the uncertainty and improves knowledge of the properties of the rock mass. During the site investigation phase, the two first alternatives will be pursued in parallel and the results will be weighed together when the geometrical and mechanical characterization model is developed.

Interpretation of rock stress distribution: The prevailing rock stress distribution is the effect of external forces on the area, geological-structural criteria and the distribution of deformation and strength properties within the area. Numerical models can be used to devise a model of the rock stresses within the area. Boundary conditions are interpreted with the support of the geological-structural criteria and focal plane analysis from the seismic monitoring. The property distribution comprises the material properties in the numerical model. The point determinations of the stress distribution that are made in boreholes during the site investigation are used to calibrate the numerical model. The numerical model can be used during the site investigation phase in the selection of drilling sites and to make predictions for planned measurements. When the descriptive rock mechanical models are constructed, the numerical model is used to describe the prevailing distribution of rock stresses within the entire studied area.

Rock mechanics site descriptive model

Figure 5-3 shows a flow scheme of the work methodology used in the construction of the rock mechanics site descriptive model. In a first step, models are devised in RVS of the properties of the intact rock, the properties of the fractures and a classification index. Two parallel lines are pursued to estimate the properties of the rock mass: an empirical line where the properties of the rock mass are estimated based on the classification index and empirical relationships, and a line where the properties of the rock mass are estimated from theoretical models and partial properties. In constructing the final property model for the rock mass, the results of these two lines are weighed together.

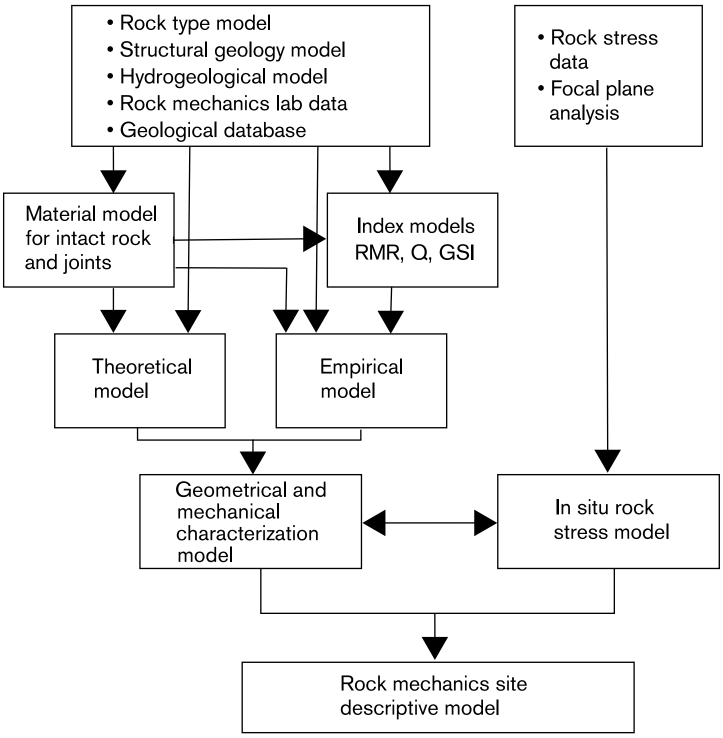


Figure 5-3. *Flow scheme for construction of rock mechanics site descriptive model.*

At the same time as the property model is being developed, a numerical model of the area is prepared where different initial stress states can be generated by applying external load and deformation conditions. When the property model is finished, the rock stress model is calibrated against the rock stresses obtained in point measurements. The numerical model gives the distribution of stress magnitudes and directions in the entire model area.

Input data from other discipline-specific programmes are needed to construct the rock mechanics site descriptive model and as input data to coupled analyses. Possible coupled analyses are thermomechanical analyses in which the temperature increase influences the stress distribution and the deformations in the rock mass that is heated. Another type of coupling is thermohydromechanical analyses where temperature increase and changes in the mechanical system influence the water flow through fractures and the rock mass as a whole. Table 5-3 provides a compilation of parameters taken from other programmes.

Table 5-3. Overview of parameters taken from other programmes.

Parameter	Determined within discipline-specific programmes
Location of regional and local fracture zones	Geological programme
Stochastic distribution of local minor fracture zones	Geological programme
Stochastic distribution (size, direction, density) of individual fractures	Geological programme
Thermal properties of intact rock	Thermal programme
Hydraulic properties of fracture zones	Hydrogeological programme
Hydraulic properties of different rock masses	Hydrogeological programme
Regional seismic activity	Geological programme

Calculation tools

Different types of rock mechanical calculation tools will be used for analysis of different mechanical processes. The calculation tools can range from analytical solutions to numerical calculation programmes. The numerical calculation tools can consist of boundary element, finite element or finite difference methods. Depending on the process or the problem to be analyzed, the rock will be modelled as a continuum material or with discrete element for rock blocks and fractures. The complexity and richness of detail in such numerical calculation models may be limited by available computer power, but this is constantly increasing.

Predictions

The rock mechanical modelling tools are used within layout and construction analysis for positioning of repository, configuration of tunnels, orientation of tunnels and positioning of deposition holes. Within performance and safety assessment, rock mechanical calculation models are used for modelling of long-term processes. These models can also be coupled e.g. thermomechanically, hydromechanically and hydrothermally.

Table 5-4 shows problems to be analyzed and which types of analyses will be performed on the material that is collected and presented in the rock mechanics site descriptive model. The analyses themselves are performed within design and safety assessment.

5.3 Characterization methods

Both field and laboratory methods are required for determination of parameters according to section 5.2.2. These methods are summarized in Table 5-5, and the methods that will be used are commented briefly on in the following sections.

5.3.1 Rock stress measurement

Rock stress measurements will be performed in order to determine the original state of stress in the rock mass on a candidate site. Several methods, more or less established, exist for rock stress measurements. The two most common methods for direct rock stress measurement are overcoring and hydraulic fracturing.

Overcoring can be carried out in boreholes with a minimum diameter of 76 mm. The method gives the three principal stresses and their direction and can be used in all borehole directions.

Hydraulic fracturing can be performed in different-sized boreholes. The method gives the stresses in the plane perpendicular to the borehole. The measurements are preferably conducted in vertical boreholes with a maximum deviation from the vertical of 30 degrees. The measurement gives the rock stresses in the horizontal plane.

The reliability of the overcoring method decreases at high stress levels due to microfracturing in the drill core. Measurement of the P-wave velocity along and across the drill core provides a good indication of whether microfracturing occurs and if the results can be compared with the equivalent measurements in-situ. If the rock type has anisotropic deformation properties (at least 10 to 15% difference in Young's modulus in

Table 5-4. Problems that are analyzed by model calculations.

Problem	Type of analysis
Tunnel orientation and assessment of risk of spalling	Numerical analysis with finite element and finite difference methods, analysis of wedge stability
Distance between deposition tunnels	Coupled thermomechanical analysis
Configuration of tunnels, rock caverns and passage through major fracture zones	Numerical analysis with finite element and finite difference methods, analysis of wedge stability
Influence of swelling pressure	Numerical analysis with finite element and finite difference methods
Influence of glaciation	Numerical analysis with finite element and finite difference methods
Influence of earthquakes	Dynamic analysis

Table 5-5. Methods and status for the discipline Rock Mechanics.

Method	Parameter	Comment (reference)
Investigation of rock stresses		
Rock stress measurements	**Rock stress results**	
• overcoring	• size and direction; 3D method	Method description /Amadei and Stephansson, 1997/.
• hydraulic fracturing	• size and direction; 2D method	Method description /Stephansson, 1983/.
• hydraulic tests on pre-existing fractures (HTPF)	• size and direction; 3D method	Method description /Ljunggren and Raillard, 1987/.
• overcoring on outcrop surfaces	• direction, 2D method	
• borehole breakouts, measurement with caliper	• direction of principal stresses in plane perpendicular to borehole	Method description /Dart and Zoback, 1987/.
• mapping of core discing	• high rock stresses in borehole wall in relation to rock strength	Mapping instructions.
• focal plane analysis from seismic monitoring, local network	• stress field (direction)	Method description /Engelder, 1993/.
Investigation of mechanical properties		
Rock mechanical laboratory tests	**Mechanical properties**	
• uniaxial compression tests	• strength, Young's modulus and Poisson's ratio	Standard /ISRM, 1999/.
• determination of P-wave velocity	• P-wave velocity	Standard /ISRM, 1977/.
• triaxial compression tests	• strength	Standard /ISRM, 1983/.
• Brazilian test	• tensile strength	Standard /ISRM, doc No 8 1977/.
• normal loading tests on fractures	• tensile strength, normal stiffness	Standard /ISRM, doc No 1 1974/.
• shear tests on fractures	• shear strength, shear stiffness	Standard /ISRM, doc No 1 1974/.
• core mapping	• RMR, Q-value	Mapping description /Bieniawski, 1976; Grimstad and Barton, 1993/.
Other laboratory tests intact rock	**Other properties**	
• determination of thermal expansion	• coefficient of thermal expansion	Standard /ASTM D4535-85/ or /ASTM D5335-92/.
• density determination	• density	Standard /DIN 52102-RE VA/.
• x-ray diffraction	• clay mineral determination	
Processing of geophysical data	**Interpretation basis**	
seismic measurements and sonic logging	dynamic propagation velocity	Method description (no reference).

Table 5-6. Parameters for describing the state of stress in the rock mass.

Parameter	Investigation method
Orientation, dip and direction of dip of the principal stresses	Determination by overcoring Failures in borehole walls
Magnitude of the principal stresses	Determination by overcoring or hydraulic fracturing Hydraulic tests on existing fractures

orthogonal directions), the method also gives erroneous results if it is routinely assumed in evaluation of overcoring data that the core has isotropic properties. Methods that take into account anisotropy in deformation properties are available for evaluation /Amadei, 1996/.

Table 5-6 summarizes the parameters that are used to describe the state of stress and how they are determined.

5.3.2 Laboratory methods for determination of mechanical properties of intact rock

General properties

The density of the intact rock is determined on recovered drill cores in accordance with the standard DIN 52102-RE VA.

Coefficient of thermal expansion

The coefficient of thermal expansion is determined at various temperatures via laboratory tests on recovered drill cores. Testing shall be done on samples with different orientations in relation to the structure of the rock, since the coefficient of thermal expansion may be different in different directions.

The test method where measurement is done using a mechanical dilatometer is described in ASTM D4535-85 and the test method where measurement is done using a strain gauge in ASTM D5335-92.

Deformation properties

Young's modulus, E, and Poisson's ratio, n, are determined by uniaxial loading tests on drill cores. Load, axial strain and radial strain are measured. Testing is conducted in accordance with the standard "Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. (Int. J. of rock and mining sciences, 36, 3, 279–289, ISRM 1999)" The standard contains requirements on specimen preparation, accuracy of measurement, loading rate and evaluation methodology. To study behaviour after failure, the test is performed with a constant deformation rate in a stiff loading machine.

Strength

/Hoek and Brown, 1980/ and /Hoek, 1983/ proposed an empirical relationship for the strength of intact rock known as the Hoek-Brown failure criterion. The criterion has been modified over the course of the years, and the most recent version was presented by /Hoek et al, 1992/. The modified criterion has the following appearance:

$$\sigma_1 = \sigma_3 + \sigma_c \, (m_i \, \sigma_3 \, / \, \sigma_c + s)^a \qquad (5\text{-}1)$$

where σ_1 is the maximum principal stress at failure

σ_3 is the minimum principal stress at failure

σ_c is the uniaxial compressive strength of the intact rock

m_i, s and a are material constants.

For determination of the compressive strength, the tests shall be performed on specimens with a diameter of approximately 50 mm and a length of approximately 100 mm. Both σ_c and m_i are determined by fitting the failure envelope to results from triaxial tests. Tests should be performed at at least three different lateral pressures, σ_3, where one test is performed at $\sigma_3 = 0$. For intact rock, a can be set equal to 0.

Table 5-7 presents a compilation of which parameters are to be determined on the intact rock and which testing methods are to be used.

Table 5-7. Properties of intact rock and methods for determination.

Parameter	Investigation method
Density	Determined on drill cores
Coefficient of thermal expansion	Determined on drill cores
Compressive and shear strength	Determined on drill cores in uniaxial and triaxial compression tests
Tensile strength	Determined on drill cores with Brazilian test
Young's modulus	Determined on drill cores in uniaxial and triaxial compression tests
Poisson's ratio	Determined on drill cores in uniaxial and triaxial compression tests
Propagation velocity of P-wave	Determined on drill cores in uniaxial compression tests

5.3.3 Determination of mechanical and hydromechanical properties of fractures

General

The mechanical properties of a rock mass are characterized by the fractures that penetrate the rock. The factors that affect the mechanical properties of the fracture include surface roughness, waviness, fracture aperture, fracture length, fracture filling and the strength and stresses in the surrounding rock. In addition there are a number of factors to take into consideration when determining the fracture-mechanical properties such as scale effects, limited stiffness, unmatched or matched fracture surfaces, high stresses and dynamic loads.

Shear strength of fractures

/Barton et al, 1973, 1976, 1977, 1990/ have studied the behaviour of natural rock fractures and have proposed the following relationship to describe the shear strength of the fractures (joints):

$$\tau = \sigma_n \times \tan\left(\phi_b + JRC \times \log_{10} (JCS / \sigma_n)\right) \qquad (5\text{-}2)$$

This relationship includes a number of different parameters that must be determined. Table 5-8 shows a compilation of these parameters and how they can be determined. If the fracture contains filling material, the strength of the fracture will be equal to the shear strength of the filling material. In this case the shear strength of the filling material is determined by direct shear tests.

Deformation properties of fractures

The deformation can be described in simplified terms in three steps: first an elastic deformation with small displacements, then with a shear along the fracture asperities with a normal deformation and shear movement, and finally a slip along the surface with primarily shear displacements. Before shear failure, the deformations are small and the relationship between normal stress, σ_n, and normal deformation, u_n, and between shear stress, τ, and shear displacement, u_s, can be written:

$$\sigma_n = k_n u_n \qquad (5\text{-}3)$$

$$\tau = k_s u_s \qquad (5\text{-}4)$$

where k_n is the normal stiffness of the fracture (joint) and k_s is the shear stiffness. /Bandis, 1980/ and /Bandis et al, 1981/ have given empirical relationships for the normal stiffness of fractures (joints). Parameters for describing the deformation properties of individual fractures and methods for determining them are presented in Table 5-9.

Hydromechanical properties of fractures

The hydromechanical behaviour of a fracture is normally reported as its hydraulic conductivity as a function of the effective normal stress or the shear movement and is determined by means of laboratory tests. In the laboratory tests, a decreasing hydraulic conductivity is normally obtained at an increasing normal stress and an increasing hydraulic conductivity at a greater shear movement.

Table 5-8. Parameters for describing the shear strength of fractures.

Parameter	Method for determination
JRC, joint roughness coefficient	Tilt test, Geological description, comparison with standard profiles, measurement with profilometer, evaluation of direct shear tests
JCS, joint compressive strength	Test with Schmidt hammer
ϕ_b, base friction angle	Tilt test, direct shear tests on dry sawn surfaces
ϕ_r, friction angle after failure	Empirical relationships, direct shear tests
Possible filling material in fracture	BIPS, Identification of material in core mapping

Table 5-9. Parameters for describing the deformation properties of fractures.

Parameter	Method for determination
k_n, joint normal stiffness	Normal loading tests in shear box, empirical relationships with JRC and JCS
k_s, joint shear stiffness	Direct shear tests, empirical relationships with JRC and JCS

The relationship between hydraulic conductivity and the effective normal stress or the shear movement can be obtained from direct shear tests by measuring the water flow through the fracture.

Direct shear tests

Shear tests in the laboratory can be performed with constant normal load, CNL, or with constant normal stiffness, CNS. CNS tests simulate actual conditions better but are more difficult to analyze and interpret. Both types of tests can be performed with water pressure and water flow through the fracture plane to study the hydromechanical couplings.

The shear test is normally started with a loading and unloading cycle in the normal direction, after which a shear force is applied at a constant deformation rate. Several tests are done with varying normal stress. During the test, the normal and shear force and the normal and shear movement are recorded. The results are normally reported in $\tau - \sigma$, $\tau / \sigma - \mu_s / \mu_n$ and $\mu_s - \mu_n$ graphs. The graphs are analyzed together with other information from e.g. tilt tests.

The results of CNL and CNS tests may differ from each other as well as from other ways of calculating strength and stiffnesses /Olsson, 1998/.

5.3.4 Methods for determination of mechanical properties of different rock masses

When the rock mass is loaded, the intact blocks are deformed and shear displacements occur (compression or expansion of fractures). Thus, the deformation properties and strength of the rock mass are not dependent only on the properties of the intact rock, but also on the frequency, orientation and mechanical properties of the fractures. The deformation and strength properties of the rock mass are scale-dependent: there is a greater likelihood of finding large fracture zones in a large rock volume.

The deformation properties and strength of individual fractures and the intact rock can be satisfactorily described with stress-strain relationships and failure criteria in accordance with previous chapters. Testing and determining the mechanical properties of a large rock volume in the field is often not practically feasible. The mechanical properties of a rock mass are therefore usually estimated with the aid of empirical relationships between the properties and some rock classification system. Providing that a studied rock volume is sufficiently large to contain four or more fracture systems, this works well. This can also be used in an initial phase to estimate the quality of the rock mass.

There are no general and simple relationships for a rock volume with few fractures. Such a rock mass normally exhibits anisotropic properties dependent on the direction of the fractures. The properties of such a rock mass can be calculated for a few defined cases if the properties of the intact rock and the fractures are known.

Individual fractures and the intact rock can be modelled in rock mechanical calculation models for local studies, but in large-scale models the fractures cannot be modelled explicitly; instead, their presence must be included in the material model for the rock mass.

Strength of the rock mass

The number of fracture systems in the rock mass and the mechanical properties of the fractures influence the main principles for determination of the strength of the rock mass. In a rock mass with one or two fracture systems, the strength of the rock mass is mainly influenced by the properties of the fractures. The strength of the rock mass is then based on the shear strength of the fractures /Hoek, 1994/. In a more fractured rock with numerous fracture systems, a more isotropic relationship is obtained and the mechanical properties can be determined from empirical relationships. Strength, for example, can be described using the Mohr-Coulomb failure criterion:

$$\tau = c' + \sigma \tan \phi' \qquad (5\text{-}5)$$

where c' and ϕ' are the cohesion of the rock mass and the friction angle, respectively, based on effective stresses. These parameters can be estimated using empirical relationships based on some rock classification system.

The strength of a more fractured rock mass can also be described using the Hoek-Brown failure criterion /Hoek and Brown, 1997/:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a \qquad (5\text{-}6)$$

where m_b, s and a are material constants that can be determined with the aid of some rock classification system. σ_{ci} is the compressive strength of the intact rock.

Mohr-Coulomb's parameters (c´ and ϕ´ according to equation 5-5), which are used in many numerical models but which are difficult to determine, can be estimated by linear regression based on the Hoek-Brown failure criterion /Hoek and Brown, 1997/.

Deformation properties of the rock mass

In a mechanical analysis of a rock cavern in a rock mass, the deformation picture of the rock cavern before failure is an important factor. The Young's modulus, E_m, and Poisson's ratio, ν, of a rock mass are difficult to determine directly. Several empirical relationships exist between E_m and different classification systems as well as descriptions of the rock mass. Examples of relationships with classification systems /Hoek and Brown, 1997/ are:

$$E_m = 10^{\frac{RMR-10}{40}} \tag{5-7}$$

$$E_m = \sqrt{\frac{\sigma_{ci}}{100}} \cdot 10^{GSI-10/40} \tag{5-8}$$

Where RMR is the classification number according to the RMR system, GSI is the Geological Strength Index and σ_{ci} is the compressive strength of the intact rock.

Another way to determine E_m in the field is to measure the seismic propagation velocity. The following relationship applies between the propagation velocity of the compressive wave, v_p, E_m, ν and the density of the rock mass, ρ.

$$E_m = v_p^2 \cdot \rho \cdot (1 + \nu) \cdot (1 - 2 \cdot \nu) / (1 - \nu) \tag{5-9}$$

As a rule, Poisson's ratio ν is assumed to have the same value in a rock mass as in the intact rock.

Empirical rock classification systems

There are a number of rock classification systems. They are normally based on experience values. The most widely used rock classification systems are the RMR, or Rock Mass Rating, system /Bieniawski, 1989/ and the Q system for Tunnelling Quality Index /Barton et al, 1974/. Parameters included in the systems are shown in Tables 5–10 and 5–11.

Table 5-10. Parameters included in the RMR system.

Parameter	Range of variation
Strength of intact rock	0–15
RQD	3–20
Distance between fractures	5–20
Properties of fractures	0–30
Groundwater conditions	Set equal to 15
Orientation of fractures in relation to structure	Set equal to 0
RMR is equal to the sum of the parameters	23–100 (for RMR_{89})

Table 5-11. Parameters included in the RMR system.

Parameter	Range of variation
RQD, Rock quality designation	10–100
J_n, Joint set number	0.5–20
J_r, Joint roughness number	0.5–4
J_a, Joint alteration number	0.75–24
J_w, Joint water reduction	Set equal to 1.0
SRF, Stress reduction factor	Set equal to 1.0
Q index = $RQD/J_n \times J_r/J_a \times J_w/SRF$	

The classification shall be performed on recovered drill cores. The parameters included in the classification systems are reported separately and continuously along the borehole together with the resulting classification value.

In order to be able to use the empirical relationships between classification values and mechanical properties, the original Q and RMR systems must be adjusted. In the Q system, the parameters J_w and SRF are set equal to 1.0, i.e.:

$$Q' = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a} \tag{5-10}$$

In the RMR_{89} system, the value that takes water conditions into account must be set equal to 15 and the value that takes the orientation of the fractures in relation to the structure into account must be set equal to 0. The adjusted RMR system is called GSI (Geological Strength Index), according to /Hoek, 1994/. The following applies for RMR_{89} greater than 23:

$$GSI = RMR_{89} - 5 \tag{5-11}$$

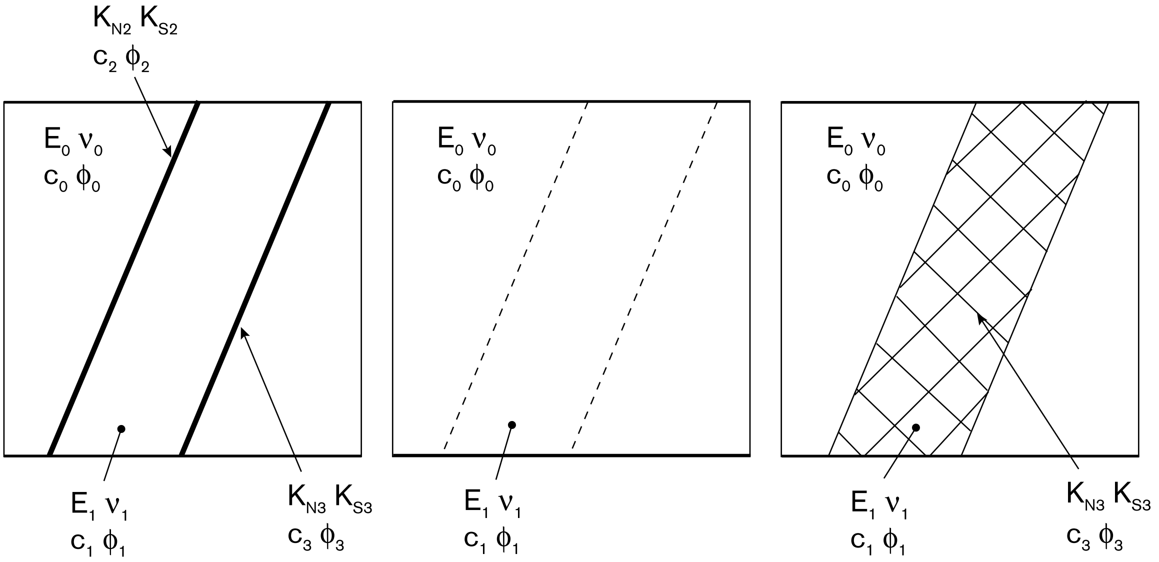
The RMR system is not recommended for RMR_{89} values less than 23, the Q system being preferable instead /Hoek, 1994/.

The relationship between GSI and Q’ is described as:

$$GSI = 9 \cdot Log_e Q' + 44 \tag{5-12}$$

5.3.5 Methods for describing mechanical properties of fracture zones

Depending on the width of the zone in relation to the size of the rock mechanical model, the zone is modelled either as a rock mass with specific properties or as a discontinuity. See further Figure 5-4. There is some possibility of determining the properties of a fracture zone in the normal direction in the field by means of compression tests and simultaneous measurement of the deformation across the zone.



Model with discrete fracture elements in contact with country rock

Model without discrete fracture elements

Model with discrete rock blocks and discrete fracture elements

Figure 5-4. *Different methods for describing the mechanical properties of the rock mass in different fracture zones /after Andersson et al, 1996/.*

5.3.6 Analysis strategy for determination of strength and deformation properties

Strength in intact rock and highly fractured rock mass can be described with the Hoek-Brown failure criterion. For these typical cases the properties are isotropic, i.e. identical in all directions. For other types of rock masses, the criterion must be used with great caution. Figure 5-5 summarizes how strength in different types of rock masses can be described.

The Hoek-Brown criterion cannot be used in a rock mass with one dominant fracture system. For this case, the criterion can only be used for the intact rock, while the properties of the fractures have to be described in accordance with equation (5-2).

For a rock mass with two fracture systems, the Hoek-Brown criterion must be used with caution, provided that neither of the fracture systems has a decisive influence on the behaviour of the rock mass. If one of the fracture systems is considerably weaker than the other, the strength of this fracture system must be treated separately according to equation (5-2).

Determination of the deformation properties of a rock mass follows basically the same principles as determination of the strength properties. Equations (5-7) and (5-8) can be used for a highly fractured rock mass, while for a rock mass with one or two fracture systems the properties of the rock mass must be based on the properties of the intact rock and the deformation properties of the fractures.

In an early phase of the site investigation, the estimate of the properties of the rock mass will mainly be based on empirical relationships to the rock classification systems. As more data from laboratory testing of intact rock, fractures and geometric data for fracture systems emerge, this material will serve as a basis for estimation of the properties of the rock mass.

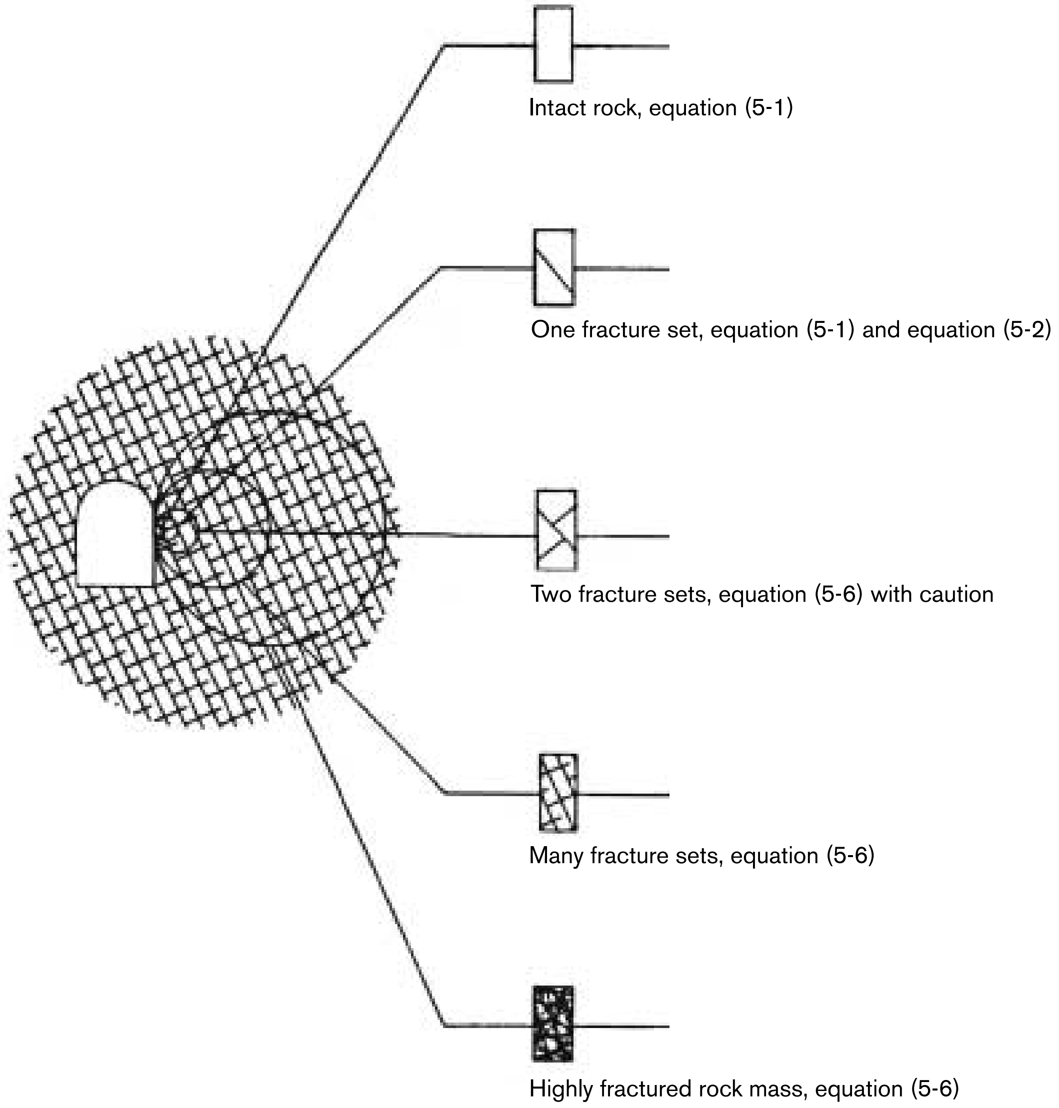


Figure 5-5. *Rock conditions under which the Hoek-Brown failure criterion can be used.*

6 Thermal properties

6.1 General

This describes which thermal properties will be determined and possible characterization methods. The chapter also describes how the measured information is interpreted in the thermal model that comprises part of the site-descriptive model.

6.1.1 Introduction

Temperature and temperature distribution are fundamental parameters in the deep repository. The temperature influences mechanical stability, groundwater flow, and the chemical/biological environment. The thermal properties and temperature conditions of the rock have a direct influence on the layout and other design of the deep repository.

The temperature variation in the rock is dependent on the decay heat of the fuel, the repository layout, the thermal conductivity, heat capacity and initial temperature of the rock, and the water saturation of the bentonite. Heat transport through the rock takes place primarily by conduction, which is determined by the heat capacity and thermal conductivity of the rock. Heat transport by radiation and convection can be neglected. The heat transport through the rock affects the temperature in the different barriers. Temperature changes also affect the volume of the rock, which is determined by the coefficient of thermal expansion. This volume expansion can influence the water flow through the rock.

The temperature increase and subsequent cooling-off cause a thermal volume change in the rock, leading to stress redistributions in the rock in and around the repository. Once the repository has been built, the temperature load represents the most important mechanical influence on the repository up to and including more dramatic climate-driven events such as permafrost and glaciation.

Good correlations between values based on modal analysis (mineral composition) and measurement of thermal conductivity in the field have been obtained in previous studies /Ericsson, 1985; Sundberg, 1988/. The difference in mineral composition leads to different thermal conductivities in different rock types. Quartz has a thermal conductivity that is 3–4 times higher than that of other minerals, which means that quartz content is of decisive importance for the heat conduction in a rock.

The size of the repository area is influenced by the thermal properties of the rock, since there is a requirement on the maximum temperature (100°C) on the canister surface, see /Andersson et al, 2000/. However, desired levels cannot always be achieved by means of a suitable layout. Provided that the thermal properties of the rock and the ambient temperature are known, the problem can be analyzed and the spacing of deposition holes and tunnels can be determined for a given heat output in the canisters. Good heat conduction and high heat capacity permit for a more densely packed repository.

The *thermal properties* of the rock (thermal conductivity and heat capacity) are determined primarily on the basis of mineral composition and by means of laboratory studies of recovered rock cores. The results of the thermal parameter determination are summarized in a *thermal description* (model) where the thermal properties for different parts of the geometric model are described, see Figure 2-4. Thermal calculation models are used to calculate the thermal evolution of the repository and its influence on repository performance. Simple geometries can be treated analytically. Numerical solution methods such as finite element or finite difference methods are used in more complicated cases.

6.1.2 Discipline-specific goals

There are no requirements on the thermal properties of the rock or the ambient temperature, since applicable functional requirements can always be met by means of a suitable repository layout. /Andersson et al, 2000/ describes preferences and requirements regarding thermal properties. With reference to the main purpose of the geoscientific investigations (section 2.2), the main task of the thermal programme is to:

- determine the initial temperature at repository level and identify the presence (if any) of a high geothermal gradient,
- determine the distribution of the thermal properties within the candidate site.

Focus during the initial site investigation

During the initial site investigation, a general assessment is made of the thermal properties of the site.

Focus during the complete site investigation

During the complete site investigation, the characterization is deepened. The site is investigated and characterized so well that forecasts of the future temperature evolution in the repository can be used as a basis for preliminary facility description /see SKB, 2000b/.

6.1.3 Working methodology and coordination

The first thermal investigations will be conducted when a priority site within the candidate area has been selected. Investigations and characterization are carried out stepwise (see section 2.3.1 and Figure 2-5 in Chapter 2). Samples for thermal laboratory investigations will be taken after routine mapping of core drills has been done and the first geological-structural and lithological models have been devised. Figure 6-1 shows that information is also taken from other discipline-specific programmes, mainly geology.

The thermal investigations will be conducted at the same time as the geological and rock mechanical investigations. The thermal properties are mainly estimated on the basis of knowledge of lithological composition. Typical value ranges for the thermal properties of the Fennoscandian Shield's crystalline bedrock have been compiled based on a modified rock type classification and a statistical processing of thermal properties based on mineral compositions in accordance with /Sundberg, 1988/.

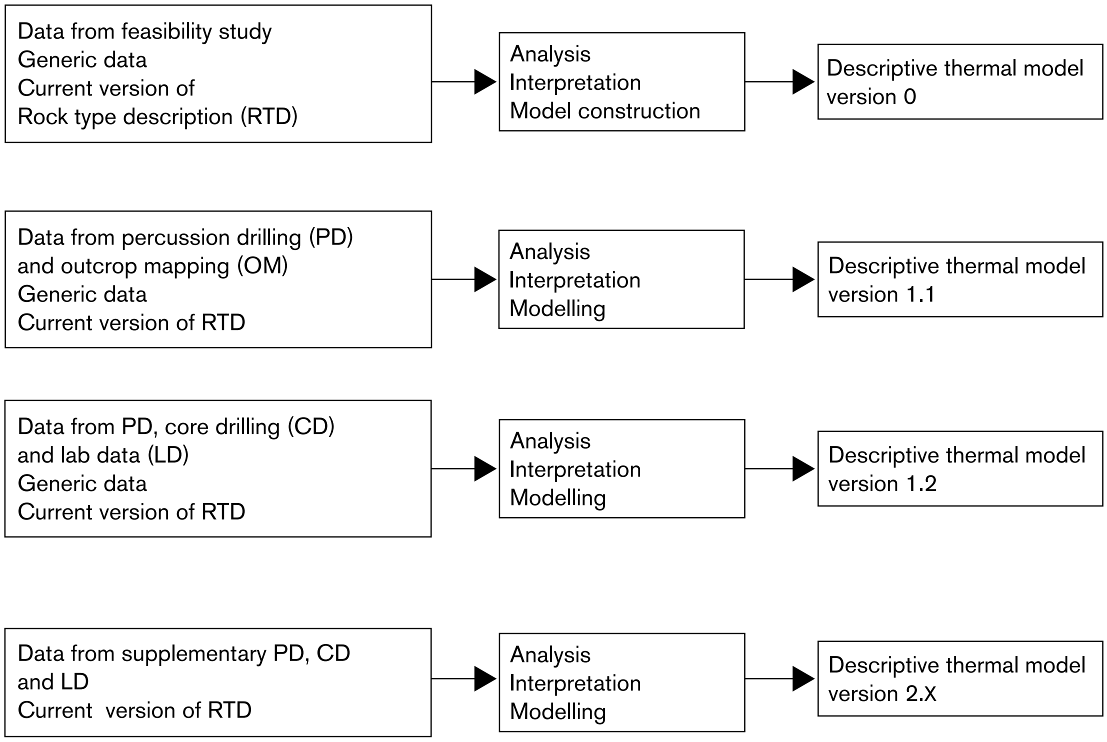


Figure 6-1. *Overview of working methodology and information needs for devising the descriptive thermal model of the site and the regional area.*

Knowledge of the main rock types in the superficial bedrock is usually good during a feasibility study. The knowledge base on rock type distribution at great depth is gradually built up during the different steps of the site investigation. The thermal properties estimated with the aid of lithological composition are checked by laboratory determination of the thermal properties on retrieved core samples from different encountered rock types. The laboratory investigations may be supplemented with thermal response tests in boreholes.

Coordination is required with other related disciplines, particularly rock mechanics and geology, with regard to both planning and execution of the investigations and co-evaluation and modelling. The discipline of geology provides the geometric premises for the structures and rock masses to be characterized. The lithological model provides the premises for subdividing the rock mass into units with the same thermal properties. Only thermal numerical models that compute the thermal evolution are dealt with in this programme. Numerical models for thermomechanical coupling are dealt with in the discipline of rock mechanics, and numerical models for hydrothermal coupling are dealt with in the discipline of hydrogeology.

6.2 Models and parameters

6.2.1 Structure of the models

The description of the thermal conditions in the site-descriptive model includes the thermal properties of the rock and the initial temperature conditions in the rock volume enclosing the deep repository. The geometric framework consists of the geometric model, which is mainly based on the structure and lithological composition of the rock (see Chapter 4). An overall picture of the geometric model is found in Table 6-1. Each part of the geometric model is assigned thermal properties and an initial thermal state.

Table 6-1. Brief presentation of the thermal model.

Descriptive thermal model

Purpose of model
The parameters included in the model shall serve as a basis for design and safety assessment and the analyses performed in these steps. The model shall describe, for a given investigated volume, the initial temperature conditions and the distribution of thermal properties in the rock volume.

Process description
Description of the processes that have given rise to the current distribution of initial temperatures and properties in the area in question.

Constituents of the model

Geometric framework
The base for the geometric framework consists of the lithological model and the geological-structural model that is set up within the discipline of geology, as well as the hydrogeological model that is developed within hydrogeology. With reference to the investigations conducted on the intact rock, the geometric model can be further subdivided to get volume units with similar properties.

Parameters
Initial temperature conditions.
Thermal properties such as thermal conductivity, heat capacity and coefficient of thermal expansion.
See further Table 6-2.

Data representation
A uniform distribution of data is striven for within the volume in question. For the most part, however, constant parameter values are associated with selected objects in the rock volume. Statistical distribution is sought after for representation.

Boundary conditions
Initial temperature conditions and heat flow.

Numerical tools
RVS is used for interpretation and presentation of the constructed model. Numerical calculation models are used to simulate the processes that have created the present-day distribution of temperature.

Calculation results
Distribution of properties in accordance with the above parameter list plus distribution and magnitude of initial temperature within the area.

Table 6-2. Compilation of thermal parameters included in the thermal description. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Thermal properties of the rock	– Thermal conductivity – rock		x	x	x	Design, thermal modelling coupled analysis
	– Heat capacity – rock		x	x	x	
Temperatures	– Temperature in rock and groundwater		x	x		Modelling, design Starting data for modelling
	– Thermal boundary conditions/gradient			x		Boundary conditions

6.2.2 Constituent parameters

Table 6-2 summarizes which parameters are included in the thermal description. As a rule, these parameters need to be interpreted from the results of the various investigations. The table is based on the tables compiled for the parameter report /Andersson et al, 1996/, the revision that took place in connection with the work on requirements and criteria /Andersson et al, 2000/ and the work on the general investigation and evaluation programme /SKB, 2000b/. Information from several other disciplines is also required to prepare the thermal description (see section 6.2.3).

6.2.3 Modelling tools and analyses

Interpretation and extrapolation of data

Each part of the geometric model (see above) is assigned thermal properties and an initial thermal state. The thermal properties are distributed based on the rock type distribution in the geological description and general knowledge of the thermal properties of different rock types. The thermal distribution is determined by an interpolation procedure and thermal numerical modelling, which is calibrated against downhole temperature logging.

With large variations in mineral composition, thermal properties will vary widely, making it more difficult to subdivide the rock mass into areas with uniform thermal properties.

Determining the thermal parameters in Table 6-2 requires input data from the geology programme in the form of the rock type distribution. (Coupled thermo-hydro-mechanical models are discussed in section 5.2.3.)

Calculation tools and predictions

Data from the thermal description will mainly comprise input data to different thermal numerical models for calculating the thermal evolution of the repository. Simple geometries are treated analytically. Numerical solution methods are used in more complicated cases. Premises for heat transport in the deep repository are important for repository design and layout. The thermal modelling tools are used in design and safety assessment.

Thermal calculation tools must be used for modelling of long-term thermal processes. Regional models are used to study thermal impact on fracture zones in and around the repository. Local models are used to study thermal impact on deposition holes and deposition tunnels.

The thermal calculation tools can be everything from analytical solutions to numerical calculation programmes. The numerical calculation tools can consist of boundary element, finite element or finite difference methods. Depending on the process or the problem to be analyzed, the rock will be modelled as a continuum material or with discrete elements for rock blocks and fractures. Coupled thermomechanical models are dealt with in cooperation with the discipline of rock mechanics and coupled thermohydraulic models are dealt with in cooperation with the discipline of hydrogeology.

6.3 Characterization methods

Both field and laboratory methods are required for determination of the parameters according to section 6.2.2. These methods are summarized in Table 6-3, and the methods that will be used are commented briefly on below. The information obtained from the geology programme is also used.

6.3.1 Field methods

Temperature logging

The initial thermal state and thermal boundary conditions are determined by temperature logging in water-filled boreholes. The boreholes must stand undisturbed for some time (about 2 weeks) before temperature logging is carried out. The water is then assumed to have the same temperature as the surrounding rock.

Thermal response tests

Thermal response tests in boreholes may be useful, primarily within the relevant repository depth (400–700 m), for determining the thermal properties of the rock mass in the field. A known quantity of heat is supplied to a water-filled cored borehole per unit time, and the temperature increase in the borehole is measured as a function of time.

6.3.2 Laboratory methods

The following parameters can be determined on retrieved drill cores.

Density and porosity

Density is determined in accordance with the standard DIN 52102-RE VA on a dry drill core. Porosity is assumed to be equal to water absorption capacity, which is determined in accordance with the standard DIN 52103-A.

Chemical and mineralogical composition

Determination of the chemical and mineralogical composition of drill cores is done within the framework of the geology programme (see section 4.3.5). The chemical analysis can be carried out by means of ICP analysis (Inductively Coupled Plasma) and the mineralogical composition can be determined by SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy).

Thermal conductivity and heat capacity

Thermal conductivity, λ, W/(m, °K), which denotes the capacity of the material to transport heat, and *heat capacity*, C, J/(m^3, °K), which denotes the capacity of the material to store thermal energy, are needed to describe the heat flow in a material. The heat capacity is the product of the material's density, ρ, kg/m^3, and its specific heat capacity, c, J/(kg, °K). The ratio between thermal conductivity and heat capacity is called thermal diffusivity, κ, m^2/s

$$\kappa = \lambda / (\rho \cdot c) \tag{6-1}$$

A laboratory method for determination of thermal conductivity is described in ASTM D5334-92, and a method for determination of heat capacity in ASTM D4611-86. Thermal diffusivity and thermal conductivity can also be determined in the laboratory by means of the TPS (Transient Plane Source) method, Gustafsson, 1991.

Table 6-3. Thermal characterization methods.

Method	Parameter	Comment (reference)
Investigation of thermal properties of the rock		
Field methods		
• temperature logging	temperature distribution of groundwater and (indirectly) rock mass with depth	Method description (reference lacking).
• thermal response test in borehole	field determination of thermal properties of rock mass	The usefulness of the method is being studied.
Laboratory methods	**Thermal properties**	
• determination of thermal conductivity	thermal conductivity	Method description, TPS /Gustafsson, 1991/.
• determination of heat capacity	heat capacity	Method description, TPS /Gustafsson, 1991/.
• determination of density	density	Standard DIN 52102-RE VA.
• determination of porosity	porosity	Standard DIN 52103-A.
• determination of chemical and mineralogical composition	chemical and mineralogical composition	Method description for ICP, SEM and EDS.

7 Hydrogeology

7.1 General

This chapter describes which hydrogeological conditions and properties will be determined and possible characterization methods. The chapter also describes how the measured information is interpreted in the hydrogeological model that comprises part of the site-descriptive model.

7.1.1 Introduction

Precipitation is what ultimately drives the groundwater flow, while the topography and the flow properties of the geosphere control the flow pattern. In Sweden, the level of the water table is closely linked to the topography. The reason is the relatively heavy precipitation and the relatively low permeability of the bedrock. Local flow systems controlled by the topography usually form near the ground surface, see Figure 7-1.

The driving force for the water flow in the geosphere consists of differences in fluid potential energy, where the fluid potential of a given point is determined by the pressure and density of the water and the vertical position of the point. The density of the water is chiefly dependent on the prevailing temperature and the chemical composition of the water, above all its salinity.

The magnitude of the water flow is dependent on the magnitude of the driving force and the water-conducting capacity of the geosphere. This water-conducting capacity is dependent on the flow properties of the pore structure and the flow properties of the water. In loose deposits, the flow properties of the pore structure are determined by the particle size distribution and the shape and compaction of the particles.

The flow properties of the pore structure in crystalline rock are determined by the fracture structure. The flow properties are dependent both on the flow properties of each fracture and on how the fractures are interconnected. The flow properties of a fracture are dependent above all on its aperture, but also its surface structure. The frequency of fractures, their spatial distribution, size distribution, shape and orientation distributions determine how hydraulically connected the fractures are. The flow properties of the fractures are influenced by the prevailing effective stress in the geosphere and any gas presence in the fracture system.

The flow properties of the water are controlled by its viscosity, which is affected above all by temperature and by the chemical composition of the water. The flow properties of the water vary within a relatively narrow range, while the flow properties of the pore structure exhibit a very wide range of variation.

Most of the groundwater flow takes place in a portion of the pore structure, which defines the flow porosity in the geosphere. The mean velocity of the groundwater flow can be calculated with the aid of the flow porosity. The compressibility of the pore system and its connection with the atmosphere determine the geosphere's storage capacity. The storage capacity is of importance for calculation of the evolution of a

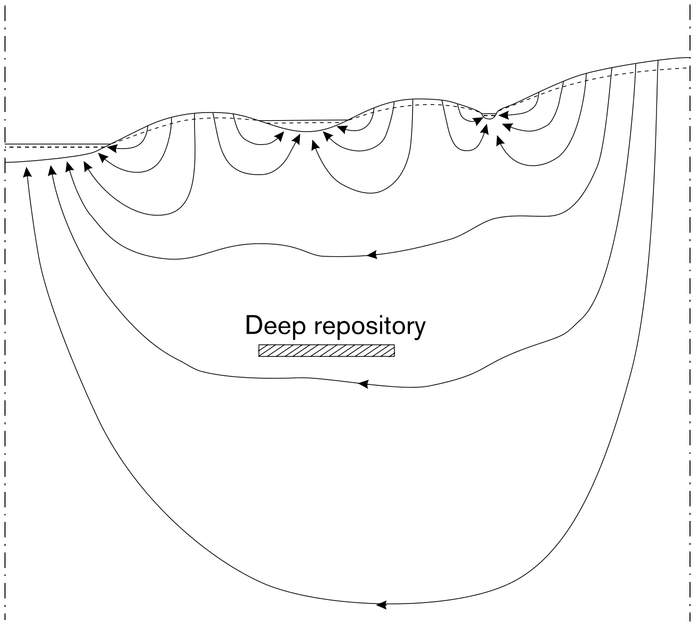


***Figure 7-1**. Schematic diagram of topographically induced flow pattern. The occurrence of water-conducting fractures and fracture zones can, however, result in a much more complicated flow pattern than the one shown in the figure. (The horizontal scale is smaller than the vertical scale.)*

hydraulic disturbance in the geosphere, e.g. the time it takes for the groundwater above a repository to return to levels similar to those that existed before the repository was built.

The hydrogeological processes are described in greater detail in SR 97 /SKB, 1999b/.

The discipline can be divided into meteorological and hydrological investigations, hydraulic borehole investigations, monitoring, and interpretation, analysis and modelling.

Meteorological and hydrological investigations mainly comprise measurements of precipitation, temperature and flows in watercourses as well as mapping of mainly Quaternary and bedrock geology, plus springs, wetlands and streams. The investigations also include surveying of land use such as ditch drainage and damming projects, source of water supply, etc, as well as areas of interest from a nature conservation viewpoint.

The permeability of the soil layers and the rock can be measured along the boreholes by different types of *hydraulic borehole investigations*. Water pressure and salinity distribution are recorded.

After the requisite investigations, all boreholes are normally sectioned off with packers. Different types of investigations (*hydraulic monitoring*) can then be done in the sealed-off sections at predetermined time intervals. The monitoring will continue even after the site investigation phase.

Hydrogeological interpretation, analysis and modelling are carried out for the purpose of describing the spatial distribution of the hydraulic properties of the soil layers and the rock. Various numerical *calculation models* are normally used to calculate groundwater flow and pressure distribution in the rock (see further section 7.2).

7.1.2 Discipline-specific goals

The overall goals of the site investigation and its two stages were presented in Chapter 2. Hydrogeological requirements and preferences linked to the functional requirements for the deep repository were presented in /Andersson et al, 2000/. No requirements have been formulated, but there are strong preferences regarding the permeability of the rock. Based on this and the main goals given in Chapter 2, a number of main tasks can be formulated for the hydrogeological programme.

The goals of the hydrogeological programme are in brief to:

- compile a hydrogeological description on a regional and local scale that is sufficiently detailed for judging the suitability of the site with respect to preferences regarding hydrogeological functions and otherwise meet the needs of safety assessment and design,
- achieve a hydrogeological understanding on the regional scale that is sufficient to delimit and define properties and boundary conditions for regional groundwater flow models and achieve a hydrogeological understanding on the local scale that justifies the local hydrogeological description.

This entails:

- describing the rock volume on the site with respect to the spatial position, extent and properties of major fracture zones as well as the frequency, size and properties (spatial distributions) of smaller structures,
- determining the permeability (magnitude and variability) of the rock at repository depth with a precision that permits judgement of performance and safety functions,
- surveying the near-surface hydrogeology (in consultation with the discipline-specific programme for surface ecosystems).

The near-surface hydrology and hydrogeology are essential for the hydrogeological understanding of the site on both a regional and local scale. The near-surface conditions influence the boundary conditions for the groundwater flow models and are essential for calculations of flow and dispersion in the biosphere. Credible groundwater flow models require an understanding of both near-surface and deeper-lying groundwater flow systems. Furthermore, access to the hydraulic properties of the rock mass and supporting data for modelling, such as groundwater pressure and knowledge of recharge and discharge areas, are also required.

Focus during the initial site investigation

The main hydrogeological activities during the initial site investigation are:

- preliminary determination of the extent of the regional area judged to be needed for the groundwater flow modelling,
- approximate determination of the hydraulic properties of regional fracture zones and the rock mass near the ground surface within the regional area and the site,
- survey of the near-surface hydrology in the form of recharge and discharge areas and topography, as well as land use and areas from a natural resource viewpoint,
- establishment (if necessary) of hydrological measurement stations for precipitation, temperature and runoff in watercourses,

- establishment of measurement systems for recording of groundwater pressure in boreholes,
- approximate determination of the hydraulic properties of the rock down to approximately 1,000 m with a few deep boreholes within the site,
- near-surface investigations to determine the locations and properties of possible major fracture zones within the site (in collaboration with geology).

After the initial investigations, an overall understanding shall have been achieved of the hydrogeological conditions down to a depth of 100–200 m within the regional area. The first hydrogeological description shall have been compiled and areas worthy of protection shall have been identified.

After the initial site investigation, an overall understanding shall have been achieved of hydrogeological conditions down to a depth of about 1,000 m within the site. A hydrogeological description of the site will be compiled describing, among other things, the permeability of the rock at projected repository depth in statistical terms.

Focus during the complete site investigation

The main hydrogeological activities during the complete site investigation are:

- determination of the extent of the regional area judged to be needed for the groundwater flow modelling,
- investigation of relevant boundary and initial conditions for the regional groundwater flow model with a few deep boreholes,
- investigation of the hydraulic properties of the rock from the ground surface and down below repository depth with deep boreholes within the site,
- more detailed investigation of the properties, position and extent of possible local major fracture zones within and near the site,
- supplementary survey of the near-surface hydrology to determine recharge and discharge areas within and near the site,
- supplementary investigation of the near-surface hydrogeology (rock and soil) within and near the site.

The properties of the rock along flow paths to and from the repository need to be described in greater detail than that provided by the regional investigations. This means that the investigations to characterize the site must cover an area that is larger than the actual repository. It is also important that boreholes be drilled near the boundaries of the regional model so that relevant boundary and initial conditions can be determined. However, the areas should be chosen so that “natural” boundary conditions can be used, if possible.

When the complete site investigation has been carried out, a good understanding shall have been achieved of the hydrogeological conditions down to a depth of approximately 1,000 m within the site. A hydrogeological description of the regional area and of the site shall have been compiled.

7.1.3 Working methodology and coordination

The working methodology and steps for setting up the hydrogeological models are illustrated in Figure 7-2. Geological and hydrological mapping provides the basis for the near-surface parts of the hydrogeological model. The largest body of background data for the hydrogeological model is obtained from hydraulic tests and downhole measurements. The descriptive hydrogeological model is then utilized by e.g. design to construct calculation models for groundwater seepage into tunnels or by safety assessment to construct calculation models of the future groundwater flow.

Related disciplines where coordination is greatest are geology, hydrogeochemistry, transport properties and surface ecosystems. Collaboration with geology relates above all to field studies and drilling for the purpose of characterizing soil layers, rock mass and conductive features. Collaboration is also required in the analysis and modelling of regional and local major fracture zones. Data gathered from the hydrogeological characterization also influences the geometric interpretation and the assessment of different uncertainties. Collaboration with hydrogeochemistry mainly concerns borehole investigations during and after drilling. Planning of superficial mappings and samplings, as well as design of borehole instrumentation for monitoring, are also done in collaboration with hydrogeochemistry. Collaboration with the discipline-specific programme for transport properties of the rock concerns the characterization of the rock that is

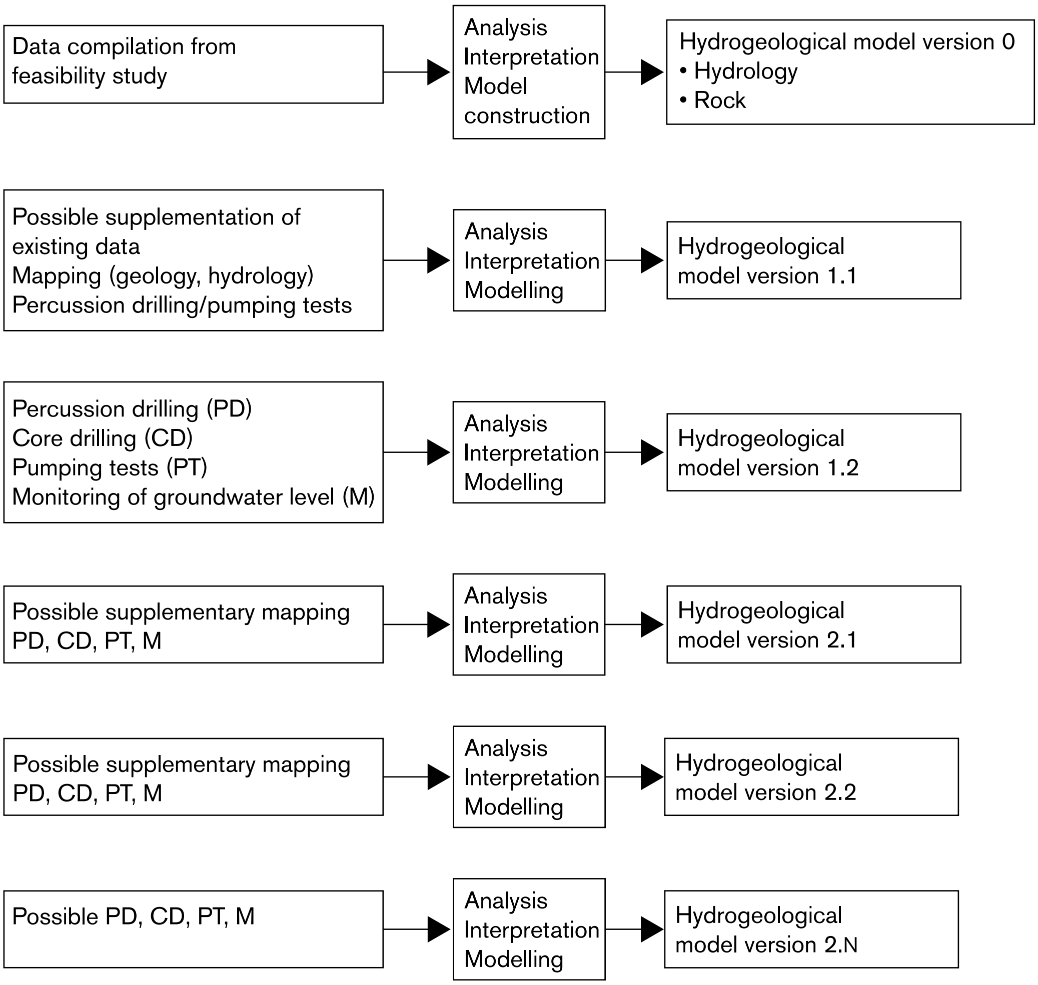


***Figure** 7-2. Overview of methodology and steps for constructing the hydrogeological model of the site and the regional area.*

done during borehole investigations and the design of borehole instrumentation for monitoring. Collaboration with surface ecosystems includes field studies, drilling and long-term measurements. The purpose is to characterize soil layers, marine and lake sediments, near-surface parts of rock mass, and precipitation, temperature, runoff and groundwater pressure. Collaboration with rock mechanics mainly pertains to borehole investigations. The rock mechanical model is also of importance in certain respects (for example in assessment of anisotropy or analysis of borehole tests) for the analysis of hydrogeological data.

7.2 Models and parameters

7.2.1 Structure of the models

The description of the site's hydrogeological properties and states is supposed to summarize the hydrogeological understanding of the site and its regional surroundings. The description comprises a basis for design and safety assessment of the deep repository. In order to compile the description, a hydrogeological model is formulated based on hydrogeological and geological information (model) and on the hydrological processes that can be regarded as relevant for the function of the deep repository. The hydrogeological model is described in greater detail below and summarized in Table 7-1.

The hydrogeological description can be divided into *hydrological description*, hydrogeological description of *soil layers* and hydrogeological description of *the rock*. The hydrogeological description is strongly coupled to the geological description. The hydrogeological processes in soil and rock are coupled to the hydrological processes that take place in the ground surface and the atmosphere. A more detailed description of the relevant hydrogeological processes is provided in SR 97 /SKB, 1999a/. It should, however, be observed that even though the site investigations strive to produce a three-dimensional description of both soil layers and bedrock, it may be justified in various applications within safety assessment and design to introduce simplifications and e.g. describe the soil layers with specified heads as a boundary condition to the groundwater flow at depth.

Description of hydrology

The hydrological description includes the distribution of precipitation, evaporation and temperature in time and possibly space, and the spatial distribution of lakes, marine areas, watercourses, drainage basins and land use. It also includes recharge and discharge areas and topography. The description is the basis for defining suitable boundary conditions on the ground surface in hydrogeological calculation models.

Description of soil layers

The hydrogeological description of the soil cover is based on division of the soil strata into hydraulic units, called Hydraulic Soil Domains (HSD), where the hydraulic properties within each domain can be regarded as uniform (absolutely or statistically), see Figure 7-3. The basis for the subdivision is the geometric subdivision in the geometric model, the geological description of the soil types within each unit and the hydrogeological characterization of the soil layers.

Table 7-1. Brief presentation of the structure and content of the hydrogeological model.

Hydrogeological model

Purpose of model
To be able to calculate groundwater flow within a given volume under natural conditions (undisturbed) and with an open deep repository.

Process description
Constitutive equation: $q = -\frac{k}{\mu} \cdot \left(grad(p) + \rho \cdot g \cdot grad(z) \right)$

Mass flow equation: $div(\rho \cdot q) + \frac{d(\rho \cdot n)}{dt} + \rho \cdot Q = 0$

State equations: $\rho = f(T, C, p)$, $\mu = f(T, C, p)$

q: flux per unit area, *k*: permeability, *μ*: dynamic viscosity, *p*: water pressure, *ρ*: water density,
g: acceleration of gravity, *z*: datum elevation, *n*: porosity (total), Q: supplied or extracted flux per unit volume,
t: time, *T*: temperature, *C*: concentration of solutes (above all salt).

Constituents of the model

Geometric framework
3D calculation volume with external limitations: upper boundary is topography, vertical boundaries and lower horizontal boundary at great depth below repository level.
3D volume which is subdivided into:

- Hydraulic Conductor Domains (HCD): major fracture zones defined as to location, extent and orientation.
- Hydraulic Rock Domains (HRD): rock volumes between HCDs defined by the limiting surfaces of the rock volumes.
- Hydraulic Soil Domains (HSD): soil/sediment volumes on the rock surface defined by the limiting surfaces of the soil volume.

Subdivision of the geosphere into HCDs, HRDs and HSDs is based on results from hydraulic tests, surface mapping and, above all, the geological model. Co-evaluation with other disciplines is essential. The outer limitations of the 3D calculation volume are divided into different areas with defined boundary conditions. Topography as well as geological and hydrogeological mapping and interpretation define areas suitable for different types of boundary conditions.

Parameters
HCDs: Transmissivity (T), Storage coefficient (S).
HRDs: Hydraulic conductivity (K) and Specific storage (S_s), or fracture data descriptions with T and S.
HSDs: Hydraulic conductivity (K), Specific storage (S_s).
T: temperature, *C*: concentration of solutes*, p*: water pressure is determined in tests where K and T are evaluated.
T, S, K, S_s are determined in hydraulic tests. Permeability k can be derived from T or K with the aid of *g*, the water's *μ*:, *p*: and at T also the structure's thickness: S and S_s comprise an estimation of d(*ρn*)/d*t*. S, S_s are dependent on the compressibility of the rock and the water as well as the total porosity. The relationship between *p*, salinity and temperature is determined in the laboratory on water samples.

Parameter representation
HCDs: T, S, constant, or statistical distributions, within domain.
HRDs: Statistical distributions of K and S_s, or statistical distributions of spatial distribution of fractures, fracture size, fracture orientation and T and S of fractures.
HSDs: K, S_s, constant, or statistical distributions, within domain.

Boundary conditions
Upper boundary: Variable infiltration depending on drawdown (land) or specified pressure, which is constant or variable with time (lakes, sea and future scenarios with coastline displacement and ice age).
Meteorological and hydrological data plus particulars on recharge and discharge areas are used for definition of boundary condition on upper boundary.
Lateral boundaries: Pressure distribution and salinity distribution.
Lower boundary: Zero flow boundary.
Inner boundaries: (tunnels): Flow or pressure.
Initial conditions: Pressure and salinity within 3D calculation volume.
Pressure is measured by section in the borehole and the level of the water table is measured in lakes and sea. Salinity is measured on water samples from borehole sections or sea and estimated from logging in borehole. Hydrological measurements provide limits on current flow conditions at upper boundary.

Numerical tools
Continuum models: NAMMU, PHOENICS etc. Discrete fracture network models: FracMan/Mafic and others.

Calculation results
Groundwater pressure, groundwater flow, salinity within 3D calculation volume.

Description of rock

The hydrogeological description of the rock is based on division of the rock into different units. The units should be a practical basis of subdivision for spatially distributing hydraulic properties in the rock mass. Within each unit, hydraulic properties are specified in the form of permeability, a statistical description of permeability or a statistically discrete fracture network with associated hydrogeological parameters, see Figure 7-3.

The subdivision into units is based on the common geometric framework and the geological description of these units, see Chapter 4 and Figure 2-4. Of these, the brittle structures are the most important for the hydrogeological model, since experience shows that they have higher permeability than the rest of the rock. The purpose of the analysis of the structure and properties of the structural model and the hydraulic tests in them is to describe the brittle structures hydraulically, which is a basis for spatially distributing properties in the rock mass. Fracture orientations, frequencies and lengths (measured on oriented rock surfaces) reported in the geological model are very essential information, which is to be combined with the hydraulic downhole measurements.

In different phases of the investigations, a number of the major brittle structures, mainly regional fracture zones and local major fracture zones, will be defined as to position, orientation, extent and width. These areas are called Hydraulic Conductor Domains (HCD). The rest of the rock is divided into different Hydraulic Rock Domains (HRD). The subdivision into different hydraulic domains is based on the subdivision in the geometric model, but a Hydraulic Rock Domain can, in principle, consist of several different geometric units representing both fracture zones and other rock. In cases where more detailed knowledge is obtained of structures that lie within HRD, the hydraulic unit subdivision may be updated.

The basis for the subdivision into HCDs and HRDs is the hydraulic tests performed in a standardized manner (test section length, test time, test technique) and can be separated into structure and rock mass units before statistical analysis of the hydraulic properties is carried out. Interference tests are another important basis for defining structure units. Co-evaluation between disciplines is essential to obtain a broad basis for both subdivision and characterization of the different units.

Hydrogeological model

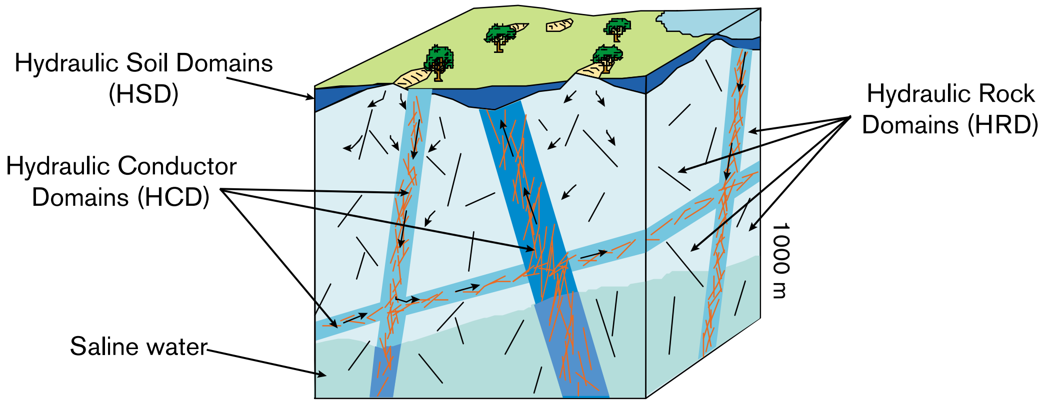


Figure 7-3. The soil layers and the bedrock are divided into units. Within each unit, hydrogeological conditions are specified as mean values or as statistical distributions.

7.2.2 Constituent parameters

Table 7-2 summarizes the parameters that comprise the hydrogeological description in the site-specific model. As a rule, these parameters need to be interpreted from the results of the different investigations. The table is based on the tables compiled for the parameter report /Andersson et al, 1996/, the revision that took place in connection with the work on requirements and criteria /Andersson et al, 2000/ and the production of the general investigation and evaluation programme /SKB, 2000b/. Information from several other disciplines, especially geology, is also needed to prepare the hydrogeological description (see section 7.2.3).

Table 7-2. Compilation of hydrogeological parameters included in the hydrogeological description. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Deterministically modelled fracture zones	– Geometry – regional and local major fracture zones	x	x	x	x	Calculation models
	– Deterministic or statistical distribution of transmissivity or of hydraulic conductivity		x	x	x	Calculation models
	– Storage coefficient		(x)	x	x	Transient calculation models
Stochastically modelled fracture zones and fractures plus rock mass	– Geometry – rock volumes with similar hydraulic properties	(x)	x	x	x	Calculation models
	– Statistical description of spatial distribution and geometric properties of fracture zones and fractures		x	x	x	DFN models
	– Statistical distributions of transmissivity					
	– Statistical distributions of hydraulic conductivity		x	x	x	SC models
	– Statistical distributions of specific storage and storage coefficient		(x)	x	x	Transient calculation models
Soil layers	– Geometry – soil volumes with similar hydraulic properties		x	x		Calculation models
	– Hydraulic conductivity		(x)	x		Calculation models
	– Specific storage		(x)	x		Transient calculation models
Hydraulic properties of groundwater	– Density, viscosity and compressibility		x	x	x	Calculation of parameters
	– Salinity		x	x	x	Calculation of parameters and included in calculation models
	– Temperature		x	x		Calculation of parameters

Parameter group	**Parameter**	**Determined primarily during**				**Used for**
		FS	**ISI**	**CSI**	**DC**	
Boundary conditions and supporting data	– Meteorological and hydrological data	x	x	x	(x)	Definition of boundary conditions and calibration of groundwater models (gwm) and biosphere models (bm)
	– Recharge/discharge areas		x	x	x	Definition of boundary conditions and calibration of gwm and bm
	– Pressure or head in borehole sections and surface watercourses		x	x	x	Definition of boundary conditions and calibration of gwm and bm
	– Salinity		x	x	x	Definition of boundary conditions and calibration of gwm
	– GW flow through borehole		(x)	x	x	Calibration of gwm
	– Regional boundary conditions (interpreted), historical and future evolution		x	x	(x)	Definition of boundary conditions (Current condition, paleohydrogeological perspective, analysis of possible scenarios)

7.2.3 Modelling tools and planned analyses

Hydrogeological analysis and modelling is the activity that ties together all results from the investigations into a hydrogeological description on a regional and local scale. It can be divided into two parts:

- modelling for the purpose of providing a basis (interpreting data) for a descriptive hydrogeological model,
- modelling (numerical calculation models of varying size etc) for the purpose of describing the groundwater flow in terms of magnitude and flow paths as a basis for interpreting data within other disciplines (mainly hydrogeochemistry and transport) and as a basis for the predictions that are made within safety assessment and design.

Interpretation of data

During the site investigations, a description is prepared on the regional scale and on the local scale. The area for the regional description should be large enough to provide sufficient information to the geological evolution model (see Chapter 4). Hydraulically speaking, the area should be adapted to what is expected to provide clear boundary conditions and should be substantially larger than the local area to permit flow patterns to be calculated, with recharge and discharge areas. Long-term scenarios and site-specific salinity conditions in the groundwater may also necessitate the inclusion of large areas in the regional description.

In comparison with the regional model, the local model will be more reliable due to a higher investigation intensity, but contain the same components in its description as the regional model. The subdivision into HCDs and HRDs can, however, be varied so that detailed units in the local description are consolidated into larger units in the regional one. In connection with this redistribution, properties that are described on a local scale need to be modified so that they correctly represent the aggregate properties of the larger units /see also Rhén et al, 1997a; Rhén et al, 1997c/.

The interpretation is based above all on analysis of hydraulic downhole measurements. The analysis of the downhole measurements provides hydraulic parameters which, together with the geological description (see Chapter 4), serves as a basis for spatially dividing soil layers and bedrock into hydraulic units. In order to determine the hydrogeological parameters, input data are also needed from other discipline-specific programmes. Table 7-3 shows a compilation of parameters taken from other programmes. The integration and co-evaluation of geological and hydrogeological data is very important in order to obtain reliable and consistent models.

Based on measurements in the field and analysis of data, a judgement is made of whether the conceptual model is suitable as a basis for making a descriptive model (quantitative model) which spatially describes the properties and conditions in an area. The descriptive hydrogeological model is the basis for the geoscientific understanding and analysis related to safety assessment and design. Numerical calculation models are based on the descriptive model but are not used only for predictions, but tested against various measurements in the field, such as pressure responses in interference tests. To some extent, this means that parameters are "fine-tuned" (calibration of the calculation model), but it also provides a check of the descriptive model that can lead to adjustment of e.g. the geometric model of one or more fracture zones.

The analysis of the fracture network, which must be described from individual fractures up to regional fracture zones, is important. However, the detailed description can only be done statistically. The basis is the geological investigations, and a common analysis of fracture mapping and lineaments is required to construct a structural model. Fracture orientations in boreholes and on outcrops, fracture distributions along boreholes, lengths of fracture traces, truncations of fracture traces and lineaments are used to identify fracture sets and their properties. The properties of each fracture set include above all (spatial distribution of) fracture density, distribution of fracture radius, and distribution of orientation. The hydraulic properties obtained from the hydraulic tests are used to define the hydraulic properties for structure and the fracture network. It is in particular injection tests with short measurement sections and detailed flow loggings which provide the basis for creating transmissivity distributions of the fracture sets. More properties can then be assigned to the fractures depending on what is to be calculated. The fracture network with its hydraulic properties is then the base, along with the geological description, for devising units (domains) in the descriptive model (see section 7.2.1 above) that can be considered to have uniform properties within the unit, and for assigning hydraulic properties to these units.

Table 7-3. Overview of parameters taken from other programmes.

Parameter	Determined within discipline-specific programmes
Location, orientation and extent of regional and local major fracture zones	Geological programme (Partly in collaboration with the hydrogeological programme)
Length distribution of lineaments down to fracture traces (orientation of fractures and mapped surface)	Geological programme
Orientation and location of fractures in borehole with interpretation of which are judged to be open	Geological programme
Stochastic distribution of local minor fracture zones (orientation, spatial distribution, size, density)	Geological programme
Stochastic distribution of individual fractures (orientation, spatial distribution, size, density)	Geological programme
Soil and sediment layer sequence descriptions and particle size analyses of these layers	Geological programme
Principal stress directions in the bedrock	Rock mechanical programme
Salinity distribution (density) of the water	Hydrochemical programme

Most hydraulic test methods are based on creating a disturbance, for example by changing the pressure instantaneously or by pumping in a section, and then measuring the response in the water pressure and/or the water flow in the disturbed section and sometimes other sections as well. The methods for interpretation and analysis of permeability in particular can be roughly divided into two groups: methods for transient conditions and methods for steady-state conditions. In the first case a time series of pressure and flow is used for interpretation, and in the second case values of pressure and flow that can be regarded as representing a steady state (constant in time) are used.

Certain hydraulic tests can only be evaluated with methods for steady-state conditions. Such conditions must be assumed to interpret flow logs. Injection tests can be interpreted by assuming steady-state conditions. If an interference test proceeds over a long time, it may be appropriate to interpret certain data with methods that assume steady-state conditions. It is normally assumed in the interpretation that the flow is radial, or that it is radial nearest the borehole section and spherical some distance out in the rock mass. These basic assumptions regarding flow dimension will be preliminarily utilized.

Hydraulic tests that provide a time series with flow and pressure provide a basis for judging the flow dimension, which in turn provides guidance in the choice of interpretation model and what time period should be used to interpret parameters. Methods for transient conditions are appropriate to use in both injection tests and interference tests.

Calculation tools

Calculation methods that are used in hydrogeology can be divided into two categories: calculation methods for interpreting/analyzing hydraulic tests and numerical calculation methods for modelling groundwater flow. There are a number of calculation methods for interpretation and analysis of hydraulic tests, and they are based on different conceptual models concerning the hydraulic system being tested and how the tests are performed technically. The basic steps in interpretation and analysis are that first a conceptual model is chosen and then one or more models are applied to the measured data. The models are analyzed and an interpretation method is chosen, after which the parameters are evaluated.

Calculation methods and conceptual models for groundwater flow that are suitable for crystalline bedrock can largely be divided into discrete fracture network (DFN) models and stochastic continuum (SC) models. Parameter fields that are used in these calculation methods derive from the geological and hydrogeological descriptions, and in some cases measurement data are utilized directly to derive certain parameters, or parameter distributions, included in the models. Interference tests are a very important basis for calibration and verification of these numerical models.

The description of the spatial distribution of HCDs and HRDs and the properties of these units is the basis for creating both DFN and SC models. Each HCD is given a defined position and extent as well as properties which are assigned as a value or a distribution within the respective unit. The fracture network with hydraulic properties for each HCD will primarily be used to create the properties in both the DFN and SC models. Fracture data cannot be used directly in the SC model, but are included in the interpretation basis to obtain properties in the continuum model that correspond to the fracture network. The statistical distributions of the fracture network and the fracture properties provide the spatial variability in the hydraulic properties. The effects of the spatial variability in the hydraulic properties on flow and pressure fields in the calculation models can be studied by making several realizations of the fracture network.

7.3 Characterization methods

Several methods are used for determination of parameters and construction of models in accordance with section 7.2. The methods that will probably be used in a site investigation are commented on in this section. The methods are also summarized in tables.

7.3.1 Meteorological and hydrological investigations

Meteorological and hydrological investigations comprise an important source of data for defining boundary conditions for the calculation models. The methods are summarized in Table 7-4.

Normally it is possible to rely on enough meteorological and hydrological data being available in an area. This includes information that can be obtained from reports, maps or in digital form. Supplementary data are obtained from newly-erected measurement stations for collection of meteorological and hydrological data. The information can be divided into meteorological observations and surface hydrology observations.

Meteorological observations in the form of precipitation, snow depth, temperature, evaporation and air pressure are obtained above all from existing meteorological measurement stations run by SMHI. An overview of available climatalogical and oceanographic data is presented by /Lindell et al, 2000/. The account in the feasibility study is augmented by current data. The collection work is coordinated with surface ecosystems (see section 10.3.10). Evapotranspiration is normally calculated on the basis of meteorological and runoff data. Air pressure can be of importance for the water pressures that are measured and must therefore be measured.

Table 7-4. Description of meteorological and hydrological methods.

Method	Information (parameter)	Comments/references
Meteorological and hydrological methods		
Analysis of existing hydrological and meteorological data Meteorology • precipitation, snow depth • temperature, evaporation • air pressure Topography, watercourses, springs etc	**General basic information, basis for boundary conditions** • meteorology and flows • drainage basins • recharge/ discharge areas	Documented methods /Lindell et al, 2000/
Meteorological and hydrological survey and long-term monitoring Meteorology • precipitation, snow depth • temperature, evaporation • air pressure Surface hydrology • topography • flows in major watercourses • springs, location and possibly flow • recharge/discharge areas • small watercourses, location and possibly flow • level of lakes and sea level fluctuations • (mapping of Quaternary geology)	**Interpretation basis for boundary conditions** • meteorology and flows: long-term recorded parameters • drainage basins • recharge/discharge areas • for description of local climate • for modelling of groundwater recharge • (see geology)	Documented methods

Surface hydrology observations in the form of topography, locations of watercourses, lakes, and, in some cases, springs are initially obtained from existing map material and can generally be obtained in digital form. Map material also provides an opportunity to determine existing recharge and discharge areas. Flows in watercourses within or in the vicinity of the regional area can in some cases by obtained from SMHI. The existing measurement series that are available for nearby watercourses provide a basis for determining runoff from the drainage basin or basins in the investigation area. Approximate levels of lakes can in general be obtained from existing maps, and measurement series of sea level fluctuations may be available at e.g. ports. Aerial and satellite photographs also provide material for defining drainage basins, the route of watercourses, the position of springs (in some cases), the extent of different biotopes, and nature protection or natural resource areas.

During the site investigation, supplementary mapping will be performed and measurement stations will be set up to obtain more detailed surface hydrology observations. The supplementary mapping consists of aerial photography and ground-based mapping. If necessary, the supplementary information is taken from topographic maps with better resolution than existing material. Ground-based mapping may be required to find springs and small streams and to determine biotope types and their extent. This mapping is coordinated with the geological mapping.

A number of measurement stations will be established to measure flows in large watercourses and levels in major lakes. A measurement station for sea level will be established in a near-coast area, if existing measurement stations cannot be considered to provide sufficiently representative values. If necessary, measurements stations will be established for measurement of flows in small watercourses and springs and levels in small lakes.

The majority of the above measurements are also essential for the discipline-specific programme surface ecosystems and will therefore be carried out in cooperation with this programme. Hydrochemical data for both precipitation and watercourses will be collected within the hydrogeochemistry programme.

7.3.2 Investigations/documentation of wells and facilities

Data from existing wells and facilities comprise an important basis for an initial estimate of the properties of an area. To some extent, these data have already been compiled during the feasibility studies. The body of data can be improved in some respects by conducting supplementary investigations in the existing boreholes/wells. The methods are summarized in Table 7-5.

Existing data from wells and facilities are analyzed. To some extent, parameters and area descriptions are obtained from reports. Flows etc can be obtained in digital form from the well archive, and these data can be processed to estimate the permeability of the rock.

During inventory of existing wells and observation pipes within the regional area, figures are collected on capacity (flow versus drawdown) and annual groundwater abstraction for a selection of wells. Water samples are taken. The groundwater level in wells and observation pipes is measured. A slug test is recommended in all observation pipes to be used for groundwater level observations. A capacity test is conducted as needed.

Table 7-5. Description of methods for investigations/documentation of wells and facilities.

Method	Information (parameter)	Comments/references
Investigations/documentation of wells		
Analysis of existing data for wells and facilities Well archive Facility documentation	**General basic information** • hydraulic and hydrogeochemical properties of soil layers and surface rock • land use • K values, pressure levels, flows • damming and drainage projects, etc	Documented methods
Data collection from existing wells and observation points Existing wells • capacity figures • groundwater abstraction figures • groundwater levels • water samples Observation pipes • capacity figures • groundwater levels	**Basic information within area of interest** • hydraulic parameters for soil layers/surface rock (as above, but more detailed within a limited area) • data for monitoring programme • together with meteorological and surface hydrology data, data collected under this point comprise an initial basis for conceptualization of groundwater recharge and modelling	Documented methods

7.3.3 Hydrogeological borehole investigations

Investigations in boreholes provide the most important basis for describing the hydraulic properties of the rock, as well as pressure and salinity distribution in the rock mass. The results of the investigations also provide a basis for calibration of numerical calculation models. The methods are summarized in Table 7-6.

Measurements and tests during drilling

During percussion drilling the flow from the borehole is estimated, flushing water colour is judged and cuttings samples are taken for rock type determination. Lithological variations are studied with the aid of cuttings samples and measurements while drilling (MWD). MWD preliminarily includes drilling rate, feed pressure and rotation pressure. Percussion drilling is interrupted at predetermined length intervals (preliminarily 100 m) in order to carry out a transient hydraulic test of the most recently drilled interval (pumping time about 1 h, recovery about 1 h). Alternatively, packers are used to permit hydraulic testing of 100 m sections after the borehole has been drilled. If observation holes exist within approximately 500 m of the pumped hole, pressure responses are measured in these holes.

MWD during core drilling also includes measurement of flushing water pressure, flushing water flow, return water flow, flushing water concentration, drawdown and electrical conductivity. The core drilling is interrupted at predetermined length intervals (preliminarily 100 m) in order to carry out a transient hydraulic test of the most recently drilled interval (pumping time about 1 h, recovery about 1 h). If observation holes exist within approximately 500 m of the pumped hole, pressure responses are measured in these holes. Within certain limits, the interval is adjusted after replacement of the drill bit to facilitate drilling but so that the established intervals are still roughly obtained.

Table 7-6. Description of methods for hydrogeological borehole investigations.

Method	Information (parameter)	Comments/references
Hydraulic borehole investigations		
Recording of flushing water parameters while drilling • flushing water pressure/flow, return water flow, flushing water concentration, drawdown (MWD), electrical conductivity • sampling of drill cuttings • recordings in existing nearby boreholes	**Interpretation basis** • flushing water balance • hydraulic features • hydraulic connections	Methodology for core drilling tested and essentially fully developed. Method improvements tested during 2000.
Hydraulic tests during drilling • pressure recording • pumping test • (water sampling)	**Hydraulic parameters** • natural groundwater pressure • hydraulic conductivity (K value) scale ≥100 m • transmissivity (T value) of major hydraulic structures • (see chemistry)	Optimal methodology for tests and sampling during core drilling identified. Equipment for wire-line under development, to be tested during 2000. Execution of tests otherwise follows /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.
Absolute pressure measurement/calculation • during drilling • indirectly from tests • from separate measurement • from monitoring	**Absolute pressure** • natural groundwater pressure; for verification and calibration of groundwater modelling • verification of circulation in open borehole	Tests during drilling are under development, but the test methodology is otherwise regarded as fully developed /Almén and Zellman, 1991; Almén et al. 1994; Rhén et al, 1997b/. The best way to determine natural groundwater pressure is being studied.
Analysis of geophysical methods • temperature • fluid resistivity • single-point resistance • caliper	**Interpretation basis for** • hydraulic features • groundwater density	Documented methods. Method study coupled to differential flow logging under way. /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.
Flow logging Spinner, UCM • accumulated flow along borehole during constant drawdown • flow • temperature • fluid resistivity	**Hydraulic parameters** • hydraulic features: location and T (estimate based on full-hole test) • frequency of major hydraulic conductors (10 m scale) • groundwater density	Use of method in SI not yet fully established. /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.
Differential flow log • sectional inflow during constant drawdown • different section lengths and drawdowns • flow • temperature • fluid resistivity • single-point resistance	• K/T value distribution for rock mass and hydraulic features (local major and local minor fracture zones) • frequency of hydraulic conductors (m to dm scale) • natural groundwater pressure • groundwater density	Use of method in SI not yet fully established. Tests under way during 2000 /Rouhianen, 1995/.

Method	Information (parameter)	Comments/references
Groundwater flow measurements Dilution probe (SKB) • undisturbed conditions • disturbed conditions (pumping tests or similar) Thermal pulse method (Posiva) • undisturbed conditions • disturbed conditions (pumping tests or similar)	**Calculation basis for** • natural groundwater flow (model calibration) • if K or T value has been determined by independent method, the pressure gradient can be calculated • flow response in pumping tests (understanding of hydraulic connectivity in evaluation of tests)	The methods (SKB's and Posiva's methods) are not yet fully evaluated. Method choice therefore not made. /Rouhianen, 1993/
Hydraulic injection tests • simple closed test section • constant pressure, optimized test times • transient recording • different section lengths and injection pressures • (possible interference between sections)	**Hydraulic parameters** • K value distribution for rock mass and hydraulic structures (local major and local minor fracture zones) (skin, evaluability) • frequency of hydraulic conductors (>m scale) • flow dimension • (natural groundwater pressure) • (possible connectivity)	Use of method in SI not yet specified in detail. Methodology is regarded as developed but existing equipment will be improved. /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.
Single-hole pumping tests Single open test section (usually whole borehole) • constant flow, optimized test time • transient recording (flow, drawdown, electrical conductivity) Single packered-off test section • constant flow, optimized test times • transient recording (flow, drawdown, electrical conductivity) • different section lengths	**Hydraulic parameters** • K value for rock mass, or T value for dominant hydraulic feature • flow dimension • (natural groundwater pressure) • (possible connectivity)	The test methodology is regarded as fully developed /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/. Methodology for efficient hydraulic tests in percussion boreholes will be optimized.
Hydraulic interference tests Pumping holes open or sectioned boreholes • constant flow • optimized test times • transient recording (flow, drawdown, electrical conductivity) Observation holes • open or sectioned boreholes • transient recording (drawdown, possible electrical conductivity) • flow change (option, in certain bh sections groundwater flow measurement by means of dilution technique or thermal pulse)	**Hydraulic conditions and parameters** • verification of geometry and connectivity of essential structures • K value for rock mass, or T value for hydraulic structures (local major and local minor fracture zones) • flow dimension • (storage coefficient)	The test methodology is essentially regarded as fully developed /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.

During core drilling, the process is also interrupted at a presumed water-bearing fracture zone for water sampling of the most recently drilled portion for hydrogeochemical analyses. In conjunction with this sampling, a hydraulic test is also performed for the primary purpose of determining the water-bearing capacity of the sampling section and the secondary purpose of determining its absolute pressure.

The absolute pressure can also be measured in the most recently drilled portion during interruptions in core drilling. The measurement is carried out with the same or similar equipment as that used for water sampling and hydrotests.

Absolute pressure measurement/calculation

In aquifers where the density of the water varies, for example in near-coast areas with an increased salinity at depth, it is necessary to estimate the absolute pressure of the water in order to define initial and boundary conditions in the calculation models. The absolute pressure is relatively difficult to measure at the great borehole depths that are planned. There are, however, several methods for carrying out measurements.

The most undisturbed pressure conditions can probably be obtained during drilling. As mentioned in preceding sections, a pressure profile can be set up along the borehole by measuring the pressure in the section that was drilled most recently.

If the hydraulic tests are performed under transient conditions and evaluated with the models that take the transient process into account, it is usually possible to evaluate the undisturbed pressure. There may, however, be considerable uncertainties in the evaluation if previous activities in the borehole affect the pressure picture in the rock.

Differential flow logging, which is described in one of the following sections, also provides a possibility for estimating the approximate flow distribution along the borehole.

The above three methods also provide a basis for calculating the circulation in the open borehole, which is a basis for the hydrochemical characterization (planning of water sampling and interpretation of hydrochemical analyses).

Sections in the borehole are sealed off with packers for the monitoring programme. The undisturbed pressures can be measured some time after installation of the packers. In this case the resolution of the pressure distribution along the borehole is limited due to the fact that only a small number of measurement sections can be installed in each borehole. See further the section below that deals with hydrogeological monitoring.

Analysis of geophysical methods

The geophysical borehole logging that is carried out during the geological programme can be used to some extent for the hydrogeological model. Among other things, temperature and fluid resistivity can serve as a basis for a density determination of the water in a borehole. Single-point resistivity measurements provide indications of open (potentially water-bearing) fractures. Caliper can provide indications of more fractured rock. BIPS logging provides a picture (and an orientation of the picture) of the borehole wall which is very useful for orientation of the drill core. Large open fractures can also usually be seen in the picture.

Flow logging

Flow logging can be done in a borehole to determine the position and approximate properties of hydraulic features along a borehole (Figure 7-4), either with a method developed by SKB – UCM – or with two similar methods developed by Posiva – differential flow logging and continuous flow logging. In all these methods, the borehole is pumped during logging, and two different flows are normally used in differential flow logging.

The first method, UCM, provides the flow distribution, temperature and fluid resistivity along the borehole. The second method, differential flow logging, uses two pump flows to determine transmissivity and undisturbed pressure in a test section with flow. The evaluation method is based on the assumption of steady-state conditions. With continuous flow logging, only one flow is used and logging is carried out faster and with good detailed resolution along the borehole, but with a higher measurement limit for flow compared with differential flow logging. In both differential and continuous flow logging, the temperature and electrical conductivity of the water are measured continuously. In addition, the single-point resistance method is used to locate fractures.

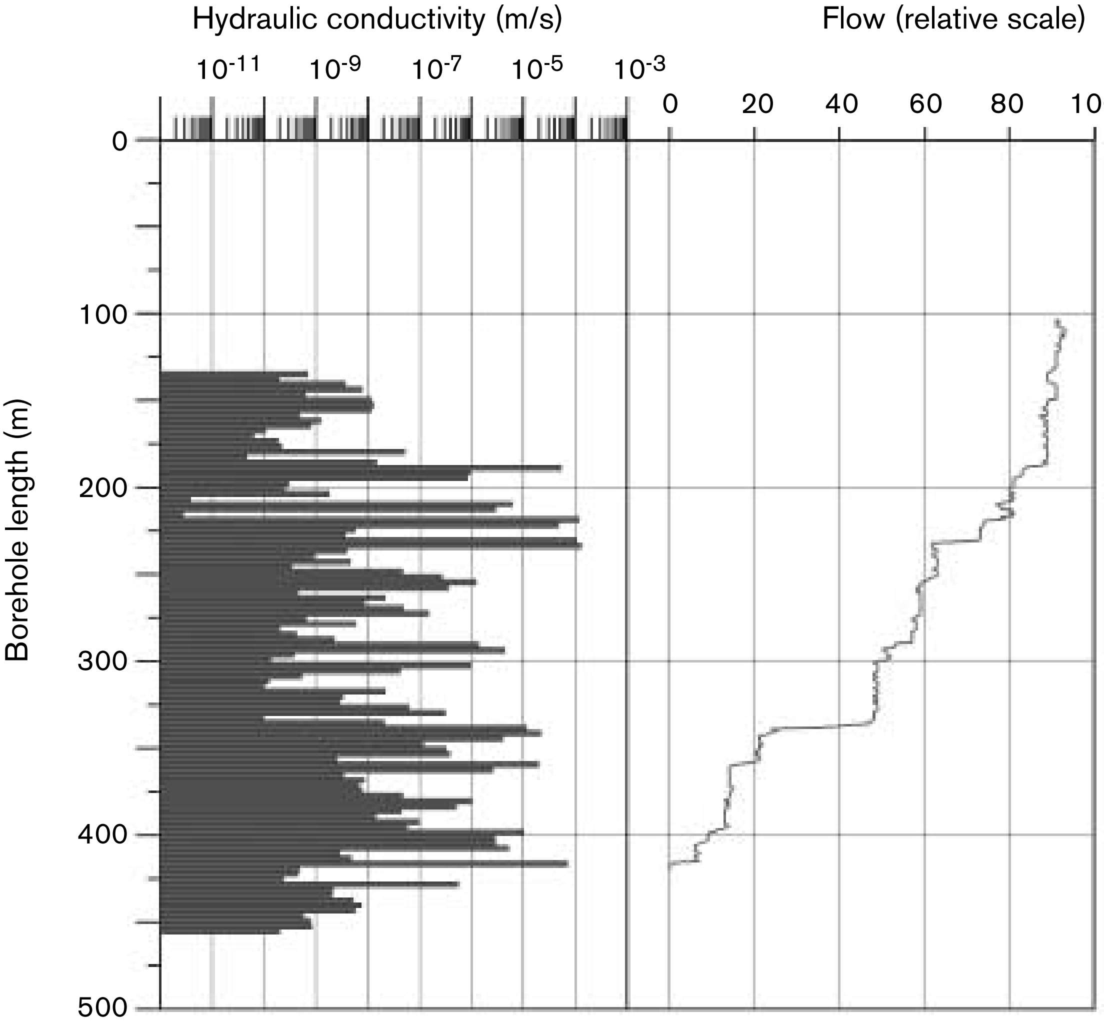


***Figure** 7-4. Example of results from injection test (left) and from flow logging (right).*

Hydraulic injection tests

Hydraulic injection tests, with a measurement section sealed off by two packers, are carried out at predetermined intervals along a number of boreholes. The tests are performed under transient conditions and evaluated with the models that take the transient process into account. This makes it possible to evaluate the transmissivity distribution (see Figure 7-4), flow dimension and the hydraulic resistance nearest the borehole (normally called "skin" in the hydrogeological literature).

When transmissivity/hydraulic conductivity is based on steady-state conditions, any "skin" can influence the magnitude of the evaluated parameter. For this reason, evaluation methods that make use of the transient process are regarded as more reliable compared with methods based on steady-state conditions. However, methods based on steady-state conditions can often provide acceptable accuracy for the permeability of the rock.

The section lengths for the injection tests are planned to be 5 m (canister scale) and 20 m, which is equivalent to a preliminary resolution in SC models on a local scale. Preliminarily, the injection time is about 15 minutes, recovery about 10 minutes for 5 m sections, while for 20 m sections the injection time is about 30 minutes, recovery about 20 minutes.

Single-hole pumping tests

Single-hole pumping tests are carried out to test the entire borehole: pumping time about 24 hours, recovery about 12 hours. The evaluated transmissivity from such a test is a prerequisite for being able to transform flow logging with UCM into an approximate transmissivity distribution along the borehole. If there are boreholes within approximately 500 m, pressure responses are measured in these holes during the hydraulic test in order to obtain an indication of major conductive features.

Hydraulic interference tests

Hydraulic interference tests provide information for the description of the deterministic hydraulic features (HCDs in section 7.2) and boundary conditions. The tests are also extremely valuable for calibration of numerical calculation models.

The interference pumping test is performed by pumping a borehole section sealed off by two packers or the whole borehole and measuring pressure responses in surrounding borehole sections as well as the pumped section, see Figure 7-5. Pumping time can be around 72 hours with a recovery of about 24 hours. In some cases, groundwater flow measurements are also carried out during the tests, see above. The tests are performed when a majority of the boreholes have been packed-off and the tests provide information on the properties of major conductive features (above all the feature contained in the pumped section) and hydraulic connections between major conductive fracture zones. The results are important in building up the site-specific structural model of the major fracture zones in consultation with geology. The results of the measurements are also essential for calibrations of the calculation models.

One or two long-duration interference pumping tests may be performed in the final phase of the complete site investigation. The pumping time in these tests is from 3 to 6 months, recovery about one to two months. One of the long tests should be conducted as a large-scale tracer test, see below. The purpose of a long-term pumping test is to create a disturbance in a large rock volume which can shed light on boundary conditions

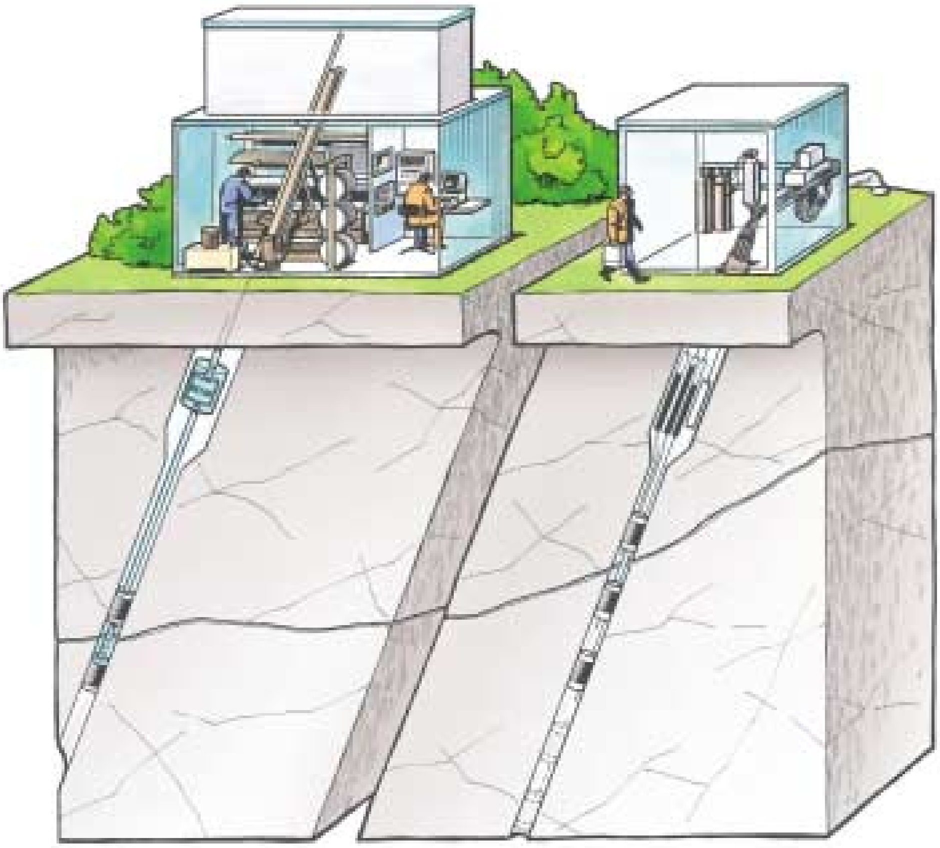


Figure 7-5. Hydraulic interference tests.

better than interference tests of short duration. Since they are carried out at the end of the complete site investigation, the monitoring system will probably be well built-out. These long-duration tests are valuable interference tests for calibration of numerical calculation models. Interference tests that have not been used for calibration are used as independent data sets for verification of the calculation models.

Hydraulic interference tests – large-scale tracer tests

Large-scale tracer tests can be used to determine transport parameters for one or several major fracture zones while obtaining a more reliable picture of how the major fracture zones are hydraulically interconnected (see also section 9.3.2). A large-scale tracer test is conducted at the end of the complete site investigation, or as a supplementary investigation after concluded site investigation. These tracer tests must be conducted before the detailed characterization is started, since severe hydraulic disturbances from the construction of the repository probably render a deep analysis of the results impossible.

A large-scale tracer test is conducted according to the above description of interference tests, with a few additional points. Pumping proceeds for several days, after which several tracers are injected into selected borehole sections. Water is then sampled regularly in both the pumped borehole and borehole sections where tracer has been injected. The duration of the interference pumping test is several months to allow tracers to break through, i.e. a pumping time of approximately three to six months with a recovery of approximately one to two months. An example of how a large-scale tracer test can be carried out is given in /Rhén et al, 1992/.

Groundwater flow measurements

The groundwater flow through a borehole section can be determined by means of several methods. If the test section in the borehole is suitably shaped and in good contact with the rock, the saturated groundwater flow will be of the same order of magnitude as the groundwater flow in the rock. The methods can be utilized either for measurements of undisturbed conditions or under disturbed conditions, for example during interference tests. In the latter case, the change in flow due to the test provides valuable information on how the structures are interconnected from a flow viewpoint. Only pressure responses in a section indicates that the structure in the section is hydraulically connected with other structures, but it is not possible to determine whether it flows or not (the measurement section is in a dead end of the structure).

SKB has developed both a probe (Dilution Probe) that can be used in open boreholes, and a methodology for conducting dilution measurements in packed-off boreholes. With the dilution method, the dilution of a tracer injected into the borehole section is measured. Posiva has also developed a probe for groundwater flow measurements in open boreholes (Cross Flow Measurements), which measure the flow between four sectors that follow the direction of the borehole. The Dilution Probe and/or the Cross Flow Measurement Probe can be used before the boreholes have been packed-off for long-term monitoring, see also section 9.3.2. In most of the cored boreholes, 1–2 borehole sections are arranged where dilution measurements can be carried out during the monitoring period.

7.3.4 Hydrogeological monitoring

Hydrogeological monitoring comprises a basis for describing the groundwater's pressure and flow distribution in the rock mass. The purpose is to measure natural groundwater variations before the construction of a deep repository, and to be able to measure pressure responses during single-hole pumping tests and interference tests. The monitoring system must also be able to measure pressure responses during construction of the deep repository. Other hydraulic disturbances can also be measured with the monitoring system, e.g. from drilling, which in some cases can provide a basis for the hydrogeological model. The monitoring is started as soon as all water samplings, borehole loggings and hydraulic tests have been carried out in the cored borehole. The layout of the monitoring in a borehole is illustrated in Figure 7-6.

The monitoring system is very important in interference tests, in which the measurement frequency is adapted to an expected dynamic process so that the time resolution is satisfactory for the subsequent analysis. The results from the monitoring also provide an important basis for calibration of numerical calculation models. The methods are summarized in Table 7-7.

Deep cored boreholes are sectioned by means of packers so that pressure levels in the groundwater can be measured at different depths below the ground surface. A preliminary estimate is that up to 8 sections may be used. Only one packer is normally put in percussion boreholes, but 2 to 3 packers may occasionally be used.

The instrumentation of the boreholes will permit pressure measurement in all packed-off sections. Certain sections are designed so that groundwater flow measurements can be performed and water samples can be taken. "Dummies" may be installed in these sections to reduce the water volume. This shortens the required measurement times and improves the chances of obtaining a homogeneous mixing of the tracers in the test section. The number of borehole sections for the groundwater flow measurements is much less than for groundwater pressure. In most cored boreholes, 1 to 2 sections are installed for groundwater flow measurements. A section may be installed for groundwater flow measurements in some percussion boreholes.

Water sampling is done according to the description in the hydrogeochemical programme, see Chapter 8. Density is determined on several samples and electrical conductivity is determined for all water samples. These analyses are the base for determining the density of the water in the geosphere, together with other measurements of the electrical conductivity. This also provides a basis for determining density in hoses between a measurement section and a pressure sensor, in cases where pressure sensors cannot be located in the measurement section.

The monitoring system permits high resolution of the measurements in time and pressure changes, which makes it possible to measure the effects of gravitational changes (tidal effect) and air pressure (barometer effect).

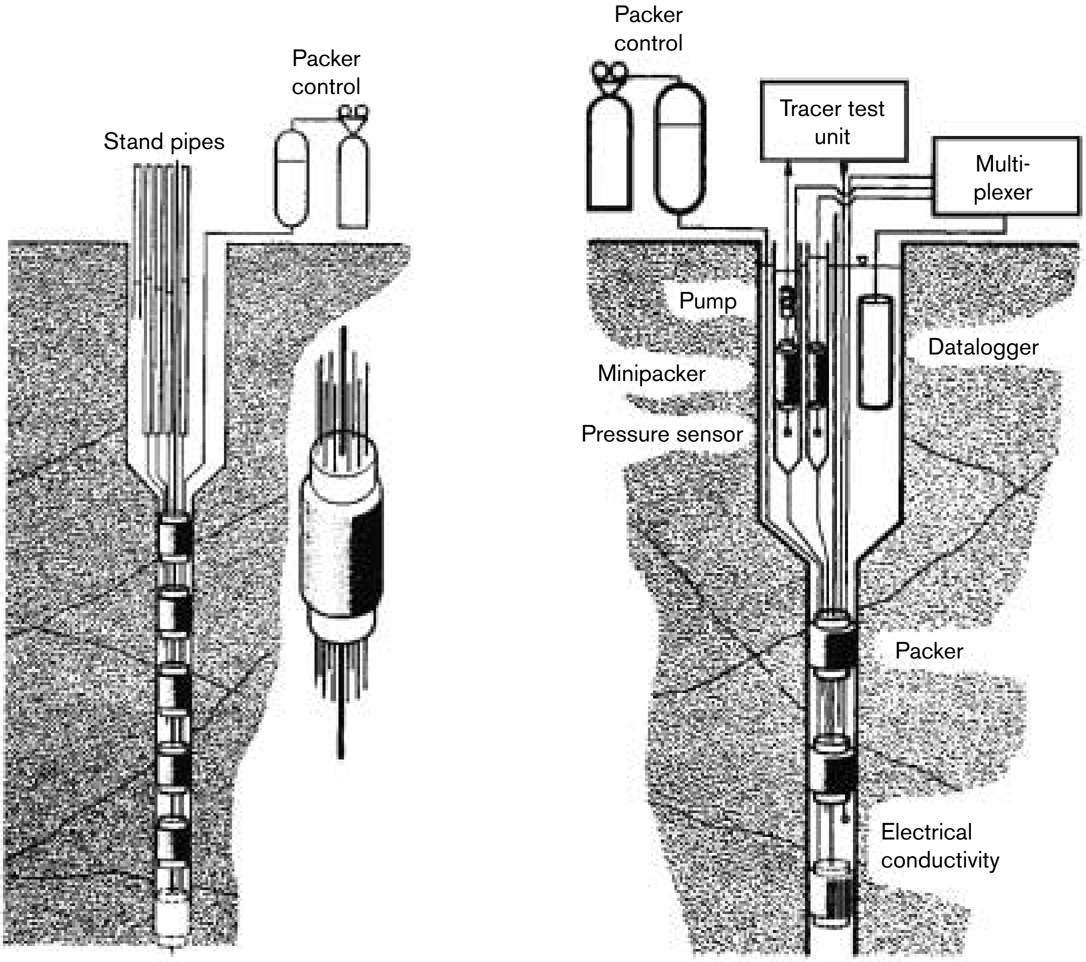


***Figure** 7-6. Groundwater monitoring.*

Table 7-7. Description of methods for hydrogeological monitoring.

Method	Information (parameter)	Comments/references
Hydrogeological monitoring		
Long-term monitoring of groundwater pressure • groundwater levels in open wells/boreholes in soil and surface rock • groundwater pressure in borehole sections (see also hydraulic interference tests)	**Groundwater variations in time and space** • natural conditions • groundwater level map • boundary conditions for groundwater modelling • calibration and verification of groundwater models	The Äspö HRL's monitoring methodologyis being evaluated and some modification may be made /Almén and Zellman, 1991; Almén et al, 1994; Rhén et al, 1997b/.
Long-term monitoring of groundwater flow • groundwater flow in borehole sections • (see also hydraulic interference tests)	**Groundwater flow variations in time and space** • natural conditions • calibration and verification of groundwater models	The Äspö technique used permits water sampling and groundwater flow measurement from isolated sections /Almén and Zellman, 1991; Almén et al, 1994/.
Analysis of groundwater fluctuations • tidal effect, correlation between borehole (sections) • barometer effect	**Interpretation basis** • orientation and connectivity of hydraulic features • properties in groundwater reservoir	Methods not yet applied, unclear about use in SI.

8 Hydrogeochemistry

8.1 General

This chapter describes hydrogeochemical characterization in site investigations. The programme describes why the hydrogeochemistry of the site is investigated and which chemical parameters are important for the construction and safety of a deep repository. Chapter 3 describes the execution of the investigation, covering the entire chain from collection of hydrochemistry data to chemical modelling. Section 8.3 provides an overview of the methods that are intended to be used for collection and evaluation of chemistry data.

8.1.1 Introduction

The purpose of the chemistry programme is to describe the chemistry of the groundwater in the deep repository volume with environs from a safety assessment perspective and collect the chemical data required for design of the deep repository. In addition, the chemistry programme contributes to an overall understanding of how the groundwater system behaves at repository depth. Hydrogeochemistry data – together with hydrogeology data – provide a description of the water flux within the area and its influence on the groundwater composition, as well as how it varies in the proposed repository volume.

In combination with groundwater flow, groundwater composition is of great importance for repository performance in both the short and long term. The interaction between the engineered barriers and the groundwater determines how long the spent nuclear fuel will remain isolated. Even in a situation when the isolation has been broken, the groundwater is of crucial importance for the dissolution and transport of radionuclides from the fuel.

The contents of dissolved oxygen in the water and the concentration of sulphide that can come into direct contact with the copper canister are of importance for copper corrosion. These substances corrode the canister in different ways. An attack of oxygen causes pitting, while sulphide corrosion is distributed evenly over the surface. Reducing conditions are therefore a requirement on the repository site.

For the buffer (bentonite), it is necessary that the groundwater contain a minimum concentration of dissolved salts. The presence of divalent cations is essential so that the bentonite will not form colloids. Very high salinities can eliminate the bentonite's swelling capacity and thereby disable its function as a diffusion barrier between the canister and the rock.

The pH and Eh of the water are important for radionuclide transport. Under reducing conditions, many of the most radiotoxic nuclides occur in a reduced form with very low solubility. Their solubility is lower at neutral pH than under acid and alkaline conditions. The normal state for the groundwater is a neutral pH and reducing conditions. The total salinity of the water influences the retention of weakly sorbing nuclides. The water's content of colloids and microbes is also of great importance for nuclide transport since they can act as carriers for the radionuclides /SR 97, Process Report, SKB, 1999b/.

The composition of the groundwater affects repository performance in different ways for the water that is present inside the repository, the water that flows into the repository and the water that flows out of the repository volume. *Water that flows into* the repository volume may carry dissolved oxygen or high salinities, which can affect the repository's isolating capacity. *Water present in* the repository volume can affect the stability of the bentonite buffer via high salinities. The salinity at repository depth also has a bearing on the total cost, since higher salinities require a higher proportion of bentonite in the backfill material. The composition of the *water that flows out of* the repository affects radionuclide transport.

The chemical composition of the groundwater is affected by physical and chemical processes. The physical processes that affect groundwater composition are diffusion and mixing. The effects of these processes are directly related to the flow of the groundwater in the fracture system in the rock.

The chemical processes that affect groundwater composition are reactions between substances dissolved in the water (solutes), leaching of substances in the fracture-filling and matrix minerals in the rock, precipitation on fracture surfaces, and the reactions that are affected by microbial activity /SR 97, Process Report, SKB, 1999b/.

The discipline of hydrogeochemistry can be divided into the following subareas: investigations of surface waters and near-surface groundwaters, downhole investigations, long-term measuring/monitoring, water and fracture-filling mineral analyses, and evaluation/modelling. Investigations of surface waters and near-surface groundwaters include sampling of water in lakes, seas, watercourses, springs, wells and soil pipes. Downhole investigations include investigations in percussion boreholes and in cored boreholes with respect to groundwater and fracture-filling minerals. The different drilling methods influence water chemistry sampling in different ways. The fracture-filling mineral analyses complement the picture of the groundwater's present and previous chemical conditions. Long-term measuring/monitoring is done as a recurrent follow-up in a selection of sampling points to follow up possible long-term changes in the water chemistry. Water analyses of different forms and scope comprise important tools for obtaining data that describe water composition. Processing of hydrogeochemical data results in both qualitative and quantitative models. These provide a basis for the hydrogeochemical description in the site-descriptive model, see Figure 2-4.

8.1.2 Discipline-specific goals

The requirements, preferences and criteria that have been identified for the discipline of hydrogeochemistry are presented by /Andersson et al, 2000/. With reference to the main goals of the geoscientific investigations (section 2.2), the hydrogeochemical work is mainly aimed at:

- characterizing the undisturbed hydrogeochemical conditions on the site and describing the origin and flux of the water in the rock, vertically and horisontally,
- obtaining specific data on parameters that are of importance for safety assessment and design, such as pH, Eh, sulphide, colloids and chloride,
- Identifying the possible occurrence of free dissolved oxygen in the groundwater at repository level.

Some of these parameters are of crucial importance in evaluation of whether the site is suitable for a deep repository.

Focus during the initial site investigation

After the initial site investigation, SKB shall have achieved an overall understanding of the site with respect to near-surface chemical conditions, chemical conditions down to a depth of 100–200 m, and the reactions that determine the chemical composition of the water. Different endmembers (see section 8.2) such as precipitation, sediment pore water, sea water and biogenously altered water will be identified and characterized. These endmembers serve as a starting point for subsequent mixing calculations.

A first version (version 1.1) of the hydrogeochemical description in the site-descriptive model is set up an early stage. The description is updated (version 1.2) after initial investigations are concluded.

Near-surface samplings are carried out on a regional scale to provide initial values for future evaluation of deep groundwaters. This is followed by groundwater investigations in percussion boreholes (approx. 0–200 m). The chemistry programme also needs chemistry-prioritized cored boreholes. Chemistry data from at least one deep cored borehole (1,000 m or deeper) comprise an important basis for confirming or dismissing the selected site. Furthermore, additional deep endmembers shall be identified and measurements requiring undisturbed conditions, such as redox status and turnover time, shall be performed.

Focus during the complete site investigation

After conclusion of the site investigation, SKB shall have achieved a broad hydrogeological and hydrogeochemical understanding of the site. This means knowledge of the water's composition, mixing proportions and residence time in different parts of the repository volume. SKB will have obtained data on the hydrochemical parameters that are used for assessment of the repository's long-term safety and the performance of the engineered barriers, as well as for design.

The hydrogeochemical description of the deep conditions and the spatial variation in conductive structures in the rock mass and in fracture zones is presented in different versions (2.1 to 2.X) and finalized when the site investigations are concluded.

The chemistry programme needs information from at least one more chemistry-prioritized cored borehole besides the hole drilled and characterized during the initial site investigation. In addition, samplings and analyses are done in conjunction with the interference pumping tests. If needed, the characterization of near-surface conditions is complemented by sampling in percussion boreholes and of surface waters.

8.1.3 Working methodology and coordination

Investigations and characterization are carried out stepwise (see section 2.3.1 and Chapter 3) and in collaboration with other disciplines. Figures 3-12, 3-20 and 3-29 in Chapter 3 show the work procedure and information needs for compiling the hydrogeochemical description.

Investigations of surface waters and near-surface groundwaters are closely linked to the programme for surface ecosystems. Sampling and analysis will be coordinated during execution. Mapping of principal rock types, fracture-filling minerals, fractures and fracture zones provides essential information that is coordinated with or taken from the geology programme. Hydraulic conductivity, pressure levels, electric conductivity and flow are important information that is provided by the hydrogeology programme. Choice of borehole sections is coordinated with the hydrogeology programme.

During the initial site investigation, the need for undisturbed groundwater samples takes top priority, and the hydrogeochemical investigations will have preference in at least one of the planned deep boreholes. Long-term monitoring is coordinated with the hydrogeology programme and the programme for surface ecosystems.

Choice of borehole for hydrogeochemical characterization is planned in the common borehole programme (see Chapter 11) and coordinated above all with the needs that arise in conjunction with the description of the rock's transport properties (Chapter 9).

8.2 Models and parameters

8.2.1 Structure of the models

The purpose of the hydrogeochemistry models is to describe the chemical conditions in and around the rock volume that encloses the repository. There are different aspects that need to be elucidated, and thereby varying needs for models and descriptions. It is essential for the long-term safety of the repository to know the value for the concentrations of certain substances now and in the future. Achieving this knowledge requires a good understanding of the conditions that have influenced these concentrations. Further, a distinction is made between qualitative (conceptual) models and quantitative (descriptive) models that permits calculations. An overall picture of the hydrogeochemical models is provided in Table 8-1.

Based on a given conceptual model, the descriptive model provides the prevailing conditions and identifies the most important processes that have contributed towards creating these conditions. The description is built up based on data collected within the investigated rock volume.

Figure 8-1 illustrates the adopted conceptual model that comprises the basis for the initial evaluation/modelling. The conceptual model will, however, be developed during the course of the work. The simplest model is a spatial distribution of the concentrations of the most important solutes in the rock volume. The salinity distribution, the individual main components Na, K, Ca, Mg, Cl, SO_4, HCO_3, and pH are the most common ones. It is also of great value to describe the stable and radioactive isotopes ^{2}H, ^{18}O, ^{34}S, ^{14}C, ^{13}C, ^{3}H and ^{87}Sr. In themselves, the distributions of the solute concentrations are in some cases indicative of ongoing processes. More information is obtained by statistical processing in so-called multivariate analysis, which provides a breakdown into different classes. The different classes represent water that has undergone a certain evolution. By comparing the different classes amongst themselves, it is possible to identify their different evolutionary pathways, regardless of where in the volume they occur. The origin for the different classes are named endmembers.

Table 8-1. Brief presentation of the structure and content of the hydrogeochemical models.

Hydrogeochemical description of the repository site

Purpose of model
Present and previous groundwater chemistry and geochemistry in the investigated rock volume. The descriptions apply to the conditions in the hydraulically conductive parts of the rock, i.e. fracture zones and single water-bearing fractures.

Process description
Physical: Waters of various types and origins are mixed due to flow conditions in the bedrock. Diffusive transport can also occur where the flow rate is low.

Constituents of the model

Geometric framework
The properties are distributed in the conductive structures in the investigated rock mass. The units are those that have been identified by the geology programme and verified in the hydrogeology and hydrogeochemistry investigations.

Parameters
The salinity distribution, the individual main components (Na, K, Ca, Mg, Cl, SO_4, HCO_3), stable and radioactive isotopes (^2H, ^{18}O, ^{34}S, ^{14}C, ^{13}C, ^3H and ^{87}Sr), redox-sensitive (trace) elements (Fe(II), Fe(III), Mn^{2+}, S(-II), U(IV)), organic material (e.g. fulvic and humic substances), colloid content and the variables pH and Eh. Determination of these parameters is done in accordance with standardized analysis classes, see section 8.3.

Data representation
Chemistry data that are evaluated given are primarily a one-dimensional distribution with depth. Interpolation tools and statistics are used for a three-dimensional distribution. Evaluation of processes is done with spatial distribution, or with time as a variable.

Boundary conditions
A hydrogeological understanding of current and historic water flow conditions comprises the most important basis for identifying flow and circulation systems. This is used to define endmembers.

Numerical tools
Geochemical equilibrium programs such as PHREEQE, WATEQ, NETPATH. Interpolation programs based on linear regression, kriging, neural networks.
Statistical multivariate programs combined with mixing calculations and mass balance calculations, M3.

Calculation results
Mixing proportions, equilibrium indices, equilibrium concentrations from which turnover times can be derived.

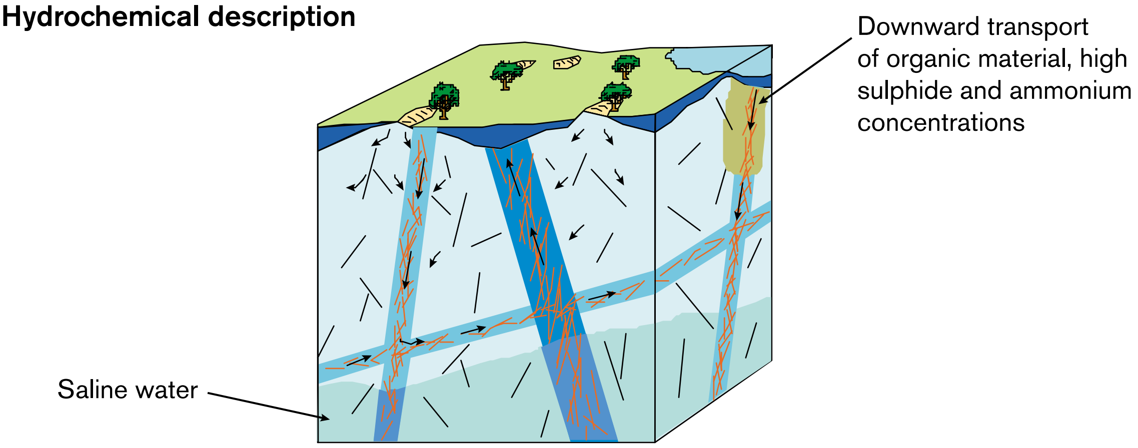


Figure 8-1. Example of conceptual model for hydrogeochemistry.

These endmembers comprise the basis for further calculations of reactions and mixing conditions. These calculations can include measurement data for e.g. the ten most important components /Laaksoharju et al, 1999/. The calculated mixing proportions and the actual measured composition comprise a basis for calculating the scope of chemical reactions in the groundwater/rock system. It is then assumed that a discrepancy in the concentration of one of the components is the result of a chemical reaction that has occurred or mixing of the water. It may be a question of dissolution or precipitation of different minerals or microbial processes that generate e.g. sulphide, carbonate, divalent iron, etc. Knowledge concerning the microbial processes has increased recently /Pedersen, 2000/. It has been found that these processes have a great influence on the hydrogeochemical evolution and thereby the hydrogeochemical interpretation.

The quantitative calculation tools can be utilized to calculate the effects of each individual process/reaction. For example, calcite dissolution/precipitation affects pH, carbonate concentration and calcium concentration. Since several processes interact and the dominant processes have varied during different periods, the models have a limited ability to clarify in what sequence and to what extent the different processes have dominated. What we see today is a result of various processes and reactions that have been proceeding to a varying extent for a long time.

The hydrogeological calculations of currently prevailing flow conditions are used as a basis for a qualitative interpretation of hydrochemical data /Laaksoharju and Wallin, 1997/. It is possible to see how the groundwater is flowing today and then ascertain e.g. the variation of the water chemistry with depth (in recharge areas) and what importance the most conductive structures have for mixing of different water volumes that may differ in terms of both origin and composition.

In the next phase the hydrochemical descriptions can be used to check the hydrogeological calculations. The prevailing groundwater chemistry provides a picture of what flow conditions probably existed previously. If the hydrogeological models are correct, they should also be able to describe the historical flow situation. Such a cross-check of models has been conducted within the framework of the joint international work being done in the Äspö Task Force for modelling of groundwater flow and transport of solutes, e.g. /Molinero, 2000/.

8.2.2 Parameters included in the descriptive model

A large number of parameters that can indicate origin and evolution are needed for an understanding of the hydrogeochemical processes and their importance for long-term safety. Certain components are of special importance for the safety assessment and the design work, since their concentrations have a direct influence on canister corrosion, bentonite function, fuel dissolution/solubility or radionuclide retention. The components are summarized in Table 8-2. The table is based on the tables compiled for the Parameter Report /Andersson et al, 1996/ and the revision that took place in conjunction with the work on requirements and criteria /Andersson et al, 2000/ and in conjunction with the preparation of the general investigation and evaluation programme /SKB, 2000b/. The table also shows when the parameter is primarily determined.

Table 8-2. Compilation of hydrogeochemical parameters included in the hydrogeochemical description. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Variables	pH, Eh		x	x	x	Transport model Canister corrosion Fuel dissolution, Bentonite
Main components	TDS (sum of main components), Na, K, Ca, Mg, HCO_3, SO_4, Cl, Si		x	x	x	Geoscientific understanding Design Canister corrosion Bentonite stability
Trace elements	Fe, Mn, U, Th, Ra, Al, Li, Cs, Sr, Ba, HS, I, Br, F, NO_3, NO_2, NH_4, HPO_4, REE, Cu, Zr, Rb		x	x	x	Geoscientific understanding Transport model Canister corrosion
Dissolved gases	N_2, H_2, CO_2, CH_4, Ar, He, C_xH_x, O_2		x	x	x	Geoscientific understanding Transport model
Stable Isotopes	^2H in H_2O, ^{18}O in H_2O and SO_4, ^{13}C in DIC and DOC, ^{34}S in SO_4 and HS, $^{87}Sr/^{86}Sr$, ^3He, ^4He, ^{11}B, ^{37}Cl, Xe-isotopes, Kr-isotopes		x	x	x	Geoscientific understanding Transport model
Radioactive Isotopes	T, ^{14}C in DIC and DOC, $^{234}U/^{238}U$, ^{36}Cl, Rn, ^{226}Ra		x		x	Geoscientific understanding Transport model
Other	DOC (Dissolved organic material), Humic acids, Fulvic acids, Colloids, Bacteria		x		x	Transport model Fuel dissolution
Fracture-filling minerals	Main and trace elements in solid phases, $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, $^{234}U/^{238}U$, morphology in calcite and iron oxides, ^{34}S in FeS, FeS_2			x	x	Geoscientific understanding Transport model
Rock matrix	Total salinity in pore water			x	x	Transport model

8.2.3 Modelling tools and planned analyses

Purpose

The primary purpose of the hydrogeochemical modelling is to describe the distribution of the groundwater composition in the entire rock volume, based on a limited number of water samples. In addition, calculations or qualitative analyses are performed to understand groundwater recharge, evolution, age and mixing. This information provides input for predictions of the long-term performance of engineered barriers and knowledge of chemical conditions that can influence construction and operation. The modelling also makes a contribution towards understanding the groundwater's flow conditions. It is particularly important to trace previously prevailing flow conditions, since they can be used to identify possible future conditions. The modelling sequence is described in general terms in Figure 8-2.

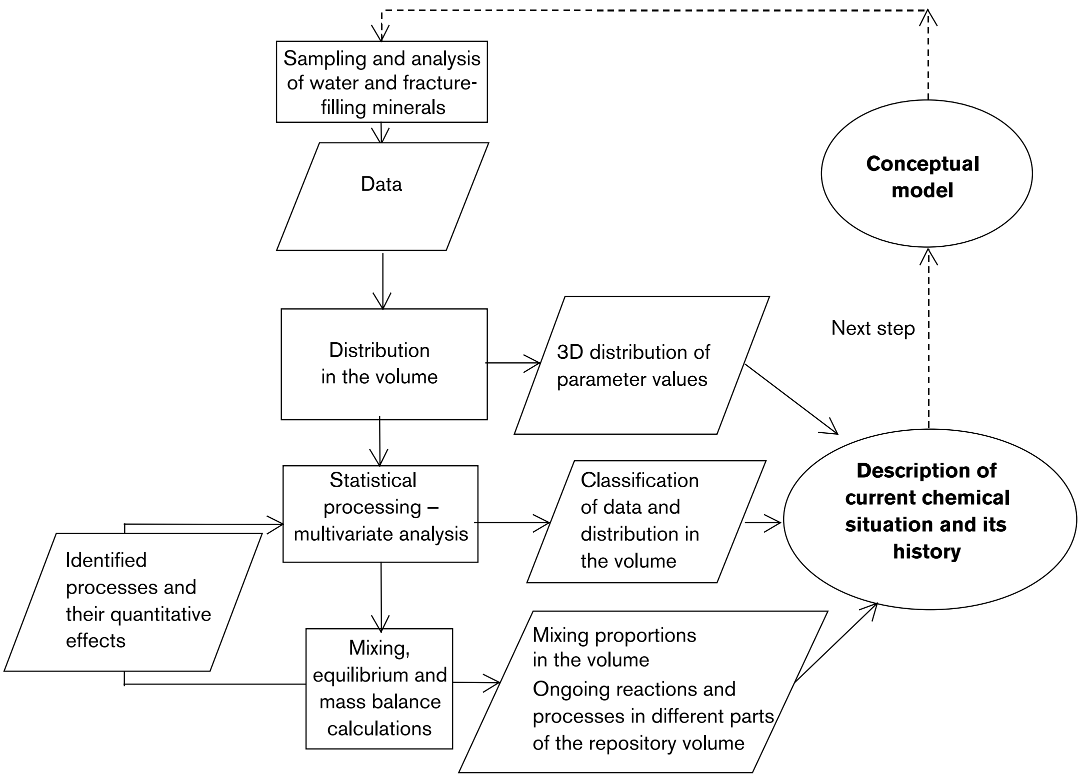


Figure 8-2. Data flow with evaluation methods and results (only hydrogeochemistry).

The modelling sequence described below is based on experience from the Äspö project. It will be similar at any other site. However, the content and scope of the different modelling steps will vary depending on the specific conditions on the site.

Premises

The hydrogeochemical investigations/evaluations are supposed to fill two different needs. One has to do with data on properties (=parameter values) that are used in calculations for assessment of the long-term safety of the repository. The other has to do with understanding of why the chemical conditions are what they are and how the chemistry will evolve in the future.

For the safety assessment, parameter values are needed for pH, Eh, colloids, fulvic and humic acids, other organic material, bacteria, nitrogen compounds, sulphide, sulphate, carbonate, phosphate and total salinity, including mainly cations. An idea of what values they assume at repository level and above and below the repository is enough. To fill this need, a few samples of absolute top quality are needed for analysis of these (sensitive) parameters. After the current parameter values have been established, the task is to predict, on good grounds, possible changes in the future. This requires a good understanding of what has influenced and created today's conditions.

To obtain knowledge about the origin and flux of the water, knowledge is needed of the spatial variability and the coupling with the hydrogeological measurements and interpretations. This means that a large number of measurement points are needed, but the quality of the samples does not have to be as high for this purpose. For example, water samples that are representative of the site where they are taken can be taken during

Table 8-3. Overview of parameters taken from other programmes.

Parameter	Determined within discipline-specific programmes
Hydrological mapping of lakes, watercourses, wells, springs	Hydrogeology
Indication of conductive sections in percussion and cored boreholes	Geology and hydrogeology (in conjunction with drilling)
Location, orientation and extent of fracture zones	Geology
Conductive fracture zones in different boreholes	Hydrogeology
Transmissivity of fracture zones and fractures	Hydrogeology
Absolute pressure in sampled borehole sections	Hydrogeology
BIPS logging and core mapping	Geology

drilling. The sampled water will then be strongly influenced by flushing water and drill cuttings, but can nevertheless be used to determine main components and isotopes that indicate the origin of the water. An important complement is obtained in conjunction with hydraulic interference pumping tests, where water representative of the most conductive structures can be sampled over an extended period. In this way an idea is obtained of the direction of the flow paths, i.e. towards which water type the tested conductor is headed.

To determine the hydrogeochemical parameters, input data (interpreted or measured) are needed from other discipline-specific programmes. Table 8-3 shows a compilation of parameters taken from other programmes.

An integration of the hydrogeochemical and hydrogeological descriptions is necessary. There are really no simple comparisons that permit an evaluation of the consistency of the two models. What is needed is a systematic comparison which presumes that data are available from all borehole sections in the rock. For the hydrogeochemical conditions, it is further necessary that data be taken at an early stage before possible disturbances have changed the original situation /Smellie and Laaksoharju, 1992/.

Methods

Processing of hydrogeochemical data results in both qualitative and quantitative interpretations. The qualitative interpretations are done to identify the essential processes that have influenced the groundwater chemistry. Knowledge of these processes is used to update the conceptual model and comprise a basis for subsequent calculations.

An example of a qualitative interpretation is the change in the carbonate-carbonic acid system with depth. In near-surface waters, the pH is low due to the fact that the water contains a great deal of dissolved carbon dioxide. The acidic carbon-dioxide-rich water reacts with minerals in the fractures further down in the rock, preferably with calcite. The effect is that the water's content of calcium and hydrogen carbonate increases as the pH rises. This can be deduced by correlating pH, carbonate concentration and calcium concentration with depth. Quantitatively, the extent to which the carbonate system is in equilibrium or not can be calculated at different points in time. The closer to equilibrium the system is, the more certain one can be that the water samples that have been analyzed really represent a groundwater system that is in balance. Since the calcite-carbonic acid system contains fast reactions, any departure from equilibrium is a sign of a natural or unnatural disturbance. From this point of view the calcite system is ideal and easier to describe than other hydrogeochemical processes, but the method is the same. Using simple or complex statistical correlation tools, it is possible to find correlations both between different dissolved components and between each component and depth. This can lead to the identification of chemical or biological processes that influence these parameter values. Then water mixtures, mass balances and equilibria can be calculated. Mixing proportions and the presence or absence of equilibrium can be utilized to predict future conditions based on the general assumption that the presence of equilibrium suggests that the system is chemically stable and will remain so until the groundwater conditions change significantly.

So-called typical waters are defined in order to ascertain the effects of mixtures and reactions. These typical waters have a given origin and a given chemical composition, see 8.2.1. Typical waters are locally defined, but are often similar on sites with similar histories. For example, precipitation in the form of rain and snow comprises a typical water, as does sea water. It is often easy to identify near-surface typical waters, while it is difficult to define deep typical waters. Extremely saline groundwater encountered at great depth is a typical water, even if its origin is unknown.

Tools

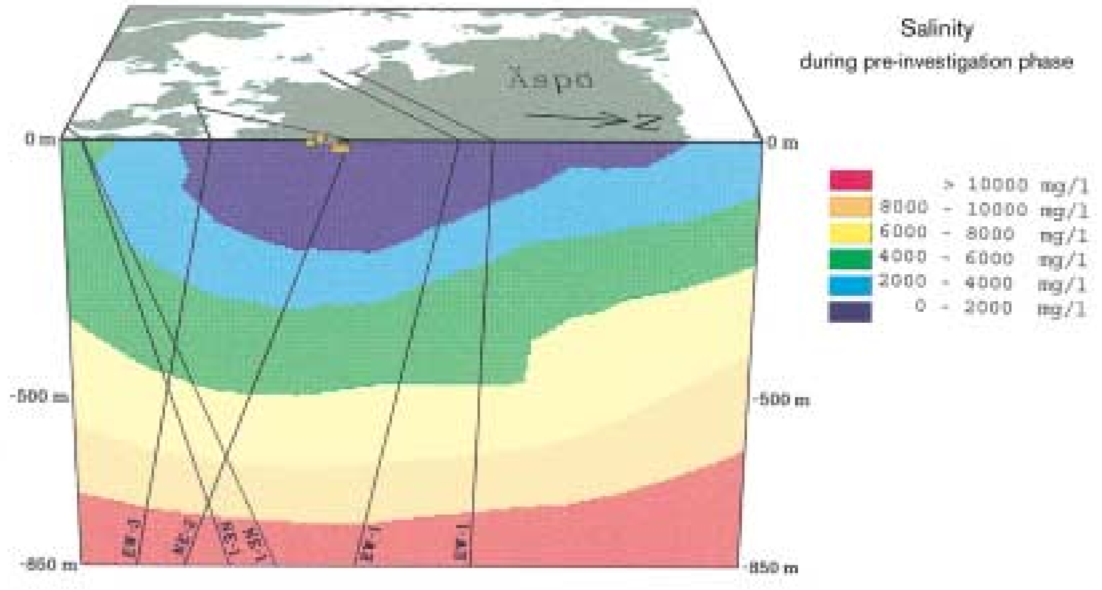
Combined interpolation and visualization is carried out with the software Voxel analyst. Figure 8-3 gives an example /SKB, 1998/. Interpolated figures of this type have uncertainties, but nevertheless offer a great opportunity to obtain information in a simple way on how the water chemistry is spatially distributed.

The calculations are carried out as equilibrium modelling and as reaction path modelling /Smellie and Laaksoharju, 1992/. Equilibrium modelling is done under the assumption that the system is steady-state and that complete equilibrium prevails in the entire system. Reliable codes used for equilibrium modelling are EQ 3, EQUIL, WATEQ, PHREEQE, and others. Reaction path modelling simulates transport where the water successively becomes equilibrated with different minerals. Useful reaction path codes are EQ 6, PHREEQEF and NETPATH. All the mentioned equilibrium codes and reaction path codes for calculations in water-mineral systems have their own thermodynamic database.

The M3 code, which handles all or many parameters simultaneously, is used to carry out simultaneous mixing and mass balance calculations to describe mixing conditions and mass balances. Calculations with M3 comprise an essential part of the modelling work, since it has been found that the chemical composition of the groundwater can to a great extent be described as the result of mixings where more than two water types are included /Laaksoharju, 1999/.

Desired result

The modelling results in a simple description of the classification and distribution of the different water types. There are uncertainties in the results, however. Part of the reason for this is the fact that it is difficult to determine how large a part of the observed mixing of different water types is in fact caused by disturbances from the investigations performed. Drilling causes the greatest disturbances. The first goal of hydrogeochemical modelling is therefore to identify and, if possible, correct for natural and artificial disturbances.



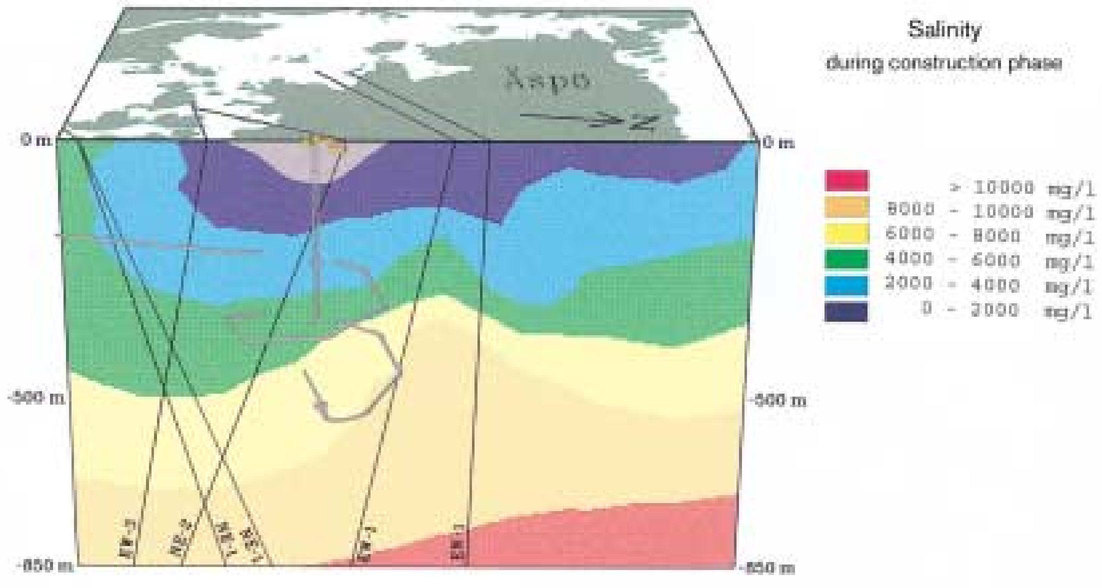


Figure 8-3. *Illustration of salinity distribution at Äspö done with visualization program Voxel analyst.*

The chemical composition of the water, in combination with various stable and radiogenic isotopes, provides information on the groundwater's turnover time. Different isotopes are suitable for identifying different processes. A combination of a large number of different isotope determinations therefore provides the best picture. Time series of selected high-quality data from different points facilitates interpretation and reduces the uncertainties (possible explanations for measurement data).

Aside from the general understanding of today's chemical conditions on the site or in the area, quantitative knowledge is obtained regarding:

- electrochemical parameters such as pH and Eh,
- main components that directly influence the engineered barriers,
- trace elements that indicate redox conditions,
- stable and radioactive isotopes that provide an indication of the water's turnover time,
- colloids, bacteria and organic substances,
- gas content and composition.

With knowledge of which chemical processes influence these conditions, it is possible to predict the short- and long-term evolution of a site for construction of a deep repository.

8.3 Characterization methods

The different methods for collecting hydrogeochemical data can be divided into the following three categories:

- Methods for water sampling and analysis including: surface waters, sediment pore water, wells, soil pipes, percussion boreholes, water sampling during core drilling (cored boreholes), hydrochemical logging (cored boreholes), water sampling during pumping tests (cored boreholes), and long-term monitoring of chemical parameters (different types of sampling objects).
- Fracture-filling mineral analysis.
- Evaluation methods.

All methods are described in brief in the following sections. For more thorough and detailed information, the reader is referred to the method descriptions that will be prepared. Experience from previous similar investigations on Äspö has been reported in /Almén et al, 1994/.

How drilling activities are carried out is of great importance for the reliability of the hydrogeochemical investigations. Of particular importance is flushing water management, washing of downhole equipment, and selection/handling of chemical products such as fuels, lubricants, etc. These aspects are dealt with in the drilling programme, Chapter 11.

In practice it is difficult to sample groundwater that is unaffected by disturbances. The reason is that the measures that are required to drill in and investigate the bedrock have a great impact on the groundwater. It is possible to distinguish between chemical and hydrological disturbances. Chemical disturbances are caused primarily by the drilling process itself. Drill cuttings, i.e. the fine rock chips formed by drilling, react with the water and affect the solutes and particle-bound material. Waste products such as oil, metal fragments and other materials also occur sporadically and affect substances and parameters that are important for assessment of long-term safety. The chemical disturbances can be reduced by means of extensive pumping. It is thereby possible to obtain a good idea of the composition of the chemically undisturbed water, but at the price of more extensive mixing. The hydrological disturbances are caused by drilling, downhole investigations and internal water flow in the borehole. The flushing water that is used during drilling can be tagged to permit correction of the results obtained from sampling during drilling. These are then the least hydrologically disturbed, but the most chemically disturbed results, see /Smellie et al, 1999/. Sampling on all other occasions results in greater hydrological disturbance.

8.3.1 Chemistry classes

SKB has defined different chemistry classes for water sampling and analysis, see Table 8-4.

Table 8-4. Description of SKB's chemistry classes for water sampling and analysis.

Class	Description
Class 1:	**Simple sampling for verification of temporal stability** – Electrical conductivity, pH, uranine*, temperature
Class 2:	**Simple sampling for type classification** – Electrical conductivity, pH, Cl, HCO_3, uranine*, temperature **Options: a, b** – a = Archiving of frozen samples – b = δ^2H, ^3H, $\delta^{18}O$
Class 3:	**Simple sampling for determination of main components (not redox)** – Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, uranine*, temperature, cations (except Fe, Mn)** and SO_4 analyzed as sulphur with ICP-AES **Options: a, b, c, d** – a = Archiving of frozen samples – b = δ^2H, ^3H, $\delta^{18}O$ – c = $\delta^{34}S$ (in SO_4), $\delta^{37}Cl$, $\delta^{87}Sr$, $\delta^{10}B$ – d = ^{14}C pmc (percent modern carbon), $\delta^{13}C$ per mill PDB (deviation from standard Peedee Belemnite)
Class 4:	**Extensive sampling for complete chemical characterization** – Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, uranine*, temperature, DOC, cations** and SO_4 analyzed as sulphur with ICP-AES, δ^2H, ^3H, $\delta^{18}O$ – HS^-, NH_4 – Archiving of acidified and unpreserved frozen samples **Options: e** – e = NO_2, NO_3 and/or NO_2+NO_3, PO_4, F^-, I^-
Class 5:	**Extensive sampling for complete chemical characterization including special analyses** – Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, uranine*, temperature, DOC, cations** and SO_4 analyzed as sulphur with ICP-AES – ^2H, ^3H, ^{18}O – F^-, I^- – HS^-, NH_4, NO_2, NO_3 and/or NO_2+NO_3, PO_4 – Archiving of acidified and unpreserved frozen samples **Options: c, d, f, g, h, i, j, k, l, m** – c = Isotopes $\delta^{34}S$ (i SO_4), $\delta^{37}Cl$, $\delta^{87}Sr$, $\delta^{10}B$ – d = ^{14}C pmc (percent modern carbon), $\delta^{13}C$ per mill PDB (deviation from standard, Peedee Belemnite) – f = Isotopes ^{226}Ra, ^{228}Ra and ^{222} Rn – g = U and Th isotopes – h = trace metals (ICP-MS, AAS and/or INAA) – i = Dissolved gas (including $\delta^{18}O$, $\delta^{13}C$, $^3He/^4He$), bacteria – j = Colloids – k = Humic and fulvic acids – l = pH and Eh measurements on-line

* Determined only when uranine is used as a marker for drilling water (flushing water).

** Cations: Na, K, Ca, Mg, Fe, Mn, Li, Sr + Si.

*** Trace metals: U, Th, lanthanoids, heavy metals or own choice.

8.3.2 Sampling of surface waters and precipitation

Purpose

Chemistry data from surface waters and precipitation comprise a subset of the data that are needed to describe the water flux in an area and its influence on the groundwater composition. These data are needed as initial values and boundary conditions in model calculations. In the initial phase of the site investigations, sampling campaigns are conducted where all types of surface waters are included to create an overall picture of the surface water systems in the area before the drilling activities become too extensive.

Premises

The sampling activities need to be started early before the area has been affected by other activities such as e.g. roadbuilding and drilling. Sampling of surface waters shall, where appropriate, be carried out at the same time as sampling of soil pipes, wells and percussion boreholes. Since surface water composition is strongly time-dependent, it is important that the points be sampled on the same occasions in order to create an overall picture of the area.

If possible, meteorological and hydrogeological information should also be collected on the same occasions and from the same points.

Equipment and execution

Sampling of surface waters does not as a rule require special equipment aside from Ruthner samplers for lake and sea water and standard meteorological equipment for collection of precipitation samples.

In the first survey sampling, samples are collected from many and different types of sampling points within an area during a short, uninterrupted period of time. The sampling objects comprise waters in lakes, seas, springs and watercourses.

Repeated samplings are performed preliminarily approximately six times per year during a two-year period to obtain information on the size of the natural variations. The sampling objects include precipitation as well as lake water, sea water and springs.

Results

Analyzed parameters for precipitation and surface watercourses correspond to class 3, while springs and sea water samples are analyzed as per class 5. In its entirety, the method results in a chemical overview of the surface waters in the area, including a rough check of the size of the natural variations.

8.3.3 Sampling of sediment pore water

Purpose

Sampling of sediment pore water is done to characterize the water that has been transported through sediment layers and therefore contains high concentrations of waste products from organic decomposition.

Premises

The single sampling is preceded by a survey of the sea or lake bottom by taking a number of sediment plugs or "scoop samples" spread over the area and possibly from different depths. The purpose is to find one or more representative sampling points.

The sampling is coordinated with the biosphere programme. This includes both samples of sediment pore water and material for analysis of the solid phase. There should also be cooperation with the geology and hydrogeology programmes.

Equipment and execution

Special samplers are used to take samples in the form of sediment plugs. There are several different types available, for example the one used at Äspö /Landström et al, 1994/ and Finnish sediment samplers such as Niemistö or Gemini.

Sampling of sediment pore water is done in the form of single sampling in several sampling points and in the form of repeated sampling in one or two of these points approximately four times a year during a two-year period, in order to determine the size of the natural variations.

Results

Analysis scope and methods must be adapted to the limited volume of pore water available. An aim is that the scope of the analysis should correspond to class 5.

8.3.4 Sampling of wells

Purpose

Sampling of wells is done to obtain a comprehensive picture of different types of near-surface groundwaters. Chemistry data from near-surface groundwaters are needed for the description of the groundwater system as a whole.

Premises

Sampling of wells shall be carried out on the same occasions as sampling of surface waters, soil pipes and percussion boreholes.

In conjunction with sampling, groundwater measurements within the hydrogeology programme are done. Drinking water quality may also be analyzed.

Equipment and execution

Sampling of wells does not require any special equipment. Some of the wells (around three) are chosen to determine the size of the natural variations. They are sampled preliminarily approximately six times per year during a two-year period.

Results

The method provides well water data as per class 3 and complements the chemical overview of near-surface groundwaters.

8.3.5 Sampling in soil pipes

Purpose

The purpose of sampling in soil pipes is to identify discharge areas and to provide data for an improved understanding of the processes that take place in the interface between the geosphere and the surface ecosystem. The method can be used to obtain a general description of the chemistry in near-surface groundwaters on soil-covered sites.

Premises

The sampling in soil pipes is done on the same occasions as sampling of surface waters, wells and percussion boreholes.

Equipment and execution

The equipment in the form of PEH pipes (bottom plug, filter pipe and extension pipe) is installed in ground holes that can be drilled with the aid of an auger, for example. Hoods are fitted in the pipes to prevent rainwater, debris and suchlike from getting in. The water level in the pipes is measured and water is collected with a water collector and immediately filtered on the site. Certain soil pipes are chosen for repeated sampling in order to determine the size of the natural variations. Sampling is done preliminarily approximately six times per year during a two-year period.

Results

The method provides data as per class 5 plus variations in the groundwater level and augments the chemical overview of near-surface groundwaters.

8.3.6 Sampling in percussion boreholes

Purpose

The purpose of sampling of percussion boreholes is to provide groundwater data for the area down to a depth of approximately 200 metres.

Premises

Conductive fracture zones are identified with the aid of drilling rate data during drilling.

An initial early sampling shall be done in each percussion borehole as soon as possible after drilling and possibly before measurement of hydraulic parameters.

Repeated samplings to determine any natural variations in the percussion boreholes shall be done on the same occasions as sampling of surface waters, wells and soil pipes.

Equipment and execution

There are several equipment options for sampling of groundwater in percussion boreholes. One type of equipment used previously in percussion boreholes is described in /Laaksoharju and Nilsson, 1989/ and in /Laaksoharju et al, 1995a/. A system based on a commercially available pump and a single or double packer will be developed.

Sampling is done in a section that is sealed off by double packers or from a packer to the bottom of the borehole. The section length is varied depending on the extent of the water-bearing fracture zones.

Flows, times and pressures in the section are recorded continuously during pumping. The pumping rate is adjusted to the water flow rate in the chosen borehole section.

Early samples are taken immediately after drilling before the groundwater has become too affected by the borehole's short-circuiting effect. Two or three samples are taken. The first sample is taken immediately after installation of the sampling equipment. The second and third samples are taken after the system's volume has been turned over three and/or five times. The system's volume consists of the section volume plus the volume of the hose.

Repeated samplings are done in a few of the boreholes to detect any natural variations. The repeated samplings in the percussion boreholes may also be done with the aid of permanently installed packers and pumps.

Results

The method provides hydrochemical data as per class 3 and class 5 down to a depth of approximately 200 metres. The results include most options.

8.3.7 Sampling during core drilling

Purpose

The purpose of sampling during core drilling is to get an early picture of the water composition in the borehole /Smellie and Laaksoharju, 1992/. One advantage of early sampling during ongoing drilling is that the groundwater is less affected by the borehole's short-circuiting effect than on later sampling occasions. The water samples correspond to existing water in the borehole section in question or in the immediate vicinity, and often with considerable flushing water contamination. Flushing water concentrations of between 5% and 50% in the samples can be expected. The concentrations of the dominant main components can be corrected for by deducting the flushing water portion.

Premises

Cored boreholes are divided into chemistry-prioritized cored boreholes and other cored boreholes, see Chapter 11 in the drilling programme. Chemistry-prioritized boreholes are percussion-drilled for about a hundred metres, after which core drilling is done using the wireline technique. Percussion drilling is used to reduce flushing water contamination in permeable soil layers and near-surface rock. The sampling technique for chemistry samples differs depending on drilling method.

The samplings are done when major water-bearing fracture zones are penetrated or when drilling has progressed 100 metres without indications of water. Indications of water-bearing fracture zones are given by such flushing water or drilling parameters as:

- flushing water loss or pressure drop in the flushing water,
- increased drilling rate,
- increased fracture frequency in the drill core.

Sampling and analysis of the flushing water that is pumped down into the borehole and the return water that comes up via airlift pumping is necessary information for making a water budget and calculating flushing water contamination of the samples.

Hydrotests within the hydrogeology programme are conducted in conjunction with water sampling with a wireline probe.

Equipment and execution

During the initial percussion drilling in chemistry-prioritized cored boreholes, water samples are taken up on the ground surface with the aid of standard equipment consisting of pump and packer.

During core drilling the samples are taken down in the borehole section with a special water sampler developed for wireline drilling. The sampling section is sealed off at the top by a packer and at the bottom by the bottom of the borehole. The section length can be varied depending on the extent of the water-bearing zone. Sampling is done when the water in the section has turned over three times (may be changed depending on experience from ongoing tests).

During core drilling, a separate programme is also carried out for chemical checking of incoming water to the flushing water tank, flushing water and return water. The programme includes regular sampling and analysis of water composition in incoming water to flushing water tank as per class 5, including isotopes and background fluorescence. After uranine addition and air purging with nitrogen, the uranine and oxygen concentrations in the flushing water are checked. Regular measurements of electrical conductivity and uranine concentration are done in the return water.

Results

The method provides an early hydrogeochemical overview. The sampled water represents sections of rock mass and hydraulic structures. The results in the form of analysis data are:

- Water composition (main components as per class 3) in a number of the major water-bearing fracture zones in the cored borehole during drilling.
- Corrected values of the water composition where the effect of flushing water contamination has been adjusted for.
- Isotope data and isotope ratios as per class 3 to the extent permitted by the limited sample volume.

The separate programme for chemical checking of flushing and return water during drilling provides:

- Chemical composition and background fluorescence in incoming water to flushing water tank.
- Check of oxygen and uranine concentrations in flushing water before use.
- Concentration of flushing water in return water and its electrical conductivity.
- Calculated water budget based on used volume of flushing water and pumped-out volume of return water and its flushing water content.

8.3.8 Hydrochemical logging

Purpose

The purpose of hydrochemical logging is to get a quick overview of the water composition along the borehole and detect any concentration anomalies, /Laaksoharju et al, 1995b/ and /Laaksoharju, 1999/. The logging entails sampling of the existing water column in the borehole under "open hole" conditions. The hydrochemical logging is as a rule done immediately after core drilling and thereby before the borehole has become equilibrated after drilling. In some boreholes (primarily the chemistry-prioritized ones), the logging is repeated on a later occasion, partly to sample under stable conditions and partly to get an idea of how great the changes are.

Premises

After completed drilling and possible subsequent airlift pumping, hose sampling is performed before other borehole logging.

Equipment and execution

Sampling takes place with a hose sampler, which consists of polyamide hose in lengths of 50 metres (o.d. = 10 mm). Each hose section has a valve and a coupling at both ends. At the bottom of the hose string is a check valve. The total depth is determined by the number of hose units. Previous samplings have taken place at depths down to 1,700 m.

Hose section after hose section is lowered into the borehole. It is important that execution can take place without stirring up the water in the borehole too much. Each new unit is connected to the preceding one with the intermediate valve open. When the hose string has reached the desired depth and filled with borehole water, retrieval begins. The hose sections are lifted one by one, the valves are closed, and the units are disconnected. Each hose unit holds 2.5 litres of water.

Normally, one hose section per 100 metres is used for analysis and the other is saved as a reserve sample. The analyses are performed as per class 3 with the options permitted by the limited water volume in the sampler. The analyses can be densified in certain sections. It is also possible to use two hose units for a complete class 3 analysis with all options.

Results

The method yields data as per class 3 with all options included and provides an early hydrochemical overview along the entire cored borehole under "open hole" conditions. It thereby provides an opportunity to identify the interface with saline groundwater.

8.3.9 Complete chemistry characterization with mobile field laboratory

Purpose

The purpose of the method "Complete chemistry characterization with mobile field laboratory" is to obtain as complete a picture as possible of the groundwater chemistry in individual fractures and local minor fracture zones. The method is by far the most important of the chemistry investigations performed in cored boreholes. Great efforts are made to obtain representative samples from a limited rock volume. Cautious pumping with continuous monitoring or the pressure in, below and above the section will minimize the risk of mixing with water from other fracture systems.

Premises

The method is used primarily in chemistry-prioritized cored boreholes where the drilling must be executed in accordance with strict requirements and where only a few investigations may be carried out prior to the chemistry sampling, see Chapter 3 and Chapter 11.

Chemistry characterization must begin within a month of the completion of drilling. The flushing water content must be kept to a level below one percent in order for the results to be considered reliable. This is normally achieved after one week of pumping in the section.

The sections and the section lengths are chosen in cooperation with the discipline of hydrogeology, since it is important that hydrogeology data and hydrogeochemistry data be obtained from exactly the same sections in the boreholes. Information from methods in the disciplines of geology and hydrogeology is needed to select the borehole sections to be investigated (approximately five sections per borehole). The decision-making steps are as follows:

1. A preliminary identification of all water-bearing fracture zones of interest is done on the basis of information from the drilling stage, BIPS imaging, flow logging and geophysics logging of temperature and electrical conductivity.
2. The investigation starts in one of the identified fracture zones. The fracture zone judged to have the greatest risk of being contaminated with borehole water is prioritized.
3. Evaluation of the data from the aforementioned methods continues during ongoing investigation.
4. A final choice of the borehole sections to be investigated is made on the basis of the continued evaluation. Criteria for this choice are: water budget calculations, depth, suitable mineralogy, and covering hydraulic and hydrochemical variation.

Equipment and execution

A mobile field laboratory consisting of a hose cart for handling borehole equipment and a laboratory cart for sample handling and analyses is used for full chemical characterization /Almén et al, 1987; Axelsen et al, 1986; Almén et al, 1994/. In addition to a comprehensive analysis programme, the chemistry characterization includes measuring parameters in situ in borehole sections (Eh, pH and temperature) and on pumped-up water in a flow cell on the ground surface (electrical conductivity, dissolved oxygen, Eh, pH, temperature and flow). The pumped-up water is conducted into the laboratory cart, where samples are taken for own analyses and for analyses performed by outside laboratories.

The pumping takes place with a flow of between 60 and 300 ml per minute and is done in packer-sealed sections with a hydraulic conductivity of between $K=10^{-8}$ m/s and $K=10^{-6}$ m/s. The section lengths are generally on the order of 2 to 15 metres. The smallest possible length is 0.5 metre.

The course of events in a chemical characterization in a water-bearing borehole section is as follows:

- Water is pumped up to the surface with simultaneous measurement of pH, Eh, electrical conductivity, dissolved oxygen, temperature and flow. Changes in the water composition are followed via recorded measurement values (conductivity) and/or regularly taken and analyzed samples as per class 2.
- When the conductivity has stabilized, water samples are taken regularly for analysis as per classes 4 and 5. Pumping and measurement in the borehole section take place continuously and, if possible, until the redox potential (Eh) has stabilized at a reasonable level. This normally takes somewhere between two and four weeks.
- At the end of the measurement sequence, before switching to a new borehole section, a sampling as per class 5 is done. In this phase the sampling unit is activated down in the borehole section for extraction of a pressurized sample. The sample may be divided into two or more containers and is analyzed with respect to gas and bacteria content /Pedersen, 1997a/. Colloid sampling can also take place under pressure in the section, depending on which equipment set-up is used. The final class 5 sampling in the section includes sampling for determination of humic and fulvic acids and possibly also colloids in the event this is not done in situ in the borehole section /Laaksoharju et al, 1994; Laaksoharju et al, 1995c; Ledin et al, 1995/.
- The hydrogeochemical sampling should be checked by geophysical logging of salinity before and after the chemical sampling in order to get an idea of the stirring caused by the sampling procedure and thereby the representativeness of the samples for a given borehole depth.

The analysis programme is adjusted depending on earlier results from water sampling during drilling and hose sampling. For example, sampling may be densified or expanded in sections situated at concentration anomalies or to verify unexpected results.

Results

The method provides complete sets of analysis data as per classes 4 and 5 including gas, bacteria, colloids, fulvic and humic acids and measurement values of pH and Eh, electrical conductivity, dissolved oxygen, and water temperature. The data represent the hydrogeochemical situation in single fractures and limited fracture zones.

8.3.10 Sampling during pumping tests

Purpose

The purpose of the method "Sampling during pumping tests" is primarily to augment and densify the quantity of chemistry data from cored boreholes by performing sampling at the same time as pumping tests within the discipline of hydrogeology. The augmentation and densification is done in part to cover a greater number of and more highly conductive fracture zones in already investigated chemistry-prioritized boreholes (in the form of complete chemistry characterization) and in part to cover more cored boreholes (including non-chemistry-prioritized ones) spread over a larger area. The water samples taken represent water from a larger rock mass and/or a more dominant hydraulic structure than the samples taken in complete chemistry characterization.

Premises

Sampling is carried out in cooperation with the discipline of hydrogeology in single-hole pumping tests and interference tests where K > 10^{-6} m/s.

Flushing water does not constitute a problem, since pumping is performed with such a high flow that contamination is reduced and becomes negligible very quickly.

Equipment and execution

The mobile field laboratory's laboratory unit is used for sampling, together with hydrogeological equipment. The hydrogeological equipment is utilized for the actual pumping.

Pumping is done with a flow on the order of tens of litres per minute, i.e. the pumping capacity is considerably higher than in complete chemistry characterization. Sampling is carried out in borehole sections with a high hydraulic conductivity (K > 10^{-6} m/s) and the section lengths are normally slightly longer than in the chemistry campaigns. Pumping and recovery take place in intervals that are controlled by the discipline programme for hydrogeology.

On-line measurement of pH, electrical conductivity, redox potential (Eh), dissolved oxygen, and temperature take place in the field laboratory. The measurements are only done on the ground surface and non in situ in the borehole section. Water samples for daily analyses are taken in the same way as in complete chemical characterization, i.e. as per class 4 and class 5, but gas and bacteria sampling as well as colloid sampling will not be included. The high flow provides good opportunities for humic and fulvic acid sampling, however. The concentrations of these components are often very low, and since large water volumes can pass the sampling columns there are greater opportunities to obtain sufficient quantities for analysis.

Results

The method provides large sets of analysis data as per classes 4 and 5 as well as the parameters pH, Eh, electrical conductivity and dissolved oxygen measured on the ground surface. Options such as gas, bacteria and colloids will be absent. The data represent a chemical characterization of a large rock mass or dominant hydraulic structures.

8.3.11 Long-term monitoring of chemical parameters

Purpose

Long-term monitoring entails recurrent follow-up of the water composition in a number of observation points consisting of wells, soil pipes, percussion boreholes and sections in cored boreholes. The purpose is above all to see if and how the activities during the site investigation phase affect the groundwater composition. Each execution step identifies a number of observation points as suitable for this continuous follow-up, and the number of observation points will increase progressively.

Premises

Observation points are chosen in cooperation with the discipline of hydrogeology. Automatic and continuous recording of electrical conductivity and groundwater level should take place in the observation points consisting of boreholes.

Execution

Long-term monitoring is carried out in semi-annual campaigns. All types of sampling objects are sampled simultaneously during a short, uninterrupted period of time.

Sampling of the boreholes included in the programme is described in section 7.4.3. The analyses are performed as per class 3.

Some of the percussion boreholes will be equipped with permanent packer installations that can be utilized for sampling. Otherwise, equipment as described in 7.4.5. is used. The analyses are performed as per class 5.

Permanent installations of packers etc are done in the cored boreholes for long-term measurements of pressure and for sampling within the long-term monitoring programme. At least two borehole sections from each borehole will be included in long-term monitoring. The analyses are performed as per class 5.

Results

The method provides time series of analysis data as per class 3 and class 5 and comprises a basis for assessment of chemical stability.

8.3.12 Water analysis as per chemistry classes 1 to 5

Premises

The methods for water analysis that are used at SKB's hydrochemical analysis laboratory in the mobile field laboratories must meet the requirements for accreditation by Swedac. Where possible, engaged external laboratories will also be accredited for the analyses to be performed.

Analysis methods and execution

All samples are analyzed in accordance with established procedures and SKB's classification into five different chemistry classes, see Table 8-4. The analyses that must be done immediately take place in a mobile field laboratory, while other analyses are performed in the chemistry laboratory on Äspö or by external laboratories. Well-established analysis methods are used to determine the various parameters in most cases. Many parameters are analyzed by more than one method and/or by more than one laboratory. Several of the determinations are carried out by means of special analyses that require sophisticated equipment and special qualifications and are performed by very specialized laboratories. The methods that will be used may vary or be changed depending on various circumstances or method development. Table 8-5 lists the most commonly used analysis methods.

Table 8-5. Components/parameters and analysis methods.

Components/parameters	Methods
pH	Potentiometry
Electrical conductivity	–
Cl, HCO_3	Titration (SIS 028120, SIS 028135)
Na, K, Ca, Mg, S, Mn, Fe, Si, Li, Sr	ICP-AES
SO_4, Cl*, Br, F	Ion chromatography
Fe (tot), Fe(+II), HS^-, NH_4_N, NO3_N, PO4_P	Spectrophotometry (Ferrozine method and SIS methods)
DOC	UV oxidation, IR
^3H	Natural decay
^2H, ^{18}O	MS
PMC, ^{13}C	Accelerator measurements
U, Th, Ra and Rn isotopes	Chemical separation, Alpha and/or Gamma spectrometry
Isotopes $\delta^{34}S$ (i SO_4), $\delta^{37}Cl$, $\delta^{87}Sr$, $\delta^{10}B$	
Trace metals	ICP-MS (high-resolution) and/or INAA
Gas (specially developed sampling technique with pressurized samples)	Gas chromatography
Humic and fulvic acids (specially developed sampling technique)	/Pettersson et al, 1990/
Colloids (specially developed sampling technique)	Analysis of filters with EDXRF
Bacteria (specially developed sampling technique with pressurized samples)	Counting, classification

* At chloride concentrations < 10 mg/l

Abbreviations and explanations

ICP-AES	Inductively Coupled Plasma Atomic Emission Spectroscopy
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
DOC	Dissolved Organic Carbon (filtered sample)
IR	Infrared Spectroscopy
MS	Mass Spectroscopy
INAA	Instrumental Neutron Activation Analysis
EDXRF	Energy Dispersive X-Ray Fluorescence

Quality control

The analysis results are quality-checked in their entirety with respect to reasonableness, comparison between different analysis methods and ion balance. The quality check is done in conjunction with entry of data in the SICADA database and subsequent reporting. When samples are taken, reserve samples are as a rule set aside for use in check analyses.

8.3.13 Fracture-filling mineral analysis

Purpose

Fracture-filling mineral analyses complement the picture of current and former chemical conditions in the groundwater /Landström and Tullborg, 1995/. The presence or absence of calcite mineral shows, for example, whether infiltration of surface water has been substantial or not. Presence of iron hydroxides in combination with absence of pyrite shows how far down an oxidizing water may have reached. Isotope analyses of fracture-filling mineral show currently or previously prevailing groundwater flow patterns. Some isotope ratios, such as $^{234/238}U$ and $^{87/86}Sr$, can be determined both in aqueous solution and in minerals. Similarities and dissimilarities are used to identify the degree of equilibrium and/or stability in today's groundwater mineral system.

Premises

Since chemistry-prioritized cored boreholes are percussion-drilled to a depth of approximately 100 metres, supplementary short cored boreholes may be needed near these boreholes in order to get a core for core mapping and fracture-filling mineral analyses from comparable sections of the rock volume.

The core mapping done by the geology programme comprises a basis for the fracture-filling mineral analysis and subsequent sampling of drill cores.

Execution

Analyses of fracture-filling minerals include detailed studies of the minerals that comprise the largest contact surface with the water and/or can provide essential information on the hydrogeochemical environment in the fractures. Three mineral groups emerge as being particularly interesting based on previous experience /Tullborg, 1997/:

- Minerals that are readily dissolved or precipitated in the fractures and are therefore often in equilibrium with the groundwater composition. This group consists primarily of carbonates (mainly calcite), sulphate minerals (for example gypsum and baryte) and fluorites (fluorspar).
- Minerals formed by weathering and alteration in situ, above all clay minerals of various types.
- Minerals controlled by redox processes, especially Fe(II)/Fe(III) minerals and sulphides.

The analyses are performed to identify the minerals and to determine their chemical composition. The analysis programme includes main components and trace elements (including U, Th, REEs, Sr and Cs) as well as Mössbauer analyses for determination of Fe(II)/Fe(III).

Calcites and sulphides are analyzed with respect to stable isotopes ($\delta^{18}O$, $\delta^{13}C$ and $\delta^{34}S$). $\delta^{87}Sr$ determination is done on calcites and clay minerals. Uranium isotope determinations are done on FeOOH precipitations and on fine-grained clay-rich material. Studies of the isotopes in the uranium series are of great value both to identify which fractures are water-bearing and as a complement to other redox studies.

Sequential extraction of fracture-sealing minerals to identify which trace elements have been sorbed or co-precipitated on the fracture surfaces or what crushed material fills the fractures is an important complement to laboratory studies of sorption and diffusion.

Dating of fractures and fracture-filling minerals is of great interest, but is unfortunately often difficult to carry out due to a lack of datable material. U-Th dating and/or ^{14}C dating will be done in cases where suitable calcites are available. Clay minerals can also be suitable for radiometric dating.

Non-lithified material (gouge) in the form of filling in fracture and fracture zones will be thoroughly investigated with respect to chemical and mineralogical composition, grain size distribution, ion exchange capacity, and specific surface area.

Results

The method provides results in the form of identified minerals and detailed mineral compositions with respect to main components, trace elements and isotopes. Fracture-filling minerals always represent the sampled depth, which does not have to be the case with the groundwater samples. It is therefore valuable to obtain a comparison between the groundwater chemistry and the fracture-filling mineral composition. The majority of fractures in the Swedish crystalline basement were initiated early in the history of the rock, and the fractures that are water-bearing now have been so for a long time, which means that there are fracture-filling minerals of varying age. Studying the composition of different generations of fracture-filling minerals provides an idea of the stability/ instability of the groundwater composition in a historical perspective (paleohydrology). A comparison between the groundwater's and the fracture-filling mineral's content of the trace elements uranium thorium, cesium and strontium furnishes information on radionuclide mobility.

9 Transport properties of the rock

9.1 General

This chapter describes which of the rock's transport properties will be determined and possible characterization methods. The investigations include determinations of transport properties for both rock matrix and flow paths. The chapter also describes how the measured information is interpreted in the model of the rock's transport properties that comprises a portion of the site-descriptive model. By the word "transport" is meant in this chapter transport of solutes in the groundwater.

9.1.1 Introduction

Figure 9-1 shows schematically which processes influence the transport of radionuclides through the rock. Radionuclides can be transported with the flowing groundwater (advection). Diffusion along the flow paths can also be important, especially under stagnant flow conditions. An important aspect of this is matrix diffusion, when radionuclides diffuse into the microfractures of the rock and are thereby transported more slowly than the flowing water in the fractures. The timescale for advection relative to the timescale for matrix diffusion determines the relative importance of the latter process. Another factor of crucial importance for radionuclide transport is sorption, i.e. where radionuclides adhere to the surfaces of the fracture system and the rock matrix. Matrix diffusion and sorption are the two most important retention processes for radionuclides in the geosphere. Another factor that may be of importance for retention is sorption on colloidal particles and transport with them; research is being conducted within this area. The chemical environment in the water determines what speciation (chemical form) the radionuclides will have, which is crucial particularly for the sorption processes. Certain nuclides can also be transported in the gas phase. Finally, radioactive decay affects the radionuclide content of the groundwater and must therefore be included in the description of the transport processes. A more detailed description of the transport processes is provided in SR 97 /SKB, 1999b/.

The discipline-specific programme includes the necessary parts that are required to achieve the goal of characterizing the transport properties of the rock on the sites where site investigations are to be conducted. An important base for the discipline-specific programme is SR 97 /SKB, 1999b/ and the TRUE project on Äspö /Winberg et al, 2000/. Within the framework of the latter project, the tracer test technique will be further developed for ground-based boreholes so that site-specific transport parameters can be obtained already during the complete site investigation. The programme for the transport properties of the rock is divided into three parts: field measurements to obtain site-specific transport parameters, laboratory measurements on site-specific rock material, and modelling of transport properties.

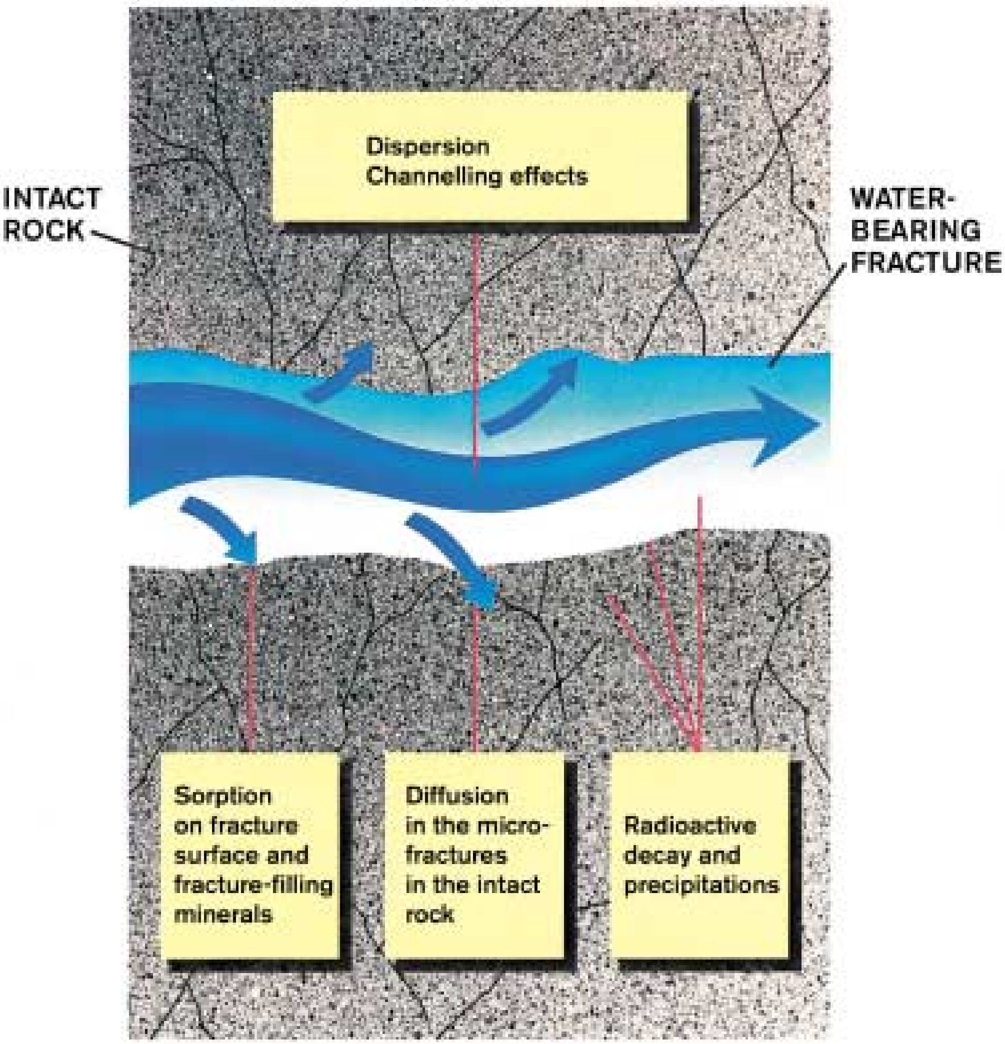


***Figure 9-1**. An illustration of the mechanisms that influence transport of nuclides from a repository to the biosphere.*

9.1.2 Discipline-specific goals

The isolating and retarding function of the deep repository is largely dependent on the transport properties of the rock. The suitability indicators that may be appropriate in different parts of the site investigation programme are identified in /Andersson et al, 2000/. The most important properties for the discipline are:

- groundwater flows on the deposition hole scale, q,
- transport resistance, F,
- diffusivity and matrix porosity of the rock mass, D_e and ε_r,
- sorption properties (sorption coefficients) for the different substances that may be transported with the groundwater.

With reference to the main goals of the geoscientific investigations (section 2.2) and the suitability indicators given above, the main focus of the transport programme is, by means of the planned investigations, to furnish the data on the transport properties of the rock that are required for an assessment of the long-term performance and radiological safety of the deep repository. More specifically, this entails:

- determining site-specific parameters for transport of reactive (sorbing) substances (matrix diffusivity, matrix porosity, sorption coefficients, transport resistance) of importance for safety assessment of a deep repository.
- determining site-specific parameters for transport of non-reactive (non-sorbing) substances (dispersivity, flow porosity, travel time, fracture aperture) to be used for calculations with and calibration of flow and transport models, which are supposed to contribute to a geoscientific understanding of the site.

Focus during the initial site investigation

In order for the common goals of the investigations during initial site investigation to be achieved, the programme for the transport properties of the rock will be focused on:

- commencing time-consuming laboratory measurements on drill core pieces and other geological material for determination of site-specific transport parameters (matrix diffusivity, matrix porosity, sorption coefficients),
- identifying unfavourable conditions such as high groundwater flows, dissolved oxygen in the water or high frequency of large water-bearing fracture zones by means of an integrated analysis of the results from hydrogeochemical sampling, pressure recordings, groundwater flow measurements, and flow distribution.

During the initial site investigation, a site-specific description (transport model) of the site will be devised based on the above integrated analysis.

Focus during the complete site investigation

In order for the common goals of the investigations during the complete site investigation to be achieved, the programme for the transport properties of the rock will be focused on:

- determining site-specific transport parameters for non-sorbing substances and a selection of moderately sorbing substances for the two to three dominant rock types within the investigation area so that an assessment of the repository's long-term performance and radiological safety can be performed,
- determining which generic data best describe transport processes on the selected site by means of comparisons between site-specific transport data and existing generic data, and taking into account the site's hydrochemical conditions.

The transport model will be updated with site-specific transport parameters.

9.1.3 Working methodology and coordination

The programme for the transport properties of the rock is dependent on a relatively large quantity of site-specific input data before a meaningful modelling of transport can be done. Efforts during the initial site investigations will therefore be focused on building up a database of parameters that are important for transport, based on the laboratory measurements that are initiated and the work that is done within related disciplines – especially geology, hydrogeology, and hydrogeochemistry.

During the complete site investigation, transport modelling and field and laboratory measurements will be carried out in an iterative process featuring the main points common to all the discipline-specific programmes (see section 2.3 and Figure 2-4). Specifically, planning of the investigations is done jointly for all disciplines to permit optimal coordination and minimize the risk of disturbances. The joint planning also includes quantification and spatial distribution of the investigations to avoid or exploit hydraulic disturbances.

Within the site investigation, the programme is largely restricted by the necessity of conducting the investigations within reasonable timeframes. Site-specific transport parameters will therefore be determined on a selection of rock material samples and flow paths in the rock and with a selection of radionuclides. The existing database, compiled from various field and laboratory measurements, is therefore of great importance. Site-specific data on groundwater chemistry and fracture mineralogy make it possible to determine which existing transport data best represent the site. Transport properties on a deposition hole scale and in flow paths in the vicinity of the deposition holes are determined in the detailed characterization phase.

The discipline-specific programme applies specifically to the transport properties of the rock, but integration with the disciplines of geology, hydrogeology, and hydrogeochemistry in particular is essential. The contributions from different disciplines are depicted in Figure 9-2. Geology contributes data on rock types and fracture-filling mineral distribution, which is essential for the sorption properties of the rock and the

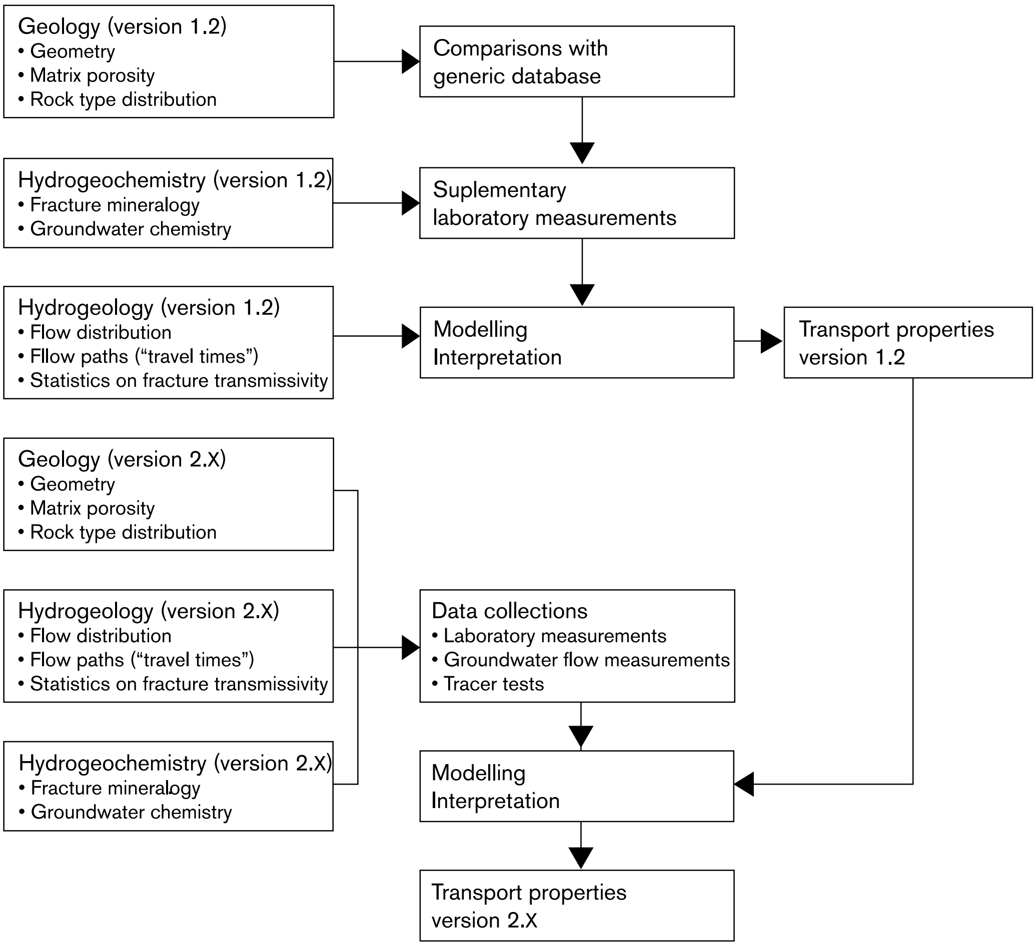


Figure 9-2. *Working methodology for construction of transport model and links to related disciplines.*

fractures. Results from the geology programme also comprise a base for selection of samples for laboratory measurements in the transport programme. Hydrogeology contributes data on the flow distribution in the rock. Hydrogeochemistry contributes hydrochemical and geochemical data of great importance for determination and calculations of the retarding properties of the rock mass and the fracture surfaces. The results from the hydrogeology and hydrogeochemistry programmes also contribute to the selection of suitable borehole sections for tracer tests.

The programme for the transport properties of the rock contributes site-specific transport properties for direct or indirect use in the safety assessment of the site. Tracer tests within the programme contribute to verification of the geological-structural model and data for calibration of the hydrogeological model.

9.2 Models and parameters

The modelling within the discipline is aimed at obtaining a geoscientific understanding of the site and delivering site-specific transport parameters for the safety assessment. Several different types of models are used. Some are models for evaluation and interpretation of tracer tests and laboratory tests, and some are descriptive transport models based on the geological, hydrogeochemical and hydrogeological models of the site. In order to provide a broad picture, several different model concepts are used to describe the distribution of the groundwater flow, for example fracture network models, channel network models, and stochastic continuum models. The calculated flow distributions and the description of the rock's retention properties along them can then be used as a basis for the models that are used in the safety assessment to calculate radionuclide transport. Difficult-to-characterize mechanisms can be conservatively simplified in the safety assessment's models. The final goal of the discipline is to deliver site-specific transport parameters to the safety assessment.

9.2.1 Structure of the models

The description of the transport properties of the rock shall provide a basis for the models that deal with transport of water, particles and solutes. The description is based primarily on the hydrogeological and hydrogeochemical descriptions, as well as certain information from the geological description. The transport modelling is divided into three different parts: near field (canister scale), bedrock (far field) and biosphere. Table 9-1 provides an overall description of the purpose, structure and constituents of the transport models.

Transport in the near field

In cases where a canister has been breached, the size of the radionuclide release is influenced not only by the properties of the fuel, the canister and the bentonite, but also by the groundwater flow, the retention properties of the rock, and the groundwater chemistry in the vicinity of the deposition holes. These properties can also influence the stability of the canister in that the groundwater can bring corrodants to the canister. Modelling of transport in the near field is not discussed further in this document, but comprises a part of the analyses that are carried out within the framework of a safety assessment. The data need is satisfied by the hydrogeological parameters and the other transport properties discussed in this document.

Table 9-1. Brief presentation of the structure and content of the transport models.

Hydrogeochemical description of the repository site

Purpose of model
Evaluation of transport-related tests (tracer tests, groundwater flow measurements, laboratory tests) and description of transport of sorbing and non-sorbing substances on the repository site.

Process description
Advection, hydrodynamic dispersion (mechanical dispersion and molecular diffusion), retention (sorption and diffusion in the rock matrix).

Constituents of the model

Geometric framework
Three-dimensional geometric distribution, orientation and extent of geological structures, as well as the connectivity of the structures, are obtained from the geology and hydrogeology programmes. As a rule, however, the three-dimensional flow field is described as a distribution of flow paths in the three-dimensional geosphere. Along the flow paths the transport description is usually one-dimensional, with matrix diffusion perpendicular to the advective transport direction.

Parameters
Flow distribution in the rock. The porosity, diffusivity and sorption properties of the rock matrix and the fracture surfaces, along with the flow porosity and dispersivity of the flow paths.

Data representation
Varies depending on the model concept (stochastic, deterministic).

Boundary conditions
Distribution of water chemistry, source terms in tracer tests, leakage from the near field in safety assessment modelling. (All boundary conditions apply for reactive transport; for groundwater flow and advective transport, reference is made to the hydrogeology section.)

Numerical tools
The modelling of flow and advective transport is separated from the modelling of reactive (nuclide) transport. Groundwater flow and advective transport are modelled with the groundwater flow models that have been defined within the hydrogeology programme. Here, different model concepts such as continuum modelling (e.g. NAMMU, PHOENICS) or discrete fracture models (e.g. FracMan/Mafic/PAWorks) can be used. Reactive transport is usually modelled with semianalytical tools such as the LaSAR (Lagrangian Stochastic Advection Reaction) concept for tracer tests or with the FAR31 model for the needs of the safety assessment.

Calculation results
The groundwater flow models provide a statistical description of the spatial distribution of the flow paths and of the associated advective travel times and the transport resistances (transport resistance only in discrete models). This information, combined with the measured transport parameters, comprise a basis for reactive transport modelling. The results of this latter modelling consist of e.g. breakthrough curves for tracers in tracer tests or of dose curves in safety assessment modelling.

Transport of radionuclides in the rock

The retention properties of the rock have a bearing on the safety assessment's calculations of transport of radionuclides that have been released from the repository. Such transport calculations comprise an essential part of the safety assessment.

The requirements on accuracy vary between the transport parameters. Only certain retention properties have the capacity to cause a substantial retardation of released radionuclides. Of the processes that are modelled today, it is primarily sorption on the surfaces of the microfractures in conjunction with matrix diffusion that have the potential to result in significant retardation. The magnitude of the influence of matrix diffusion and associated sorption depends on an interaction between groundwater flow, flow geometry, the porosity and diffusivity of the rock matrix, and the chemical properties of the groundwater and the rock mass.

There is no complete, widely accepted consensus on how the transport parameters are to be described in detail or related to possible measurements in the field. In the safety assessment's migration calculations, this problem is handled by analyzing different conceptual hypotheses and by conservative choices of parameter values. This means that information on retention properties that has been obtained in the field is weighed together with knowledge obtained from previous investigations, various research projects or theoretical considerations. This is especially true of estimates of parameters corresponding to the so-called transport resistance /Andersson et al, 1998; Andersson, 1999; Moreno and Neretnieks, 1993; Cvetkovic et al, 1999/.

An exhaustive account of all processes that influence the evolution of the deep repository, including the transport processes, is provided in the Process Report compiled within the framework of SR 97 /SKB, 1999b/.

Transport in the soil layers

The data need for biosphere transport models is discussed in Chapter 10. To a great extent the data need is of a hydrogeological nature. In order to be able to judge the turnover in different parts, however, these data need to be complemented with transport properties for the soil layers.

Assessment of changes in groundwater chemistry

Knowledge of migration is also of importance for being able to assess the long-term stability of the groundwater chemistry in the repository in conjunction with various scenarios, which has already been discussed in Chapter 8. It can, for example, be important to know whether changes in the groundwater chemistry of more near-surface groundwaters could affect the groundwater chemistry at greater depth. Such changes could affect both isolation and retardation. Besides the geochemical information, the retention properties of the rock can also be important information in such assessments.

9.2.2 Included parameters

Table 9-2 summarizes which data or parameters are needed to describe the rock's ability to transport radionuclides dissolved in the groundwater (transport properties) and which parameters need to be measured to determine these transport properties. The table also shows in which phase of the site investigations the parameter is primarily determined. The table is based on the tables compiled for the Parameter Report /Andersson et al, 1996/ and the revision that took place in conjunction with the work on requirements and criteria /Andersson et al, 2000/ and in conjunction with the preparation of the general investigation and evaluation programme /SKB, 2000b/. Information from several other disciplines, especially hydrogeology, is also required to prepare the description of the transport properties of the rock (see section 9.2.3).

Table 9-2. Compilation of transport parameters included in different transport models. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameters	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Properties on deposition hole scale	Groundwater chemistry		x	x	x	Parameters in source term model (solubilities, sorption) Assess stability of canister, bentonite,
	Groundwater flow		(x)	x	x	Source term model (Canister corrosion)
	Fracture aperture, geometry			(x)	x	Source term model (Canister corrosion)
Properties of flow paths	Flow paths		(x)	x	x	Safety assessment
	Transport resistance along flow paths		(x)	x	x	Safety assessment
	Dispersivity			x	x	Transport calculations
	Flow porosity			x	x	Transport calculations
Properties of rock	Sorption coefficients			x	x	Safety assessment
	Matrix diffusivity			x	x	Safety assessment
	Matrix porosity			x	x	Safety assessment
	Max. penetration depth			x	x	Safety assessment
	Groundwater chemistry			x	x	Determine relevant sorption data
Transport properties of soil layers/ recipients	Water flux			x		Biosphere models, land and environment, see surface ecosystems
	Flow porosity			x		
	Sorption coefficients			x		
	Biological activity			x		
Supporting data	Tracer tests			x	x	Validation/calibration
	Chemical analysis of fracture filling			x	x	Geoscientific understanding
	Chemical analysis of wall rock			x	x	Geoscientific understanding
	Groundwater chemistry, colloids, gas etc in groundwater			x	x	Exclude other transport mechanisms Geoscientific understanding, predictions of changes

9.2.3 Modelling tools and planned analyses

Interpretation of data

The transport properties of the rock are determined on the basis of an interpretation of results from other disciplines and the various measurements that are performed within the framework of the programme. Table 9-3 shows which information is needed from other disciplines.

Different regional studies or feasibility studies do not provide any new knowledge regarding groundwater flux or fracture apertures at repository depth compared with the general knowledge that already exists. In a site investigation, the groundwater flow can be calculated numerically based on the hydraulic conductivity that can be estimated from hydraulic tests in boreholes, see Chapter 7. The modelling results provide statistical information, which can be used to assess the spatial variation of the Darcy velocity on the deposition hole scale. There are also methods for directly measuring the groundwater flow in a portion of a borehole /e.g. Rouhianen, 1993/. The methods are usable

Table 9-3. Overview of parameters taken from other programmes.

Parameter	Determined within discipline-specific programmes
Geometry of fractures and fracture zones	Geology
Matrix porosity	Geology
Rock type distribution	Geology
Flow distribution	Hydrogeology
Flow paths ("travel times")	Hydrogeology
Statistics on fracture geometry and transmissivity (or direct estimation of transport resistance) for discrete network models	Hydrogeology
Fracture mineralogy	Hydrogeochemistry
Groundwater chemistry	Hydrogeochemistry

but only provide information in a number of points that can be used as a statistical basis. It is only during detailed characterization or later that individual canister positions can be assessed.

Very little information on the flow-related transport parameters is available after a feasibility study. Knowledge of topography and an estimate of the large-scale groundwater recharge provide some information on groundwater flow and transport pathways. Since data on hydraulic parameters is otherwise lacking at this stage, no detailed picture of groundwater conditions can be obtained.

Site investigations provide essential knowledge of the distribution of hydraulic conductivity in the rock. But it is unclear whether it will be possible to estimate the transport resistance (F) for different transport pathways with high precision. It cannot be measured directly, but must be estimated by modelling or by simple field measurements combined with scoping calculations. The result is a statistical distribution that describes the spatial variation and the uncertainties.

The best opportunity to obtain a good estimate of the transport resistance (F) is provided by discrete fracture models where the individual fracture geometries are explicitly described in the model. The modelling results are a statistical distribution describing the spatial variation and the uncertainties in the transport resistance. This methodology for calculation of the transport resistance was used for supplementary analyses within SR 97 /Dershowitz et al, 1999/ and comprised part of the supporting material for estimating transport resistance, see /Andersson, 1999/ for further details. Flow measurements in boreholes (see Chapter 7), combined with assumptions concerning the extent of the transport pathways, can also provide a rough idea of the magnitude of the transport resistance.

Besides being an important input data parameter for transport modelling within safety assessment, knowledge of the transport resistance can also be used to modify the layout of the repository (prior to repository construction) in order to increase the proportion of canister positions that are connected with transport pathways with high transport resistance. Some development work remains to be done on the methodology for estimating transport resistance. Partially open questions are how a regional/local continuum model should be coupled to a fracture network model on the detailed scale, and to what extent the estimated transport resistance can be verified against different types of field data.

Feasibility studies do not make any further contribution to the general knowledge of diffusivity and matrix porosity. In site investigations, matrix diffusivity and matrix porosity can be determined via laboratory experiments on drill cores and possibly also in situ in boreholes. If the method works, in-situ measurements can provide opportunities to distribute the matrix diffusivity spatially. However, the method requires support from laboratory measurements. Ideally, matrix diffusivity and matrix porosity can then be extrapolated to the entire rock mass based on rock type and hydrogeochemical conditions. Sorption coefficients for the rock mass will be based on a smaller number of laboratory measurements and possibly one or two verifying in-situ measurements, using previously well-investigated substances. Sorption coefficients for all substances will be obtained via a link to an existing database by comparisons with laboratory results and groundwater chemistry on the site.

Results from tracer tests are important sources of indirect information on the retention properties of the rock. Previously executed tracer tests (Stripa, Äspö, and others) have been used only to a limited extent to indirectly estimate important properties in the migration models such as flow distribution and "flow wetted" surfaces, although they have been used to justify the reasonableness of the chosen model and model parameters. The TRUE project on Äspö furnishes important knowledge concerning the coupling between laboratory data on site-specific material and data from in-situ tests, from single fractures on the 2–5 m scale up to fracture networks on the 10–50 m scale. The tracer tests that are carried out in the site investigations will be analyzed with the methodology now being developed within the TRUE project /Winberg et al, 2000/.

Chemical analyses of fracture fillings and wall rock can provide essential support for the reasonableness of interpreted transport parameters on a selected site. These analysis can provide information on natural mobility, natural background concentrations and the occurrence of natural analogues for some of the nuclides. It is therefore of importance to go through and analyze, in both water and minerals, the trace elements that resemble radionuclides chemically such as U, Th, Ra, Se, Mo, Sn, Rb, Zr, Ni, Sr, Cs, lanthanides, or other important components from a repository, such as Cu. But in order for this to be meaningful, it must of course really be possible to analyze the element in question. In summary, it can be observed that geochemical characterization of fracture filling, wall rock and groundwater can contribute essentially to the geoscientific understanding of the site. The information could also be used directly to estimate important transport properties, such as transport resistance and sorption coefficients, but a developed method to make estimations based on this material is not available. The transport properties of the rock are estimated using other methods.

Calculation tools

Transport modelling is done for evaluation of completed field experiments where the influence of different transport processes is determined, as well as for an understanding of transport on the selected site. Furthermore, a transport modelling is done at the end of the safety assessment. A number of different model concepts and calculation tools will be used, see Table 9-1. Models that incorporate all the processes that contribute to the character of the measured breakthrough curve (such as LaSAR) are used for evaluation of executed field experiments. Models that only incorporate the processes that are of the greatest importance for final retention are used in safety assessment modelling. These processes include e.g. matrix diffusion and sorption. Compared with the transport model for safety assessment that is used in SR 97 (FARF31), some development is expected to occur prior to future safety assessments. Specifically, there is a need for the transport model to be able to utilize the distributions of the transport resistance that are calculated in the discrete fracture models or that are estimated from field data.

9.3 Characterization methods

The majority of the transport parameters that are used during the site investigation phase are generic and determined by means of previous experiments on various rock materials, in the field and in the laboratory. As regards sorbing radionuclides, whose properties are used in numeric modelling for calculation of nuclide transport, there is even greater reliance on generic knowledge concerning retarding properties determined by means of laboratory experiments on a small scale or by means of theoretical calculations. The generic data are site-adapted by judging whether the rock composition and hydrogeochemical states on the site are equivalent to the conditions that apply for the generic data. Certain supplementary site-specific investigations are also carried out.

The discipline's characterization methods – broken down into laboratory measurements, field measurements and transport modelling – are summarized in Table 9-4. The methods are described in brief in the following sections.

Table 9-4. Summary of the discipline's methods, evaluated parameters, and literature references.

Investigation methods	Parameters (information)	Comment (reference)
Laboratory measurements		
Through diffusion measurements	Sorption coefficients, K_a, K_d, Matrix diffusivity, D_e Matrix porosity, ε_p	/Byegård et al, 1998; Ohlsson & Neretnieks, 1995, 1997/
Gas diffusion measurements	Matrix diffusivity, D_e Matrix porosity, ε_p	New method, under evaluation /Autio,1997; Laajalahti et al, 2000/
Porosity measurements	Matrix porosity, ε_p	/Byegård et al, 1998; Ohlsson & Neretnieks, 1995, 1997/
Batch sorption measurements	Sorption coefficients, K_a, K_d	/Byegård et al, 1998; Ohlsson & Neretnieks, 1995, 1997/
Field measurements		
Resistivity measurement	Matrix diffusivity, D_e	New method, under evaluation
Radon measurement	Flow wetted surface, a_r, a_w	/Glynn & Voss, 1999/ New method, under evaluation
Groundwater flow measurement	Groundwater flow, Q Darcy velocity, q Verification of structural model (in combination with pumping)	Comparative study between Posiva and SKB's concept under way
Single-hole tracer test (push-pull)	Flow porosity, ε_f Flow wetted surface, a_r, a_w Dispersivity, D Indication of matrix diffusion Comparative sorption data	/Meigs et al (eds), 2000; Elert, 1997/ Not tested within SKB programme Study of method initiated
Single-hole tracer (in-situ sorption)	Sorption coefficient, K_d Matrix diffusivity, D_e (T)	New potential method Study of method initiated
Multi-hole tracer test	Travel time, t_p Dispersivity, D Flow porosity (effective aperture), ε_f Flow wetted surface, a_r, a_w Verification of structural model (connectivity) Comparative sorption data Indication of matrix diffusion	/Winberg et al, 2000; Rhén & Svensson (ed) et al, 1992/
Transport modelling		
Transport modelling	Geoscientific understanding Transport parameters for safety assessment	Several different model concepts used

9.3.1 Laboratory measurements

Laboratory measurements on rock samples and drill cores provide direct information on the transport properties of the rock matrix and the fracture surfaces. The parameters that are determined are the porosity and diffusivity of the rock matrix, and the sorption coefficients for a number of nuclides. These measurements are performed on rock cores from several different parts of the candidate rock volume under well-controlled conditions. The analysis must also take into account to what extent selected drill cores have been altered from the in-situ conditions due to the change in rock stress conditions after extraction.

Through diffusion measurements

Diffusivity measurements are carried out by measuring how quickly an added substance diffuses through a piece of a drill core, so-called through diffusion measurements /Ohlsson and Neretnieks, 1995; Byegård et al, 1998/. The measurement is normally performed on a 1–5 cm thick sawn-out slice of a drill core placed in a measurement cell where one side of the core piece is in contact with a purely synthetic groundwater and the other with a groundwater tagged with the nuclides to be studied. Samples are then taken on the untagged side, and the effective diffusion constant D_e for the rock matrix can be calculated. This measurement also provides indirect determinations of matrix porosity (by measurement and modelling of through diffusion of tritium) and sorption coefficients (by measurement and modelling of through diffusion of selected sorbing tracers).

Gas diffusion measurements

Posiva has developed a new, faster method for determination of matrix diffusivity and matrix porosity by diffusion of helium through pieces of rock /Autio, 1997; Laajalahti et al, 2000/. The method has the advantage of being very fast, but cannot be combined with determination of sorption coefficients. Comparative study between the methods is under way.

Porosity measurements

The porosity of the rock matrix can be determined in several different ways by means of laboratory measurements on slices of rock cores. The most common method is the water saturation technique, which is determined according to standard DIN 52103-A. Recently a new method, the ^{14}C-PMMA method, has given good results /Hellmuth et al, 1993/. The method entails drying slices of drill cores and impregnating them with a ^{14}C-tagged polymethylmethacrylate, whereby both the matrix porosity and its spatial distribution in the rock matrix are determined. This provides information for estimation of penetration depth for radionuclides. A third method is to calculate the matrix porosity by modelling of through diffusion measurements with tritiated water (HTO) (see above). A comparative study of the three methods /Byegård et al, 1998/ shows good agreement. The water saturation technique is used as a standard method, but certain selected samples are also measured with the other methods, which also provide other important information (see above).

Batch sorption measurements

Sorption coefficients (K_a, K_d) are usually determined by batch experiments, where a water with a selection of nuclides is in contact with crushed rock in different fractions for a period of days to months. The nuclide content of the aqueous solution is measured as a function of time. The measurement can also be done by replacing the nuclide solution with untagged water and measuring the desorption phase, whereby data on the reversibility of the sorption is obtained. Certain transport models also handle so-called surface sorption (K_a), where it is assumed that the sorption can be divided into a fast equilibrium sorption on the surface of the mineral grains and a slower diffusion-controlled sorption on the internal surfaces. The surface sorption coefficient K_a can also be determined from batch experiments with assumptions concerning the size of the contact surface.

Comparison between the methods /Byegård et al, 1998/ show that batch experiments on small fractions of rock material give significantly higher sorption coefficients than through diffusion measurements. Larger fractions will therefore be used.

Site-specific sorption coefficients will only be determined for a selection of nuclides. Other data are obtained from generic databases, for example /Ohlsson and Neretnieks, 1995 and 1997/, /Byegård et al, 1998/ or /Carbol and Engkvist, 1997/.

9.3.2 Field measurements

Resistivity measurement

One method that is currently being studied is to use resistivity loggings in the field to determine matrix diffusivity in a manner similar to that done in laboratory experiments. The method is under development /Löfgren et al, in prep./.

Radon measurement

Measurement of the radioisotope ^{222}Rn in water samples can, with certain assumptions, be utilized to estimate the “flow wetted” surface per volume of water /Glynn and Voss, 1999/. ^{222}Rn analyses are included as an option in the water analyses described in the chemistry section (Chapter 8) and should be done on one occasion at each sampling level.

Groundwater flow measurement

Groundwater flow measurements are carried out in a number of borehole sections during different stages in the site investigation. When the boreholes are instrumented for monitoring, several sections should be equipped for executing groundwater flow measurements. The groundwater flow can thereby be followed from undisturbed conditions to controlled disturbances (long-term pumping tests, LPT), through the construction phase, and finally into the monitoring programme during the operating phase.

There are currently two different concepts for groundwater flow measurements. SKB and Posiva have each developed their own method for logging of the groundwater flow in deep boreholes. SKB’s method is based on the dilution of an injected tracer, while Posiva’s method measures the flow thermally. Dilution measurement is a single-hole method where very low groundwater flows (Q) can be determined by measuring the dilution of an injected tracer with time in a sealed-off section of a borehole. With certain assumptions concerning geometry and in combination with other measurements, Darcy velocity (q) and hydraulic gradient (I) can also be calculated. Posiva's method can also be used to determine the direction of the flow across the borehole section within a quadrant. The dilution technique can also be utilized to measure in fixed sections of boreholes with the intention of following changes in time, caused e.g. by various activities within the site investigation area. Experience from the TRUE Block Scale project shows that the method provides valuable information on connectivity and geometry for hydraulic structures by creating controlled pressure disturbances and measuring changes in the groundwater flow.

Single well injection and withdrawal tests

The Single Well Injection and Withdrawal tests (SWIW, also called push-pull) are performed by first injecting a tracer pulse under pressure, allowing it to be in contact with the fracture surfaces for a brief time, and finally pumping the tracer solution back again. An advantage of this method is that it is not dependent on several boreholes intersecting the same geological structure, which can be crucial since the boreholes are generally situated relatively far from each other. The method provides in-situ values of dispersivity and flow porosity. Data from SWIW tests can potentially also be used for estimations of the flow wetted surface and sorption parameters for a selection of weak-to-medium-sorbing substances.

There is no direct field experience of SWIW tests within the SKB programme, but an inventory of the potential of SWIW tests is under way within the TRUE project. There is, however, good experience from single-hole tracer tests for determination of dispersivity, flow porosity, matrix diffusivity, and sorption coefficients within other site investigation programmes such as WIPP in the USA /Meigs et al (eds), 2000/ and Leuggern in Switzerland /McNeish et al, 1990/.

Single-hole tests (in-situ sorption)

It has been noted within a number of other projects for determination of transport properties that there is a need to verify that laboratory-determined values of matrix diffusivity and sorption coefficients are representative, for example the TRUE project /Winberg et al, 2000/ and at URL in Canada /Vilks et al, 1999/. One reason for this is that when samples are brought up to the surface, the depressurization and change in chemistry can lead to changes in the transport properties as well, for example micro-fractures can form. A new method for site-specific in-situ determination and verification of laboratory-determined values of matrix porosity (ε_p), matrix diffusivity (D_e) and sorption coefficients (K_d) has therefore been proposed. The method is based on circulating a mixture of selected tracers (reactive and non-reactive) in a sealed-off section of fracture-free rock (matrix rock). After a certain period of time (months), the solution is replaced with formation water and rediffusion of tracers is recorded. A study of the practical prospects of being able to perform these in-situ tests has been initiated.

Multi-hole tests

The most common tracer test method is the radially converging tracer test, where a centrally located borehole or borehole section is pumped and tracer is injected in a number of surrounding boreholes. The length and time scale depend on the hydraulic transmissivity of the structures, but are normally in the range of 10 m to 200 m and hours to months, respectively. One variant is to inject under pressure so that a so-called dipole geometry is obtained. Resultant breakthrough curves can then be evaluated with a number of different model hypotheses to determine transport parameters in accordance with Table 9-4.

Multi-hole tests are used to calibrate transport models on the larger scale (applicable to water transport and transport pathways) and to verify the reasonableness of the calculated results. An example is the use of the combined large-scale tracer test and the LPT-2 pumping test on Äspö that has been used by the Äspö Task Force for calibration of flow and transport models /Gustafson et al, 1997/. Large-scale tracer tests in conjunction with long-term pumping tests (LPT) were described previously under hydrogeological investigations (see section 7.3.3) and should be carried out during the concluding stage of the complete site investigations, or as a supplementary investigation after the completion of the site investigations.

It is possible to determine dispersivity on several scales during a site investigation. If single-hole tracer tests (SWIW tests) can be developed, dispersivity can be determined on a small scale in single fractures. If two boreholes are located near each other, the dispersivity in a single structure can be determined. And finally, large-scale dispersivity can be determined in a combined interference test and tracer test (LPT).

10 Surface ecosystems

10.1 General

This chapter describes which conditions and properties of the surface ecosystems will be determined and possible characterization methods. The chapter also describes how the measured information is presented in the form of models of the site's surface ecosystems. Conditions and premises for the surface of an area are also dealt with as regards biological, geological and hydrological parameters. The parameters that are of importance for assessment of the surface ecosystems are presented in this chapter, even if they do not specifically belong to the discipline.

10.1.1 Introduction

The surface ecosystems, or the biosphere, are the part of the earth where most organisms – animals, plants and animals – live. They consist of watercourses, agricultural areas, forests and cities, plus the near-surface soil layers and the groundwater reservoirs. The surface ecosystems can be defined in several different ways /see e.g. Lindborg and Schüldt, 1998/. In practice, SKB has defined them as the area above the bedrock. This means that – in addition to plants, animals, human beings and climate – they also include the loose deposits and the near-surface hydrology and are therefore delimited spatially rather than in terms of a given discipline.

Escaped radioactive substances will not be of any consequence until they reach the surface. That is where the effects of the radionuclides in terms of dose can be measured or calculated. Safety and radiation protection regulations are therefore based to a large extent on doses to humans in the biosphere, and the calculated doses are used as a measure of comparison between different disposal alternatives or sites. It is the possible consequences of radionuclides in the surface ecosystems which present the most immediate cause of concern for most population groups.

In order to be able to judge the radiological consequences of radioactive releases from a final repository, radionuclide transport from the rock to human beings and other organisms has to be described and calculated. The overall goal is to be able to carry out credible consequence calculations in the safety assessments in compliance with the regulations issued by the authorities. Besides developing the methods and collecting the data needed to calculate radiological doses and risks associated with possible releases, the programme for surface ecosystems shall describe events and processes in a realistic manner, giving reasons why certain processes are important, as well as why other processes have been excluded.

Since general sites have been used in the previous safety assessments, the surface ecosystems have also been generalized. In SR 97 /SKB, 1999a/, a site comparison was performed and attempts were made to use site-specific data for surface ecosystems. They show that a large part of the uncertainties in dose calculations in the safety assessment are due to the lack of data on the surface ecosystems. SR 97 and the ongoing safety assessment of SFR also show that uncertainties regarding present-day and future conditions can be reduced considerably with site-specific knowledge. One of the overall goals of the investigations is to reduce the uncertainties in the calculations and be able to describe, based on up-to-date scientific knowledge, the most important processes from a radiological point of view. Another goal is that the siting of the deep repository should have the least possible impact on nature and the environment. To be able to assess the impact on the environment, plan the deep repository and site investigations, and obtain the data necessary for environmental impact assessments, comprehensive documentation of the surface ecosystems is needed.

SKB has not previously carried out extensive investigations of surface ecosystems, but experience and methods exist in society from other projects, environmental monitoring and research. Furthermore, the quantity of parameters and methods is largely determined by the selected site, so some descriptions are very general in this report. This means that the methods and parameters described in this chapter may change when work is begun on a definite site.

The discipline of surface ecosystems includes both the living (biotic) environment, i.e. animals and plants and their interactions, and the non-living (abiotic) environment, e.g. climate and water. The biotic and abiotic conditions affect each other, where the abiotic factors (such as climate) control the ecosystems while the biotic factors respond by influencing the abiotic ones, for example vegetation influences evaporation. The surface ecosystems are also affected by man via e.g. land use.

Knowledge of human activities is necessary in order to make relevant dose calculations and discuss uncertainties in the safety assessment. Many of the phenomena that are associated with human activities affect the ecosystems, but the ecosystems create the fundamental premises that determine how man can utilize the area. Depending on the activity and biosphere conditions, the degree of influence between different ecosystems varies. Generally, human behaviour controls the design of the ecosystems and is sometimes the dominant factor for creating ecological conditions and changes within many areas, such as agriculture, forestry, outdoor recreation /Götmark et al, 1998/.

The climate indirectly influences the water flux in an area. The water flux is one of the most important factors that influence the dispersal of radionuclides in the ecosystems. The climate in the area is a controlling and thereby a limiting factor for the ecosystems and the extent of different ecosystems /Schulze and Mooney, 1994/. Knowledge of the climate provides an understanding of the biological premises in an area, e.g. the premises for different vegetation types and land use, and is necessary as background data for the site investigations.

Deposits refer here to the area's geomorphology and Quaternary geology. With knowledge of the area's large- and small-scale landscape forms and the occurrence and type of deposits, the premises for the structure of the ecosystems (e.g. vegetation) can be described. The area's topography and stratigraphic sequences are important for the near-surface hydrological models that describe the dispersal of radionuclides at the surface. The stratigraphic sequence provides information on the large-scale processes that have occurred in the area, which is important as a starting point for projections of possible future changes in the area /Chambers, 1999/.

The term biota includes all living organisms, both plants and animals. Knowledge of the area's biota is a prerequisite for understanding and calculating the dispersal and accumulation of radionuclides in the ecosystems and in human food. Information on and monitoring of biota provide a foundation for being able to evaluate changes in the ecosystems.

The discipline describes water conditions in lakes, seas and running waters. These parameters provide an understanding of processes in limnic and marine ecosystems (e.g. sedimentation, water currents and particle concentration) and furthermore interface with other disciplines. In dose calculations in the safety assessment, this knowledge is essential for calculating dispersal and dilution of radionuclides within the ecosystems.

10.1.2 Discipline-specific goals

The discipline-specific programme aims at identifying what knowledge is required about the surface ecosystems in order to be able to carry out a comprehensive assessment of the biosphere conditions in the area. This comprises a basis for the safety assessment in particular, but also for facility design, and particularly the facility's infrastructure on the ground. The site investigations of surface ecosystems are also supposed to furnish the information on area conditions that enable the site investigations to be carried out in consideration of nature conservation and environmental protection. This means that the investigations will proceed over a long period of time and start at the beginning of the initial site investigation. Early data collection is of great importance in obtaining background data for parameters that may be affected by the disturbances associated with the investigations.

With reference to the main goals (see Chapter 2), the main tasks of the surface ecosystem programme are to:

- characterize the undisturbed ecosystem conditions in the candidate areas,
- collect relevant data for safety assessment and design,
- obtain a general understanding of the candidate area's surface ecosystems so as to be able to develop and justify models and make predictions of the area's future evolution,
- with the aid of collected data, present a framework for the further execution of the investigations with consideration for nature and the environment.

Focus during the initial site investigation

During the initial site investigation, the discipline-specific programme is focused on:

- identifying and characterizing biologically sensitive areas in studied candidate areas,
- identifying the parameters in the surface ecosystems that are needed to achieve sufficient knowledge of the area,
- compile existing data on the areas,
- collect data requiring undisturbed conditions,
- commence monitoring programmes for parameters that require long time series.

A preliminary site description is prepared for the discipline.

Focus during the complete site investigation

During the complete site investigation, the programme is focused on:

- supplementary data collection to gather the information needed for safety assessment, design and environmental impact assessment and achieve a fundamental understanding of the surface ecosystems in the areas,
- in-depth investigations of specific parameters,
- continued long-term monitoring.

A site description is prepared for the discipline.

10.1.3 Working methodology and coordination

The work is divided into three main phases: collection, compilation and interpretation of data. Data collection is done by compiling existing material together and conducting supplementary field inventories. The purpose of each individual parameter and the collection requirements that are made (e.g. undisturbed conditions) influence when in the site investigation documentation of the parameter should be carried out /Lindborg and Kautsky, 2000/. As a result, the investigation of the surface ecosystems is controlled more by the other activities during the site investigation than the defined subdivision into execution steps in the main programme, as far as the requirements made on precision are concerned (regional surroundings and site). This does not, however, apply to the parameters that require longer time series or that will be included in future monitoring programmes for deep repositories.

When the areas for site investigation have been decided, compilation of existing data is begun. Based on this compilation and the location of the area (e.g. near-coast, lake or inland), the question of which parameters will be included in the site-specific field studies is judged and evaluated. Parameters requiring undisturbed conditions and parameters where long measurement series are striven for are identified. Then the field studies are initiated with regard for the parameters' specific requirements as regards season, area precision and other investigations on the site. A running presentation of site investigation data will be done with the aid of GIS applications. The purpose is to be able to assist all disciplines and projects that need information on the parameters from surface ecosystems and to act as a tool for the collection of other parameters. After initial site investigation, collected data and working methodology are evaluated. During complete site investigation, supplementary data collection is carried out and the information needed to characterize the area in accordance with the purposes defined for surface ecosystems is compiled.

Surface ecosystems is the most heterogeneous discipline and interfaces with virtually all other disciplines, especially hydrogeology, hydrogeochemistry and geology. This means that much of the data needed for ecosystem analyses will be of interest to other disciplines as well, which in turn means that certain parameters will be determined under the responsibility of other disciplines in the site investigation. The information needs are described in Table 10-1 in section 10.2 and illustrated schematically in Figure 10-1.

The discipline is supposed to function during the site investigation period. Certain investigations may extend longer than this and are then also included in monitoring programmes not yet established.

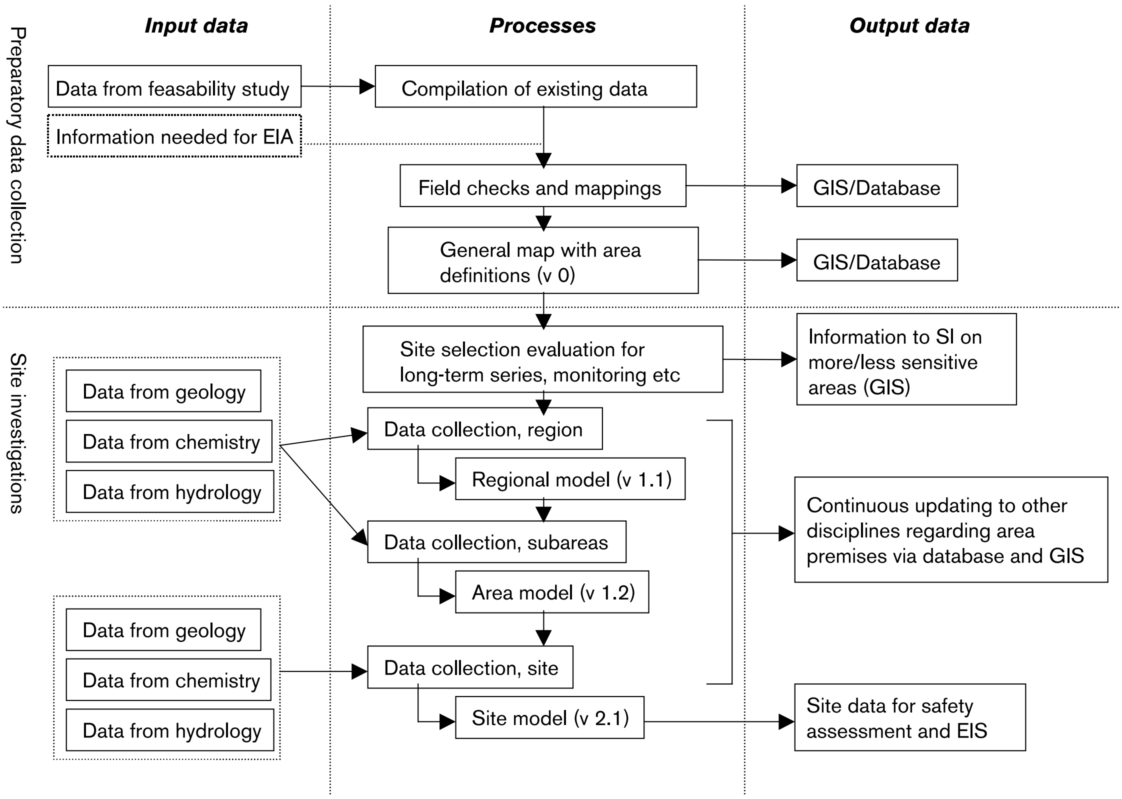


***Figure 10-1**. Flow scheme and information needs for preparing the description of the surface ecosystems.*

10.2 Models and parameters

10.2.1 Structure of the models

In order to permit data on the surface ecosystems to be documented and compiled in a simple and comprehensible manner, data are grouped into different parameter groups. The parameter groups are in turn subdivided into parameters according to their functions in the ecosystems.

Since much of the information will be used in the safety assessment models, which are under development, it is difficult at the present time to know how the parameters will be used and therefore not possible to concretely describe the models that will be used. In general the safety assessment's models are simple /see e.g. Bergström et al, 1999/, but the parameters that are used are based on other models, for example the water turnover in a bay of the sea is based on a large model which is dependent on such parameters as the topography of the bottom in the area, runoff, wind, temperature, salinity and water level /Engqvist, 1997; Engqvist and Andrejev, 1999, 2000/.

In order to be able to construct the simplified site-specific models, larger models are used which describe the flow of materials through the ecosystems /e.g. Kumblad, 1999/. The structure of the model, i.e. which model is used in the safety assessment, is dependent on the appearance of the area. A great deal of knowledge is therefore needed on what the area looks like today in order to use the right model. The future appearance of the area is modelled in landscape and vegetation models which are dependent on land uplift, loose deposits, wind forces and fetch /see e.g. Brydsten, 1999a,b; Påsse, 1997/. Experience from the ongoing safety assessment of SFR shows that the more site-specific information there is, the smaller the uncertainties are regarding both present-day but above all future ecosystems up to the next ice age. It is of great importance to reduce the uncertainties for surface ecosystems, since they contribute to great uncertainties in the safety assessments /SKB, 1999a,c/.

The data that are collected for monitoring, biological understanding or background information on the candidate area will not primarily be processed in models, but used for comparisons in time and space. In order to be able to make this comparison, a statistically large enough body of material is needed to be able to verify changes with any certainty (statistical analysis). This means that certain statistical models will be used for this purpose, e.g. BACI design /Stewart-Oaten et al, 1986/. GIS will be used to a great extent in order to get an overview of the area and to visualize the area's structure. Several different GIS models will be used to analyze and weigh together several parameters /e.g. Brydsten, 1999a/.

10.2.2 Constituent parameters

The selection of parameters that need to be determined is based on the various purposes (motives) that exist for describing the surface ecosystems. One and the same parameter can of course fulfil a number of purposes.

Parameters that are used in *safety assessment* give data that are expected to be important and serve as a basis for the safety assessment or future assessments. Parameters that are used for assessment of *impact on nature and the environment* are data that are explicitly asked for or can serve as a basis for describing consequences in supporting documents for a licence application. The parameter serves as a basis for the EIS (see section 2.1). (The consultation that takes place in the preparation of an environmental impact statement falls under a separate activity and is not described in this report.) Parameters that may have a bearing on other environmental legislation (e.g. regarding protection areas and water rights court judgements), and parameters that are important for environment impact and social responsibility but are not regulated directly by legislation, also belong to this group. The parameters are also used in the planning of the site investigation to minimize effects on the environment.

Parameters that are used for *monitoring* provide important information on background values for detecting any changes in conjunction with a siting of the deep repository and to some extent also the activities of the site investigation. These also include parameters that must be collected to enable the results of other measurements to be interpreted despite changes in the weather and the like (background data).

Certain parameters are determined to provide a better *understanding* of important processes in surface ecosystems. Understanding interacts with other purposes and is essential for e.g. choice of site, modelling, design of monitoring programmes, and interpretations of events, while providing perspective on the work of preparing an environmental impact statement. The parameter also provides background data for scientifically correct descriptions and interpretations for e.g. the safety assessment.

The description of the surface ecosystems utilizes information from a variety of disciplines. Table 10-1 presents the parameters that are relevant to investigate from a biosphere perspective. The table is broken down according to the concerned disciplines that are responsible for method description and the performance of data collection. For a more detailed breakdown of the parameters and further description, see /Lindborg and Kautsky, 2000/.

Table 10-1. Compilation of parameters included in the model description of surface ecosystems. The table also shows when the parameter is primarily determined (see explanation in Table 2-3).

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Geology	Topography Land uplift Soil layers Exposed rock	x	x	x		Understanding Safety assessment Nature and environment Monitoring
Hydrogeology Groundwater	Recharge/discharge areas Soil water and groundwater Groundwater levels Wells		x	x		see above
Hydrogeology Surface water, lakes, watercourses and seas	Bottom topography Water level Water turnover, Volumes, salinity		x	x		see above
Hydrogeology Metrology	Precipitation Runoff Evapotranspiration	x	x	x		see above
Hydrogeochemistry Soil and sediment in lakes and seas	C (POC, DOC, DIC), N (NO_3, NO_2, NH_4, Tot N, Org N) P (PO_4, Org P, Tot P) Si, I, K, Fe, Trace substances Radionuclides Toxic organic pollutants Water content Redox zone		x	x		see above
Hydrogeochemistry Soil water and groundwater, lakes, watercourses and seas	C (POC, DOC, DIC, Alk.) N (NO_3, NO_3^+, NO_2, NO_2, NH_4, Tot N, Org N), P (PO_4, Org P, Tot P) Si, I, K, Fe Trace substances Radionuclides Toxic organic pollutants pH, O_2, Salinity in surface water also chlorophyll and particle content		x	x		see above
Ecosystems Forestry	Quantity (m^3/ha) Production Rotation Age structure		x			see above
Ecosystems Agriculture	Production crops Animal husbandry, meat production Scope, position and area		x	x		see above

Parameter group	Parameter	Determined primarily during				Used for
		FS	ISI	CSI	DC	
Ecosystems Fishing, hunting and outdoor recreation	Scope of fishing and hunting Scope of mushrooms and berry-picking, etc		x	x		see above
Ecosystems Toxic pollutants	Toxic pollutants in biomass		x			see above
Ecosystems Flora	Vegetation type, key habitat population, dominant species red-listed species	x	x	x		see above
Ecosystems Fauna	Species, biomass, production red listed species	x	x	x		see above
Climate	Ground frost (days, depth) Ice conditions Winds Air pressure Day length Insolation Insolation angle Vegetation period		x	x		see above
Aquatic parameters Lakes, water-courses and seas	Lake type Sediment type Oxygen content Oxygenation Stratification Light conditions Temperature Water turnover for seas also Currents Degree of exposure Salinity		x	x		see above

The investigations will be arranged so that parameters that can be influenced by the investigations are determined early, since there is a need for background data and initial values for later comparisons. The parameters that require long time series or need initial data should have high priority in the work sequence, while those that are not needed until during supplementary investigations will have lower priority. However, it may be practical to carry out some collection of different parameters simultaneously. This means that parameters for which collection time is not important may be investigated earlier than necessary.

10.2.3 Modelling tools and planned analyses

The manner in which the collected data will be analyzed and interpreted is described under the various subheadings under section 10.3, "Characterization methods". Figure 10-2 provides an overview of activities during investigations of surface ecosystems, and the products and data they result in.

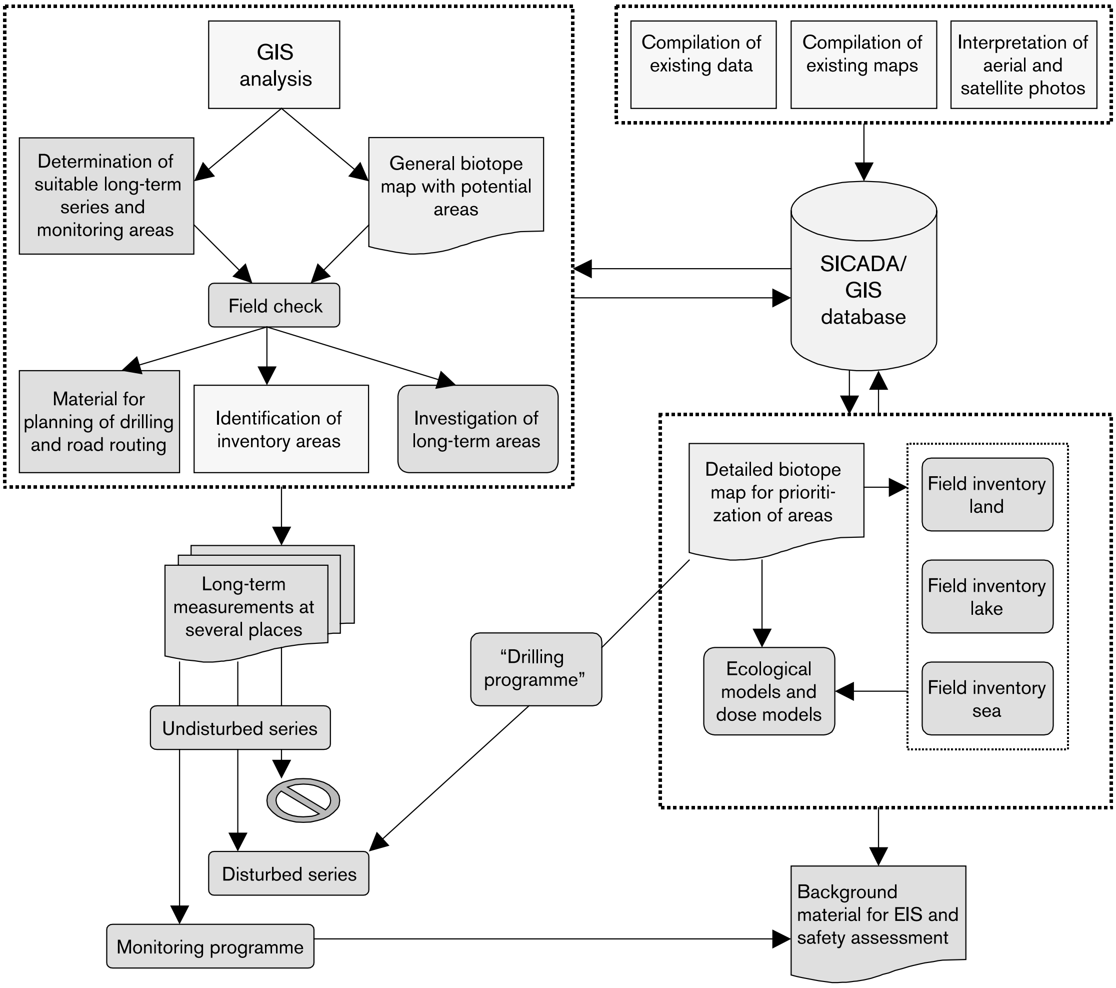


Figure 10-2*. An overview of activities during investigations of surface ecosystems, and the products and data they result in.*

10.3 Characterization methods

Since the discipline-specific programme for surface ecosystems spans over a wide variety of disciplines, no general methodology has been arrived at for the programme. To achieve best results, specific methods and models for collection and processing of each individual parameter will be used. Established techniques for data collection and processing will be used wherever possible to facilitate comparisons with other areas for calibration /see e.g. Lawesson, 2000/. In cases where new methods are devised, they will be applied in accordance with strict scientific methodology with regard to repeatability and objectivity.

Which methods will be used in the site investigation will be decided when the investigation sites have been determined, since parameters and thereby measurement methods are often specific for different environments. A compilation and evaluation of possible methods is under way /see Blomqvist et al, 2000; Lindell et al, 1999; Kyläkorpi et al, 2000; Haldorson, 2000/. Table 10-2 provides an overview of the methods that may be used. The methods are described in greater detail in the subsections below. Methods for other parameters are presented under the relevant disciplines, see Chapters 4 to 9.

Table 10-2. Methods for characterization of surface ecosystems in site investigation.

Method	Parameter	References
Surface ecosystem methods		
Land		
Inventory of key habitats	Key habitats in forestry and agriculture and general biotope protection	Eklund et al manuscript
Vegetation and biotope mapping • Collect existing material • Aerial photo interpretation • Map interpretation • Field check and inventory of soil/brush layer and cultural landscape	Vegetation and biotope map Forestry – quantity (m^3 sk/ha) – production – rotation – age structure Agriculture – production of crops Vegetation type – population/production – species of vascular plants, fungi, lichens, mosses and algae	/Kyläkorpi et al, 2000/
Compilation of red-listed species	Red-listed species	
Biomass and production • Collect existing material • Area assessment • Area inventories	Hunting, allotment, felling statistics Species, number and occurrence Biomass Production	/Kyläkorpi et al, 2000/ See also aquatic parameter collection
Sampling of pollutants and radionuclides in plants and animals	Toxic pollutants Radionuclides	
Sampling of soils and bogs • Existing material from SLU • Supplementary field work	Soil Soil chemistry Soil, type and thickness Toxic pollutants/radionuclides	
Soil type mapping, see Geological methods	Elevation difference Land uplift/Shoreline displacement Stratigraphy Soil types Exposed rock	
Aquatic		
Aquatic parameter collection Bottom mapping • Vegetation and animal zonations • Bottom type distribution	Vegetation zonation map Lake types Sediment type Oxygen content/oxygenation Stratification Light conditions Turnover/Currents Degree of exposure	/Blomqvist et al, 2000/
Aquatic parameter collection Sampling • Water fetching • Dip-netting • Probes, oxygen, salinity, pH, light and temp • Bottom samples with scraper, divers etc • Production measurement	Species compositions and quantity of fauna and flora Production Water chemistry Water physics Lake types Sediment type Oxygen content/oxygenation Stratification Light conditions Temperature Toxic pollutants Turnover/Currents Degree of exposure	/Blomqvist et al, 2000/

Method	Parameter	References
Aquatic parameter collection Fishing • Compilation of existing knowledge • Net fishing • Electrofishing • Echo sounder	Species composition Toxic pollutants/radionuclides in fish Fishing licences (n) Catches Professional fishers (n)	/Kyläkorpi et al, 2000/
Aquatic parameter collection Bathymetry measurements • Depth sounding • Bottom sediment stratigraphy	Morphometry	/Blomqvist et al, 2000/
Aquatic parameter collection Water turnover measurements • Modelling of runoff • Flow measurement • Current measurement • Modelling of currents	Water flows Currents	/Blomqvist et al, 2000; Engqvist, Andrejev, 1999; Lindell et al,1999/
Climate/hydrology		
See meteorological and hydrological methods	Ground frost/ice Number of days with ground frost Ground frost depth Ice formation Ice break-up Wind force Wind direction Air pressure Sunshine Day length Insolation, angle of insolation Vegetation period Length of season (days) Precipitation Runoff Temperature Evapotranspiration Water level Relative humidity Water divides Recharge/discharge areas	/Lindell et al, 1999/ Integration with other disciplines
Human activities		
Compilation of existing information	Outdoor recreation Berry and mushroom picking Animal husbandry, meat production Number/position of farms Farming area Dietary habits Reserve, restricted area, area of national interest Industries, type Industries, position Industries, area Development plans, land Number of residents, permanent/leisure Occupation of residents Dietary habits of residents History of area, ancient monuments Transportation Societal development, demographics	/Haldorson, 2000/

10.3.1 Inventory of key habitats

Compilation of existing information

Key habitat is a quality term referring to areas where red-listed (threatened) species are found or can be expected to be found. A key habitat is biotope (i.e. a uniform and limited ecological environment) which is of crucial importance for the threatened or rare portion of the fauna and flora. The term "key habitat" has no legal significance, nor does any automatic protection exist for key habitats. The key habitat inventory of forest land is a biological inventory of national scope.

In order to identify potential forest key habitats in the area, the work is begun by interpreting and analyzing infrared aerial photographs with the aid of stereo instruments. If the investigation area has already been compiled from existing key habitat inventories in the feasibility study stage, they are merely supplemented. The criteria for a key habitat vary between forest land, agricultural land and other biotope protection. For forest land, a distinction is made as to whether a biotope lies above or below the qualification limit for a key habitat in accordance with the County Forestry Board's rules. Regarding agricultural land, protection-classified biotope types have already been identified by the Swedish Environmental Protection Board /Bernes, 1994/, for example field islands, cairns and stone walls.

Field inventories

The main part of the key habitat inventory is field work. When interesting areas have been identified, the actual inventory work begins, where the character of the biotope and interesting subobjects are identified, Table 10-3. The work is divided into steps where the accuracy increases as the size of the investigation area is narrowed down.

Table 10-3. Example of filled-in inventory form from key habitat inventory of forest land.

Biotope type	Deciduous meadow type		**Area (ha)**		2.2
Biotope character	Former pasture		Bouldery		
	Fallen trees lying in haphazard fashion		Lots of deadwood		
	Lush moss coating				
Economic mapsheet	06H 4A	**Object number**	01	**Subobject number**	1
County	Kalmar	**Municipality**	82	Parish	02
X coordinate	6370543	**Y coordinate**	1550414		
Date of inventory	96-05-23	Change date			
Element			**Frequency**		
Old littleleaf linden			Widespread		
Old, large hardwood tree			Fairly common		
Pollard (delimbed tree)			Fairly common		
Tree rotted on the inside			Occasional-sparse		
Late-growth tree			Occasional-sparse		
Mossy boulder			Widespread		
Dry tree			Occasional-sparse		
Fallen dead hardwood tree			Occasional-sparse		

Long-term measurements

The key habitat inventory is only done in an initial stage of the site investigation and will not be included in any long-term studies.

Archiving and presentation

Data from inventories and existing investigations are entered in SKB's database (SICADA) and linked to a GIS application.

10.3.2 Vegetation and biotope mapping

Compilation of existing information

A general vegetation mapping of the area's vegetation types will be carried out in the initial phase of the site investigation. An estimate will be made of the area's vegetation and biotopes and presented in GIS format with the aid of IR aerial photos, the key habitat inventory and digital satellite photos such as Swedish Land Cover (SLD) or Swedish Terrain Type Classification (TTC). In order to determine the area's previous utilization and potential, historical maps such as land division (cadastral) maps will also be used. These can also serve as a basis for assessments of future area utilization based on previous development rate and trend.

Field inventories

In the initial phase, only supplementary field mappings will be done to check the existing information. Previous field inventories could possibly be used as information, depending on investigation area.

Long-term measurements

Vegetation mapping is done in an initial stage of the site investigation and will not be included in any long-term studies during the site investigation, but may be included in the long-term monitoring and then be repeated at intervals of several years.

Archiving and presentation

Data from inventories and existing information are compiled in SKB's database (SICADA) and linked to a GIS application.

10.3.3 Compilation of red-listed species

Compilation of existing information

The number of red-listed (threatened) species in the area needs to be determined. The Centre for Biological Diversity (CBM) hosts a database of red-listed species in Sweden. The database describes finds of species that are classified in accordance with defined criteria and where these finds are made. New definitions of red list categories were recently proposed. The overall purpose of the new system is to provide clear and objective rules for classification of species according to their risk of extinction.

Extinction risk under different circumstances is calculated by means of a quantitative analysis (Population Viability Analysis), or other quantitative analysis methods based on knowledge of the biology of a species.

For more information about red-listed species, methods of listing and collection of data, see /Kyläkorpi et al, 2000/. A compilation of existing knowledge of threatened (red-listed) species in the investigation area is being carried out by CBM.

Field inventories

Field inventories of the area to identify special species will not be conducted in an initial phase. An indirect estimation of the area's potential to harbour threatened species will be done in the field, e.g. in connection with the key habitat inventory. Finds of red-listed species during the key habitat inventory, the vegetation mapping and other investigation will be noted and appended to the compilation.

Long-term measurements

The compilation of red-listed species is done in an initial phase of the site investigation and may be included in some long-term studies, but finds of red-listed species can in some cases be followed up during a longer period of time.

Archiving and presentation

Data from inventories and existing information are compiled in SKB's database (SICADA) and linked to a GIS application. To protect certain rare species, exact positions or species names will be classified as secret in official compilations.

10.3.4 Biomass determination

Existing information on the total quantity (biomass) of the dominant species is compiled and calculated from vegetation maps and completed estimations, e.g. of agricultural yield or timber quantity. The quantities are integrated for each object (e.g. forest area, arable land, mire).

Field inventories

The information obtained from vegetation maps will mainly be used on land, but the material will be supplemented with quantity estimates in the field to permit calibration of the information from the maps. In water, the information from the quantitative bottom investigations will be used (see below).

Long-term measurements

Biomass calculation is done in an initial phase of the site investigation and will not be included in any long-term studies, except for aquatic environments.

Archiving and presentation

The biomass per unit surface area is presented in GIS and population estimates are stored in SKB's database (SICADA).

10.3.5 Sampling of toxic pollutants and radionuclides in plants and animals

Compilation of existing information

Existing information from the Swedish Environmental Protection Agency's (EPA) and SSI's environmental monitoring will be compiled. The distance to the monitoring stations will be evaluated to enable ongoing monitoring to be supplemented with sites in the investigation area.

Field inventories

After evaluation of existing data in the Swedish EPA's environmental monitoring programme, possible supplementary data will be gathered in the field. Tissue samples from hunting and fishing will be augmented with own catches. Wherever possible, the methodology used by the Swedish Museum of Natural History, the Swedish EPA and SSI will be used.

In the chemistry programme, samples will be taken from water and soil. In the site investigation programme, a survey will be performed to obtain a good idea of the background levels in the area.

Which species will be collected during the site investigations and methods for this cannot be determined until the site for investigation has been selected.

Long-term measurements

In general, the sampling of toxic pollutants in biomass entails annual collection of material from different areas for chemical analysis of toxic pollutants. After the first survey of the area, samples will probably be collected at several places. Most will be archived in specimen banks and a few will be analyzed annually. A proposal for cooperation between the Swedish Museum of Natural History and SKB is in the process of being drawn up where methods and possible resources can be coordinated.

The national environmental monitoring programme (Environmental Specimen Bank, ESB) prepares and stores the samples that are annually collected from specific locations within the terrestrial, limnic and marine programmes. Samples from previous research and investigation activities are also stored in the ESB. The homogeneous and continuous series of samples available there can also be used for e.g. retrospective analysis to detect the trend and concentrations of recently discovered contaminants.

Archiving and presentation

The results from sampling of biomass will be presented in report form, SKB's database SICADA and in the GIS application.

10.3.6 Production estimates

Compilation of existing information

Based on the biomass determination, the annual production of biomass will be calculated in order to be able to determine material flows of carbon, water and nutrients. This is then used to calculate the turnover of radionuclides in the ecosystems. General literature values can be used for most species. An example of this is presented in the SAFE project /Kumblad, 1999/. For terrestrial areas, primary production can be estimated with the aid of forestry and agricultural data as well as vegetation inventories /Eriksson, 1991; Lindborg and Schüldt, 1998/.

Field investigations

Supplementary estimates of the production and turnover of materials may be necessary for certain dominant species. This will probably be done in the field, but the methods are completely independent of species and habitat. The scope is dependent on the flow models used.

Long-term measurements

It is likely that no long-term measurements will be made of production, but the calculations are based on regular long-term measurements of hydrochemical parameters (e.g. oxygen, pH, nutrients) and growth measurements during a vegetation season.

Archiving and presentation

Data from inventories and existing information are compiled in SKB's database (SICADA) for modellings of e.g. carbon flow and radionuclides.

10.3.7 Sampling of soil and peat bogs

Compilation of existing information – soil

By soil means here the upper levels of the soil that are affected by organisms, water, wind and climate and are thereby altered in one respect or another. The term solum is sometimes used. This influence has often resulted in the formation of visible soil horizons. The soil here includes the humus layer but not the litter layer.

Site mapping carried out by SLU provides knowledge regarding the chemical and physical properties of the soil. Site mapping also provides information on soil moisture content, supracrustal boulder frequency, soil depth, cultural impact, soil type, solum and humus form, as well as the concentrations of 29 elements and pH. The mapping is done in permanent sample plots (23,500 all over Sweden) by collection of soil samples, classification in the field, and chemical analyses.

Field inventories – soil

Possible supplementary investigations on additional sample plots will be conducted during the site investigation in accordance with SLU's methods if the information on the area proves to be inadequate. The soil is characterized in one point per sample plot, where a sample pit is dug. The assessment is done according to certain categories, see Table 10-4.

A rough assessment of the plot's "average soil depth" is also made on each sample plot.

Long-term measurements

Soil mapping is done in an initial phase of the site investigation and will not be included in any long-term studies. But the results must be followed up if the site is selected for a deep repository.

Peat bogs

Any peat bogs in the area will be investigated in terms of thickness and stratigraphy. With the aid of stratum type and stratigraphic sequence, the evolution of the area can be described together with land uplift, climate and sedimentation models. For method description see the geology chapter.

Archiving and presentation

The results from sample plots will be presented in report form, SICADA and in the GIS application.

Table 10-4. Types and categories of soils (solum) determined on sample plots in accordance with SLU's methods.

Type	Category	Comment
Types with B horizon	Cultural soil	The profile exhibits more or less clear evidence of ploughing, so-called "plough sole"
	Brown forest soil	
	Transition type	Transition brown soil > podzol podzol > brown soil
	Iron podzol	
	Iron humus podzol	
	Humus podzol	
Types without B horizon	Swampy soil	
	Dense "soil type"	Soil formation unclear due to fine texture/poor drainage
	Coarse "soil type"	Soil formation unclear due to coarse material/small weathering surface
	Bouldery soil	Stones and/or boulders; little or no fine material
	Lithosol	As a rule no more than 10 cm mineral soil; may in some cases have B horizon
	Exposed bedrock	

10.3.8 Determination of land use (plant and animal husbandry)

Compilation of existing information

Land use in the area is described with the aid of statistics from Statistics Sweden (SCB), the County Forestry Board (SVS) and the vegetation mapping. Satellite photographs of the area will also be used to determine land use. Examples of two types of databases with satellite photographs that may be used are: Swedish Land Cover (SLD) and Swedish Terrain Type Classification (TTC) from the Swedish Space Corporation (Rymdbolaget). Data from the compilations will be processed in the GIS application together with other collected parameters and also be included in methods for the collection of other parameters, see e.g. 10.3.10, lakes.

Field inventories

Collected existing information will be checked in the field in conjunction with other field investigation, e.g. vegetation mapping.

Long-term measurements

Land use in the area will be included in a monitoring programme to detect any changes of importance for other parameter collection, e.g. logging.

Archiving and presentation

The results of the compilation will be presented in report form, SICADA and the GIS application.

10.3.9 Determination of other land use

Hunting

Hunting statistics are used for estimates of population sizes and species composition for certain species. As a basis for the safety assessment, the area's utilization also needs to be calculated. This gives some idea of the degree of self-sufficiency of the population.

Felling statistics for hunting areas are kept by local hunting associations, the Swedish Sportsmen's Association and the county administration boards and are compiled for the area. No field inventories will be done. The statistics should be followed up regularly and possibly included in monitoring programmes.

The results from the compilation will be presented in report form, SICADA and the GIS application. The calculations will also be presented as input values in the safety assessment.

Fishing

Fishing statistics are used for estimates of population sizes and species composition for certain species. This gives some idea of the degree of self-sufficiency of the population.

Existing fishing statistics will be obtained from local fishery conservation associations and sport fishing associations, county administration boards (regional investigations), the National Board of Fisheries (professional fishing) and the Swedish Freshwater Fisheries

Laboratory (Electrofishing Register). Depending on the availability of existing data, it may be necessary to undertake test fishing to get an idea of the size and condition of the fish stock. In conjunction with test fishing, samples are taken to test for toxic pollutants and radionuclides. The statistics should be followed up regularly and possibly included in monitoring programmes with periodic test fishing.

The results from the compilation will be presented in report form, SICADA and the GIS application. The calculations will also be presented as input values in the safety assessment.

Berry and mushroom picking

As a basis for the safety assessment, the utilization of the area for berry and mushroom picking needs to be calculated. The quantity of mushrooms and berries within the investigation area is estimated based on vegetation type, see vegetation and biotope mapping. Then the potential per-capita consumption is calculated (weight/person) based on regional data on population density from SCB.

Field inventories of the area will not be carried out, since an estimation of the area's potential for production of mushrooms and berries can be done with the aid of e.g. vegetation maps. No long-term studies of mushroom and berry production will be conducted, but sampling of mushrooms and berries can be done to estimate the content of toxic pollutants and radionuclides.

10.3.10 Aquatic parameter collection

Lakes

Limnological parameters will be collected using the methods presented by /Blomqvist et al, 2000/. Lake type and ecological functioning are then described with the aid of models based on the constituent lake parameters. These are divided into five groups: 1) position of the area in relation to controlling factors such as climate zones and height above sea level, 2) drainage (catchment) area and surrounding boundary conditions, 3) the lake's morphometry, 4) the lake's ecosystems, and 5) human impact on the lake's ecosystems. Initially, the lakes are characterized with the aid of parameters that describe the lake's surroundings (groups 1 and 2). The analysis is based on information on drainage areas, running waters, natural geographic regions, soils, land uplift, vegetation and land use, and is compiled as themes in a GIS application. Moreover, a compilation is made of previous investigations and regional data for lake parameters. These include information on red-listed species and human activities in the drainage and catchment area. The compilation will show which lakes in the area have similar properties and in which lakes field inventories should be prioritized.

The field inventories are commenced by establishing the character of the shoreline in terms of substrate and vegetation and previous human impact (e.g. regulation, drainage, damming). The depth range of the vegetation is determined by means of echo sounding and measurement of the transparency of the water to light (Secchi depth). In conjunction with the echo soundings associated with GPS, the lake's bottom topography can be measured. A thorough inventory of the lake's abiotic parameters such as temperature, stratification, light conditions, pH, buffering capacity, colour, nutrients and oxygen conditions will also be done during at least one annual cycle. This information is supplemented with quantitative fauna and flora inventories of dominant species (groups). If the lake is situated at an interesting place (origin), a determination will be made of the bottom stratigraphy by means of sediment borings during the winter during the complete site investigation. This provides information on the sedimentation environment in the lake and its evolutionary history, which is needed for the safety assessment and future predictions. The lake's water turnover and hydrological properties are determined in the hydrological discipline-specific programme.

The large-scale factors, groups 1 and 2, plus a number of physical and morphometric parameters, will be modelled with the aid of GIS based on existing digital maps and collected field data. The GIS application is also used to calculate parameters such as e.g. the surface area, volume and depth of the lake, length of shoreline, islands, turnover time and land use within the drainage area.

Lakes in the investigation area will probably be included in long-term series for chemical and physical parameters. Depending on site-specific conditions, other types of monitoring may also be of interest, e.g. occurrence of red-listed species (fish and amphibians).

The results from the compilation will be presented in report form, SICADA and the GIS application. The calculations will also be presented as input values in the safety assessment.

Watercourses

The properties of watercourses will be described in a manner similar to that for lakes, i.e. 1) position of the area in relation to controlling factors such as climate zones and height above sea level, 2) drainage area and surrounding boundary conditions, 3) length and cross-section of the watercourses, 4) the watercourses' ecosystems and 5) human impact. The analysis is based on information on drainage areas, lakes, natural geographic regions, soils, land uplift, vegetation and land use, and compiled as themes in a GIS application. Moreover, a compilation is made of previous investigations and regional data. These include information on red-listed species and human activities in the drainage and catchment area. The compilation will show which watercourses in the area have similar properties and where field inventories should be prioritized.

Field inventories are commenced by establishing the character of the shoreline in terms of substrate and vegetation and previous human impact (e.g. regulation, drainage, damming). A thorough inventory of the watercourses' abiotic parameters such as temperature, light conditions, pH, buffering capacity, colour, nutrients and oxygen conditions will also be done during at least one annual cycle. This information is supplemented with quantitative fauna and flora inventories of dominant species (groups). Water turnover and hydrological properties are determined in the hydrological discipline-specific programme.

The large-scale factors, groups 1 and 2, plus a number of physical and morphometric parameters, will be modelled with the aid of GIS based on existing digital maps and collected field data. Systems-ecological models will be used to calculate turnover times in the ecosystems.

Watercourses in the investigation area will probably be included in long-term series for chemical and physical parameters. Depending on site-specific conditions, other types of monitoring may also be of interest, e.g. occurrence of red-listed species (fish and amphibians).

The results from the compilation will be presented in report form, SICADA and the GIS application. The calculations will also be presented as input values in the safety assessment.

Seas

Existing information from environmental monitoring programmes and previous studies are compiled. Information from SMHI and other regular measurements of the sea's temperature, salinity, currents and water level variations are compiled. The bottom topography is entered into GIS from available depth databases and nautical charts. Based on this information, a preliminary assessment is made of what zonations of fauna and flora can be expected in depth.

If there are no ongoing measurements in monitoring programmes, a measurement series is started for seasonal variations of above all hydrochemical (e.g. oxygenation, nutrients, chlorophyll) and physical parameters (e.g. water transparency and temperature). Certain biological parameters are also noted, such as dominant species in the water and on the shallow bottoms. During the complete site investigation, but before any drillings in the marine area, a general quantitative bottom mapping is carried out to determine the plant and animal zonation and bottom type in the area. Sediment plugs with long sediment profiles are also performed. The content of radionuclides and toxic pollutants is determined for fish and in sediment profiles. If needed for the flow models, production measurements are carried out in the pelagic zone and on bottoms.

During the complete site investigation, water turnover in the area and the exposure of the bottoms to wave action are calculated. The sedimentation environment is modelled and compared with conditions during the past 10,000 years, and in conjunction with this an assessment is also made of the future sedimentation environment. Moreover, a systems-ecological model is used to describe the flow of material through the marine area and the ecosystems.

The seasonal measurements, which start at an early stage, will be followed by a measurement series for long-term measurements. Some collection of fauna and flora takes place at regular intervals, the length of which are dependent on how the area will be utilized.

The results from the compilation will be presented in report form, SICADA and the GIS application. The calculations will also be presented as input values in the safety assessment.

10.3.11 Compilation of climate information

When a site has been determined for the investigation, existing parameter data for the area will be compiled based on SMHI's databases. The climate parameters where the discipline of surface ecosystems is responsible for collection and compilation comprise only a part of the site investigation's total climate investigation (see Table 10-1). However, much of the collection will be done at the same time and by the same agent (SMHI). Data collection will be done with the aid of existing material from measurement stations in the vicinity of the candidate area and via special measurements at field stations deployed in conjunction with the site investigation. Data from possible local weather stations are utilized. In addition, the water discharge rate can be measured in running water. Data collection is coordinated with the hydrogeological data collection (see section 7.3.1).

Based on existing data, interpolation of climate data can be done by means of Mesan modelling. The results from data collection and modelling will also determine whether extra field stations need to be used and where they should be located. Two or more measurement stations may possibly be used initially and later decreased to one when a priority site within the candidate area is selected for investigation. For further information on SMHI's methods for collection and calculation of data and existing parameter data on the feasibility study municipalities, see /Lindell et al, 1999/.

Climate parameters will be followed continuously in the investigation area. Which measurement series will be carried out is dependent on the investigation site and the availability of existing stations. The results from the compilation of existing measurement station data will be presented as a report and be included in GIS. Data from measurement stations will be continuously logged in SICADA during the site investigation.

11 Drilling programme

11.1 General

This chapter describes the drilling programme which SKB plans to apply during the site investigations. A number of drilling methods of both conventional and more specialized kinds are described, as well as their application. The drilling programme also describes methods for flushing water management, recording of drilling parameters, and cleaning of drilling and other borehole equipment prior to use in the borehole. The drilling programme is a support programme and presents drilling methods which are optimally adapted to the requirements on investigation boreholes that are made within the different discipline-specific programmes. Planning and execution of the drilling work is integrated with the discipline-specific programmes.

11.1.1 Introduction

The borehole investigations are planned for a depth of approximately 1,000 m, see Chapter 2. Drilling permits study of bedrock and soil layers in three ways:

- The drilling process in itself provides some information on the penetrated soil and rock volume by recording of drilling and flushing water parameters and through the observations of the drilling process documented by the drilling personnel.
- Material (drill cores, drill cuttings and groundwater) from different depths is brought up to the surface and studied from various aspects.
- The borehole offers an opportunity to lower different types of measuring instruments into the hole after drilling, whereby geoscientific parameters can be determined at different levels.

Through progressive compilation and evaluation of data from drilling and subsequent measurements during the site investigations, knowledge of the site's geological character and groundwater conditions is gradually accumulated.

The drilling and subsequent measurements entail some disturbance. The hole itself acts as an artificial drainage channel, in addition to which new fractures can be induced and others closed. Foreign substances such as drilling water, lubricating oils and dirt may be introduced into the rock by the drilling. There are, however, various methods for limiting or in any case quantifying the magnitude of the disturbance. In designing the drilling programme, considerable effort is therefore devoted to:

- minimizing unwanted side-effects of the drilling,
- documenting unavoidable disturbances and contamination to as great an extent as possible, see also 11.3.1.

The drilling market offers certain special methods of interest in these respects from a site investigation viewpoint. SKB has also developed its own methods for e.g. flushing water management that are specially adapted to the requirement of minimizing the disturbances and documenting the drilling as much as possible.

In terms of time and costs, the drilling activity takes up a considerable portion of the total resources for site investigation. It is therefore highly justified to put a great deal of effort into the planning and execution of drilling. The drilling programme must be adapted to different types of investigations of differing geoscientific focus, where the applied methodology varies considerably.

Relatively heavy equipment is used for rock drilling, which can lead to some ground damage and other environmental disturbances in the form of e.g. noise and exhaust emissions. It is possible to limit this kind of disturbance by the right choice of engine type and noise-suppressing insulation. The drilling programme is permeated by environmental awareness as well as consideration to landowners, nearby residents and other members of the public.

Different drilling methods will be used, above all *soil drilling*, *percussion drilling* and *core drilling*. Different quality requirements will be met in the execution of drilling with regard to such aspects as *cleanliness*, *flushing fluid management*, *positioning*, and *alignment* of boreholes. Different procedures will be employed for chemistry-prioritized boreholes as compared with other boreholes. Furthermore, drilling parameters (e.g. drilling rate) and flushing water parameters will be recorded during drilling. In addition, initial measurements of the composition of the groundwater used as flushing water will be made.

11.1.2 Goals of the drilling programme

With reference to the main goals of the investigations (section 2.1.1), and taking into account the fact that the drilling programme comprises a support programme for the various discipline-specific programmes, the drilling work is aimed at:

- producing the number of boreholes to such depth, with such geometry (diameter, length, orientation, inclination, deviation) and in conformance with such other quality requirements as are needed for the discipline-specific programmes to achieve their respective goals,
- producing the boreholes in a sequence in relation to the various measurements that is necessary in accordance with criteria and requirements in the geoscientific discipline-specific programmes,
- using such drilling methods and such peripheral methods and equipment so that the penetrated formation is disturbed as little as possible, and so that unavoidable disturbances can be quantified and documented so accurately that measuring errors caused by them can be determined.

The drilling programme can be said to be both production-oriented and guided by the principle of least disturbance. Both of these lines can be followed through the drilling programme, as well as in associated method instructions.

11.1.3 Working methodology and coordination

The drilling programme comprises a service function for the discipline-specific programmes. The drilling programme can be regarded as an independent activity programme with a direct coupling to the discipline-specific programmes in accordance with the role division purchaser-provider, see Figure 11-1.

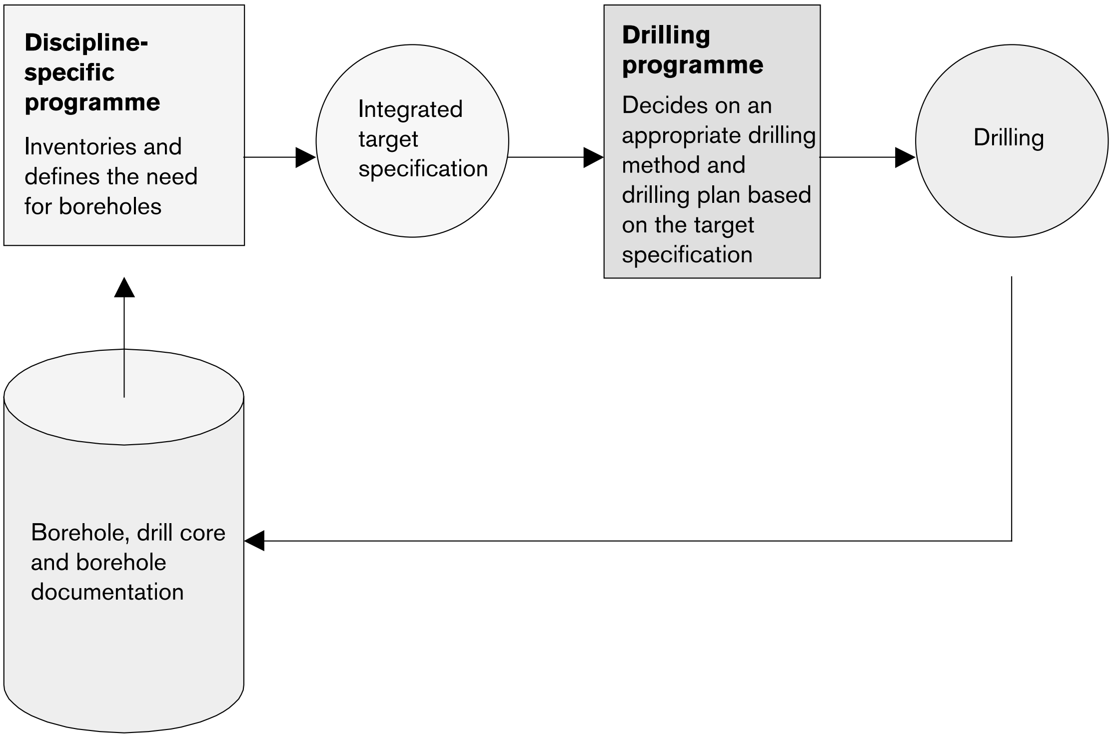


Figure 11-1. *Coupling between discipline-specific programme and drilling programme in site investigation.*

In addition to making the hole, the drilling programme also includes taking various kinds of samples (of drill cores, drill cuttings, flushing water and return water). Various parameters (drilling and flushing water parameters) are measured, and certain hydraulic tests are performed. These activities are initiated by the geoscientific disciplines, to which data is also delivered, but their execution is integrated with the drilling programme.

An essential part of the planning work prior to drilling of the holes consists of drawing up procurement specifications that include all drilling-related and environmental aspects of execution, and conform to SKB's purchasing procedures. To the extent that conventional drilling services are to be procured, this is no great problem. However, much of the drilling, particularly core drilling, involves unconventional aspects, requiring careful preparation of the procurement specifications.

When the work of different actors in drilling and measurement has to be coordinated, the use of standard procedures for contract review, joint planning and follow-up meetings are important quality activities. When drilling has got under way, continuous quality control must be exercised in accordance with a pre-established activity plan.

Essential aspects of the planning and execution of the drilling programme are illustrated in Figure 11-2.

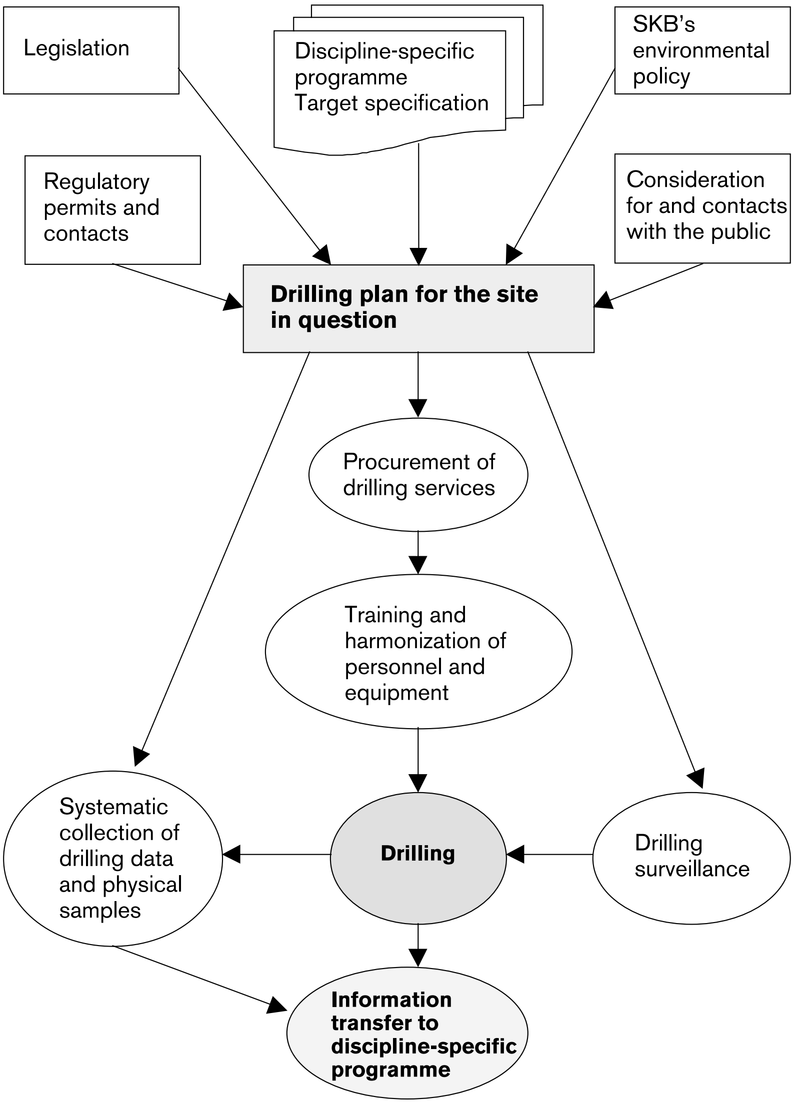


Figure 11-2. *Flow chart for planning and execution of drilling programme.*

11.2 Drilling

11.2.1 Soil drilling/probing

Drilling/probing in loose soil layers is done for the purpose of:

- determining the depth to the rock surface and, in certain cases, sampling the rock surface,
- determining the soil layer sequence,
- collecting soil samples,
- driving pipes to permit hydraulic tests and groundwater sampling.

There are standardized methods for drilling in loose soil layers. In general, drilling is carried out with machines of the type that are usually referred to as geotechnical drilling equipment and that are smaller and lighter than, for example, down-the-hole hammer rigs such as those used for well drilling. Such down-the-hole hammer equipment may be an alternative for sampling in deeper or bouldery soil layers.

The following presentation provides an overview of some commonly occurring soil drilling methods that will be employed in the site investigations. The equipment will be adapted to site requirements, so it is far from certain that all the methods described here will be used.

Probing methods

Probing methods can be subdivided into static and dynamic methods. Dynamic methods are mainly used in the site investigation, since they are suitable for determining the thickness of the soil cover, i.e. the depth of the rock surface, and the soil layer sequence. The dynamic methods can be divided into:

- Percussion probing.
- Ram probing.
- Sr probing (soil-rock probing).

By probing is meant that a drill steel is driven down to the rock surface by percussion, rotation or a combination of these methods.

Geotechnical drilling is surrounded by strict rules for execution and quality assurance, and a number of standardized methods are routinely employed. This is particularly true of Sr probing (soil-rock probing), which is divided into three classes with specified execution instructions for each class. Standardized procedures will be used for the most part in the site investigations.

Modern geotechnical drilling equipment with multifunctional options usually consists of rotary drilling rigs mounted on crawler chassis. This type of rig is top-driven, i.e. the hydraulically driven rotary unit with percussion hammer is mounted on the top of the drilling string. With the usual sizes of geotechnical drilling rigs, holes are drilled in diameters up to about 90 mm (casing drilling). Without casing, the most common hole sizes are 48–64 mm, whereby 44 mm drill steels are used during drilling. Soil boreholes with depths of several tens of metres can generally be managed without any problems.

What diameters to be applied in the site investigations is decided at a late stage, when the terrain conditions are known, when the equipment resources of consulted contractors have been inventoried, and when the purpose of tests and sampling in the individual borehole (or group of boreholes) has been established.

With geotechnical drilling it is possible to continue the drilling a bit down into the rock. In this way it can be ensured that the rock surface has really been reached and not just large boulders. A fairly powerful geotechnical drilling rig can drill several tens of metres into rock, provided that the overburden layers are not too thick and/or hard-packed. In normal geotechnical investigations, holes are drilled 3–5 m below the top surface of the rock.

Rock surface determination over large areas is done by means of geophysical ground surveys, mainly soil radar or seismic refraction, but drilling is a complement. Probe holes drilled in the measurement profiles thereby serve as calibration points in evaluation of the geophysical measurements.

Soil sampling

Geotechnical drilling equipment is used for soil sampling as well. The technology for soil sampling varies to a high degree depending on the purpose of the sampling and on the character of the formation to be sampled. Taking a soil sample in, for example, a deeply situated, hard-packed basal till requires a completely different kind of equipment and technique than taking a superficial peat sample. In most types of soil sampling the sample is disturbed, i.e. the stratification of mineral grains or the organic layers that exist in situ cannot be retained. Methods have, however, been developed for undisturbed sampling as well, mainly for cohesive soils. Completely avoiding disturbance of the samples is, however, often difficult even with such methods. It is particularly difficult to take samples of till. Recently, the prospecting companies have, however, developed improved methodology for till sampling.

In soil drilling, the soil is crushed and pressed aside from the borehole. Much of the soil material is, however, flushed up to the surface by the flushing fluid, generally compressed air or water, that is used in drilling. The flushed-up material, e.g. drill cuttings, is crushed and mixed-up. It is therefore difficult to relate the cuttings to exact levels in the borehole, but analysis of lifted material nevertheless offers an opportunity for general assessments of penetrated layers. The cuttings can also be said to comprise a continuous sample from the ground surface to the level where drilling has stopped.

A number of well-known sampling methods are mentioned in Table 11-1. The diversity of sampling methods is an advantage, since it broadens the options for adapting to different soil layer conditions. The question of which sampling methods are to be used in site investigation is completely dependent on the character and variation of the soil layers in the investigation area in question.

Sampling of rock surface

In areas with poor rock exposure, the top rock surface can be sampled by means of boreholes drilled through the soil layers. In such an investigation area, it is a clear advantage if probing and soil sampling can be combined with sampling of the top rock surface in one and the same campaign and with the same base equipment. There are a number of possibilities here. With previously mentioned geotechnical drilling equipment, probing can be carried out with simultaneous cuttings lifting. A more or less continuous sample is thereby obtained from the ground surface down through the soil layers to 3–5 m below the top rock surface.

Table 11-1. Geotechnical sampling methods for soil.

Sampling of disturbed samples	Sampling of undisturbed samples
Helical auger	Piston sampler
Spoon sampler	Foil sampler
Flow-through sampler	
Soil sampling probe	
Lifting of soil and cuttings during rotary/percussion drilling with flushing fluid	

If soil sampling by cuttings lifting is deemed to be insufficient, different types of samplers can, as mentioned above, be mounted on the drill steel (e.g. helical auger, flow-through sampler or sampling probe). However, only cuttings can be obtained from the rock portion. Mineralogical assessments are therefore possible, while accurate rock type determinations are more difficult to achieve.

Besides with geotechnical drilling equipment, sampling of the rock surface can also be done with heavy percussion drilling equipment or as core drilling. One variant is percussion drilling with rough cuttings sampling, which has been developed in ore prospecting for quick sampling of the surface rock. The method entails driving a casing down to the rock surface. A tubular sampler equipped with a cross bit is lowered into the borehole and drilled some distance down into the rock. The cross bit is then locked and the tubular sampler, which has cutting tips, is driven down into the rock to its full length (approximately one metre). The drill cuttings, some of which are very coarse, are packed into the sampler.

Another alternative is to utilize lightweight, crawler-mounted core drilling equipment for combined rock surface determination and soil (lifting with water) and core sampling. The advantage of such a solution is that the rock samples are sure to be good (e.g. cores ∅ 42 mm or larger), but it is on the other hand slower, since core drilling is only rotary, while other methods are both rotary and percussive.

Pipe driving for groundwater investigations

In driving of sampling pipes, a hole is predrilled, after which the sampling pipe is pounded down. A pipe-fitted borehole of this type can be used for groundwater sampling, level measurement and hydraulic tests. Only colourless PEH (polyethylene) plastic pipes are used for high-quality hydrogeochemical sampling. Steel pipes can be used when the requirements on chemical purity are not as strict. The pipes can be provided with different types of slots and surrounded by sand filters to prevent fine matter from entering the borehole. Seals with e.g. bentonite must often be used to prevent surface water from entering.

An alternative type of groundwater sampling where the sample is not depressurized is sampling with so-called BAT samplers. Measurement with a BAT permeameter can be a good alternative for permeability determination of low-permeability soil layers (e.g. fine-grained till). Special pipes are required for installation of the BAT system.

Pipe driving can be carried out with both light drilling equipment (e.g. of the geotechnical type) or with heavier drilling equipment. In general, the larger the pipe size used, the higher the price of drilling and materials. Under very difficult conditions (thick and/or hard-packed soil layers, high boulder content), or if larger borehole sizes are desired, it may be advantageous or necessary to utilize heavy drilling equipment, mainly percussion drilling equipment of the ordinary well-drilling type. If, for example, esker material is to be characterized hydraulically by means of short- or long-term pumping tests, a relatively large-diameter casing-lined borehole with slotted filter, drilled and pipe-fitted with the aid of a well-drilling rig, is normally required to accommodate a powerful enough pump.

11.2.2 Percussion drilling

Percussion drilling will be employed in the site investigation for characterization of the near-surface bedrock, by which is meant here the bedrock down to a depth of 200 m below the ground surface.

Conventional percussion drilling

Percussion-drilled holes with a length of a few tens of metres down to about 200 m are best drilled by rotary, hammer-driven drilling, i.e. percussion drilling, see Figure 11-3 (at left). Normally, compressed air is used as a flushing fluid, to drive the hammer, and to transport the cuttings to the surface. The most common borehole sizes in percussion drilling are 115 mm, 140 mm and 165 mm. Boreholes are also drilled in much larger or smaller diameters for special purposes.

The advantage of conventional percussion drilling is that the method produces boreholes quickly and cheaply compared with core drilling. The information on rock type and fracture distribution that can be obtained directly from drilling is more limited, however, since the rock material is crushed and no rock core is obtained. While samples of the cuttings can be taken for mineralogical analysis, it is relatively difficult to relate the cuttings samples to exact levels in the borehole.

Figure 11-3. *Shallower holes are normally percussion-drilled (at left in figure), whereby the rock is crushed to cuttings, while deep boreholes are core-drilled with a diamond drill bit, whereby the drill core is retrieved for geological mapping. The figure illustrates diamond drilling in accordance with the telescopic drilling method (see section on core drilling).*

The percussion drill bit becomes worn during the course of drilling, the degree of wear depending on the hardness of the rock being drilled. It is not possible to "ream up" the narrowed-down part of an already drilled percussion borehole by switching to a larger, unused drill bit, so this part always remains slightly tapered. It is important to be aware of this reduction in diameter in connection with subsequent downhole investigations and instrument installations. However, it is limited to at most a couple of millimetres per 100 m of borehole length in normal Swedish crystalline rock.

Either top hammer or down-the-hole hammer technique is used. Given the relatively strict requirements on straightness, only down-the-hole hammer will be used, since the top hammer technique gives poorer results in this respect. Down-the-hole hammer drilling can lead to some contamination of the borehole, see also 11.3.1.

The hammer function in percussion drilling is normally driven by compressed air, which is generated in a compressor on the ground surface and delivered to the drilling hammer via the drill pipes. When the compressed air has passed the hammer it reaches the borehole, where it creates an airlift pump effect. The air rises in bubbles towards the ground surface, bringing water and drill cuttings with it, which are continuously pumped up out of the borehole. The compressed air causes some contamination of the borehole and the groundwater, but the problem is reduced by the fact that the borehole is pumped out continuously.

Casing

All percussion boreholes will be provided with a *casinghead* at the ground surface, regardless of whether the holes are drilled directly on an exposed rock surface or overburden has to be drilled through first. The casing is driven through the soil layers, if any, and down into the rock. In normal cases, the casing is driven to healthy, fracture-poor rock and then another 10 m before it is cemented in place. In exceptional cases, for example if the borehole is characterized by substantial stability problems, the casing may have to be driven much deeper. Casing drilling is carried out to such a diameter that a gap of at least 10 mm is left between the outer wall of the casing and the borehole wall to permit gap grouting. After grouting, watertightness is checked. If surface water continues to leak in, either the casing must be lengthened and/or further grouting must be done.

Casing drilling is carried out as ODEX drilling or NO-X drilling. In the former method, a circular pilot drill bit pre-drilles a borehole, which is then reamed with aid of an excentric reamer bit to a diameter large enough for the casing. In NO-X drilling a circular pilot drill bit connected with an annular reamer bit via an inner bayonet coupling rotate simultaneously, thereby drilling a hole large enough for the casing to easily slip down into the borehole. The casing can be made of steel, stainless steel or plastic. In all boreholes, percussion as well as cored, it is essential to ensure that surface water does not penetrate down along the casing and into the borehole. Great importance is therefore attached to effective grouting of the gap between the soil/rock and the casing and of connecting fractures.

The casinghead will consist of a lockable lid, or a lockable hood. Around the casing there will be an outer seal of bentonite that lies up against the casing and has a circular surface with a radius of at least 1.5 m to prevent surface water from leaking in. Furthermore, the soil layers will be tapered off in the direction away from the casing. In the case of percussion boreholes drilled directly on rock, it may be necessary to seal off the casing against the rock with cement. Hammer boreholes used for extended measurements are provided with the same type of borehole container as telescopic boreholes, see section 11.2.3.

If the percussion boreholes are to be used for chemical sampling, casing of stainless steel or colourless PEH plastic is used. Casing drilling should be done using the ejector-ODEX technique, see below.

Reverse circulation

The method of reverse circulation, which has mainly been developed for exploration drilling, differs from conventional drilling in that dual drill pipes are used. The compressed air that drives the hammer is conducted down in the gap between the outer and inner pipes. A cross over sub is fitted a bit above the down-the-hole hammer. This device, which guides the returning air (after passage through the drilling hammer) and the cuttings to the inner drilling pipe, lies flush up against the borehole wall to prevent cuttings from passing between the borehole wall and the drilling pipe. The return air, cuttings and water are then conducted up to the ground surface in the inner pipe. On the surface, the cuttings are separated from air and water in a cyclone, after which the cuttings can be sampled. The pipes and borehole are flushed clean after each sampling interval. Otherwise the same technique is used as in conventional percussion drilling.

The method has a couple of advantages compared with conventional percussion drilling. In the first place, it is considered to provide better certainty when it comes to referring the cuttings samples to specific levels in the borehole. In the second place, there is less oxygen and oil contamination of the borehole, since the compressed air comes into contact with the formation only around the drill bit and not during upward transport in the borehole. Since cuttings cannot come into contact with the borehole wall above the aforementioned seal above the bit either, it is probable that cuttings penetration will also be less than in conventional percussion drilling.

Ejector-ODEX (or ejector-NO-X) is a method for casing drilling with compressed air that leads to less exposure of the formation to oxygen and oil than in ordinary ODEX (or NO-X) drilling, due to the fact that the special design of the nozzles forces the compressed air flow up inside the casing before the borehole wall has been heavily exposed to the air flow. Percussion drilling with reverse circulation combined with casing drilling in accordance with the ejector-ODEX (or NO-X) method is of interest since contamination with oxygen, compressor oil and drill cuttings is less than with conventional percussion drilling.

11.2.3 Core drilling

Drilling method

The rock will have to be investigated to a depth of about 1000 m in the site investigation. This is done with the core drilling method, which is a form of rotary drilling with an annular, diamond-tipped drill bit, see Figure 11-3. As the drill bit works its way downward, a cylindrical drill core is produced. The drill bit is followed by a core barrel, which is gradually filled up by the drill core as drilling proceeds. When the core barrel – which is generally 3 m, 4.5 m or 6 m long – is full, it is brought up to the surface and emptied of its contents. The drill core is carefully placed in a core box. It is very important that loose pieces are arranged in exactly the same order as they were located in the bedrock before they were drilled out. The core barrel is lowered once again and drilling continues. Ideally, when drilling is completed, continuous core samples will have been obtained from the rock surface to full borehole depth. Now and then core losses may occur, however, particularly in fractured, loose rock. The core losses may be due to either (minor) cavities in the rock, i.e. open fractures, to the fact that loose and crushed-up rock cannot be captured in the core barrel, or to malfunctioning core recovery equipment.

There are two options for recovering the core barrel: conventional pipe handling or wireline technique. The former entails that all drill pipes have to be lifted up so that the core barrel can be emptied, since it is mounted at the bottom of the pipe string. With the wireline technique, the core barrel runs inside the pipe string and is lifted up by means of a wireline winch. The pipe string can thereby be left in the borehole, making core recovery much faster. Wireline drilling will mainly be used for the site investigation.

Core capture can be accomplished by various techniques. Normally a double-tube core barrel is used, which is designed so that the flushing water passes between the outer and inner tubes on its way towards the drill bit. The drilled-out core is surrounded by the inner tube, which is often surface-treated to reduce friction. There is also a triple-tube technique, where the core tube consists of an outer and an inner tube, plus an extra split inner steel tube. The triple-tube technique will probably mainly be used in the site investigation.

Core drill bits are cooled with flushing water that is pumped down from the ground surface. In conventional core drill bits, the flushing channel is annular and located concentrically around the drill core. The mouth of the flushing channel is very close to the bottom part of the core. Triple-tube technique is often combined with a so-called front-loaded drill bit, which is considered to reduce the risk that loose material in the core will be flushed away. Using a front-loaded bit in core drilling can therefore be an option, especially for core recovery in highly fractured rock.

Core drilling is normally carried out at smaller diameters than percussion drilling. Unlike percussion boreholes, however, the cored borehole retains its full diameter along its entire length. This is accomplished by means of a caliper ring. In the site investigations, core drilling will be done to the diameters ∅ 56 mm and 76 mm, where 76 mm is the standard size, while 56 mm is used for special purposes.

Telescopic drilling

Telescopic drilling entails that the uppermost part of the borehole, about 100 m, is drilled to a much larger diameter, e.g. ∅ 200–250 mm than the rest of the cored borehole, which is drilled to ∅ 56 mm or 76 mm, see Figure 11-3. One advantage of the method is that it reduces penetration of cuttings and flushing water into the rock. If it is very important to avoid flushing water penetration, which is the case with chemistry-prioritized holes, the upper, larger-bore part of the hole is drilled directly by percussion drilling. An alternative method, but one which involves flushing water penetration in the upper part of the hole, is to first core-drill the upper part and then ream the hole to the desired size.

The large-bore part of the borehole has room for airlift pumping equipment, which consists of compressed air hoses with nozzles and connectors that is lowered close to the bottom of the large-bore part of the borehole. During continued core drilling at a smaller diameter, compressed air is pumped down in to the borehole, and the upward-flowing air bubbles carry a slurry of cuttings and water out of the borehole. By performing continuous airlift pumping during the entire core drilling phase, i.e. drilling down to the reamed-out part of the borehole, a larger portion of the flushing water and drill cuttings is forced up out of the borehole than would otherwise be the case.

The telescopic shape of the borehole also means that after finished drilling, the upper part of the borehole offers better opportunities for installing different types of bulky equipment, such as pumping equipment for test pumping, than a conventional borehole. The normal length of the large-bore hole is about 100 m. A stainless steel taper is fitted in the transition between the large-bore and smaller-bore parts of the borehole so that a smooth, narrowing transition is achieved between the two sections. This is necessary in order that measurement equipment can be lowered down into and raised up out of the borehole without difficulty.

Wellhead

Cored boreholes are also always provided with a wellhead at the top of the borehole in the form of casing with a lockable borehole hood. The casing must be driven down into healthy, fracture-poor rock and then cemented in place. Leakage of surface water into the borehole is not tolerated, which can make grouting necessary if this should be discovered during drilling.

The measures that must be adopted to eliminate surface water leakage into both telescopic and "ordinary" percussion boreholes are necessitated by above all hydrogeochemical but also hydraulic requirements on the boreholes. If large quantities of superficial water leak into the borehole, this hinders hydraulic testing of the deep parts of the rock. However, grouting can also pose a contamination problem from a hydrogeochemical point of view, since all grouts consist of substances that are foreign to the geological formation and the groundwater. Only certain (low-contaminating) grouts are therefore permitted in boreholes during the site investigations. In general, only cement-based grouts are approved. The pH of the borehole water should be measured before and after grouting.

A cement slab is poured around the casing to help prevent surface water from leaking in along the casing and to serve as a foundation for the drill rig during drilling as well as a borehole container and measurement equipment after drilling. After the slab is poured, the surrounding land is filled up with gravel or crushed rock to even out any level difference between the slab and the surrounding area.

After completed base measurements, a specially designed steel freight container measuring 2 x 2 x 2 m is fixed to the casing as a locking device during the time the site investigations are in an active phase. The borehole container comprises an effective collision (and other accident) protection as well as lock for the borehole, and can also house moderately sized measurement equipment. This means that measurements can be carried out without guard. If needed, a bigger container can be used to hold more bulky measurement equipment. After the active phase, the borehole containers can be replaced with hood locks of the type (or similar to that) used on Äspö and other, older investigation areas. The borehole protection can be supplemented with a purpose-designed borehole packer positioned near the top of the borehole.

A road capable of supporting heavy vehicles will be built up to each cored borehole. A gravelled, level, loadbearing apron will be prepared around the borehole, large enough to permit a heavy truck to turn around and unload goods, to allow the drilling rig and flushing water containers to be set up, and so that all types of measurement equipment can later be set up. The apron should be as flat as possible.

11.3 Quality aspects

Special requirements are made on cleanliness, flushing water management and position measurement, alignment and stabilizing of the boreholes in order that the boreholes can be used for investigations.

11.3.1 Cleanliness requirements

During drilling the drill bit, drill hammer (in down-the-hole hammer drilling) and drill pipes are lowered into the borehole. If this downhole equipment is dirty, contaminating substances may also be spread to the groundwater, the borehole walls, and the fracture surfaces. The same applies to borehole investigations after drilling, when various types of instruments, pipes, hoses etc are raised from and lowered into the borehole. Dirt in this context can consist of e.g. petroleum products from the drilling equipment (lubricating and hydraulic oils, petrol and diesel oil), chemicals of various kinds, soil particles, humus-contaminated water, etc. Even slight contamination can have a negative effect on the investigation, since it may affect hydrogeochemical and microbial conditions.

Foreign chemical substances impair the chemical characterization of the undisturbed groundwater, for example by initiating chemical reactions. Microbes, such as bacteria, can start chemical reactions which alter the original groundwater chemistry. Both the chemical and microbial in situ conditions are utilized in the safety assessment, so it is important that they be correctly determined.

For these reasons, certain cleanliness requirements must be met in work with borehole equipment. The following aspects must particularly be heeded *in all boreholes*:

- All loose dirt (mud, plant parts, sand, etc) must be washed off of the borehole equipment before it is used in the borehole.
- Petroleum products are often used at the borehole, especially during drilling. Special attention must be devoted to this so that oil is not spilled into the hole and so that all traces of oil are washed off of the equipment.

The following rules also apply to *chemistry-prioritized holes*:

- Drill pipes and other borehole equipment that has not been used for some time often acquire a surface coating. Such coatings often harbour colonies of bacteria. It is therefore important to wash off these coatings or, if this is not possible, to remove them mechanically.
- Pipes must be cleaned both inside and out.
- Microbial impurities must be disinfected to remove them, either with hot steam or with chemical disinfectant. If chemicals are used, it is essential that all residues also be washed off before the equipment is used in the borehole.

Detailed instructions for cleaning of borehole equipment are given in method descriptions and in special cleaning instructions.

11.3.2 Flushing fluid management

Flushing water

Flushing water must be used in both core drilling and percussion drilling, for cooling of the drill bit (core drilling), driving of the drill hammer (down-the-hole hammer drilling), and cuttings lifting (both methods). In core drilling, water cooling is the only realistic alternative. Water is pumped through the pipe string down to the drill bit, where it is ejected under relatively high pressure (30–60 bar in relation to the hydrostatic pressure at that level). If there are no fractures in the borehole, all the water is forced up into the borehole between the borehole wall and the drill pipe. But if the borehole is highly fractured and conductive, all flushing water may be forced out into the formation (so-called total flushing water loss). During drilling in less conductive crystalline rock, it is common that some of the flushing water disappears out into the formation. Flushing water penetration also entails that cuttings, which are suspended in fine fractions in the flushing water and groundwater, are to some extent forced out into the fracture system.

In the site investigations it is essential to reduce as much as possible the negative effects of flushing water and cuttings penetration in the drilled formation. The most important initiative taken by SKB so far to deal with these problems in the execution of deep boreholes is the development and application of the telescopic drilling concept, see section 11.2.3. In addition, special requirements apply to the selection and handling of flushing water.

The flushing water is taken from a wellbore near the borehole to be drilled or from a municipal tap, i.e. water with a more or less different physical-chemical composition compared with the groundwater in the formation to be drilled through. This means that the in situ hydrogeochemical conditions are disturbed when the flushing water enters the formation. It is important that the flushing water used does not contain organic or other impurities. The flushing water should preferably be of potable quality and pumped from a rock-drilled well from the same formation as that penetrated by the borehole in the case of core drilling. In any event, the flushing water must be thoroughly hydrochemically analyzed prior to use. Suitable wells are chosen by a hydrogeologist or a hydrogeochemist.

Since the flushing water must first be pumped up into tanks prior to use, there is a risk that it will be exposed to oxygen, which can thereby dissolve in the water. Prior to use the water is therefore purged by injection of nitrogen gas, and then stored in tanks under nitrogen gas pressure. It may also be advisable to take into account the temperature difference between the flushing water and the rock. Large temperature differences could theoretically cause tension cracks in the borehole wall, but experience shows that such problems are insignificant.

Groundwater sampling for hydrochemical characterization will be carried out both during drilling (when interruptions are made for hydraulic tests) and during various sampling campaigns after drilling. To determine the concentration of flushing water contamination in the groundwater, a non-reacting, non-toxic, organic dye tracer, usually uranine, is added to the flushing water. In connection with subsequent groundwater sampling, the tracer concentration reveals the amount of flushing water in the groundwater sample.

For balance calculations of the flow conditions during drilling, it is essential to measure the flow and total volume of injected flushing water and the tracer concentration, as well as the flow and total volume of return water, see further section 11.4.

Compressor air

The normal flushing fluid used in percussion drilling, compressed air, causes some contamination of the groundwater. In conventional down-the-hole hammer drilling the borehole wall, the fracture surfaces and the groundwater are thereby exposed to oxygen. The effect of this oxygen contamination is, however, reduced due to the constant in-flow of groundwater towards and up out of the borehole during drilling. A previous study /Smellie et al, 1987/ describes the consequences of contamination due to oxygen in percussion drilling to great depth.

The other aspect that can be noted here is hydrocarbon contamination. The compressor air in a modern standard compressor contains on the order of 3 mg of oil per m^3. If the compressor is worn, much greater oil quantities may be involved. In addition, some lubricating oil leaks from the drilling hammer out into the borehole. Compressors have been manufactured for oil-free air, but only a few of these are left on the market today and may be difficult to get a hold of for large jobs. However, efficient oil filters have been developed in recent years, enabling the problem of oil in the compressor air to be managed.

Soil drilling with geotechnical crawler drilling rigs (see section 11.2.1) is also a form of percussion drilling. These machines are top-driven, however, i.e. the drilling hammer is mounted on top of the drill string and is moreover usually hydraulically powered, which means that compressed air is not used to power the hammer. Nor is lubricating oil contamination a problem in that case. However, flushing fluid must be used for cuttings lifting. If compressed air is used, the aforementioned problems with oxygen and compressed air oil in the borehole will nevertheless arise. If water is used instead, the same contamination problems are encountered as in core drilling. This problem must be taken into account in connection with hydrogeochemical investigations in the soil layers.

11.3.3 Position measurement of the borehole

The top edge of the casing (the lower part of the top edge of the casing in the case of inclined boreholes) is the borehole's zero point, i.e. the reference point for all borehole investigations. This means that all rock drilling, core drilling as well as percussion drilling, must begin with driving and grouting in place of the casing until it is completely and permanently immobile vertically and horizontally under "normal" circumstances. The casing is then cut to the length it will have when the borehole is finished.

A point at exactly the same height as the top edge of the casing is fixed a few metres to the side of the borehole. The fixed point serves as a reserve zero point from which a sighting can be taken on the borehole if the casing should subsequently be damaged. All activity in the borehole is thereafter referred to the zero point, whose absolute level (in metres above sea level) is also documented in a protocol down to centimetre accuracy. If the casing must be temporarily cut or lengthened, it should be restored to its original length (and level) as soon as possible with the aid of the reserve point and/or the measured level.

All three coordinates of the casing and the height coordinate of the reserve zero point are measured in as soon as possible after concluded drilling with cm accuracy. The casing is then provided with a nameplate with borehole name, borehole coordinates and other data. The plane coordinates should be in the national grid (RAK) unless special circumstances dictate otherwise. The zero point should be clearly marked with a small welded-on tab of characteristic appearance on the outside of the casing.

The same strict position measurement needs do not exist for most soil boreholes as for cored and percussion boreholes. In that case, a special position measurement programme adapted to the location, use etc of the boreholes is used.

11.3.4 Alignment of boreholes

Boreholes with a dip (inclination) that varies between 50 degrees from the horizontal to nearly vertical (not fully 90 degrees) are desired. Sharply inclined boreholes make both drilling and measurement more difficult and increase the risk of stability problems. Completely vertical boreholes also entail difficulties for drilling and direction measurement of the borehole, so that 85 degrees can be preferable to 90 degrees.

The dip and strike of a borehole are decided on in each individual case by the concerned discipline supervisors. Boreholes that are drilled to confirm and characterize presumed zones are given such a direction and inclination that they can be expected to penetrate the zone at approximately a right angle, which often entails a relatively sharp inclination of the borehole. A nearly vertical borehole can be best for investigation of a rock unit to great depth.

When the desired direction and inclination are known, the drilling rig is aligned very carefully with measuring instruments (compass and protractor or theodolite) and fixed. The bottom of the borehole will thereby ideally reach a given point with known coordinates. However, no drilling method can produce completely straight boreholes; there is always some deviation from the starting direction during drilling. For this reason, repeated deviation measurements must always be made during the course of the drilling in accordance with a special method description. In this way it will be discovered if the borehole deviates more than a maximum permitted amount (from the radius of curvature and final endpoint) in accordance with the procurement specifications and quality plan. Based on the deviation measurement, each measurement point is assigned a spatial coordinate, so that the position of the entire borehole in space is determined, which is necessary in devising a geometric structural model, see also section 4.3.1.

If the measured deviation is too great, so-called guided drilling can be employed, whereby the borehole is returned to the right direction and inclination by means of a special technique. For percussion drilling there are systems with carefully controlled guide tubes which reduce the risk of excessive deviation of the borehole. It is decided in each individual case whether such devices will be used.

11.3.5 Borehole stability

In certain boreholes, especially ones that are drilled through highly deformed zones, stability problems can arise to such an extent that borehole investigations are difficult or impossible to carry out. It may be necessary to try to stabilize the borehole. The basic aim in site investigation is that grouting for the purpose of stabilizing should be limited, but that safety in borehole investigations must nevertheless be ensured. Only approved grouts may be used, and the grouting work must be well documented in accordance with specially prepared protocols.

The following are deemed to be necessary grouting measures:

- Grouting to eliminate water influx into the borehole at the transition between soil and rock and via superficial rock fractures.
- Grouting of unstable sections of cored boreholes if it is not possible to keep the borehole open by means of other methods, e.g. mechanical cleaning.
- Equivalent stabilization of those percussion boreholes that are deemed necessary to keep open in the future; determined from case to case.

Set procedures will be established for characterization of borehole sections that are to be stabilized later on.

11.4 Measurements while drilling (MWD)

Measurements while drilling refers to recording of drilling parameters in percussion boreholes and recording of drilling parameters and flushing water parameters in core drilling. Data collection is usually done via an automated parameter recording system. Detailed procedures for MWD are described in method descriptions.

11.4.1 Drilling parameters

By drilling parameters is meant a number of parameters that are related either to the drilled material or to the equipment. These include feed pressure, torque, and drilling rate. Measurement of drilling parameters is primarily of interest for judging the progress of the drilling work in a purely technical sense. The measurement results, or some of them, are also of geoscientific interest, since they directly or indirectly reflect properties of the drilled rock formation. This is true, for example, of drilling rate, which shows the speed with which the drill bit moves through the rock. The drilling rate is a function of rock properties such as hardness and fracture content, but is also dependent on feed pressure, rotary speed and bit condition. By measuring and analyze the drilling rate, it is thus possible to obtain certain information on the drilled formation directly during drilling, which can be valuable input data for several of the discipline-specific programmes.

11.4.2 Flushing water parameters

Flushing water management during core drilling has been described above. It is of great importance for the disciplines of hydrogeology and hydrogeochemistry that a number of flushing water parameters be measured during the entire drilling process. The parameters of interest here are:

- *Flow parameters*: Flushing water flow, flushing water pressure, accumulated volume of flushing water per borehole section and for the entire borehole, return water flow, accumulated volume of return water per borehole section and for the entire borehole, drawdown in the borehole on the return side.
- *Physical-chemical parameters of the flushing water*: Tracer content, oxygen content.
- *Physical-chemical parameters of the return water*: Tracer content, electrical conductivity.

Flow surges during drilling provide a direct indication of changes in groundwater discharge when water-bearing fractures are encountered.

Measurement of the pH of the return water may be advisable, especially in conjunction with grouting in the borehole. The electrical conductivity of the flushing water is measured in conjunction with its initial chemical characterization. If there is reason to believe that this parameter may change during drilling, for example due to the intrusion of saline water in the flushing water well, the parameter should be measured regularly or even continuously.

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