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Forsmark – site descriptive model version 0

Svensk Kärnbränslehantering AB

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Preface

During 2002, Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company) is starting investigations at two potential sites for a deep repository, Forsmark and Simpevarp. An important part of the necessary preparations concerns site descriptive modelling. SKB has conducted two parallel subprojects in this field. The first entailed the establishment of the first version ("version 0") of the site descriptive model of the two sites. An essential part of this work is the compilation of existing data and interpretations for each site at a regional scale. This report presents the version 0 regional site descriptive model of Forsmark. The other subproject was aimed at testing the methodology for site descriptive modelling, by applying it to the existing data obtained from an earlier, detailed investigation of the Laxemar area, which is a part of the Simpevarp site.

The basic ambitions, content and principles for site descriptive modelling are described in the general execution programme for the site investigations /SKB, 2001b/. The site descriptive model, as developed during the site investigation stage, should be an integrated description of the site and its regional environments with respect to current state and naturally ongoing processes, covering geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, transport properties and surface ecosystems. The description should serve the needs for Safety Assessment and Design. The selection of parameters and the geometrical framework is based on an underlying conceptual model of the site. Estimations of geometry and parameter values for a full three-dimensional description rest on extrapolation of data measured at a few locations. The confidence in the description should be tested with simulations to the extent that these are useful.

The version 0 site descriptive model has obvious limitations, since it is solely based on knowledge before the start of the site investigations. Moreover, the report is quite a complex mixture of an inventory of the available data for the regional area surrounding Forsmark, and a first attempt at descriptive modelling. The level of interpretation, or synthesis, of the site for each discipline is quite different. As an example of the kind of site descriptive model that is to be expected during the initial site investigation stage, the Laxemar subproject is to be preferred. Most of all, this report should serve as the natural starting point or platform for all forthcoming modelling work, as well as for the investigations to be performed at the site.

The work has been conducted by a project group with representatives from the main disciplines; geology, hydrogeology, hydrogeochemistry, rock mechanics and surface ecosystems. The different experts assessed and evaluated the data. The following participants contributed to the project and the report:

Hans Isaksson, Mikael Keisu, Carl-Axel Triumf	– data inventory
Tobias Lindborg, Sara Karlsson	– ecosystems
Michael Stephens, Philip Curtis	– geology, modelling
Eva Hakami	– rock mechanics
Sven Follin	– hydrogeology, hydrogeochemistry
Peter Wikberg, Ebbe Eriksson, Berit Lundqvist	

Rune Johansson acted as editor. Thanks are also due to Alan Geoffrey Milnes who proofread and scientifically reviewed the manuscript.

Anders Ström
Site Investigations – Analysis

Summary

During 2002, the Swedish Nuclear Fuel and Waste Management Company (SKB) is starting investigations at two potential sites for a deep repository in the Precambrian basement of the Fennoscandian Shield. The present report concerns one of those sites, Forsmark, which lies in the municipality of Östhammar, on the east coast of Sweden, about 150 kilometres north of Stockholm.

Site description

The aim of the planned investigations at both sites is to produce a *site description*, i.e. a body of documentation which presents an integrated description of the site and its regional setting, covering the current state of both the geosphere and the biosphere, and the ongoing natural processes which affect their long-term evolution. The site description should present all collected data and interpreted parameters of importance for the overall scientific understanding of the site, for the technical design and environmental impact assessment of the deep repository, and for the assessment of long-term safety. The site description will have two main components: a written *synthesis* of the site, summarising the current state of knowledge, as documented in the *databases* containing the primary data from the site investigations, and one or several *site descriptive models*, in which the collected information is interpreted and presented in a form which can be used in numerical models for rock engineering, environmental impact and long-term safety assessments. SKB maintains two main databases at the present time, a site characterisation database called SICADA and a geographic information system called SKB GIS. The site descriptive model will be developed and presented with the aid of the SKB GIS capabilities, and with SKB's Rock Visualisation System (RVS), which is also linked to SICADA. RVS is an active instrument for interpreting and visualising the primary data in SICADA, and for building and representing deformation zones and other bedrock structures, in order to set up the geometrical lattice for the site descriptive models.

Site descriptive model, version 0

The site descriptive models are devised and stepwise updated as the site investigations proceed. The point of departure for this process is the *regional site descriptive model, version 0*, which is the subject of the present report. The version 0 model forms an important framework for subsequent model versions, which are developed successively, as new information from the site investigations becomes available. Version 0 is developed out of the information available at the start of the site investigation. In the case of Forsmark, this is essentially the information which was compiled for the Östhammar feasibility study (/SKB 2000a/ and related background reports), which led to the choice of that area as a favourable object for further study, together with information collected since its completion. This information, with the exception of data from tunnels and drillholes at the sites of the Forsmark nuclear reactors and the underground low-middle active radioactive waste storage facility, SFR, is mainly 2D in nature (surface data), and is general and regional, rather than site-specific, in content. For this reason, the Forsmark site descriptive model, version 0, as detailed in the present report, has been developed at a regional scale. It covers a rectangular area, 15 km in a southwest-northeast and 11 km in a northwest-southeast direction, around the area identified in the feasibility study as favourable for further study. This rectangular area has now been designated the *Forsmark regional model area*.

Against this background, the present report consists of the following components:

- an overview of the present content of the databases SICADA and SKB GIS, and an inventory and assessment of relevant data in other databases (Chapter 2),
- a systematic overview of data needs and availability for developing a site descriptive model for the surface ecosystems (biosphere) in the Forsmark regional model area (Chapter 3),
- a more detailed treatment of the present data base for the geosphere in the Forsmark regional model area, and its transformation into the format of a site descriptive model, version 0 (Chapters 4-7).

Databases

Version 0 modelling is based on data available before the start of site investigations, mostly collected for reasons not directly related to the deep disposal of spent nuclear fuel. An important component of the present work, therefore, is a *data inventory*, in which the location and scope of all potential sources of data is detailed and evaluated with respect to prospective usefulness for future site descriptive modelling for deep disposal (Chapter 2). This includes a general description of existing geographical data, of which most are stored in SKB GIS, a survey of data already stored in the SICADA database, and an inventory of other data sources, whose information content has not yet been evaluated and/or inserted in SICADA or SKB GIS (i.e. not yet converted to a digital form). Data sources relevant to the Forsmark regional model area which still, to some degree, need to be evaluated/converted/inserted include the siting and construction of the three nuclear reactors (Forsmark 1-3), the feasibility study for an underground spent nuclear fuel interim storage facility at Forsmark, the pre-investigations and construction of the SFR, and the SAFE project.

The present version 0 report is above all at a regional scale, and the information identified as lacking in SICADA and/or SKB GIS is mainly very local and therefore not of crucial consequence in the present context. However, the information will be of potential interest when modelling different parts of the Forsmark regional model area in more detail, and when establishing the variation ranges of model parameters. In this sense, the version 0 data inventory and the newly established inventory database will provide an important platform for future work.

Biosphere

The present report describes the current level of knowledge of the *surface ecosystems* in the Forsmark regional model area, in a highly condensed form (Chapter 3). It refers to, and draws its examples from, a series of SKB background reports which have been produced since the completion of the Östhammar feasibility study, and a number of other sources of information which are gathered here for the first time. The data sources are outlined with reference to a series of functional ecosystem types: drainage areas, forest, wetland, agricultural land, lakes and rivers, and sea, each further subdivided into appropriate entities (topography, vegetation, fauna, soil characteristics, sediments, etc.). A systematic approach has been used, even though, at the current level of knowledge, the information in many subdivisions is inadequate or lacking. In this way, the weaknesses of the data base are easily identified and priorities for future problem-oriented investigations can be set. The aims of biosphere studies within the site investigation programme are to define baseline (pre-construction) conditions, to provide the necessary data base for the environmental impact statement, and to contribute to the dose estimations in the safety analysis. This version 0 compilation of data sources and contents is intended to provide guidelines for future site investigations, in order to achieve these aims.

Geosphere

The main emphasis of the report is on the preparation of a site descriptive model, version 0, for the *geosphere*, since data acquisition and processing in this area, in contrast to the biosphere, is sufficiently advanced for some initial modelling exercises. The available information on the geosphere in the Forsmark regional model area is quite extensive, at least locally (especially SFR). In order to develop and test the modelling procedures, this information has been collected and transformed into appropriate formats under four separate headings: Geology (Chapter 4), Rock mechanics (Chapter 5), Hydrogeology (Chapter 6), and Hydrogeochemistry (Chapter 7). As an example of the envisaged modelling process, geometrical modelling in RVS has been carried out in 3D using the presently available data on regional fracture zones in the Forsmark regional model area. The lithological model (metagranitoids enclosing narrow zones of metavolcanic and metasedimentary rocks, with a complex structure) is still essentially 2D, at present, but the structural data suggest an anastomosing system of subvertical zones of high ductile strain which have undergone reactivation by brittle faulting (e.g. Singö fault zone), providing a basis for a preliminary testing of RVS modelling procedures.

This first attempt to develop a 3D geological and geometrical framework for rock engineering and hydrogeological purposes (Chapter 4), is accompanied by a discussion of how best to assess uncertainty in relation to geological data, depending on the scale of compilation, the level of knowledge and the interpretation of surface geometry. In the areas of rock engineering, hydrogeology and hydrogeochemistry (Chapters 5-7), modelling activities were mainly confined to parameterisation exercises, using presently available data from the Forsmark regional model area to put limits on, for instance, the *in situ* stress field, the mechanical properties of the rock mass, the hydraulic properties of the fracture zones and rock mass between them, and the hydrogeochemical evolution.

The site descriptive model, version 0, is intended as the basic platform and natural starting point for all groups involved in the site investigations at Forsmark, especially for the regional model area. The main results of the present project were to focus attention on the strengths and weaknesses in the available data coverage and data storage and processing systems, and to provide a basis for developing and testing ways of transforming diverse types of geoscientific information into a form appropriate for modelling. At the same time, the project provided concrete guidelines for the planning of the initial site investigations at Forsmark.

Contents

1 Introduction

1.1 The project “Site descriptive models v0”

A site investigation is an important step in the process of siting a deep repository for spent nuclear fuel. SKB aims at conducting thorough investigations in at least two municipalities and arriving at detailed proposals of how a deep repository can be built and operated. SKB has proposed site investigations to be conducted in Östhammar, Oskarshamn and Tierp /SKB, 2000b/ of which the two first-mentioned municipalities have consented to the proposal.

One of the necessary preparations for the planned site investigations is to collect and compile existing data and information for each area and their surroundings, and to transform this information into the format of a site descriptive model (version 0). This has been done in the project “Site descriptive models v0” during the period July 2001 to April 2002, and the results regarding Östhammar are described in this report. For further testing of the modelling methodology and tools, the project includes the setting up of a more detailed site descriptive model, approximately corresponding to model version 1.2 in /SKB, 2001b/ for the Laxemar area in Oskarshamn /Andersson et al, 2002b/.

1.2 The site descriptive model version 0 as related to the site investigation process

The main product of the site investigation is a *site description document*. 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 collected data and interpreted parameters of importance for the overall *scientific understanding of the site*, for the *design of the deep repository* and for the *safety assessment.* The safety assessment is made with respect to the repository’s layout and construction as well as its long-term performance and radiological safety.

The investigations provide primary data (measurement values and directly calculated values) that are collected in two databases, SICADA and GIS. 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 *site descriptive model*. The site descriptive model consists of a description of the geometry and different properties of the site and comprises, together with the databases, the backbone of the site description (Figure 1-1).

The generalisations in a model that are necessary depend on the scale of presentation and use. 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 the access routes 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.

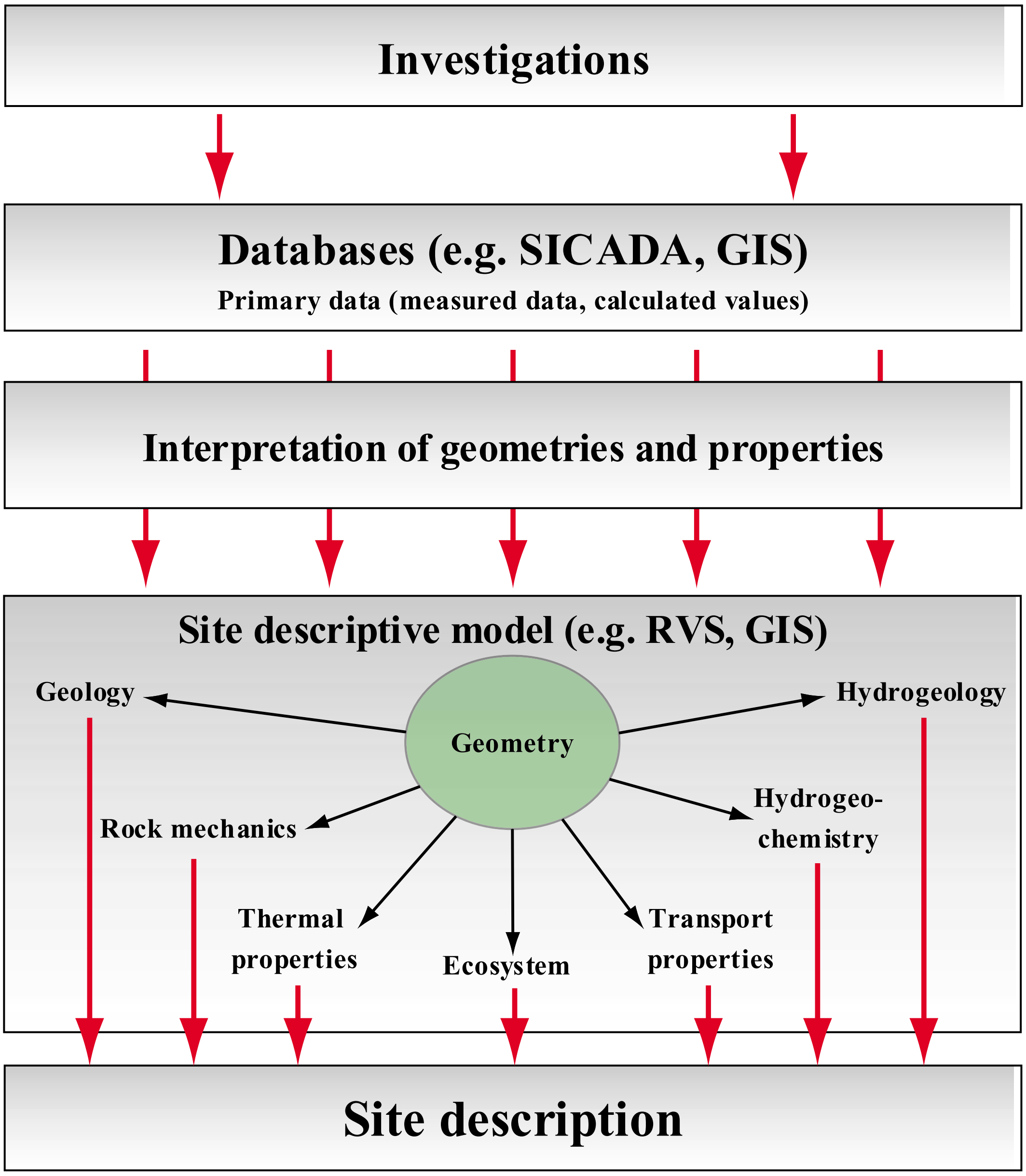

***Figure 1-1.** The primary data from the investigations are collected in databases. Data are interpreted and presented in a site descriptive model, which consists of a description of the geometry of the different units in the model and the corresponding properties of the site. The "site description" then consists of the site descriptive model together with the databases on which the model is based.*

Subdivision of the site investigation 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, 1997/. The site descriptive model is devised and updated stepwise as the site investigation progresses (Table 1-1). The starting point for this process of model development is the *site descriptive model of version 0*. It forms the important framework for the new model versions, which are successively developed, as new information becomes available. Each discipline-specific model is developed progressively from general regional to more detailed local descriptions during the stepwise execution of the site investigation.

Table 1-1. Different versions of the site descriptive models that are developed during the site investigation /SKB 2001b/. The first site descriptive model, version 0, is developed prior to 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 priority site will be chosen.	General model, above all on regional scale (version 0).
Initial site investigation	General surveys from air, surface and short boreholes.	Area and priority site (regional and local scale).	Choice of priority site. General model (version 1.1).
	Investigations from surface and some deep boreholes.	Priority site (regional environs).	Preliminary model on local and regional scales (version 1.2). Preliminary site description.
Complete site investigation	Investigations in several deep boreholes and supplementary ground surveys.	Priority site. Regional environs.	Model on regional and local scale (version 2.1).
	More deep boreholes and supplementary ground surveys.	Priority site. Regional environs.	Revised model on regional and local scale (version 2.2).
	More supplementary surveys.	Priority site. Regional environs.	Finished model on regional and local scale (version 2.x). Site description.

The site descriptive model version 0 is above all developed on a regional scale. Its prime merit is that it highlights the strengths and weaknesses in the data coverage and the knowledge of the present state as well as of naturally ongoing processes in the regional environs of the potential site. It is furthermore expected to reflect the current view of the site-specific tasks to be addressed, especially at the initial stage of the site investigation. As such, it provides the necessary constraints for early survey design. This model, hereafter called the regional model v0, is based on the information available at the start of the site investigation, that is, mainly data from the feasibility studies, other existing data and field checks. Its character is predominantly two-dimensional.

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

1.3 The Forsmark regional model area

1.3.1 The Forsmark candidate area

The Forsmark candidate area, as defined by the feasibility study /SKB, 2000a/, is located in northern Uppland within the municipality of Östhammar, adjacent to the Forsmark nuclear power plant (Figure 1-2). The town Östhammar is located 20 km southeast of the area.

The access to the Forsmark candidate area is good, mainly by way of road 76 running along the coast, immediately southwest of the area. There is also an excellent road to the Forsmark nuclear power plant and the final repository for radioactive operational waste (SFR). Within the candidate area there are a few minor roads, mainly used for forestry and local transports. The area can also be accessed from the sea via the harbour located at the Forsmark nuclear power plant and SFR. There is no railway connection to the area.

1.3.2 Extension of the Forsmark regional model area

The Forsmark candidate area is located adjacent to the shoreline of Öregrundsgrepen (Figure 1-2). It forms an area approximately 6 km long and 2 km wide, elongated parallel to the larger deformation zones in the region, i.e. northwest to southeast. The main direction for groundwater flow is perpendicular to the coastline, i.e. from southwest towards northeast. Studies within the SAFE-project /Kautsky, 2001/ have shown that future land rise (shoreline displacement) could create new land areas, which could be used for future agricultural activities in the present Öregrundsgrepen.

The regional deformation zones on the inland side of the site were considered important to include in the regional model area since they may affect boundary conditions for groundwater flow and rock mechanics. Of these zones, the fracture zone which extends through the village Forsmark, is one of the more prominent (see also Chapter 4, Geology).

Based on the extent of the Forsmark candidate area, the topography, future shore level displacement and the bedrock structures, the extension of the regional model v0 area is defined by the coordinates (defined in RAK RT 90 2.5 gon V) in Table 1-2. This national grid is hereafter referred to as RAK. The regional model area (Figure 1-2) forms an area of 165 km², 15 km long and 11 km wide, extending in a NE-SW direction. Around 100 km², or 60% of the area is covered by the sea. This regional model area is considered to capture both the upstream and downstream hydrogeological conditions.

Table 1-2. Geographical definition of the Forsmark regional model area. Co-ordinates given in meters (RAK RT 90 2.5 gon V).

RAK Y (East)	RAK X (North)
1625400	6699300
1633178	6691522
1643785	6702129
1636007	6709907

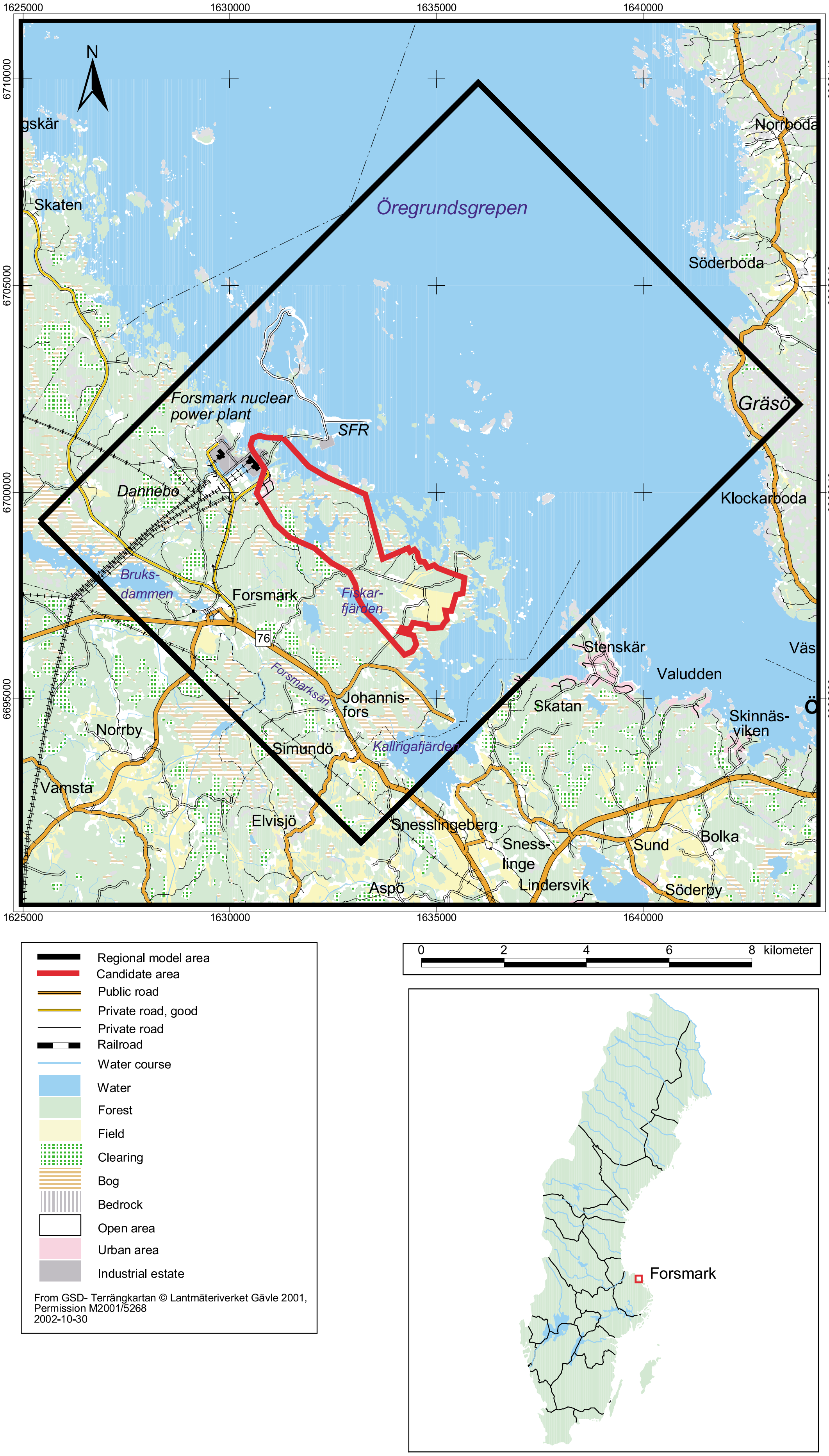

Figure 1-2. *The Forsmark candidate area and the Forsmark regional model area.*

1.3.3 Geomorphology

The Precambrian crystalline bedrock primarily determines the features of the present relief of the northern part of the province Uppland. The influence of overlying glacial and postglacial deposits is less marked, with the exception of the esker Uppsalaåsen. During Late Precambrian times, weathering and erosion processes wore down an originally mountainous landscape to a fairly flat and low-lying peneplain, called the sub-Cambrian peneplain. Structurally controlled valleys and fault-line escarpments are however typical bedrock forms of which the valley of the river Forsmarksån is one example.

The surface of the Forsmark regional model area forms a part of the sub-Cambrian peneplain. The peneplain in this region is rather flat with a gentle slope to the NE. The area also shows a low terrain relief with gentle valleys/depressions mainly oriented in a NW-SE direction. The Forsmark candidate area, between the Forsmark nuclear power plant (Forsmarksverket) and Kallrigafjärden, constitutes a low altitude area. The area immediately to the SW, between Fiskarfjärden and the river Forsmarksån, builds a slightly elevated area, elongated in a NW-SE direction. Kallrigafjärden defines a local, gentle depression, extended in a NE-SW direction. In the sea area, referred to as Öregrundsgrepen, a major depression in a NNW-SSE direction occurs directly west of the island Gräsö.

Bruksdammen and Forsmarksån constitute the major drainage in the area. The drainage system runs from the NW to an outlet in the southwestern part of Kallrigafjärden.

The highest point in the Forsmark regional model area is located in the eastern corner, approximately 2 km north of Bruksdammen. The elevation is around 25–27 m above sea level, without any clear peak. About 100 km² of the regional model area, or 60%, is covered by the sea and the lowest part, at around 40 m depths, is located in Öregrundsgrepen, directly west of Gräsö.

1.3.4 SFR – Final repository for radioactive operational waste

SFR is the final repository for radioactive operational waste located close to the Forsmark power plant, see Figure 1-3. It consists of access tunnels and deposition tunnels for different kinds of low and intermediate level radioactive waste. The largest rock cavern of SFR is a silo with a height of 60 metres and a diameter of 30 metres. The total amount of rock excavated from SFR during construction is about 430,000 m^3. The total inflow of groundwater to SFR is measured at a regular basis. In 1994 this figure was 550 litres per hour which is considered normal for a facility of this size.

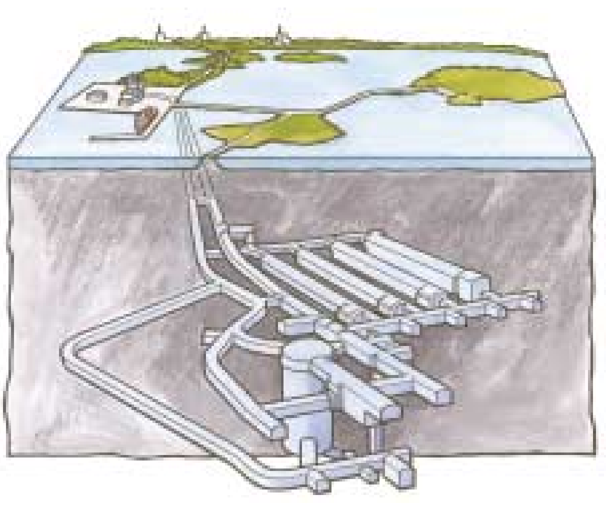

Figure 1-3. *The final repository for radioactive operational waste (SFR).*

1.4 Regional model v0 – content and modelling tools

As described in Section 1.1 and shown in Figure 1-1, the site descriptive model, independently of scale, is expected to describe the geometry and properties of the site in terms of the seven different "disciplines" (SKB terminology) geology, rock mechanics, thermal properties, surface ecosystems, transport properties, hydrogeochemistry and hydrogeology. In this report all disciplines but "Thermal" and "Transport properties" are addressed. The two exceptions are motivated by the absence of relevant data at this stage.

The site-descriptive model is developed and presented with the aid of both geographic information systems (GIS) and SKB's CAD-based computer tool, Rock Visualization System (RVS), together with underlying databases. The GIS utilizes the programs ArcView® and ArcInfo®. 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 for the interpretation of the database's primary data, especially for identification of deformation zones and their extent, i.e. for setting up the geometric lattice of the site-specific models.

At present, RVS is being refined such that interpreted properties for the geometric units can be entered and administrated in a given discipline-oriented structure /Munier and Hermanson, 2001/. The application will include standard procedures for version management to provide traceability and consistency between different disciplines. It will also show what data underlie a given model version and who has performed the interpretation. Model version and other information on traceability are 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 other software.

2 Data inventory

The primary data from the Forsmark regional model area is collected in a database, either SICADA or GIS. Specifically, version 0 differs from subsequent site description models in that the collection of new data is very limited. The major source of data for version 0 is information from the performed feasibility studies together with other existing data sources. The preparatory work for the site investigation has however also included data collection and compilation not carried out during the feasibility studies, especially regarding the discipline “Ecosystems”.

This chapter contains:

- A general description of existing geographical data, of which most is stored in GIS.
- An inventory of data already inserted into the databases SICADA or GIS at SKB, as well as data from other sources.

2.1 Geographical data

The major source of digital and analogue geographical data is Lantmäteriet (the National Land Survey of Sweden). Important digital information that has been acquired from Lantmäteriet and stored in the GIS database of SKB is briefly described below. The different areas in the region covered by digital maps, orthophoto and elevation data are presented in Figure 2-1. All data described are represented in the Swedish national grid. The co-ordinate system is for:

- X/Y (N/E): the national 2.5 gon V, RT 90 system (“RAK”).
- Z (elevation): the national RH 70 levelling system.

The general map (previously called the red map) database provides a uniform national coverage regarding the presentation of area, line and point objects, adapted to the scale 1:250,000 and the database contains the following components:

- Public and private roads and railway lines.
- Sea, lakes, built-up areas (two classes), forest, open land, alvar, mountain areas above the tree line, glaciers and marshland.
- Watercourses.
- Administrative divisions (national, territorial, county, municipal and parish boundaries) and provincial boundaries.
- National parks, nature and private reserves.
- Nature conservancy areas and Crown Forest reserves.
- Bird and seal protection reserves.
- Military areas.

- Power transmission lines.
- Line symbols (dams, airports, mountain tracks, hiking trails, etc).
- Point symbols (elevation points, mines, towers, houses etc).
- Names of buildings, natural features and explanatory text.

The topographic map (previously called the green map or version T5) represents a uniform national coverage regarding the presentation of area, line and point objects, adapted to the scale 1:50,000. The information is divided into separate layers that contain the following themes (according to the terminology of the ArcView software):

- Roads and railways, symbols for stations, bascule bridges and tunnels.
- Other line and point objects such as boundaries, power transmission lines, streams and various symbols.
- Depth contours.
- Land-use classification: bodies of water, forest (2 classes), arable land, fruit farms, clearings, built-up areas (5 classes), and open land (2 classes).
- Areas, which overlap the areas listed above: marshland (3 classes), rock outcrops and peat cutting areas.
- Areas with large boulders.
- Text.

The cadastral index map (previously called the economic map) provides presentation of area, line and point objects, adapted to the scale 1:10,000–20,000. The database contains:

- Administrative division and real estate boundaries.
- Hydrography.
- Land use.
- Communications.
- Developed areas.
- Restricted land-use.

The digital orthophoto is stored in a raster format produced by scanning, image processing and ortho-rectification of high-quality aerial photographs. When the database is created or updated, the latest aerial photography taken for the national mapping program is utilised and a national coverage is provided. Up-to-date raster databases are produced on a regular basis. The base comprises an 8-bit image for each 5x5 km grid and the spatial resolution is 1 metre. Thus, each file contains 5,000 x 5,000 pixels.

Elevation data, covering the land area, is available for the whole of Sweden from the GSD – Elevation database. The elevation data are produced as 50 m grid cells by means of stereo-model digitalisation of aerial photographs and automatic digitisation of elevation curves from the cadastral index maps. The data have a maximum standard error of ±2.5 metres, and are delivered with an accuracy of 0.1 metre. The latest revision of the database was completed in 1993. Complementary data in the sea area are *bathymetric data* from nautical charts, available from the Swedish Maritime Administration.

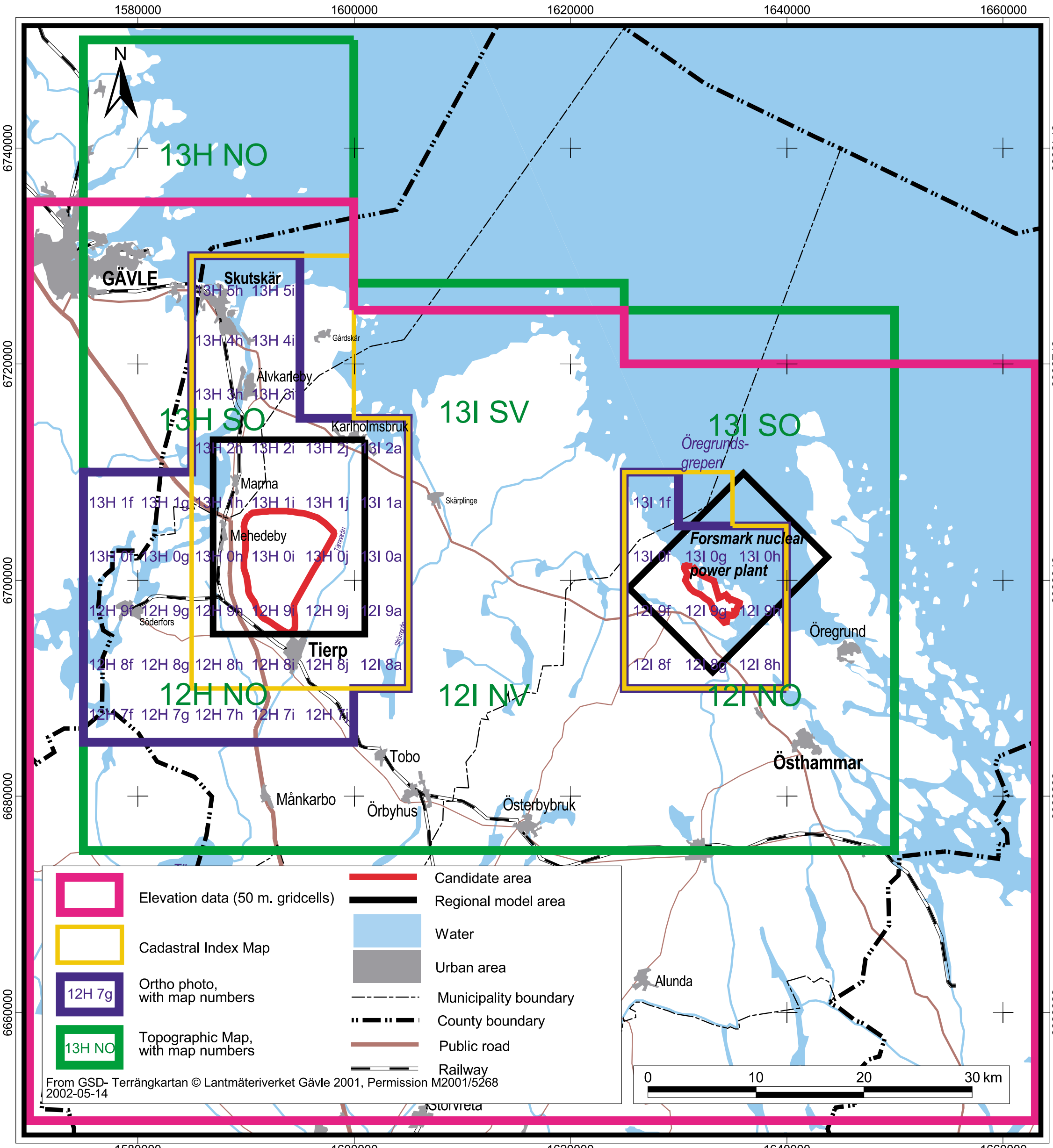

Figure 2-1. The distribution of maps, orthophotos and elevation data available in the GIS database of SKB over the northern part of the province Uppland and the Forsmark regional model area.

2.2 Inventory of data sources

The inventory of data aimed both at listing data which were already included in the databases SICADA or GIS at SKB, as well as finding data from other sources. This subdivision is also noted in the presentation of the results where the general inventory of data sources is presented in Section 2.2.1 and the inventory of SICADA in Section 2.2.2. Conclusions on the results from both activities are presented in Section 2.2.3.

The overall aim of the inventory was to visualise and structure existing data in the Forsmark regional model area in order to facilitate forthcoming modelling and planning of field investigations. The results also serve for planning of future data input. Some digitalisation has already started within the framework of the current project, such as collection of co-ordinate information on primary data, e.g. locations of drill-holes and tunnels. The major data insertion, however, remains the responsibility of the site investigation team at Forsmark.

The results from the entire inventory work, including a complete listing of the inventory database (see Table 2-1), will be presented as a separate report.

2.2.1 Inventory of data sources other than SICADA

Methodology

The inventory covered data from the Forsmark regional model area, as defined in Section 1.3, and was focused on complementary data sources containing information not fully evaluated in the Östhammar feasibility study. The work was adapted to the scale 1:50,000–1:100,000. Consideration of more detailed information was, in general, beyond the scope of the study.

The first step of the work consisted of making compilations and listing of different data sources, followed by an inventory of these sources. The inventory was initially guided by interviewing key persons and, subsequently, follow-up inventories were made. A literature search was performed using selected keywords, map-sheet identities, co-ordinate windows, project and location names etc., all specifically adapted to the area. The search criteria that revealed a hit were listed in the inventory database. The "Georegister" at SGU (Geological Survey of Sweden) and the register "Bibas" at SKB were the main sources for the literature search.

In the next step, certain judgements regarding the data sets were made. The judgements were related to the importance of each data set for the site investigations and furthermore to the need for insertion of the data set into the GIS- and/or SICADA-databases of SKB.

Before the inventory started, a data base structure was designed. The structure was to a high degree dependent on the structure listed in the /SKB, 2001b/ and oriented towards the major disciplines. The format was Microsoft Access. The database is constructed in Swedish and the structure is further explained in Table 2-1. Successively during the inventory, information found about each data set was inserted into the database. Some fields were compulsory (**bold text**) while others could be left blank.

The inventory was divided into a number of Inventory objects (major sources of information), see Table 2-2.

The sources of data identified were subsequently catalogued into different information epochs, often related to a specific project, such as different phases of investigations, engineering or construction work. These epochs are often associated with a specific geographic area and this information has been used to geographically describe the information source in an ArcView GIS presentation of the Forsmark regional model area (Figure 2-2 and 2-3). In some cases, it was difficult to decide to which epoch the information belonged. Also, some work within a given epoch may have been performed at another locality.

Table 2-1. The structure of the database used for the inventory

Field	Content
ID_nr	**10** ***<unique serial number together with the area name in the field ID_Plats>***
ID_Plats	**Area name: TN=Tierp norra; FM=Forsmark; SM=Simpevarp.**
Ämnesområde	**Discipline, according to nomenclature in SKB R-01-10.**
Parametergrupp	Parameter group, according to nomenclature in SKB R-01-10.
Informationsmängd_1	Type of information. General description. Heading or title in Report or Figure.
Informationsmängd_2	More detailed description of the information.
Parameter	Parameter, according to nomenclature in SKB R-01-10.
Referens	Report or Figure. Individual. Or other reference.
Geografisk beskrivning	Area, coverage and extension. Information density. Scale. Co-ordinate system. Type of coverage: area/line/point.
Datakälla	Data producer. Storage of data.
Aktualitet	Date of creation/revision of the data.
Dataform	Information state: Digital format, map, plan, report etc.
Sökväg	Data tracking. How to search for data.
Värdering	**Valuation of information.** **A. Necessary to examine the information in more detail for further prioritisation.** **B. No further inventory needed.**
Modell, Regional/Lokal	Significance for the regional or local model
Prioritet	**Priority:** **1. Data insertion recommended.** **2. Data insertion may be considered.** **3. No data insertion necessary.** **4. Cannot judge (detailed examination needed).**
ÄA beslut	Recommendation by person responsible for each discipline.
SKB beslut	Decision by SKB.
Kommentar	Other information. Foreseen problems. Timing.
Inventeringsobjekt	**Inventory object. Source of inventory entry.**
Epok	**Epoch for which the information was collected.** ***<link to ArcView GIS>***
Datainlagring – status	Status of data storage.

Table 2-2. List of inventory objects.

Inventeringsobjekt	Inventory object
Basdata (stödjande data)	SKB GIS-data, support data in ongoing projects.
Bergsstaten	Mining Inspector register.
Litteratursökning FM	Literature search performed.
Geosigma AB	Geosigma AB's archives.
Mineralkontoret SGU	SGU Minerals Information Office, Malå.
SICADA	SICADA version valid 2001-11-01, see Chapter 2.2.2 below.
SGU	Delivery of "Förstudie Östhammar" data. Compilation valid 2001-11-01.
SKB GIS ver.5.0	Basic data from SKB GIS version 5.0. Valid: 2001-10-16.
FM Intervjuer och uppföljningar	Interview of key persons and subsequent inventories that were called to attention.
Ytnära ekosystem	Ecosystem. Data compilation, valid 2001-10-02.

The results are primarily presented with regard to the information epochs of the Forsmark regional model area. In the database, the results are briefly described in a table format, with important comments highlighted in **bold** text (see Table 2-3). The data quantity and the extent of storage in SKB GIS or SICADA systems have been summarised in general terms, as described in Table 2-4. The epochs for which the data to a major extent are already stored in SKB GIS or SICADA are highlighted in **blue**.

A general assessment of the items "Valuation" and "Priority" of the full data-set is also added. The classification is the same as in Table 2-1;

A. Necessary to examine the information in more detail for further prioritisation.

B. No further inventory required.

1. Data insertion recommended.
2. Data insertion may be considered.
3. No data insertion necessary.
4. Cannot judge (detailed examination needed).

Table 2-3. Example of an epoch from the Forsmark regional model area.

No	Epoch	Time Period	Information content Comments *No of entries, No of A-valuation and No of entries in priority class 1,2,3,4*	Data Quantity ----- Fraction stored in SKB GIS/SICADA	Valuation ----- Priority
2	**Förundersökningar Forsmarksverket**	1970–71	Investigations for establishing nuclear power plants at Forsmark. **Important primary geology data.** *No of Entries: 18 No of A-valuation: 18* *Priority class 1,2,3,4: 16,0,0,2*	Moderate ----- None	**A** ----- **1**

Table 2-4. Concepts used to describe data quantity and data storage.

	Data Quantity	Stored in SKB GIS/SICADA
None	No data available	No data stored
Low	Limited amount of data	Only a limited fraction of the available data stored
Moderate	Moderate amount of data	Moderate amount of available the data stored
High	Large amount of data *(i.e. Data collected at the Äspö HRL is regarded as a large amount)*	Most of the available data stored

Results

Table 2-5 describes the results in relation to the inventory object. This table gives an overview of how the data is distributed between different disciplines and inventory objects.

The information content and different epochs, as identified in the Forsmark regional model area, are presented in Table 2-6 and are linked to geographical areas presented in Figure 2-2 and 2-3.

Table 2-5. Results distributed per Inventory object.

Inventory object	Information content Comments *No of entries, No of A-valuation and No of entries in priority class 1,2,3,4*	Data Quantity ----- Fraction stored in SKB GIS/SICADA	Summary Valuation ----- Priority
Basdata_ stödjande data Basic data Support data	Mainly data produced in the preparation for site investigations. Most of the data is in SKB GIS-format. *No of entries: 17 No of A-valuation: 0 and No of entries in priority class 1,2,3,4: 0,0,17,0*	Moderate ----- High	**B** ----- **3**
Bergsstaten The Mining Inspector	No data noted in the Forsmark model area. *No of entries: 0 No of A-valuation: 0 and No of entries in priority class 1,2,3,4: 0,0,0,0*	None ----- None	**B** ----- **3**
Litteratursökning_FM Literature search	76 entries concern Geology and 48 entries concern Hydrogeology. 12 entries are directed towards Rock mechanics. Most of the data is from the Forsmark power plant construction epochs. 35 entries concern the discipline Ecosystems. *No of entries: 171 No of A-valuation: 171 and No of entries in priority class 1,2,3,4: 115,53,0,3*	High ----- Low	**A** ----- **1(2)**
Geosigma AB	Mainly drillhole data from KFO01 and SFR. Also drillcore storage. *No of entries: 16 No of A-valuation: 16 and No of entries in priority class 1,2,3,4: 15,0,0,1*	Moderate ----- Low	**A** ----- **1**
Mineralkontoret_SGU SGU Minerals Office	Limited surface geochemistry data and ore deposit data. Airborne and ground geophysical data. Drillcore storage in Malå. *No of entries: 15 No of A-valuation: 15 and No of entries in priority class 1,2,3,4: 11,1,1,2*	Low ----- None	**A** ----- **1**
SICADA	The SICADA entry represents “summary” entries from The SICADA inventory, further described in Chapter 2.2.2. *No of entries: 5 No of A-valuation: 0 and No of entries in priority class 1,2,3,4: 0,0,5,0*	Moderate ----- High	**B** ----- **3**
SGU	Delivery of “Förstudie Östhammar” geology data is on going. Most of the data will be delivered in SKB GIS-format. Remaining data from field follow up stages will need some data input. *No of entries: 29 No of A-valuation: 19 and No of entries in priority class 1,2,3,4: 19,1,9,0*	Moderate ----- High	**A** ----- **1**

Inventory object	Information content Comments *No of entries, No of A-valuation and No of entries in priority class 1,2,3,4*	Data Quantity ----- Fraction stored in SKB GIS/SICADA	Summary Valuation ----- Priority
SKB_GIS_ver_5_0	Data stored in SKB GIS-database, version 5.0. Valid 2001-10-16. Hence all data in SKB GIS format. Mainly support data. *No of entries: 149 No of A-valuation: 0 and No of entries in priority class 1,2,3,4: 0,0,149,0*	Moderate ----- High	**B** ----- **3**
FM_Intervjuer_ Uppföljningar Interviews and subsequent follow-up	42 entries concern Geology and 14 entries concern Hydrogeology and Hydrogeochemistry. 3 entries are directed towards Rock mechanics. Most of the data is from the Forsmark power plant construction epochs. *No of entries: 68 No of A-valuation: 64 and No of entries in priority class 1,2,3,4: 38,5,16,9*	Moderate ----- Low	**A** ----- **1**
Vattenfall_Arkiv Vattenfall AB archive	This information source is very important and comprehensive and holds 448 entries. 166 entries concern Geology and 8 entries concern Hydrogeology and Hydrogeochemistry. 142 entries are directed towards the discipline Rock mechanics. Most of the data is from the Forsmark power plant construction epochs. 7 entries concern the discipline Ecosystems. 127 entries concern the discipline Support data/Basic data. *No of entries: 448 No of A-valuation: 277 and No of entries in priority class 1,2,3,4: 128,0,0,320*	High ----- Low	**A** ----- **1**
Ytnära_ekosystem Ecosystem	Most of the data collected in the preparation for site investigations. Mainly stored in SKB GIS-format. *No of entries: 90 No of A-valuation: 26 and No of entries in priority class 1,2,3,4: 0,0,62,28*	Moderate ----- High	**B** ----- **3**

Table 2-6. Information content and epochs identified in the Forsmark regional model area. The epochs are linked to the geographical areas presented in Figure 2-2 and 2-3.

No	Epoch	Time Period	Information content Comments *No of entries, No of A-valuation and No of entries in priority class 1,2,3,4*	Data Quantity ––––– Fraction stored in SKB GIS/SICADA	Summary Valuation ––––– Priority
1	**Lokaliserings-förutsättningar Upplandskusten**	1960´s	Prerequisite for establishing a nuclear power plant on the Uppland coast. No information found from this epoch. *No of Entries: 0 No of A-valuation: 0 Priority class 1,2,3,4: 0,0,0,0*	None ––––– None	**B** ––––– **3**
2	**Förundersökningar Forsmarksverket**	1970–71	Investigations for establishing nuclear power plants at Forsmark. **Important primary geology data.** *No of Entries: 18 No of A-valuation: 18 Priority class 1,2,3,4: 16,0,0,2*	Moderate ––––– None	**A** ––––– **1**
3	**Norr-Kasudden**	1970´s	Military installation. Might provide geological information. Close to the Singö line. *No of Entries: 1 No of A-valuation: 1 Priority class 1,2,3,4: 0,0,0,1*	None ––––– None	**A** ––––– **4**
4	**Förundersökningar F1 och 2**	1971–73	Site investigation for the Forsmark 1&2, power plants. **Important primary geology data.** *No of Entries: 41 No of A-valuation: 40 Priority class 1,2,3,4: 31,0,0,10*	Moderate ––––– None	**A** ––––– **1**
5	**Biotestsjön**	1971–73	Biototest lake, developed during the construction of the Forsmark 1&2, power plants. Some geotechnical and geological data. *No of Entries: 11 No of A-valuation: 11 Priority class 1,2,3,4: 6,0,0,5*	Low ––––– None	**A** ––––– **1(4)**
6	**Byggnation F1 och 2**	1971–78	Construction of the Forsmark 1&2, power plants. **Important primary geology data.** *No of Entries: 62 No of A-valuation: 53 Priority class 1,2,3,4: 21,2,1,29*	Moderate ––––– None	**A** ––––– **1(4)**
7	**Hamn, inseglingsränna**	1973	Harbour investigation and construction, bathymetry. **Some geotechnical data.** *No of Entries: 8 No of A-valuation: 8 Priority class 1,2,3,4: 2,0,0,6*	Low ––––– None	**A** ––––– **4**
8	**Grundvatten-utredningar**	1970–75?	Investigations on water supply to Forsmark power plants. **Some primary geology data and possibly hydro-data.** *No of Entries: 6 No of A-valuation: 6 Priority class 1,2,3,4: 3,3,0,0*	Low ––––– None?	**A** ––––– **1(2)**

No	Epoch	Time Period	Information content Comments ***No of entries, No of A-valuation and No of entries in priority class 1,2,3,4***	Data Quantity ----- Fraction stored in SKB GIS/SICADA	Summary Valuation ----- Priority
9	**Forsmarks bruk, Bruksdammarna**	1970´s	As above and engineering work for pipeline. **Some primary geology data**. *No of Entries: 24 No of A-valuation: 9* *Priority class 1,2,3,4: 5,0,0,19*	Low ----- None	**A** ----- **4**
10	**Förundersökningar F3 och (4,5,6)**	1973–76	Site investigation for the Forsmark 3 (4,5,6) power plants. **Important primary geology data.** *No of Entries: 22 No of A-valuation: 22* *Priority class 1,2,3,4: 18,0,0,4*	Moderate ----- None	**A** ----- **1**
11	**Byggnation F3**	1977–85	Construction of the Forsmark 3 power plant. **Important primary geology data.** *No of Entries: 85 No of A-valuation: 58* *Priority class 1,2,3,4: 28,1,1,55*	Moderate ----- None	**A** ----- **1(4)**
12	**FUD** *Research work performed mainly by Anders Carlsson, Vattenfall AB and Tommy Olsson, SGU*	1977–78, -85	Research projects on mainly **rock mechanics**. Deep drillhole. **Important primary geology data.** *A large amount of work performed was located to the area immediately north of the Forsmark 3, power plant. However, work identified to this epoch, has in several cases also partly been performed in other parts of the Forsmark area.* *No of Entries: 29 No of A-valuation: 28* *Priority class 1,2,3,4: 23,2,2,2*	Moderate ----- None?	**A** ----- **1**
13	**KBS**	1974–78	Initial work within the nuclear waste programme. Deep drillhole. **Important primary geology data.** *No of Entries: 13 No of A-valuation: 13* *Priority class 1,2,3,4: 8,3,0,2*	Low ----- None	**A** ----- **1**
14	**Förstudie CLAB Forsmark**	1977–78	Feasibility study for CLAB. **Important primary geology data.** *No of Entries: 7 No of A-valuation: 7* *Priority class 1,2,3,4: 7,0,0,0*	Moderate ----- None	**A** ----- **1**
15	**Förundersökningar SFR**	1980–83	Site investigation for SFR. **Important primary geology data.** *No of Entries: 23 No of A-valuation: 21* *Priority class 1,2,3,4: 18,1,2,2*	Moderate ----- Low	**A** ----- **1**
16	**Byggnation SFR**	1983–86	Construction of SFR. **Important primary geology data**. **Also Hydrogeology, hydrogeochemistry and rock mechanical data.** *No of Entries: 301 No of A-valuation: 179* *Priority class 1,2,3,4: 73,37,5,186*	Moderate ----- Moderate	**A** ----- **4(2,1)**

No	Epoch	Time Period	Information content Comments ***No of entries, No of A-valuation and No of entries in priority class 1,2,3,4***	Data Quantity ----- Fraction stored in SKB GIS/SICADA	Summary Valuation ----- Priority
17	**Likströmskabel**	1988–?	Direct-current (D.C.) cable, Sweden-Finland. **Some geotechnical data.** *No of Entries: 4 No of A-valuation: 4* *Priority class 1,2,3,4: 3,0,0,1*	Low ----- None	**A** ----- **1**
18	**Förstudie kolkraftverk FM**	1980´s	Feasibility study for a coal power plant. No information found from this epoch. *No of Entries: 1 No of A-valuation: 1* *Priority class 1,2,3,4: 0,0,0,1*	None ----- None	**A** ----- **4**
19	**SGU kartering**	1980´s	Regular geological mapping by SGU. **Important primary geology data.** *No of Entries: 1 No of A-valuation: 1* *Priority class 1,2,3,4: 0,1,0,0*	Low ----- None	**A** ----- **2**
20	**Förstudie Östhammar**	1996	Feasibility study Östhammar municipality. **Important primary geology data.** Ongoing data delivery in SKB specified formats. *No of Entries: 67 No of A-valuation: 13* *Priority class 1,2,3,4: 12,1,54,0*	Moderate ----- Moderate	**B** ----- **3**
21	**Förstudie Fältkontroll Östhammar**	1996, 1998	Feasibility study Östhammar municipality. Field reconnaissance. **Some primary geology data.** Ongoing data delivery in SKB specified formats. *No of Entries: 15 No of A-valuation: 8* *Priority class 1,2,3,4: 8,1,6,0*	Low ----- Low	**B** ----- **3**
22	**SAFE-projektet**	Late 1990´s	No specific inventory performed. **Important primary geology data.** **Also hydroand rock mechanical data.** A lot of data in digital form. Geometry model in CAD. Source for bathymetric data. *No of Entries: 52 No of A-valuation: 52* *Priority class 1,2,3,4: 23,0,0,29*	Moderate ----- Low/None?	**A** ----- **1(4)**
23	**Ospecificerat och regionalt i FM-området**	xxxx	Unspecified sources and regional data. The majority of the data are related to “Ytnära ekosystem” and “Stödjande data”, already in SKB GIS-format. **Only a few entries have Valuation A and Priority 1 or 2.** *No of Entries: 109 No of A-valuation: 23* *Priority class 1,2,3,4: 9,9,87,7*	Moderate ----- Moderate	**B** ----- **3**
24	**PLU-förberedelser FM**	2001–	Most of the data collected in the preparation for site investigations. Most data in SKB GIS-format. *No of Entries: 110 No of A-valuation: 15* *Priority class 1,2,3,4: 15,0,93,2*	Low ----- High	**B** ----- **3**

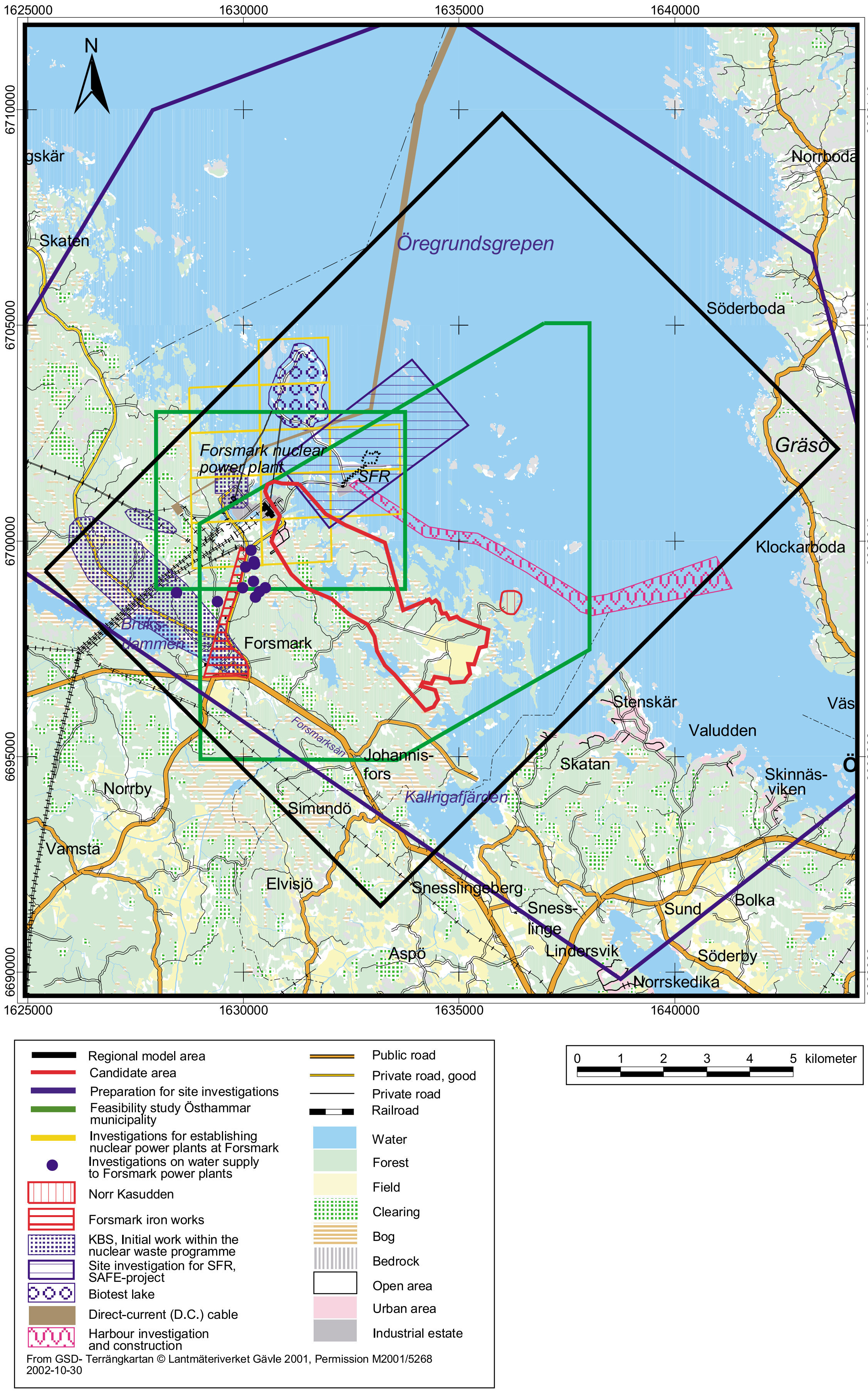

Figure 2-2. *Geographical areas, investigated in connection with the feasibility studies of the municipalities Tierp and Östhammar (Forsmark), linked to information epochs in the data inventory.*

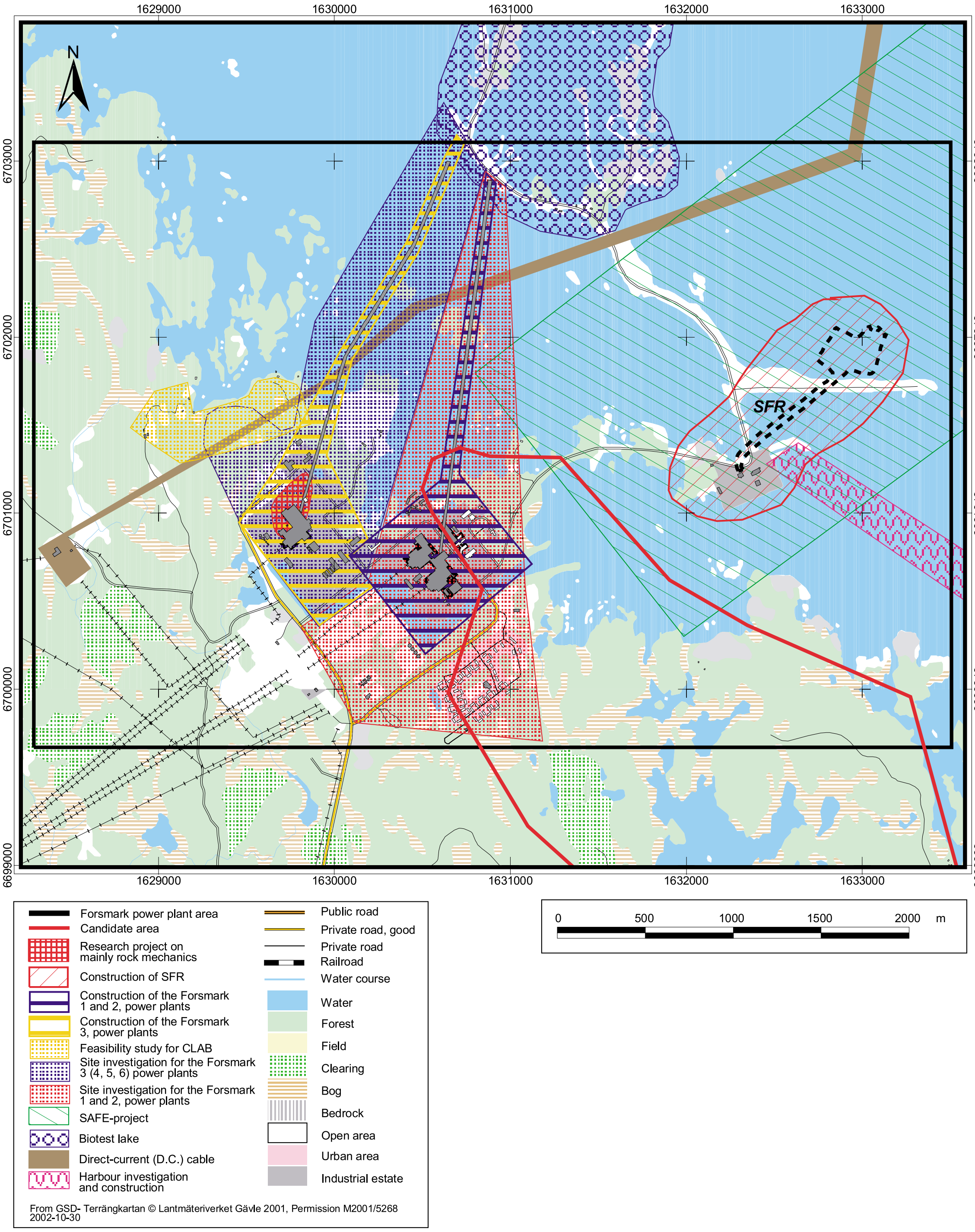

Figure 2-3. *Geographical areas, in the vicinity of the Forsmark nuclear power station and SFR, linked to information epochs in the data inventory.*

Table 2-7 gives a summary of the number of entries for different information epochs in relation to items such as valuation, priority, discipline and SKB data storage. This presentation serves as a guideline in the subsequent prioritisation of which data should be inserted into the SKB SICADA and/or GIS databases. The storage of data in SICADA is further described in Section 2.2.2.

All together 1,010 entries have been recorded. Only a minor portion of this information is already stored in SKB SICADA and/or GIS-format. 591 entries have valuation A, i.e. should be examined more in detail. Of these, 326 entries are given the priority 1, i.e. data input is recommended. However, the majority of the data is related to the pre-investigations and constructions of the nuclear power plants at Forsmark. The original information is in most cases stored at the archives of Vattenfall AB and has not yet been investigated in great detail.

The inventory indicates that a large amount of data is of primary interest for further evaluation. Figure 2-4 is an example of an important data set, which will give important geological information and where re-utilisation of the data will imply a great cost saving. The example shows an overview drawing of seismic profiling performed in the Forsmark construction area, carried out up to 1976, with the corresponding entry in the inventory database.

Table 2-7. Summary of the number of entries for different information epochs in relation to concepts like; valuation, priority, discipline and SKB data storage.

		No. of entries		Valuation		Priority				Discipline								SKB Data storage			
No	Epoch	Time period	Total	A	B	1	2	3	4	Geology	Rock mechanics	Hydrogeology	Hydrogeo-chemistry	Ecosystems	Support data	Transport properties	Thermal properties	Sicada	GIS (ver. 5.0 alt Support data)	Eco-system (GIS)	SGU (GIS)
1	Lokaliseringsförutsättningar _Upplandskusten	1960´s	0	0	0	0	0	0	0												
2	Förundersökningar_Forsmarksverket	1970-71	18	18	0	16	0	0	2	12					6						
3	Norr_Kasudden	1970´s ?	1	1	0	0	0	0	1						1						
4	Förundersökningar_F1ochF2	1971-73	41	40	1	31	0	0	10	38					3						
5	Biotestsjön	1971-73	11	11	0	6	0	0	5	4					7						
6	Byggnation_F1ochF2	1971-78	62	53	9	21	2	1	29	38	14	3			10						
7	Hamn_inseglingsränna	1973	8	8	0	2	0	0	6	6					2						
8	Grundvattenutredningar	1970-75 ?	6	6	0	3	3	0	0	1		4	1								
9	Forsmarks_bruk_Bruksdammarna	1970´s	24	9	15	5	0	0	19	7				8	9						
10	Förundersökningar_F3och4_5_6	1973-76	22	22	0	18	0	0	4	21					1						
11	Byggnation_F3	1977-85	85	58	27	28	1	1	55	45	18	4			19						
12	FUD	1977-78,-85	29	28	1	23	2	2	2	14	7	8									
13	KBS	1974-78	13	13	0	8	3	0	2	12		1									
14	Förstudie_CLAB_Forsmark	1977-78	7	7	0	7	0	0	0	7											
15	Förundersökningar_SFR	1980-83	23	21	2	18	1	2	2	16	1	5			1			1			
16	Byggnation_SFR	1983-86	301	179	122	73	37	5	186	76	117	37	1	1	72			3			
17	Likströmskabel	1988-?	4	4	0	3	0	0	1						4						
18	Förstudie_kolkraftverk_FM	1980´s ?	1	1	0	0	0	0	1	1											
19	SGU_kartering	1980´s	1	1	0	0	1	0	0	1											
20	Förstudie_Östhammar	1996	67	13	54	12	1	54	0	35		2	1	29					40	6	8
21	Förstudie_Fältkontroll_Östhammar	1998	15	8	7	8	1	6	0	15									5		1
22	SAFE_projektet	1990´s late	59	52	7	23	0	0	29	4		3		52							
23	Ospecificerat_regionalt_FM	xxxx	109	23	86	9	9	87	7	16		7		35	51				85		
24	PLU_förberedelser_FM	2001-	103	15	88	15	0	93	2			1		85	17			1	36	50	
		Sum:	1010	591	419	329	61	251	363	369	157	75	3	210	203	0	0	5	166	56	9

Nr	438
Område/plats	Forsmark
Ämnesområde	Geologi
Parametergrupp	Geofysik
Informationsmängd_1	Seismisk grundundersökning. Översikt
Informationsmängd_2	
Parameter	
Referens	905010
Geografisk beskrivning	Forsmark, 1:10000
DataKälla	Vattenfalls arkiv
Aktualitet	72-11, MO
Dataform	Cronaflex A1
Sökväg	0917, Råcksta
Värdering	A
Regional/Lokal?	
Prioritet	1
ÄA beslut	
SKB beslut	
Kommentar	Karin Lindberg 72-05 BSU. Omritad 76-03-05
Inventeringsobjekt	Vattenfall_Arkiv
Epok	Förundersökningar_Forsmarksverket
Datainlagring – status	

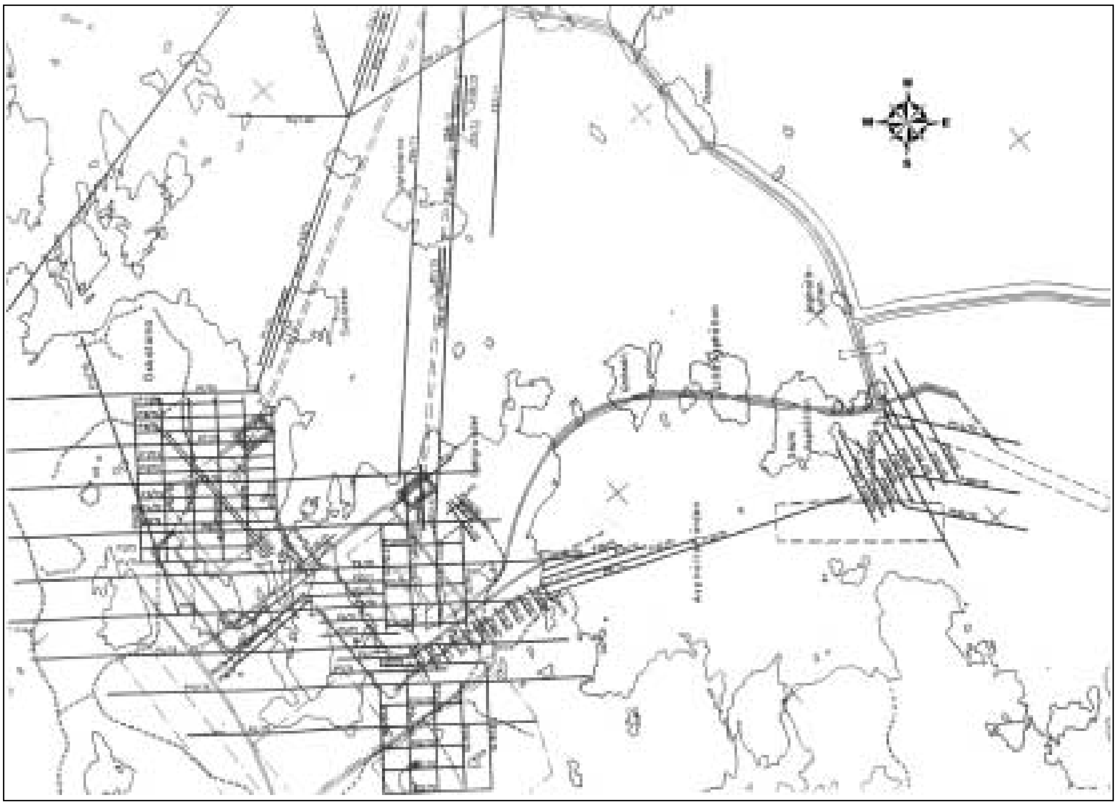

Figure 2-4. *Above: Example of an inventory database entry from the Vattenfall Archive, describing an overview drawing of seismic profiling performed in the Forsmark construction area. Below: Map (an extract from the actual drawing), showing the Forsmark construction area and the location of seismic profiles performed up to 1976.*

2.2.2 Inventory of SICADA

Within the project, an inventory of the SKB database SICADA was carried out in order to describe its content of data for the Forsmark regional model area.

SICADA database structure

The database SICADA contains descriptions of activities, such as investigations, constructions, installations etc. All activities are catalogued in the following structure:

- Biology
- Chemistry
- Engineering
- Geography
- Geophysics
- Geotechnics
- Hydrochemistry
- Hydrology
- Meteorology
- Rock mechanics

In SICADA, a series of tables are linked to the activities. The tables contain information about the activity and data from the activity. The number of tables typically varies between one and six. However, some activities are even linked to more tables. The structure of SICADA also allows insertion of an activity without entering data into the associated table.

Methodology

At the time of the inventory, data from the Forsmark regional model area had been stored in SICADA under the following three sub-areas ("sites" in SICADA vocabulary):

- Forsmark
- Forsmark New
- Forsmark SFR

The sub-area "Forsmark" basically covers the area near the Forsmark nuclear power plant. The sub-area "Forsmark New" covers the Forsmark candidate area, defined in the feasibility study as the area recommended for site investigation /SKB, 2000a/.

The result of the inventory was stored in Microsoft Excel-files. The activities found were examined with respect to data content by checking the tables associated with the activity. The data content was judged in a fast and rather subjective manner in order to achieve the goal within the limited time available. This pragmatic method did not give a very detailed description of the content in SICADA but was, however, considered to provide a useful diagnostic description. The result was inserted into the data base structure developed for the general inventory work, see Section 2.2.1 above, where also a brief list of the objects for the activities is found.

It was not considered possible to rank the quality of inserted data. However, it could be assumed that the quality is a function of several factors of which a few and likely the most important could be mentioned: year of activity, maturity of the investigation method applied, the skill of the entrepreneur and type of equipment used.

Results

A compilation of the result is displayed graphically in Figure 2-5. The height of the bar shows the amount of activities in every one of the ten groups (cp. SICADA database structure above). The colour of the bar shows the proportion of data, which appear to have been inserted from the activities. Besides Engineering, the Hydrochemistry group contains most activities from Forsmark/SFR. It was also recognised as a result of the inventory, that SICADA contains no data on Geology and Rock Mechanics from the Forsmark regional model area.

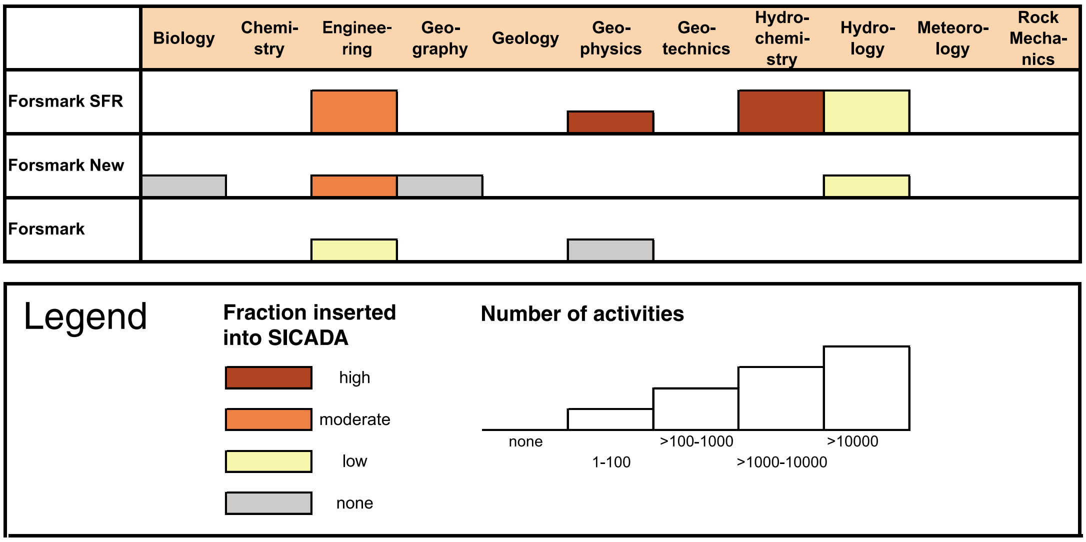

Figure 2-5. Forsmark regional model area. Number of activities and estimate of the fraction of data inserted from the activities in SICADA, as of November 2001.

2.2.3 Conclusions

The inventory of data from the Forsmark regional model area has indicated a large amount of information describing the pre-investigations and construction of the nuclear power plant and SFR at Forsmark. The databases at SKB (SICADA and GIS) have mainly been used to store data from site investigations and scientific experiments and not data from construction work. Hence, none of, or only very limited parts, of the construction related data, is stored in the databases at SKB. Furthermore, most of the data are not available in digital format. Much of the data can be classified as primary geological data, such as information from drillholes and tunnels as well as seismic profiles.

The inventory has also verified that geological information and information regarding rock mechanics from the entire Forsmark area in general, and for SFR in particular, never have been stored in the SICADA database.

The present site descriptive model (version 0) is above all a regional scale model. However, the local information described above, is of potential interest when modelling the geosphere in the northwestern part of the Forsmark area in more detail. It thus indicates the necessity for the site investigation team to consider what should be inserted into the databases of SKB. The planning of such an insertion should be based on the results of the present inventory work.

An inventory database has been created which is expected to provide an overview of the information identified. Furthermore, the results are displayed in a number of presentations in the ArcView GIS system.

3 Ecosystems

3.1 Introduction

This chapter describes the present (2001) status of knowledge of the ecosystems in the Forsmark regional model area and is a compilation over selected reports and papers, which describe the ecosystems. The biosphere may be defined in slightly different ways /e.g. The Biosphere, 1970; Campbell, 1993/. In this report, the biosphere has been defined as the surface ecosystem above the bedrock. This means that it includes the Quaternary deposits, surface water, groundwater in Quaternary deposits, humans and other biota as well as the surface hydrologic cycle and climate.

The intention has been to summarise all available data, but some sources of information may not have been recognised during the compilation. Upcoming versions of this report will remedy this effect. The information has been collected from different studies and therefore the investigated areas differ. The definition of these areas is not of importance for this presentation as long as the data is relevant for the Forsmark regional model area. In this chapter, the term "Forsmark area" is used in a more generall way, meaning different parts of the area close to the model area. For a definition of the different areas of investigation the reader is referred to the original references. No further synthesis has been made in this report, and the data and figures shown are chosen only as illustrative examples.

The major discipline "Ecosystems" is divided into different functional ecosystem types, which will be investigated and described further during the site investigation.

The functional ecosystem types are:

- Drainage areas
- Forest
- Wetland
- Agricultural land
- Lakes and rivers
- Sea

These ecosystems are built up of different entities, as further discussed in Section 3.1.1. Data for the different functional ecosystems is presented in Sections 3.2–3.7.

3.1.1 Biosphere system and entities

During the last years, SKB has continuously adapted and developed tools for ecosystem modelling /SKB, 2001a/. To identify the interactions and flux pathways in different ecosystems, a general interaction matrix has been developed, reproduced here as Figure 3-1. The matrix contains all identified interactions and should be seen as a tool which will be used to ascertain that no important entities or pathways involved in the transport of radionuclides in ecosystems are neglected when the safety analysis of the area is performed.

GEOSPHERE (B.C.)	a)Erosion/weath. b)Change in rock surface location	NONE	NONE	NONE	NONE	NONE	a)Material supply b)Settlement
a) Mech. load b) Consolidation	**Quaternary deposits** a)Relocation	a)Settlement b)Deposition	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption	a)Settlement b)Consumption c)Material supply
Root penetration a) Rock b) Tunnels c) Biological	Root growth	**Primary producers** a)Stimul/Inhib.	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply d)Material supply
Potential intrusion	a)Decomposition b)Bioturbation	a)Stimul./Inhib.	**Decomposers** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Material supply
Potential intrusion	Bioturbation	a)Stimul/Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	**Filter feeders** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply d)Material supply
Potential intrusion	Bioturbation	a)Stimul./Inhib. c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply	**Herbivores** a)Stimul/Inhib.	a)Stimul./Inhib. b)Food supply	a)Stimul./Inhib. b)Food supply d)Resource
Potential intrusion	Bioturbation	a)Stimul./Inhib.	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. c)Feeding	**Carnivores** a)Stimul/Inhib. b)Food supply c)Feeding	a)Stimul./Inhib. b)Food supply c)Feeding d)Resource
NONE	Disturbance *(dredging, digging)*	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. c)Feeding d)Dispersal/ Extermination	a)Stimul./Inhib. b)Food supply c)Feeding d)Dispersal/ Extermination e)Material use	**Humans** a)Stimul/Inhib.
a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath.	a)Erosion b)Water content change	a) Settlement b) Water uptake	a) Settlement b) Water uptake	NONE	a) Settlement b) Water uptake	a) Settlement b) Water uptake	a) Settlement b) Water use
a) Rech./disch. b) Press. change c) Mass flux d) Erosion/weath. e) Ice-load	Erosion *(icescoring)*	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water uptake	a)Settlement b)Relocation c)Water use
a) Mass flux b)Erosion/weath.	a) Sedimentation b) Precip./dissol. c) Erosion/weath.	a)Settlement b)Stimul./Inhib. c)Light attenu.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.
Gas transport	a)Erosion b)Deposition c)Oxidation	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	NONE	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.	a)Settlement b)Stimul./Inhib. c)Relocation d)Depos./Remov.
a)Heat transport b)Erosion/weath.	a)Weathering b)Thermal expans/contr	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.	a)Settlement b)Stimul./Inhib.
Contaminant transport	a) Surface dep./uptake b) Irradiation	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure	a) Int. exposure b) Ext. exposure
NONE	a) Import b) Land rise	a) Import b) Insolation	Import	Import	Import	Import	a)Import of energy b)Immigration

Figure 3-1. *The biosphere matrix, after /Kautsky et al, 2001/.*

	Discharge/ recharge	Discharge/ recharge	Mass flux	Gas transport	Heat transport	Contaminant transport	NONE
	a) Water transport b) Dehydration	a)Water transport b)Wave formation	a)Resuspension b)Leaching c)Sorpt./desorpt.	a)Resuspension b)Non-biol decomp c)Wind field changes d)Air pressure	a)Radiation b)Heat transport c)Heat storage	a)Sorption/desorpt. b)Dissolution	Export
	Root uptake	a)Interception b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod c)Wind retard.	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *detached outflow of plankton*
	Decomposition	a)Decomposition b)Retard./Accel. c)Uptake/Excret. d)Movement	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
	NONE	a)Water-pumping b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	NONE	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *detachment spawn*
	NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export
	NONE	a)Movement b)Retard./Accel. c)Uptake/Excret.	a)Uptake./Excret. b)Particle prod	a)Gas uptake/rel b)Part. trap/prod	a)Radiation b)Exo/Endo react. c)Heat transp.	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	Export *swimming running*
	a)Water extraction b)Artific.infiltr.	a)Movement b)Retard./Accel. c)Uptake/Excret. d)Covering	a)Excretion b)Filtering c)Pollution	a)Gas uptake/rel b)Part. trap/prod c)Pollution d)Wind retard/acc.	a)Radiation b)Exo/Endo react. c)Heat transp. d)Antropogen eff	a) Uptake/sorpt. b) Excretion c) Degradation d) Growth	a)Export of energy b)Emigration?
NONE (former topography)							
	Water in quarternary deposits	Discharge (recharge)	a) Erosion b) Mixing c) Dens. effects	a)Evapo./Cond. b)Sublimation	a)Heat transp. b)Heat storage	Mixing	Export
	Recharge (discharge)	**Surface water**	a) Mixing b)Dens. effects	a)Evapo./Cond. b)Sublimation c)Erosion *(seaspray/snowdrift)*	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Light reflection	Mixing	Export/import
	Water transport	Water transport	**Water composition**	a)Spray/Snowdrift b)Dissol./Degas.	a)Exo/Endo react. b)Light absorb. c)Light reflect./scatt. d)Adiab. compr.	a) Sorpt./desorpt. b) Dissol./precip. c) Sedimentation	Export
	a)Water transport b)Evapo./cond. c)Sublimation	a)Water transport b)Evapo./Cond. c)Precipitation d)Wind stress e)Sublimation	a)Precipitation b)Deposition c)Evapo./Cond. d)Dissol./Degas.	**Gas** **--------------** **Atmosphere**	a)Radiation b)Exo/Endo react. c)Heat transp. d)Heat storage e)Adiab.temp.change f)Phase changes	a)Mixing b)Sorpt./desorpt. c)Photochem. reactions	Export
	Phase transitions	a)Phase transitions b)Convection	a)Kinetics & chem equil. b)Property changes c)Mixing	a)Pressure change b)Phase transitions	**Temperature**	a)Kinetics & chem equil. b)Phase transitions	Export of heat
	NONE	NONE	a) Radiolysis b) Stab. isotopes c) Chem. react.	Phase transition	Heat from decay	**Radionuclides and toxicants** a) Decay	Export
	Import	a) Sea level changes b) Sea currents	Import	a)Import b)Photochem-reactions	a) Import of heat b) Insolation	External load of contaminants	**External conditions (B.C.)**

The biosphere matrix displays interactions (processes) between the different physical and biological components in the local biosphere. Further, the interactions between the local biosphere and the global biosphere are also included. This means that also the interactions with the geosphere and with the biosphere outside the Forsmark regional model area are considered, representing different boundary conditions of the system.

Some of the interactions and flux pathways in the biosphere matrix represent the surface environment at the Forsmark site, including:

- The parts of the surface environment that potentially may have an impact on a repository.
- Potential discharge areas and regions where any significant parts of potentially released radionuclides may migrate and give significant concentrations.

System state variables

The physical and biological components of the biosphere system are:

- Quaternary deposits
- Bedrock at the surface (outcrop)
- Buildings and structures such as roads, road-banks, bridges etc
- Vegetation
- Animal life
- Human life
- Water
- Gas and atmosphere
- Temperature
- Radionuclides and toxicants

These components are represented as diagonal elements in the biosphere matrix (Figure 3-1) and are numbered as element 1.1, 2.2 etc. The interactions between two components are numbered according to the lines of the components, e.g. the interactions between element 1.1 and 2.2 are shown as element 1.2 (influence of element 1.1 on element 2.2) and 2.1 (influence of element 2.2 on element 1.1).

For further definitions of the diagonal elements in the biosphere matrix and a thorough description of the identified interactions, see /Kautsky et al, 2001/.

Variables

Using the biosphere matrix (Figure 3-1), a number of variables have been selected. These variables are to be studied during site investigations to describe the different ecosystems and fluxes at the site. The variables are presented in /Lindborg and Kautsky, 2000/. This chapter uses the same variable system to describe the present knowledge of the different ecosystems selected.

3.1.2 Availability of data

Data concerning ecosystems in the Forsmark regional model area and its surroundings have been compiled and presented in a number of SKB reports. Important compilations, for other purposes and not focused on the Forsmark regional model area, have also been made by other organisations, e.g. Naturvårdsverket and Länsstyrelsen i Uppsala län. In the present report, references are generally made to these compilations.

3.2 Drainage areas

In a subdivision of major river catchment areas and residual catchment areas in Sweden, the Swedish Meteorological and Hydrological Institute identified 17 units, which are partly or in their entirety located within the county of Uppsala, /SMHI, 1985/. /Brunberg and Blomqvist, 1998/ further divided these units into 269 sub-units. The coastal area includes five major river catchment areas (terminology according to /SMHI, 1985/): catchment areas 53 (Dalälven), 54 (Tämnarån), 55 (Forsmarksån), 56 (Olandsån), and 57 (Skeboån). Between these river catchment areas there are another 5 residual catchment areas which, at least partly, are located in the county and which drain directly to the coast. The remaining catchment units of the county all drain to Lake Mälaren, the outlet of which is termed 61 River Norrström /Brunberg and Blomqvist, 1999/. The drainage areas of the Forsmark regional model area are shown in Figure 3-2.

The geology in the catchment areas of the Forsmark regional model area includes bedrock dominated by metagranitoids, covered by calcareous sandy till, postglacial clay and peat. The forest cover is dominantly coniferous, and the lakes, which are most commonly oligotrophic hardwater lakes, are to a large extent surrounded by mires. Inflow as well as outflow of water is often diffuse, via the surrounding mire. The lakes are small and shallow, with nutrient-poor and highly alkaline water. For more information about the lakes in the area, see Section 3.6.

The drainage areas in Forsmark regional model area will be described under the following headings:

- Meteorology
- Topography
- Surface hydrology
- Wells
- Pollutants

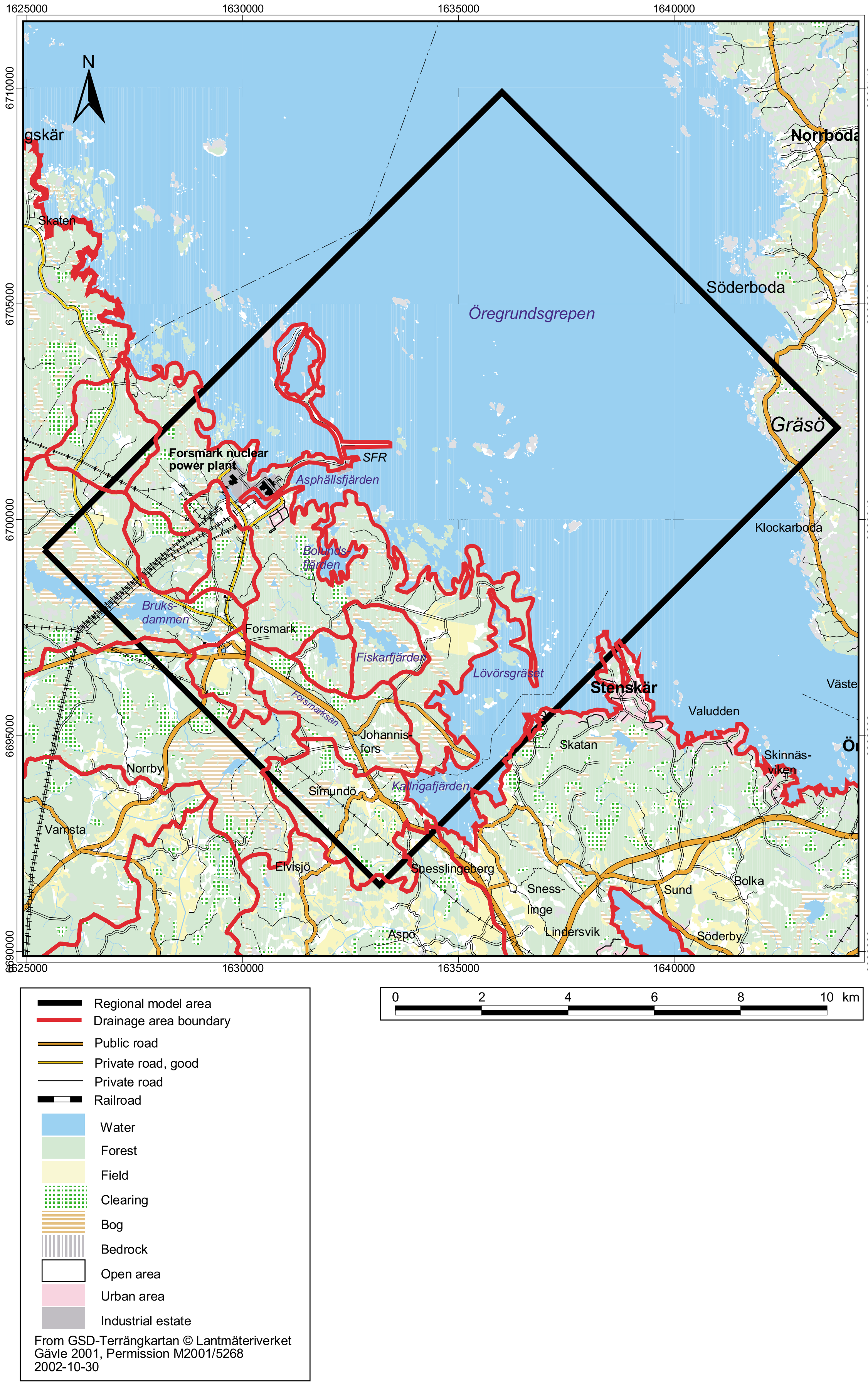

Figure 3-2. *Drainage areas in Forsmark after /SMHI, 1985/ and /Brunberg and Blomqvist, 1998/, as compiled in SKB-GIS 2002.*

3.2.1 Meteorology

Data input

The variables describing the meteorological conditions at Forsmark are wind direction, precipitation, temperature, length of vegetative period, sunshine time, snow coverage and snow depth. The available data has been compiled by /Lindell et al, 1999/ and /Larsson-McCann et al, 2002/, and the following summary is based on these compilations.

Distribution and character

Data from SMHI-stations are used for long term statistics. For most meteorological variables, data from the station Örskär are regarded as representative for coastal areas in the Östhammar area, including Forsmark. Örskär is an island north of Gräsö (Figure 1-2), approximately 20 km northeast of the Forsmark regional model area.

Northeastern Uppland, especially the coastal area, shows a *wind direction* distribution that differs from the common pattern of southern Sweden. The most frequent wind direction is from the north, but southern and southwestern winds are also frequent (Figure 3-3). Near-coast locations are far more exposed to strong winds than inland sites. The coastal areas are to a large extent composed of forest, so the high wind exposure at the coastline has very markedly decreased a few km inland (cf. Figure 3-3, Örskär and Uppsala airport represent coastal and inland conditions, respectively).

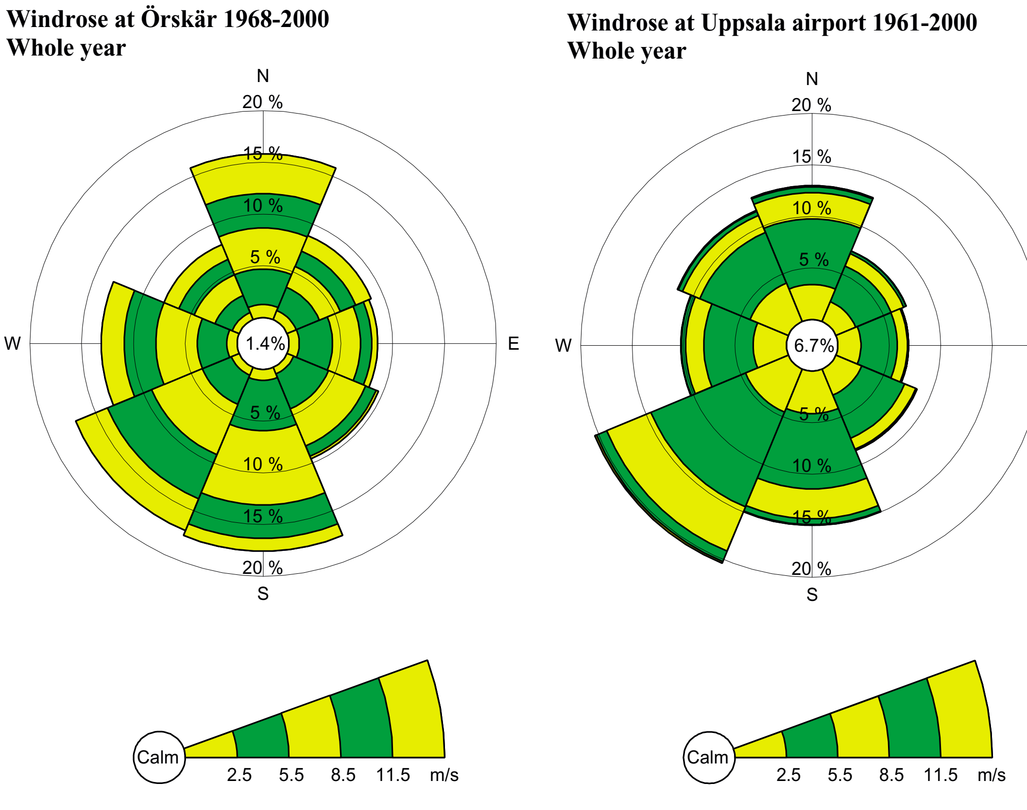

Figure 3-3. *Wind roses showing the average annual distribution of the wind direction and wind velocity for a coastal station (Örskär) and an inland station (Uppsala airport). Frequencies (%) of wind (simultaneous direction and speed). Percent of calm is noted in the centre of each windrose. Wind direction is grouped into 8 classes of 45° (N, NE, E, SE, S, SW, W and NW). Wind speed is classified in intervals of 3 m/s.*

In winter, strong northern winds often bring heavy snowfall. This is due to the moisture uptake from an open sea surface followed by rising air movements over land. On these occasions the *precipitation* maximum usually occurs further inland, some 5 to 15 km from the coast. The total measured precipitation is about 600 mm annually at the coastline. A maximum can be identified 5–15 km inland with some tens of mm more, whilst the precipitation amount decreases further southwest in Uppland. A minimum is reached over Lake Mälaren with an annual precipitation of about 500 mm. In relative terms, this geographical distribution applies throughout the year. The estimated true precipitation (adjusted for measuring losses) exceeds the gauged amounts by about 100 mm or more, as annual value.

The *temperature* conditions in the Forsmark area are typical for central Sweden with an annual mean of 5 to 6°C. This could be compared to Stockholm (6.6°C), Malmö (8.2°C) and Östersund (2.5°C). The average monthly mean temperature in January is about –4°C and in July 15–16°C. The *vegetative period* (daily mean temperature exceeding 5°C) has a duration of about 180 days, i.e. approximately half the year.

The temperature variation over northern Uppland largely depends on the sea-land dualism, implying smaller annual variations over sea, i.e. higher winter and lower summer temperatures than over land. This is, combined with a similar day-night pattern, connected to the small diurnal variations over sea. The monthly mean temperature has its largest coast-inland difference in November-December, with 1°C lower mean temperature 10–15 km inland than at the coastline. In May-June an almost as large opposite difference is observed. May has a difference in average daily maximum temperature amounting to 2°C between locations 10 km inland relative to sites at the coastline.

The annual *sunshine time* is about 1,700 hours in northeastern Uppland, somewhat more (up to 1,800 hours) at the coast, somewhat fewer (1,600–1,700 hours) in the interior parts. Few places in Sweden have much higher values than the studied near-coast sites. This fits in a general pattern of comparatively abundant sunshine along the coast, while in the interior of Götaland the values go down to 1,300 hours. Data on monthly global radiation is presented in /Larsson-McCann et al, 2002/ but is not shown here. The cloudiness percentage is 65% or slightly more, as annual mean, and does not vary much over Uppland. In early summer the cloudiness tends to decrease near the coast compared to inland conditions.

The ground is covered by *snow* in average 120–130 days a year, with an average annual maximum depth of snow of about 50 cm. The conditions at the coast does not differ much from those 20–30 km inland, but further to southwest, at Lake Mälaren, the number of snow-cover days decreases to below 100 and the mean maximum snow-depth diminishes to about 30 cm.

A summary of the meteorological data for the Forsmark area is presented in Table 3-1.

Table 3-1. Meteorological data for the Forsmark area /Larsson-McCann et al, 2002; Lindell et al, 1999/.

Variable	Value for Forsmark regional model area
Annual precipitation	c. 600 mm (25% as snow)
Annual evapotranspiration	511–545 mm[1]
Annual mean temperature	5–6°C
Mean temperature, January	–4°C
Mean temperature, July	15–16°C
Vegetation period	180 days
Sunshine time	1,600–1,800 hours
Mean global radiation, June	c. 170 kWh/m^2 * month
Snow coverage period	120–130 days
Maximum snow depth	c. 50 cm

[1] The lower value is for Norrtälje and the higher for Uppsala airport /Eriksson, 1981/.

3.2.2 Topography

Data input

The key variables affecting topographical conditions in the Forsmark regional model area are shoreline displacement and bedrock structures. Most of the following information is taken from /Jerling et al, 2001/ and /Brydsten, 1999a/.

Distribution and character

Östhammar municipality is situated on the border between two different landscape types: "Woodlands south of Limes Norrlandicus" and "Coasts and archipelagos of the Baltic sea" /NMR, 1984/. The region is part of the sub-Cambrian peneplain and quite flat. The Quaternary deposits on the flat peneplain are naturally rich in nutrients, but the areas closer to the coast have more exposed bedrock, resulting in less opportunity for agriculture /Jerling et al, 2001/. The shoreline displacement in this area is of major scientific interest because of the occurrence of a special type of wetland connected to the land uplift; "havsstrandspåverkat topogent kärr" – a fen affected by the topography and the seashore /Jerling et al, 2001/.

In /Brydsten, 1999a/ a digital elevation model (DEM) of the Forsmark area is used to predict future shoreline displacement. At present, the vertical *shoreline displacement* in the Öregrundsgrepen area is approximately 60 cm per 100 years /Påsse, 1996/. This is expected to decrease slowly but will still be substantial for many thousands of years. Since Öregrundsgrepen is a relatively shallow part of the Bothnian Sea, the positive shoreline displacement will greatly effect the proportions of land and sea in the future. Within 2,000 years (4,000 AD) half of the current water area in Öregrundsgrepen will be land and the water volume will be decreased by two thirds. By 7,000 AD, the whole Öregrundsgrepen area will be without brackish water. The effects on the landscape evolution due to shoreline displacement in the Öregrundsgrepen area are illustrated in a chronological series of digital maps (PowerPoint format) available on a CD-rom supplied in /Brydsten, 1999a/. A map, showing the predicted shoreline of the area at about 4,500 AD is shown in Figure 3-4.

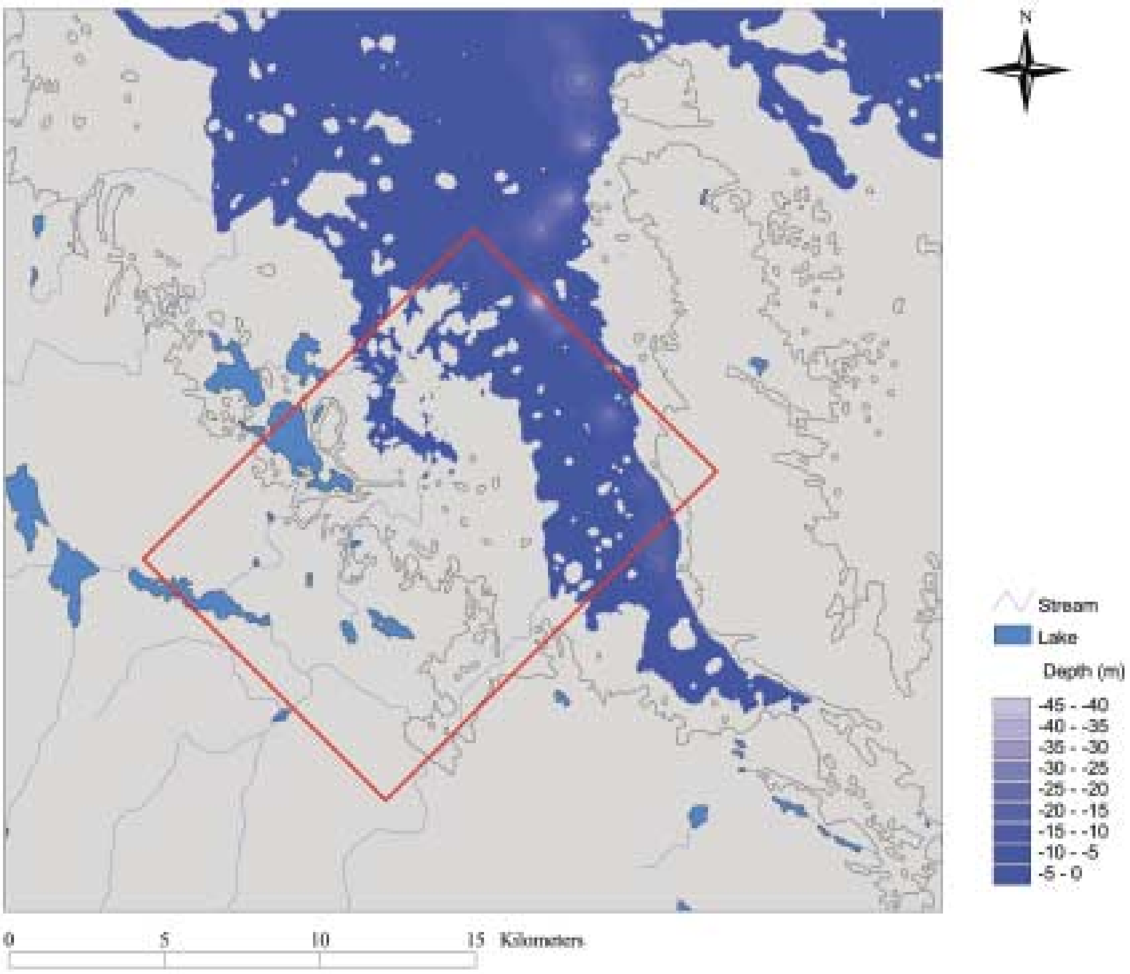

Figure 3-4. *The shoreline of the Forsmark area at about 4,500 AD, from /Brydsten, 1999a/. The shoreline of today is shown as a grey line. The Forsmark regional model area is shown by a red line.*

The *topographic features* in the area extend in two dominating directions: one northerly that can be seen along the western shoreline of the island Gräsö and one in a northwesterly direction seen in the shoreline of the mainland. Many of the large basins that will be established in the area due to the shoreline displacement will extend in one of these directions. Some of the basins are relatively shallow and will therefore probably be totally filled with organic-rich sediments and form peatbogs. Other basins are deep and will form about 20–35 m deep lakes. This is true especially for Gräsörännan (the deep channel on the western side of Gräsö) which will form a long chain of deep lakes.

3.2.3 Surface hydrology

Data input

The variables describing conditions of surface hydrology in the Forsmark regional model area are discharge and runoff area. Compilations and evaluations of existing data have been presented by /Brunberg and Blomqvist, 1998, 1999/, /Lindell et al, 1999/ and /Larsson-McCann et al, 2002/.

Distribution and character

In the Forsmark area, streams and rivers are rare due to the flat terrain. The river Forsmarksån is the largest watercourse and drains the chain of lakes located between the nature reserve Florarna in the west and Kallrigafjärden in the east. The waterflow in Forsmarksån is strongly affected by dams and water regulation works, which has also affected the natural thresholds in the lakes and other parts of the catchments /Brunberg and Blomqvist, 1999/. Another large water course, river Olandsån, discharges into Kallrigafjärden. The discharge area of this river is situated outside the Forsmark regional model area but the large amount of water discharging into Kallrigafjärden (about twice as much as the amounts from Forsmarksån) significantly effects the water turnover of this bay.

The hydrological station 50110 Vattholma has been chosen as the main representative for stations in the Östhammar-Tierp area (monthly discharge shown in Figure 3-5). It has a continuous record series with registrations since 1917, an annual mean specific *discharge* of 7.5 l/s*km^2 (237 mm/year) and a *runoff area* of medium size (294 km^2). Other stations that supplies additional data are 910 Uvlunge (represents Östhammar-Tierp), 573 Gimo and 1256 Fors (represents Östhammar only). The characteristics of discharge at a minimum of 50 years and a maximum of 50 and of 100 years were determined by frequency analysis. Moreover, long term minima and maxima as well as long term averages have been determined by mean value calculation /Larsson-McCann et al, 2002/.

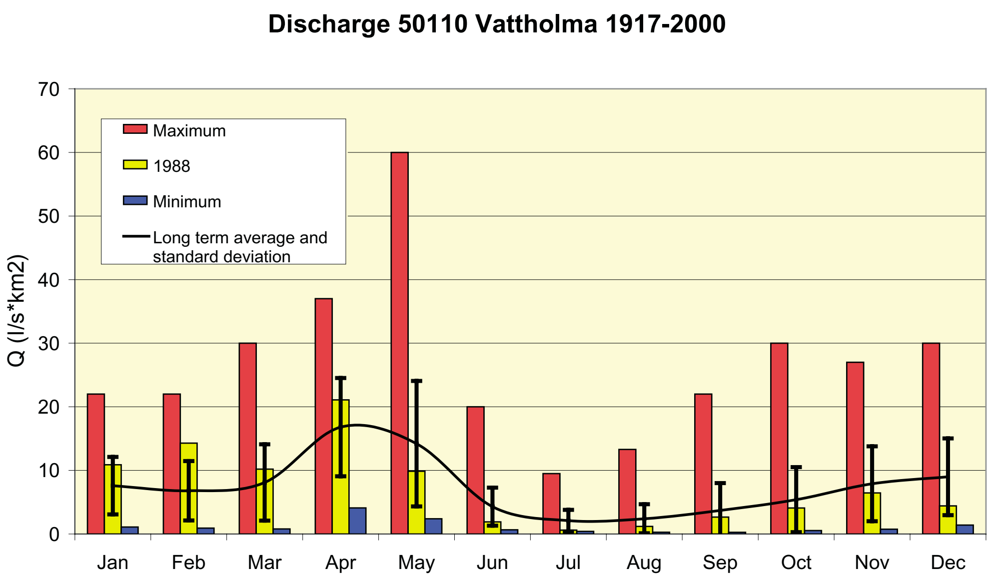

***Figure 3-5.** Monthly discharge at the hydrological station 50110 Vattholma during 1917–2000 /Larsson-McCann et al, 2002/.*

3.2.4 Wells

See Chapter 6 (Hydrogeology) and Chapter 7 (Hydrogeochemistry).

3.3 Forest

The forests in the Forsmark regional model area will be described under the following headings:

- Vegetation
- Fauna
- Soils
- Chemistry
- Land use
- Pollutants

3.3.1 Vegetation

Data input

The variables describing of the vegetation conditions of the forests in the Forsmark regional model area are forest type, distribution of tree species, undergrowth and production. /Boresjö Bronge and Wester, 2002/ have conducted vegetation mapping based on satellite data. Other key information has been presented by /Berggren and Kyläkorpi, 2002/, /Jerling et al. 2001/, /Jacobsson, 1978/ and /Svensson, 1988/.

Distribution and character

A vegetation map for the Forsmark area is shown in Figure 3-6. The most common *forest type* is the 70-year old pine forest, typical of broken terrain in eastern Svealand. The *distribution of forest trees* in the region is pine (*Pinus sylvestris*) 40–60%, spruce (*Picea abies*) 20–40%, birch (*Betula pendula*) 10–20%, oak (*Quercus robur*) < 1% and other broad-leaved trees 5–10%. Closer to the coast and the Forsmark region, the amount of pine *(Pinus sylvestris*) increases at the expense of spruce *(Picea abies*).

The most common *undergrowth* is the nutrient-rich herb type, which is often found in calcareous areas. Some 25–50% of the undergrowth in the Forsmark region is of this rich herb type, but it decreases further inland to c. 15–25% /Jerling et al, 2001/. In general, the coniferous forests in the area often have a major element of deciduous trees and shrubs as undergrowth. In more wet parts, the deciduous trees are dominant together with increasing amounts of herbs and grasses. Pine forest is found on the thin soils of rocky outcrops of bedrock. The shores are often bordered by alder (*Alnus glutinosa*) and sometimes ash (*Fraxinus excelsior*) /Jerling et al, 2001/.

In the national forestry inventory "riksskogstaxeringen" the following two variables describe the *production* (growth):

AVSTILLV	5 years of bark growth (1/10 m^3sk/ha)
KORTILLV	5 years of bark growth, corrected for weather (1/10 m^3sk/ha)

Both of these variables are calculated according to quite complicated methods. Growth and bark volume for coniferous trees have been estimated by /Svensson, 1988/. For deciduous trees, functions estimated by /Jacobsson, 1978/ are used.

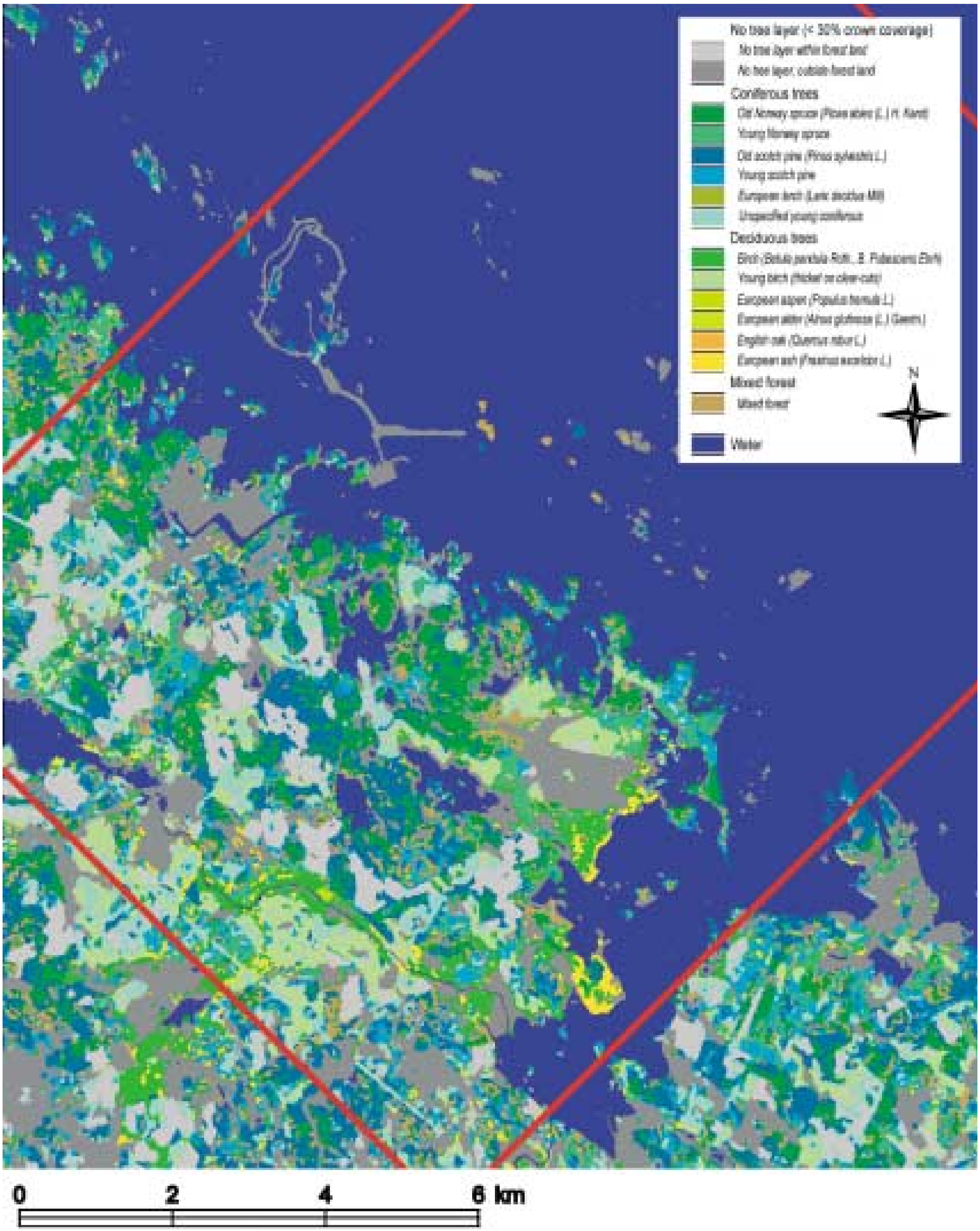

Figure 3-6. *Vegetation map, after /Boresjö Bronge and Wester, 2002/. The Forsmark regional model area is shown by a red line.*

The difference between the two calculated variables is that AVSTILLV is an estimate of the actual growth rate which has been calculated for a sample area, whereas KORTILLV displays growth rate corrected for potential effects due to deviations in the local climate. In short, this is done by correcting the values for the latest five years with a "normal weather" which has been calculated for the latest 60-year time period. The result gives the growth which should have been gained if the weather had been "normal". In another inventory "ståndortskarteringen" only one variable, TILLVAX, is used for growth. This variable is gained through division of AVSTILLV with 50 /Berggren and Kyläkorpi, 2002/.

Production estimates, as average values for these variables are given in /Berggren and Kyläkorpi, 2002/, see Table 3-2. The definition of "all sampling sites" is the area 1613700–1659100 E / 6680500–6716700 N (RAK).

Table 3-2. Forest growth rate variables, average values and standard deviation (Std), after /Berggren and Kyläkorpi, 2002/.

Variable	Average value, all sampling sites (550 values)	Std	Average value, sampling sites within the Forsmark area [1] (97 values)	Std
AVSTILLV	25.76 m^3sk/ha/5 year	20.51	22.16 m^3sk/ha/5 year	17.24
KORTILLV	25.11 m^3sk/ha/5 year	19.87	22.04 m^3sk/ha/5 year	17.17
TILLVAX	5.15 m^3sk/ha/year	4.10	4.43 m^3sk/ha/year	3.45

[1] Approximately the Forsmark regional model area.

3.3.2 Fauna

Data input

At the present stage, the only available data describing the fauna of the forest in the Forsmark regional model area is the number of moose shoot. This information has been compiled by /Berggren and Kyläkorpi, 2002/.

Distribution and character

A number of sources for statistics over the *number of moose shoot* exist and the information differs somewhat between the sources. The only source of data concerning other kind of animals is the game monitoring of the association of Swedish hunters ("Svenska Jägareförbundets viltövervakning") which is based on voluntarily reported information.

The information in Table 3-3 is from the hunting area ("jaktvårdskrets") of Östhammar /Berggren and Kyläkorpi, 2002/.

Table 3-3. Moose shot in the hunting area of Östhammar during the hunting seasons of 1998–1999 and 1999–2000 /Berggren and Kyläkorpi, 2002/.

Area (hectares)	Moose shot 1999–2000	Moose shot 1998–1999
84482	411 (4.9/1,000 ha)	365 (4.3/1,000 ha)

Of the moose shot in 1999–2000, 129 were males, 112 females and 170 calves.

3.3.3 Soils

In this report, soil is used in the enginering geological sense, i.e. as synonymous with "regolith", which is defined as follows /Bates and Jackson, 1987/:

"A general term for the layer of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess and colian deposits, vegetal accumulations, and soil (*solum*)…"

The term soil, as used here, thus constitutes a subgroup to the more general term "unconsolidated deposits" which includes terrestrial, marine and lacustrine deposits.

Data input

The variables describing conditions in the soils of the forests in the Forsmark regional model area are soil texture, soil depth and soil type. The information, deriving from various sources, has been compiled by /Berggren and Kyläkorpi, 2002/.

Distribution and character

Information about forest soils in the area is detailed in the National forestry inventory "Riksskogstaxeringen". 540 sampling sites are located within the region around Forsmark (the definition of "all sampling sites" is the area 1613700–1659100 E / 6680500–6716700 N (RAK). Of those, 93 sampling sites are located within the Forsmark regional model area. The data on soil texture and soil depth are presented in Table 3-4 and 3-5.

Table 3-4. Texture of forest soils according to the National forestry inventory "Riksskogstaxeringen".

Soil texture	All sampling sites		Forsmark regional model area	
	Share	Nr	Share	Nr
Stony till/stone	2.59%	14	3.23%	3
Gravelly till/gravel	0.19%	1	0.00%	0
Sandy till/coarse sand	8.89%	48	13.98%	13
Sandy-silty till/medium sand	27.04%	146	30.11%	28
Sandy silty till/fine sand	34.81%	188	27.96%	26
Fine sand till/silt	15.19%	82	11.83%	11
Silty till/silt	2.78%	15	3.23%	3
Clayey till/clay	8.52%	46	9.68%	9
Sum	100.00%	540	100.00%	93

Table 3-5. Soil depth of forest soils according to the National forestry inventory "Riksskogstaxeringen".

Soil depth	All sampling sites		Forsmark regional model area	
	Share	Nr	Share	Nr
Thick (> 70 cm)	57.32%	329	63.81%	67
Moderately shallow (20–70 cm)	25.96%	149	22.86%	24
Shallow (< 20 cm)	14.11%	81	13.33%	14
Very variable	2.61%	15	0.00%	0
Sum	100.00%	574	100.00%	105

Another important source of information is "Ståndortskarteringen". Data from "Ståndortskarteringen" are included in the compilation made by /Berggren and Kyläkorpi, 2002/.

The data presented above provide a relatively good picture of the general situation within the area. The desire for data with high precision described in /Lindborg and Kautsky, 2000/ is however far from fulfilled. Data from Sveaskog concerning this area could possibly offer higher resolution, but data with the desired precision are hard to acquire without further field investigations.

3.3.4 Chemistry

No data has been compiled concerning the chemistry of forest soils in the Forsmark regional model area.

3.3.5 Land use

Data input

The variables describing the land use in the Forsmark regional model area are: the proportions of land/fresh water/sea and the proportions of forest/field/pasture/other land. Compilations and evaluations of data, including the results of vegetation mapping based on satellite data are found in /Berggren and Kyläkorpi, 2002/, /Jerling et al, 2001/ and /Boresjö Bronge and Wester, 2002/.

Distribution and character

A comparison of land class distribution in Östhammar and the whole country is shown in Figure 3-7. Compared to the rest of Sweden, there is more forest and agricultural land in Östhammar municipality /Jerling et al, 2001/. This distribution is assumed to be valid also for the Forsmark regional model area.

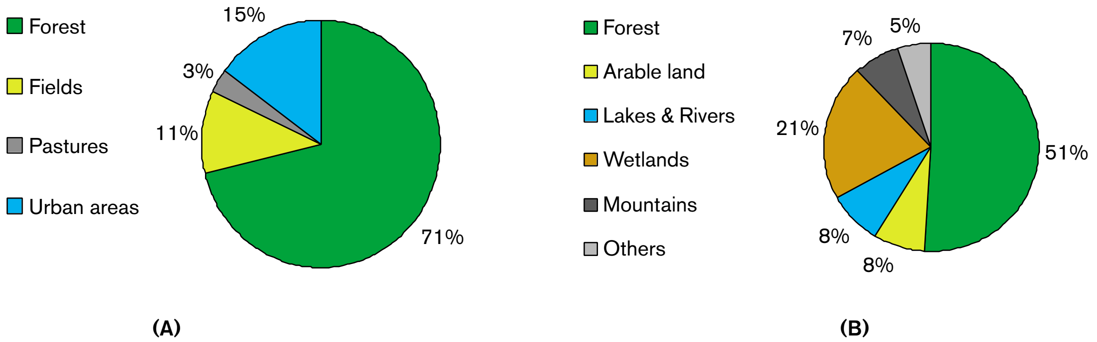

Figure 3-7. *Land class distribution in Östhammar municipality (A) and Sweden (B) /after Jerling et al, 2001/.*

3.3.6 Pollutants

In /Berggren and Kyläkorpi, 2002/, some national surveys concerning pollutants in forests are listed. A study of the distribution of metals in roots of macrophytes in streams has been performed by SGU in order to quantify the variation of heavy metals in surface and groundwater. The metals analysed are As, Cd, Co, Cu, Cr, Hg, Mo, Ni, Pb, Se, U, V, W and Zn /Berggren and Kyläkorpi, 2002/.

For this description, no data has been compiled.

3.4 Wetlands

The wetlands in the Forsmark regional model area will be described under the following headings:

- Vegetation
- Fauna
- Soil deposits
- Chemistry
- Land use
- Pollutants

3.4.1 Vegetation

Data input

The variables describing the vegetation within the wetlands in the Forsmark regional model area are geological substratum and vegetation. As mentioned earlier, vegetation mapping based on satellite data has been made by /Boresjö Bronge and Wester, 2002/. Important information is also found in /Brunberg and Blomqvist, 1999/.

Distribution and character

The Forsmark area has a high percentage of wetlands compared to the county of Uppland as a whole. The wetlands are underlain by the calcareous post-glacial clay, which is a prerequisite for the high amount of rich-fens and extreme rich-fens which are characteristic for the area. The Forsmark catchment area is dominated by oligotrophic hardwater lakes surrounded by mires. The undergrowth mostly consists of different shrub species and mosses (i.e. *Sphagnum*) /Brunberg and Blomqvist, 1999/.

3.4.2 Fauna

See Section 3.3.2.

3.4.3 Sediments

Data input

Data on the stratigraphy of the sediments beneath one bog in northern Uppland (Vissomossen) represent the information about the underlying materials of the wetlands in the Forsmark regional model area /Bergström, 2001/.

Distribution and character

The diatom *stratigraphy* in the Vissomossen bog shows an example of the natural succession in lake ontogeny from sediment accumulation in the Litorina Sea, followed by the isolation and the formation of a freshwater lake. Lacustrine sedimentation filled the lake and the latest stage in the succession is overgrowth to form a bog. The isolation of the basin is interpreted to have been distinct and fast, as reflected by changes in the diatom flora. The lithostratigraphy shows a relatively thin sequence of silt/sand and clay gyttja/gyttja clay. The thickness of the algal gyttja is 1–1.5 metres. A thin layer of reed peat is overlain by moss peat. In the surrounding fen, the moss peat is replaced by fen wood peat /Bergström, 2001/.

3.4.4 Chemistry

See Section 3.6.2.

3.4.5 Land use

See Section 3.6.6.

3.4.6 Pollutants

The limited data available has been listed by /Berggren and Kyläkorpi, 2002/ but has not been compiled for this description.

3.5 Agricultural land

The amount of arable land has decreased over the years. Today c. 17,200 ha of the Östhammar municipality is cultivated land and c. 2,500 ha is pastures and meadows. There are 550 farmers in the municipality and four of them are defined as large companies, i.e. farms with more than 100 cattle /Birgersson and Sidenvall, 1996/.

The agricultural land in the Forsmark regional model area will be described under following headings:

- Vegetation
- Fauna
- Soils
- Chemistry
- Land use
- Pollutants

3.5.1 Vegetation

Data input

The variables describing the vegetation of the agricultural land in the Forsmark regional model area are land use and standard yield values for barley, oat and potatoes. This information has been compiled by /Jerling et al, 2001/, /Boresjö Bronge and Wester, 2002/, /Berggren and Kyläkorpi, 2002/ and /SCB, 1997/.

Distribution and character

The *different kinds of agricultural land areas* in the Östhammar municipality are presented in Table 3-6. The amount of semi-natural grasslands in the Forsmark region is today c. 1% of the total land area. Forest grazing and grazing on the shore-meadows has almost totally ceased and the landscape is changing character with increased growth in accordance with the successional development. Where grazing still exists, the intensity is low /Jerling et al, 2001/.

Table 3-6. Land use for land owners with more than 2 ha agricultural land in the Östhammar municipality compared with the Forsmark area (from /Berggren and Kyläkorpi, 2002/, source: /SCB, 1999/).

Geographical area	Year	Area (ha) Cultivated area	Pasturage	Forest	Other land	Sum
Östhammar	1990	17,257	2,274	36,591	6,357	62,478
municipality	1995	17,089	3,770	36,865	6,058	63,782
	1999	17,130	3,751	36,589	5,770	63,240
Forsmark area	1995	1,036	381	1,975	635	4,027
	1999	1,009	364	1,875	495	3,743

The “Forsmark area” refers to an area, which includes the Forsmark regional model area and its surroundings.

Standard yield values are calculated every year for all crops covered by the objective yield surveys /SCB, 1997/. Sweden is divided into 104 yield survey districts. Standard yield values (for year 2000) for the Östhammar municipality are shown in Table 3-7.

Table 3-7. Standard yields in the Östhammar municipality year 2000 /Berggren and Kyläkorpi, 2002/, source: /SCB, 1999/.

Geographical area	Standard yield (kilo/hectare) Barley	 Oats	 Potatoes
Yield area 0322*	2,853	2,746	none
Östhammar municipality	3,125	2,843	20,922

* Yield area 0322 contains Börstil, Forsmark, Gräsö, Harg, Valö, Öregrund and Östhammar parishes and is included in the Östhammar municipality.

3.5.2 Fauna

Data input

The variables describing the fauna of agricultural land in the Forsmark regional model area will be based on statistics concerning domestic animals (cattle, swine and poultry) in the Östhammar municipality. This data has been compiled by /Berggren and Kyläkorpi, 2002/.

Distribution and character

The distribution of different kind of *domestic animals* in the Östhammar municipality is presented in Table 3-8.

Table 3-8. Domestic animals in the Östhammar municipality compared to the Forsmark area (from /Berggren and Kyläkorpi 2002/, source: /SCB, 1999/).

Geographical area	Year	Cattle Milk-producing cattle	 Breeding cattle	 Heifers, bulls and bullocks 1 year or less	 Calves less than 1 year	Sheep and lamb	Swine Boars and sows	 Other swine	Laying hens and chickens
Östhammar	1990	5,218	284	4,004	3,480	2,126	892	5,122	22,635
municipality	1995	4,343	857	4,783	3,773	3,010	877	6,247	16,741
	1999	3,965	931	4,902	3,899	2,607	777	7,220	11,288
Forsmark area	1995	274	57	316	210	425	3	194	236

The “Forsmark area” refers to an area, which includes the Forsmark regional model area and its surroundings.

3.5.3 Soils

Data input

The variable describing the soil deposits of the agricultural land in the Forsmark regional model area is soil type. The information available has been compiled by /Berggren and Kyläkorpi, 2002/, see also /Eriksson et al, 1997/.

Distribution and character

In a systematic investigation of Swedish agricultural land with regard to the humic content of the soils and the most important soil chemical characteristics /Eriksson et al, 1997/, about 3,100 samples of top-soil and 1,700 of sub-soil were taken from sampling sites randomly distributed over the cultivated area of Sweden. The top-soil samples (0–20 cm depth) were taken during 1988–1995, most of them during 1994–1995. The sub-soil samples (40–60 cm depth) were taken during 1995. The soil type was analysed in samples from 16 sites in the Östhammar municipality. The locations of the sampling sites are not revealed by SCB, which was responsible for the selection of the sites, and primary data has not been accessible. The statistics in Table 3-9 and 3-10 is based on data from these 16 sampling sites.

Table 3-9. Soil type, cultivated soil in the Östhammar municipality [% of total soil, dry weight], according to "Tillståndet i svensk åkermark" /Eriksson et al, 1997/.

	No	Average	Standard deviation	Median
Sand	16	17.03	13.62	14.81
Fine sand	16	21.21	12.08	21.16
Coarse silt	16	10.08	5.55	9.08
Silt	16	15.58	6.64	14.33
Clay	16	22.76	10.90	21.88

Table 3-10. Soil type, cultivated soil in the Östhammar municipality [% of mineral soil, dry weight], according to "Tillståndet i svensk åkermark" /Eriksson et al, 1997/.

	No	Average	Standard deviation	Median
Sand	16	19.01	14.91	16.90
Fine sand	16	24.73	16.19	22.99
Coarse silt	16	11.80	7.20	10.09
Silt	16	18.32	8.93	16.65
Clay	16	26.13	12.01	25.24

3.5.4 Chemistry

Data input

Data on the chemistry of the soils forming agricultural land in the Forsmark regional model area has been compiled by /Berggren and Kyläkorpi, 2002/, se also /Eriksson et al, 1997/. The variables consist of the contents of the different metallic species and other soil-chemical parameters.

Distribution and character

In a systematic investigation of Swedish agricultural land /Eriksson et al, 1997/, the soil chemistry was analysed in detail (see Section 3.5.3). Data from the sampling sites within the Östhammar municipality are shown in Table 3-11.

Table 3-11. Soil chemistry in the Östhammar municipality /Eriksson et al, 1997/.

	No	Average	Standard deviation	Median	Method	Unit
As	18	3.84	1.78	3.63	7M HNO_3	mg/kg TS
B	18	0.95	0.63	0.65	hotwater	mg/kg TS
Pb	18	15.07	4.34	15.67	7M HNO_3	mg/kg TS
Cs	18	2.92	1.17	2.75	7M HNO_3	mg/kg TS
Cd	18	0.31	0.16	0.26	7M HNO_3	mg/kg TS
Co	18	7.50	2.86	6.56	7M HNO_3	mg/kg TS
Cu	18	24.61	9.40	25.51	7M HNO_3	mg/kg TS
Cr	18	28.32	10.49	26.60	7M HNO_3	mg/kg TS
Hg	18	0.05	0.02	0.04	7M HNO_3	mg/kg TS
Mn	18	314	176	261	7M HNO_3	mg/kg TS
Mo	18	2.16	3.02	0.65	7M HNO_3	mg/kg TS
Ni	18	20.40	7.03	19.49	7M HNO_3	mg/kg TS
Se	18	0.42	0.34	0.28	aqua regis	mg/kg TS
Sr	18	29.89	14.26	27.58	7M HNO_3	mg/kg TS
V	18	35.38	12.10	33.38	7M HNO_3	mg/kg TS
Zn	18	65.47	24.73	56.40	7M HNO_3	mg/kg TS
pH	19	6.46	0.82	6.50	pH-H_2O	
PAL	19	10.72	9.55	6.74	AL soluble P	mg/100 g TS
PHCl	19	103.43	38.86	96.46	HCl soluble P	mg/100 g TS
Ca	19	33.97	27.53	21.51	exchangeable	cmol(+)/kg TS
Mg	19	1.63	1.16	1.22	exchangeable	cmol(+)/kg TS
K	19	0.43	0.22	0.36	exchangeable	cmol(+)/kg TS
Na	19	0.11	0.12	0.08	exchangeable	cmol(+)/kg TS
Utbacid	19	0.60	1.32	0.14	exchangeable acidity	cmol(+)/kg TS
Humus	19	14.41	14.70	5.82	(organic carbon)/0.58	% TS
N	19	0.72	0.68	0.32	tot N	% TS
S	19	0.15	0.16	0.05	tot S	% TS
$CaCO_3$	19	0.27	0.98	0.00	carbonate as $CaCO_3$ equivalents	% TS
CECeff	19	36.75	28.26	24.78	effectivebase saturation	cmol(+)/kg TS
Bseff	19	97.74	5.19	99.48	cation exchange capacity	% TS
C/N	19	10.71	1.84	10.74	ratio	

3.5.5 Land use

See Section 3.3.5.

3.5.6 Pollutants

See Section 3.5.4.

3.6 Lakes

The lakes in northern Uppland have been relatively well studied. A large amount of data concerning e.g. discharge areas, morphometry, fish fauna and human intrusions can be found in /Brunberg and Blomqvist, 1998/. Another potential source of data is the Department of Environmental Assessment at Swedish University of Agricultural Sciences, which performs different kinds of environmental monitoring. Data which may be useful are available on their website (www.info1.ma.slu.se/db.html, accessed May 2002). Data concerning lakes in the Forsmark regional model area are presented in this section. For information about rivers, the reader is referred to Section 3.2.3, which concerns surface hydrology of drainage areas in the Forsmark regional model area.

The lakes in the Forsmark regional model area will be described under the following headings:

- Lake types and physics
- Chemistry
- Biology
- Morphometry
- Sediments
- Human activities
- Pollutants

3.6.1 Lake types and physics

Data input

The lakes in the Forsmark area belong to three different classes; oligotrophic hardwater lakes, brownwater lakes and deep eutrophic lakes. The physical characteristics of these lake types are described by the following variables: water turnover, lake size and key habitats. The characteristics of the catchment area of the most abundant of these lake types are also presented.

Data on physical characteristics of the lakes is found (or referred to) in /Brunberg and Blomqvist, 1998, 1999, 2000/, /Brunberg et al, 2002/, /Bergström, 2001/, /Larsson-McCann et al, 2002/ and /Bergren and Kyläkorpi, 2002/.

Distribution and character

According to /Brunberg and Blomqvist, 2000/, three main types of lake ecosystems could be identified in the Forsmark area:

1) The oligotrophic hardwater lakes are to a large extent surrounded by mires. *Inflow* as well as *outflow* of water is often diffuse, via the surrounding mire. The lakes are small and shallow, with nutrient-poor and highly alkaline water. Three *key habitats* have been identified within the lakes; i) the pelagic zone, characterised by low production of biota, ii) the presumably moderately productive emergent macrophyte zone, dominated by *Sphagnum* and *Phragmites*, and iii) the light-exposed soft-bottom zone with *Chara* meadows and an unusually rich and presumably highly productive microbial sediment community. In later stages of the lake ontogeny, *Sphagnum* becomes more and more dominant in the system, which successively turns acidic. The final stage is likely to be a raised bog ecosystem with an autonomous hydrological functioning.

2) The brownwater lakes are typically found within the main part of the river Forsmarksån and are characterised by a high waterflow from the upper parts of the drainage area, which are dominated by mires. Their lake water is highly stained by allochthonous organic carbon imported from the catchment area. Also in this lake type a *Sphagnum*-littoral successively develops, and in a mature lake three key habitats can be identified; i) the pelagic zone, most likely the dominant habitat in terms of production of organisms and in which bacterioplankton dominates the mobilisation of energy while phytoplankton are restricted by low light availability, ii) the emergent macrophyte zone, and iii) the profundal zone. Due to the characteristically short water renewal time, sedimentation processes are of relatively small importance and most of the carbon imported and produced is lost through the outlet. Production at higher trophic levels (e.g. benthic fauna and fish) within the brownwater lake type is very limited.

3) The deep eutrophic lakes are characterised by a limited drainage area, a large lake volume and a slow turnover time of the water. All five key habitats that optimally can be found in lakes are represented in this lake type: i) the pelagial, ii) the emergent macrophyte-dominated littoral zone, iii) the wind-exposed littoral zone, iv) the light-exposed soft-bottom zone and, v) the profundal zone. Traditionally, the pelagial has been regarded as the dominant habitat in terms of mobilisation of carbon energy in the system. However, the productivity in the littoral habitats together may be just as important as the pelagial. As a result of the long turnover time of the water, most of the production of carbon is retained within the lake basin and sedimentation to the profundal zone is the main retention process.

The most abundant type of lake in the Forsmark regional model area is the oligotrophic hardwater lake. Characteristics of the *catchment areas* of such lakes in the Forsmark regional model area are presented in Table 3-12. Morphological characteristics of the lakes are presented in /Brunberg and Blomqvist, 1999/.

Table 3-12. Characteristics of the catchment areas of oligotrophic hardwater lakes in the Forsmark regional model area, after /Brunberg and Blomqvist, 1999/.

Catchment	Area	Forest	Wetland	Farmland	Lakes	Other land use
	km^2	%	%	%	%	%
54/55: 9 Själsjön	4.83	80	15	2	3	0
54/55: 10 Degertrusket	2.66	78	16	3	3	0
54/55: 11 Storfjärden (Hållen)	2.11	79	15	0	6	0
54/55: 13 Storfjärden (Slada)	54.80	69	11	20	0	0
54/55: 14b Hällefjärd	0.60	–	–	–	–	–
54/55: 15 Västersjön (St Hållsjön)	0.22	59	23	4	14	0
54/55: 16 Dalarna	0.36	70	19	0	11	0
54/55: 21 Käringsjön	1.85	83	6	1	10	0
54/55: 22 Strönningsvik	0.65	57	28	3	12	0
54/55: 27 Eckarfjärden	1.51	73	7	5	15	0
54/55: 28 Fiskarfjärden	2.70	60	22	1	17	0
Average	6.57	70.8	16.2	3.9	9.1	0
Median	1.85	71.5	15.5	2.5	10.5	0
Max	54.80	83	28	20	17	0
Min	0.22	57	6	0	0	0
N obs	11	10	10	10	10	10

3.6.2 Chemistry

Data input

The chemistry of lakes in the Forsmark regional model area can be described in terms of the content of Ca, Mg, Na, K, HCO_3, SO_4 and Cl in their water.

Data on the physical chemistry of the lakes are found (or referred to) in /Brunberg and Blomqvist, 1999, 2000/ and /Brunberg et al, 2002/.

Distribution and character

A specific type of hardwater lakes, which is common in the Forsmark regional model area is called *Chara* lakes (see further "The littoral zone" under Section 3.6.3). The *Chara* lakes are chemically characterised as hardwater lakes, distinguished from softwater lakes by their high conductivity and by their richness in calcium and magnesium which are dissolved in the water. Hardwater lakes occur all over the world, in areas of alkaline sedimentary rocks or, in this case, in areas with high content of limestone blocks in the Quaternary till. These rocks/blocks are easily weathered and yield alkaline water rich in calcium and many other elements, e.g. micro-nutrients for the biota. However, due to both chemically and biologically induced interactions in the lake water, the amounts of nutrients (e.g. phosphorus) transported to the lakes may be effectively reduced by precipitation of calcium-rich particulate matter. Nitrogen, on the other hand, tends to be present in relatively high concentrations in the water, due to the combination of high input but low biotic utilisation /Brunberg and Blomqvist, 1999, 2000/. The ionic composition of *Chara* lakes in Uppland, which is used to distinguish two main types ("biocarbonate group", "sulphate group"), is shown in Table 3-13.

Table 3-13. The ionic composition of *Chara* lakes in Uppland (equiv. %, average values, after /Brunberg and Blomqvist, 1999/).

Water	Ca	Mg	Na	K	HCO_3	SO_4	Cl
Chara lakes of "bicarbonate group"	79.1	10.9	8.3	1.7	71.9	22.7	5.4
Chara lakes of "sulphate group"	73.3	16.0	8.8	1.9	37.2	55.4	7.4
Standard composition*	63.5	17.4	15.7	3.4	73.9	16.0	10.1

* Standard composition of freshwater lakes (according to /Rodhe, 1949/).

3.6.3 Biology

Data input

Three different main habitats are traditionally recognised in lakes; the open water or pelagic zone, the littoral zone, i.e. bottom areas with photosynthesising plants, and the profundal zone, i.e. the deeper parts of the bottom area which lack photosynthesising plants. The littoral zone is further divided into the emergent macrophyte zone, the light-exposed soft-bottom zone and the wind-exposed littoral zone. The riparian zone is situated on the border between the lake and the terrestrial ecosystem. The description of the biology of lakes in the Forsmark regional model area is based on this structure. The biology is characterised by the following entities: phytoplankton, macroflora, benthic fauna and fish.

The key data sources are found (or referred to) in /Brunberg and Blomqvist, 1998, 2000/ and /Brunberg et al, 2002/.

Distribution and character

Since oligotrophic hardwater lakes in general, and those of the county of Uppsala, in particular, are small, shallow, and have relatively clear water, a typical oligotrophic hardwater lake can be characterised as having three distinguishable key habitats, the open water (pelagic zone), the emergent macrophyte zone, and the light-exposed soft-bottom zone (littoral zone). The other key habitats, the profundal zone and the wind-exposed littoral zone, are missing.

The pelagic zone

There are very few studies of the *phytoplankton* communities in lakes of the Forsmark area and those that have been performed mainly concern phytoplankton community biomass and composition. /Kleiven, 1991/ studied environmental conditions and phytoplankton in some *Chara* lakes in the county of Uppland and included three lakes in the Forsmark area in that study: Hällefjärd, Käringsjön, and Strönningsvik. The lakes were sampled just once, in September 1984 (two lakes) and 1985 (Strönningsvik). Phytoplankton total biomass was low, 113, 815, and 451 µg wet weight/l, respectively, indicating oligotrophic conditions in the systems /Rosén, 1981; Brettum, 1989/. In all three lakes, chrysophytes dominated the community and accounted for approximately 50% (42–62) of the biomass. Green algae was the second most important group in two lakes, and Cryptophytes in the third lake. Dinoflagellates and diatoms made up most of the remaining biomass, while cyanobacteria were less important despite the time of the year /Brunberg and Blomvist, 2000/.

Of the totally 11 lakes in the Forsmark area, 6 have been subject to standardised survey gill-net fishing. *Fish* was caught in all lakes. The average catch (catch per unit effort, CPUE) was 3.6 kg in terms of biomass and 36 individuals in terms of abundance. The average number of species found was 3.7. In total for all 6 lakes, 6 species were encountered; roach (*Rutilus rutilus*), Crucian carp (*Carassius carassius*), tench (*Tinca tinca*), perch (*Perca fluviatilis*), ruffe (*Gymnocephalus cernua*), and pike (*Esox lucius*), for Swedish names, see glossary in appendix in /Brunberg and Blomqvist, 2000/. Crucian carp dominated in terms of numbers and/or biomass in four of the lakes. In the two other lakes, roach and perch were dominant. The other three species were less abundant in the lakes in which they occurred, pike and ruffe being found in three lakes and tench in one lake. In one of the lakes in which Crucian carp dominated, it was also the only fish caught /Brunberg and Blomqvist, 2000/.

In comparison with data from the entire fish survey, including 81 lakes in the county of Uppsala, the oligotrophic hardwater lakes have a lower abundance of fish (36 compared to 81 individuals per gill net). The biomass of fish is almost exactly the same (3.6 kg in both cases) whereas the oligotrophic lakes have a lower diversity in the fish community, 3.7 compared to 5.8 species encountered /Brunberg and Blomqvist, 2000/.

The littoral zone

The *macroflora* of the littoral zone (i.e. mostly the floating outer edge of the mire) of the lakes in the Forsmark area is characterised by two species: *Sphagnum* in the bottom layer and *Phragmites* in the field layer. Quantitative data on the biomass and production of these organisms are apparently lacking from the Forsmark area /Brunberg and Blomqvist, 2000/.

The stoneworths, *Charales*, is the best studied of all groups of organisms in the oligotrophic hardwater lakes (for references see /Brunberg and Blomqvist, 2000/). These submersed macroalgae strongly dominate parts of the light-exposed soft-bottom sediments, and the characteristic *Chara* meadows have given rise to the name "*Chara* lakes". There are few, if any, quantitative studies of the *benthic fauna* of the illuminated soft-bottom sediments of the lakes in the Forsmark area /Brunberg and Blomqvist, 2000/.

According to /Brunberg and Blomqvist, 2000/, there have been no studies of biomass, nor of the production of heterotrophic bacteria or fungi in the light-exposed soft-bottom zone.

The riparian zone

The outermost parts of floating mats constituting the littoral zone of the lakes are mires. These surrounding mire systems have been subject to a large number of inventories, especially concerning their *vegetation* /Brunberg and Blomqvist, 1998/, while studies of functional aspects are lacking. The mires often have a mixed character with components of pine bog, poor fen, rich fen, extremely rich fen and, at the edge of the lake, *Phragmites*-populated floating *Sphagnum*-mats. The bottom layer of the pine bog is dominated by *Sphagnum*, and in the field layer *Ledum palustre*, *Rubus chamemorus*, and *Eriophorum vaginatum* are important compartments. The poor fen also has *Sphagnum* as a dominant constituent of the bottom layer, and a field layer with *Rhyncospora alba*, *Scheuchzeria palustris*, *Carex rostrata*, and *C. lasiocarpa*. Rich fens, interspersed with components of extremely rich fens, often dominate the mires. The bottom layer in these fens is dominated by a variety of brown-coloured mosses. Important constituents of the field layer are *Parnassia palustris*, *Primula farinosa*, *Dactylorhiza incarnata*, *Epipactis palustris*, *Liparis loeserii*, and *Dactylorhiza traunsteineri* /Brunberg and Blomqvist, 2000/.

3.6.4 Morphometry

Data input

The morphometry of lakes in the Forsmark regional model area can be described using the variables: lake area, average and maximum depth, volume, water renewal time and lowering of water level. Data is found (or referred to) in /Brunberg and Blomqvist, 1999, 2000/ and /Bergström, 2001/.

Distribution and character

Chara lakes are in general very shallow. The oligotrophic hardwater lakes in the Forsmark area have an *average depth* of 1 m (Table 3-14), while the average depth for all lakes in the county is 2 m. The oligotrophic hardwater lakes within the Forsmark area also have small *areas*, compared to the other lakes in the county, although this is not a characteristic of *Chara* lakes in general /Brunberg and Blomqvist, 1999/.

Due to their small size and shallowness, the lakes also have a small *water volume* and consequently a short *renewal time* of the water. In some of the lakes, which as yet have not been sufficiently separated from the shoreline, the hydrological conditions also include intrusions of water from the Baltic Sea during low pressure weather conditions which create a high sea level /Brunberg and Blomqvist, 1999/.

Table 3-14. Lake morphometry for oligotrophic hardwater lakes in the Forsmark area, after /Brunberg and Blomqvist, 1999/.

Lake	Area, km^2	Average depth, m	Maximum depth, m	Volume, Mm^3	Water renewal time, days	Lowering of water level, m
Själsjön	0.07	–	–	–	–	0.8
Degertrusket	0.07	–	–	–	–	0.4
Storfjärden (Hållen)	0.11	0.6	1.1	0.066	47	0.3
Storfjärden (Slada)	0.03	1.2	2.2	0.036	1.2	0.4
Hällefjärd	0.05		2			
Dalarna	0.07	0.5	1.3	0.035	301	0
Käringsjön	0.04	0.6	0.9	0.024	138	0
Västersjön	0.19	1.9	3.2	0.361	331	0
Stönningsvik	0.08	1.0	1.7	0.080	229	0
Eckarfjärden	0.23	1.5	2.6	0.345	383	0.3
Fiskarfjärden	0.61	0.7	2.0	0.427	251*	0
Average	0.14	1.0	1.9	0.172	210	0.22
Median	0.07	0.9	2.0	0.073	240	0.15
Max	0.61	1.9	3.2	0.427	383	0.75
Min	0.03	0.5	0.9	0.024	1.2	0
N obs	11	8	9	8	8	10

* The value given here is the theoretical water renewal time calculated from freshwater supply and lake volume. As this lake also receive some brackish water (located near the coastline) the actual renewal time may be shorter.

Some of the oligotrophic hardwater lakes have been subject to drainage projects and *lowering of the water level.* However, both the frequency and the extent of these projects are less than that for the other lakes in the county /Brunberg and Blomqvist, 1999/.

3.6.5 Sediments

Data input

The sediments within the lakes in the Forsmark regional model area can be described in terms of sediment stratigraphy and composition, as well as the influence of human activities. Compilations of data and references to data sources are found in /Bergström, 2001/, /Brunberg and Blomqvist, 2000/ and /Brunberg et al, 2002/. Data provided by Tord Ingmar, Uppsala University, which are mostly unpublished, are also presented.

Distribution and character

Oligotrophic hardwater lakes are often characterised as "bottomless", i.e. there is no distinct border between the very soft sediment and the lake water. The calcareous and highly organogenic sediment is of autochthonous origin, with minor contribution of mineral particles /Brunberg and Blomqvist, 2000/.

The sediments of the oligotrophic hardwater lakes in the Forsmark area are of two types, depending on the amount of mineral particles that are transported to the lake. The typical cyanophycée gyttja is reddish-brown, gelatinous and almost free from mineral particles, except for precipitated $CaCO_3$, which in some cases may add a greyish colour to the sediment ("lime gyttja"). Lakes where mineral particles from the drainage area are mixed into the sediments have a green or bluegreen coloured non-gelatinous surface sediment. This is the case when the in-flowing water reaches the lake by visible inlets instead of being filtered through the riparian zone from diffuse sources /Brunberg and Blomqvist, 2000/.

/Bergström, 2001/ describes the lake sediment conditions in North Uppland as follows:

A general sediment *stratigraphy* consists of, from bottom to top: till, glacial clay (varved), postglacial clay, silt and sand (gravel), clay gyttja/gyttja clay and gyttja. Normally, the sequences of clay gyttja/gyttja clay are thin or absent. Exceptions are the lakes Skälsjön, Norra Åsjön and Limmaren, where clay gyttja/gyttja clay displays thicknesses of up to 3.5 m. The thickness of gyttja also varies considerably between the investigated lakes.

Different *compositions* of gyttja have been found in the investigated basins. Algal gyttja, reddish to green, has been found in 50% of the investigated sites. *Charales* is one of the components in the formation of algal gyttja. *Vaucheria* gyttja (found when levelling the isolation threshold at the Vissomossen bog) is a stratified greyish-brown gyttja (in Swedish pappersgyttja) also with algae as the main component. *Vaucheria* gyttja is supposed to form during an early lagoonal stage, with a salinity of 5–6‰, before the water becomes lacustrine. The calcareous gyttja, found in the lakes Barsjö and Eckarfjärden reflects the calcareous soils in the area. Remains of freshwater mollusc shells have been commonly found in this sediment. Sedimentation of calcareous gyttja reflects the locally high amounts of calcium in the till and glacial clay. The use of hydrochloric acid on sediment have shown traces of limestone in the calcareous gyttja but very seldom and only in the gyttja found in lakes Barsjö and Eckarfjärden.

The lake basins are generally shallow with protruding rocks, skerries or small, forested islands. They are strongly affected by *human activities* in the form of dams, ditching, water regulation works or lowered lake surfaces, which most likely affect the rate of sedimentation. The only exception is the lake Limmaren, the southernmost situated site. This lake is fairly deep and lies in an undulating fissure valley landscape. Another common feature is the overgrowth by reed, a result of the ongoing infilling and overgrowth of the lakes. Several factors affect the rate at which lakes become filled, such as rate of sediment supply, productivity, lake size, anthropogenic activities and size of the catchment area. Many of the lakes will in due time fill in and turn into mires.

During the period 1967–1972, a large number of sediment cores from lakes and shallow gulfs in the northeastern part of Uppland were analysed by Tord Ingmar, Department of Ecological Botany, Uppsala University. Some of the data are published in scientific journals, but the major part is unpublished and only exists as hand-written field notes. Some of these field notes have been converted to a digital database by Lars Brydsten (sediment structures) and Tom Korsman (diatom data) at the Department of Ecology and Environmental Science, Umeå University.

The northeastern part of Uppland is characterised by a relatively high rate of shore displacement (50 cm in 100 years), a flat topography and high content of calcium carbonate in the till. These conditions have caused a landscape with shallow lakes and gulfs with sediments influenced by the leaching of calcium carbonate from the till.

The sediment data are of three types:

1. Sediment cores along transects in two lakes (Vikasjön and Finnsjön, both situated in the river Forsmarksån catchment), where the sediment structure, and the pollen and diatom content in the cores, are described in detail, and also the level in the sediment core at time for lake cut-off.

2. Sediment cores along a transect in one lake (Lilla Agnsjön in the catchment area of the river Forsmarksån), where the levels of the sediment surface and the wave washed sand (settled in an marine environment) can be used for the calculation of the total sedimentation of fine-grained particles during both the shallow gulf phase and the lake phase.

3. Sediment cores in 57 young lakes or shallow marine basins that will become lakes in a near future. In most of these sites one sediment core has been taken in the deepest part of each basin. The sedimentary layering is described in detail for 26 of the cores with notes on the upper and lower boundaries, and grain size, colour and consistency for each stratum.

A generalised sediment structure for a sediment core in an Uppland lake is presented in Table 3-15. The total sediment thickness above the wave washed sandy/silty layer is typically 1–3 meter, where as much as 25–50% of the sediment was settled in a brackish environment. Most sediment cores, both from lakes and from shallow gulfs, show gyttja with high presence of algae.

The sediment and biological data in the mire Vikasjömyren allow the assessment of the lake development in typical shallow and carbonate-rich Uppland lakes. This sediment profile represents the former gulf and lake phases at 2.8–4.4 meter depth below the present mire surface. The data, which were digitised from a hand-written diagram, contain diatom data at a high temporal resolution. Relative frequencies of c. 100 diatom taxa (mostly enumerated at species level) were calculated at usually 5-cm sediment intervals, with a higher temporal resolution during the major shifts in the former lake

Vikasjön (as assessed from the notes on sediment structure). At present, these data can be used to illustrate general diatom changes during the shifts from brackish water to freshwater (oligotrophic and eutrophic) conditions. However, some quantitative aspects of the data need to be addressed before these data can be used for modelling of biological changes following lake development.

Table 3-15. Generalised sediment structure for a sediment core in a lake (based on the data mentioned in the text).

0–115 cm	Water	
115–190 cm	Algae gyttja, red	Lake phase
190–230 cm	Algae gyttja, green	Lake phase
230–270 cm	Clay gyttja	Lake phase and/or shallow gulf phase
270–280 cm	Sandy clay gyttja	Shallow gulf phase
280–312 cm	Silty sand	Wave wash phase
312 cm–	Postglacial clay	Postglacial sedimentation phase

3.6.6 Human activities

Information about human activities in catchment areas and lakes in Uppsala County is presented in /Brunberg and Blomqvist, 1998/.

3.6.7 Pollutants

No data has been compiled concerning pollutants in lakes in the Forsmark regional model area.

3.7 Sea

The sea in the Forsmark regional model area will be described under the following headings:

- Physics
- Chemistry
- Biology
- Morphometry
- Sediments
- Human activities
- Pollutants

The characteristics of the sea in the Forsmark area have been analysed in reports during the SAFE project /Kautsky, 2001/, which are summarised below, together with data from SMHI.

3.7.1 Physics

Data input

The variables describing the physical characteristics of the sea in the Forsmark regional model area are temperature, hydrography, maximum depth, water exchange, oxygen saturation and water level. The sources of information are presented in /Lindell et al, 1999/, /Engqvist and Andrejev, 1999/ and /Larsson-McCann et al, 2002/.

Distribution and character

As the spring proceeds, the increased solar radiation heats the surface water in the Bothnian Sea and *temperature* stratification has developed by the end of June. The depth of this surface layer is between 20–25 meters. In the fall, the surface layer is cooled and the temperature stratification breaks down. By October, the temperature is again homogenous throughout the water column. During the winter months, the cooling of the uppermost surface layer can bring the temperature below 0°C resulting in the formation of sea ice. Temperature profiles of monthly measurements during 1972–1976 are presented in Figure 3-8. During winter and spring the variations in temperature are small from year to year, whereas the variations are larger in summer and autumn /Larsson-McCann et al, 2002/.

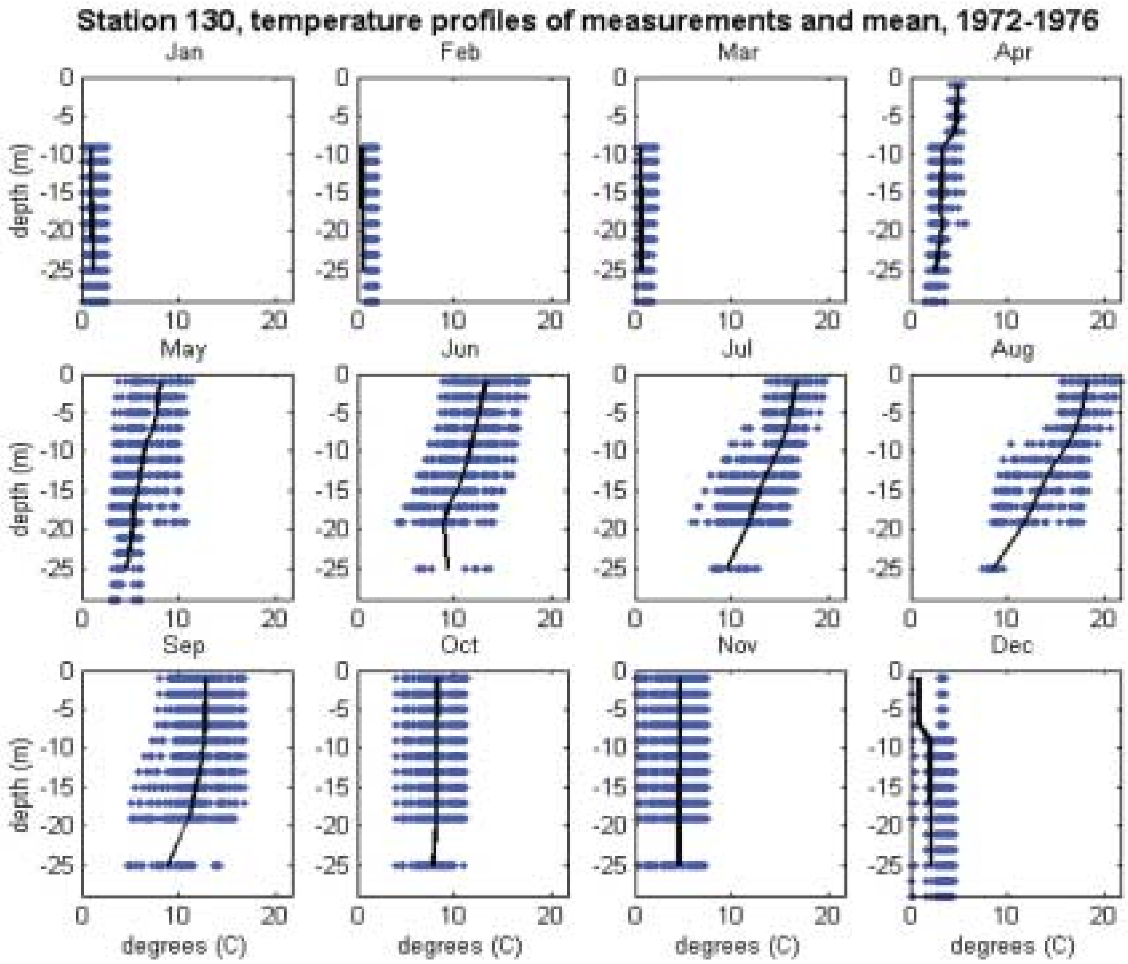

Figure 3-8. *Temperature profiles at station 130 (Table 3-16), 1972–1976. The daily mean value of measurements (dots) and mean value over depth (solid line) are plotted in the diagrams. After /Larsson-McCann et al, 2002/.*

The shoreline between Gävle bay and Svartklubben (SMHI station at Singö, approximately 30 km southeast of the Forsmark regional model are) consists to a relatively large part of archipelago mixed with open exposed areas. The *hydrography* is dominated by the freshwater discharge from rivers which flow into Gävle bay but also by the wind. The freshwater discharge from Gävle bay travels south along the coast and passes the Öregrundsgrepen causing a lower salinity in this area than that found at the more exposed Grundkallen, east of Gräsö. There is no salinity stratification in the area /Larsson-McCann et al, 2002/. Salinity is further treated in Section 3.7.2.

The *maximum depth* of Öregrundsgrepen is about 60 m. In the relatively open Öregrundsgrepen, the *water exchange* is considered good. In a model study /Engqvist and Andrejev, 1999/, the water retention time of Öregrundsgrepen was found to vary between 12.1 days (surface) and 25.8 days (bottom) as an annual average.

Rapid motions in the temperature stratification have been observed, indicating substantial exchange of water. During northerly winds, a counter-clockwise circulation is set up. Surface water is then brought into the area, pressing down the thermocline and resulting in deep water leaving the area along the bottom. During southerly winds, the circulation is clockwise and surface water is brought out of the area allowing inflow of deep water along the bottom under the thermocline. The *oxygen saturation* is on average 95%. Stagnation in the bottom water can occur in the deepest parts of Öregrundsgrepen, west of Gräsö /Larsson-McCann et al, 2002/. Automatic registration of temperature was made in the sea outside Forsmark at different stations between 1972–1981. The temperature was registered at several levels 1–2 times every hour during parts of the years. The stations around Forsmark, where SMHI has available data, are presented in Table 3-16.

Water level is measured hourly with an accuracy of 1 cm, see Figure 3-9. The gauge is connected to the national Swedish datum level RH70. Land rise is significant and must be corrected for, otherwise old positive and young negative extremes will be biased. The correction made consists of equating the long-term annual mean water level to zero. Note that the actual annual mean water level is not necessarily zero by this procedure.

Table 3-16. Stations in the Forsmark area where SMHI has available data. After /Larsson-McCann et al, 2002/.

Station	Co-ordinates, RAK		Variable	Depth	Sampling year
S	6704904 N	1629069 E	Temperature	~7 m	Parts of 1977–1980
130	6700185 N	1642114 E	Temperature	~29 m	Parts of 1972–1976
TEK	6699809 N	1634586 E	Temperature	~7 m	Parts of 1977–1979
XS-A	6713197 N	1621903 E	Temperature	~4 m	Parts of 1977–1981
Forsmark 2179	6701250 N	1632370 E	Water level	–	1976–2001

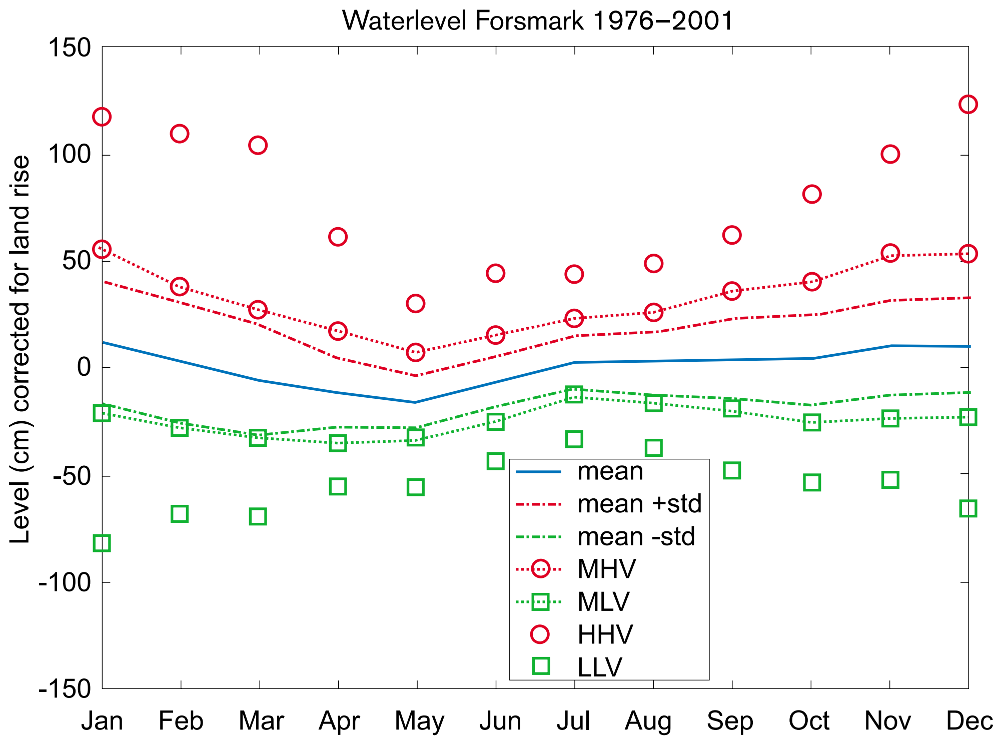

Figure 3-9. *Monthly sea water level (cm) statistics at Forsmark 1976–2001. Monthly mean water level and one standard deviation are shown. MHV/MLV signifies mean high/low water level, i.e. mean of all years 1976–2001. HHV/LLV signifies highest/lowest water level ever during 1976–2001. Based on hourly measurements. After /Larsson-McCann et al, 2002/.*

3.7.2 Chemistry

Data input

The variables describing the chemistry of the sea in the Forsmark regional model area are oxygen saturation, abundance of nutrients and salinity. The information has been compiled by /Larsson-McCann et al, 2002/, /Nitchals, 1985/, /Persson et al, 1993/ and /Engqvist and Andrejev, 1999/.

Distribution and character

Due to the rapid water turnover of Öregrundsgrepen, the *oxygen saturation* is high, on average 95%. Stagnation in the bottom water can occur in the deepest parts of Öregrundsgrepen, west of Gräsö /Larsson-McCann et al, 2002/.

The concentration of *nutrients* in the water varies throughout the year with the highest concentration at the time for break-up of the ice. Generally, the open water area is poor in nutrients during summer. The content of total nitrogen in Öregrundsgrepen varies between c. 200 and 300 µg/l and total phosphorus between c. 10 and 15 µg/l. According to /Nitchals, 1985/, the mean levels of PO_4-P, NH_4-N and NO_3-N at the Biotest basin close to the nuclear power plant at Forsmark was 8.0, 7.0 and 1.0 µg/l, respectively, during the one-week period 1989-07-26 to1989-08-01.

The *salinity* in Öregrundsgrepen in 1977–78 was between 4.5–5.8‰ in surface water and 5.6–6.4‰ at a depth of 40 m /Persson et al, 1993/. A monthly mean from twenty years of salinity measurements in Åland Sea (1971–1991) shows a variation of only 0.5‰. The salinity in Åland Sea is somewhat higher and more stable compared to that of Öregrundsgrepen. During the winter period, when Öregrundsgrepen can be ice-covered, the salinity can decline to less than 1‰ in the upper decimeter of the water column because freshwater from the ice accumulates /Persson et al, 1993/.

The surface salinity of Öregrundsgrepen was modelled by /Engqvist and Andrejev, 1999/ and is partly shown in Figure 3-10. The salinity depletion at the mouth of Kallrigafjärden, where two streams discharge, is clearly visible. Except for this, the salinity surface distribution is homogeneous.

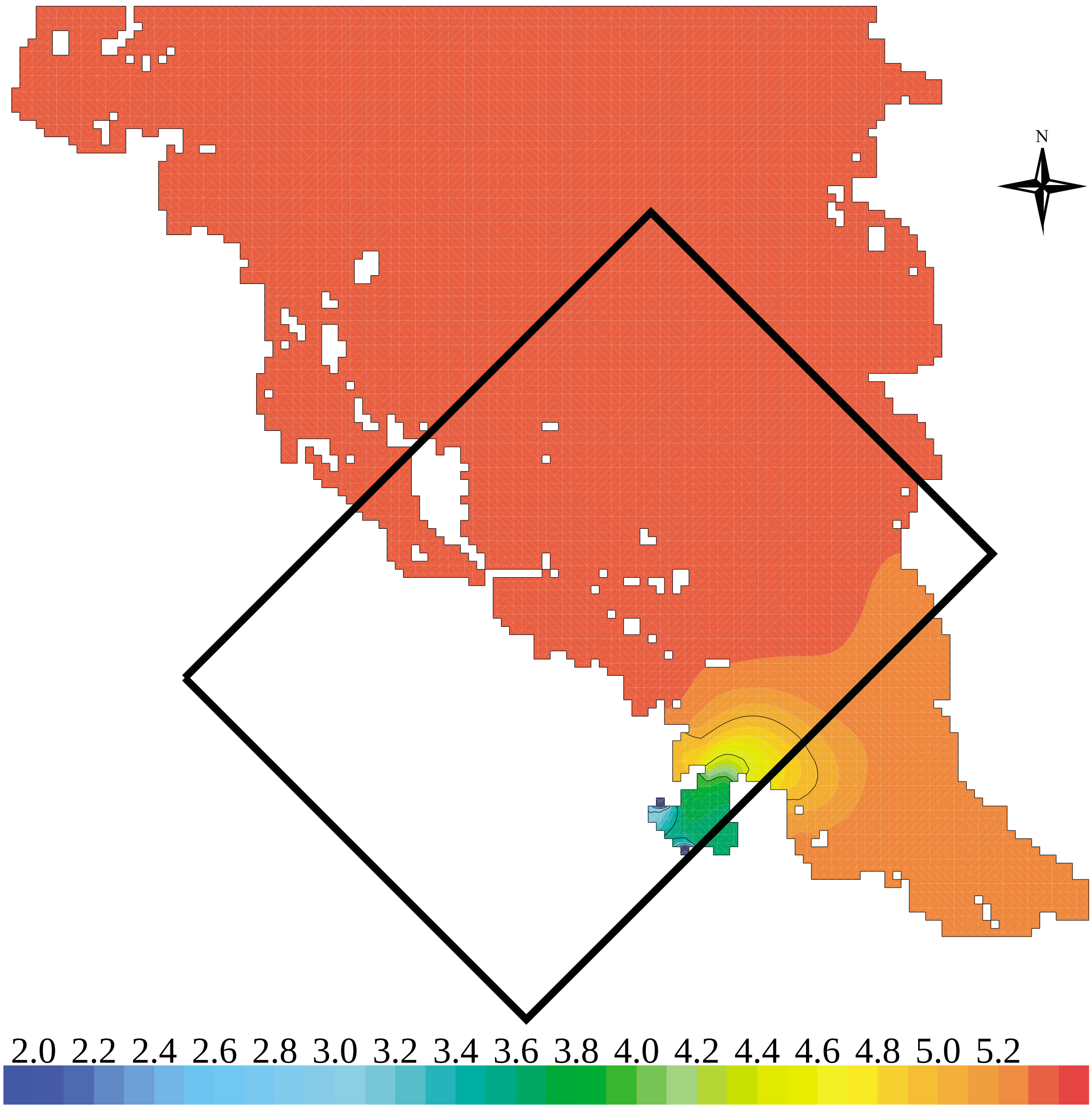

Figure 3-10. *Modelled surface salinity distribution of Öregrundsgrepen 1992-12-31 /Engqvist and Andrejev, 1999/. Salinity in ‰. The Forsmark regional model area is shown by a black line.*

3.7.3 Biology

Data input

The brackish water coastal ecosystem in Forsmark regional model area can be divided into two habitats; the pelagic and the shallow soft bottoms. The variables describing the biology of this ecosystem are biomass and composition of plankton, macrophytes (water plants), benthic fauna, fish, and species composition of seabirds and seal.

Information is mainly available from the vicinity of SFR /Kautsky, 2001; Kumblad 1999, 2001/ but /Kautsky et al, 1999/ have reported data from other parts of the Forsmark area. Detailed information on the bottom vegetation, and to some extent also the bottom fauna, was collected during inspections performed in connection to an Environmental Impact Assessment concerning the construction of wind power plants in Öregrundsgrepen /HYDROGIS AB, 2000/.

Distribution and character

The brackish water coastal ecosystem is the ecosystem of today in the area, and it will be found within the area at least for the next 3,000 years. The major biological components and energy flows between them are described below.

The *pelagic community* embraces the water mass with phytoplankton, bacterio*plankton*, zooplankton and fish. During the spring, the phytoplankton community in Öregrundsgrepen is dominated by diatoms (*Bacillariaophyceae*) and dinoflagellates (*Dinophyceae*) while the biomass in summer and autumn mainly is composed of bluegreen algae (*Cyanophyceae*) and small flagellates /Lindahl and Wallström, 1980/.

The zooplankton community is of low diversity since *Acartina bifilosa* and *Eurytemora affinis*, both copepods, constitute about 80% of the zooplankton biovolume. The rest is composed of cladocerans, mainly the genera *Bosmina* spp, *Podon* spp and *Evadne* spp, rotatorians with the genera *Keratella* spp and *Synchaeta* spp, ciliates with both *Tintinnida* and naked forms and also different larvae stages from benthic animals /Eriksson et al, 1977; Persson et al, 1993/.

The most common species of *fish* in Öregrundsgrepen are herring, roach and perch, followed by ruffe, smelt, four-horned sculpin, sprat and cod. Other species that occur in Öregrundsgrepen are pike and eel. There was no survey on small-sized species e.g. three-spined stickleback, sand goby, common goby, bleak and minnow since the nets used had meshes too large to catch these species /Neuman, 1982/. The distribution of the most abundant species is given in Table 3-17.

Table 3-17. The distribution of fish species in a study area in Öregrundsgrepen (% of the total catch in gill nets), from /Neuman, 1982/.

Herring	Roach	Perch	Ruffe	Smelt	Others
78.0%	10.0%	4.7%	3.0%	1.7%	2.6%

The area offers good conditions for sea birds. The most common *birds* are goldeneyes, tufted ducks, gooseanders, mute-swan, mallards and eider-ducks. The sea eagle is also a frequent visitor in the area /Andersson et al, 1996/. Seals are occasional visitors in Öregrundsgrepen.

On *shallow soft bottoms* the *vegetation* is dominated by vascular plants. In the bay Forsmarksfjärden, west of the Biotest basin, vascular plants like *Myriophyllum spicatum* and different species of *Potamogeton spp.* were common in a survey in 1974. *Chara tomentosa* and/or *Potamogeton pectinatus* can dominate down to a depth of two meters and are often found in the shallow bays called flads and gloes, which have limited water exchange with the sea. On these bottoms, *Chara baltica* and *Najas marina* often form small stands. In places where the sediments are more stable, *Chara marina* is usually found, and in sandier sediment the diversity can be great and include many vascular plants like *Potamogeton pectinatus*, *P. perfoliatus*, *Ranunculus baudotti*, *Zanichellia palustris*, *Myriophyllum spicatum* and *Callitriche spp.* Some of the Charophytes found in these areas are redlisted (i.e. are on the list of species in Sweden which are under threat of extermination) /Kautsky, 2001/.

At 2–4 m depth, the soft bottoms are often covered by *Vaucheria spp.* On these bottoms, sparse stands of *Potamogeton perfoliatus*, *Myriophyllum spicatum* and *Ranunculus baudotti* can also be found /Kautsky, 2001/.

The occurrence of macrophytes was verified by a diving survey /Kautsky et al, 1999/. On the hard, more stable substrata (boulders, rock) a luxuriant growth of the bladder wrack (*Fucus vesiculosus*) could be seen. Also, the moss *Fontinalis dalecarlica* was common. The filamentous green algae (*Cladophora* spp.) and some filamentous brown algae (*Ectocarpus/Pilayella* and *Sphacelaria arctica*) dominate the first two meters. Between 2 to 4 m, the bladder wrack (*Fucus vesiculosus*) dominates the biomass (totally 214 gDW/m^2). Vascular plants (*Potamogeton* spp. and *Zostera* sp.) contribute to the total biomass as well as perennial redalgae (*Furcellaria lumbricalis*). Perennial redalgae dominate the vegetation down to 10 m depth, where the macroscopic vegetation ends.

Compared to what was found in nearby studies, the Forsmark area had somewhat lower maximum biomass in the zone between 2–4 m depth (580 and 214 g DW/m^2 respectively). This is probably due to the lack of suitable substrata in the area. Observations in the area partly indicate a rich growth of *Fucus* especially on hard substrates /Kautsky et al, 1999/.

In the diving survey, the bottom from the surface down to a maximum of 18 m was investigated in an area including the bottoms above SFR. The biomass and diversity of *benthic fauna* peaks between 2–4 m depth with a high contribution of filter feeders (mainly *Cardium* sp.), herbivores (*Theodoxus fluviatilis* and *Lymnaea peregra*) and detrivores (mainly *Macoma balthica)* with a mean biomass of 60 gDW/m^2. At lower depths, the detrivores dominate (mainly *Macoma balthica*), with a high biomass down to 15 m. The blue mussel (*Mytilus edulis*) was to a large extent missing, although suitable substrate was present. In the Bothnian Sea, blue mussels extend up to Norra Kvarken, but usually few individuals are found at each site along the coast and the density is never as high as can be observed further south in the Baltic proper. Data on the soft bottom fauna of Öregrundsgrepen have been collected in studies performed by Swedish Environmental Protection Agency between 1978–1986 /Mo and Smith, 1988/.

/Kumblad, 2001/ has compiled data concerning biomass in the coastal ecosystem in the area above SFR from various sources. The total standing stocks and flow of matter (carbon) within this area are shown in Figure 3-11.

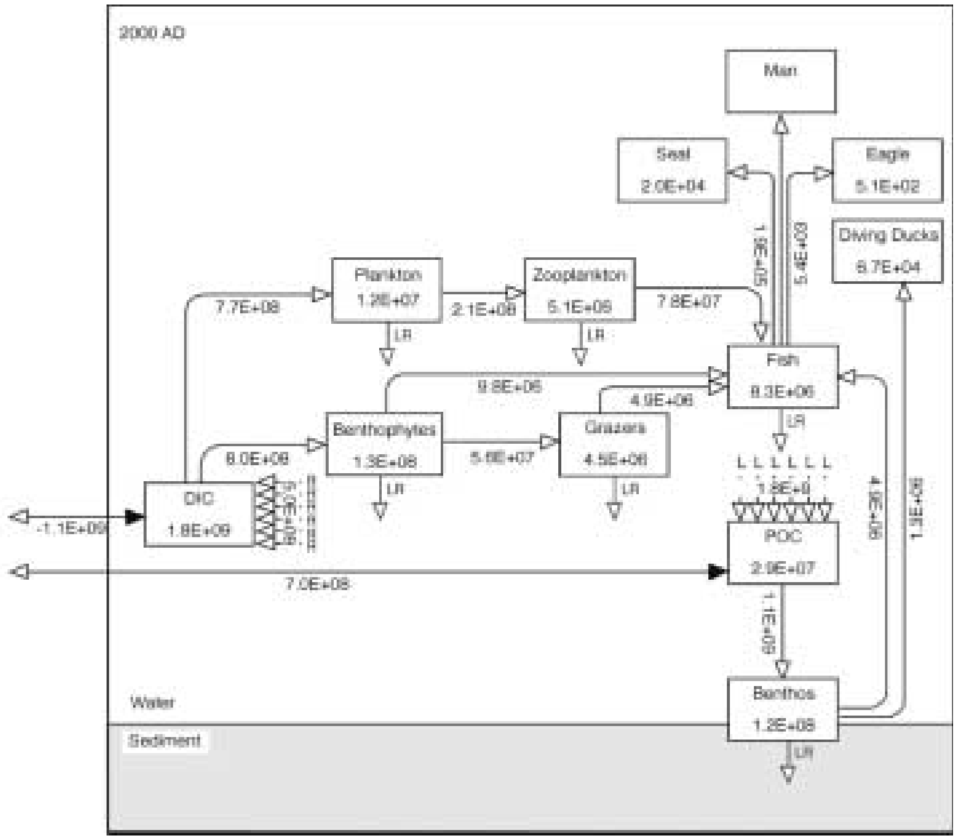

Figure 3-11. Annual carbon budget for year 2,000 AD for the area above SFR. Stocks (inside squares) in gC and flows (arrows) in gC/year /Kumblad, 2001/.

A carbon budget was set up for the area above SFR. It was based on biomasses and flows of carbon between thirteen functional groups (Figure 3-11, which includes POC (particulate organic carbon) and DOC (dissolved organic carbon)) in the ecosystem above SFR. The results indicate that the organisms are self-sufficient in carbon, and that the area exports carbon corresponding to approximately 50% of the annual primary production. The largest organic carbon pool is DOC (one and a half time larger than the total biomass) and the major functional organism groups are the macrophytes (37% of the total biomass), benthic macrofauna (36%), and the microphytes (11%). The soft bottom and phytobenthic communities appear to have important roles in the ecosystem since these communities comprise the main part of the living carbon in the studied area.

The phytobenthic community contributes to the larger share (61%) of the primary production, whereas the larger part of the consumption has taken part in the soft bottom community (53%).

3.7.4 Morphometry

See Section 3.2.2

3.7.5 Sediment

Data input

The variable describing the sediment of the sea in the Forsmark regional model area is the amount of accumulation bottoms. A report on coastal sedimentation in Öregrundsgrepen has been presented by /Brydsten, 1999b/.

Distribution and character

In /Brydsten, 1999b/, a mathematical model is used to simulate the resuspension of fine particles caused by wave movement in the Forsmark area. The model simulates the wave-induced near-bottom water dynamics based on meteorological data. First, the characteristics of waves in deep water are calculated (wave height, length, and direction). Then the gradual change of the characteristics as the wave reaches shallower water is calculated. The maximum near-bottom orbital velocity is calculated for the entire fetch distance, and the wave's ability to resuspend fine-grained particles is determined using well-known semi-empirical methods. A large variety of weather conditions are simulated, and the results are shown as a map for two different bottom types: accumulated bottoms (continual accumulation of fine-grained particles) and erosional/accumulation bottoms (periods with accumulation alternating with periods with erosion) /Brydsten, 1999b/.

The results of the simulation show that sedimentation conditions change quickly, but normally a clear pattern is evident. When the most recent glaciers melted away from the region, the entire area was made up of accumulation bottoms. As the land rose and the area became more shallow, many of the bottoms became more erosional (at maximum approximately 14% at 500 AD). Some of these areas later again became accumulation bottoms as a result of sheltered conditions created by the growing archipelago which provided protection from the waves of the open sea /Brydsten, 1999b/.

Large areas close to SFR have recently been transformed into accumulation bottoms and this trend will continue until the area becomes terrestrial (2,400–3,500 AD). The *amount of accumulation bottoms* in the area is at present 23% /Brydsten, 1999b/.

3.7.6 Human activities

Data input

A variable describing the human activities in the sea of the Forsmark regional model area is the number of professional fishermen who are active within the area. Today, 23 professional fishermen utilise the water east of Gräsö for their profession /Berggren and Kyläkorpi, 2002/.

3.7.7 Pollutants

Data input

The variables describing pollutants of the sea in the Forsmark regional model area are levels of zinc, lead, cadmium and radionuclides in sediments and levels of zinc and cadmium in mussels. Compilations of data are found in /Berggren and Kyläkorpi, 2002/, /Länsstyrelsen i Uppsala Län, 1996/, /Notter, 1988/ and /Persson et al, 1993/.

Distribution and character

Coast-parallel currents run anti-clockwise around the Baltic Sea basins. These currents transport do not affect the Öregrundsgrepen as much as the outer archipelago. Pollutants discharged along the Norrland coast and in river Dalälven thereby affect the water quality at the Uppland coast. In Öregrundsgrepen, enhanced levels of *zinc, lead and cadmium*, about 5–10 times normal values, have been measured in the *accumulation bottoms*. Values for other metals were considered low or normal /Länsstyrelsen i Uppsala län, 1996/. East of Gräsö, the highest levels of *zinc and cadmium in mussels* in the whole Baltic Sea have been measured /Länsstyrelsen i Uppsala län, 1996/. According to this work, the need for a complete investigation of heavy metals in sediment and organisms in the whole Uppland coastal area is urgent.

Concerning *radionuclides*, mainly ^{60}Co has been observed in sediment samples from the Öregrundsgrepen. The activity of ^{137}Cs in the sediment in the Gräsö channel rose from 80 Bq/kg DW in 1983 to 4,800 Bq/kg DW in 1987 due to the Chernobyl fallout /Notter, 1998/. During 1989, an increased discharge of ^{134}Cs, ^{137}Cs and ^{131}I was noted /Persson et al, 1993/.

Swedish Radiation Protection Authority, SSI, carries out environmental control programmes for radionuclides in the areas where the Swedish nuclear power plants are located. In these programmes, the concentrations of radionuclides in the surroundings are measured continuously. The main target is biota but radionuclide concentrations in water, air and sediments are also measured. Data from this monitoring is available from SSI, but have not been compiled for this description.

4 Geology

4.1 Introduction

The Forsmark regional model area in central Sweden forms part of an old area of Precambrian crystalline rocks, referred to as the Fennoscandian Shield. Forsmark lies within the southernmost part of a complex, structural domain with predominantly high-grade metamorphic rocks. This domain extends from the coastal area in the northern part of Uppland to the Hudiksvall-Ånge area, south of Sundsvall, to the north. It is characterized by a relatively high concentration of ductile high-strain zones with NW to NNW strike, which anastomose around lenses in which the bedrock is folded and generally displays lower strain (Figure 4-1). These so-called tectonic lenses are also conspicuous on a smaller scale within the Forsmark regional model area (see below).

The structural domain constitutes the northern part of a broader lithological province, which extends from the Hudiksvall-Ånge area in the north to the Loftahammar-Linköping area in the south. This province consists of metagranitoids with associated metavolcanic and metasedimentary rocks. The meta-igneous rocks vary in age from c. 1,906 to 1,840 million years (Figure 4-1), rocks older than c. 1,870 million years being conspicuous south of Gävle. It includes one of Sweden's important ore provinces – Bergslagen and adjacent areas /Frietsch, 1975; Åkerman, 1994/. The northern boundary of this ore province is situated within the southwestern part of the Forsmark regional model area.

In accordance with other older Precambrian shield areas, the Fennoscandian Shield is transected by a complex network of brittle-ductile and brittle fracture zones. They initiated their development after c. 1,700 million years ago. Locally, it has been shown that individual zones were active at different times during the last c. 1,700 million years.

The Forsmark regional model area was affected by glacial activity during the Quaternary period (1,635–0 million years). Only the effects of the Weichselian glaciation, which started to affect Swedish latitudes c. 115,000 years ago, and the post-Weichselian development during the latest c. 10,000 years, are preserved in the Forsmark area.

The presentation of the geology begins with *a model for the geological evolution* in the part of central Sweden where the Forsmark regional model area is situated (Section 4.2). This model focusses on the lithological and structural development in the bedrock. The Weichselian glacial deposits, the sediments deposited after this glaciation and the possible effects of late- or post-glacial faulting in the regional model area are treated separately, and in more detail, under the section entitled ”Quaternary geology” (Section 4.3). A description of the main geological “parameter groups” /SKB, 2001b/, *Quaternary geology*, *bedrock – rock type and potential for ore deposits* and *bedrock – structure* is given in Sections 4.3, 4.4 and 4.5, respectively. With regard to the brittle structures, only what have been called “local major and regional fracture zones” /Stråhle, 2001/ are addressed in Section 4.5. *A description of the 3D geological modelling* (Section 4.6), which has been carried out within the project, and *an assessment of the uncertainty in the geological data* (Section 4.7) complete this chapter.

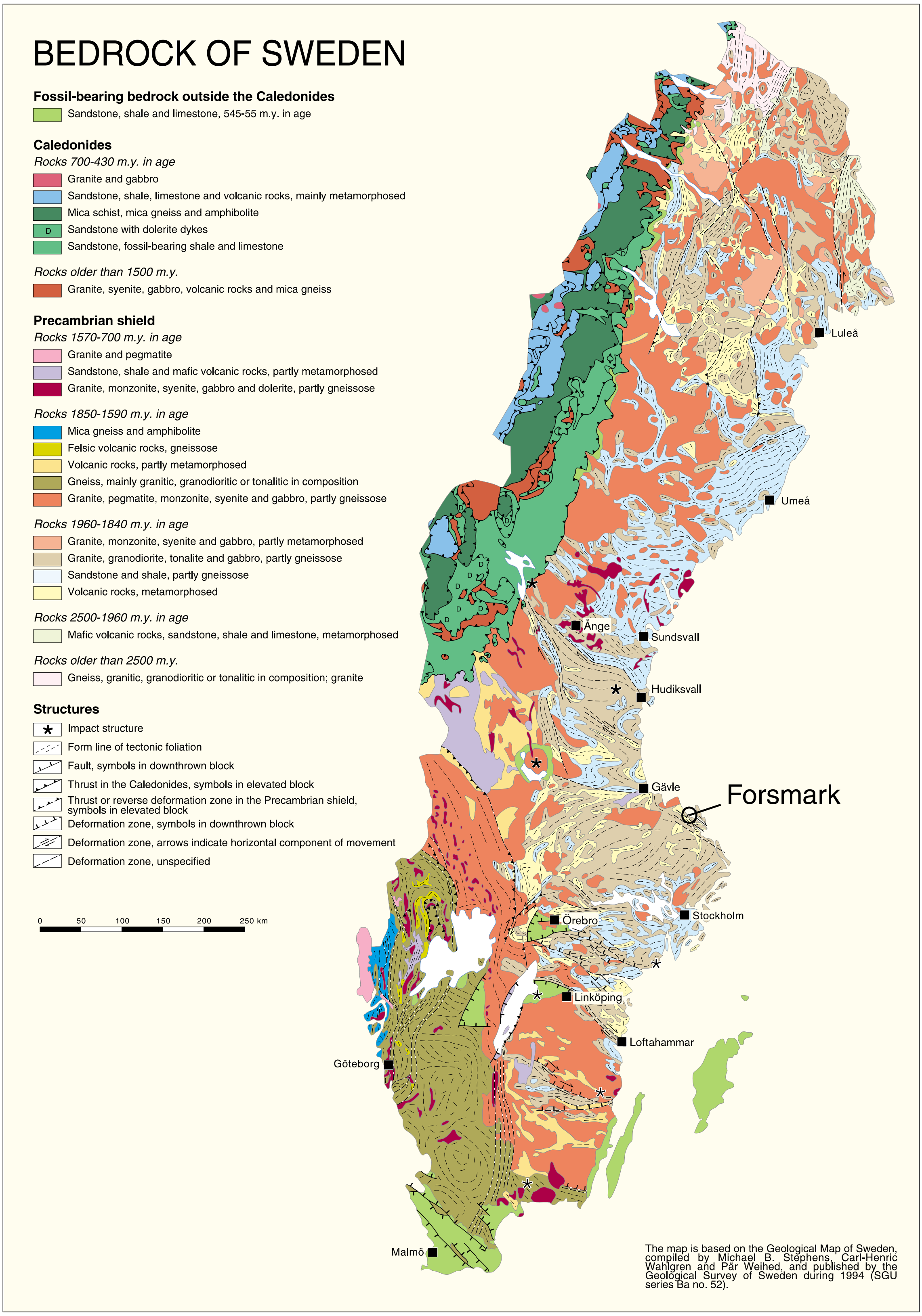

Figure 4-1. *Simplified map of the bedrock geology of Sweden. The position of the Forsmark regional model area is shown.*

4.2 Regional setting of the Forsmark area – geological evolutionary model

A model for the geological evolution in the Stockholm-Gävle-Örebro area in central Sweden, at the edge of which the Forsmark regional model area is situated, is presented for six key stages related to different time periods. The Stockholm-Gävle-Örebro area has been chosen since, firstly, the rocks in this area are generally better preserved relative to the rocks further north and, secondly, considerable geochronological data are available in the area. Each of these six stages is described briefly in tabular format. The parts of the tables which are shaded in a grey colour refer specifically to the lithological or structural development of the Stockholm-Gävle-Örebro area, during a particular stage in the geological evolution. Where the effects of geological events are of more limited character and, in general, less well understood (stages 3–6), information from outside the Stockholm-Gävle-Örebro area has also been taken into account.

The model has utilized the following information:

- A country-wide compilation of the bedrock geology /Stephens et al, 1997/.
- A review of tectonic régimes in the Fennoscandian Shield during the last 1,200 million years /Larson and Tullborg, 1993/.
- A reconstruction of the tectonic history of the Fennoscandian Shield during the last 100 million years, based on data available along its margins to the south and west /Muir Wood, 1995/.
- Summaries of the geology of central Sweden in several county reports /Antal et al, 1998a,b,c,d; Bergman et al, 1999a,b/.
- Key references of more local interest which are referred to directly in the following tables.

Stage 1 – Time period pre-1,906 to 1,870 (1,855) million years.

Crustal growth and early-stage reworking of the crust (Svecokarelian orogeny, early stage).

Time period	Lithological development in the Stockholm-Gävle-Örebro area
Prior to 1,906 million years.	1. Deposition of, in part, volcanogenic, distal turbidites /Stephens et al, 2000/.
1,906 to 1,891 million years.	2. *Main volcanic stage* /Allen et al, 1996/ with deposition of juvenile, volcaniclastic rocks, formation of lava domes and emplacement of subvolcanic intrusions. Mineralization, including the metals Fe and Zn-Pb-Ag-(Cu-Au). *Waning volcanic stage* /Allen et al, 1996/, with deposition of predominantly bedded, reworked volcanic rocks, skarn deposits and carbonate rocks, and intrusion of mafic dykes and sills. Mineralization, including the metals Fe-Mn and Zn-Pb-Ag-(Cu-Au).
After 1,891 million years.	3. Deposition of post-volcanic, sedimentary rocks.
1,901 to 1,870 million years.	4. Intrusion of tonalite, granodiorite, granite, quartz monzonite and associated mafic to intermediate rocks.

Structural development in the Stockholm-Gävle-Örebro area (ductile deformation)
Ductile deformation and metamorphism with development of a planar grain-shape fabric, including gneissosity in higher-grade rocks, prior to 1,855 million years /Stephens et al, 2000/. Uncertain tectonic régime in central Sweden. A comparison with the Finnish segment of the Fennoscandian Shield suggests important, dextral transpressive deformation. The transpression was taken up in the Finnish segment by dextral displacement along ductile high-strain zones with NW strike, combined with shortening across an older continental margin which also trends NW (thrusting to the NE). Oblique collision against the older continental margin, with a N-S to NNW-SSE movement direction, is inferred.

Stage 2 – Time period 1,855 to 1,750 million years.

Extensive igneous activity, deformation and metamorphism associated with crustal reworking (Svecokarelian orogeny, late stage). Exhumation of deeper crustal levels and erosion.

Time period	Lithological development in the Stockholm-Gävle-Örebro area
1,855–1,840 and 1,825–1,750 million years.	1. Intrusion of granite, quartz monzonite, monzonite and associated mafic to intermediate rocks. Some volcanic activity and sedimentation immediately west of the Stockholm-Gävle-Örebro area. 2. Intrusion of granite and pegmatite often with high U and Th contents. Mineralization, including metals W-Mo.

Structural development in the Stockholm-Gävle-Örebro area (ductile deformation)
Ductile deformation and metamorphism at mid-crustal depths with development of the following structures: • Tectonic foliation in the intrusive rocks which are 1,855–1,840 million years in age. • Major, regional-scale folding and minor folds which deform earlier planar fabrics. • High-strain zones, exhumation of deeper crustal levels and erosion. • Intense, linear grain-shape fabric. Gradual waning of the ductile deformation under lower-grade metamorphic conditions and at shallower crustal depths occurred after c. 1,800 million years. The tectonic régime involved dextral transpressive deformation which was taken up partly by major regional-scale folding between ductile high-strain zones, and partly by dextral displacement along ductile high-strain zones with NW strike, combined with shortening in a NE direction across the zones /Stephens and Wahlgren, 1996; Beunk and Page, 2001/. Continued oblique collision against the older continental margin to the NE, with a N-S to NNW-SSE movement direction, is inferred.

Stage 3 – Time period 1,750 to 850 million years.

Far-field effects of continued crustal growth and crustal reworking with deformation and metamorphism to the south and west (including Gothian, Hallandian and Sveconorwegian orogenies), which ultimately resulted in the assembly of the supercontinent Rodinia.

The tectonic scenario in the Stockholm-Gävle-Örebro area was characterized by:

- **Exhumation of deeper crustal levels and erosion.**
- **Local subsidence and formation of sedimentary basins during the Mesoproterozoic.**
- **Subsidence and formation of a foreland sedimentary basin to the east of the Sveconorwegian orogenic belt, related to the exhumation of deeper crustal levels and erosion within this belt.**

Time period	**Lithological development to the south, west and north of the Stockholm-Gävle-Örebro area**	**Lithological development in the Stockholm-Gävle-Örebro area**
1,700–1,675 million years.	Major igneous activity (intrusive/volcanic) and sedimentation.	No lithologies exposed at the present-day Earth's surface.
1,610–1,100 million years.	Major igneous activity (intrusive/volcanic) and sedimentation.	1. Intrusion of mafic dykes with WNW strike (c. 1,560 million years old). 2. Local intrusion of granite (1,500 million years old), quartz syenite (1,470 million years old) and possibly alkaline intrusive rock (Almunge, east of Uppsala). 3. Sedimentation (exposure around Gävle and west of Stockholm; also offshore near Gävle and between Åland and Sweden). 4. Intrusion of mafic sills and dykes in the Gävle area (1,250 million years old).
1,000–900 million years.	Intrusion of granite, pegmatite, gabbro, anorthosite and mafic dykes.	Intrusion of mafic dykes with NNW strike.

Time period	**Structural development to the south, west and north of the Stockholm-Gävle-Örebro area**	**Structural development in the Stockholm-Gävle-Örebro area**
1,700–1,675 million years.	Ductile deformation (Gothian orogeny – early stage). A dextral transpressive high-strain zone with NNW strike displays dextral displacement along the zone, together with shortening in a ENE direction across the zone /Bergman and Sjöström, 1994/. An oblique collision with a NE-SW movement direction is inferred.	Uncertain.
1,610–1,100 million years.	1. Ductile deformation during the time period 1,610–1,560 million years (Gothian orogeny). 2. Uncertain structural development during the time period 1,560–1,100 million years (including Hallandian orogeny, during the time period 1,460–1,420 million years).	U-Pb dating of pitchblende in quartz-, calcite- and chlorite-filled fractures and Rb-Sr dating of epidote-filled fractures have yielded ages between c. 1,590 and 1,450 million years /Welin, 1964; Wickman et al, 1983/. Rb-Sr dating of prehnite- and calcite-filled fractures has yielded ages between 1,250 and 1,100 million years /Wickman et al, 1983/.

1,100–900 million years.	Ductile deformation (Sveconorwegian orogeny). A major, sinistral transpressive, high-strain zone with NW to N-S strike displays variable amounts of sinistral strike-slip and reverse dip-slip deformation, respectively, depending on the strike of the zone /Stephens et al, 1996/. Inferred movement direction WNW-ESE to E-W. Extensional ductile deformation also identified along the same high-strain zone /Berglund, 1997/.	Uncertain. Ductile-brittle high-strain zones with NE strike, which display dextral transpressive strain, are present directly west of Örebro /Wahlgren et al, 1994/. Subsidence related to the development of a Sveconorwegian foreland basin /Tullborg et al, 1996; Larson et al, 1999/.

Stage 4 – Time period 850 to 400 million years.

Far-field effects of:

- **The break-up of Rodinia with the formation of the ocean Iapetus and the continent Baltica.**
- **The rotation and drift of Baltica northwards over the globe.**
- **The destruction of Iapetus and the birth of the continent Laurussia (Caledonian orogeny).**

The tectonic scenario in the Stockholm-Gävle-Örebro area was characterized by:

- **Rifting, erosion and final establishment of the sub-Cambrian peneplain.**
- **Marine transgression and deposition of a sedimentary cover during the Early Palaeozoic.**
- **Subsidence and formation of an Upper Silurian to Devonian, foreland sedimentary basin to the east of the Caledonian orogenic belt, related to the exhumation of deeper crustal levels and erosion within this belt.**
- **Possible minor disturbance of the sub-Cambrian peneplain along some faults.**

Time period	Lithological development to the south, west and north of the Stockholm-Gävle-Örebro area	Lithological development in the Stockholm-Gävle-Örebro area
800–520 million years.	1. Syn-rift sedimentation. 2. Glacial episode. 3. Intrusion of mafic dykes related to rifting in western areas and opening of the Iapetus Ocean. Alkaline intrusive rock near Sundsvall (Alnön). 4. Deposition of mature sandstone, siltstone and shale (Vendian-Cambrian).	Syn-rift sedimentation, at least in the Vättern area (800–700 million years). Deposition of mature sandstone, siltstone and shale (Cambrian), preserved today in isolated, fault-controlled outliers on land and offshore near Gävle.
520–400 million years.	1. Sedimentation on a shelf and in outboard basins. 2. Igneous activity associated with convergent plate margin setting in westernmost areas. 3. Syn-rift sedimentation.	Deposition of Cambrian to Silurian shale and limestone, preserved today in isolated, fault-controlled outliers on land and offshore near Gävle (Ordovician limestone).

Time period	Structural development to the south, west and north of the Stockholm-Gävle-Örebro area	Structural development in the Stockholm-Gävle-Örebro area
800–520 million years.	Rifting. Establishment of the sub-Cambrian peneplain and a marine transgression during the Vendian-Cambrian.	Rifting (Vättern area). Establishment of the sub-Cambrian peneplain and a marine transgression during the Cambrian.
510–400 million years.	1. Continent-arc and continent-continent collisions in connection with the Caledonian orogeny. Shortening in a WNW-ESE direction with major thrusting to the east. 2. Extensional collapse and sinistral strike-slip.	Faults with NNE and c. E-W (ENE and WNW) strike and uncertain kinematics steer the geometry of outliers with Lower Palaeozoic rocks. These faults disturb the sub-Cambrian peneplain and the Lower Paleozoic rocks. They were active during or after the Caledonian orogeny (or both). Subsidence related to the development of a Caledonian foreland basin /Tullborg et al, 1995, 1996; Larson et al, 1999/.

Stage 5 – Time period 400 to 250 million years.

Far-field effects of:

- **Hercynian-Variscan orogeny in central Europe and final assembly of the supercontinent Pangaea.**
- **Rifting along the southern margin of the Fennoscandian Shield.**

The tectonic scenario in the Stockholm-Gävle-Örebro area was characterized by possible minor disturbance of the sub-Cambrian peneplain along some faults.

Time period	Lithological development to the south and west of the Stockholm-Gävle-Örebro area	Lithological development in the Stockholm-Gävle-Örebro area
295–275 million years.	1. Main phase of volcanic and intrusive igneous activity in the Oslo graben, Norway. Mafic dykes and sills in southern Sweden. Alkaline intrusive rock near Särna, in the county of Dalarna. 2. Syn-rift sedimentation.	No lithologies exposed at the present-day Earth's surface.

Time period	Structural development to the south and west of the Stockholm-Gävle-Örebro area	Structural development in the Stockholm-Gävle-Örebro area
360–295 million years.	Hercynian-Variscan orogeny in central Europe.	Uncertain.
295–275 million years.	Extensional deformation along the Oslo Graben, Norway. Dextral transtensional deformation along the Sorgenfrei-Tornquist Zone in southernmost Sweden /Erlström and Sivhed, 2001/.	Possible faulting, at least in the Vättern area.

Stage 6 – Time period 250 to 0 million years (excluding Quaternary developments, see Section 4.3).

Far-field effects of:

- **Rifting along the southern and western margins of the Fennoscandian Shield and marine transgression during the Cretaceous (especially the Late Cretaceous).**
- **Alpine orogeny in southern Europe.**
- **Opening and spreading of the North Atlantic Ocean.**

The tectonic scenario in the Stockholm-Gävle-Örebro area is uncertain during this time period. Minor disturbance of the sub-Cambrian peneplain along some faults may have occurred.

Time period	Lithological development to the south and west of the Stockholm-Gävle-Örebro area	Lithological development in the Stockholm-Gävle-Örebro area
250–60 million years.	Sedimentation and volcanic activity (Jurassic and Cretaceous).	No lithologies exposed at the present-day Earth's surface.

Time period	Structural development to the south and west of the Stockholm-Gävle-Örebro area	Structural development in the Stockholm-Gävle-Örebro area
250–95 million years.	Fault-controlled, differential subsidence along the Sorgenfrei-Tornquist Zone /Erlström and Sivhed, 2001/.	Uncertain.
95–60 million years.	Marine transgression increased during the Cretaceous. Inversion tectonics with dextral transpression along the Sorgenfrei-Tornquist Zone in southernmost Sweden /Erlström and Sivhed, 2001/. Inferred maximum principal stress (σ_1) in a NNE-SSW direction /Muir Wood, 1995/.	Uncertain.
60–0 million years.	Opening and spreading of the North Atlantic Ocean.	Evidence for the presence of late- or post-glacial faulting in the northern part of Uppland is lacking. *In situ* stress measurements in the Forsmark regional model area /Carlsson and Christiansson, 1987/ indicate that the maximum principal stress (σ_1) at the present day is oriented in a NW-SE direction. This is consistent with the stress field generated by plate movements in the North Atlantic Ocean /Slunga, 1989/.

4.3 Quaternary geology

4.3.1 Data input

The distribution and composition of Quaternary deposits in the Forsmark regional model area, as well as the extent of late- or post-glacial crustal movement, have been defined primarily with the help of the compilations made in connection with the Östhammar feasibility study /Bergman et al, 1996/. The cartographic data were extracted from SKB's GIS database (version 5.0). Details on data files and references to corresponding reports and figures are found in Appendix 1.

The compilation carried out during the Östhammar feasibility study utilized the Quaternary deposit maps (with descriptions) over map-sheets 12I Östhammar NO and 13I Österlövsta SO/13J Grundkallen SV. These were published in connection with the mapping programme (Quaternary geology) of the Geological Survey of Sweden (SGU) at the scale 1:50,000 /Persson, 1985, 1986/. The maps are based on an interpretation of infra-red aerial photographs, detailed geological mapping in the field, shallow trenching and drilling, and sample analysis carried out during the years 1982 and 1983.

The base data assembled during the mapping of the Quaternary deposits, including, for example, field observations, have not been studied within the context of the present project. Information on soil texture and soil depth from specific sampling sites in the forest areas of northern Uppland and of soil type in agricultural land in the Östhammar municipality are summarized in Chapter 3. Data bearing on the character of the Late Holocene sediments in two lakes in the regional model area, Eskarfjärden and Fiskarfjärden, are presented in /Bergström, 2001/.

The character of Quaternary deposits in the offshore areas directly northeast of the Forsmark nuclear power station is summarized in /Carlsson et al, 1985/. Offshore data above SFR, in an area which is 500x500 m in areal extent, is described in /Sigurdsson, 1987/. The offshore work utilized the results of both seismic surveys and sampling of bottom sediments.

The assessment of the variation in thickness of the Quaternary cover deposits used the onshore information in /Persson, 1985, 1986/ and /Bergström, 2001/, the offshore information above SFR in /Sigurdsson, 1987/, and summaries of onshore and offshore data in /Carlsson et al, 1985/ and /Carlsson and Christiansson, 1987/.

The recent relative uplift in Fennoscandia is recorded by precision levellings and tide gauge data. /Ekman, 1996/ has compiled such information from a variety of sources in Fennoscandia in order to define the present rate of crustal movements. The maps presented by /Ekman, 1996/ have been used to estimate the present rise in land relative to sea level (shoreline displacement) in the northern part of Uppland.

A database from the Department of Earth Sciences, University of Uppsala, was used as the main source of information for seismic activity in Sweden during historical time (registration of data from 1375 to 1996).

On the basis of the GIS geological data from SKB, a cartographic 2D model for the distribution of Quaternary deposits in the Forsmark regional model area is presented (Figure 4-2). The map shows the distribution of deposits at the surface and only the deposits on land are presented in this compilation. A description of the key geological "parameters" /SKB, 2001b/ for the different Quaternary deposits addressed in the site descriptive model version 0 follows in Section 4.3.2. The deposits are described essentially in stratigraphic order from base to top.

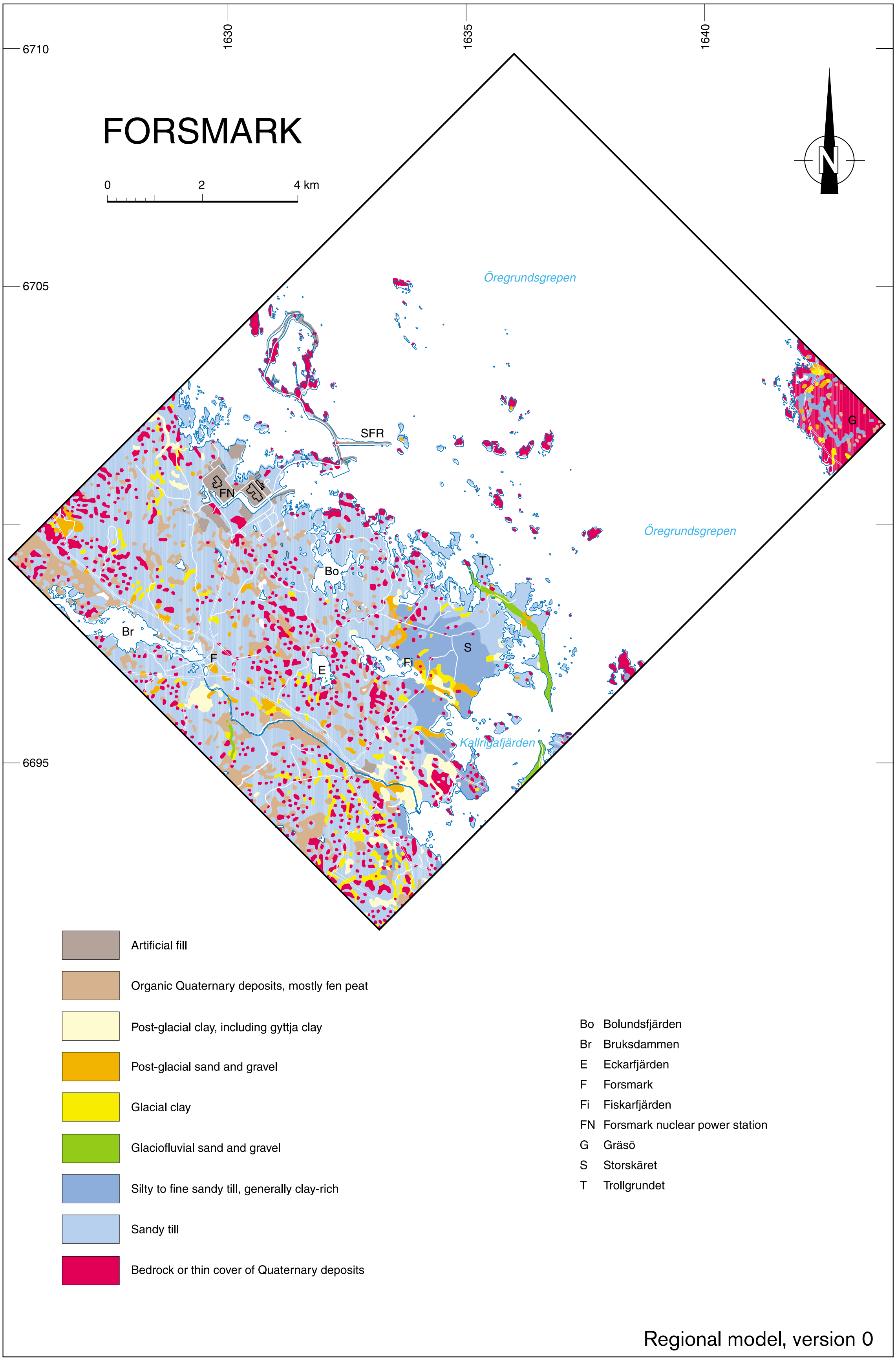

***Figure 4-2.** 2D cartographic model for the distribution of onshore Quaternary deposits in the Forsmark regional model area.*

4.3.2 Quaternary deposits – distribution, description and thickness

Onshore Quaternary deposits

Quaternary deposits occupy c. 82% of the land in the regional model area and artificial fill, principally around the Forsmark nuclear power station, c. 3%. Exposed bedrock or bedrock with only a thin (< 0.5 m) Quaternary cover occupies c. 15% of the land area (Figure 4-2). The Quaternary deposits consist of two components:

- Glacial deposits which were deposited either directly from the inland ice or from the water derived from the melting of this ice. These deposits include till, glaciofluvial sand and gravel, and varved clay. Glacial striae on bedrock outcrops are common and indicate an older ice movement from the NW to NNW and younger movements from the north.
- Post-glacial deposits which formed after the inland ice had melted and retreated from the area during the time period 10,180 to 9,970 years ago /Strömberg, 1989; Lundqvist, 1994/. The area lies beneath the highest shoreline which was established after retreat of the ice and these units were deposited at an early stage, when present land areas lay beneath the sea. Subsequently, following regression of the sea (see below), they were deposited in lakes and on land. The deposits include sand and clay deposits, and organic Quaternary deposits dominated by fen peat.

The dominant glacial deposit is *sandy till* which occupies c. 56% of the land in the regional model area. In the coastal area northeast of Storskäret and in several minor areas south and west of the Forsmark nuclear power station, this till contains a high frequency of boulders. Otherwise, it displays a normal block frequency. *Silty to fine sandy till*, which is generally clay-rich (7–12%) and contains a low frequency of boulders, is prominent around Storskäret on the northwestern side of Kallrigafjärden. This type of till occupies c. 7% of the land in the regional model area. A documentation of forest soil textural type from a limited number of sampling sites in the Forsmark area (see Table 3-4 in Chapter 3) yields somewhat lower estimates for the occurrence of sandy till and correspondingly higher estimates for the occurrence of silty to fine sandy till. Ordovician limestone is a conspicuous boulder component in the till deposits, i.e. the till is commonly calcareous in composition.

Till is generally considered to be less than 5 m thick. However, a thickness of 10 m has been documented in the clay-rich, silty to fine sandy till at Storskäret and a maximum till thickness of 14 m was indicated by /Carlsson and Christiansson, 1987/ from the area around the Forsmark nuclear power station. It is assumed that the till rests directly on the crystalline bedrock.

Glaciofluvial, sand and gravel deposits occupy only c. 1% of the land in the regional model area and are restricted to the northern part of Kallrigafjärden. The esker in this area crosses Kallrigafjärden and can be followed in a southeasterly direction towards Harg, c. 25 km from the Forsmark village.

Varved *glacial clay* occupies c. 3% of the onshore part of the regional model area and is restricted to three, relatively small areas; around Storskäret, southeast and northwest of the Forsmark village, and west of the Forsmark nuclear power station. It is commonly calcareous in composition and overlies till. Glacial clay probably occupies larger areas than those shown on the map since this type of deposit is generally hidden beneath post-glacial sediment and peat.

Post-glacial sediment and peat form the youngest group of Quaternary deposits. In general, they overlie till and, locally, glacial clay or crystalline bedrock. *Post-glacial sand and clay*, *including gyttja clay* (clay with 2–6% organic material), occupy only c. 5% of the land in the regional model area. Gyttja and clay gyttja occur at the bottom of the lakes Eckarfjärden and Fiskarfjärden and are up to 1.5 m thick /Bergström, 2001/. A more detailed summary of lake sediments in northern Uppland is presented in Chapter 3.

The dominant, post-glacial Quaternary deposits are organic in character and comprise c. 10% of the land area. *Fen peat* is by far the most important type of organic deposit. Conspicuous deposits of fen peat are situated north of Bruksdammen and southeast of the Forsmark village towards Kallrigafjärden, in the southwesternmost part of the regional model area, and in an area from Eckarfjärden northwestwards towards the Forsmark nuclear power station. The peat deposits vary up to 2 m in thickness.

Offshore Quaternary deposits

Offshore Quaternary deposits have been studied in the area directly northeast of the Forsmark nuclear power station, and above SFR, where they are dominated by till which rests on the bedrock. Locally, till is covered by fine sediment (clay). In the small area studied in detail above SFR /Sigurdsson, 1987/, the clay is glacial in character and is overlain by a thin layer of sand and gravel. The clay in this area occurs most conspicuously in a narrow belt which trends in a NNW direction. /Carlsson et al, 1985/ have speculated that the occurrence of clay may be linked, in some cases, to fracture zones in the bedrock.

The thickness of the offshore Quaternary deposits varies considerably from < 2.5 m to > 10 m (see Figure 3-5 in /Carlsson et al, 1985/). In the area above SFR, till varies in thickness between 4 and 14 m and clay between 0 and 4 m.

4.3.3 Late- or post-glacial crustal movement, and seismic activity in historical time

A major crustal phenomenon which has affected and continues to affect northern Europe, following the latest melting of inland ice, is the interplay between land rise (isostasy) on the one hand and sea level rise or fall (eustasy) on the other. In the northern part of Uppland, where Forsmark is situated, shoreline displacement studies /Robertsson and Persson, 1989; Bergström 2001/ have documented the relative rise in land with respect to sea level (regression) during the period c. 5,500 to 3,600 years ago. Studies of the sediments at the bottom of four lakes in northern Uppland are at present being carried out, in order to document shoreline displacement during the last 3,600 years. At present, the land is rising with respect to sea level at the rate of c. 60 cm per 100 years /Ekman, 1996/.

Mathematical modelling of shoreline displacement in Fennoscandia permits predictions to be made concerning future developments /Påsse, 1996; Morén and Påsse, 2001/. Modelling work has also allowed predictions to be made concerning changes in coastal sedimentation conditions in Öregrundsgrepen over the next 5,000 years /Brydsten, 1999a,b/. In particular, the development of future lakes and sediment accumulation bottoms, which are linked to a continued regressive shoreline development in the area, are addressed (see also Chapters 3 and 6).

Direct evidence for the presence of late- or post-glacial faulting in the northern part of Uppland is lacking. Furthermore, the mapping of Quaternary deposits on map-sheets 12I Östhammar NO and 13I Österlövsta SO/13J Grundkallen SV by SGU during 1982 and 1983 /Persson, 1985, 1986/ did not yield any observations which could be interpreted as supporting the presence of late- or post-glacial faults in these areas. A discussion of certain phenomena which have inspired some authors to speculate on the presence of such faulting was presented in /Bergman et al, 1996/. It is apparent that further study of the significance of late- or post-glacial faulting in the regional model area will be necessary during the site investigation programme.

The Forsmark regional model area is situated east of a belt that extends from southwestern Sweden via the coastal areas of Norrland to inland Norrbotten, along which there is a relatively high concentration of registered earthquake epicentres with a magnitude of 5 or less on the Richter scale (Figure 4-3). Apart from frequent yet minor seismic activity registered during the 1980's in the Dannemora and Finnsjön areas, southwest of the regional model area, which is thought to have been caused by human activity /Bergman et al, 1996/, natural earthquake epicentres are sparse in the northern part of the county of Uppsala. The strongest earthquake registered in the county (year 1776) had an epicentre c. 10 km northwest of Tierp and a magnitude of 3.6 on the Richter scale. Recent seismic activity has been related to ongoing plate-tectonic processes including spreading of the North Atlantic Ocean /Slunga and Nordgren, 1990/. However, this activity may also be related to post-glacial rebound, i.e. there is no consensus that it is due to plate-tectonic processes alone.

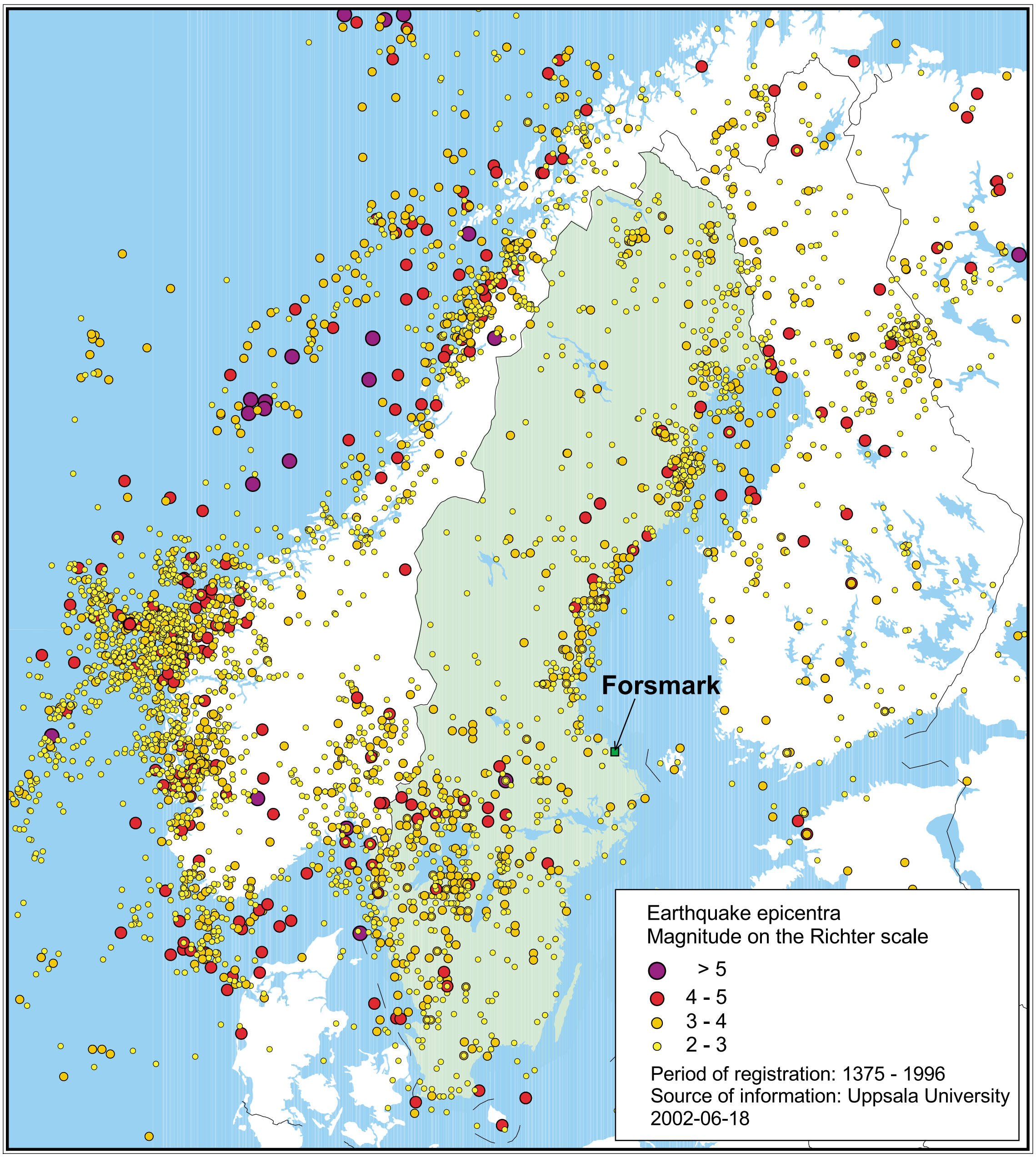

Figure 4-3. *Earthquake epicentres in Scandinavia and Finland 1375–1996. Data from the University of Uppsala.*

4.4 Bedrock – rock type and potential for ore deposits

4.4.1 Data input

The distribution, characteristics, inhomogeneity and age of the rock units in the bedrock of the Forsmark regional model area have been defined primarily with the help of the cartographic database and the description of the bedrock geology which were compiled in connection with the Östhammar feasibility study /Bergman et al, 1996/. These data were supplemented during the Tierp feasibility study /Bergman et al, 1999c/ and, for this reason, the cartographic data were extracted from SKB's GIS database version 5.0 for Tierp, which also covers the Forsmark regional model area (Appendix 1). Some new age-dating results in the Stockholm-Gävle area, which have recently been completed by SGU, more closely constrain the age of the bedrock in the regional model area.

South of RAK coordinate 6700000 N, the compilation carried out during the Östhammar feasibility study utilized the bedrock map (with description) over map-sheet 12I Östhammar NO. This map was published in connection with the mapping programme (bedrock geology) of SGU at the scale 1:50,000 /Stålhös, 1991/. The map is based on an interpretation of aerial photographs and satellite images, airborne geophysical data, detailed geological mapping in the field, and analytical work, including optical microscopy and geochemistry. All these investigations were carried out during the years 1982 and 1983.

North of RAK coordinate 6700000 N, the compilation work in the feasibility study utilized the bedrock map (with description) of the Forsmark area /Hansen, 1989/ and information on map-sheet Forsmark and Björn, published in connection with SGU's older combined Quaternary geology and bedrock mapping programme /Svenonius, 1887/. Information from restricted field investigations in the area around the Forsmark nuclear power station, completed during the feasibility study work, was also utilized.

In order to allow cartographic presentation at the scale 1:100,000, some simplifications of the bedrock geology information collected from these sources were carried out in connection with the feasibility study. Furthermore, some problems with the source geological information emerged during subsequent field activities, which were completed during the later stages of the feasibility study /Bergman and Isaksson, 1996; Bergman et al, 1998/. These problems are referred to in more detail below.

Base data, including, for example, field observations, have not been studied within the context of the present project.

Information on the location and character of mineral deposits as well as an assessment of the potential for the future discovery of new ore deposits in the Forsmark regional model area have been adopted from the feasibility study work (/Lindroos, 1996/ and Appendix 1).

On the basis of the GIS geological data, a cartographic 2D model for the bedrock geology in the Forsmark regional model area is presented (Figure 4-4). This map includes the surface distribution of different rock types. A description of key geological "parameters" /SKB, 2001b/ for the different rock types follows below. This description predominantly addresses the rock types observed onshore.

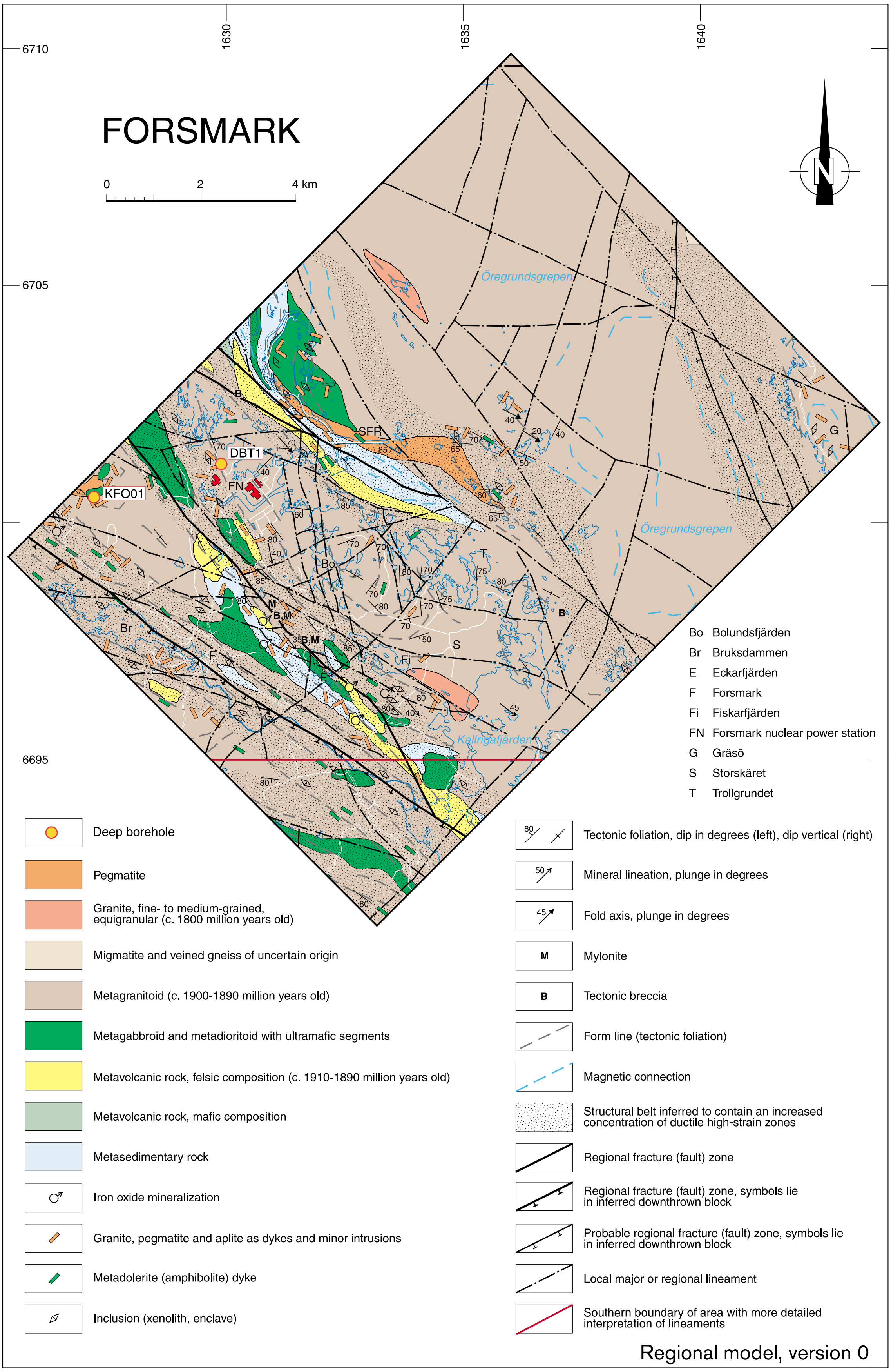

Figure 4-4. *2D cartographic model for the bedrock geology at the surface, both onshore and offshore.*

4.4.2 Rock type – distribution, description and age

The Forsmark regional model area is dominated by intrusive igneous rocks, whilst supracrustal rocks form a subordinate component (Figure 4-4). Apart from some younger granites and pegmatites, which display only a weak foliation, all these rocks were more or less affected by ductile deformation and underwent a recrystallization at depths probably greater than 15 km and under amphibolite-facies (> 500–550°C) metamorphic conditions. For this reason, most of the rock names in the regional model area are prefixed with the term "meta". All rocks except the younger granites and pegmatites formed during stage 1 in the geological evolutionary model (see Section 4.2). The younger granites and pegmatites formed during stage 2. The ductile deformation and metamorphism probably occurred during both these stages.

The supracrustal rocks are dominated by metasedimentary and felsic metavolcanic rocks. They occur predominantly along two conspicuous belts which trend NW. The southern belt extends from the area between Forsmark village and the Forsmark nuclear power station southeastwards, towards Eckarfjärden and Kallrigafjärden. The northern belt extends along the coast from northeast of the Forsmark nuclear power station south-eastwards, to the area north of Trollgrundet. Mafic metavolcanic rocks are also inferred to be present in the northwesternmost part of the northern belt, and such rocks are exposed on the small island Hästen, immediately northwest of the regional model area /Hansen, 1989/. The two belts of supracrustal rocks are closely linked in space to structural belts on the geological map inferred to contain a high concentration of ductile high-strain zones.

The *metasedimentary rocks* are estimated to occupy c. 8% of the land in the regional model area. This and following estimates of bedrock areal extent ignore the thin Quaternary cover which dominates in the regional model area (see Section 4.3). The metasedimentary rocks appear on the geological map as narrow strips, strongly elongate in the strike direction of the tectonic foliation. The rocks consist of alternating quartz-feldspar-rich and locally garnet-bearing, mica-rich layers, in a sequence which resembles that usually found in metagreywackes. They are injected at several places by veins and segregations of pegmatite and granite, and tend to merge into veined paragneisses. Paragneiss possibly occupies larger areas under Öregrundsgrepen than that shown in the present 2D cartographic model /Bergman et al, 1998, subarea D/.

The *felsic metavolcanic rocks* are estimated to occupy c. 6% of the land in the regional model area and occur in a similar manner as the metasedimentary rocks on the geological map (Figure 4-4). They display a dacitic to rhyolitic composition and are grey to pale red, fine-grained and generally banded. At Dannemora, c. 30 km southwest of the regional model area, metarhyolite inferred to belong to the same metavolcanic sequence has yielded an U-Pb (zircon) age of 1,894 ±4 Ma (SGU, unpublished data; Ma = million years). Similar metavolcanic rocks in central Sweden have yielded a group of U-Pb (zircon) ages which fall in the time frame 1,906 ±3 to 1,891 ±2 Ma (SGU, unpublished data). These ages are interpreted as the age of extrusion of the volcanic rocks, before metamorphism.

Metagabbroid and metadioritoid with segments of ultramafic rock occupy c. 11% of the land in the regional model area. They generally display an elongate form on the geological map with their long axis parallel or subparallel to the tectonic foliation. Two intrusive bodies are conspicuous west of Kallrigafjärden in the southernmost part of the regional model area and several bodies occur in association with the southern belt of supracrustal rocks which extends from north of the Forsmark village to Kallrigafjärden. They are also conspicuous either within or directly in contact with the northern belt of supracrustal rocks, northeast of the Forsmark nuclear power station (biotest area). One of the bodies in this area is c. 2 km^2 in areal extent.

Grey to red, equigranular *metagranitoids*, which are estimated to comprise c. 71% of the land in the regional model area, form the most widespread rock type in the area. However, it is important to note that the type of bedrock beneath Öregrundsgrepen is not known. Other rock types (e.g. paragneiss, migmatite and veined gneiss of uncertain origin) possibly form significant components in the offshore area /Bergman et al, 1998, subarea D/.

The metagranitoids are metamorphosed equivalents of quartz- and feldspar-rich, meta-intrusive rocks with subordinate contents of the darker mafic minerals, biotite and hornblende. They vary in composition from tonalitic to granitic. Plagioclase feldspar, hornblende and biotite are conspicuous in the tonalitic varieties which are generally grey in colour. There is a continuous increase in the proportion of K-feldspar relative to plagioclase feldspar and a decrease in the proportion of hornblende relative to biotite as the composition changes from tonalitic to granitic /Stålhös, 1991/. The metagranites are red to greyish red and are conspicuous in the area to the north, east and southeast of the Forsmark nuclear power station, e.g. at Bolundsfjärden.

Various attempts have been made to produce a cartographic 2D model which separates the different varieties of metagranitoid in different parts of the regional model area /Hansen, 1989; Stålhös, 1991; Bergman and Isaksson, 1996/. However, there is some discrepancy in these studies concerning how the contacts between the different metagranitoids can be traced. More detailed bedrock mapping, analytical follow-up, and, probably, closer integration with geophysical data will be necessary before a consistent, cartographic 2D model for the whole area can be constructed. For this reason, the metagranitoids are grouped together as a single rock type in this study, as presented in /Bergman et al, 1996/.

Field work in connection with the feasibility study /Bergman and Isaksson, 1996; Bergman et al, 1998/ revealed a fine-grained and diffusely banded rock unit of granitic composition and uncertain origin along the coastal area east and southeast of the Forsmark nuclear power station. This unit can be followed westwards around a major fold structure (see below) immediately northwest of reactors 1 and 2 at the power station. These observations differ somewhat from the cartographic configuration presented in /Hansen, 1989/. Once again, further work is necessary to refine the 2D cartographic model for the Forsmark regional model area.

The age of the metagranitoids is indicated by recent U-Pb (zircon) age-dating results from two localities southeast of the regional model area. A metatonalite at a locality north of Grisslehamn, c. 45 km to the southeast, has yielded an age of 1,901 ±6 Ma (SGU, unpublished data). A fine-grained and diffusely banded metagranite dyke which intrudes the tonalite at the same locality is 1,891 ±13 Ma in age (SGU, unpublished data). A red to greyish red metagranite on the island Vätön, which is located c. 80 km southeast of the regional model area and resembles the metagranite at Bolundsfjärden in the model area, has yielded an age of 1,889 ±19 Ma /Persson and Persson, 1999/.

A minor area of migmatite and veined gneiss of uncertain origin is indicated in the northeasternmost part of the regional model area. The rocks in this area lie beneath Öregrundsgrepen and are not exposed. However, lithologies of similar type are exposed in the northern part of Gräsö, immediately northeast of the regional model area. Furthermore, they possibly occupy much larger areas under Öregrundsgrepen than what is shown in the present 2D cartographic model /Bergman et al, 1998, subarea D/.

Previous studies have indicated the presence of four larger bodies of *reddish grey, fine- to medium-grained, equigranular granite* and *pegmatite*. These rocks are a subordinate component and comprise only c. 4% of the land in the regional model area. They are only weakly foliated and are considered to be intrusive into the surrounding metagranitoids, mafic to intermediate meta-intrusive rocks and metasedimentary rocks. Comparison with similar rocks within and north of Stockholm, which have yielded U-Pb (zircon) ages of 1,803 +23/–19 Ma /Ivarsson and Johansson, 1995/ and 1,779 ±8 Ma /Öhlander and Romer, 1996/ for the granites, and U-Pb ages of c. 1,795 Ma /Welin and Blomqvist, 1964; Welin, 1979/ and 1,795 ±2 Ma /Romer and Smeds, 1994/ for the pegmatites, tentatively suggests that these rocks were intruded c. 1,800 million years ago.

Preliminary field investigations in connection with the feasibility study /Bergman et al, 1998/ raised some questions concerning the areal extent of two of these bodies; the granite south of Storskäret and the pegmatite body which trends NW close to the SFR site. Furthermore, this field activity also indicated the possible presence of a larger body of grey, medium-grained, weakly foliated granite in the area northeast of Trollgrundet. Such a granite had not been indicated in earlier investigations. These scattered observations emphasize again the need for renewed bedrock mapping and refinement of the cartographic 2D model for the distribution of rock types in the Forsmark regional model area.

4.4.3 Inhomogeneities including inclusions and dykes

Bedrock inhomogeneity can be assessed at different scales. Inspection of the cartographic 2D model for the surface distribution of rock types (Figure 4-4) reveals an inhomogeneous bedrock on the several hundred metre to kilometre scale in especially two areas:

- Between Forsmark village and the Forsmark nuclear power station southeastwards to Eckarfjärden and Kallrigafjärden.
- North of the Forsmark nuclear power station southeastwards to north of Trollgrundet.

These areas correspond to the supracrustal belts and to the structural belts inferred to contain an increased concentration of ductile high-strain zones (see below).

An attempt has also been made in the feasibility study to assess the variation in bedrock inhomogeneity on the more detailed, centimetre to several hundred metre scale /Bergman et al, 1996/. Documentation of the occurrence of three types of bedrock inhomogeneity has been carried out:

- Inclusions in intrusive rocks, including both xenoliths and enclaves.
- Metadolerite (amphibolite) dykes.
- Granite, pegmatite and aplite dykes and minor intrusions.

The inclusions and metadolerite dykes generally trend parallel or subparallel to the tectonic foliation in the regional model area, while the granite, pegmatite and aplite dykes display a more random orientation pattern.

Inhomogeneous bedrock at the centimetre to several hundred metre scale is conspicuous in several areas:

- The area around Bruksdammen southeastwards to Kallrigafjärden (subarea A in the field control study of /Bergman et al, 1998/).
- The area north of Forsmark village southeastwards to Eckarfjärden and Kallrigafjärden (subarea A in the field control study).

- The area north of the Forsmark nuclear power station southeastwards to north of Trollgrundet (subarea C in the field control study).
- The area close to the western shore of Gräsö (area not investigated in the field control study).

Field work in connection with the feasibility study also showed that the bedrock exposed on the more outboard islands in Öregrundsgrepen (subarea D in the field control study) is also inhomogeneous on the centimetre to several hundred metre scale.

Apart from occasional metadolerite and pegmatite dykes, the bedrock appears to be homogeneous on the centimetre to several hundred metre scale in the area which extends from the Forsmark nuclear power station southeastwards towards Storskäret and Kallrigafjärden (subarea B in the field control study). This area corresponds to the Forsmark candidate area which emerged as a result of work during the Östhammar feasibility study /SKB, 2000a/.

4.4.4 Potential for ore deposits

Six, small iron oxide deposits, which have been the focus of limited mining activity in historical time, occur in the southwestern part of the regional model area, in the area close to the Forsmark village (Figure 4-4). The host rock to five of these deposits is supracrustal in character /Stålhös, 1991/. They occur along the southern belt of supracrustal rocks which extends from north of Forsmark village southeastwards to Eckarfjärden and Kallrigafjärden. One of the deposits in the regional model area, which is located north of Bruksdammen, appears to occur in a metagranitoid /Stålhös, 1991/.

The area with ore potential close to Forsmark extends southwestwards to the Dannemora ore field near Österbybruk and southeastwards to the Norrskedika ore field near Östhammar. There is an abundant occurrence of iron oxide deposits in the Forsmark-Österbybruk-Östhammar area, and manganese is another important metal at, for example, Dannemora. Some of these iron oxide deposits also contain base metal (copper, zinc, lead) sulphides. Furthermore, occasional base metal sulphide deposits without any direct relationship to iron oxide mineralization are also present in the area. The host rock to many of these deposits is supracustal in character. Both the types of metal-rich deposits and their association with supracrustal rocks are typical of the important ore province in the Bergslagen area and surroundings in central Sweden /Frietsch, 1975; Åkerman, 1994/.

Data compilation within the Östhammar feasibility study has led to the conclusion that the southwestern part of the regional model area is potentially of interest for ore deposits /Lindroos, 1996/. The northern belt of inferred supracrustal rocks which extends along the coast from northeast of the Forsmark nuclear power station southeastwards, to the area north of Trollgrundet, was judged to be without any ore potential.

4.5 Bedrock – structure

4.5.1 Data input and integration

The compilation of representative, single field measurements of *ductile structures*, the interpretations of both form lines related to the tectonic foliation and magnetic connections, and the description of these structural features, have been carried out with the help of the cartographic database and the description of the structural geology which were completed in connection with the Östhammar feasibility study /Bergman et al, 1996, 1998; Bergman and Isaksson, 1996; Isaksson, 1998; Stephens and Isaksson, 2000/. Structural information was recompiled during the Tierp feasibility study, the areal extent of which also covered the Forsmark regional model area /Bergman et al, 1999c/. For this reason, the cartographic data have been extracted in this report from SKB's GIS database 5.0 for both Östhammar and Tierp (Appendix 1).

Work during the feasibility studies suggested the occurrence of structural belts with an increased frequency of ductile high-strain zones, which anastomose around intermediate areas of generally lower ductile strain with a lens-like geometry, so-called tectonic lenses. The location of these structural belts has been extracted in this study from SKB's GIS database 5.0 for Tierp (Appendix 1).

The feasibility study compiled field measurements of ductile structures from both the bedrock map (with description) over map-sheet 12I Östhammar NO /Stålhös, 1991/ and from limited field activities carried out at different times during the feasibility study /Bergman et al, 1996, 1998; Bergman and Isaksson, 1996/. Field observations with numerical data have not been studied within the context of the present project. For this reason, and bearing in mind the restricted number of field measurements, orientation data in stereographic plots have not been completed in this report.

All the ductile structural data – areas, lines and points – are displayed in the 2D cartographic model (Figure 4-4).

North of RAK coordinate 6695000 N, the present study has utilized the interpretation of *lineaments* over Öregrundsgrepen and adjacent land areas, with a length of at least 1–2 km. This work was completed during a later stage of the Östhammar feasibility study and in preparation for the field control work /Isaksson, 1998/. These lineaments reflect linear, low-magnetic features in the magnetic anomaly data and generally occur, on land, together with depressions in the digital topographic relief data. Some lineaments also display a high, electromagnetic VLF-signal. All the geophysical data were derived from airborne surveys. Only the data in the field control area were included in SKB's GIS database 5.0 for Östhammar. All the lineament data have been archived in a complementary GIS file in this study (Appendix 1).

A new interpretation of detailed, orthorectified aerial photographic data over the small area around Bolundsfjärden has been carried out. Seven lineaments with a NNW to N-S strike and one with an ENE strike, which showed no significant linear features in the magnetic anomaly and digital topographic relief data, have been integrated in the present study. They have also been archived in a complementary GIS file (Appendix 1).

South of RAK coordinate 6695000 N, the present study has utilized the interpretation of lineaments, with a minimum length of 5 km, which was completed in connection with the Tierp feasibility study /Bergman et al, 1999c/. Minor revisions were carried out at this stage to the interpretation completed during the Östhammar work /Bergman et al, 1996/. Once again, only low-magnetic lineaments and topographic depressions were included. These lineament data have been extracted from SKB's GIS database 5.0 for Tierp (Appendix 1).

The lineaments are displayed in the 2D cartographic model (Figure 4-4). For purposes of communication alone, certain lineaments (e.g. the lineaments XFM0003A0–XFM0010A0, around Bolundsfjärden, interpreted from orthorectified aerial photographic data) have been assigned an identification number (Figure 4-5), according to the scheme recommended by SKB (see Appendix 2). The selection of these lineaments bears no relationship to their level of importance.

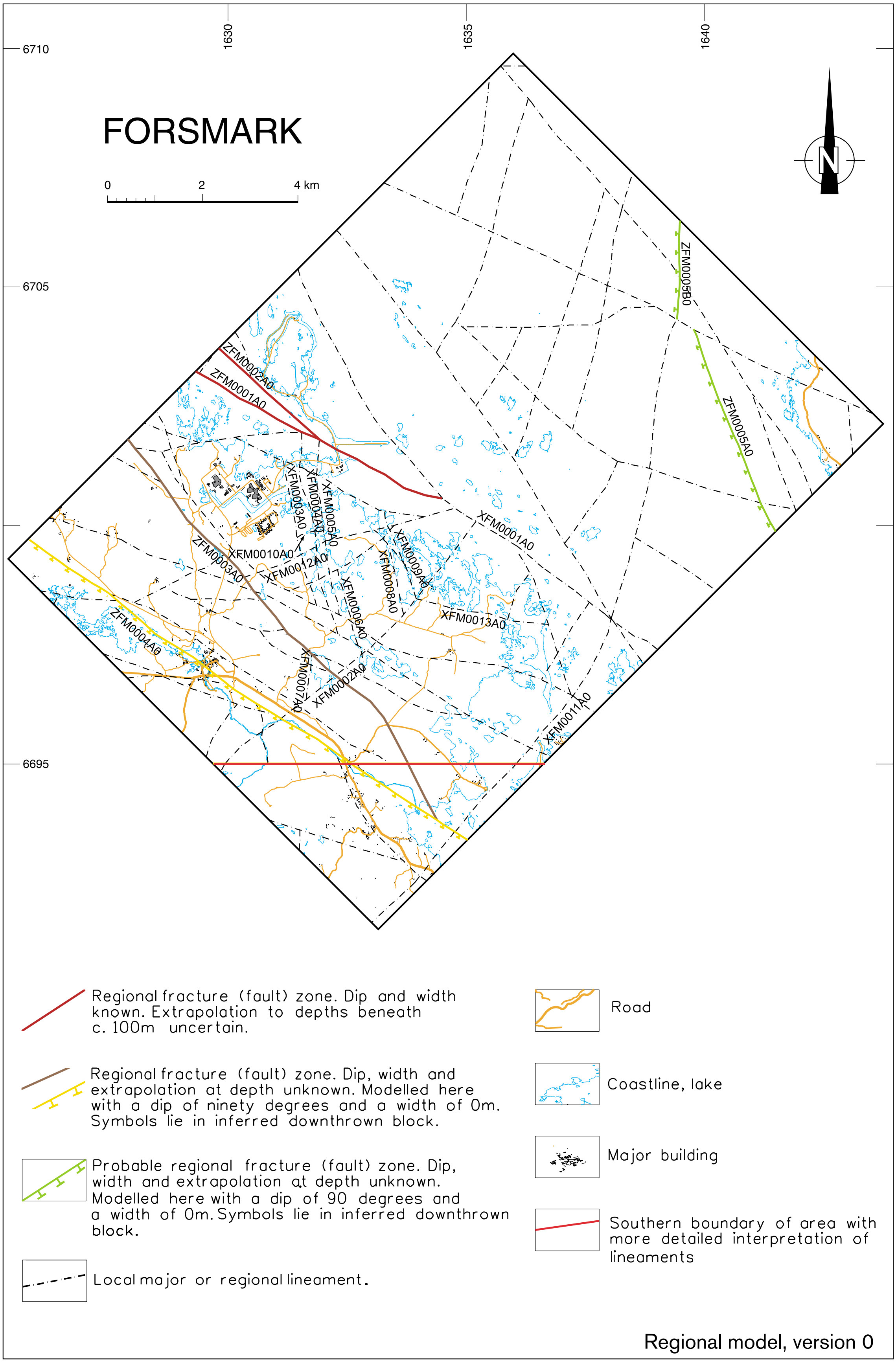

***Figure 4-5.** Local major and regional lineaments and fracture zones at the surface. The lineaments with an identification number have been selected for communication purposes alone. The selection bears no relationship to their level of importance.*

Based on the presence of critical geological and/or geophysical information, four lineaments in the regional model area have been upgraded as highly probable to certain, *regional fracture zones* (see Table 4-1). For purposes of communication, they have been assigned the identification numbers ZFM0001A0, ZFM0002A0, ZFM0003A0 and ZFM0004A0 (Figure 4-5). Furthermore, two lineaments in the northeastern part of the regional model area have been upgraded as a probable, regional fracture zone with two separate segments, referred to as ZFM0005A0 and ZFM0005B0 (Figure 4-5). The key sources of literature which have formed the basis for the upgrading of these lineaments to regional fracture zones, and which provide some information on the characteristics of these zones, are displayed in Table 4-2. Some ground geological information, which indicate the occurrence of brittle or low-temperature brittle-ductile deformation in the bedrock, were documented during field activities in connection with the Östhammar feasibility study /Bergman et al, 1998/. These data have been combined with similar information presented in /Bergman et al, 1996/, and archived in a complementary GIS file in this study (Appendix 1).

Table 4-1. Classification and naming of brittle structures, and ambition level for geometric description during site investigation (length and width measurements are approximate) /Andersson et al, 2000/.

Name	Length	Width	Ambition for geometric 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

Table 4-2. Key data sources for the regional fracture zones.

Zone	Key data sources
ZFM0001A0	/Carlsson and Christiansson, 1987; Axelsson and Hansen, 1998 (Figure 6-3c); Bergman et al, 1996, 1999c; Isaksson, 1998/
ZFM0002A0	/Hansen, 1981; Carlsson and Christiansson, 1987; Isaksson, 1998; Bergman et al, 1999c/
ZFM0003A0	/Stålhös, 1991; Bergman et al, 1998, 1999c; Isaksson, 1998/
ZFM0004A0	/Moberg, 1973–1984; Eriksson and Henkel, 1988; Stålhös 1991; Bergman et al, 1996; 1999c; Isaksson, 1998/
ZFM0005A0	/Lidmar-Bergström, 1994; Bergman et al, 1996, 1999c; Isaksson, 1998/
ZFM0005B0	/Lidmar-Bergström, 1994; Bergman et al, 1996, 1999c; Isaksson, 1998/

Due to the scale of study within the present work, local minor to local major fracture zones in the Forsmark area, several of which are well-documented, have not been addressed in this study. These include the zones referred to as "smaller structures, known or interpreted" /Carlsson and Christiansson, 1987/ as well as the zones with identification numbers H2, 3, 6, 8 and 9 in the vicinity of the SFR repository site /Axelsson and Hansen, 1997; Holmén and Stigsson, 2001/. Further work will be necessary during the site investigation programme to integrate all these zones within the next round of structural models for the Forsmark area. Since hydraulic testing results are available for the zones in the vicinity of the SFR repository, these zones are nevertheless addressed in a later part of this report (Hydrogeology, Section 6.5.1).

A description of some key geological "parameters" for the *ductile structures*, *lineaments*, *bedrock fractures and regional fracture zones* in the Forsmark regional model area is presented below. The section on regional fracture zones also includes some comments on the regional significance of subhorizontal to horizontal fracture zones in the area and a comparison with other 2D regional structural models.

4.5.2 Ductile structures

Field measurements of the tectonic foliation, the inferred orientation of form lines for this planar structure and limited field observations during the feasibility study /Bergman et al, 1996, 1998; Bergman and Isaksson, 1996/ show that the foliation in the Forsmark regional model area varies considerably in both strike direction and intensity.

In several of the structural belts shown in Figure 4-4, which are typically 1–2 km wide, the foliation strikes SE to E and dips steeply (70–80°) towards the SW to S or is vertical. On the islands east of SFR, more moderate dips (50–70°) in the same directions are also present. This structural pattern dominates in the southwestern and central parts of the Forsmark regional model area (Figure 4-4) which include subareas A and C in /Bergman et al, 1998/. In contrast, along the western coast of Gräsö, in the northeastern part of the regional model area, the foliation strikes NNW and dips steeply (75–80°) towards the E. The limited field observations have shown that the foliation development is strong in at least two of these belts:

- The belt which extends southeastwards from the area between Forsmark village and the Forsmark nuclear power station towards Eckarfjärden and Kallrigafjärden.
- The belt which extends along the coast north of the Forsmark nuclear power station southeastwards to north of Trollgrundet.

In the areas between these different structural belts, the tectonic foliation displays a more variable orientation with, in part, N or NE strike and moderate to steep (40–70°) dips to the E or SE. This is particularly well-illustrated in the area between Bolundsfjärden and Storskäret (subarea C in /Bergman et al, 1998/). Preliminary field observations in this area demonstrate the lower intensity of ductile deformation relative to the surrounding structural belts. The foliation also strikes, in part, NE and dips moderately (40°) to the SE in the more outboard islands in Öregrundsgrepen (subarea D in /Bergman et al, 1998/).

Ductile linear structures in the Forsmark regional model area include a mineral lineation and minor fold axes which deform the foliation. These structures plunge with a variable angle (20–70°) towards the SE. Minor folds with more or less horizontal axes, and both approximately N-S and E-W trends, have also been reported from the Forsmark area /Carlsson and Christiansson, 1987/.

The observations described above permit a preliminary structural model for the ductile deformational features in the Forsmark regional model area. The structural belts along which the foliation strikes SE to E, and is, at least partly, strongly developed are inferred to contain an increased concentration of *ductile high-strain zones* (Figure 4-4). The overall higher strain in these belts is suggested to account for the tight clustering of different rock types and the inhomogeneity of the bedrock on the several hundred metre to kilometre scale in two of them. Nevertheless, detailed mapping is required to constrain the location of the individual high-strain zones within these structural belts. They form part of the regionally important, anastomosing network of ductile high-strain zones in the northern part of Uppland, which has been referred to as the Singö shear zone /Talbot and Sokoutis, 1988/.

The intervening areas, where the foliation displays a more variable orientation and is, at least partly, less well developed, are inferred to represent *tectonic lenses* where the ductile strain is of less intense character. One or more major fold hinges occur as internal structures within these lenses. The most conspicuous tectonic lens in the Forsmark regional model area extends from the Forsmark nuclear power station southeastwards to Bolundsfjärden, Storskäret and Kallrigafjärden. A major Z-shaped fold structure, which plunges moderately to steeply (up to 70°) to the SE, is inferred to be present within this lens /Stephens and Isaksson, 2000/. The Forsmark candidate area is situated within this tectonic lens, in the area around Bolundsfjärden.

There are no direct data available which determine the timing of the ductile deformation in the Forsmark regional model area. However, ductile deformation in the Stockholm-Gävle-Örebro area affects rocks which are c. 1,890 million years in age and appears to have been at a waging stage of development when the younger granites and pegmatites intruded c. 1,800 million years ago, i.e. ductile deformation probably occurred during both stages 1 and 2 in the geological evolutionary model (see Section 4.2).

4.5.3 Lineaments

Lineaments, which can be followed for at least 1–2 km, form a consistent structural pattern in the Forsmark regional model area (Figures 4-4 and 4-5). Essentially, four broad orientation arrays have been recognized. The trends of these different arrays are in close agreement with the orientation of what was referred to as the "main directions of steep structures" identified in /Carlsson and Christiansson, 1987, p. 50–51/:

- Array 1 trends c. NW (e.g. XFM0001A0, see Figure 4-5) and is conspicuous in the southwestern, central and northeastern parts of the regional model area. There are probably two different sets in this array with trends 310–320°(array 1A) and 300–305° (array 1B). The lineaments with approximately NW trend generally occur in close spatial relationship to the structural belts which are inferred to contain an increased concentration of ductile high-strain zones. Together with two of the regional fracture zones (Singö fault zone and fracture zone ZFM0003A0, see below), they amplify the geometric form of the tectonic lens between the Forsmark nuclear power station and Kallrigafjärden (see Figure 4-4). Lineament XFM0001A0 has been referred to as an "interpreted regional fault line" in /Carlsson and Christiansson, 1987/.

- Array 2 trends c. NE (050°) but changes orientation to c. NNE (015–020°) in Öregrundsgrepen. This array is recognizable throughout the regional model area. Several of these lineaments (e.g. XFM0002A0) transect the tectonic lens between the Forsmark nuclear power station and Kallrigafjärden. Lineament XFM0011A0 along Kallrigafjärden was also referred to as an "interpreted regional fault line" in /Carlsson and Christiansson, 1987/.

- Array 3 trends c. E-W. Two different sets which trend 070–080° (array 3A) and 280° (array 3B) appear to be present. Lineaments with both these orientations transect the tectonic lens between the Forsmark nuclear power station and Kallrigafjärden (e.g. XFM0012A0 and XFM0013A0, respectively).
- Array 4 trends c. NNW to N (340–0°) and is conspicuous, for example, in two groups in the tectonic lens between the Forsmark nuclear power station and Kallrigafjärden. The lineaments in these two groups are located 400 m or less from each other. One of the groups passes through Bolundsfjärden (XFM0003-6A0) and the second (XFM0008-9A0) passes c. 1.5 km east of Bolundsfjärden.

The character and length of the lineaments indicate that they are all possible, local major or regional fracture zones. However, there are no data available at the present time that permits an upgrading to fracture zones. A speculative scenario in which all lineaments are displayed as vertically-dipping fracture zones, with an unconstrained extension at depth, is addressed in a later part of this report (Hydrogeology, Section 6.3).

4.5.4 Bedrock fractures

Various epochs of detailed work in the Forsmark regional model area (see Chapter 2) has shown that the bedrock is affected by different sets of fractures which are both open and filled. Around reactor 3 and close to SFR, these fractures are oriented in the following directions /Carlsson and Christiansson, 1987/:

- Strike NW (dip 90°).
- Strike NE (different subsets, in general subvertical dip).
- Strike E (two subsets dipping 90° and 40–60°S).
- Subhorizontal or horizontal (dip 25–0°).

The subhorizontal or horizontal set of fractures and the subvertical set with NE strike dominate. Fractures with SSE strike and a dip of 40° to the west have also been observed in the various tunnels, close to the Singö fault zone.

Chlorite is a common fracture filling in all fracture sets /Carlsson and Christiansson, 1987/. Laumontite, calcite, quartz and other phyllosilicate minerals, besides chlorite, are also present. The fracture frequency along the discharge tunnel for reactor 3, in the sections which are situated outside inferred fracture zones, falls in the range 0.6–2.2 fractures/m.

The strike of the bedrock fractures which are moderately dipping (40–60°) to vertical strongly resembles the trend of the different lineament arrays in the regional model area (see Section 4.5.3). Furthermore, it has not been possible to identify subhorizontal to horizontal structures in connection with the lineament interpretation work. These observations provide support to the hypothesis, discussed above, that the lineaments presented in the 2D cartographic model are possible, local major or regional fracture zones.

Observed subhorizontal or horizontal fractures are concentrated in the upper part of the bedrock (< 30 m below the rock surface). They are rather long (10–100 m) and undulating, and display a median aperture which is more than 100 times greater than that observed in the subvertical fracture sets /Carlsson and Christiansson, 1987/. They are also more closely spaced than the subvertical sets. The material which fills these fractures includes both glacial sediment, possibly of Weichselian age, and various phyllosilicates /Stephansson and Ericsson, 1975; Carlsson and Olsson, 1976; Carlsson, 1979; Carlsson and Christiansson, 1987/. It has been observed that an increased frequency of the subhorizontal or horizontal fractures gives rise to a more hydraulically conductive bedrock volume /Carlsson and Christiansson, 1987/.

Details concerning the properties of bedrock fractures in the area around reactor 3 at the Forsmark nuclear power station are presented in /Carlsson, 1979/ and /Carlsson and Olsson, 1981/. The parameters trace length (persistence), width or aperture size, spacing, surface roughness and fracture filling are addressed. Furthermore, a study of the fractures in two vertical boreholes in this area (DBT-1 and DBT-3; 503 m and 249.5 m in length, respectively) indicates a mean fracture frequency of 2.0 and 2.3 fractures/m, respectively, for the total core length /Carlsson and Olsson, 1982/. The data for borehole DBT-1 includes a heavily fractured bedrock zone, related to an assumed horizontal fracture zone at c. 320 m depth, with a frequency of 4.7 fractures/m. A summary of these data is provided in /Carlsson and Christiansson, 1987/.

4.5.5 Regional fracture zones

The specific data which indicate and, to a variable extent, help to verify the occurrence of regional fracture zones in the model area are summarized in Table 4-3. Structural data, which have steered the appearance of these zones in various diagrams in this report and, most importantly, the 3D geometric modelling in RVS (see Section 4.7) are displayed in Table 4-4.

Each of the regional fracture zones is located within and strikes more or less parallel to the trend of one of the structural belts inferred to contain an increased concentration of ductile high-strain zones. This spatial association opens the possibility that the regional fracture zones represent reactivated, ductile deformation zones. However, at the present time, there are insufficient data pertaining to the location and geometry of individual ductile high-strain zones within the structural belts as well as to the dip of several of the regional fracture zones.

Table 4-3. Indication and verification of regional fracture zones.

Zone	Indication	Verification	Assessment
ZFM0001A0	Airborne geophysics (magnetic data)	Ground geophysics, borehole, tunnel	Highly probable to certain
ZFM0002A0	Airborne geophysics (magnetic data)	Tunnel	Highly probable to certain
ZFM0003A0	Topographic data, airborne geophysics (magnetic data)	Ground geology	Highly probable to certain
ZFM0004A0*	Topographic data, airborne geophysics (magnetic data)	Ground geology, ground geophysics	Highly probable to certain
ZFM0005A0*	Bathymetric data, airborne geophysics (magnetic data)		Probable
ZFM0005B0*	Bathymetric data, airborne geophysics (magnetic data)		Probable

* Sub-Cambrian peneplain disturbed.

Table 4-4. Summary of estimated structural data on the regional fracture zones.

Zone	Position (m)	Length (km)	Depth	Strike	Dip	Width (m)	Displacement
ZFM0001A0	+/– 50–100	18.5 (minimum)	Uncertain under c. 100 m beneath sea level	300–305°	c. 90°	200–250	
ZFM0002A0	+/– 50–100	c. 13	Uncertain under c. 100 m beneath sea level	310–315°	c. 90°	c. 75	
ZFM0003A0	+/– 50	c. 34		c. 320°			
ZFM0004A0	+/– 50	c. 70		300–305°			Southwestern side downthrown
ZFM0005A0	+/– 100	10 (minimum)		c. 340°			Western side downthrown
ZFM0005B0	+/– 100	16 (minimum)		0–005°			Western side downthrown

ZFM0001A0 (Singö fault zone)

The Singö fault zone /Carlsson and Christiansson, 1987; Erlström, 1987/ has been documented along the two discharge tunnels for reactors 1 and 2 and reactor 3 at the Forsmark nuclear power station and along the two access tunnels to SFR. The primary verification is based on borehole and seismic surveys as well as detailed tunnel mapping. The fault zone occurs along a "known and interpreted regional fault line" in /Carlsson and Christiansson, 1987, Figure 5-9/ and corresponds to a significant low-magnetic anomaly. It is the trace of this anomaly which has been used to mark the fault on the figures in this report. On this basis, the fault "line" is marked with a positional accuracy of ±50–100 m.

Based on this definition, the fault zone can be traced at least from a point c. 2 km southeast of SFR northwestwards to the boundary of the regional model area, a distance of c. 5.5 km (Figure 4-5). The interpretation of low-magnetic anomalies during the feasibility studies indicates that this zone probably continues c. 13 km to the northwest where it is truncated by a lineament with ENE trend which belongs to lineament array 3A. Furthermore, it is possible that the Singö fault zone continues to the southeast along the lineament XFM0001A0 ("interpreted regional fault line" in /Carlsson and Christiansson, 1987/) to the Öregrund area, a distance of at least 11.5 km, and further southeastwards to the Singö area /Carlsson and Christiansson, 1987/. However, there are uncertainties concerning how different lineaments integrate in the Öregrund area and question marks remain concerning how much the Singö fault zone may be broken down into smaller segments with slightly different orientations /Carlsson and Christiansson, 1987/. In summary, the Singö fault zone is judged to display a minimum length of 18.5 km on the Earth's surface. Bearing in mind this minimum strike length, it is probable that the zone extends to a depth of several kilometres. However, data available at the present time do not constrain its extrapolation to depths under c. 100 m beneath sea level.

The Singö fault zone in the regional model area strikes 300–305° and dips approximately vertically. The width of the zone is 200–250 m. Where the deformed bedrock is meta-granitoid or pegmatite, rock fragments within the crush breccia along the zone are c. 5–15 cm in size /Carlsson and Christiansson, 1987/. There remains some uncertainty concerning the direction, amount and timing of movement along the fault zone. However, it is apparent that the rock fractures along it are filled with different fracture minerals and that cross-cutting relations between fractures with different mineral fillings indicate that the fault zone has been active at different times throughout geological history /Larsson, 1973; Carlsson, 1979/. An investigation of the isotopic composition of calcite in some calcite-filled fractures along the zone tentatively suggests that it was active after c. 450 million years ago /Erlström, 1987/.

The foliation along the Singö fault zone strikes between 140° and 125° and dips 80–85° SW. The rock fractures along the zone are oriented in the following sets:

- Strike 210–215° (dip 70–80°NW).
- Strike 055–060° (dip 70–80°SE).
- Strike 170° (dip 40°W).
- Subhorizontal.

ZFM0002A0

The regional fracture zone ZFM0002A0 was recognised in the northern part of the discharge tunnel for reactor 3 and verified with the help of detailed tunnel mapping. The zone occurs along a "known and interpreted regional fault line" in /Carlsson and Christiansson, 1987, Figure 5-9/ and corresponds to a significant low-magnetic anomaly. It is the trace of this anomaly which has been used to mark the fracture zone on the figures in this report. On this basis, it is marked with a positional accuracy of ±50–100 m.

Based on this definition, the fracture zone can be traced from a point c. 3.5 km northeast of reactors 1 and 2, where it splays off the Singö fault zone, northwestwards to the boundary of the regional model area, a distance of c. 3 km (Figure 4-5). The interpretation of low-magnetic lineaments during the feasibility studies indicates that this zone probably continues c. 10 km to the northwest where it is truncated by a lineament with NE trend which belongs to lineament array 2. In summary, this fracture zone extends for a length of c. 13 km on the Earth's surface. Bearing in mind this strike length, it is probable that the zone extends to a depth of several kilometres. However, data available at the present time do not constrain its extrapolation to depths under c. 100 m beneath sea level.

The zone strikes 310–315° and dips approximately 90°. It is estimated to be c. 75 m wide. This estimate is based on the occurrence of several zones of crush breccia and chlorite schist along a tunnel section in paragneiss and pegmatite which is c. 75 m long. The individual zones of crush breccia and chlorite schist are up to c. 10 m wide, The direction, amount and timing of movement are not known (note, however, comments above in connection with the Singö fault zone).

ZFM0003A0

The regional fracture zone ZFM0003A0 was recognized on the basis of:

- The occurrence of low-temperature mylonites and both quartz- and epidote-filled, crush breccias with mylonite fragments (ground geological information).
- The occurrence of these structures along both a significant low-magnetic anomaly and a topographic depression.

It is the trace of the low-magnetic anomaly which has been used to mark the fracture zone on the figures in this report. On this basis, the zone is marked with a positional accuracy which is judged to be ±50 m. The southeastern part of the zone, through the small lake Eckarfjärden, corresponds to an "interpreted smaller structure" in /Carlsson and Christiansson, 1987, Figure 5-9/.

The zone ZFM0003A0 can be traced from a point c. 11 km southeast of Forsmark village, where it splays off ZFM0004A0 (see below), to the northwestern boundary of the regional model area, a distance of c. 10 km (Figure 4-5). The interpretation of low-magnetic and topographic lineaments during the feasibility studies indicates that this zone probably continues c. 24 km to the northwest towards Lövstabukten, where it is truncated by a lineament (inferred regional fracture zone) with NE trend which belongs to lineament array 2. In summary, ZFM0003A0 is judged to extend for a length of c. 34 km on the Earth's surface. Bearing in mind this strike length, it is probable that the zone extends to a depth of several kilometres. However, data available at the present time do not constrain its extrapolation at depth.

The strike of ZFM0003A0 is, generally, c. 320°. However, smaller segments along the zone display slightly variable orientations (c.f. Singö fault zone). The dip and the width of the zone are not known. The long length and relatively straight trajectory through the terrain suggest that it is steeply dipping. The direction, amount and timing of movement are not known. However, the occurrence of brecciated mylonites indicates that this fracture zone has also been active at different times (c.f. Singö fault zone). Deformation occurred within different temperature régimes, or under different strain rates, or both.

ZFM0004A0

The regional fracture zone ZFM0004A0 was recognized on the basis of ground geophysical measurements, including seismic and electromagnetic measurements, and the occurrence of mylonites and crush breccias along its southeasterly continuation, east of Östhammar. The fault zone also corresponds to a significant low-magnetic anomaly and a marked topographic depression which corresponds to a break in the sub-Cambrian peneplain. It is the trace of the low-magnetic anomaly which has been used to mark the fracture zone on the figures in this report. On this basis, the zone is marked with a positional accuracy which is judged to be ±50 m. The regional significance of this structure has previously attracted attention /Svedmark, 1887; Stephansson and Carlsson, 1976 (the Forsmark-Granfjärden "line"); Stålhös, 1991/ and it was referred to as an "interpreted regional fault line" in /Carlsson and Christiansson, 1987, Figure 5-9/.

ZFM0004A0 can be traced across the whole regional model area, a distance of c. 11 km (Figure 4-5). The interpretation of low-magnetic and topographic lineaments during the feasibility studies indicates that this zone can probably be traced both to the northwest, where it is truncated close to Älvkarleby by a lineament with NNW trend which belongs to lineament array 4, and to the southeast, where it terminates southeast of Östhammar against a lineament with WNW trend which belongs to array 3B. These observations indicate that the zone extends c. 70 km. Bearing in mind this strike length, it is probable that the zone extends to a depth of several kilometres. However, data available at the present time do not constrain its extrapolation at depth.

The strike of the fracture zone ZFM0004A0 is 300–305°, i.e. parallel to the Singö fault zone. The dip and width of the zone are not known. Nevertheless, the long length and relatively straight trajectory through the terrain suggest that it is steeply dipping.

The topographic surface which is inferred to mark the sub-Cambrain peneplain /Lidmar-Bergström, 1994/ lies up to c. 10 m lower on the southwestern relative to the northeastern side of fracture zone ZFM0004A0. Based on this observation, a component of downthrow to the southwest has tentatively been inferred /Bergman et al, 1999c/. Inspection of the altitude of the sub-Cambrian peneplain suggests that the coastal and offshore area between fracture zones ZFM0004A0 and ZFM0005A0/-B0 (see below), within which the Forsmark nuclear power station, SFR and the Forsmark candidate area are situated, represents an uplifted bedrock block. The highest topographic point (c. 20 m) within this block lies in the southwestern part of the block, close to fracture zone ZFM0004A0, and the block is tilted gently towards the northeast.

The amount and timing of movement along the fault zone are not known. However, the occurrence of both mylonites and crushed breccias east of Östhammar indicates that this zone has been active at different times (cf. the Singö fault zone). Deformation occurred within different temperature régimes, or under different strain rates, or both. Furthermore, the disturbance of the sub-Cambrian peneplain indicates that at least some movement along the fault zone occurred after formation of the peneplain, probably during the Phanerozoic.

ZFM0005A0/-B0

The probable regional fracture zone ZFM0005A0/-B0, which has been divided into two separate segments with different strike orientations, is situated offshore close to the western coast of the island Gräsö (Figure 4-5). The two segments of this zone are referred to as ZFM0005A0 (southern segment) and ZFM0005B0 (northern segment). They have been recognized on the basis of a significant low-magnetic anomaly and a topographic feature defined by a sharp break in the sub-Cambrian peneplain. Bathymetric data have been utilized in the recognition of the topographic break. It is the trace of the low-magnetic anomaly which has been used to mark the zone on the figures in this report. On this basis, it is marked with a positional accuracy which is judged to be ±100 m. This structure has earlier been interpreted as a fault zone /Lidmar-Bergström, 1994/.

ZFM0005A0/-B0 can be traced across the northeastern corner of the regional model area, a distance of c. 6.5 km. The interpretation of low-magnetic and topographic lineaments during the feasibility studies indicates that this zone extends both northwards to at least a point north of the island of Örskär and southeastwards to the Öregrund area, where it possibly merges together with the Singö fault zone. These observations indicate that ZFM0005A0/-B0 extends at least 26 km. Segment A is judged to be at least 10 km long and segment B is at least 16 km. Bearing in mind the minimum strike length, it is probable that the zone extends to a depth of several kilometres. However, data available at the present time do not constrain its extrapolation at depth.

The strike of the segments ZFM0005A0 and ZFM0005B0 is c. 340° and c. 0–005°, respectively. The dip and width of the zone are not known. Nevertheless, the long length and relatively straight trajectory through the terrain suggest that it is steeply dipping.

The topographic surface which is inferred to mark the sub-Cambrain peneplain /Lidmar-Bergström, 1994/ lies at a lower topographic altitude on the western side of the fracture zone. Based on this observation, a component of downthrow to the west has tentatively been inferred /Lidmar-Bergström, 1994; Bergman et al, 1999c/. The bedrock unit, which is exposed on Gräsö and which continues offshore to the east of this island, is an uplifted block similar in character to that between the fracture zone ZFM0004A0 and the probable fracture zone ZFM0005A0/-B0 (see above).

The amount and timing of movement are not known. However, the disturbance of the sub-Cambrian peneplain indicates that at least some movement along the zone occurred after formation of the peneplain, probably during the Phanerozoic.

Subhorizontal to horizontal fracture zones – regional importance?

A subhorizontal fracture zone – zone H2 – has been documented beneath the SFR repository, c. 90–150 m beneath sea level (see /Axelsson and Hansen, 1997/ for a summary of key data sources). Zone H2 dips 15–20° to the southeast, and consists of horizontal lenses of highly fractured and altered rock which define a 5–15 m wide, hydraulically conductive zone. Alternative structural models have been presented for the continuation of this zone, both within and even outside the SFR site. Earlier models were regionally restrictive /Christiansson, 1986/. Later models have speculated that zone H2 extends southwest of the Singö fault zone /Axelsson and Hansen, 1997; Holmén and Stigsson, 2001/.

Model 1 for zone H2 suggests that it is one of several, local minor fracture zones which are subhorizontal to horizontal in the Forsmark regional model area /Axelsson and Hansen, 1997/. This model maintains the regionally restrictive approach for zone H2 /Christiansson, 1986/.

Model 2 has speculated that zone H2 extends southwest of the Singö fault zone /Axelsson and Hansen, 1997/. In this alternative, zone H2 strikes in an E-W direction and connects up with inferred subhorizontal fracture zones which were penetrated at a depth of c. 320 m in borehole DBT-1 /Carlsson and Olsson, 1982/, close to reactor 3, and at a depth of c. 450 m in borehole KFO01, c. 2.5 km west of reactor 3 /Axelsson and Hansen, 1997/. These extrapolations suggest that zone H2 is a local major or regional fracture zone. This alternative was discussed in connection with the construction of geological cross-sections in /Stephens and Isaksson, 2000/. It should be noted that the hydraulically most significant zone in the Finnsjön study site is a subhorizontal zone.

Model 3 maintained the local major or regional character of zone H2 but placed its surface projection in a NE strike direction, c. 500 m northwest of SFR /Holmén and Stigsson, 2001/. As for model 2, this model also speculates that Zone H2 extends southwest of the Singö fault zone. It agrees better with the observed dip of the zone at the SFR site.

It is apparent that there are considerable uncertainties concerning the strike and the regional extension of zone H2. At the present state of knowledge, this zone can be classified as a certain, local minor fracture zone. It is also a possible, local major or regional fracture zone. A closer assessment of the geometry and regional importance of subhorizontal to horizontal fracture zones are questions which need to be addressed during the site investigation programme in the Forsmark candidate area.

Comparison of 2D regional structural models

The interpreted regional fracture zones, both *probable and highly probable to certain*, are displayed in the 2D cartographic model presented in Figures 4-4 and 4-5. As argued above, the character and length of the interpreted lineaments shown in these figures, in combination with a comparison with the bedrock fracture data in the Forsmark area, indicate that these lineaments are *possible candidates for local major or regional fracture zones*. Figure 4-6 displays a comparison with the 2D regional structural model presented by /Holmén and Stigsson, 2001/. The differences betwen the two models can be explained as follows:

1. With one exception (zone H2), /Holmén and Stigsson, 2001/ have utilised the local structural model for SFR /Axelsson and Hansen, 1997/ in combination with the original regional interpretation of lineaments in the feasibility study /Bergman et al, 1996/. The latter was completed prior to acquisition of new airborne geophysical data over Öregrundsgrepen and before various revisions of the lineament interpretation were carried out during and after the feasibility study /Isaksson, 1998; Bergman et al, 1999c/. The new airborne geophysical data were not made use of in the model by /Holmén and Stigsson, 2001/.

2. The structural model by /Holmén and Stigsson, 2001/ places the surface projection of the subhorizontal fracture zone H2 in a NE strike direction, c. 500 m northeast of SFR. As pointed out above, different structural models have been presented for the regional extension of zone H2, including its possible extension south of the Singö fault zone. Bearing in mind the question marks which remain concerning the regional importance and the strike of this zone, it has not been included in the version 0 regional structural model for the Forsmark area. A renewed assessment of the significance of this zone will be necessary in the next model version, when new borehole data are available.

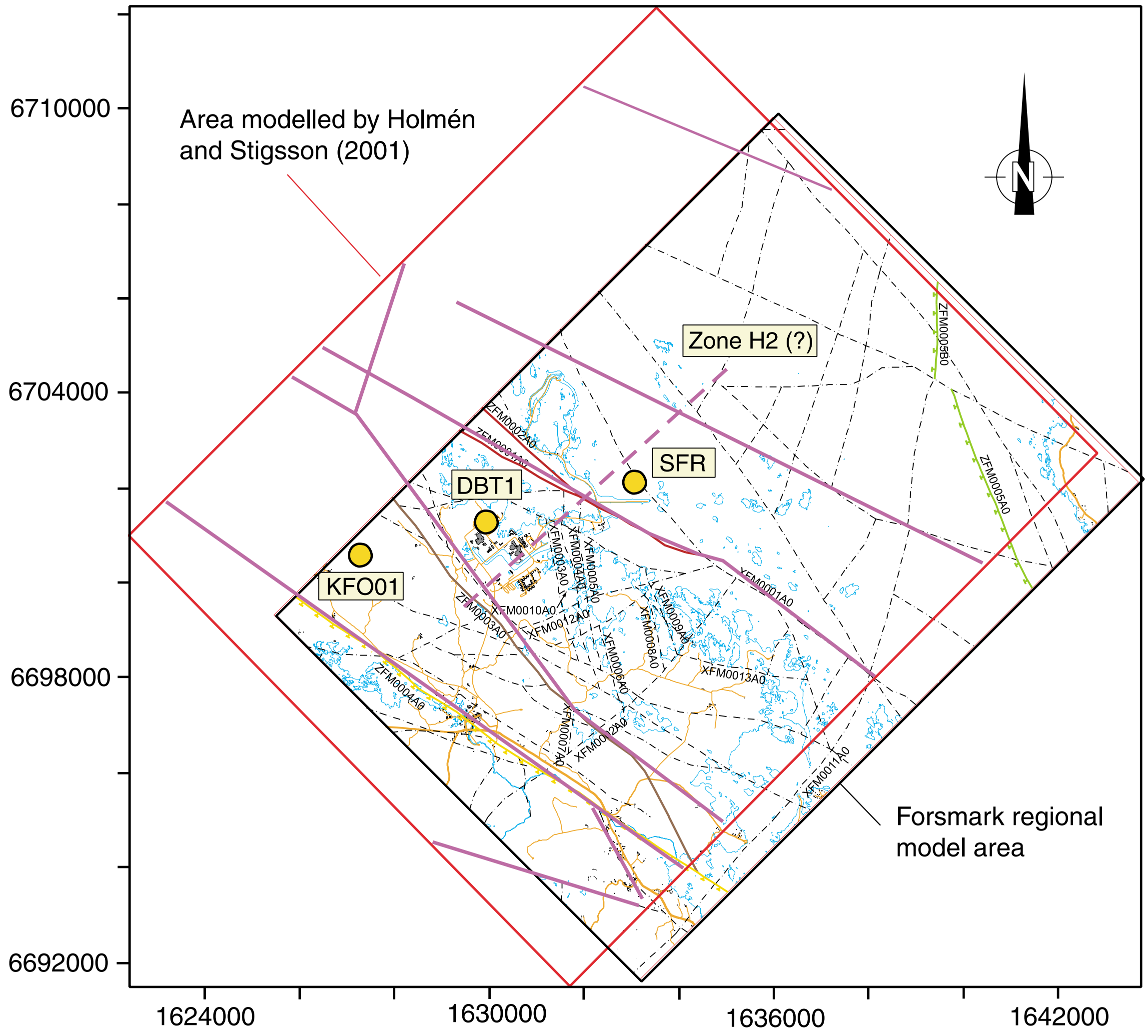

Figure 4-6. *Comparison between the current (version 0) structural model of the Forsmark regional model area (Figure 4-5) and the structural model proposed by /Holmén and Stigsson, 2001/. The latter has utilised the local structural model for SFR /Axelsson and Hansen, 1997/ in combination with the original regional interpretation of lineaments in the feasibility study /Bergman et al, 1996/, with one exception, the regional appearance of the subhorizontal zone H2, c. 500 m northwest of SFR. /Holmén and Stigsson, 2001/ gave zone H2 an extensive deterministic NE strike direction, despite the uncertainties involved. It should be noted that the interpreted lineaments of the current structural model (dotted-dashed lines in black) are considered possible candidates for local major or regional fracture zones.*

4.6 Modelling process in 3D

4.6.1 General

The 3D modelling process begins with the definition of the model block volume, in this case within a region containing a potential disposal site. The process continues with the assembly of relevant 2D surface data which are imported into the model and allow the development of initial projections of 3D geometries. Initially, only structures relevant on a regional scale are considered. The process results in the generation of a regional model version 0 (v0), as presented in the current report. It should be emphasised that the v0 model in reality marks only the starting point of the modelling work. It helps to define what is not known about a site and provides a framework for the planning of relevant field investigations. The model is developed with the help of the RVS geometric rock modelling system.

Subsequent model versions, both at regional and local scale, will be produced as more data become available from the field investigations. The modelling process will ultimately result in the construction of a 3D block model with individual blocks being demarcated by such structures as interpreted fracture zones and faults. This geometrical model will be used as the basis for further specialised modelling activities such as rock mechanics and hydrogeology. Based on the results of the field investigations as well as subsequent interpretations and modelling, the individual blocks and zones will then be assigned physical properties such as density, strength and permeability.

A brief description of the procedures used and the results of the version 0 modelling in the Forsmark regional model area are presented below.

4.6.2 Boundaries of the model block volume and data input

The Forsmark regional model area, as described in Section 1.3, was defined in RVS. The top of the model volume was set at an elevation of +50 m to allow for the generation of a topographic surface. The base of the model volume was set at an arbitrarily chosen elevation of –2,200 m to allow for the future inclusion of deep structures from, for example, seismic and gravity data.

The Forsmark regional model v0 has been based on surface data and an interpretation of how at least some of the geological features can be extrapolated with depth. The following surface data have been imported into the model:

- Distribution of rock types.
- Area potentially of interest for ore deposits.
- Form lines for the tectonic foliation.
- Magnetic connection lines.
- Structural belts inferred to contain an increased concentration of ductile high-strain zones.
- Local major and regional lineaments and fracture (fault) zones.
- Major infrastructure based on the National Land Survey's 1:50,000 map series.

The extrapolations which have been made to depth are based on the interpretation of available data. No 3D base data, for example from boreholes, have been imported into the model.

4.6.3 Lithological model

Field measurements of ductile structures, in combination with an attempt to model magnetic data at three locations, have previously been used to tentatively constrain the dip of the contacts between different rock types along two, schematic cross-sections within the regional model area /Stephens and Isaksson, 2000/. These sections extend down to 1,000 m beneath sea level. However, data which directly confine the dip of these contacts and, thereby, the 3D geometry of the rock units are lacking. For this reason, a 3D lithological model has not been constructed in this study and only the distribution of rock types on the top surface of the block is presented (Figure 4-7).

4.6.4 Structural model

The surface distribution of the structural belts that are inferred to contain an increased concentration of ductile high-strain zones has been marked on the top surface of the block (Figure 4-8). However, the location and geometry of individual, ductile high-strain zones within these belts are not constrained. For this reason, construction of a 3D structural model for the ductile structures has not been completed in this study. The boundaries of these belts were assumed to extrapolate downwards with a vertical or subvertical dip in a schematic cross-section presented by /Stephens and Isaksson, 2000/.

All the local major or regional lineaments addressed in this study are considered to be possible fracture zones. They are displayed on the top surface of the block (Figure 4-9). The geometry of lineaments that had been identified during the early stage of the feasibility study was adjusted due to the more detailed identification in connection with the field control work, during the later stage of the feasibility study. The difference in the level of detail between these two stages is responsible for the apparent termination of some lineaments at the boundary of the field control study area (Figure 4-5). These terminations at the boundary line mark the geographical limits of our knowledge from the field study rather than the interpreted terminations of the individual lineations based on real evidence.

All five lineaments which have been upgraded to highly probable to certain or probable, regional fracture zones have been modelled in 3D with the help of the RVS geometric rock modelling system (Figure 4-9). Details of these zones and supporting data are presented in Section 4.5.5. All zones are inferred to dip at 90° down to the base of the block. Where there are no data pertaining to the width of a particular zone, a default thickness of 1 m was used.

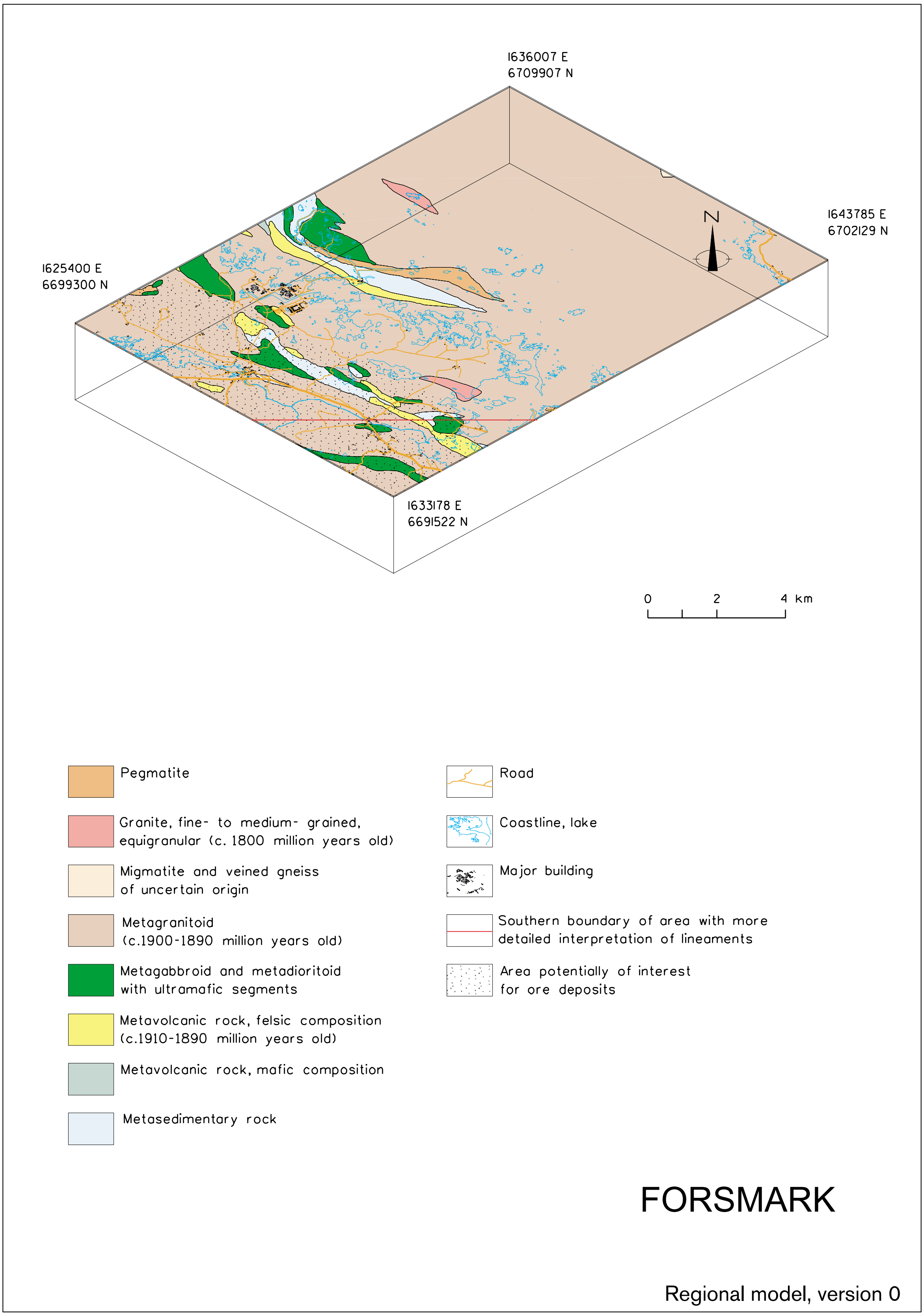

Figure 4-7. *Lithological model, version 0 for the Forsmark regional model area. 3D view from the south.*

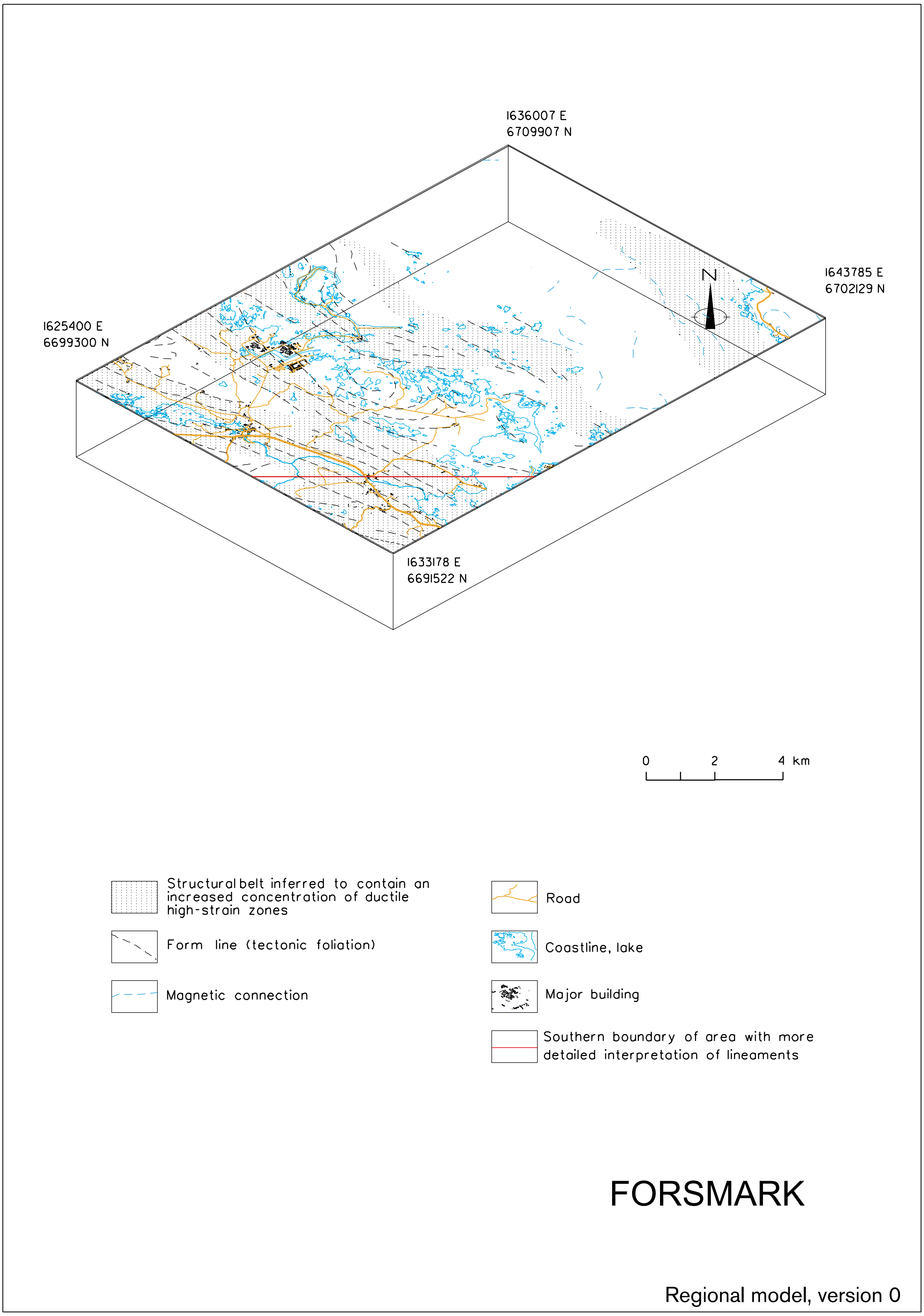

Figure 4-8. *Structural model, version 0 for the ductile deformation in the Forsmark regional model area. 3D view from the south.*

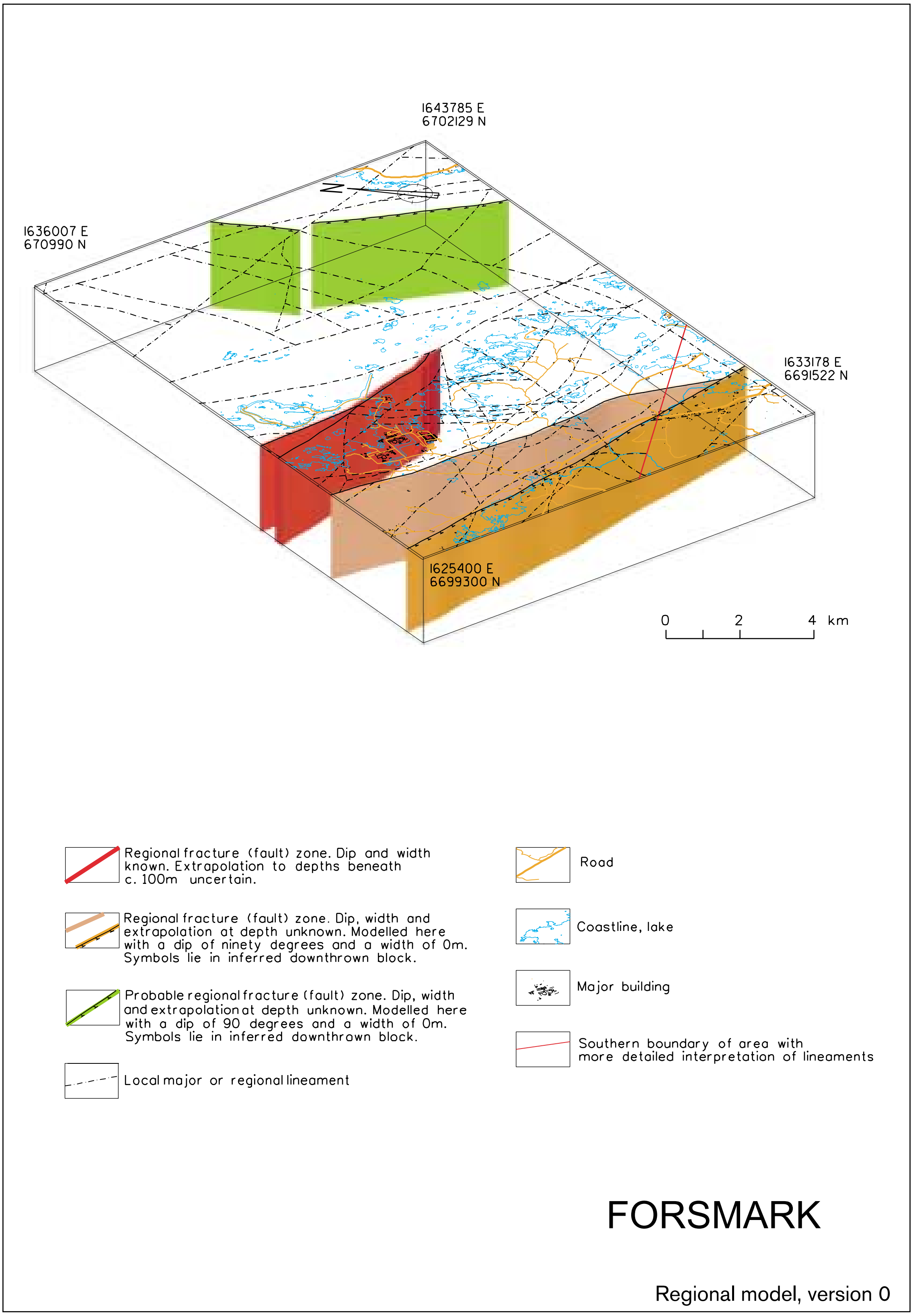

Figure 4-9. *Structural model, version 0 for the local major and regional lineaments and fracture zones in the Forsmark regional model area. 3D view from the west.*

4.7 Assessment of uncertainty in the geological data

The geology of the Forsmark regional model area is presented with the help of several compilations and some interpolations of primary data. These data are both observational and quantitative in character. The primary sources of information are:

- SKB's GIS database 5.0 which has been constructed in connection with the feasibility study work.
- Complementary GIS data summarized in this study.
- The description of the various "parameter groups" /SKB, 2001b/ in the feasibility study work.
- Key references included in the data inventory which is summarized in Chapter 2. These references document, for example, structural data which describe the character of bedrock fractures. They are also pertinent to the modelling of the inferred fracture zones in the regional model area.

An assessment of the uncertainty in this information needs to address:

- The scale at which the data have been compiled.
- The level of knowledge in different parts of the regional model area.
- Uncertainty in the definition of lineaments in the 2D models, and the extrapolation of fracture zones to depth in the 3D model.
- Uncertainty in the interpolation of the structural parameter "form line (tectonic foliation)" between different measurement points.

These aspects of uncertainty correspond to the factors *scale*, *level of knowledge*, *uncertainty in the interpretation of geometry or spatial variability* and *uncertainty during the interpretation of primary data*, respectively /Andersson et al, 2001; Munier and Hermanson, 2001/.

Quantitative assessment of uncertainty is provided here for some parameters. However, the assessment is generally qualitative in character and utilizes the terms "low", "high" and "variable" for level of knowledge and the terms "possible", "probable" and "highly probable to certain" for the uncertainties in the interpretation of geometry and primary data.

The level of knowledge in the model presented for the geological evolution of central Sweden is relatively high for stages 1 and 2, i.e. the older stages, and low for stages 3, 4, 5 and 6, i.e. the younger stages. The assessments of the data in the geological "parameter groups" /SKB, 2001b/ are presented in the form of three tables for Quaternary geology, bedrock including rock type and potential for ore deposits, and bedrock structure (Tables 4-5, 4-6 and 4-7, respectively).

Table 4-5. Assessment of uncertainty. Quaternary geology.

	Scale of compilation	Level of knowledge	Comment
Distribution and description of Quaternary deposits	1:50,000	High	
Thickness of Quaternary deposits		Variable	Generally high level of knowledge offshore around SFR and onshore close to the nuclear power station.
Land rise		High	
Late- or post-glacial crustal movement		Low	Conflicting interpretations in area close to the regional model area.
Seismic activity in historical time		High	

Table 4-6. Assessment of uncertainty. Bedrock – rock type and potential for ore deposits.

	Scale of compilation	Level of knowledge	Comment
Distribution, description and inhomogeneity – south of RAK coordinate 6700000 N	1:100,000	Variable	High level of knowledge onshore. Low in offshore area. Information in 2D model generalized from 1:50,000 to 1:100,000. Location of point information +/– 100–200 m.
Distribution, description and inhomogeneity – north of RAK coordinate 6700000 N	1:100,000	Variable	Assumed to be high level of knowledge in coastal area close to the nuclear power station. Elsewhere low or poorly documented, especially offshore. Information in 2D model generalized from 1:50,000 to 1:100,000. Location of point information +/– 100–200 m.
Age of rocks		Low	
Potential for ore deposits	1:100,000	High	

Table 4-7. Assessment of uncertainty. Bedrock – structure.

	Scale of compilation	Level of knowledge	Interpretation of surface geometry/primary data	Comment
Form lines (tectonic foliation) and field measurements of ductile structures	1:100,000	Variable	Possible to probable	Interpolation of primary structural field data. Location of point information +/– 100–200 m.
Magnetic connections	1:50,000	High	Highly probable to certain	High-quality airborne geophysical data, 200 m flight line separation, 17–40 m point separation, ground clearance 30–60 m.
Structural belts with an increased frequency of ductile high-strain zones	1:100,000	Low	Possible	Boundaries to structural belts and location of high-strain zones within them are both poorly constrained.
Lineaments north of RAK coordinate 6695000 N, possible local major or regional fracture zones	1:50,000	High	Highly probable to certain. Position of lineaments +/– 50–100 m in offshore areas, +/– 50 m in onshore areas.	High-quality airborne geophysical data, 200 m flight line separation, 17–40 m point separation, ground clearance 30–60 m. Topographic relief data, 50 m grid.
Lineaments south of RAK coordinate 6695000 N, possible local major or regional fracture zones	1:100,000	High	Highly probable to certain. Position of lineaments +/– 100 m.	High-quality airborne geophysical data, 200 m flight line separation, 17–40 m point separation, ground clearance 30–60 m. Topographic relief data, 50 m grid.
ZFM0001A0, regional fracture zone	1:50,000	High	Highly probable to certain. Position of fracture zone +/– 50–100 m. Uncertain extrapolation under c. 100 m beneath sea level.	See verification criteria, Section 4.5.5.
ZFM0002A0, regional fracture zone	1:50,000	High	Highly probable to certain. Position of fracture zone +/– 50–100 m. Uncertain extrapolation under c. 100 m beneath sea level.	See verification criteria, Section 4.5.5.
ZFM0003A0, regional fracture zone	1:50,000	Low	Highly probable to certain. Position of fracture zone +/– 50 m. Uncertain extrapolation at depth.	See verification criteria, Section 4.5.5.
ZFM0004A0, regional fracture zone	1:50,000 north of RAK coordinate 6695000 N, 1:100,000 south of RAK coordinate 6695000 N.	Low	Highly probable to certain. Position of fracture zone +/– 50 m. Uncertain extrapolation at depth.	See verification criteria, Section 4.5.5.
ZFM0005A0/B0, regional fracture zone	1:50,000	Low	Probable. Position of fracture zone +/– 100 m. Uncertain extrapolation at depth.	See verification criteria, Section 4.5.5.

5 Rock mechanics

To describe a site from rock mechanical point of view there are two components to consider, the *in situ* stress and the mechanical properties of the rock. The combination of stress and strength determines the stability conditions of future repository excavations. The following two sections present the stress model and the mechanical property model, respectively. The models are based on the limited data available at this stage.

5.1 *In situ* stress model

5.1.1 Available data

The Forsmark/SFR sub-area includes the Forsmark nuclear power station and SFR, and data from stress measurements are available from this area. /Carlsson and Christiansson, 1987/ have made a compilation and evaluation of the data. Table 5-1 specifies the borehole data used as a base for the version 0 stress model. At Finnsjön, not very far from Forsmark (c. 20 km, see Figure 6-2), SKB has performed measurements in a deep borehole (KFI-06) and these data are also included. The location of boreholes DBT-1 and DBT-3 is shown in Figure 6-4.

Table 5-1. Stress measurement data from Forsmark/SFR. (Borehole KFI-06 is located at Finnsjön, 20 km from Forsmark).

Borehole	Method	Data source	Reference to measurement report
DBT-1	Overcoring (also ring disking observations)	Report	/Carlsson and Olsson, 1982/
DBT-1	Hydraulic fracturing	From SwedPower	/Stephansson and Ångman, 1984/
DBT-3	Overcoring	Report	/Carlsson and Olsson, 1982/
KB-21	Overcoring	SICADA*	/Andersson, 1985a/
KB-22	Overcoring	SICADA*	/Andersson, 1985a/
KB7-S	Overcoring	SICADA*	/Strindell et al, 1981/
SFR 1/177	Overcoring	SICADA*	/Andersson, 1985b/
KFI-06	Hydraulic fracturing	Report	/Bjarnason and Stephansson, 1988/

* Not yet available.

5.1.2 Lithological and structural model implications

Two main factors may influence the *in situ* stress field, stiffness differences in rock material and/or fracture zones /Hakami et al, 2002/. For the conditions at Forsmark/SFR, the first factor is expected to be minor because the difference in stiffness will not be sufficient to cause considerable stress differences (see Section 5.2.2). The second factor is therefore expected to be the major cause for any stress variation. With 'stress variation' is meant here stress differences apart from the stress increase with depth related to the gravitational forces.

The structural model description (Section 4.6.4) indicates that the area is intersected by several fracture zones and that these zones have been reactivated several times during the geological history. It is therefore reasonable to believe that the strengths in the zones are significantly lower than the surrounding rock and that, therefore, the zones may influence the stress field. The existing weaker zones will tend to deflect the principal stress axes so as to lie parallel and perpendicular to the zone boundaries, since they would not be able to sustain shear forces.

The most dominant zone at Forsmark, ZFM0001A0 (the Singö fault zone), and sub-parallel zones strike approximately NW. The regional stress field expected from the tectonic forces on the Fennoscandinan shield also gives a NW orientation of the major horizontal stress, which can be seen from the World Stress Map /Müller et al, 1992/. Thus, both the primary stress sources and the structures indicate that NW-SE should be the preferred orientation of the maximum compressive stress. The tectonic forces are the dominating source for the prevailing stress field in the whole Sweden, resulting in compressive horizontal stresses clearly larger than vertical stresses /Hakami et al, 2002/. Vertical stresses normally correspond to gravity, i.e. the weight of overlying rocks /Amadei and Stephansson, 1997/.

Subhorizontal fracture zones can influence the stress magnitudes more than the steep zones, because a gently dipping zone that reaches the ground surface may have experienced a shear slip. In such a case, the rock mass overlying the zone will be de-stressed compared to the rock mass below. Such zones could thus potentially cause an abrupt increase in stress with depth. Large stress changes across a subhorizontal fracture zone have been observed at Forsmark in borehole DBT-1 (Section 5.1.4), but the possible existence of *regional* subhorizontal zones is uncertain (Section 4.5.5). The major zone in the Forsmark/SFR area, the Singö fault zone, is suggested to be steeply dipping (Section 4.5.5).

5.1.3 Stress model and uncertainties

The results from the stress measurements are shown in Figures 5-1 to 5-3. The hydraulic fracturing data from Forsmark is sparse but the results coincide well with the corresponding data from Finnsjön. The model chosen for the minimum principal stress is a linear equation with depth based on the best fit trend of the Finnsjön data (see Table 5-2, at the end of this section). The accuracy of hydraulic fracturing measurements is considered to be within 25%. For the model, an uncertainty of 30% is selected down to 500 m depth and 50% deeper then 500 m. These slightly higher u-parameters (uncertainty spans) down to 500 m were selected because the data from Forsmark are very scattered, and because the data from Finnsjön may be less representative. This model, however, is similar to the generally found stress level for the minimum stress in Sweden (e.g. it is similar to the results at Simpevarp).

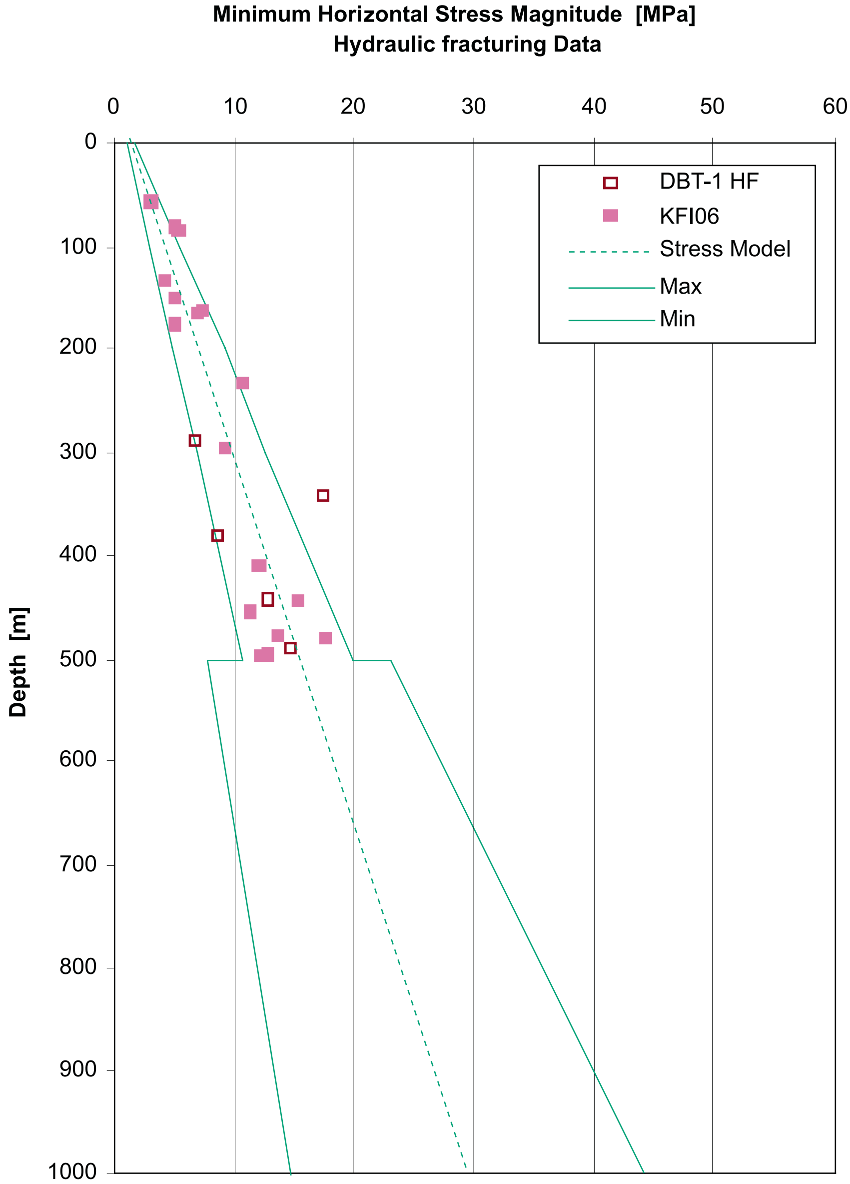

Figure 5-1. *Minimum horizontal stress magnitude determined by hydraulic fracturing in a borehole at Forsmark (DBT-1) and a borehole at Finnsjön (KFI06). The model chosen for Forsmark/SFR is shown by the green line. The expected spatial variation around the mean stress, ±15%, is not shown in the diagram.*

At depth, the uncertainty is higher because there are no data available and we do not have any reliable structural model. A weak subhorizontal structure intersecting the Forsmark/SFR area could cause the stresses to increase below and the structural model is still uncertain at depth.

The available overcoring results show a large scatter and even tensile stresses at considerable depth (Figure 5-2). The quality of the data has not been examined within this project. The general picture, that the stresses will increase with depth, is however clear.

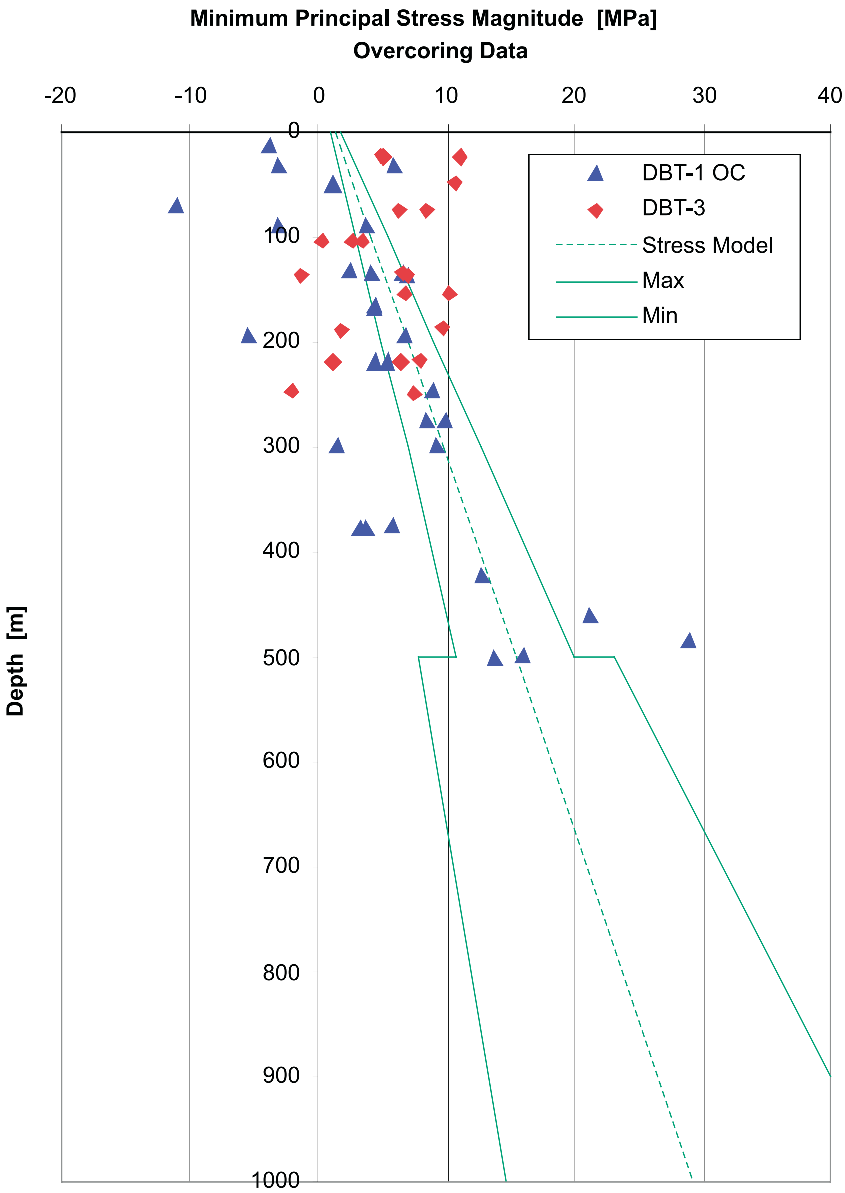

Figure 5-2. *Minimum principal stress results from overcoring test in boreholes DBT-1 and DBT-3. The model chosen for Forsmark/SFR is shown by the green lines.*

Scatter in the overcoring data is expected for the small scale overcoring method, but the magnitudes are also sensitive to the Young's modulus used in the interpretation. The presented magnitude values for the maximum horizontal stress from hydraulic fracturing method has not been used here as a base for the model because the underlying assumptions make them unreliable /e.g. Rutqvist et al, 2000/.

The model for the maximum principal stress is based on the equation for the minimum stress multiplied by 3.4, which is the mean of the median $\sigma 1/\sigma 3$ ratio from the overcoring data in borehole DBT-1 (3.8) and DBT-2 (3.0). This model is also compared to the actual magnitude results from the overcoring tests (Figure 5-3). The fit of the model is fairly good, although data are scattered. The uncertainty of the maximum stress has again been chosen to increase for the deep part of the bedrock, for the same reason as for the minimum stress. The uncertainty of the maximum stress is larger than for the

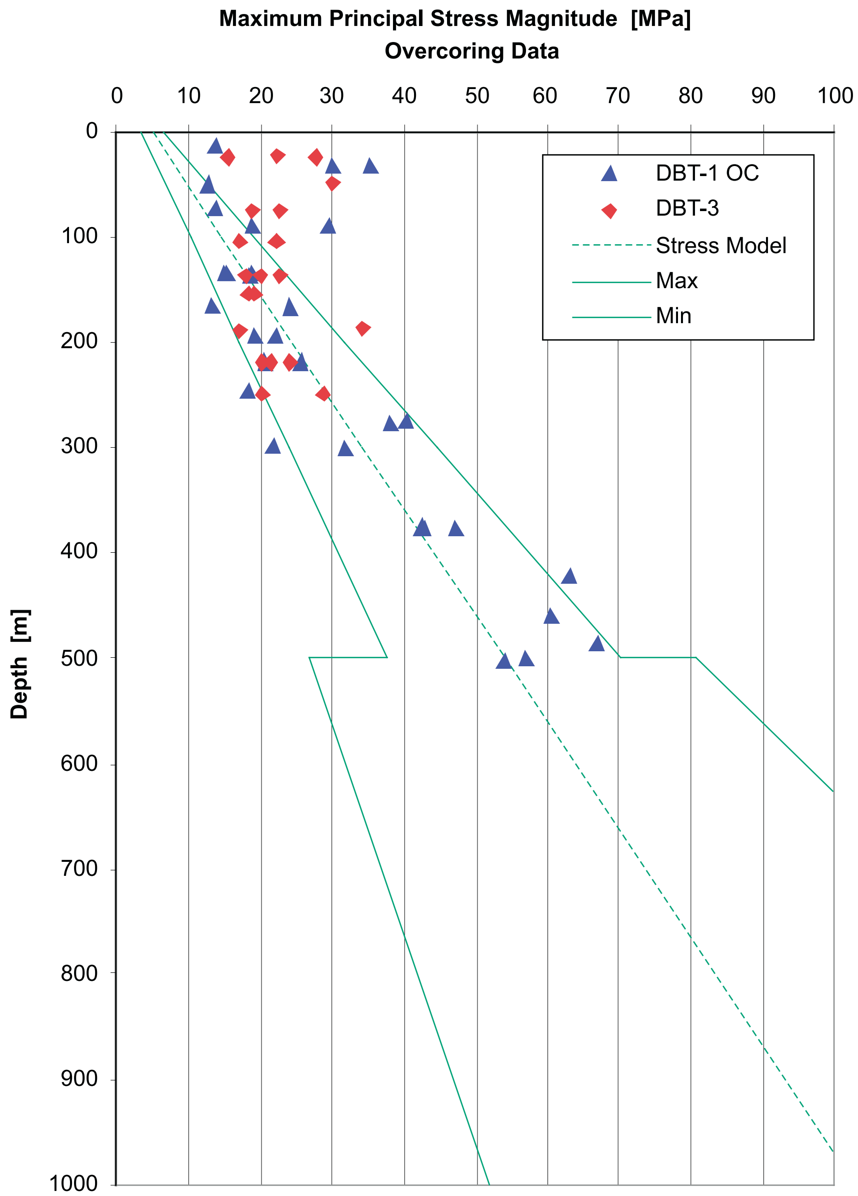

Figure 5-3. *Maximum principal stress data from overcoring test in boreholes DBT-1 and DBT-3. The model chosen for the Forsmark/SFR is shown by the green lines.*

minimum stress because of the scarce and scattered data available. Stress data from shallow depth should always be expected to vary more because the topography and structures are influencing the stresses more at shallow depths. The intermediate principal stress of the model is vertical and expected to correspond to the overburden, with a mean density of 2,700 kg/m^3. The uncertainty of the vertical stress is estimated to 25%.

Within the fracture zones the stresses are generally expected both to vary more around the mean but also to vary on a larger scale because of the varying mechanical properties within the zones. The uncertainty within the zones is large also concerning the orientation since the structures and the inclinations of the zones itself may well deflect the stress field locally. If possible, measurement values taken from fracture zones should be separated from measurements from the more intact rock in-between to give a better prediction of the stress fields.

The orientation of the maximum horizontal stress is based on the measurement data from both hydraulic fracturing and overcoring methods (Figure 5-4). The mean of the median values from the four series, 134°, was used. It should be noted that this SE direction (calculated from measurement data) fits well to the direction expected from the structural model and regional pattern, i.e. the maximum horizontal stress is parallel to the Singö fault zone (Section 4.5).

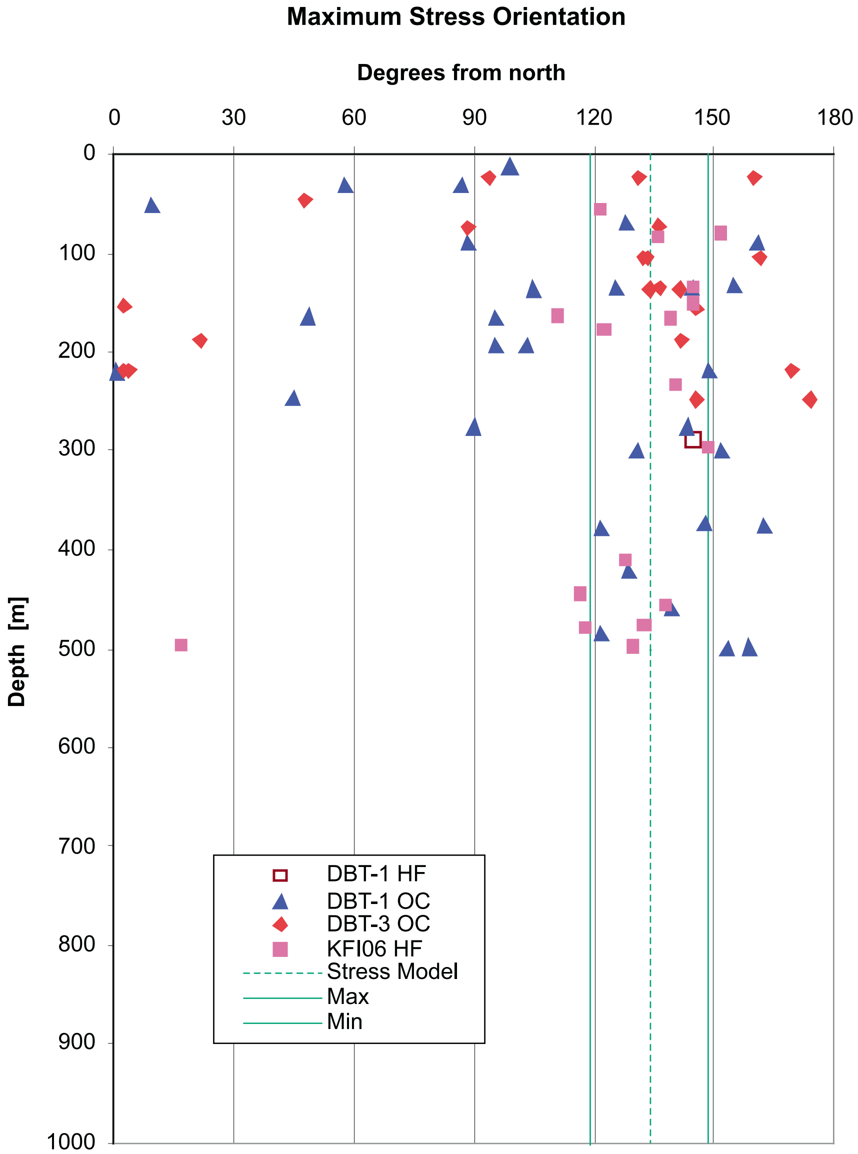

Figure 5-4*. Maximum stress orientation measured with overcoring and hydraulic fracturing methods from Forsmark/SFR and KFI06 in Finnsjön. (Trend values higher than 180 degrees have been reduced by 180).*

Table 5-2. Predicted *in situ* stress magnitudes in Forsmark/SFR.

Parameter	σ1	σ2	σ3
Mean stress magnitude, MPa	0.095·z + 4.8	0.027·z	0.028·z + 1.4
Uncertainty, 0–500 m	±30%	±25%	±30%
Uncertainty, 500–2000 m	±50%	±25%	±50%
Spatial variation, rock mass	±15%	±15%	±15%
Spatial variation, fracture zones	±50%	±50%	±50%

Table 5-3. Predicted *in situ* stress orientations in Forsmark/SFR.

Parameter	σ1, trend	σ1, dip	σ3, dip
Mean stress orientation	134°	0°	0°
Uncertainty, 0–500 m	±15°	±10°	±15-45° *
Uncertainty, 500–2000 m	±15°	±10°	±10°
Spatial variation, rock mass	±15°	±15°	±15°
Spatial variation, fracture zones	±25°	±30°	±30°

* At some level σ2 and σ3 may have similar magnitude and the dip then becomes undefined and irrelevant.

In Tables 5-2 and 5-3, the stress estimations are described for Forsmark/SFR. The change in the model at 500 m depth should not be understood as an expected sudden change in stress at this depth but just as a way to describe the increased uncertainty. In the fairly intact rock between major zones the spatial variation of the stress is expected be less than within the zones. The rock volume involved in a single measurement is small, in the range 0.01–1 m^3 depending on the method applied. The mean stress values in the tables are meant to represent the mean stress level in a rock volume of 30x30x30 m.

5.1.4 Alternative stress model

An alternative stress model, based on data from borehole DBT-1, is presented by /Christiansson and Martin, 2001/, see Figure 5-5. They have considered the core disking observed during the stress measurements and interpreted this as an effect of significant anisotropy in the stress magnitude, caused by an increase in maximum principal stress. They attribute the stress increase to the fracture zone situated just above the core disking observations in the borehole. With this model the stress is predicted to increase non-linearly with depth, as depicted by the dashed line in the Figure 5-5.

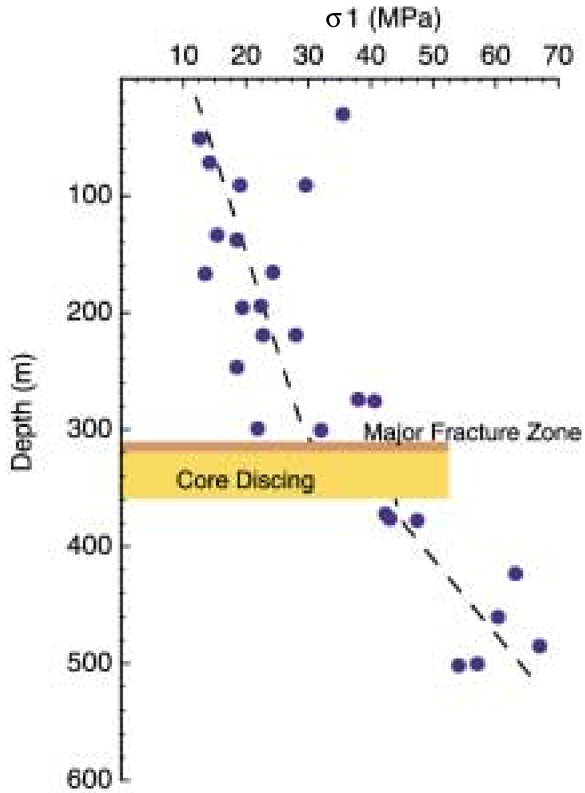

Figure 5-5. Maximum principal stress versus depth for the borehole DBT-1 at Forsmark. Data is modified from /Carlsson and Olsson, 1982/. Figure from /Christiansson and Martin, 2001/.

5.2 Mechanical Rock Mass Properties

5.2.1 Available data

Significant experience from the underground constructions in the area exist, as compiled by Larsson and Leijon /1996/. They conclude that a rock mass classification in the area as a whole should be expected to fall within the span between the "good" and "very good" quality classes, but local conditions may vary and even be "difficult" when passing larger fracture zones. It should be pointed out here that none of the existing excavations at Forsmark are situated at depths similar to what is planned for the repository.

/Stille et al, 1986/ present strength values from cores at SFR. The unconfined compressive strength value given for amphibolite was 148 MPa, for pegmatite 157 MPa and for gneiss 241 MPa. These authors further present an analysis of the large silo constructed at SFR and the predicted performance was considered to fit well with the outcome.

/Swan, 1977/ made laboratory tests on granodioritic core samples from Finnsjön (about 20 km from Forsmark) and the mean Young's modulus was found to be 82.5 GPa and the mean uniaxial compressive strength 241 MPa.

5.2.2 Lithological and structural model implications

The lithological model shows that in the Forsmark/SFR area, the bedrock is dominated by metagranitoids and associated mafic to intermediate intrusive rocks (Section 4.4). Metavolcanic and metasedimentary rocks also exist. From general testing experience we know that intact cores from these crystalline rock types all have a fairly high strength and high stiffness. Data from e.g. /Persson, 1998/, /Persson et al, 1998/, /Rhén et al, 1997/, /Staub et al, 2002/ and /Lama and Vutukuri, 1978/ show that the possible spans for deformation and strength parameters for these rock types are to a large extent overlapping. This means that the intact rock property estimates, at this stage when site specific laboratory tests results are not available, will not be sensitive to the lithological description.

However, the mechanical properties on a larger scale (rock mass scale) will be strongly dependent on the fractures in the rock, and the degree of fracturing will determine the expected mechanical properties of the rock between the zones. The occurrence and location of major fracture zones (i.e. the structural model, see Section 4.5) directly determines the expected mechanical properties. This is not only because of the increased fracturing in zones but also because of increased occurrence of softer fracture-fill material. The mechanical properties of the rock mass inside the fracture zones should thus be expected to differ significantly from the properties of the rock mass between the zones. The geological modelling does not include at this stage any statistical analysis of the fracture data from the site.

5.2.3 Mechanical property model and uncertainties

At this stage there is a limited amount of site specific data, and the parameters that makes up the descriptive model have been based on expert judgement. Naturally, the site specific data that do exist on uniaxial strength and Young's modulus for intact rock samples, see Section 5.2.1, fall within the selected span for these parameters.

The parameters used for the rock mechanical description are: (i) Young's modulus for intact rock, (ii) Poisson's ratio for intact rock, (iii) uniaxial strength for intact rock, (iv) tensile strength for intact rock, (v) Young's modulus for rock mass, (vi) Poisson's ratio for rock mass, (vii) uniaxial strength for rock mass, (viii) cohesion of rock mass and (ix) internal friction of rock mass. The last five of these parameters, concerning "rock mass" are not regarded as standard parameters and the definitions should be carefully considered before use (the reader is referred to /Andersson et al, 2002a/ for a more detailed description and discussion). The scale of a "rock mass" is taken as 30x30x30 meter block and the reference level for the confining stress is 10 MPa.

Table 5-4 presents the preliminary parameter spans chosen for Forsmark/SFR. The rock mass is divided into two categories the "normally fractured rock mass" and the "fracture zones". The prediction for a certain point will thus depend only on whether this point is expected to be located inside a zone or not.

The uncertainty in the parameters stems from different factors:

- For intact rock: lack of comprehensive laboratory studies.
- For rock mass: poor knowledge of the parameter concepts.
- For rock in fracture zones: complex geology and lack of tests.

Table 5-4. Predicted rock mechanical properties in Forsmark/SFR. (Shaded areas correspond to parameters that are suggested to be determined in later versions of site descriptive models. When laboratory data from the site is available, rock mechanical properties may be estimated for the specific rock types within the domain).

Parameter for intact rock (drill core scale)	All rock types	Rock type I	Rock type II	Rock type III
Young's modulus	40–85 GPa			
Poisson's ratio	0.20–0.30			
Uniaxial strength	150–300 MPa			
Tensile strength	5–20 MPa			
Parameter for the rock mass ***	**Rock Mass All depths (30x30x30 m scale)**	**Rock Mass Certain depth interval**	**Fracture Zones All depths interval**	**Fracture Zones Certain depth interval**
Young's modulus*	30–75 GPa		10–40 GPa	
Poisson's ratio*	0.20–0.30		0.20–0.26	
Uniaxial strength*	100–160 MPa		55–85 MPa	
Friction angle**	35–50°		25–40°	
Cohesion**	10–30 MPa		5–20 MPa	

* Confining stress magnitude 10 MPa.
** Linear model between 10 and 20 MPa confining stress magnitude.
*** See /Andersson et al, 2002a/.

6 Hydrogeology

6.1 Introduction

Figure 6-1 illustrates SKB's systems approach to hydrogeological modelling of groundwater flow through fractured crystalline rocks. The division into hydraulic domains (HSD, HRD and HCD) is described in the general programme for site investigations /SKB, 2001b/. This chapter describes the present knowledge of the hydrogeological setting of the Forsmark regional model area. The hydrogeological setting is described by means of parameters, which detail:

- The *geometric and hydraulic properties* of the Quaternary deposits (HSD) and the crystalline bedrock (HRD and HCD).
- The *hydrological processes* that govern the hydraulic interplay between surface water and groundwater, including groundwater flow at repository depth.

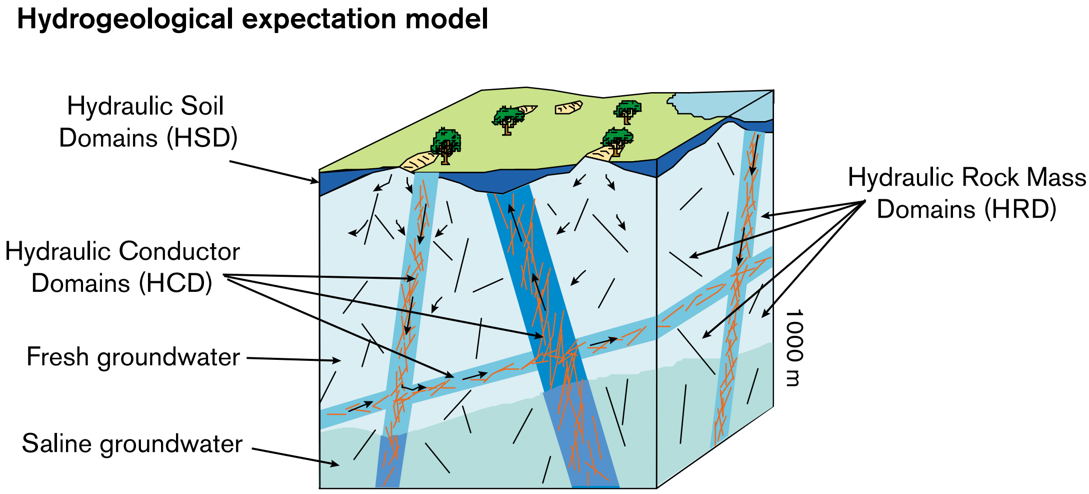

Figure 6-1. *The Quaternary deposits and the crystalline bedrock are divided into separate hydraulic domains denoted HSD, HRD and HCD. Within each domain the hydraulic properties are represented by mean values or by spatially distributed statistical distributions (modified after /SKB, 2001b/).*

6.2 Sources of information

6.2.1 Data compilations and interpretations

The present knowledge of the hydrogeological setting of the Forsmark regional model area is based on four different sources of information. The four sources are: (*i*) mapping of Quaternary deposits and bedrock geology (rock type, lineaments and deformation zones) (*ii*) meteorological and hydrological investigations, (*iii*) hydraulic borehole investigations and monitoring, and (i*v*) hydrogeological interpretation, analysis and modelling.

The existing investigations and documentation of the *Quaternary deposits and bedrock geology* are reviewed and scrutinised in Chapter 4 of this report. From a hydrogeological perspective, the geological data and interpretations constitute the basis for the version 0 *geometric modelling* of the different hydraulic domains in the Forsmark regional model area. Thus, Chapter 4 and its underlying references provide input to:

- The geometry of deterministic fracture zones and lineaments (HCD) and the rock mass in between (HRD).
- The distribution of Quaternary deposits (HSD), including genesis, composition, stratification, thickness and depth.

The existing investigations and documentation of the *meteorology and hydrology* (see Chapter 3) constitute the basis for the version 0 *hydrological process modelling*. In concrete words, the references provide input to:

- The present-day interpretation of drainage areas, as well as mapping of springs, wetlands and streams, surveying of land use such as ditching and dam projects, water supply resources, nature conservation areas, etc.
- Mean estimates of the present-day precipitation and runoff, heads and flows in watercourses.
- An assessment of the relative impact of local topography, shore level displacement, variable-density groundwater flow and inferred fracture zones for the definition of initial and boundary conditions and the numerical simulation of present-day and future recharge and discharge areas of groundwater flow.

Existing investigations and documentation of *hydraulic borehole investigations* and *monitoring* are of interest for the version 0 definition of *hydraulic properties* of the different hydraulic domains. There are basically two main sources of information:

- Hydraulic tests and hydrogeological monitoring in boreholes within the model area. At present, such data from deep boreholes only exist for a very small part of the model area, i.e., in the proximity to the Forsmark power plant and to the final repository for radioactive operational waste (SFR), see Figure 6-2. For the uppermost part of the bedrock (e.g. less than 100 metres), some information of interest may be deduced from the Archive of Wells at the Geological Survey of Sweden (SGU). Concerning hydraulic properties of the Quaternary deposits, the current knowledge is more or less
constrained to general hydrogeological information found in the literature.
- Hydraulic tests and other hydrogeological observations in boreholes from the nearby Finnsjön study site, see Figure 6-2.

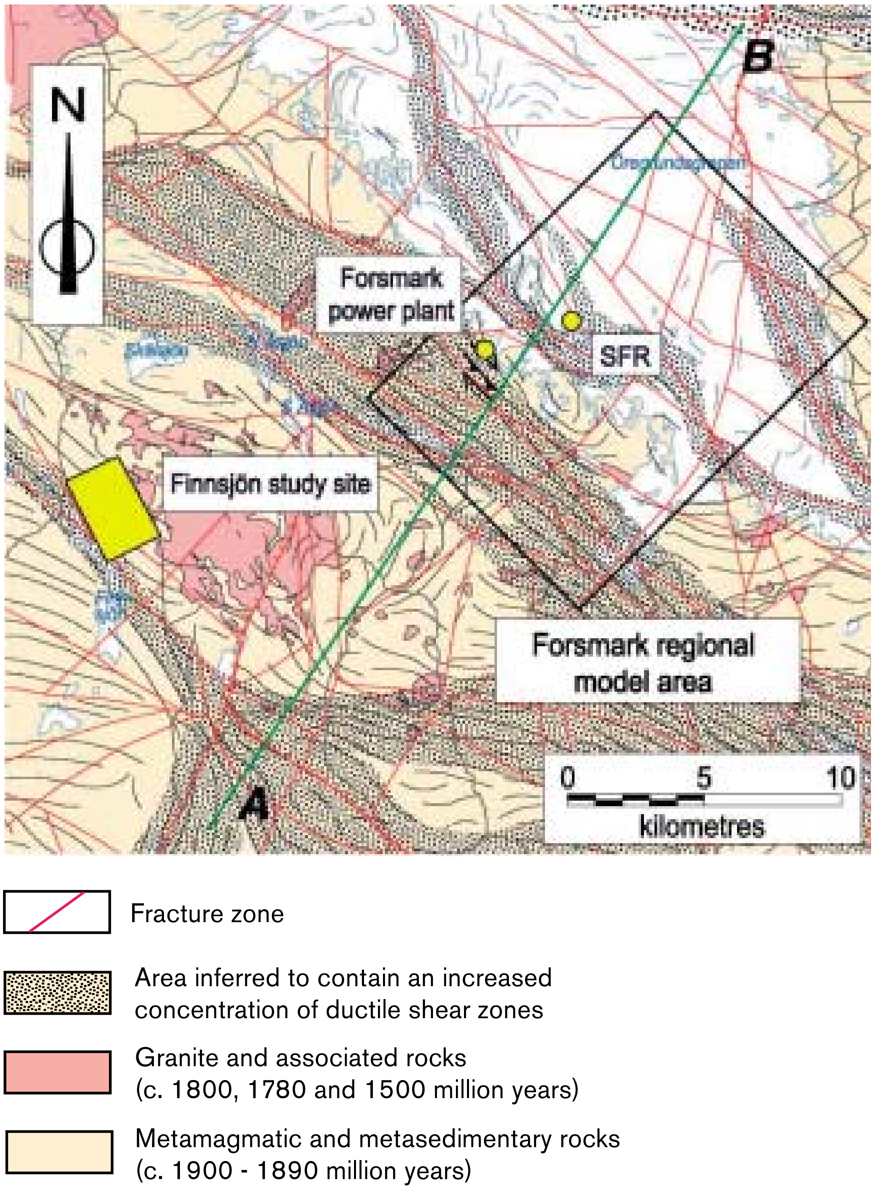

Figure 6-2. *Deformation map showing the extent of the Forsmark regional model area and the locations of the Forsmark power plant, SFR and the Finnsjön study site. The deformation map is an excerpt of the regional deformation map shown in Figure 8-4 in /Bergman et al, 1999/. The topography along the green line between A and B is shown in Figure 6-11.*

It is an open question to what extent data from hydraulic tests and hydrogeological observations gathered in specific boreholes at the Forsmark power plant, the SFR and the Finnsjön study site can be extrapolated and used to define parameter values for the regional model area /cf. Uppsala University, 1998/. It is advocated here that the structural interpretations presented in /Bergman et al, 1996, 1998, 1999/ indicate that the existing boreholes at the specified locations are located either within (Finnsjön) or close to the boundary of (Forsmark and SFR) different tectonic lenses within the system of ductile high-strain zones which is often referred to as the Singö shear zone (Figure 6-2). Hence, all three sources of information are of potential interest from a structural point of view for the assignment of hydraulic parameter values.

The region where the Forsmark regional model area is located has been subjected to extensive *hydrogeological interpretations, analyses and modelling* during the past two decades. A large body of work has been carried out in support of SKB's investigations and modelling of the Finnsjön study site /Andersson et al, 1991; Lindblom et al, 1991/, particularly in connection with the safety assessments SKB 91 /Lindblom and Boghammar, 1992; SKB, 1992/ and SR 97 /Walker et al, 1997; Hartely et al, 1998; SKB, 1999/. The experiences gained from the flow and tracer tests performed at the Finnsjön study site have also been used in two international groundwater modelling intercomparison projects, INTRACOIN /SKI, 1986/ and INTRAVAL /NEA/SKI, 1990/, and by SKI in the safety assessment project entitled Project 90 /SKI, 1991/. A summary of the scope and results of work carried out at the Finnsjön study site is compiled by /Ahlbom et al, 1992/.

Another large body of work has been carried out in conjunction with the construction and licensing of the SFR repository, c. 3 km northeast of the Forsmark power station. Table 6-1 shows a selection of the documentation on performed hydrogeological data interpretation and mathematical modelling which has been carried out at SFR. It should be noted that each report in Table 6-1 reflects the prevailing descriptive (conceptual) model of the fracture zone network at SFR at the time of execution. In consequence, the most recent data interpretation study by /Axelsson and Hansen, 1997/ and the most recent modelling study by /Holmén and Stigsson, 2001/ are likely also the most important studies for the present study (Forsmark regional model, version 0).

However, the current structural interpretation of the Forsmark regional model area has evolved over the last few years and some of the more recent changes are not included even in the two aforementioned studies. In conclusion, the underlying structural model of the version 0 hydrogeological model remains to be examined and modelled hydraulically as a means of gaining an updated understanding of the hydrodynamics of the Forsmark regional model area.

Table 6-1. Compilation of the documentation on hydrogeological data interpretation and mathematical modelling carried out in conjunction with the construction and licensing of the SFR repository.

Reference	Type of report
/Carlsson and Olsson, 1977/	Data interpretation
/Axelsson and Carlsson, 1981/	Modelling/Code GEOFEM-G
/Carlsson and Olsson, 1981/	Data interpretation
/Carlsson et al, 1985/	Data interpretation
/Axelsson, 1986/	Modelling/Code SLAEM
/Carlsson et al, 1986/	Data interpretation
/Christiansson, 1986/	Data interpretation
/Carlsson and Christiansson, 1987/	Data interpretation
/Carlsson et al, 1987/	Modelling/Code GWHRT
/Axelsson et al, 2002/	Data interpretation
/Axelsson, 1997/	Data interpretation
/Axelsson and Hansen, 1997/	Data interpretation
/Stigsson et al, 1998/	Modelling/Code SUTRA
/Holmén and Stigsson, 2001/	Modelling/Code GEOAN

6.2.2 Data in SKB's databases

Wells and boreholes

Figure 6-3 shows the boundary of part of the Forsmark regional model area, together with the positions of the all together 90 wells and boreholes that are recorded in SKB's databases (SICADA and GIS). 41 of the 90 wells and boreholes were drilled at SFR. The remaining 49 wells and boreholes are mainly private wells. Nine of these are found in the Archive of Wells of the Geological Survey of Sweden (SGU).

It should be noted that the two deep boreholes DBT-1 and DBT-3 are drilled in the vicinity of the Forsmark power plant. These are not shown on Figure 6-3, but their positions are indicated on Figure 6-4. DBT-1 is c. 500 metres deep and DBT-3 c. 250 metres.

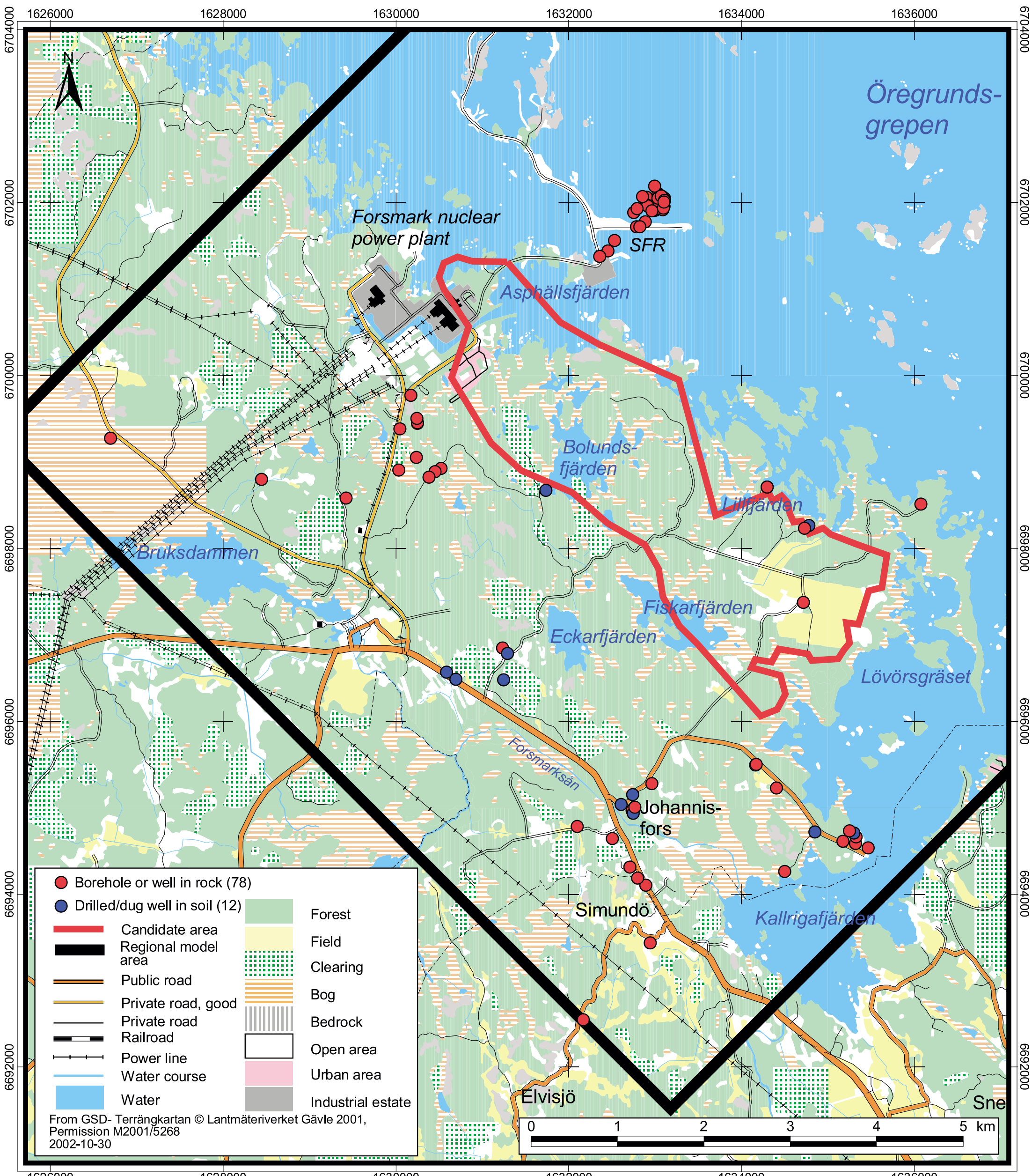

Figure 6-3. *Within the regional area (black line) 90 wells and boreholes have been found (not counting the two deep boreholes DBT-1 and DBT-3 drilled nearby the Forsmark power plant – see Figure 6-4. Blue circles indicate wells drilled in the Quaternary deposits and red circles indicate wells/boreholes drilled in the bedrock.*

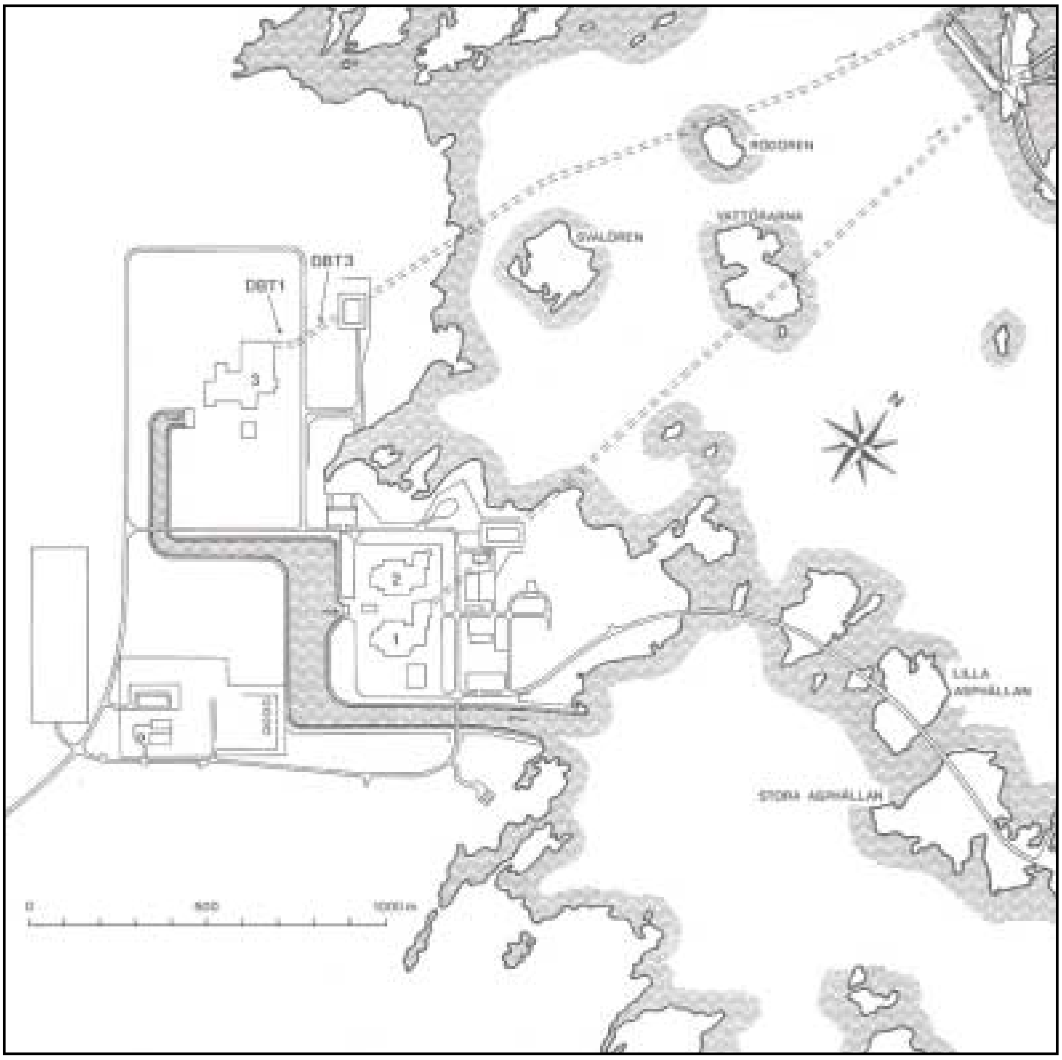

Figure 6-4. Positions of the deep boreholes DBT-1 and DBT-3 in the vicinity of reactor 3 of the Forsmark nuclear power plant. Modified after /Carlsson and Olsson, 1982/.

SFR

The data from the hydraulic borehole investigations at the SFR repository are archived in SKB's database SICADA. An overview of the hydraulic activities recorded in SICADA for SFR is shown in Table 6-2. SICADA contains a total of 104 records of hydraulic data (mainly *hydraulic conductivity*) in 41 boreholes. The measurements were made between 1981–1987.

The monitoring programme at the SFR repository has been subjected to changes over time. The present status is described in /SKB, 1990/. Besides inflows to the different rock caverns, the monitoring programme also measures the water chemistry and the piezometric pressure in sealed-off sections at predetermined time intervals. The recorded data are archived in SKB's database SICADA. The activity log in SICADA for SFR contains in total 184 records between 1984–Present.

Table 6-2. Hydraulic activities recorded in SICADA for SFR (as of 2001-12-18).

References	Methods	Period	Measurement limit on K (m/s)
SKB/SICADA	Pressure build-up tests	1985–1987	$1 \cdot 10^{-11}$
SKB/SICADA	Interference tests	1985–1986	–
SKB/SICADA	Transient injection tests	1984–1986	$1 \cdot 10^{-11}$
SKB/SICADA	Steady state injection tests	1981–1983	$2 \cdot 10^{-8}$
SKB/SICADA	Falling head tests	1981–1981	$1 \cdot 10^{-9}$

Archive of Wells at SGU

The Archive of Wells at the Geological Survey of Sweden is an information and documentation project without specified usage objectives. About 1,500 wells are recorded in the archive for the municipality of Östhammar. However, only nine wells out of a total of 49 wells and water prospecting boreholes that are found within the Forsmark regional model area outside the SFR repository, are found in the archive. Table 6-3 shows an overview of the contents of SKB's version of the Archive of Wells.

Table 6-3. Overview of the contents of SKB's version of the Archive of Wells.

References	Parameter	Unit/Info
SKB/GIS	Yield (air-lifting/pumping)	L/h
SKB/GIS	Well diameter (drill bit)	mm
SKB/GIS	Total depth	m
SKB/GIS	Soil depth (if present)	m
SKB/GIS	Casing (steel/plastic)	m
SKB/GIS	Usage	Farming, Water Supply, Industry, Energy, etc

Well inventory

A well inventory was conducted in the central part of the Forsmark regional model area during 2001. The inventory revealed 25 private wells and 15 water-prospecting boreholes. Twelve of the 25 private wells are dug wells. The result of the inventory is reported by /Ludvigson, 2002/. In addition to the type of well (dug/drilled/soil/bedrock), the inventory data comprise well coordinates, total depth and water chemistry. The results concerning water chemistry are dealt with in Chapter 7.

6.3 The Forsmark regional structural-hydraulic model v0

Figure 6-5 visualises the topography of the terrestrial part of the Forsmark regional model area together with an X-ray view of a possible 3D interpretation of the structural model presented in Section 4.6.4. It should be noted that the vertical dip and the lateral extensions of the lineaments are *highly tentative*. Thus, Figure 6-5 is merely a 3D working hypothesis, built on the version 0 structural model (cf. Figure 4-4). In Figure 6-6, the outcropping of the subhorizontal zone H2, as modelled by /Holmén and Stigsson, 2001/, has been added to the structural version 0 model. The reader is referred to Section 4.5.5 for a general discussion about the regional importance of subhorizontal zones, one of which is zone H2. The point made here is to alert the possibility that subhorizontal zones may exist at several places and depths within the model area, thus potentially connecting the system of subvertical fracture zones over a wide area.

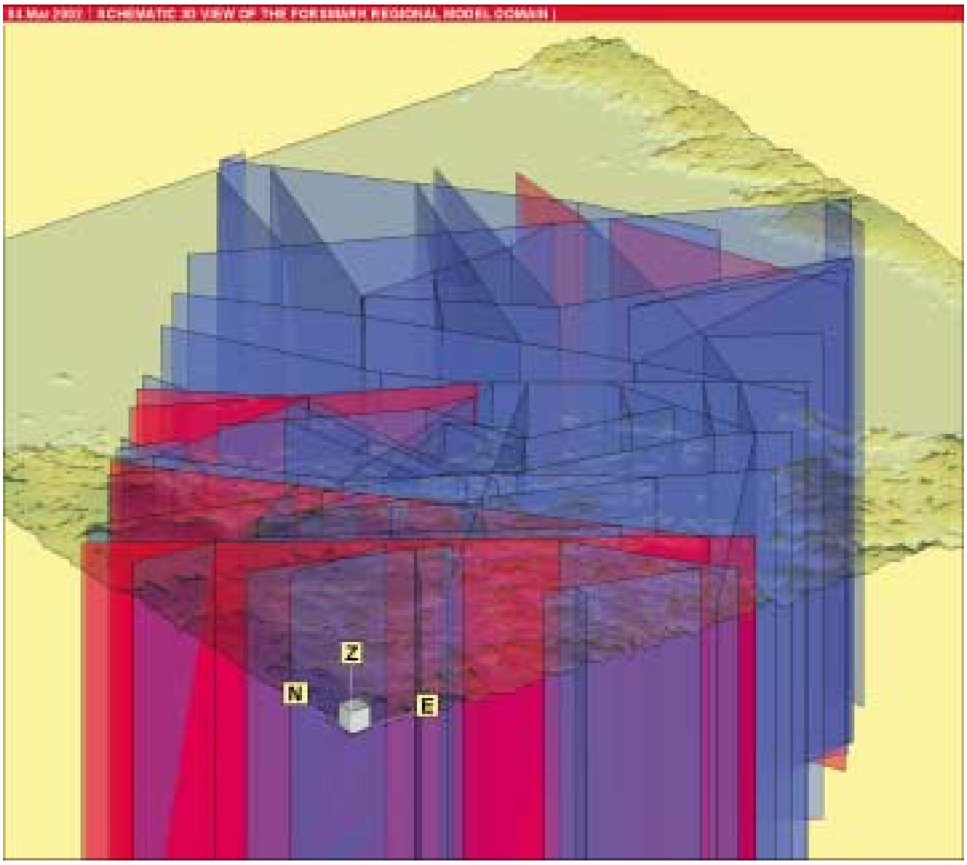

Figure 6-5. *Schematic 3D visualisation of the topography of the Forsmark regional model area together with an X-ray view of a possible 3D interpretation of the version 0 structural model. It should be noted that the blue surfaces are simply vertical extensions of the lineaments mapped at the surface. The interpretation as fracture zones is highly tentative and needs to be verified. The red surfaces represents the regional fracture zones described in Section 4.5.5. Some of these are thought to be vertical on the basis of structural data, and all are judged to reach considerable depths (at least 2 kilometres). The topography is taken from Lantmäteriverket's DEM, 50 m resolution.*

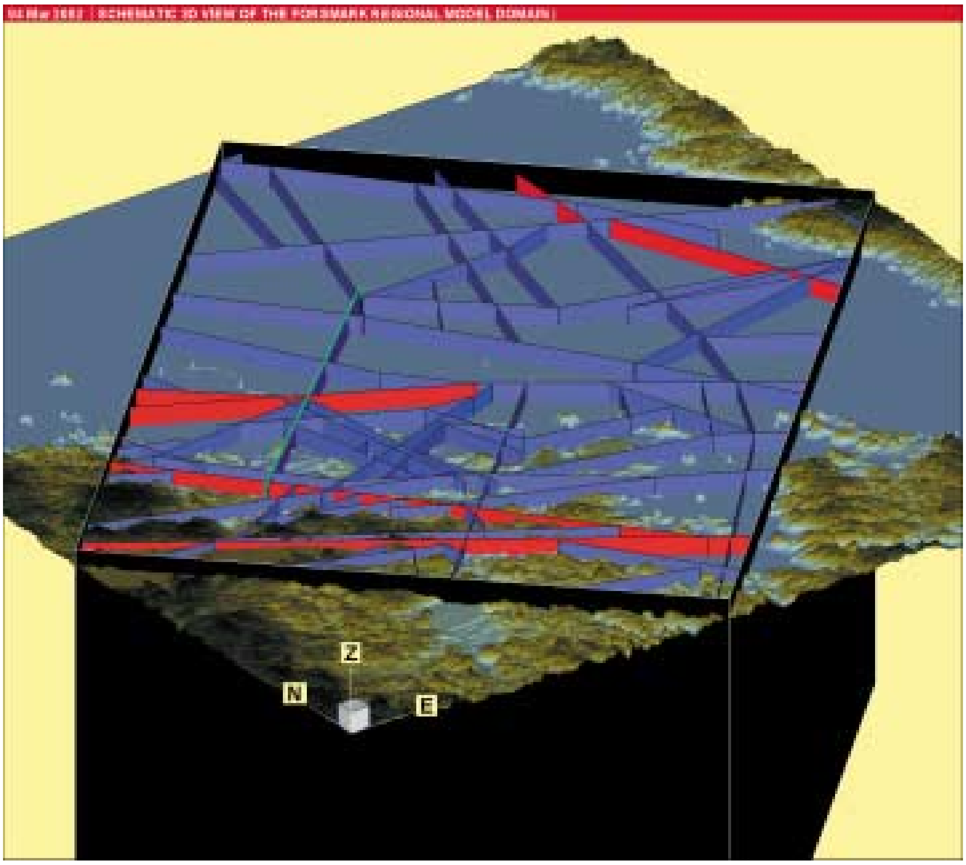

***Figure 6-6.** Schematic 3D visualisation of the topography of the Forsmark regional model area, showing the interpretation in Figure 6-5, together with the outcropping of the subhorizontal zone H2 (blue surface with green border), as modelled by /Holmén and Stigsson, 2001/. The point made here is to alert the possibility that subhorizontal zones may exist at several places and depths within the model area, thus potentially connecting the system of subvertical fracture zones over a wide area. The dip direction of zone H2 is c. 15–20° SE and its thickness is c. 3–19 metres. It should be noted that the vertical direction is exaggerated and that the dip angle of zone H2 can not be correctly visualised. The topography is taken from Lantmäteriverket's DEM, 50 m resolution. The border of the Forsmark regional model domain is indicated with a black box.*

6.4 Geometric uncertainties and scale effects

The Forsmark version 0 structural model is based on available geological and geophysical data on a fairly large scale. From a hydraulic modelling point of view, it is important to conclude whether the mapped discrete fracture network (DFN) statistics is biased in any sense. For example, /La Pointe et al, 1999/ has advocated that the scale of the mapping window censors the identification of possible fault traces (lineaments). If an identified fault trace is large with regard to the size of the utilised mapping window, the estimated length of the perceived trace line will be censored. One way to treat this problem is to increase the size of the mapping window, although the problem of censoring can never be completely avoided in this manner. Since the resolution of the chosen mapping window is coupled to the map scale, there is a risk that short fault traces will be missed (or omitted for practical reasons) if the chosen scale of the mapping window is too small. In conclusion, both the size of the mapping window and the map scale may distort the length-frequency statistics of mapped fault traces.

/La Pointe et al, 1999/ have analysed the structural geology of Swedish crystalline rock from a statistical point of view at three different places, one of which was the Finnsjön study site. According to the analyses of the trace maps reported by /Bergman et al, 1996/ (1:400,000), /Ahlbom and Tirén, 1991/ (1:87,000 and 1:20,000) and /Andersson et al, 1991/ (1:20), the length-frequency statistics of possible fault traces in the province of Uppland, and in particular in the Finnsjön study site, scales in a fractal manner over a large range of scales. Moreover, the analyses suggest that a Poisson process[1] is appropriate for generating fracture locations of the stochastic component of a discrete fracture network model of the Forsmark regional model area. Based on the length-frequency analyses of the province of Uppland and the Finnsjön study site, /La Pointe et al, 1999/ also concluded that a power law exponent of –2.7 should be diagnostic for 3D structural-hydraulic model of this region. Given this value and the size of the Forsmark regional model area it is feasible to compute preliminary estimates of the number of fracture zones of different sizes in 3D.

6.5 Hydraulic properties of bedrock

The geometric and hydraulic representation of a fracture network in a numerical flow model depends on the conceptual approach. In the discrete fracture network approach, each fracture maintains its geometric and hydraulic characteristics as inferred from the field investigations. In the continuum approach, the fractures' geometric and hydraulic properties may be implicitly accounted for by means of an equivalent hydraulic conductivity tensor. For those parts of the bedrock that are not intersected by regional or local major fracture zones, the effective hydraulic conductivity tensor represents groundwater flow through the fracture network of the rock mass between the fracture zones. Due to the large size of a regional model area, SKB's systems approach to hydrogeological modelling on a regional scale probably will entail a mixture of the two modelling approaches (see, e.g., /Follin and Svensson, 2002/).

6.5.1 Fracture zones

/Axelsson et al, 2002/ and /Axelsson and Hansen, 1997/ have summarised the results from the hydraulic testing of the fracture zones that occur in the vicinity of the SFR repository and compiled an updated structural-hydraulic model for the SFR area. It should be noted that this model is not included in the version 0 structural model shown in Figure 4-5. However, the results from the testing of the Singö fault zone are directly applicable to the version 0 fracture zones denoted ZFM0001A-2A and the lineament denoted XFM0001A, see Figure 4-5. None of the other zones or lineaments of the version 0 structural model have yet been subjected to hydraulic testing.

As previously described in Chapter 4, the Singö fault zone is complex and the width can be quite large from a geological perspective. According to /Axelsson et al, 2002/, however, the central part is more hydraulic conductive than the edges. The hydraulically active width has been estimated to c. 30 metres and the total transmissivity has been estimated to $2.4 \cdot 10^{-5}$ m^2/s /Axelsson et al, 2002/. In the study by /Holmén and Stigsson, 2001/, the geometry of all regional zones (Figure 4-8) were simplified by giving them a fixed width and transmissivity, 2 meters and $2 \cdot 10^{-5}$ m^2/s, respectively. Moreover, the storativity was set to 10^{-6} m^{-1} and the specific yield to $5 \cdot 10^{-3}$ m^2/s throughout the model domain.

[1] A Poisson process is characterised by independent and totally random events in time or space.

SFR

Figure 6-7 shows a 3D view of the SFR structural model by /Axelsson and Hansen, 1997/. Besides the Singö fault zone, the model contains the subhorizontal zone H2 and a number of local minor fracture zones, denoted 3, 6, 8 and 9. The geological characteristics of the structural model by /Axelsson and Hansen, 1997/ may be summarised as follows:

- Zone H2 is a subhorizontal fracture zone which strikes NE and dips c. 15–20 degrees towards SE. It is a complex zone of varying geological and hydraulic properties. Following the interpretation by /Axelsson and Hansen, 1997/ and subsequently /Holmén and Stigsson, 2001/, this zone occurs on both the local and the regional scale. It should be noted, however, that Zone H2 is not included in the present version 0 structural model shown in Figure 4-5.
- Zone 3 strikes NNE and has an almost vertical dip. It is a composite zone, consisting of several narrower zones and fractures, which diverge and converge, in a complex pattern.
- Zone 6 strikes NNW and has an almost vertical dip. It is for most of its extension a slightly water-bearing gouge-filled joint, occasionally with increased wall rock fracturing on one or both sides.
- Zone 8 strikes towards NW and has an almost vertical dip. It is characterised by increased jointing along the gneissic foliation of the host rock.
- Zone 9 strikes towards ENE and has an almost vertical dip. It is for most of its extension a water-bearing gouge-filled joint, occasionally with increased fracturing on one or both sides.

The transmissivity of the subhorizontal zone H2 is complex. According to the single-hole test interpretations, its geometric mean transmissivity is c. $1.7 \cdot 10^{-6}$ m^2/s. The corresponding value for the interference tests, however, is about one order of magnitude greater, c. $1.4 \cdot 10^{-5}$ m^2/s. The hydraulically active width of zone H2 is reported to vary between 3–19 metres.

The transmissivity of the local minor fracture zones 3, 6, 8 and 9 varies between $2.7 \cdot 10^{-8}$ m^2/s (zone 9) and $2.1 \cdot 10^{-5}$ m^2/s (zone 3). The hydraulic width varies between 2.5 metres (zone 6) and 40 metres (zone 8).

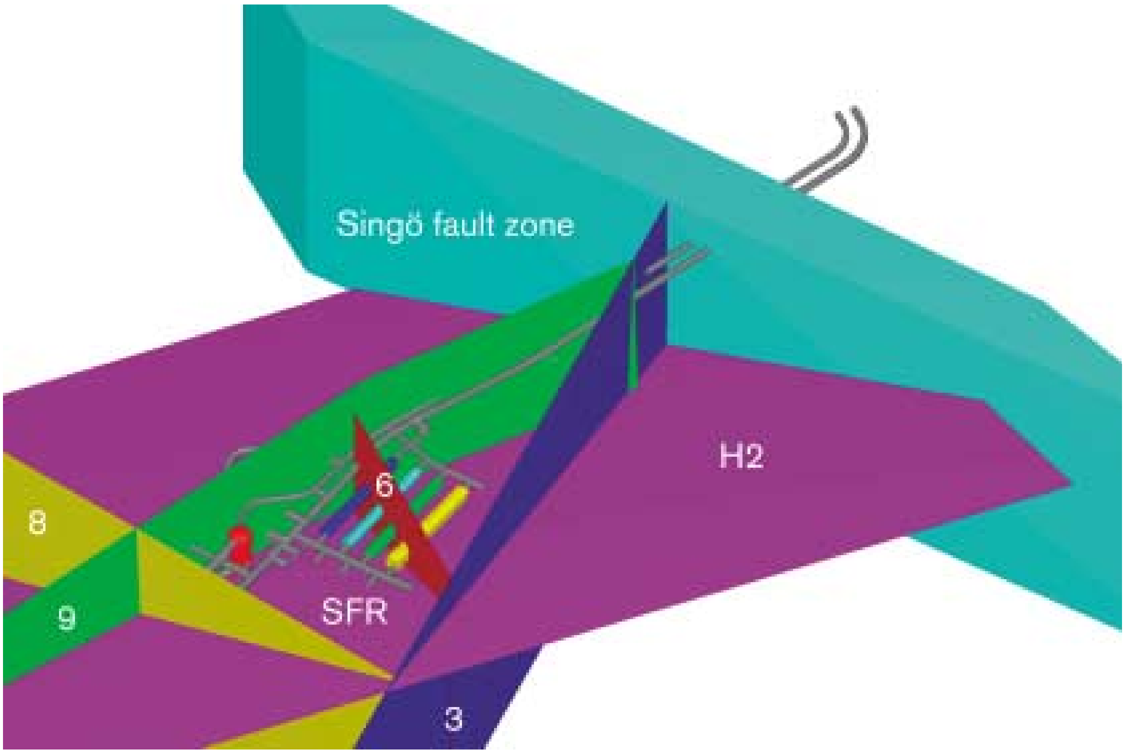

Figure 6-7. *Fracture zones of the updated local structural geological interpretation of the SFR area, and the general layout of the tunnel system at SFR. Modified after /Axelsson and Hansen, 1997/.*

Finnsjön

Figure 6-8 shows the interpreted fracture zones at the surface within the Finnsjön rock block, which represents the local scale of the Finnsjön study site. The vertical cross-section along the line A–A' is shown in Figure 6-9. The hydraulically most dominating and also the most investigated fracture zone is the subhorizontal fracture zone denoted zone 2. The interpreted width and transmissivity of zone 2 and the other tested zones within the Finnsjön rock block are compiled in Table 6-4.

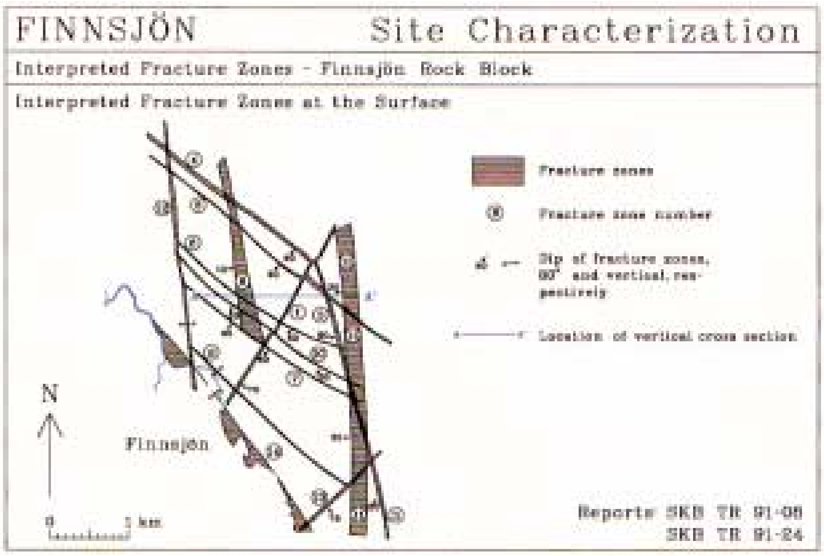

Figure 6-8. *Interpreted fracture zones at the surface within the Finnsjön rock block. Reproduced from /Ahlbom et al, 1992/.*

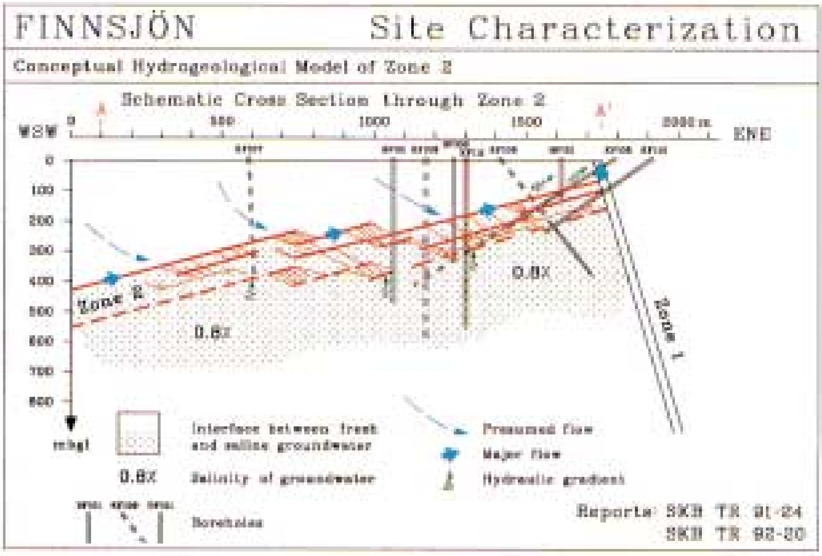

Figure 6-9. Schematic illustration of groundwater movements in and around zone 2 in the Finnsjön rock block. Reproduced from /Ahlbom et al, 1992/.

Table 6-4. Estimated average hydraulic widths and transmissivities of the tested fracture zones within the Finnsjön rock block. /Ahlbom et al, 1992/.

Fracture zone	No. of boreholes	Width (m)	Transmissivity (m^2/s)
1	1	20	$2 \cdot 10^{-4}$
2	8	100	$(2–3) \cdot 10^{-3}$
3	1	50	$1 \cdot 10^{-4}$
5	3	5	$4 \cdot 10^{-5}$
6	1	5	$3 \cdot 10^{-8}$
9	1	50	$3 \cdot 10^{-6}$
10	1	5	$3 \cdot 10^{-8}$
11	4	100	$2 \cdot 10^{-4}$

6.5.2 Rock mass between fracture zones

The derivation of the equivalent hydraulic conductivity of the rock mass between the fracture zones from field data, and its subsequent use in a regional flow model are two issues that need to be tackled with great care /Follin, 1992; Follin and Thunvik, 1994/. The reason for this concern is twofold:

- The inferred hydraulic conductivity from field tests are, among other things, dependent on the length of the test section, the duration of the testing and the heterogeneity of the fracturing.
- By definition the equivalent hydraulic conductivity of a heterogeneous medium is dependent on the direction of flow and on the resolution (discretisation) of the mesh of the flow model.

Based on the measured inflow to the SFR repository, /Holmén and Stigsson, 2001/ calibrated a local flow model surrounding the vicinity of the repository. The calibration resulted in an equivalent hydraulic conductivity of $6.5\cdot10^{-9}$ m/s for the rock mass between the deterministically modelled fracture zones (Figure 6-7). For future regional simulations of groundwater flow, the authors advocated that the effect of a coarser discretisation and the use of other boundary conditions imply that the concept of an equivalent hydraulic conductivity for the rock between the fracture zones must be revised. The reason is that, on the regional scale only the large regional zones are known outside the local model domain. Hence, the equivalent hydraulic conductivity must be upscaled in order to account for the presence of unknown, yet existing minor fracture zones. /Holmén and Stigsson, 2001/ used two different methods for the derivation of the equivalent hydraulic conductivity of the rock mass between the fracture zones on a regional scale:

- The first method utilised an assumed scale dependency similar in magnitude to that reported for the investigations at the Äspö Hard Rock Laboratory /Gustafson et al, 1989; Wikberg et al, 1991/. This approach resulted in an equivalent hydraulic conductivity of $6.5\cdot10^{-8}$ m/s for the rock mass between the fracture zones, which is one order of magnitude greater than the corresponding value on the local scale.
- The second method utilised the concept of uniform average flow, which is a common assumption in the literature for the derivation of an effective hydraulic conductivity through a statistically stationary and isotropic conductivity field /Dagan, 1979/. This approach rendered an equivalent hydraulic conductivity of $1.5\cdot10^{-8}$ m/s for the rock mass between the fracture zones, which is half an order of magnitude greater than the corresponding value on the local scale.

The issue of hydrogeological scale dependence and upscaling has also been treated in the numerical flow modelling of the Finnsjön study site. In the SKB 91 project /Andersson et al, 1991; Lindblom and Boghammar; SKB, 1992/, the hydraulic conductivity determined by 3 metre long double-packer tests were regularised to a 36 metre support scale /Norman, 1992/. The magnitude of the regularisation is shown in Figure 6-10.

A significant difference between the most recent groundwater flow studies of the SFR repository and the Finnsjön study site, i.e. /Holmén and Stigsson, 2001/ and /Hartey et al, 1998/, and the previous ones, i.e. /Carlsson et al, 1987/ and /SKB, 1992/, is that the latter studies have modelled a depth dependence in the hydraulic conductivity (Figure 6-10). However, as a result of the SR 97 hydrogeological assessment by /Walker et al, 1997/ it has been shown that a functional depth dependence in the hydraulic conductivity, of the type shown in Figure 6-10, does not exist. /Bengtsson, 1997/ and /Wladis et al, 1997/ have also studied this issue. Like /Walker et al, 1997/, these authors conclude that there are noticeable differences in the hydraulic conductivity between the uppermost 100–200 metres of rock and the rock beneath in some boreholes, but that these differences occur in discrete steps rather than as a continuous function. Based on these results, no continuous depth dependency in the hydraulic conductivity is assumed in the Forsmark hydrogeological model, version 0.

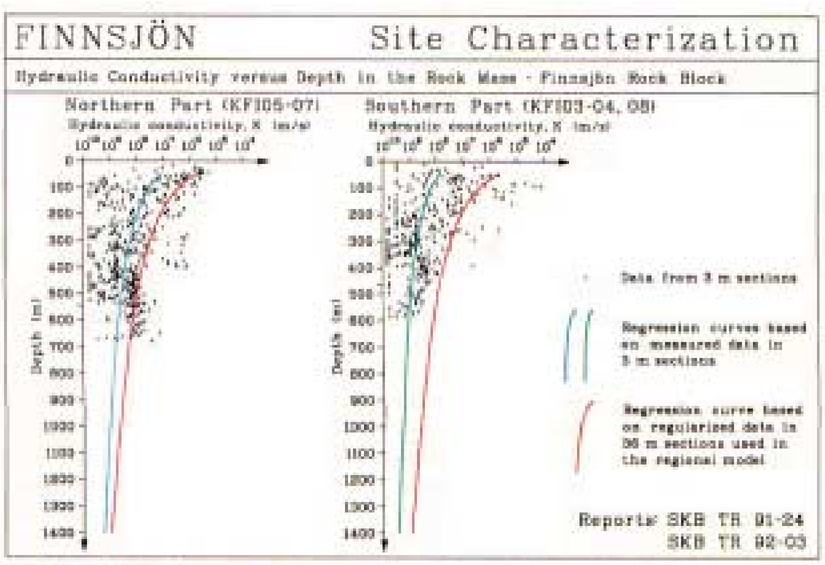

__Figure 6-10.__ Measured hydraulic conductivity from 3 metres long double-packer tests in the southern and northern parts of the Finnsjön rock block together with calculated regression curves for the presumed depth dependence. The regression curves for the upscaled conductivity data used in the groundwater modelling is also shown. Reproduced from /Ahlbom et al, 1992/.

6.6 Hydraulic properties of Quaternary deposits

6.6.1 Onshore deposits

Figure 4-2 shows a map of the version 0 interpretation of the Quaternary deposits within the regional model area. According to the data compilations provided by /Carlsson et al, 1986/, /Bergman et al, 1996/ and /Bergström, 2001/, the total thickness of the Quaternary onshore deposits varies between 0–14 meters. Current knowledge about the hydraulic conductivity and the porosity of these deposits is more or less restricted to data found in the literature. Table 6-5 shows a summary of the reported ranges in thickness together with suggested median values of the saturated hydraulic conductivity and the total porosity.

Table 6-5. Summary of the reported ranges in thickness of the Quaternary deposits /Carlsson et al, 1987; Bergman et al, 1996; Bergström, 2001/ together with estimates of the median value of the saturated hydraulic conductivity and the median value of the total porosity /Todd, 1959; Knutsson and Morfeldt, 1993/.

Quaternary deposit	Thickness[1] (m)	K_{50}[2] (m/s)	n_{50}[2] (–)
Glacial till, sandy	0.1–10	10^{-7}	0.30
Thin layers of flushed till	0.1–0.3	10^{-6}	0.20
Glacial till, clayey	0.5–2.5	10^{-9}	0.45
Glaciofluvial deposits, sand and gravel	2–14	10^{-4}	0.35
Glacial deposits, varved clay	0.5–5	10^{-10}	0.55
Post-glacial sediments, sand	0.5–2	10^{-5}	0.35
Post-glacial sediments, clay	0.2–2	10^{-9}	0.55
Post-glacial sediments, gyttja	0.2–2	10^{-9}	0.55
Post-glacial sediments, peat (moss, fen wood)	0.5–2.5	10^{-6}	0.60

[1] Data from the Forsmark regional area.

[2] General data from the literature.

6.6.2 Offshore deposits

Offshore investigations for the construction of the harbour at the Forsmark power station have revealed 2–4 metres of clay on top of 3–6 metres of glacial till /Carlsson et al, 1986/. Investigations of the seabed above SFR, which is located c. 600 m from the shoreline have revealed that the bedrock is mainly covered by 5–10 metres of a sandy glacial till. The till shows a high content of boulders and a small amount of fine-grained material /Sigurdsson, 1987/. According to /Brydsten, 1999b/ the offshore deposition of fine-grained sediments within the Forsmark regional model area has recently begun to increase as a result of the positive shore level displacement /Påsse, 1997; Brydsten, 1999a/.

The hydraulic properties of the offshore deposits in the Forsmark harbour area indicate a hydraulic conductivity of 10^{-10}–10^{-9} m/s for the clay and 10^{-8}–10^{-7} for the till /Carlsson et al, 1986/. The hydraulic conductivity of the glacial till above SFR has been estimated to be in the range 10^{-5}–10^{-8} m/s /Sigurdsson, 1987/.

6.7 Hydrological conditions and processes

The topography of the northeastern part of the province of Uppland is characterised by a gently undulating relief without major hills or valleys. The general trend of the topography in the region is c. 2–3‰ towards the Bothnian Sea. The topographic relief along the green line between A and B in Figure 6-2 is shown in Figure 6-11.

The shore level displacement in the area is significant, presently c. 6 mm/year. At 8,000 BC the shore level was c. 180 metres higher than the current shore level /Påsse,1996/. Subsequently, the province of Uppland has been covered by both freshwater stages (Baltic Ice Lake and Ancylus Lake) and seawater stages (Yoldia Sea and Litorina Sea) during the evolution of the Baltic Sea. The Litorina Sea is the most important aquatic stage for the present-day groundwater composition within the Forsmark regional model area. Between 5,200 BC – 3,200 BC, the salinity in the Litorina Sea was 12–15‰ /Westman et al, 1999/. Since then the salinity has decreased to the present-day salt concentration of the Bothnian Sea, c. 5‰.

Since c. 1,500 BC, the Forsmark regional model area has been subjected to freshwater flushing (Figure 6-11). The present-day annual mean runoff (net precipitation) is c. 240 mm/year /Brandt et al, 1994/. According to /Holmén and Stigsson, 2001/, however, only a minor portion of this amount recharges to the groundwater, c. 4–15 mm/year. The reader is referred to Table 3-1 for more detailed meteorological data.

Öregrundsgrepen is a relatively shallow part of the Bothnian Sea and the shore level displacement will greatly affect the future proportions of land and sea. /Brydsten, 1999a/ predicts that about two thousand years from today (c. 4,000 AD) half of the current area of Öregrundsgrepen will be land and the current water volume will be decreased by two thirds. Moreover, at c. 7,000 AD the entire Öregrundsgrepen will be without brackish water.

Figure 6-12 shows a map of the predicted future lakes in Forsmark regional model area during the next 10,000 years in relation to the current structural model. The number adjacent to each lake denotes the year of it´s formation (AD). Many of the interpreted fracture zones and lineaments coincide with the topographic depressions that will form lakes in the future.

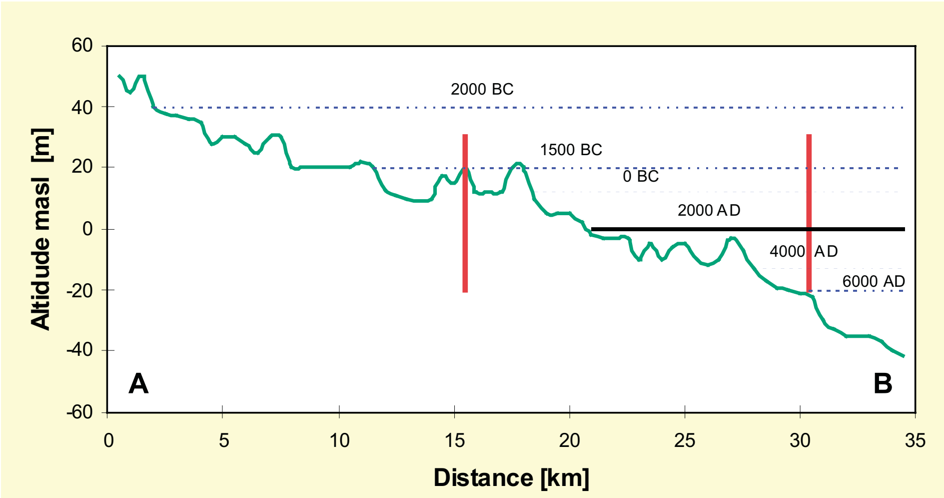

Figure 6-11. *Topographic relief along the green line between A and B in Figure 6-2. The horizontal blue lines show the sea level at c. 2,000 BC, 1,500 BC, 0 BC, 2,000 AD, 4,000 AD and 6,000 AD /Påsse, 1996/. The vertical red lines indicate the location of the upstream and downstream vertical sides of the Forsmark regional model area. Modified after /Stigsson et al, 1998/.*

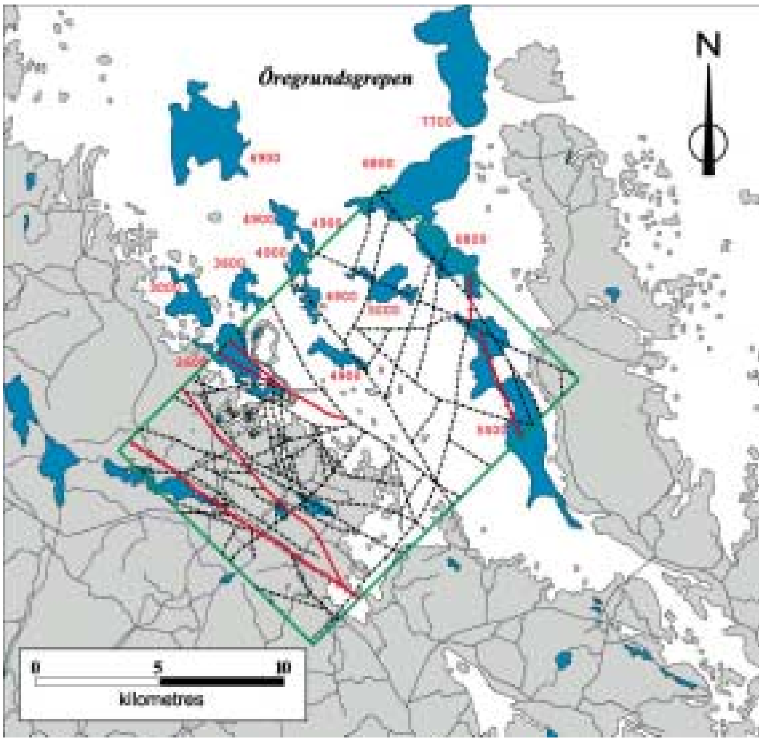

Figure 6-12. *Map showing the formation of larger lake basins in the vicinity of the Forsmark regional model area during the coming 10,000 years with regards to the version 0 structural model (Figure 4-4). The number adjacent to each lake denotes its year of formation (AD). Many of the interpreted fracture zones and lineaments coincide with topographic depressions. Modified after /Brydsten, 1999a/.*

The assessment above is considered sufficient for the version 0 definition of initial and boundary conditions required for the numerical simulation of present-day and future recharge and discharge areas of variable-density groundwater flow from repository depth (400–700 metres). Concerning the size of the regional model area, it is concluded that the upstream side of the model area is intersected by several local major to regional fracture zones, some of which are likely to reach extensive depths (Figure 6-5). The predominating strike direction of these zones is more or less orthogonal to the predominating runoff direction.

It is noteworthy that the hydraulic modelling carried out by /Holmén and Stigsson, 2001/ considered most of the hydrodynamics described above, including transient boundary conditions. However, the objective of their study was to focus on the future hydrogeological conditions of the SFR repository. As a result of the shallow depth of the repository (c. 60 m below the seabed), the authors did not consider variable-density flow. Furthermore, the authors treated the Quaternary deposits in a simplistic way (as part of the fractured rock).

Concerning the hydraulic interplay between surface water and groundwater, it has been recognised that the resolution of the current digital elevation model is probably insufficient for a detailed characterisation of the often diffuse inflow and outflow through the mires that surround the small and shallow lakes /Brunberg and Blomqvist, 1998/. In addition to a high resolution elevation model, it is also important to improve the understanding of the hydraulic interplay between the small and shallow freshwater lakes on top of the Quaternary deposits and the more brackish groundwater within and beneath these deposits /Bergström, 2001; Widén et al, 2001/. Of particular importance is the hydraulic characterisation of the post-glacial deposit gyttja.

7 Hydrogeochemistry

7.1 Introduction

A site's hydrogeochemical state is described by means of various parameters. The parameters detail the *chemical properties* of the groundwater in the Quaternary deposits and in the crystalline bedrock, and the *hydrogeochemical processes* that govern the chemical interplay between surface water and groundwater, including groundwater flow at repository depth. In /SKB, 2001/, hydrogeochemical evaluation should include the following tasks:

- Characterisation of the undisturbed groundwater chemistry including the origin, depth/lateral distribution and the turnover time.
- Emphasised characterisation of those chemistry-related features of the groundwater which are of importance for the safety evaluation, such as pH, Eh, chloride, sulphide, colloids and microbes.
- Identification of possible dissolved oxygen at repository depth.

Currently, SKB is developing standard procedures for the hydrogeochemical modelling to be used to attain these goals. This chapter describes the present knowledge and uncertainties of the hydrogeochemical setting of the Forsmark regional model area, as documented in the literature and SKB's report series.

7.2 Sources of information

The present knowledge of the hydrogeochemical setting of the Forsmark regional model area is based on three different types/sources of information. The three sources are: (*i*) investigations of surface water and near-surface groundwater, e.g. sampling of water in lakes, sea, watercourses, springs, wells, percussion-drilled boreholes and observation holes, (*ii*) investigations and monitoring in deep boreholes, e.g. water and fracture-fill mineral investigations in core-drilled boreholes, and (*iii*) hydrogeochemical interpretation, analysis and modelling.

7.2.1 Surface water investigations

The Forsmark regional model area has a high percentage of wetlands compared to the province of Uppland in general. The wetlands are characterised by calcareous post-glacial clay, which is a prerequisite for the high amount of rich- and extreme rich-fens in the area.

According to /Brunberg and Blomqvist, 2000/, three main types of lake ecosystems could be identified in the Forsmark regional model area:

1. *The oligotrophic hardwater lakes* are to a large extent surrounded by mires. Inflow as well as outflow of water is often diffuse, via the surrounding mire. The lakes are small and shallow with nutrient poor and highly alkaline water, but dominate the Forsmark catchment /Brunberg and Blomqvist, 1999/.

2. *The brownwater lakes* are typically found within the main part of the river Forsmarksån and are characterised by a high flow-through of water from the upper parts of the drainage area, which are dominated by mires. Their lake water is highly stained by allochtonous organic carbon imported from the catchment area.

3. *The deep eutrophic lakes* are characterised by a limited drainage area, a large lake volume and a slow turnover time of the water.

The hydrogeochemistry of the dominating hardwater lakes has been presented earlier in this report (Section 3.6.2).

No data or published reports have been found on the chemistry of the precipitation gathered at the meteorological station at the Forsmark power plant.

7.2.2 Shallow groundwater investigations

The current knowledge of the hydrogeochemistry of the near-surface groundwater in the Forsmark regional model area comes from an evaluation of water samples in shallow groundwater wells. SKB's version of the Archive of Wells contains information about the following chemical parameters: Electrical conductivity, pH, Cl, HCO_3, SO_4, NH_4, NO_2, NO_3, F, PO_4, Fe, Mn and aggressive CO_2

Archive of Wells at SGU

Out of a total of c. 1,500 wells in the municipality of Östhammar which are recorded in the Archive of Wells at the Geological Survey of Sweden, only nine wells are located within the Forsmark regional model area. However, due to the similarities with regard to geological conditions and hydrogeological evolution, the spatial variations of the hydrogeochemical composition of the near-surface groundwater in northern Uppland are believed to be of great interest for the site-descriptive modelling of the Forsmark regional model area. An overview of the spatial variations of different chemical constituents is found in /Aastrup et al, 1995/. The overview confirms the impact of the hydrogeological evolution of northern Uppland on the groundwater composition. That is, the wells are drilled/dug in a coastal system of aquifers covered by calcareous glacial till, post-glacial clay and fen wood peat.

Well inventory

A well inventory was conducted by SKB in the *central part* of the Forsmark regional model area during 2001. The inventory encompassed 25 private wells and 15 water-prospecting drillholes. Twelve of the 25 private wells are dug wells. The results of the inventory are reported by /Ludvigson, 2002/. In addition to the type of well (dug/drilled/soil/bedrock), the inventory data comprise well coordinates, total depth and water chemistry. The water samples have been analysed according to Swedish drinking water standard, which by and large coincides with SKB's chemical Class 3 /SKB, 2001/. Figure 7-1 shows the location of the private wells and the water prospecting drillholes that were positioned with a handheld GPS receiver during the inventory.

Figures 7-2 and 7-3 show plots that exemplify the encountered chemical and microbiological composition of the groundwater in the 25 private wells. These figures confirm the impact of the aforementioned post-glacial evolution of northern Uppland on the groundwater composition. The quality of the hydrogeochemical data reported from the well inventory is considered high as far as the sampling methods, handling, shipping and analysis techniques are concerned.

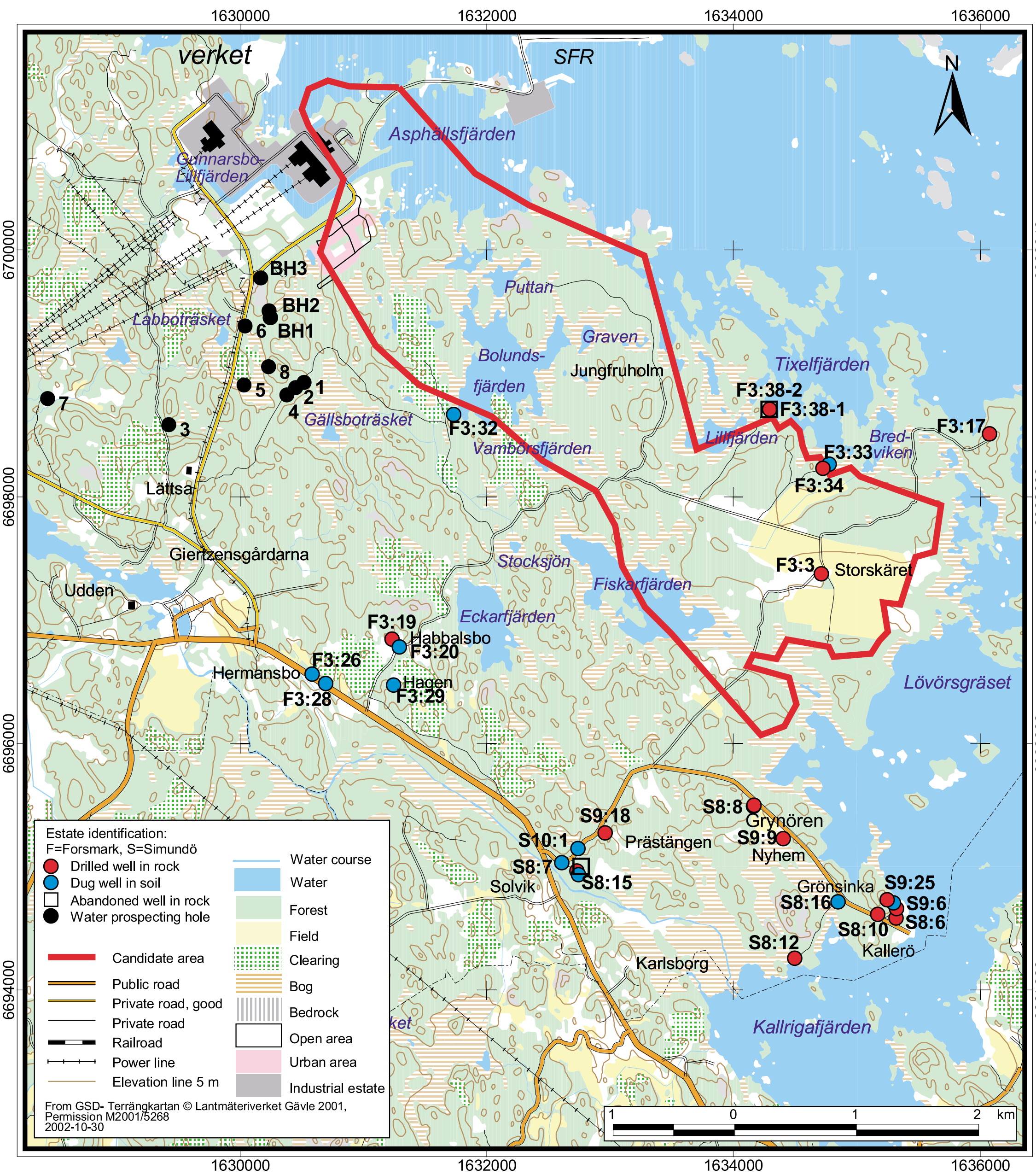

Figure 7-1. *Map showing the location of the private wells and the water prospecting drillholes that were positioned with a handheld GPS receiver during the inventory. Blue circles indicate dug wells in the Quaternary deposits and red circles indicate drilled wells in the bedrock. Black circles indicate old and new water prospecting drillholes. /Ludvigson, 2002/.*

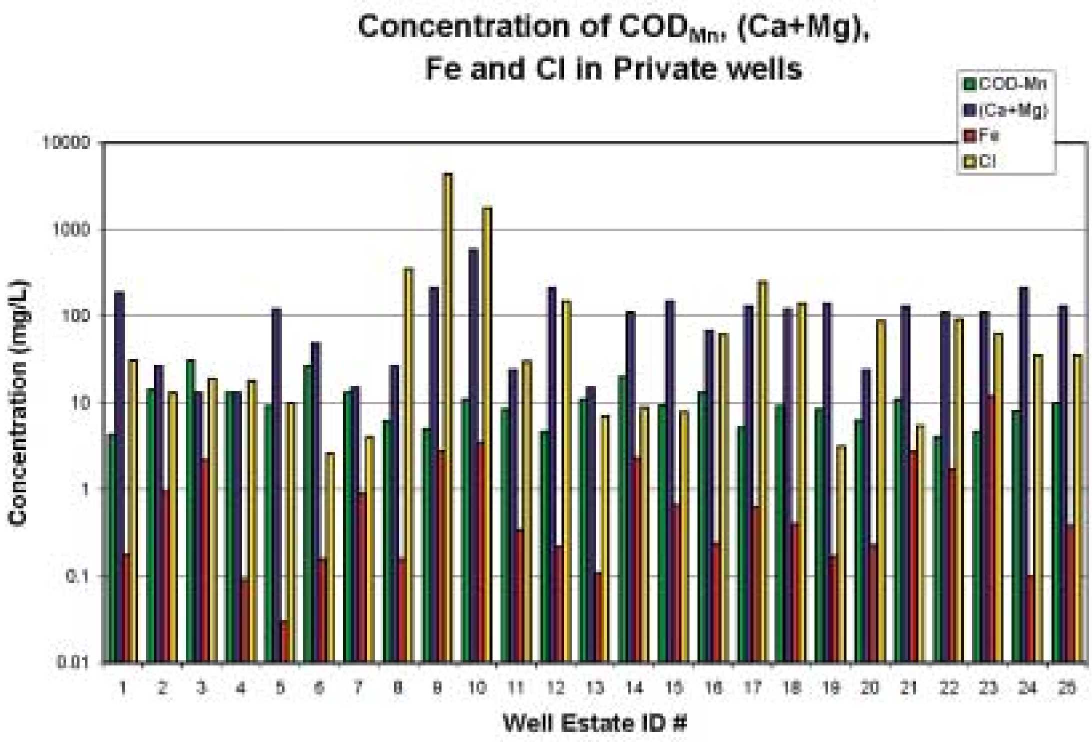

Figure 7-2. *A plot showing concentrations of COD$_{Mn}$, (Ca+Mg), Fe and Cl in the 25 private wells investigated during the well inventory /Ludvigson, 2002/.*

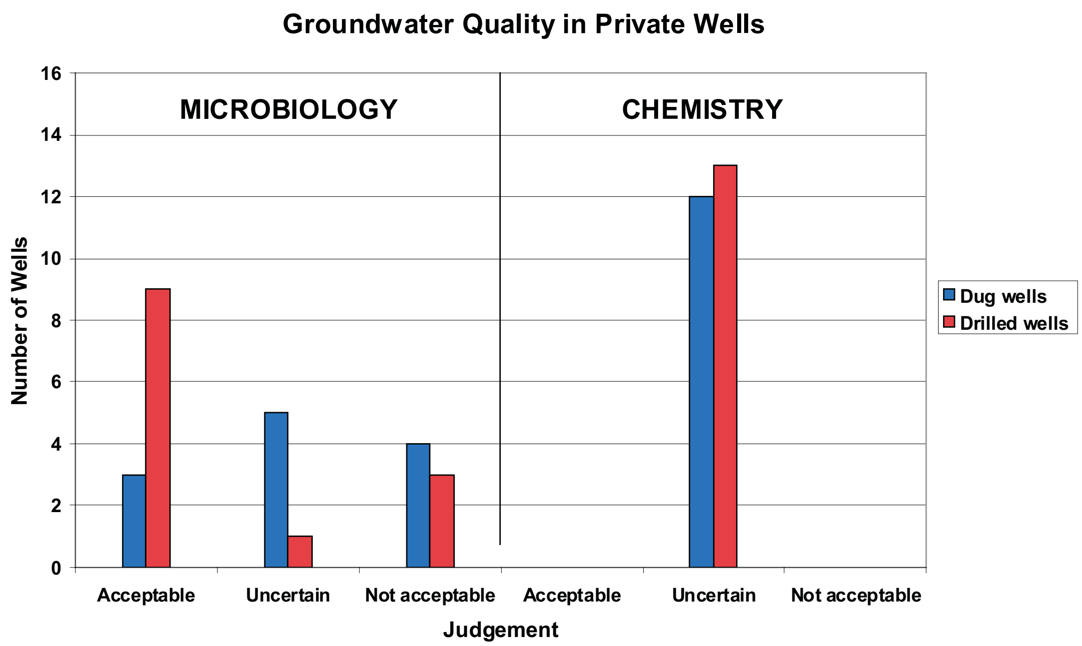

Figure 7-3. *A plot showing a classification of the encountered microbiological and chemical drinking water quality in the 25 private wells investigated during the well inventory. Qualifiers are given in relation to Swedish drinking water standard. Blue bars indicate dug wells in the Quaternary deposits and red bars indicate drilled wells in the bedrock. /Ludvigson, 2002/.*

7.2.3 Deep groundwater and fracture-fill mineral investigations

There are currently no deep water samples taken within the Forsmark regional model area. The deepest existing records within the area come from the moderately deep water samples (25–167 meters) collected in the core-drilled boreholes at the SFR repository.

The composition of the groundwater at SFR has been monitored on a regular basis since 1989. /SKB, 1990/. The monitoring programme measures inflows to the different rock caverns, and the water chemistry and the piezometric pressure in sealed-off sections at predetermined time intervals. A complete compilation of all data collected since 1989 is given in /Nilsson, 2002/. A comparison between the hydrogeochemical composition of the Baltic Sea and the sampled water from boreholes in SFR /see Wikberg, 1986; Laurent, 1991; Follin et al, 1996/ confirms the interpretation that the groundwater composition in the Forsmark regional model area is in a transitional state. The sampled water from boreholes at SFR indicates a limited hydraulic contact with the Baltic Sea. That is, the chemical composition of the groundwater below the Baltic Sea shows a strong impact of the saline intrusion associated with the previous Litorina Sea.

Table 7-1 shows an overview of the hydrogeochemical investigations carried out at SFR. A printout of the activity log reveals c. 325 records of hydrogeochemical data from c. 20 boreholes.

The quality of the monitoring programme may be considered sufficiently high as far as the sampling methods, handling and analysis techniques are concerned. The data are reported on an annual basis to SKI.

Table 7-1. Overview of the hydrogeochemical activities at SFR recorded in SICADA (as of 2001-01-11).

References	Methods and parameters	Period
SKB/SICADA	Microbiology	2000–Present
SKB/SICADA	CHEMAC measurement	1986–Present
SKB/SICADA	Sampling, dissolved gas	2000–Present
SKB/SICADA	Sampling of particulate matter	1987–1987
SKB/SICADA	Water sampling, class 2	1992–1992
SKB/SICADA	Water sampling, class 3	1989–Present
SKB/SICADA	Water sampling, class 4	1989–Present
SKB/SICADA	Water sampling, mixed classes	1984–1987
SKB/SICADA	Water sampling series	2000–Present

Concerning fracture-fill minerals and the hydrogeochemical interaction between these minerals and the groundwater, a discussion of the geochemical associations between the deep groundwater and the fracture-fill minerals in the nearby Finnsjön study site is found in /Tullborg and Larson, 1982/. According to the site description and inter-comparison between seven bedrock sites in Fennoscandia compiled by /Puigdomenech, 2001/, it may be expected that the dominant fracture minerals in the Forsmark regional model area are: epidote, calcite, phrenite, haematite, laumontite, chlorite, amorph. Fe^{2+} oxy-hydrox. precip., pyrite, kaolinite and clay. Moreover, according to the same author the expected dominant hydrogeochemical processes are:

- Inorganic redox reactions
- Silicate hydrolysis
- Calcite precipitation/dilution
- Ion exchange
- Methanogenesis
- Microbal sulphate reduction

Chlorite is a common fracture-fill mineral in all fracture sets analysed in tunnels excavated in the SFR and Forsmark areas /Carlsson and Christiansson, 1987/. Laumontite, calcite, quartz and other phyllosilicate minerals, besides chlorite, are also present.

7.2.4 Hydrogeochemical interpretation, analysis and modelling

Although there is currently little or no data from the Forsmark regional model area to support a detailed hydrogeochemical site descriptive model, all known post-glacial events in Fennoscandia are also believed to have affected the groundwater composition in Forsmark. Hence, the major post-glacial stages, all of which have been identified at the Äspö, Finnsjön, Gideå, Hästholmen and Olkiluoto sites (Figure 7-4, cf. /Puigdomenech, 2001/), are considered relevant for the hydrogeochemical evolution of the Forsmark area:

1. The continental ice melted and retreated and glacial melt water flushed the bedrock (> 13,000 BP). At large depths (> 800 m) glacial melt water was mixed with ancient brine groundwater in the bedrock. A saline groundwater with a glacial signature was formed at the interface. Fresh glacial water was present in the upper part of the bedrock.

2. The flushing on the mainland started directly after the deglaciation commenced. However, since the sites were below the prevailing sea level, the post-glacial marine water stages of the Baltic Sea, i.e., the Yoldia Sea and the Litorina Sea, affected the groundwater composition. The continuous shoreline displacement has elevated the site to its present-day altitude above the sea level. The increasing hydraulic flushing has created a mixture of existing groundwater types, i.e., glacial, brine, marine and meteoric groundwater.

The conceptual model describing these events is shown in Figure 7-5. The uncertainty of the conceptual model increases with modelled time. The largest uncertainties are therefore associated with the stage showing the flushing of glacial melt water. The driving mechanism behind the flow lines in Figure 7-5, the shore level displacement, is previously reviewed in Section 6.7.

/Laaksoharju et al, 1995/ and /Laaksoharju and Skårman, 1995/ have subjected the complex groundwater evolution in Figure 7-5 to an extensive analysis and developed a chemical calculation model, where the origin and evolution of a groundwater sample can be described. The calculation model consists of three steps; principal component analysis, mixing calculations and mass balance calculations. Figure 7-6 shows the result of applying the principal component analysis (PCA) method to borehole data from Äspö, Finnsjön and Gideå. The location of the Forsmark regional model area in this context is not shown in Figure 7-6, but may be estimated from the location of the data points from the Olkiluoto and Hästholmen sites in Figure 7-7, which is a PCA plot for all sites shown in Figure 7-4.

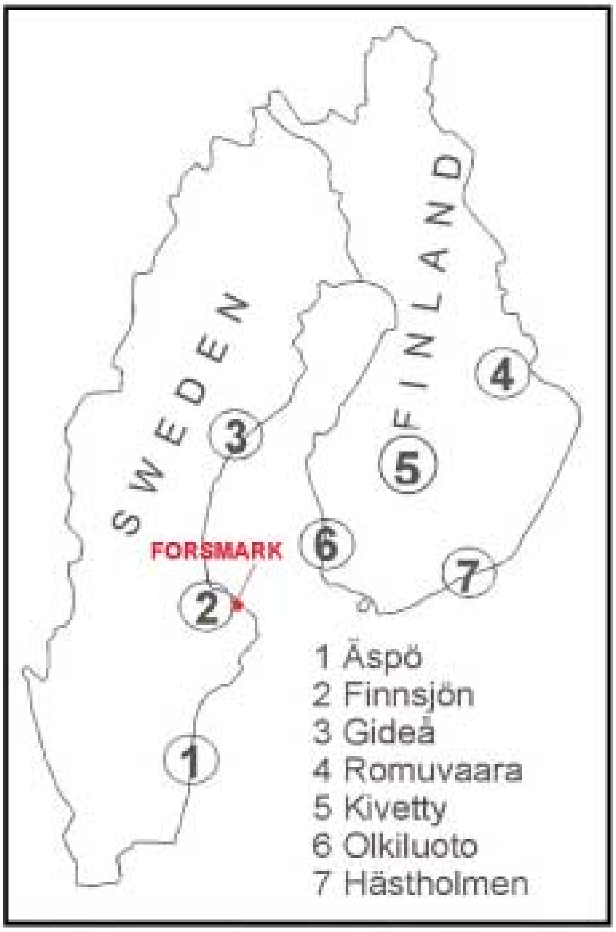

Figure 7-4. *Map showing the location of the seven hydrogeochemically evaluated sites in Finland and Sweden. Modified after /Puigdomenech, 2001/.*

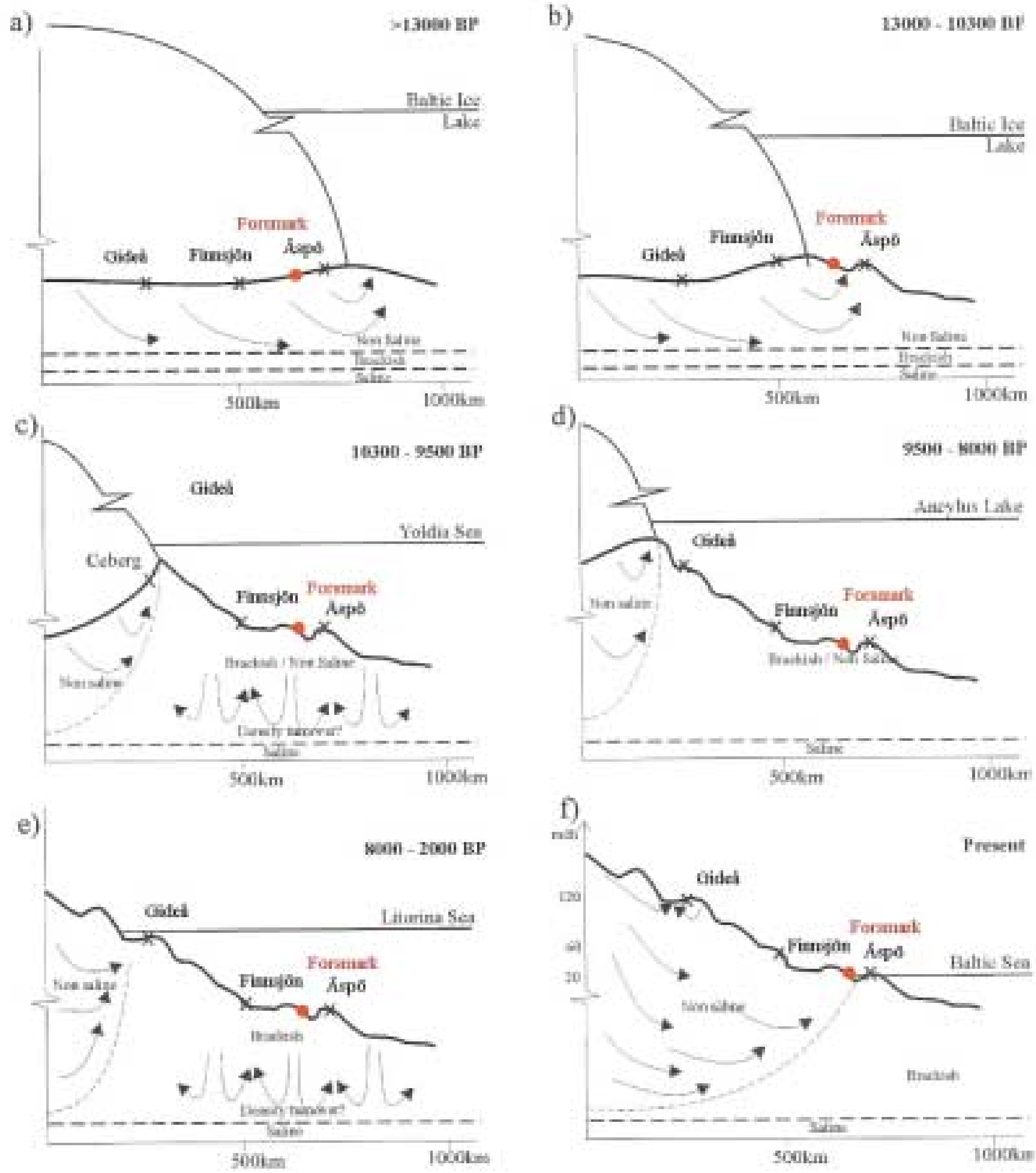

Figure 7-5. *A conceptual post-glacial scenario showing the hydrogeochemical evolution of the Äspö, Finnsjön, Gideå and Forsmark sites (for locations in relation to the Baltic Sea, see the map in Figure 7-4). The known post-glacial stages are: a) Injection of glacial melt water into the basement, b) Baltic Ice Lake, c) Yoldia Sea, d) Ancylus Lake, e) Litorina Sea, and f) Baltic Sea. The figures show possible flow lines, density driven turnover, non-saline, brackish and saline water interfaces. Modified after /Laaksoharju, 1999/.*

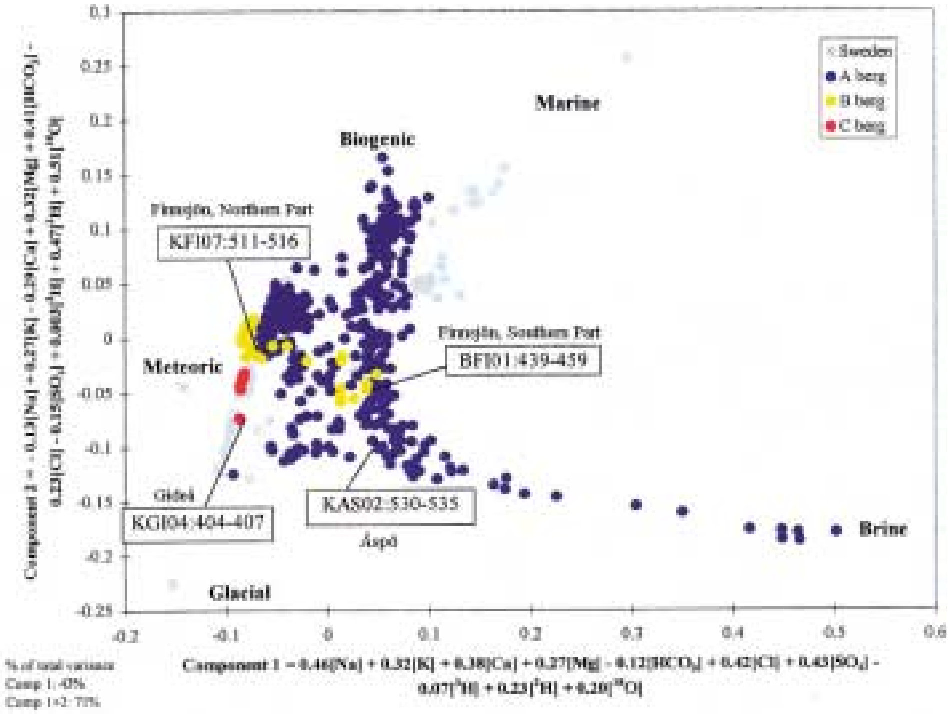

__Figure 7-6.__ PCA-plot based on the major components, stable isotopes and tritium values from the SKB's study sites compared to data from Äspö (Aberg), Finnsjön (Bberg) and Gideå (Cberg). Reference water samples at 500 ±100 meters depth from the three sites are indicated. Modified after /Laaksoharju et al, 1998/.

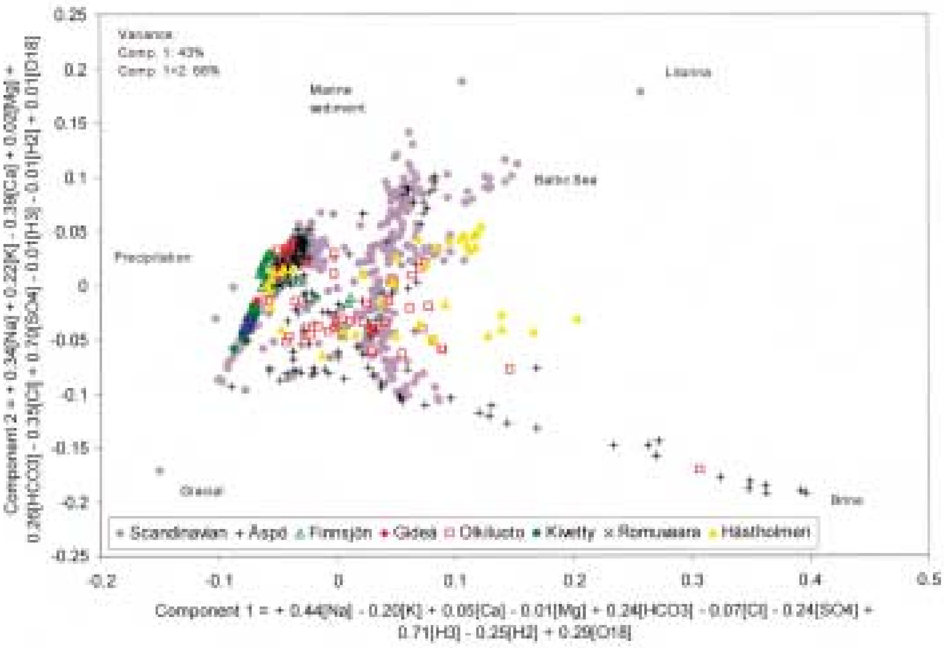

__Figure 7-7.__ PCA-plot based on the major components, stable isotopes and tritium values from the sites shown in Figure 7-4. The location of the Forsmark regional model area may be estimated from the location of data points from the Olkiluoto and Hästholmen sites which are approxemately equally close to thr Baltic Sea. Reproduced from /Puigdomenech, 2001/.

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Appendix 1

Geology – data extraction from SKB GIS 5.0

Quaternary geology

Data input from SKB GIS 5.0

Catalogue	File name	Type	SKB report/figure	Geographic application
New delivery SGU to SKB 2001-10-12	New delivery SGU to SKB 2001-10-12	Area	Bergman et al, 1999c/5-1	Whole regional model area

"Parameters" /SKB, 2001b/ addressed in the version 0, regional site descriptive model under section entitled, "Quaternary geology" and chapter entitled, "Ecosystems"

"Parameter group"	"Parameter"	
Soil cover	Thickness of soil cover	x
	Soil distribution	x
	Soil description	x
	Soil type	x
	Bottom sediment	x
	Indication of neotectonics	x

Bedrock – rock type and potential for ore deposits

Data input from SKB GIS 5.0

Catalogue	File name	Type	SKB report/figure	Geographic application
\fs_tierp\sgu\sgu_kartor\	berggrundsytor_r99_53fig6_1	Area	Bergman et al, 1999c/6-1	Whole regional model area
\fs_osthammar\mirab\	malmgeo	Area	Lindroos, 1996/7	Whole regional model area
\fs_tierp\sgu\sgu_kartor\	amfibolitgang_r99_53fig6_1	Point	Bergman et al, 1999c/6-1	Whole regional model area
\fs_tierp\sgu\sgu_kartor\	granit_pegmatitgangar_r99_53fig6_1	Point	Bergman et al, 1999c/6-1	Whole regional model area
\fs_tierp\sgu\sgu_kartor\	inneslutningar_r99_53fig6_1	Point	Bergman et al, 1999c/6-1	Whole regional model area
\fs_osthammar\mirab\	malmp_p	Point	Lindroos, 1996/8	Whole regional model area
\fs_osthammar\mirab\	min_fynd	Point	Lindroos, 1996/7	Whole regional model area

“Parameters” /SKB, 2001b/ addressed in the version 0, regional site descriptive model under section entitled, “Bedrock – rock type and potential for ore deposits”

“Parameter group”	“Parameter”	
Bedrock – rock type and potential for ore deposits. Occurring rock types	Rock type distribution (spatial and percentage)	x
	Xenoliths	x
	Dykes	x
	Contacts	
	Age	x
	Ore potential	x
Bedrock – rock type and potential for ore deposits. Rock type description	Mineralogical composition	x
	Grain size	x
	Mineral orientation	
	Microfractures	
	Density	
	Porosity	
	Susceptibility, gamma radiation etc	
	Mineralogical alteration/weathering	

Bedrock – structure

Data input from SKB GIS 5.0

Catalogue	File name	Type	SKB report/figure	Geographic application
\fs_tierp\sgu\sgu_kartor\	plastisk_skjuvzon_r99_53fig8_4	Area	Bergman et al, 1999c/8-4	Whole regional model area
\fs_tierp\sgu\sgu_kartor\	formlinj_magnkonn_r99_53fig8_4	Line	Bergman et al, 1999c/8-4	Whole regional model area
\fs_tierp\sgu\sgu_kartor\	sprickzon_r99_53fig8_4	Line	Bergman et al, 1999c/8-4	Regional model area south of 6695000
\fs_osthammar\sgu\sgu_kartor\shape\	struktursymboler_r00_24fig1	Point	Stephens and Isaksson, 2000/1	1629000–1638000/6695000–6705000
\fs_tierp\sgu\sgu_kartor\	forskiffring_r99_53fig6_1	Point	Bergman et al, 1999c/6-1	Regional model area outside 1629000–1638000/6695000–6705000
\fs_tierp\sgu\sgu_kartor\	forskiffring_vertikal_r99_53fig6_1	Point	Bergman et al, 1999c/6-1	Regional model area outside 1629000–1638000/6695000–6705000

Complementary data not previously submitted to SKB in digital format

Catalogue	File name (SGU)	Type	SKB report/figure	Geographic application
	sprickzoner_r98_57_del2_fig2	Line	Isaksson, 1998/2	Regional model area north of 6695000
	ortoline_ver0_forsmark	Line	None prior to version 0 project	Area close to Bolundsfjärden
	symbol_breccia_mylonit_forsmark	Point	Revised version after feasibility study	Whole regional model area

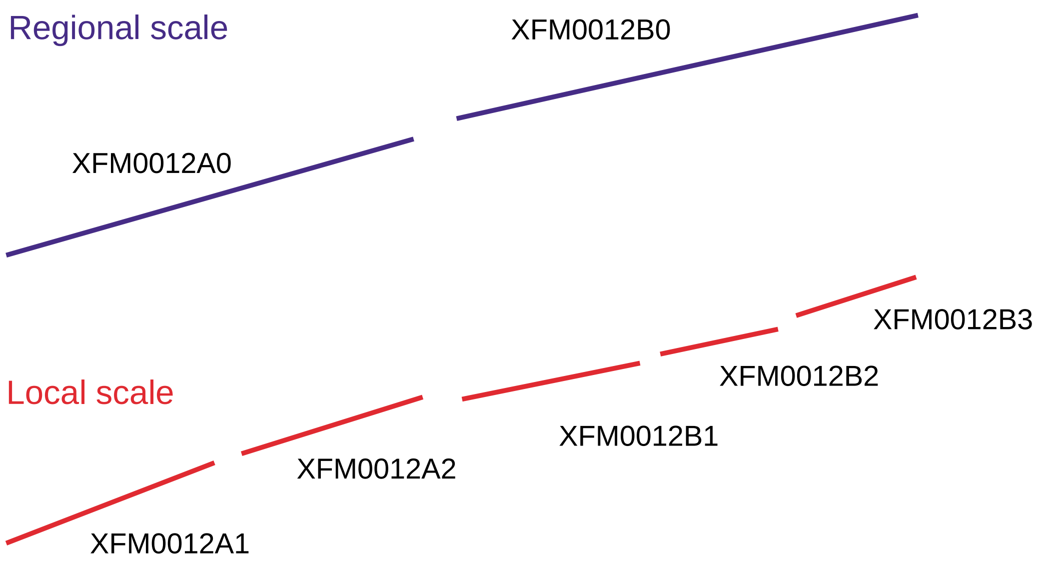
"Parameters" /SKB, 2001b/ addressed in the version 0, regional site descriptive model under section entitled, "Bedrock – structure"

"Parameter group"	"Parameter"	
Bedrock – structure. Ductile structures	Folding (geometry)	x
	Foliation	x
	Lineation	x
	Veining	
Bedrock – structure. Ductile high-strain zones	Age	x
	Extent	x
	Properties	
Bedrock – structure. Local major and regional fracture zones	Location	x
	Orientation	x
	Length	x
	Width	x
	Movements (size, direction)	x
	Age	x
	Properties	

Denomination of lineaments and deformation zones

Lineaments and deformation zones are denominated according to the scheme **ABBCCCCDE**, where

A	=	Type of object; X for lineament, Z for deformation zone (including fracture zone)
BB	=	Area; FM for Forsmark and SM for Simpevarp
CCCC	=	Numeration of object; 0001–9999
D	=	Regional segment of object; A–Z
E	=	Local segment of object; 1–9 (E=0 for regional segments)



XFM0012A0, B0	Regional segments of lineament XFM0012
XFM0012A1, A2	Local segments of regional segment (XFM0012A0) of lineament XFM0012
XFM0012B1, B2, B3	Local segments of regional segment (XFM0012B0) of lineament XFM0012