R-05-14

Forsmark site investigation

Programme for further investigations of geosphere and biosphere

Svensk Kärnbränslehantering AB

January 2005

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Photos: Göran Hansson, Alf Linderheim, Alf Sevastik, SKB.

Preface

Since the beginning of 2002, SKB, Svensk Kärnbränslehantering AB (the Swedish Nuclear Fuel and Waste Management Co) has been conducting a site investigation in Forsmark in the municipality of Östhammar for siting of the deep repository for spent nuclear fuel. An equivalent investigation is also being conducted at Simpevarp and Laxemar in Oskarshamn Municipality. SKB's goal is to submit an application under the Environmental Code and the Nuclear Activities Act for siting of the deep repository at one of these sites by the end of 2008/beginning of 2009. When the application is submitted, everything of importance for the deep repository's safety, constructability and environmental impact shall have been investigated and analyzed. The investigations shall also provide data as a basis for selecting a site and configuring the facility to suit conditions on the site.

SKB submitted a programme for the initial site investigation in Forsmark at the end of 2001. The investigations described there have now been completed. This report describes the programme that has now been prepared for the remainder of the site investigation. The points of departure are the general goals for the Deep Repository Project during the site investigation phase, the data needed for evaluation of the site, plus experience and results from the work to date. The programme has been prepared with the support of investigation data as of August 2004.

The investigations described here will, as before, be conducted with great consideration given to residents, property owners and natural and cultural values so that they are not unnecessarily exposed to impact or disturbances. Just as before, the programme will be continuously adapted to the knowledge that is gradually accumulated on the site. All important changes will be reported to the authorities and other concerned parties.

Kaj Ahlbom
Site Manager Forsmark

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Summary

SKB submitted a programme for the initial part of the site investigation in Forsmark at the end of 2001. The investigations described there have now been completed. This report presents the programme that has now been compiled for the remainder of the site investigation. The points of departure are the general goals for the Deep Repository Project during the site investigation phase, experience and results from the work to date, and the data needed for evaluation of the site and siting alternatives for the deep repository. The account mainly covers the investigations on the site. All other work – analyses, facility design, safety assessments and studies and assessments of consequences for the environment, human health and society – are only mentioned to the extent necessary in order to place the investigations in their context.

Goal

The overall goal of the site investigation phase is to obtain the permits required to site and build the deep repository. The site investigations must therefore provide the data required for an evaluation of the suitability of the investigated sites for a deep repository. The material must accordingly be comprehensive enough to:

- Show whether the selected site satisfies fundamental safety requirements.
- Show whether the construction-related prerequisites are met.
- Serve as a basis for adapting the deep repository to the conditions and features on the site.
- Permit an assessment of the impact of the deep repository on the environment and society.
- Permit comparisons between the two investigated sites.

The site

Figure 1 provides an overview of the Forsmark area with environs. After the feasibility study that preceded the site investigation, SKB designated the area marked in red southeast of the Forsmark Nuclear Power Plant, known as the candidate area, as having priority for a site investigation. The blue and green squares in the figure show the boundaries defined for the local and regional models that SKB works with when processing data from the site investigation.

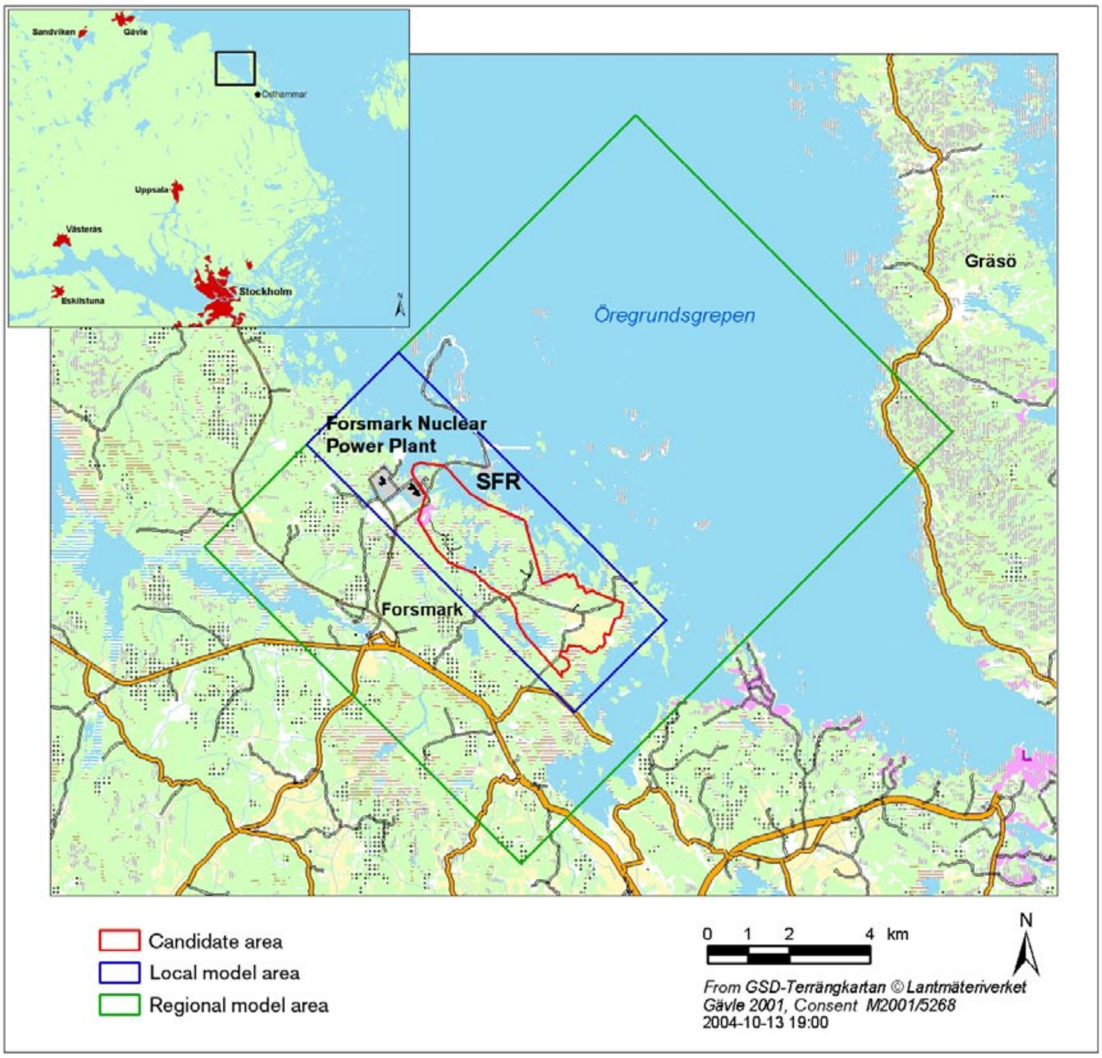


Figure 1. Forsmark area with environs.

State of knowledge

The investigations that have been conducted (as of August 2004) and their results can be summarized in the following points:

- The surface characterization of the geological and ecological conditions in the area has largely been completed.
- In order to investigate the bedrock at depth, five deep (1,000 m) and two shallower cored boreholes have been drilled and documented. Drilling of a sixth deep cored borehole is under way.
- 19 percussion boreholes have been drilled, partly to supply core drilling with flushing water and partly to investigate the bedrock.
- A comprehensive, preliminary site description (version 1.1) has been published. The work of compiling all information from the initial site investigation is under way and will result in version 1.2 of the site description.
- The consultation process for a possible deep repository in Forsmark has been established in accordance with the provisions of the Environmental Code.

- An active information and communication programme has been established for ongoing dialogue with nearby residents, the public, Östhammar Municipality, neighbouring municipalities and other local stakeholders.

Figure 2 illustrates the current situation (August 2004) for drilling. Core drilling has been done from six specially established drilling sites. A number of percussion boreholes have also been drilled in different directions around these sites. In addition there are percussion boreholes on several more sites plus some sixty-odd soil boreholes.

Cross-check against fundamental requirements

Prior to the site investigation phase, SKB presented fundamental requirements whose fulfilment had to be demonstrated in order for a site to be considered for the deep repository. Conversely, if one or more requirements are not met, the site has to be regarded as being disqualified.

During the initial part of the site investigation, the aim has been to gather data which – directly or indirectly – provides a basis for deciding whether the requirements can be considered to be met, and thereby whether further investigations are warranted. There is then reason to evaluate the current state of knowledge in relation to the stipulated basic requirements. The remaining data needs for each of the requirements are briefly summarized below.

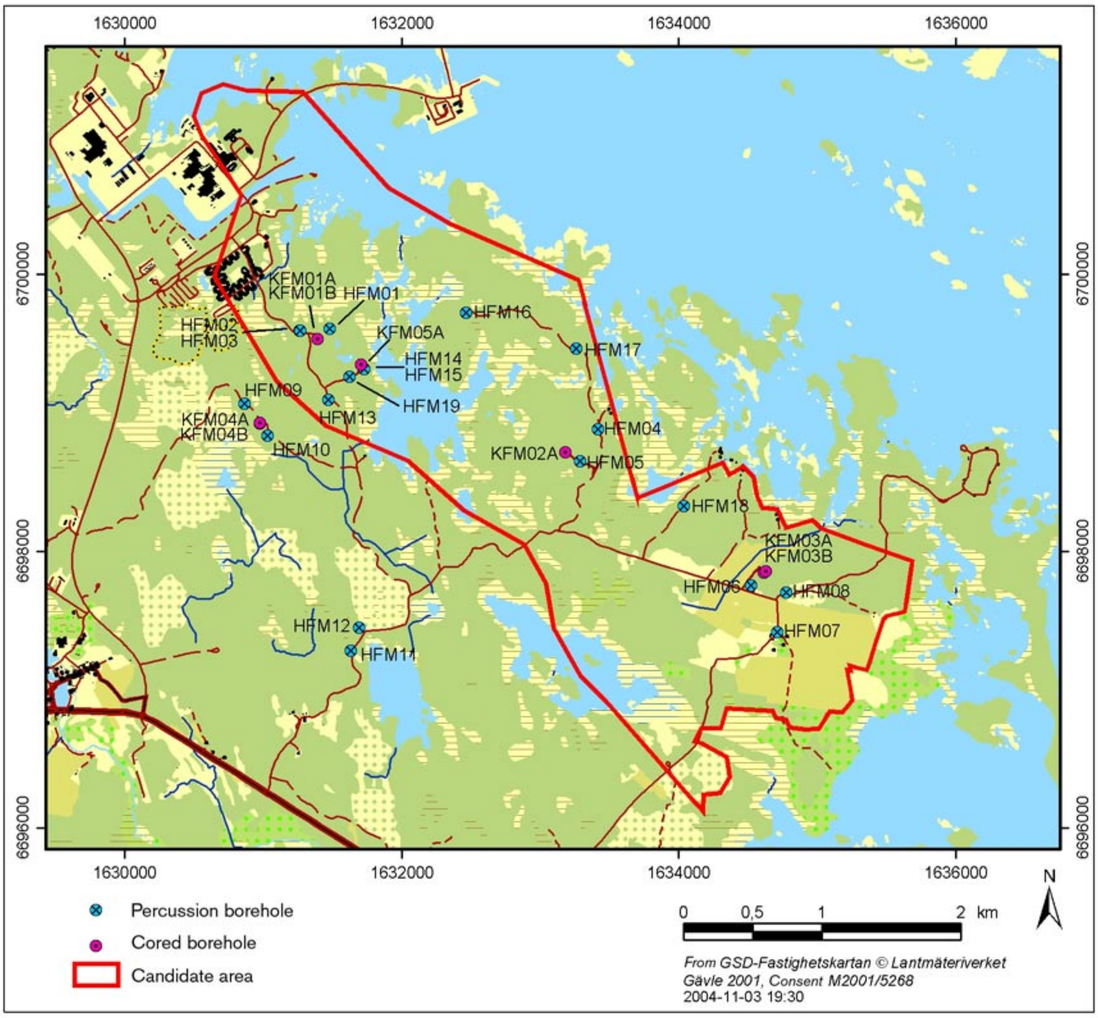


***Figure 2.** Investigation area with all cored and percussion boreholes drilled during the initial part of the site investigation.*

Basic geoscientific requirements – remaining data needs

- **Regional ductile shear zones shall be avoided**

  The requirement is met, but in order to better be able to describe the hydrogeological and hydrochemical conditions in the area, new knowledge is needed about the presumed function of the surrounding regional deformation zones as hydraulic boundary conditions for the site.

- **No ore potential**

  The requirement is judged to be met and no additional data are needed. The issue will nevertheless be followed up in conjunction with future drilling.

- **A repository must be able to be emplaced and given a technically reasonable layout within the available rock volume**

  Three factors determine whether the requirement can be satisfied:

  1) The vertical extent and shape of the tectonic lens
  The tectonic lens is judged to provide enough space for a repository. However, there is not yet sufficient knowledge for facility configuration. In particular, knowledge is lacking regarding the geological boundaries on the area's northwest end and northeast side.

  2) Individual fracture zones at repository level
  No unexpected conditions have been found, but the properties and importance of interpreted fracture zones need to be clarified better. The same applies to the importance at depth of interpreted but not yet verified lineaments (indications on the ground surface of possible fracture zones). Possible, not yet discovered fracture zones within the repository volume similarly constitute a remaining uncertainty.

  3) Rock properties within deposition areas
  Major fractures, water flow rate: The boreholes consistently show low fracture frequency and water flow rate at repository depth. However, more detailed data are needed, especially in the northwestern part of the area.

  Thermal conductivity: The results indicate conditions that are normal for granitic bedrock. Additional data are needed, in particular regarding scale dependence and the possible importance of thermal anisotropy.

- **No extensive instability in deposition tunnels/holes**

  The characterization of the stress state, including vertical and lateral variations, is incomplete and will be given priority in further investigations. Data on mechanical properties are constantly being supplemented.

- **No dissolved oxygen in groundwater at repository level**

  Even though the requirement is now considered to be satisfied, further measurements will be carried out.

- **Salinity (TDS) of groundwater at repository level lower than 100 g/l**

  The salinity increases from fresh water near the ground surface to 8 g/l at a depth of 150 m. After that the salinity is constant to about 600 m. Below this depth an increase occurs. At most, 13 g/l has been measured at a depth of 980 m. In the northwestern part of the candidate area, data are lacking below a depth of 200 m. Every opportunity for performing chemical investigations at greater depths must therefore be taken advantage of.

In SKB's view, the above summary provides a good foundation for continuing the site investigation in Forsmark. It is highly unlikely that further investigations could alter SKB's judgement that the site satisfies the fundamental requirements. The remaining data need is mainly attributable to the fact that more data are needed for both facility design and safety assessments.

In general it can be said that the investigations so far have revealed some clearly distinctive features as regards fracture situation and water flow. The average fracture frequency in the near-surface bedrock is normal for Swedish crystalline bedrock. Sections with distinct, usually gently-dipping, highly conductive fractures are encountered down to a depth of about 200 metres. This pattern seems to exist throughout the tectonic lens. High water flow rate in gently-dipping fractures near the surface can be positive from a repository viewpoint, since the groundwater flux at deeper levels is then limited, but may require special measures in connection with tunnelling and shaft sinking.

At greater depths, below 200–300 m, the bedrock in the candidate area is distinguished by low fracture frequency and low water flow rate. With isolated exceptions, the few water-conducting fractures encountered at repository depth and below are associated with interpreted gently-dipping fracture zones, especially in the southeastern part of the candidate area. The preference that most of the rock mass between fracture zones should have a permeability lower than 10^{-8} m/s thus appears to be satisfied with good margin.

Industrial establishment

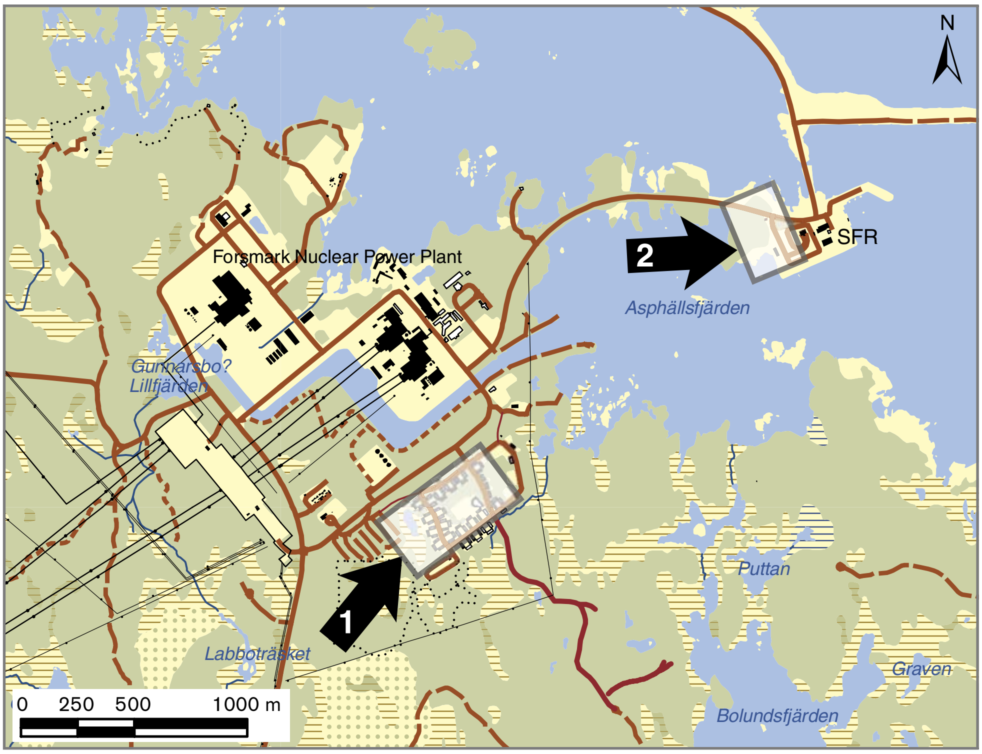
Design, which includes the work on a site-adapted configuration of a deep repository in Forsmark, is being pursued in parallel with the site investigation. The data gathered thus far confirm that the technical and environmental prerequisites for establishment are met, which, along with the availability of potentially suitable bedrock, was the main reason Forsmark was chosen as a siting alternative. Possible locations and layouts of above-ground facilities required by the deep repository were studied in the initial phase. Figure 3 illustrates the two alternative solutions that have been sketched. In the one case, the deep repository's surface facilities are located south of the Forsmark Nuclear Power Plant. In the other case the complex is instead sited on partially filled-in land adjacent to the SFR facility (SFR = Final repository for radioactive operational waste). The alternatives do not entail any essential difference for the deep repository's underground facilities – which in both cases are assumed to be situated in the northwestern part of the candidate area – but are based on partially different system solutions. The intention is, at a later stage, to prioritize one of the alternatives for complete design.

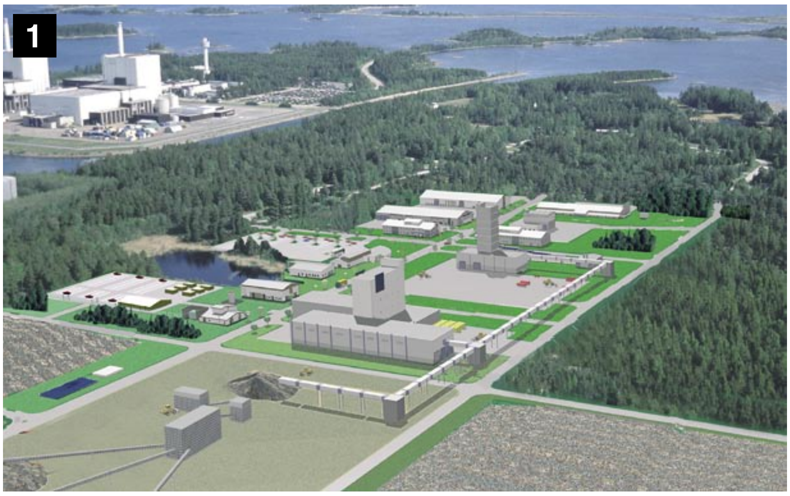
Strategy

Taking into account the results obtained so far and the goals and requirements presented for the site investigation, a strategy in four points has been arrived at for the remainder of the site investigation in Forsmark:

1. Choose the northwestern part of the investigation area as a priority site. By "priority site" is meant the area that is of particular interest for the repository and on which further investigations will be focused.
2. Determine, for the priority site, the geological boundaries of the available rock volume at repository depth.
3. Characterize the available rock volume on this site to the required extent and level of detail.
4. Characterize the priority site's hydraulic boundary areas.

The deep repository's facilities can be placed along the road out to SFR. Some fill is needed along the shores since space is limited. Heavy shipments to and from the deep repository would go via an inclined tunnel whose entrance is to the right of the building in the middle. SFR and the harbour are furthest away in the picture.





Land for the deep repository's facilities is available from the entrance to the Forsmark plant (the present roundabout) eastward towards the barraks village. The need for temporary housing must then be solved in some other way. Nearest in the picture is a proposed stockpile for rock spoil that is hoisted via a shaft that discharges underneath the tall, narrow building. Further away is a shaft for a passenger elevator and ventilation

Figure 3. *Alternative locations for the deep repository's above-ground facilities – south of the Forsmark Nuclear Power Plant or at SFR.*

The reasons for this strategy are presented below point for point, along with a general discussion of what investigations may be necessary to implement the strategy.

1) Choose the northwestern part of the area as a priority site.

The candidate area can be divided into a northwestern and a southeastern part, situated on either side of the interpreted relatively thick fracture zone (zone A2) which intersects the area at repository depth at the level of drilling site 2. Both the northwestern and the southeastern part are judged to have bedrock that warrants further investigations. The difference noted is a higher frequency of gently-dipping, permeable fracture zones in the southeastern part. The technical and environmental advantages of a location in the northwest are obvious: nearness to existing industrial facilities, roads, etc. Layout studies and underlying investigation results indicate a high probability that a deep repository can be accommodated within the northwestern part. In view of this, SKB chooses the northwestern part of the candidate area as the priority site.

The strategy of focusing on the northwestern part of the tectonic lens has advantages, but is also associated with risks. The advantages include good prospects of achieving the goals of the site investigation with a reasonable input of resources and within the allotted time frame. The obvious risk is that the properties of the relatively limited rock volume that is investigated will not live up to expectations. If this should happen, a modified strategy will be required, with consequences in terms of both time and resources.

2) Determine, for the priority site, the geological boundaries of the available rock volume at repository depth.

The boundaries of the tectonic lens in the northwestern part are only partially known today. There is therefore reason to continue the survey of the boundaries of the rock volume suitable for a deep repository that has been initiated with the completed or ongoing drilling work. Another question with a bearing on the available volume is the location and properties of the gently-dipping fracture zone (A2) that borders the priority site on the southeast.

3) Characterize the available rock volume to the required extent and level of detail.

The main tasks when it comes to characterizing the rock on the priority site are to clarify the properties and importance of already interpreted fracture zones at repository level, as well as the presence and importance of additional, as yet unknown zones. This includes examining the geological equivalents of interpreted lineaments and their importance at repository depth. Other main tasks are continued characterization of rock stress conditions and groundwater chemistry at depth and of hydraulic connections in the horizontal and vertical directions, measurements of natural groundwater flow and tracer tests.

If the drilling indicates sufficient volumes of good rock on the priority site, the design of descents and the deep repository's central area will be pursued further, based on the current, preliminary placement of the central area. Boreholes are needed to obtain the requisite engineering geology data in the form of rock stresses, rock quality and groundwater conditions in locations for descents and the central area. The design of the deep repository's surface facilities will also require certain investigations of soil and foundation conditions.

4) Characterize the priority site's hydraulic boundary areas.

The hydraulic and hydrogeochemical models of the site that are constructed as a basis for the safety assessment require boundary conditions in the form of hydraulic properties of bounding structures. A fundamental question is whether the water-conducting zones that intersect the tectonic lens more or less transversely end against the dominant deformation zones that bound the lens along its long sides, i.e. the Singö Fault in the northeast and the Forsmark and Eckarfjärd zones in the southwest. This is tentatively judged to be the case, but it is also conceivable that the transverse zones cross the longitudinal ones, at least in a hydraulic sense. A special drilling and investigation programme is required to shed light on this question.

In view of the region's generally flat topography and the dominant role which the aforementioned hydraulic margins are deemed to have, it is difficult to see what additional investigations on a regional scale could add from a hydrogeological or hydrogeochemical viewpoint. For this reason, no drilling is planned at greater distances from the site.

Programme

Figure 4 shows the main features of the work plan that has been devised based on the strategy presented above.

According to the plans, all core drilling on the priority site will be completed in 2005. What will then be missing is data from investigations that require undisturbed conditions. These will be done in 2006. The results are primarily of importance for the safety assessment. The focus in 2006 will be on characterization of the site's hydraulic boundary areas. Any supplementary work will also be done then.

2004	2005	2006	2007	2008
Focus on priority site		Focus on hydraulic boundary areas	Finish site investigation by mid-year	Waiting position
Conclude characterization on the surface	Finish drilling within priority site	Finish all drilling in hydraulic boundary areas	Conclude all field investigations	Surveillance monitoring
	Data freeze 2.1 Data for cross-checking of investigation programme	**Data freeze 2.2** Data for facility design	**Data freeze 2.3** All data from site investigation	
		Possible supplementary investigation		Site selection, application

Figure 4. *Work plan for the site investigation.*

Drilling

Based on the chosen strategy, a drilling programme has been prepared. The programme is detailed for the first cored boreholes, after which it is necessarily more preliminary. It includes deep (700–1,000 m), medium-deep (200–700 m) and short (100–200 m) cored boreholes. The map in Figure 5 illustrates the programme with markings on a simplified geological map. Existing cored boreholes have also been marked. The exact directions and depths of the holes are often determined by the results obtained along the way.

The majority of the planned boreholes will be documented and investigated with geological, geophysical and hydrogeological methods in roughly the same way as so far. Hydrogeochemical sampling at depth will be given particular priority to compensate for the current shortage of data for hydrogeochemical characterization of the site. Rock mechanical investigations, in particular rock stress measurements, will also be accorded great attention in view of the fact that stress conditions have been identified as an incompletely resolved, site-specific key issue.

Percussion boreholes reach a maximum depth of about 300 metres and do not yield a core, but are much faster and less expensive to drill than the cored holes. Besides supplying the cored boreholes with flushing water, they are suitable for investigating the importance of interpreted lineaments and for investigating near-surface, gently-dipping fracture zones. It is tentatively estimated that 10–15 percussion boreholes are needed, with a concentration to the priority site and the hydraulic margins.

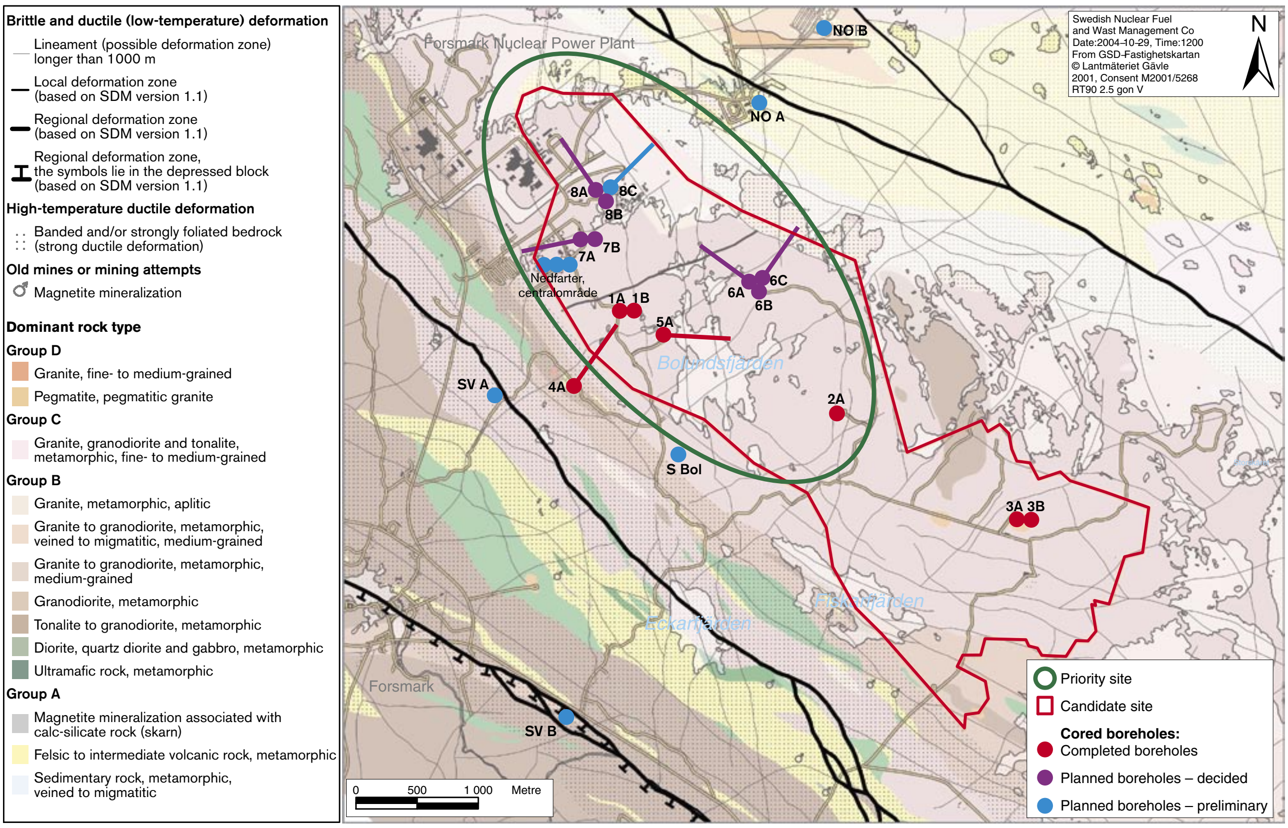


Figure 5. Existing cored boreholes and planned core drilling during the remainder of the site investigation.

Surface ecosystems

The remainder of the site investigation will focus mainly on process measurements, in other words quantification of the most important ecosystem functions. The process measurements include surveying of primary production, consumption and decomposition, which are measured by respiration, transport of water or other substances, for example via plant transpiration and immobilization of substances. Quantification of the ecosystem functions is as important as characterization of the different subcomponents biomass and range.

What happens in the boundary area between biosphere and geosphere is of great importance for an understanding of how the deep and superficial groundwater interact. A number of important processes that control what happens with radionuclides in this zone remain to be explored. These include fluctuations in the groundwater table as well as permeability and the variation of sorption properties with depth.

Another issue that needs to be explored is the hydrology of the wetlands in the Forsmark area. These ecosystems may be important recipients in the event of a leakage of radionuclides from the deep repository. They may also be affected by a lowering of the groundwater table.

Geology

Bedrock

The main purpose of the planned drilling programme is to geologically define and characterize the rock volume on the priority site, as well as surrounding hydraulic boundary areas. In addition, the investigations that have been conducted have given rise to questions that warrant a number of special studies.

Our understanding of the formation of the brittle deformation zones in Forsmark and their patterns of movement needs to be improved to enable models with higher certainty to be developed. Kinematic analysis of representative brittle deformation zones that have been verified both on the surface and at depth in boreholes therefore needs to be done.

Interpreted lineaments need to be investigated with respect to how representative they are as indicators of deformation zones. A lineament study is therefore planned during the autumn of 2004, where the intention is to dig pits across a number of representative and distinct lineaments for detailed study of the rock surface. In addition, a percussion drilling campaign will be carried out during the autumn of 2005.

A supplementary geochronological investigation is planned for the purpose of arriving at a better chronological picture of the geological evolution of Forsmark under the temperature conditions when the brittle deformation zones were formed. This will provide important data as a basis for establishing the timescale for the oldest movements and the relative direction of movement along the deformation zones between the blocks.

Supplementary bedrock geological mapping in the area southeast of Kallrigafjärden and in the northwestern part of Forsmark's tectonic lens is needed in order to confirm and gain a better understanding of the geometry of the large-scale folding in this part of the area. This study is of importance for the three-dimensional modelling of the rock domains in the Forsmark area.

Further, a detailed fracture mapping is planned to be done, if possible, in the area northwest of the fracture zone A2. The reason is that the fracture mapping that was done on drilling sites 2, 3, 4 and 5, as well as at Klubbudden, is not representative of the rock volume where the investigations will now be focused. The detailed mapping will serve as a basis for the discrete fracture network (DFN) model.

Finally, there is a need for a special study of the pretectonic alteration that has affected both the granite in the northwestern part of the candidate volume and the fine-grained granitic rocks in the adjacent rock domain in the northwest.

Overburden

Most of the Quaternary geological work within the site investigation has been done. What remains is to fill the geographic gaps and to answer certain key questions of importance for input data and boundary conditions for modelling of the surface ecosystems.

The Quaternary deposits on the bottom of sea areas with a water depth of more than 3 m have not yet been surveyed, but a mapping is planned. This will provide a complete Quaternary deposit map that includes both land and sea areas, and that will serve as an important basis for modelling of the future landscape.

One of the important tasks will be to construct a three-dimensional soil layer model that shows both depth to rock and the different soil layers. The results will constitute an important basis for the surface hydrology modelling as well as for the modelling of transport pathways for radionuclides. The soil layer model will be based on both data from drilling and excavation and results from ground-penetrating radar surveys, seismic and other geophysical surveys.

Work is under way on a shoreline displacement curve for Forsmark. The curve presents the water depth at Forsmark, from 10,000 years before present up to 10,000 years in the future. It will serve as a basis for modelling future land areas where new lakes will be isolated from the sea, and gradually silt up to form peatlands.

The central questions surrounding the area's postglacial geological evolution, on land and at sea, have to do with the evolution of climate and vegetation, as well as sedimentation and erosion. This can be studied in sediment and peat cores. Pollen analyses of marine sediment and/or peat profiles are needed to describe the evolution of the regional area's postglacial vegetation. The results can provide information on climate variations and vegetation succession over a long period of time. Sedimentation rates for the different Quaternary deposits will also be determined, and the erosive phases in marine and lake sediments, as well as peat sequences, will be dated. The marine environment can be studied in a sediment core that was taken in connection with the marine geological investigations in 2002. A key question that can then be answered is whether the Yoldia Sea, a predecessor to the Baltic Sea, was affected by brackish water in the Forsmark area. This is important information for defining the boundary conditions in the hydrogeological and hydrogeochemical modelling.

Questions relating to the glacial transport of rock material and the dynamics of the ice are important for our conceptual understanding of the site. Mapping of rock types in the large blocks encountered near the Börstilåsen esker can provide information on transport pathways.

Geophysics

As before, the geophysical investigations will serve as support for the geological site description. Issues where geophysics is expected to make valuable contributions are:

- Verification of lineaments, particularly whether they can be linked to steeply-dipping fracture zones.
- Soil depth determinations.
- Determinations of the location and geometry of fracture zones.
- Vertical extent of quartz-poor rock types.

The following investigations (among others) are planned for the priority site:

- Conventional borehole geophysical logging in the same manner as to date in the newly drilled boreholes.
- Supplementary ground geophysical surveys on the priority site, primarily seismic refraction and ground-penetrating radar (GPR). This permits determinations of soil depth and P-wave velocities in rock.
- Vertical Seismic Profiling (VSP surveys), where boreholes are also used for a more detailed determination of the three-dimensional geometry and orientation of fracture zones.

In addition, supplementary seismic reflection surveys are planned, which also include the environs and interpreted margins of the priority site. Finally, the possibilities of modelling rock volumes on the basis of gravimetric data will be studied. This can contribute valuable knowledge about the quartz-poor rock types west and south of the priority site.

Rock mechanics and thermal properties

In the geological environment that characterizes the investigated formation in Forsmark, with relatively high rock stresses and fracture-poor rock, it is important to be able to make reliable predictions of the stability conditions in a possible deep repository. This is particularly true if there is a risk of splitting of intact rock nearest deposition tunnels or deposition holes. To make such predictions, knowledge is needed of prevailing rock stresses and the strength properties of the rock. It is therefore necessary to obtain more detailed data on these parameters.

The most important issue is rock stresses and their possible consequences for stability and rock support needs. In-depth and more detailed knowledge is needed about the sum of the stresses in particular, including their distribution vertically and laterally. This requires further measurements, concentrating on the part of the area that has priority for further investigations.

For the strength properties of the rock, further knowledge is needed about the conditions within the priority area and at probable facility depth in order to confirm the current, more general picture and obtain more detailed data for the prediction work.

As far as thermal properties are concerned, measurements on drill cores in the manner performed to date provide expected and consistent data. The questions concern how these data are to be extrapolated to a scale that is relevant for the deep repository, and taking into account the directional dependence that has been observed for thermal conductivity. Better knowledge is needed on this point. Relatively simple field tests on outcrops in the area are planned for this.

Hydrogeology

The hydrogeological programme includes meteorology, hydrology and hydrogeology in soil layers and bedrock. There is a close link to the programmes for surface ecosystems and hydrogeochemistry.

One of the most important remaining tasks is to further clarify the hydraulic contacts between surface water, soil groundwater and rock groundwater in the investigation area. Lakes and wetlands can in principle be assumed to comprise discharge areas. However, the measurements performed so far indicate that certain lakes can comprise recharge areas during parts of the year. It is also important to clarify to what extent the wetlands are discharge areas with good groundwater contact and to what extent they are more or less isolated systems separated by impervious bottom sediments. Other questions relate to the properties of the soil-rock contact and how the large fracture zones are hydraulically connected.

A few deep-lying water-conducting fractures have been detected in some of the cored boreholes. These fractures do not have extremely high hydraulic conductivity, but sufficiently high to be regarded as deviating from the normal pattern and therefore of great interest. Individual water-conducting fractures could constitute a part of an otherwise widely-spaced network of conductive fractures. What this fracture network looks like and whether it has contact with the water-conducting surface rock is one of the important questions that will be studied in the further investigations.

The gently-dipping fracture zones should be further characterized. The zone that is most important to investigate from a repository perspective, for example with respect to hydraulic properties and lateral extent, is designated A2. The zone is assumed to dip towards the south-southeast and intersect the candidate area. It is essential to survey permeability and whether it decreases with depth, as well as the natural water flow in the zone. It should also be clarified whether the A2 zone gives rise to hydraulic contact between the boreholes that intersect the zone. It should also be investigated whether the gently-dipping fracture zones, including A2, are bounded by the Singö, Eckarfjärd and Forsmark zones, or whether they continue through and on the other side of them.

The body of data for describing the permeability of the rock mass between the fracture zones must also be improved. It is of great importance for the safety assessment to quantify the number of fractures with low permeability and their properties. This particularly applies to Forsmark, where the rock between the fracture zones has very low conductivity.

Hydrogeochemistry

The discipline of hydrogeochemistry includes investigations of chemical conditions in surface water and groundwater down to a depth of about 1,000 metres in the bedrock. The two main purposes of the hydrogeochemical investigations are:

1. To characterize and describe the groundwater with respect to chemical composition, origin, evolution, principal flow paths and retention times, and to identify the chemical reactions and processes that have influenced the evolution of the groundwater up until today in order to be able to predict its future evolution.
2. To obtain representative and reliable values for certain chemical components that are important for designing a deep repository and for carrying out assessments of the long-term safety of the repository.

There are no chemical data from the prioritized northwestern part of the candidate area from greater depths than 200 m. Experience from previous boreholes in the area indicates that water-conducting fracture zones will be very scarce at repository depth and thereunder, even in future boreholes. Every opportunity for performing chemical investigations at greater depths must therefore be taken advantage of.

Since there are so few water-conducting fracture zones in the northwestern part, the pore water in the rock matrix may be of great importance. Sampling and analysis of this water will therefore be done from borehole KFM06A and possibly another borehole.

Sediment pore water remains to be analyzed. The reason is that water that has passed through sediment contains high concentrations of waste products from organic degradation and therefore has a composition that deviates from that of other types of water.

The water's colloid content may be of importance for nuclide transport, since colloids can act as carriers of radionuclides. It is difficult to determine the colloid content of the groundwater, since the concentration can be affected by virtually every change in e.g. pressure, pH, concentration and temperature of the groundwater. So far no presence of colloids has been detected in the groundwater with the two methods that have been used for determination. In order to ensure that the colloid content of the groundwater is very low or non-existent, a third method based on laser technology will be tested.

Transport properties

The main purpose of the programme is to furnish the safety assessment with data for calculations of radionuclide transport. The most important transport properties in this context are the rock's capacity to retard radionuclides by sorption and diffusion. Since only a few site-specific transport data have been obtained so far, a number of important questions remain to be answered.

The most important task will be to accumulate a good body of data on the diffusion and sorption properties of the rock mass for the safety assessment. It is important to investigate the spatial variations in the parameter values for the intact rock and to collect data for an identification and description of "typical fractures". It should be possible to obtain this information for the most part from ongoing laboratory experiments, augmented to some extent by the continued site investigation.

It is also important to clarify the natural movements of the groundwater within the candidate area and its boundary zones. How large are the water flows through the area? What are the most important zones from a flow viewpoint, and what are their flow properties? Such questions can be answered by measuring groundwater flows in fractures and fracture zones and by estimating the hydraulic gradient. Connections between fracture zones at depth and the highly transmissive superficial part of the bedrock are hereby of special interest, but connections between fracture zones are also important to establish, as well as how the water flow varies with depth along a fracture zone. Since no field tests have yet been performed, transport parameters from flow paths within the area are also lacking.

Other important questions for the disciplinary programme are the extent of the superficial, gently-dipping and highly transmissive fractures and fracture zones and their interconnections. The investigations have shown that these fractures are filled with sediment in places, but may nevertheless have "channels" with high permeability. Pumping tests in combination with tracer tests can provide more information on this. Since the soil layers are relatively thick within the area, their sorption properties may also play a role in the retardation of radionuclides. A study is currently under way concerning the best way to investigate the sorption properties of the soil layers.

It will also be investigated whether it is possible, with the conditions prevailing in the deep rock in Forsmark, to conduct tracer tests with both sorbing and non-sorbing tracers.

Monitoring

The site investigations include collection of time series for all important parameters that show a clear variation over time, i.e. parameters for which an instantaneous "snapshot" is not enough to characterize undisturbed conditions or processes or processes that can be expected to change as a result of the construction and operation of a repository. Natural variations of this kind are mainly associated with ecological, hydrological, hydrogeological and hydrogeochemical parameters measured near the ground surface. But there may also be parameters, mainly hydrogeological ones, that exhibit considerable variation over time at great depth as well. The programme further includes recording of seismic activity.

The site investigations will only yield time series covering a few years. To find out about more long-term trends, this information will therefore be supplemented with already available long-term measurements of e.g. meteorological data. Furthermore, monitoring is planned to be carried out during the entire construction and operating phase.

Investigations for operating facilities

On the whole, the foundation requirements for the deep repository's facilities do not differ from what is usual for industrial construction, but there are certain differences between different parts. Most of the area will be occupied by conventional buildings, roads and storage yards. The exceptions are production buildings and shaft superstructures, which may require more foundation work. Knowledge of soil and groundwater conditions is also required for the rock heaps that are planned.

The planned investigation programme includes the following points:

- Compile existing material from previous investigations that have been done in parts of the area.
- Roughly assess the geotechnical conditions for the entire area in question.
- Assess the foundation requirements for different parts of the deep repository's facilities.
- Identify the need for supplementary investigations, and perform them. It is expected that such investigations will be limited and can be carried out using conventional technology.

Investigations after the summer of 2007

According to SKB's plans, the site investigation's field activities will be concluded in the summer of 2007. After that, in principle only follow-up and monitoring will be performed on site in Forsmark.

During the period following the site investigation and up until SKB has selected one of the two sites, Forsmark or Oskarshamn, monitoring and also possibly some supplementary investigations will be carried out on both sites. A reasonable assumption is that SKB will then wind down all field activities on the site not chosen to a minimum. It is, however, likely that we will pursue activities of some kind for follow-up and monitoring on the site not chosen as well.

1 Introduction

1.1 SKB's plan for final disposal of spent nuclear fuel

Spent nuclear fuel from the Swedish nuclear power plants is taken to the Clab (Clab = Central interim storage facility for spent nuclear fuel) near Oskarshamn for interim storage in water pools. The plan is that after about 30 years of interim storage the fuel assemblies will be transferred to canisters, which will be sealed and transported to a deep repository[1], where they will be permanently deposited in crystalline bedrock. Figure 1-1 shows the main features of SKB's plan for accomplishing this. The goal is to have a system for final disposal of spent nuclear fuel ready for operation in around 2017.

After a period of initial operation, intended to serve as a final test and demonstration of the system, the goal is that a transition can take place to regular operation. How long regular operation then needs to continue is directly dependent on the operating times of the NPPs. SKB's planning assumption is that all reactors except Barsebäck 1 (shut down in November 1999) are operated for 40 years[2]. This would mean that the operation of the deep repository is concluded in the early 2050s and that the entire programme can be concluded in around 2060. The programme permits both larger and smaller fuel quantities to be managed, the only consequences being that the total operating time of the waste management system, and the space requirement in the deep repository, are affected /SKB, 2004a/.

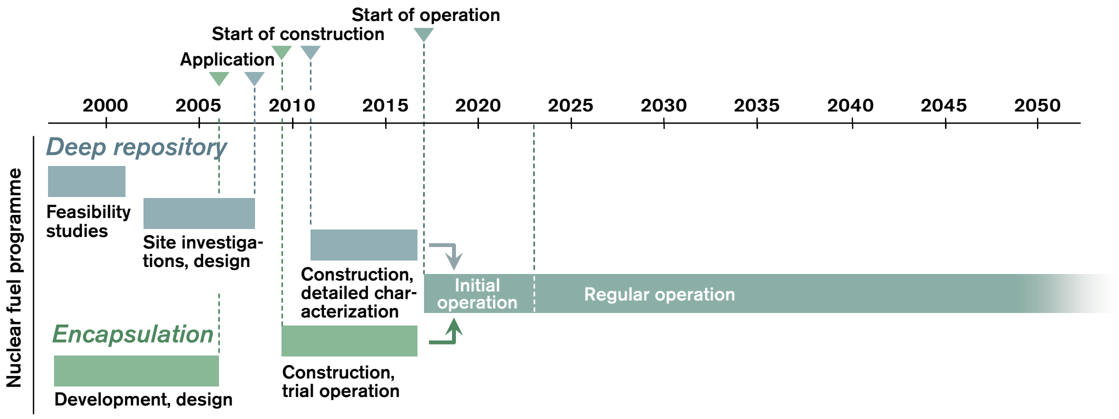


Figure 1-1. *SKB's plan for siting, construction and operation of encapsulation plant and deep repository for spent nuclear fuel.*

[1] The term "final repository" is used in legal texts and regulations to refer to the facility for final disposal of spent nuclear fuel. SKB uses both the terms final repository and deep repository for the same thing.

[2] On 16 December 2004, the Government decided that Barsebäck 2 should be closed on 31 May 2005.

Before the system can be taken into operation, however, two nuclear installations – an encapsulation plant and a deep repository – must be planned, approved and erected. This work is proceeding in stages and has been going on for many years. SKB's goal for the current stage, the site investigation phase, is to obtain the permits that are needed to site and build the encapsulation plant and the deep repository. The current situation can be summarized in the following points:

- Two candidate sites are being investigated for the siting of the deep repository: Forsmark in the municipality of Östhammar and Simpevarp/Laxemar in the municipality of Oskarshamn. These sites were prioritized after a decision process based on broad information gathered from general siting studies and feasibility studies (see box). The intention is that one of the candidate sites will be chosen later on as the site of the deep repository, provided that the site satisfies the requirements on safety, environment and constructability.
- The basis for siting of the deep repository that is currently available also includes other sites that remain as possible alternatives, in the event the investigations of the candidate sites do not have satisfactory results. Furthermore, a large body of comparison material is available from the study site investigations conducted previously at some ten sites in various parts of the country, as well as from investigations in the Finnish nuclear waste programme /SKB, 2000b/.
- An encapsulation plant is planned at Clab. Design of the plant is under way, at the same time as development of the encapsulation technology is proceeding. As an alternative, siting at a possible deep repository in Forsmark is being examined.
- Both the encapsulation plant and the deep repository require permits under the Environmental Code and the Nuclear Activities Act. Statutory consultation procedures for this have been commenced, and the coming decision processes are well defined, see Figure 1-2.
- The development of the KBS-3 method, the disposal method that is SKB's main alternative, is in a phase featuring pilot- and full-scale tests and demonstrations of parts of the system. The Canister Laboratory and Äspö HRL are the main venues for these activities.

From feasibility study to site investigation

In the autumn of 2000, based on feasibility studies in a total of eight municipalities, among them Östhammar, SKB made an integrated evaluation of the siting alternatives arrived at for the deep repository. The purpose was to prioritize some of the alternatives for site investigation /SKB, 2000b/. The evaluation resulted in a plan for site investigations on three sites, among them an area at Forsmark. The other alternatives proposed for site investigation were the Simpevarp/Laxemar area in the municipality of Oskarshamn, plus an area in the municipality of Tierp. Further siting studies were also proposed in the municipality of Nyköping.

In keeping with the division of roles for the nuclear waste programme laid down in the Nuclear Activities Act, a decision process then followed beginning with SKB's submission of its plan to the regulatory authorities. SKI, the authority responsible for review and commentary, recommended site investigation according to SKB's plan and the Government made a decision in November 2001 that gave the go-ahead to the plan.

Both SKB and the concerned municipalities had made it clear at an early stage that site investigations should be preceded by municipal approval, even though this was not a formal requirement. In December 2001, Östhammar's municipal council approved SKB's proposal to conduct a site investigation at Forsmark. Following this local political decision, SKB was able to start work on the site investigation. Oskarshamn Municipality made the equivalent decision in March 2002, after which SKB initiated a site investigation there as well. Other concerned municipalities declined further participation in the siting process for the deep repository.

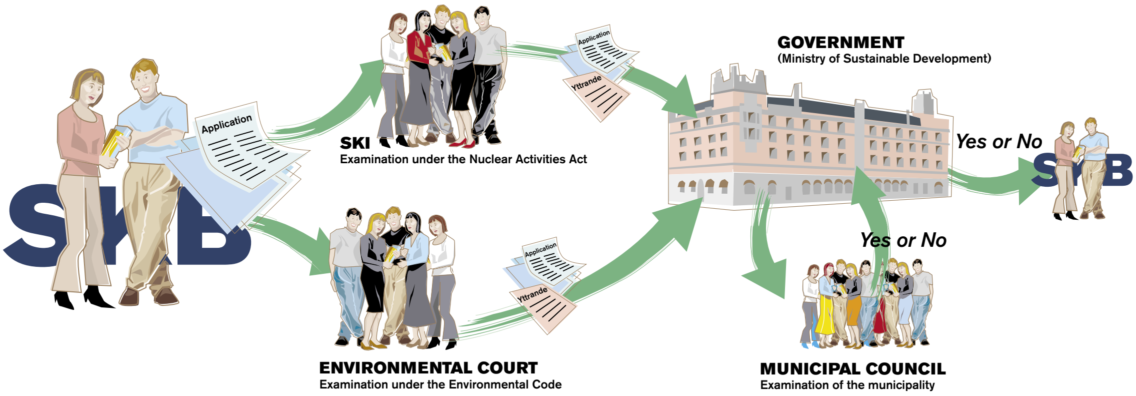


Figure 1-2. *Licensing process under the Environmental Code and the Nuclear Activities Act.*

SKB's main task during the next few years is to gather and compile all the supporting material required for applications for permits to site and build the facilities. The applications will be considered under the Nuclear Activities Act, the Environmental Code and the Planning and Building Act. The principal decision-making bodies are SKI, SSI the concerned environmental court, the Government and the concerned municipality. Each application must be accompanied by an environmental impact statement (EIS), which describes the direct and indirect effects the planned activity may have on man, the environment and society. The scope of the EIS is arrived at within the framework of the consultations that are held in accordance with the provisions of the Environmental Code.

Figure 1-3 schematically illustrates the components of the supporting material and the expected times of the permit applications. It is projected that an application for the deep repository can be ready by the end of 2008. The corresponding time for the encapsulation plant is mid-2006. This means the decision process can start in 2006. The formal permissibility assessment and licensing process is well defined, see Figure 1-2. How the process unfolds and how long it takes will depend on the quality of SKB's supporting material, how the regulatory authorities and the environmental court handle the cases, as well as how ready and willing the political bodies are to make the final decisions. SKB's own judgement is that the decision on the deep repository should have been made by the end of 2010, which would mean that the entire decision process will take about 4.5 years.

There are obvious links between the facilities, which affects both SKB's work with supporting material and applications and the subsequent decision process. The decision on the encapsulation plant is expected to be made shortly after the application for the deep repository has been submitted. At the time of the decision, SKB will have selected a site for the deep repository and carried out a complete safety assessment for it. The processing of the deep repository application should then, in SKB's view, be considerably facilitated by the fact that the review of the encapsulation plant will have been under way for more than two years when the licensing process for the deep repository begins.

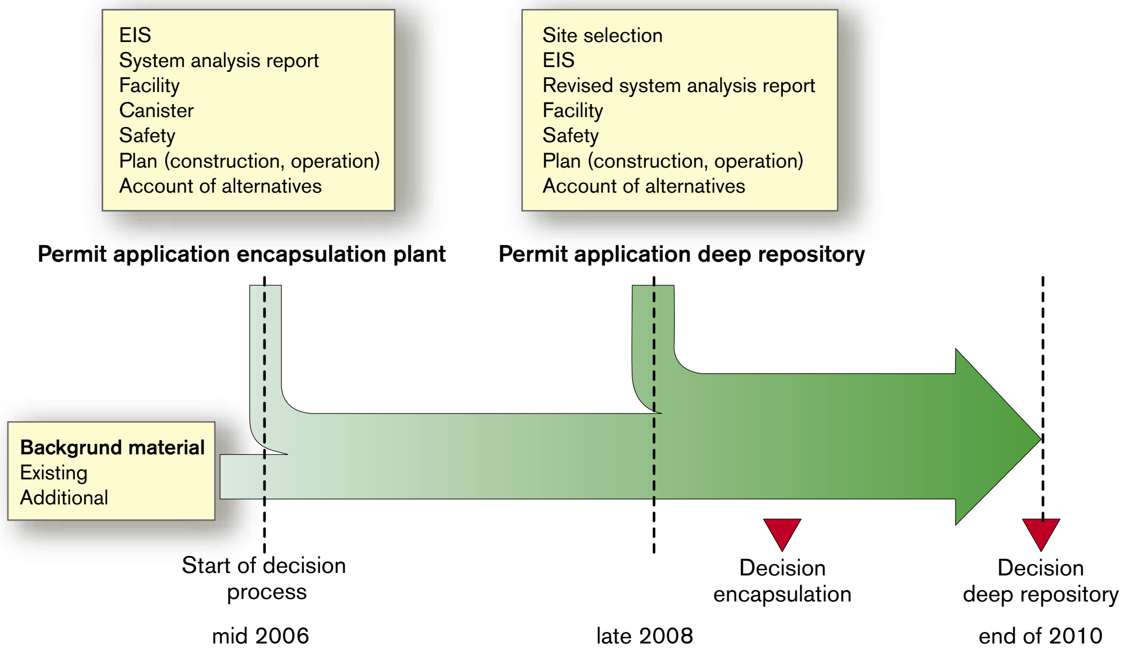


Figure 1-3. *Applications and decision process for encapsulation plant and deep repository.*

1.2 The Deep Repository Project

The work of gathering supporting material for the two siting alternatives for the deep repository, up to the planned permit application in 2008, is being pursued in project form. The goals of the project are to:

- Gather material for an application for a permit to site and build the deep repository for spent nuclear fuel.
- Gather the other material needed to initiate the construction phase.

Subprojects are to:

- Carry out **investigations in Forsmark**.
- Carry out **investigations in Oskarshamn**.
- Produce **descriptions of the investigated sites** as a basis for site-adapted repository solutions, safety assessments, environmental studies and environmental impact assessments.
- **Design** facilities, systems and infrastructure for deep repositories on the investigated sites to a level that can serve as a basis for the facility descriptions and safety assessments that are to be included in the application.
- Devise a **programme for the construction phase**.
- Produce **safety reports** for the long-term safety of the deep repository and the operation (including transportation) of the facility on the investigated sites.
- Perform an **analysis of the system** (Clab, encapsulation plant and canister fabrication, final repository for spent nuclear fuel and transportation system) for disposal of spent nuclear fuel according to the KBS-3 method.
- Carry out studies as a basis for assessing the **impact on environment, human health and society** of planned facilities and activities.

- Carry out **statutory consultations** and other communication with concerned parties and the public.
- Produce the **environmental impact statement** that must accompany the application.

In the final part of the site investigation phase, an integrated evaluation of all background material is made in order to be able to:

- **Select a site** for the deep repository and justify this choice.
- Compile the **permit application**.

The project is carried out in two stages: initial and complete site investigation. After the initial stage, an evaluation is made that includes a preliminary evaluation of the long-term safety of a deep repository on the investigated site. Collected data concerning conditions on the site are compared with pre-established criteria /Andersson et al. 2000/. Furthermore, the possible configuration of a deep repository with regard to local conditions is studied, and preliminary evaluations are made of the safety of such a repository. The goal is to verify the judgement that warranted the choices of candidate sites, i.e. that they have good prospects for meeting the requirements for a deep repository. If it turns out that any of the sites does not meet the requirements, the site investigation can be discontinued. SKB's planning assumption is, however, that the site investigations will be completed on both the sites.

In Oskarshamn, the initial stage of the site investigation includes the two subareas Simpevarp and Laxemar. The initial investigations for Simpevarp were concluded in April 2004 and for Laxemar in October. An initial evaluation of the results from Simpevarp indicates an uncertainty as to whether the Simpevarp subarea can accommodate a repository in one level or whether two levels should be resorted to. Since the limited space may entail difficulties in dealing with surprises that may arise during detailed characterization, SKB has preliminarily chosen the Laxemar subarea for further investigations. A final decision on the priority subarea is planned for the latter part of 2005 /SKB, 2004e/.

In Forsmark, data collection for the initial stage was finished in the summer of 2004. Evaluation in the form of analyses and site description, preliminary facility design and preliminary safety evaluations is under way. Subject to the results of incomplete parts of the evaluation, SKB's conclusion is that the site investigation should be pursued further.

How the complete stage of the site investigation is arranged depends to a great extent on the results of the initial stage. What this means for Forsmark is explained in section 2.4. The goal is to raise the level of knowledge on the site in question to the level required for preparing a permit application. The goal of being able to submit the application at the end of 2008 means that work in the field should be concluded during 2007. Monitoring will continue after this.

Site investigation is conducted in steps with investigations and data freezes followed by analyses and feedback. Such an iterative approach is necessary in order to maintain an overview of the current state of knowledge and manage the investigations in such a way that optimum use is made of resources and the users of the data can provide feedback. Investigation data are used to prepare the site description, facility design, safety assessment, environmental study and environmental impact assessment. Figure 1-4 is a simplified illustration of the links between the most important subprojects in the Deep Repository Project and the control of the information flow.

The organization of the project has been adapted to suit the described mode of working. Figure 1-5 shows a general organization chart for the Deep Repository Project.

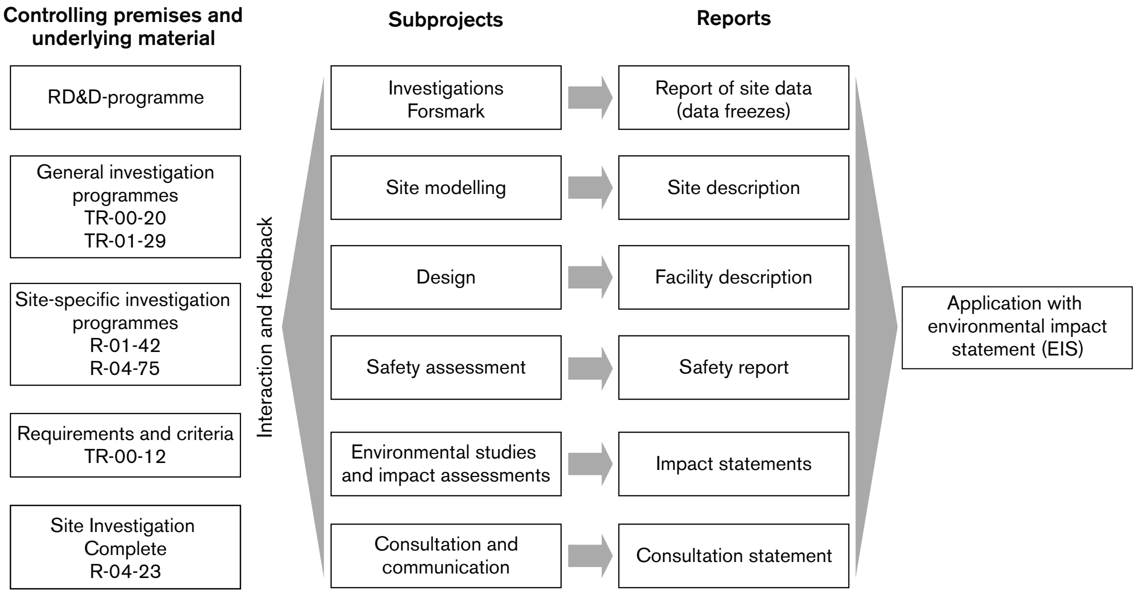


Figure 1-4. *Information flow within Deep Repository Project.*

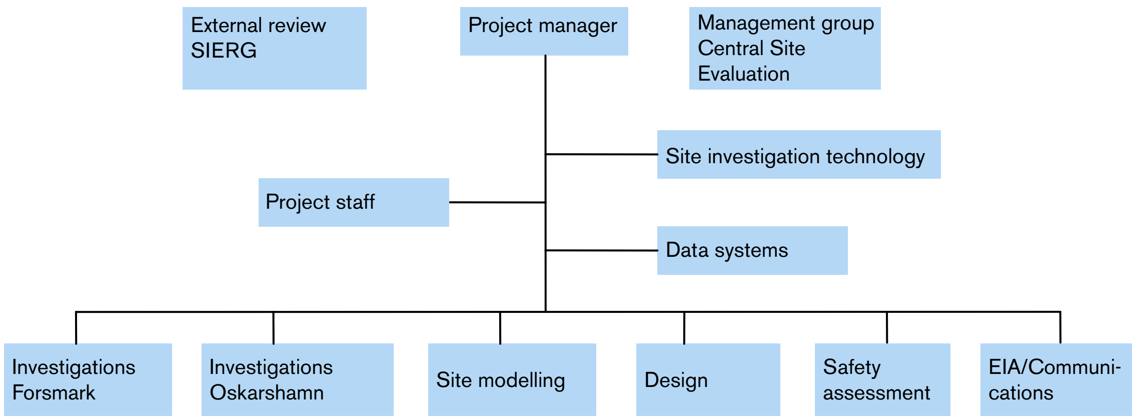


Figure 1-5. *Organization of the Deep Repository Project.*

1.3 This report

1.3.1 Background

SKB submitted a programme for the initial site investigation in Forsmark at the end of 2001 /SKB, 2001a/. The investigations described there have now been completed. It is therefore time to submit a programme of the investigations of geosphere and biosphere (mainly surface ecosystems) which SKB plans for the remainder of the site investigation.

Prior to the site investigations, SKB presented a general programme for investigation and evaluation of sites for the deep repository /SKB, 2000a/, which was based in part on previous safety assessments and on experience from SKB's Äspö HRL. Furthermore, SKB presented an in-depth and detailed description of how the investigations of the bedrock and the surface ecosystems can be carried out /SKB, 2001b/. This report specified what will or can be measured, what methods can be used, and how site-descriptive models will be set up.

The above-mentioned programmes and the results obtained thus far during the initial site investigation in Forsmark have been an important point of departure for the present account of the remaining investigation work.

1.3.2 Scope

The report describes the investigations of geosphere and biosphere which SKB plans for the remainder of the site investigation. All other work – calculation and analysis, design, safety assessments and studies and assessments of consequences for the environment, human health and society – are only mentioned to the extent necessary in order to place the investigations in their context.

Other work is reported continuously in a large number of reports, for example preliminary site description version 1.1 /SKB, 2004c/, interim report for SR-Can /SKB, 2004d/ and in annual reports and newsletters. Detailed accounts of investigation results are presented regularly in P-reports, which are available on SKB's website. The website also contains general information on all of SKB's activities.

2 Prerequisites

2.1 Goal

The overall goal of the site investigation phase is to obtain the permits required to site and build the deep repository. The site investigations must therefore provide the data required for an evaluation of the suitability of the investigated sites for a deep repository. The material must accordingly be comprehensive enough to:

- Show whether the selected site satisfies fundamental safety requirements.
- Show whether the construction-related prerequisites are met.
- Serve as a basis for adapting the deep repository to the conditions and features on the site.
- Permit an assessment of the impact of the deep repository on the environment and society.
- Permit comparisons between the two investigated sites.

Another way to express this is that the supporting material for the application should show that all parts of the deep repository and its associated systems are feasible and safe and that there are sufficient rock volumes on the selected site that satisfy this requirement.

2.2 Site

2.2.1 Background

Figure 2-1 provides an overview of the Forsmark area and environs. After the feasibility study that preceded the site investigation, SKB designated the area marked in red southeast of the Forsmark Nuclear Power Plant, known as the candidate area, as having priority for a site investigation. This area, together with the nearby environs that are significantly affected by the site investigation, will hereinafter be referred to as “the Forsmark area”. The blue and green squares in the figure show the boundaries defined for the local and regional models that SKB works with when processing data from the site investigation. Reasons for the model areas, as well as boundaries and definitions, are presented in site model version 1.1 /SKB, 2004c/.

The feasibility study was concluded in 2000 and included the entire municipality. By reason of the compilation of bedrock and groundwater conditions that was done, several areas in the municipality are designated as potentially interesting for further studies with regard to their prospects for satisfying the safety requirements for a deep repository. After a comprehensive evaluation, the area in Figure 2-1 was prioritized for a possible site investigation. The main arguments were the availability of a well-delineated area with potentially favourable geological conditions, plus the proximity of Forsmark’s nuclear installations. A siting of the deep repository at the NPPs and SFR would enable the existing harbours and other infrastructure to be utilized, the overland transport distance to and from the deep repository would be short, and industrial land is available for the surface facilities required by a deep repository. This would offer considerable advantages from an establishment viewpoint, above all good opportunities to limit the environmental impact of a deep repository.

The Kallriga Nature Reserve is located southeast of the candidate area. A siting that infringes on the nature reserve is out of the question, and the boundary of the reserve

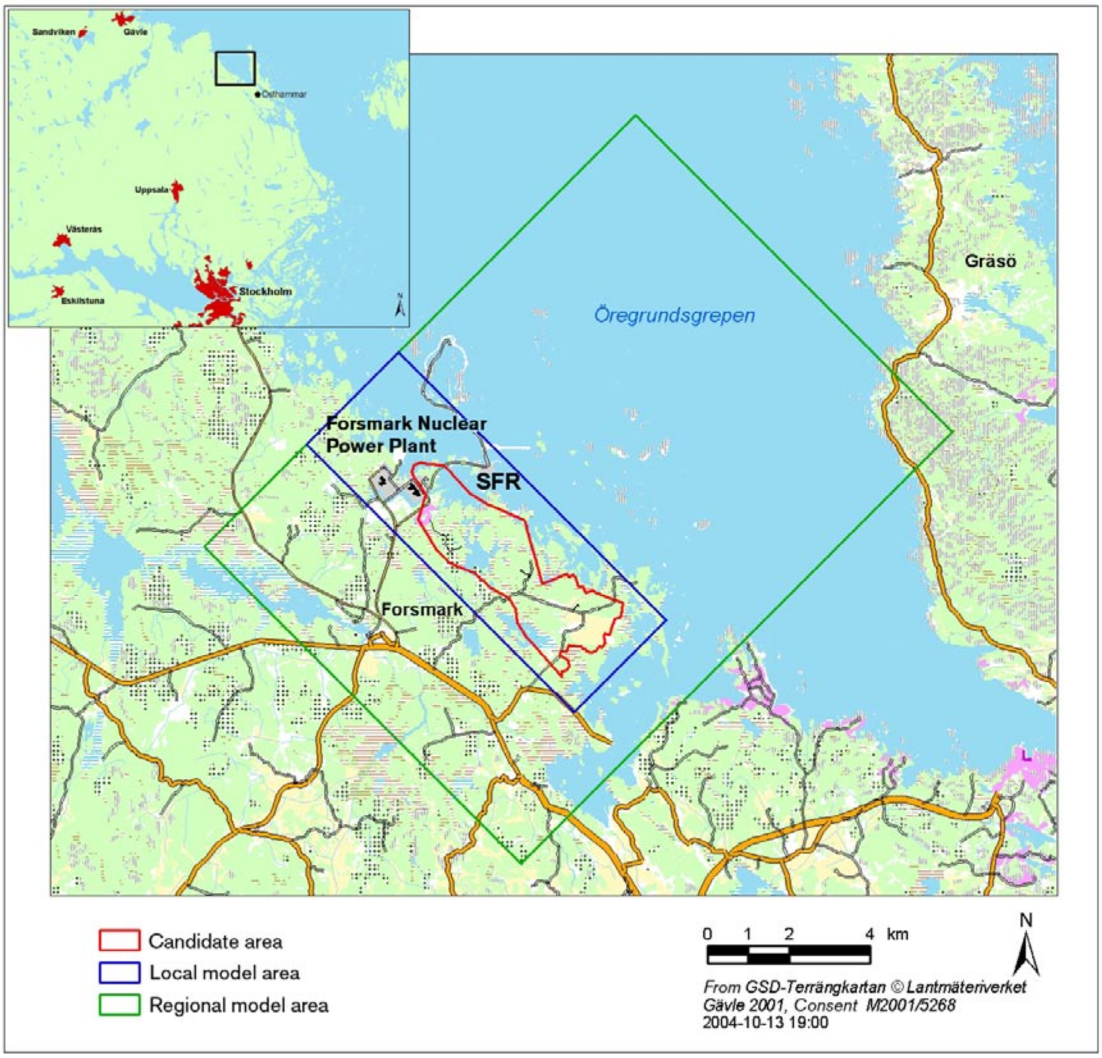


Figure 2-1. *Forsmark area with environs.*

therefore constitutes the boundary of the candidate area on the southeast. This delimitation was also based on existing knowledge of the geological limits of the rock volume judged to be of interest.

The Forsmark area and its environs are characterized by high natural values. It was nevertheless considered possible to conduct a site investigation without unacceptable disturbances, provided that both the programme as a whole and individual investigations were adapted to the area's special nature conservation interests.

2.2.2 Geological conditions

Figure 2-2 shows a bedrock geological model of the area. The bedrock in the Forsmark area is part of an elongated rock block – a so-called tectonic lens – that extends from the Forsmark NPP to Öregrund and on to the southeast. On the northeast and southwest, the area is bounded by zones with deformed bedrock. These types of relatively well-preserved, more or less lenticular blocks between bands of deformed bedrock can be found at numerous locations in the region, as well as in other regions with a similar geological history. Their origin can be traced to deformation processes that acted while the rock was still subject to high pressures and temperatures. The result was wide zones that run in long bands where the rock has been deformed in a ductile manner and formed banded and folded

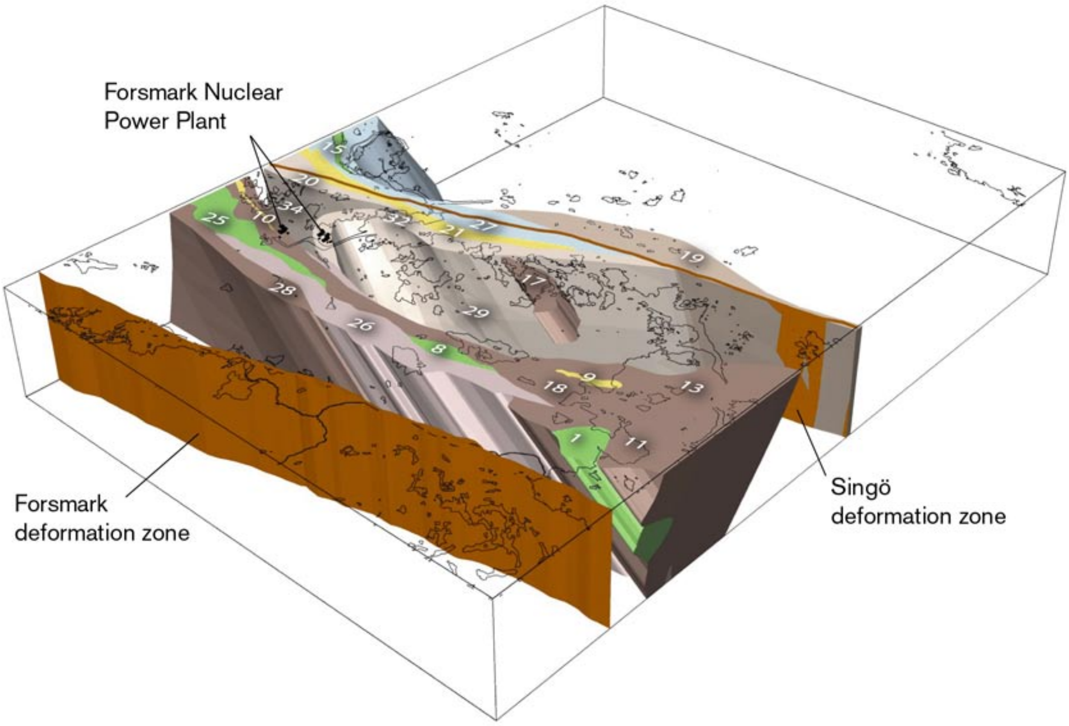


***Figure 2-2.** Bedrock geological model of the Forsmark area.*

structures. More distinct zones of fractured rock are often superimposed, the result of brittle deformation at later stages when the rock had solidified. Deformations and movements have, naturally enough, had a tendency to become concentrated to the bands where they were once initiated, since the bedrock there is weakened. The intervening rock has therefore remained relatively unaffected.

The rock types in the candidate area itself are relatively uniform and are dominated by metamorphosed granite (metagranite). Towards both the southeast and the northwest there are other granitoid variants, for example tonalite. Southwest of the candidate area are basic rocks such as diorite and gabbro, as well as metavolcanic rocks. The latter contain accumulations of ore minerals, particularly the iron mineral magnetite.

Most of the bedrock is till-covered, but bare outcrops lie scattered throughout the area. Smaller areas also have overlying regolith such as glacial and postglacial clay, gyttja and peat. The till, which can in some places be very thick (10–15 m), is made up of several beds with varying grain size distribution. The till is generally highly calcareous.

2.2.3 Nature and Culture

The Forsmark area is flat and low-lying. As recently as the early Middle Ages, the region lay beneath the sea, after which the process of land uplift led to the formation of islands in what is now a coastal area. The landscape of today contains many small shallow lakes and bays. The rate of land uplift is about 6 mm per annum, and the water areas are in different stages of being pinched off from the sea. This process of evolution from sea to land also leads to a rapid succession of different biotopes, which is interesting from an ecological perspective. Productive coniferous forest dominates in the higher parts of the area, except for at the far southeast, where the landscape opens up into fields, meadows and deciduous glades. Due to the combination of open water, wetlands and woodlands, the bird life is diverse and numerous (Figure 2-3). The flora is also rich (Figure 2-4). The calcareous soils provide good conditions for many calcium-dependent species (Figure 2-5).

Figure 2-3. *Due to the combination of open water, wetlands and woodlands, the bird life is rich.*

Figure 2-4. *Sea buckthorn is common in the Forsmark area. The berries are used to make juice, jelly and sauce, as well as liqueur and wine. The bark can be used for dyeing textiles reddish-brown. The wood is hard and tough and is suitable for handicrafts.*

Figure 2-5. *Lady's slipper occurs on calcareous soils in the woodlands and pasturelands of Forsmark.*

The map in Figure 2-6 shows different types of natural values and nature protection. The Forsmark area is of national interest for nature conservation. It features important ornithological values and has been designated as particularly valuable in several nature conservation plans and in nature and bird inventories. The Kallriga Reserve has been set aside to preserve these values and has the status of a Natura 2000 site. The stretch of coast south of the industrial area at Forsmark is designated a protected shore. The protection normally extends 100 m inland, sometimes farther. Equivalent protection is provided around bays and islands. Construction and other measures that prevent the public from moving about freely are prohibited within the shore protection area.

Figure 2-6 also shows the area of national interest for a final repository for spent nuclear fuel according to SKI's decision of 2 December 2004. If Forsmark is chosen as the site for the deep repository, this national interest must be considered along with other national interests. According to Chapters 3 and 4 of the Environmental Code, activities that may be prejudicial to the national interest are not allowed. In its decision, SKI particularly mentions drilling down to repository depth and any activities planned to be located on sites that may be considered for the final repository's surface parts.

Figure 2-7 shows in a similar manner culture protection interests etc in the Forsmark area. Due to the brief history of the area, archaeological remains are almost completely absent. The only known exception is a graveyard from the Iron Age. The cultural values from recent times are mainly building remains. Southwest of the area is Forsmarks Bruk, which is of national interest for preservation of the cultural environment as one of the country's most valuable historical industrial sites.

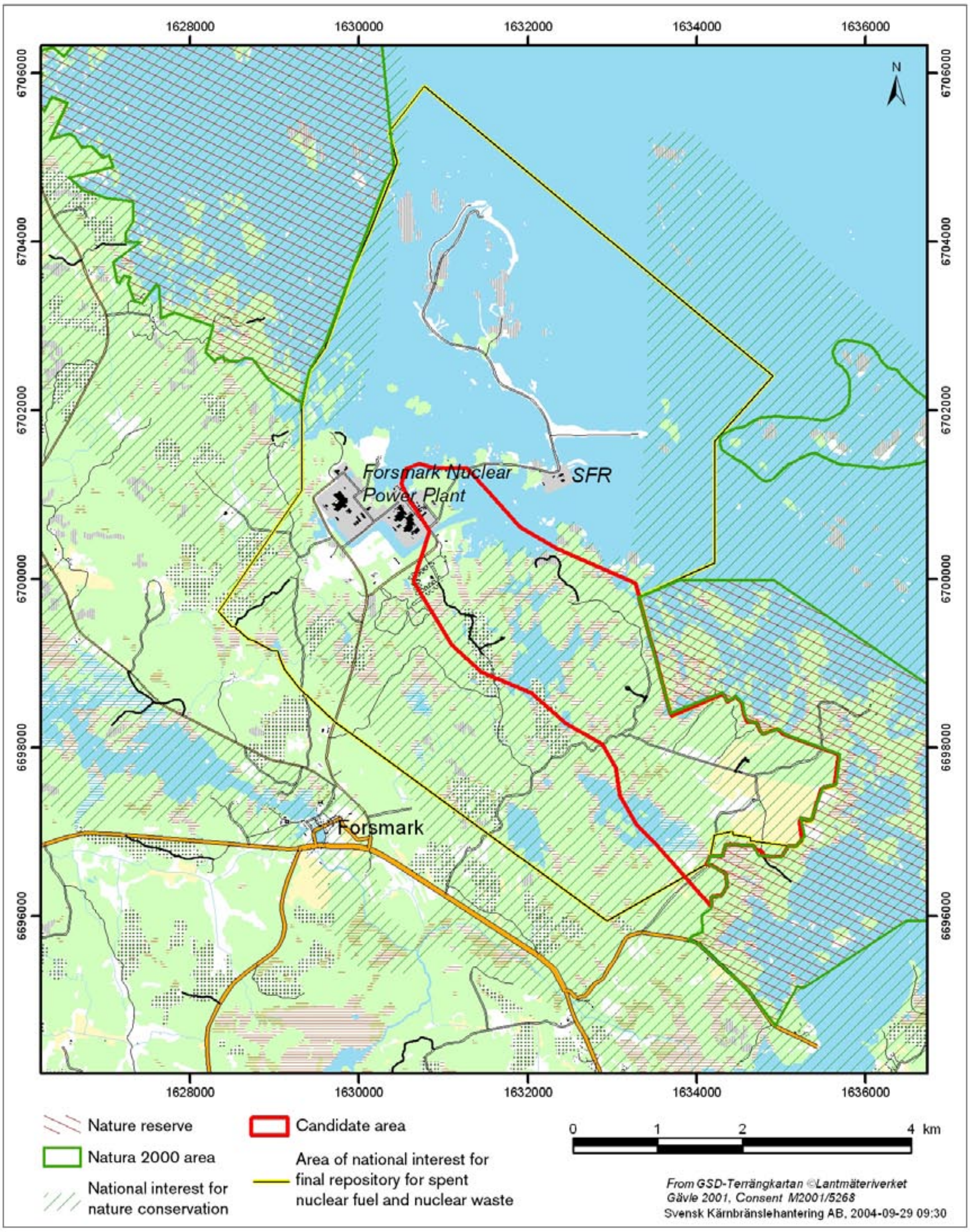


Figure 2-6. *Protected nature and areas of national interest for natural values in the Forsmark area. The map also shows the area of national interest for a final repository for spent nuclear fuel and nuclear waste according to SKI's decision of 2 December 2004.*

Most of the land where the site investigation is being conducted is owned by Sveaskog AB. The company recently set aside 18 square kilometres around Forsmark as a so-called ecopark, where special attention will be given to nature protection and other preservation interests. Large parts of the candidate area are included in this ecopark. In the southeastern part there is a large area, around Storskäret Farm, that is privately owned. This area is farmed, and there are also pasturelands that are maintained. The meadows and grazing lands at Storskäret have high natural and cultural values. In addition to these large properties, there are a number of vacation properties, most of which are located along

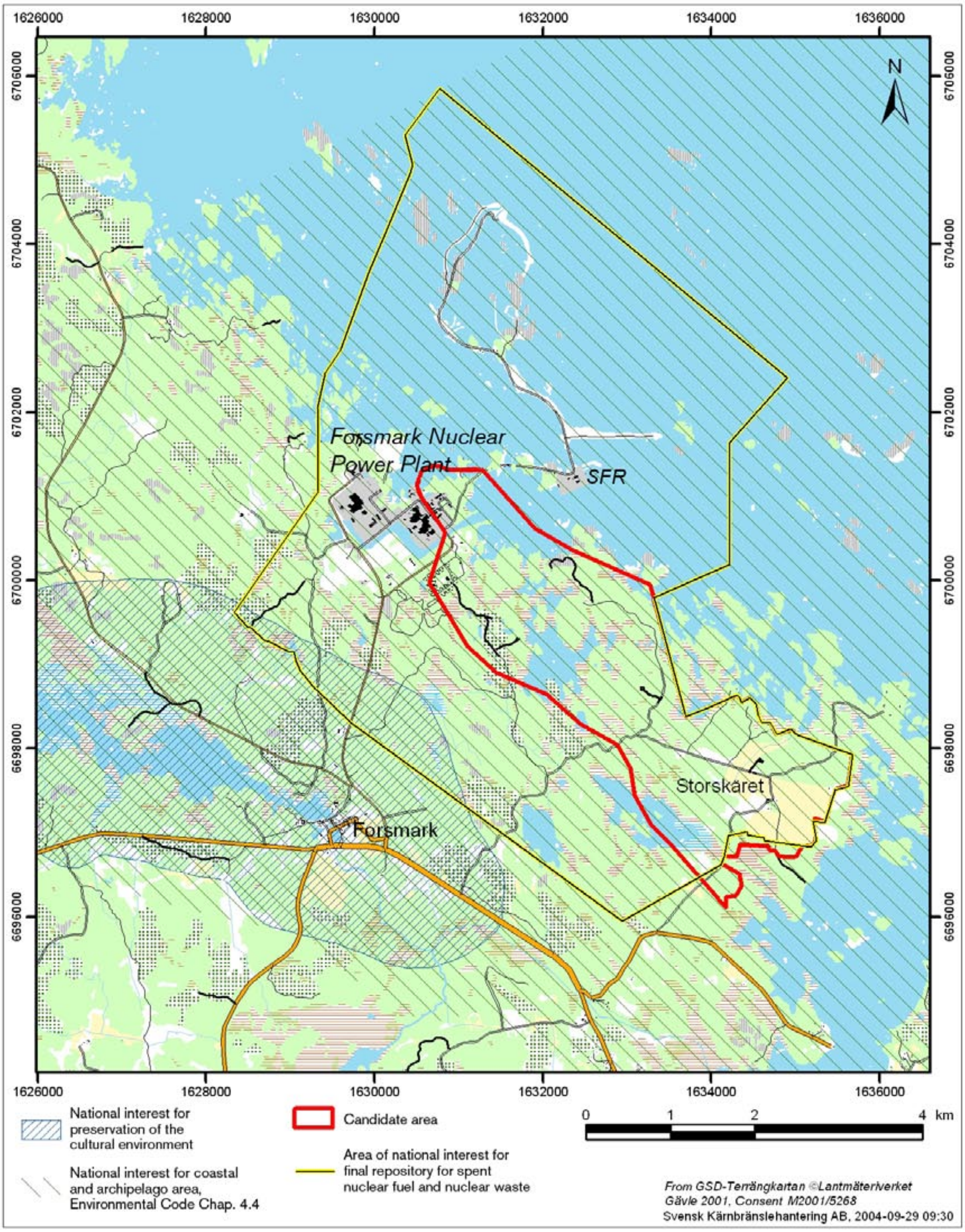


Figure 2-7. *National interests for preservation of the cultural environment as well as for coastal and archipelago areas.*

the border of the Kallriga Reserve. SKB has concluded agreements that regulate access for investigations, compensation etc with the property owners affected by the site investigation.

On the northwest, the candidate area includes part of the industrial area in Forsmark that is covered by a detailed development plan. The area covered by a detailed development plan covers about 1,200 ha of land area and 1,800 ha of water area (including islands and islets), see Figure 2-8. The industrial installations in the area (including power lanes) together occupy about 260 ha of land. The industrial land is owned by companies within the Vattenfall Group and Svenska Kraftnät. There are in the area three nuclear power reactors, SFR and activities associated with these facilities, see Figure 2-9. Approximately 850 persons work in the area. An approach road with high loadbearing capacity links the industrial area with highway 76, and there are a number of supply roads within the area. The internal harbour, situated adjacent to SFR, is used mainly for receiving shipments of low- and intermediate-level waste to SFR and dispatching shipments of spent nuclear fuel from the Forsmark plant to Clab. According to a decision by the Swedish Business Development Agency (now the Swedish Energy Agency), the developed industrial area and an area northeast of it comprise areas of national interest for energy production.

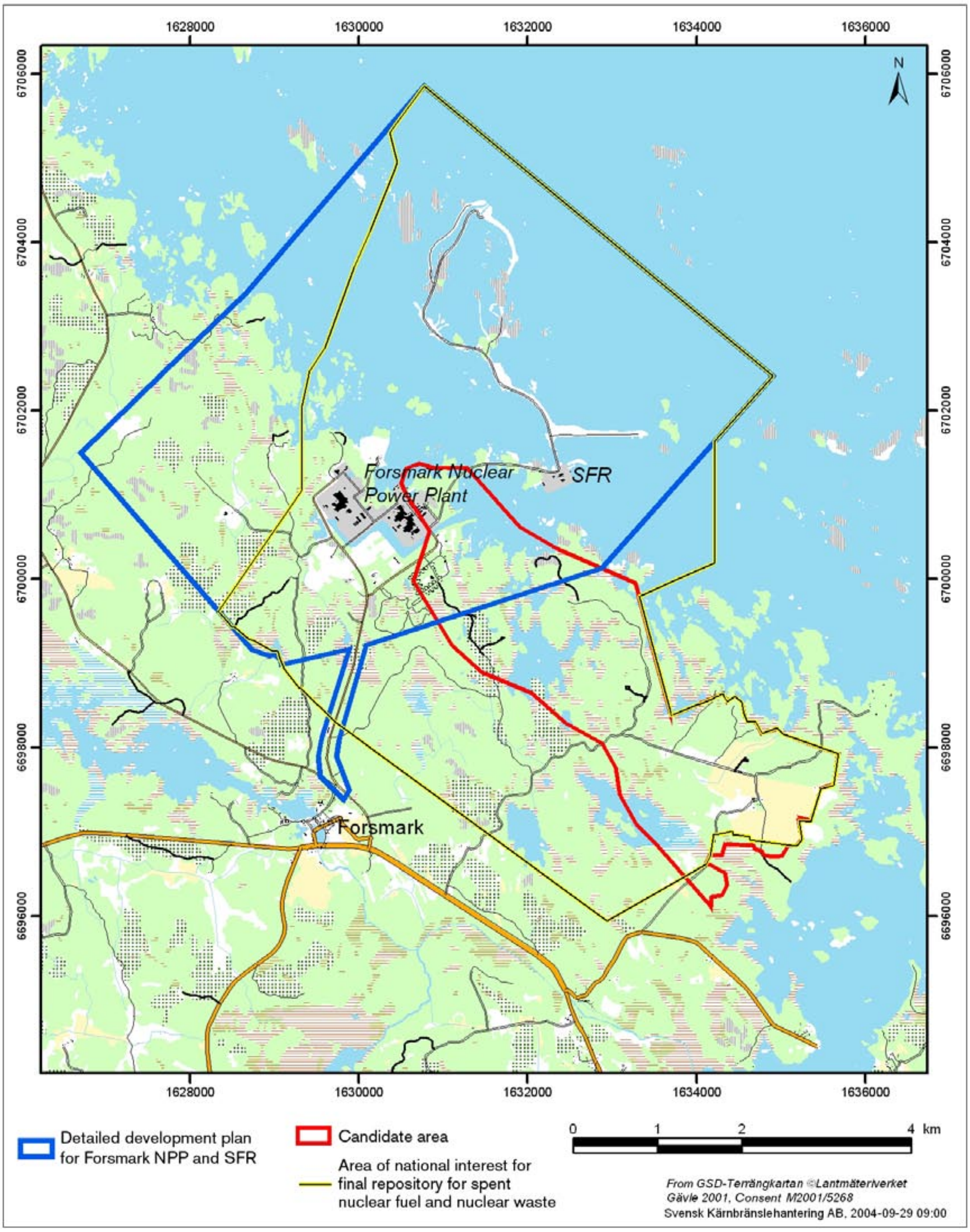


Figure 2-8. Area in Forsmark covered by detailed development plan.

Figure 2-9. *Industrial area in Forsmark, with the three reactor buildings, and in the background the SFR facility.*

2.3 State of knowledge after initial site investigation

2.3.1 Points of departure and overview

The site investigation in Forsmark was commenced in February 2002. The plan was based on the following general programmes for site investigations:

- "Geoscientific programme for investigation and evaluation of sites for the deep repository" /SKB, 2000a/.
- "Site investigations – Investigation methods and general execution programme" /SKB, 2001b/.

These documents were produced by SKB and reviewed by the regulatory authorities in conjunction with SKB's integrated account of method, site selection and programme prior to the site investigation phase /SKB, 2000b/. A special programme /SKB, 2001a/, adapted to site-specific questions and conditions in Forsmark, was published before the site investigation started.

The programmes together reflect the initial planning. Since then the iterative mode of working has meant that the planning has been periodically updated in response to the results. Requirements and viewpoints that have emerged from the authorities and their external expert groups within the framework of the established consultation process have also had a considerable impact on the investigation programme.

In December 2001, SKB gave notice of consultation for the site investigation to the Uppsala County Administrative Board, pursuant to Chapter 12 of the Environmental Code. The County Administrative Board stipulated in its decision that SKB could conduct the site investigation in keeping with the presented programme, and with the environmental protection measures described in the notice. SKB has since given notice of all investigations and other activities within the site investigation that could have an impact on the natural environment. In its decisions on these notices, the County Administrative Board has stipulated conditions and recommendations for the activities in question.

The organization for the site investigation, numbering 35 persons in all, was established during the first year of operation. The activities were accommodated in SFR's[3] premises in the Forsmark harbour, where temporary extensions were added. Special premises have been provided for mapping of drill cores, various laboratory activities and storage. Infrastructure to and within the investigation area has been established gradually, with consideration given to the area's sensitive natural environment. This includes a new service road from the industrial area, improvements of the existing road network, drilling sites and build-out of the cable network for electricity supply and data communications.

Investigations and results are presented under the appropriate discipline headings in Chapter 3. The current situation (August 2004) can be summarized in the following points:

- The surface characterization of the geological and ecological conditions in the area has largely been completed.
- In order to investigate the bedrock at depth, five deep (1,000 m) and two shallower cored boreholes have been drilled and documented. Drilling of a sixth deep cored borehole is under way.
- 19 percussion boreholes have been drilled, partly to supply core drilling with flushing water and partly to investigate the bedrock.
- A comprehensive, preliminary site description, version 1.1 (SKB, 2004c), has been published. The work of compiling all information from the initial site investigation is under way and will result in version 1.2 of the site description.
- The consultation process for a possible deep repository in Forsmark has been established in accordance with the provisions of the Environmental Code.
- An active information and communication programme has been established for ongoing dialogue with nearby residents, the public, Östhammar Municipality, neighbouring municipalities and other local stakeholders.

Figure 2-10 and Figure 2-11 illustrate the current drilling situation. Core drilling has been done from six specially established drilling sites. A number of percussion boreholes have also been drilled in different directions around these sites. In addition, there are percussion boreholes on several more sites plus some sixty-odd soil boreholes.

[3] SFR – Final repository for radioactive operational waste; put into operation in 1988.

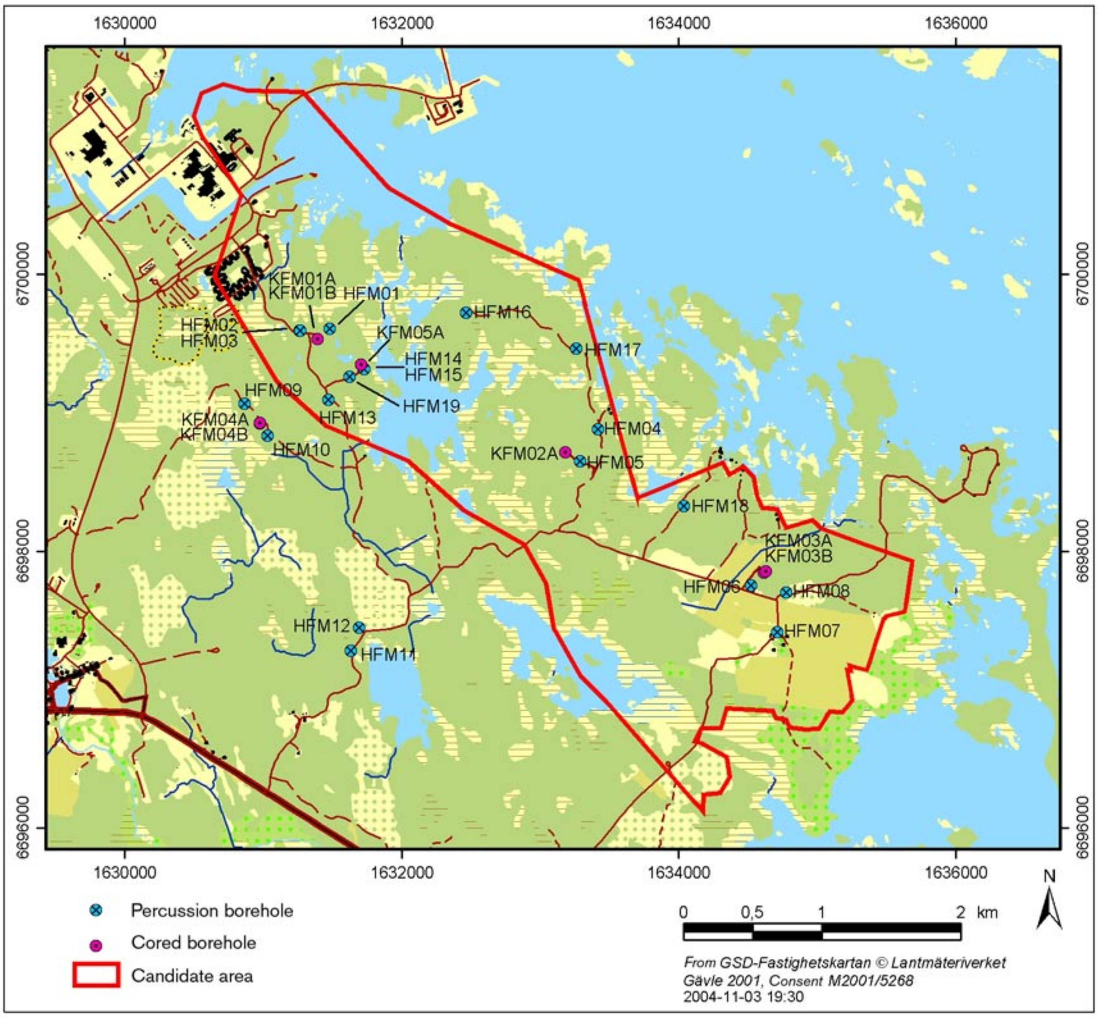


Figure 2-10. *Investigation area with all cored and percussion boreholes drilled during the initial part of the site investigation.*

2.3.2 Cross-check against fundamental requirements

Geoscientific key questions

Prior to the site investigation phase, SKB presented fundamental requirements whose fulfilment had to be demonstrated in order for a site to be considered for the deep repository /Andersson et al. 2000/. Conversely, if one or more requirements are not met, the site has to be regarded as being disqualified. Formulated briefly, the requirements are as follows:

- It must be possible to avoid regional ductile shear zones.
- The bedrock within the repository volume may not have ore potential.
- A repository must be able to be located and given a technically reasonable layout within the available rock volume and taking into account fracture zones etc.
- The rock mechanical conditions must be such that serious stability problems do not arise in deposition tunnels or deposition holes.
- The groundwater at repository level may not contain dissolved oxygen.
- The total salinity (TDS = Total Dissolved Solids) of the groundwater at repository level must be lower than 100 g/l.

Figure 2-11. *Investigation area with all soil boreholes.*

Beyond these requirements, it was stipulated that the suitability of a site can be questioned if a large fraction of the rock mass between fracture zones has a hydraulic conductivity greater than 10^{-8} m/s.

During the initial stage of the site investigation, the aim has been to gather data which – directly or indirectly – provides a basis for deciding whether the above requirements can be considered to be met, and thereby whether further investigations are warranted. There is then reason to evaluate the current state of knowledge in relation to the stipulated basic requirements. Table 2-1 summarizes, for each of the requirements, aspects that are important to take into account with regard to site-specific conditions and the current state of knowledge. Remaining data needs are also summarized briefly. More detailed descriptions of data requirements and planned programmes are given in Chapter 3.

Table 2-1. Summary of requirements, state of knowledge and remaining data needs.

Requirements	Regional ductile shear zones shall be avoided
Site-specific aspects	The requirement to avoid the regional ductile shear zones that surround the tectonic lens on both long sides was met even before the site investigation started through the choice of candidate area.
Status/ state of knowledge	The conclusion that the choice of candidate area satisfies the requirement has been confirmed by the investigations /Stephens et al. 2003a,b; and, 2003; Petersson and Wägnerud, 2003; Petersson et al. 2003a,b/.
Remaining data needs	The requirement is met, but in order to better be able to describe the hydrogeological and hydrochemical conditions in the area, new knowledge is needed about the presumed function of the surrounding regional deformation zones as hydraulic boundary conditions for the site. By this is meant that due to the locations of the deformation zones and presumed high permeability of brittle deformed (reactivated) sections within the zones, they control the hydrological and, to some extent, the hydrochemical situation within the area.

Requirements	No ore potential
Site-specific aspects	The Forsmark area is located in a region where ores and mineralizations are common, especially in connection with metavolcanic rocks. The near-surface bedrock in the candidate area is dominated by metagranite, which has no ore potential as far as is known, but evidence of this is needed and the situation at depth needs to be investigated.
Status/ state of knowledge	The geological mapping has verified that the rock at the surface lacks ore potential /Nilsson, 2003c/. The cores from all cored boreholes, as well as the cuttings from percussion boreholes, have been mapped, whereby a mineralogical assessment of the rock has been made. No signs of ore potential have been detected. The vertical shape of the tectonic lens also means that the composition of the bedrock at repository depth is comparable to that at the surface. A special study confirms these results /Lindroos et al. 2004/.
Remaining data needs	The requirement is judged to be met and no additional data are needed. The issue will nevertheless be followed up in conjunction with future drilling.

Requirements	A repository must be able to be located and given a technically reasonable layout within the available rock volume
Site-specific aspects	Three factors determine whether the requirement can be satisfied: **1) The vertical extent and shape of the tectonic lens** This factor determines what "gross volumes" of suitable rock may exist at repository depth. Prior to the site investigation there were indications that the lens is bounded by nearly vertical boundary zones, but this must be investigated. **2) Individual fracture zones at repository level** Fracture zones which (taking the respect distance into account) reduce the available rock volume at repository level and/or divide it into smaller units may be of crucial importance for the positioning and configuration of a repository. For this and other reasons, the occurrence and importance of gently-dipping zones was identified prior to the site investigation as a particularly important issue. **3) Rock properties within deposition areas** Parameters that determine the local prospects for utilizing available space for deposition (degree of utilization) are: – Occurrence of major fractures. – Groundwater flow. – Stability/rock stresses. – Thermal conductivity. Prior to the start of the site investigation, rock stresses were identified as a particularly important issue, in light of the fact that earlier measurements in the area showed relatively high values – see the requirement regarding local stability below.

Status/ state of knowledge	**1) The vertical extent and shape of the tectonic lens** The depth boundary of the tectonic lens has not been reached anywhere within the area, despite five boreholes down to depths of 850–1,000 m /Claesson and Nilsson, 2003b, 2004a,b/. Seismic reflection measurements indicate no clear boundary down to at least 3,000 m /Juhlin et al. 2002/. Results from borehole KFM04A show that the lens's boundary in a section on the southwest is nearly vertical. There is much to indicate that there are areas with suitable bedrock even further towards the northwest (in the longitudinal direction of the lens) that had previously been thought. **2) Individual fracture zones at repository level** The investigations have identified a dominant fracture zone (A2) which is interpreted as cutting straight across the candidate area and inclining approximately 20–25 degrees to the southeast, see Figure 2-15. At repository level, this zone preliminarily divides the area into a northwestern and a southeastern part /Claesson and Nilsson, 2004a; Petersson et al. 2003a/. There are indications of more zones with a similar orientation in the southeastern part of the area, but not in the northwestern part (except for a possible bounding zone in the far northwest). Other fracture zones that have been interpreted at repository depth are judged to be of more limited importance from a layout point of view /Juhlin et al. 2002/. **3) Rock properties within deposition areas** As a whole both *fracture frequency* and *groundwater flow* at repository depth are much lower than expected /Petersson and Wägnerud, 2003; Berglund et al. 2004; Rouhiainen et al. 2004; Ludvigson et al. 2004/. The loss of possible deposition positions that can result from these factors is therefore judged to be limited. Requirements regarding *rock stresses and stability* are commented on below. The rock's *thermal conductivity* controls the minimum distance between deposited canisters in a deep repository. Completed measurements show that thermal conductivity is normal for rocks with granitic composition /Adl-Zarrabi, 2004a,b/. This would entail a canister spacing in accordance with the assumed reference design. *Overall assessment:* The knowledge that is needed to determine whether the requirement is met is emerging gradually as a result of new boreholes and the work with facility design. The parameters that comprise a basis for layout are currently being analyzed. Subject to the results of this analysis, SKB's preliminary judgement is that the site offers good prospects for emplacing and configuring a repository, see also Figure 2-14.
Remaining data needs	**1) The vertical extent and shape of the tectonic lens** The tectonic lens is judged to provide enough space for a repository, see Figure 2-14. However, there is not yet sufficient knowledge for facility configuration. In particular, knowledge is lacking regarding the geological boundaries on the area's northwest end and northeast side. **2) Individual fracture zones at repository level** The properties and importance of interpreted zones (particularly A2) need to be clarified better. The same applies to the importance at depth of interpreted but not yet verified lineaments (indications on the ground surface of possible fracture zones). Possible, not yet discovered fracture zones within the repository volume similarly constitute a remaining uncertainty. **3) Rock properties within deposition areas** *Major fractures, groundwater flow:* There is a great need for more detailed data, particularly in the northwestern part of the area. *Stability/rock stresses*: See requirements regarding stability below. *Thermal conductivity:* Additional data are needed, particularly regarding scale dependence and the possible importance of thermal anisotropy.

Requirements	**No extensive instability in deposition tunnels or deposition holes**
Site-specific aspects	Stability is determined by the rock stress conditions, the mechanical properties of the rock and design parameters such as tunnel directions and cross-sections. High rock stresses may entail some fracturing adjacent to openings and require rock support measures. Extreme rock stresses may make the site unsuitable for a repository. Measurements at the end of the 1970s indicated elevated stresses in parts of a borehole near block F3 in Forsmark.

Status/ state of knowledge	The investigations have invariably indicated rock with normal strength, which, together with low fracture frequency, ensures good mechanical properties. This is in many ways positive from a stability viewpoint, but can also have negative consequences in an environment with elevated rock stresses. Rock stress measurements have been done down to a maximum depth of about 450 metres. The results contain considerable method-related uncertainties, but as a whole the data confirm the previous picture with relatively high horizontal rock stresses /Sjöberg, 2004/. Possible consequences are being studied but are preliminary judged to be quite manageable.
Remaining data needs	The characterization of the stress state, including vertical and lateral variations, is incomplete and will be given priority in further investigations. Data on mechanical properties are constantly being supplemented.

Requirements	**No dissolved oxygen in groundwater at repository level**
Site-specific aspects	Prior to the start of the site investigation, no local data were available. At the same time there was no reason to expect that the conditions would deviate from those that are normal for Swedish bedrock, i.e. anoxic (oxygen-free) conditions.
Status/ state of knowledge	The measurements to date – altogether seven sections in three cored boreholes – have verified oxygen-free conditions /Wacker et al. 2003, 2004b,c/. The requirement is therefore considered to be satisfied.
Remaining data needs	Even though the requirement is now considered to be satisfied, further measurements will be carried out.

Requirements	**Salinity (TDS) of groundwater at repository level lower than 100 g/l**
Site-specific aspects	The coastal location means that saline groundwater was expected, but no local data from repository level were available prior to the start of the site investigation.
Status/ state of knowledge	The salinity increases from fresh water near the ground surface to 8 g/l at a depth of 150 m. After that the salinity is constant to about 600 m. Below this depth an increase occurs. At most, 13 g/l has been measured at a depth of 980 m /Nilsson, 2003a,b; Wacker et al. 2003, 2004b,c/.
Remaining data needs	In the northwestern part of the candidate area, data are lacking below a depth of 200 m. Every opportunity for performing chemical investigations at greater depths must therefore be taken advantage of.

In SKB's view, the above table provides a good foundation for continuing the site investigation in Forsmark. It is highly unlikely that further investigations could alter SKB's judgement that the site satisfies the fundamental requirements. The remaining data need indicated in Table 2-1 is mainly attributable to the fact that more data are needed for both facility design and safety assessments.

The site description (version 1.2) that is currently being prepared and that is based on data as of 31 July 2004 will provide an up-to-date interpretation of the complete geoscientific state of knowledge. In general it can be said that the investigations so far have revealed some clearly distinctive features as regards fracture situation and water flow. Figure 2-12 exemplifies this with data from the first, deep cored borehole.

The average fracture frequency in the near-surface bedrock (down to a depth of about 300 metres in borehole KFM01A) is normal for Swedish crystalline bedrock. Sections with distinct, usually gently-dipping, highly conductive fractures are encountered down to a depth of about 200 metres. This pattern seems to exist throughout the tectonic lens. Large groundwater flows in gently-dipping fractures near the surface can be positive from a repository viewpoint, since the groundwater flux at deeper levels is then limited, but may require special measures in connection with tunnelling and shaft sinking.

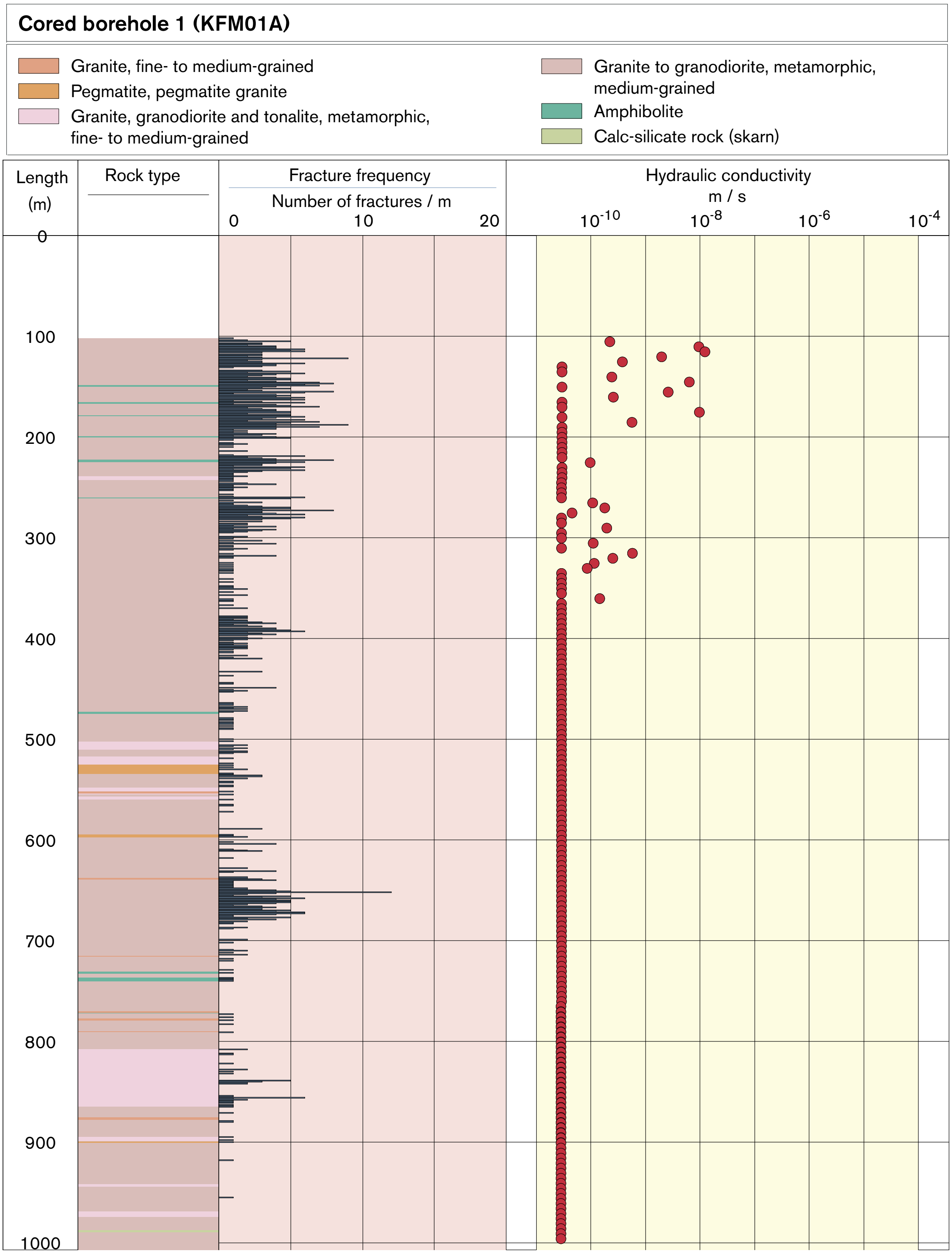


Figure 2-12. *Cored borehole KFM01A. Metamorphosed granite (metagranite) dominates. The fracture frequency is normal down to about 300 m, below which it is very low with the exception of two sections, around 400 and 650 m. Below about 360 m, the hydraulic conductivity is below the measurement limit.*

At greater depths, below 200–300 m, the bedrock in the candidate area is distinguished by low fracture frequency and low hydraulic conductivity. With isolated exceptions, the few water-conducting fractures encountered at repository depth and below are associated with interpreted gently-dipping fracture zones. The preference that most of the rock mass between fracture zones should have a hydraulic conductivity lower than 10^{-8} m/s thus appears to be met with good margin.

As always when rock is investigated, unexpected observations have also been made. One such observation concerns the surface rock at drilling site 5. When the overburden on the site was removed, displacements were found in the glacially polished rock surfaces. Some blocks in the outcrop had moved upward several decimetres and open, often soil-filled fractures had formed. A special examination showed that the block movements took place more than 10,000 years ago, when the rock was covered by the continental ice sheet, or even earlier. Besides studies of the outcrop surface and the overlying till, two percussion boreholes were drilled at an angle under the surface rock. The conclusion was that the phenomenon is associated with the surface, while the deeper rock did not exhibit any disturbances. Similar conditions were observed and documented when the nuclear power plant in Forsmark was built /Carlsson, 1979/.

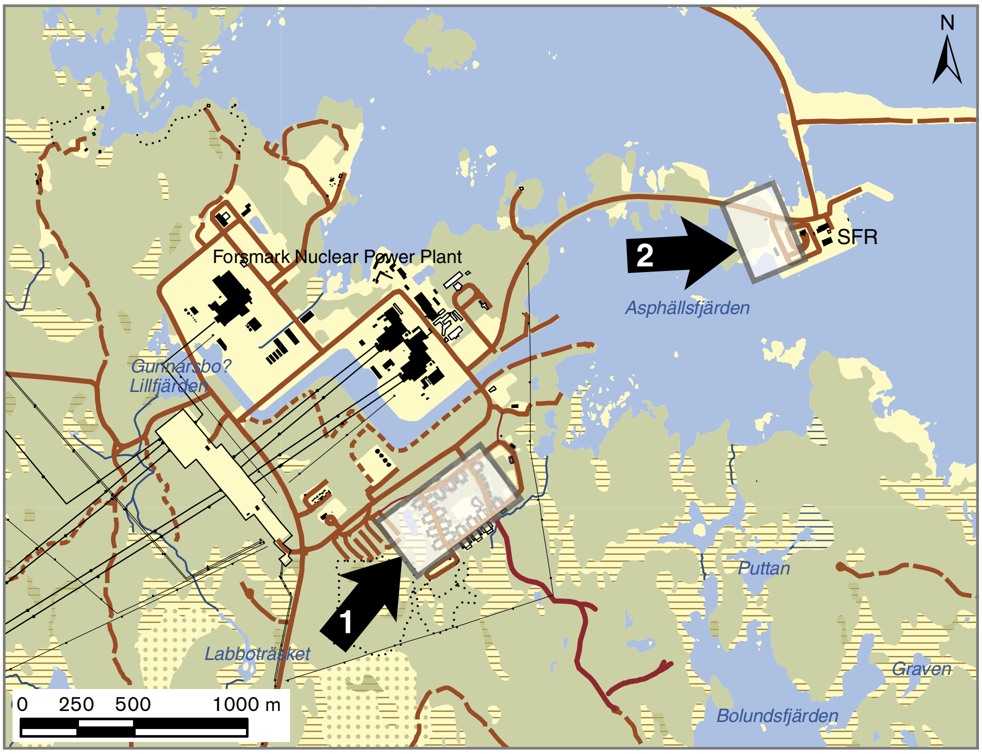
Another unexpected observation was made when the second deep cored borehole (KFM02A) was drilled. It was then found that the granite had been subjected to a strong alteration (episyenitization) at depths of 175 m and 180 m, as well as in the interval between 250 and 300 m. At these places, quartz has been dissolved, causing the granite to become porous. Studies will be conducted to get an idea of the extent of the porous granite around the borehole.

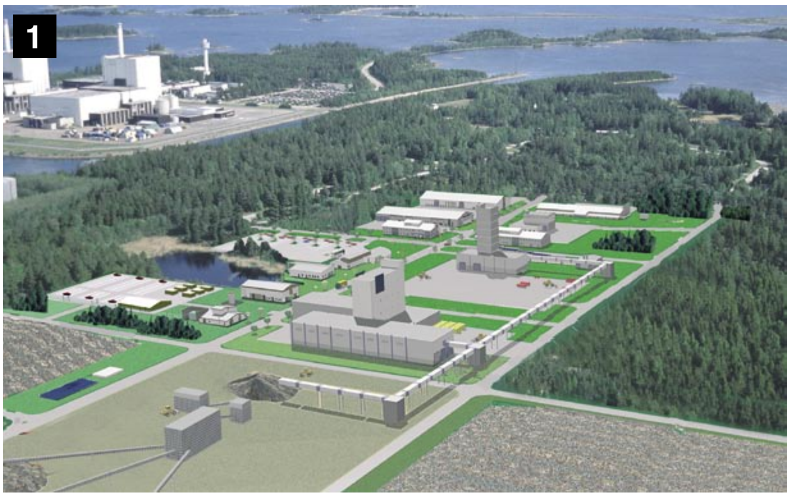
2.3.3 Industrial establishment

Design, which includes the work on a site-adapted configuration of a deep repository in Forsmark, is being pursued in parallel with the site investigation. The data gathered thus far confirm that the technical and environmental prerequisites for establishment are met, which, along with the availability of potentially suitable bedrock, was the main reason why Forsmark was chosen as a siting alternative. Possible locations and layouts of above-ground facilities required by the deep repository were studied in the initial phase. Figure 2-13 illustrates the two alternative solutions that have been sketched. In the one case, the deep repository's surface facilities are located east of the roundabout at the entrance to Forsmark's industrial area. The Forsmark NPP's temporary housing is located on parts of the area today. In the other case the plant is instead sited on partially filled-in land adjacent to the SFR facility. The alternatives do not entail any essential difference for the deep repository's underground facilities – which in both cases are assumed to be situated in the northwestern part of the candidate area – but are based on partially different system solutions. The intention is, at a later stage, to prioritize one of the alternatives for complete design.

Based on the geological information, early sketches have also been prepared of possible layouts for the deep repository's rock facilities with central area, deposition areas and connecting tunnels. The main purposes have been to clarify whether sufficiently large volumes of suitable rock are available, and to provide a basis for improving the investigations. Different assumptions have been made regarding, for example, locations and properties of fracture zones and other geological conditions where remaining uncertainties can have a great influence on space needs and layout. Figure 2-14 shows an example of a layout, where the deep repository is assumed to be built at a depth of 400 metres. An important conclusion from the layout work is that the rock volumes in the northwestern part of the investigation area are judged to be sufficient to accommodate a deep repository.

The deep repository's facilities can be placed along the road out to SFR. Some fill is needed along the shores since space is limited. Heavy shipments to and from the deep repository would go via an inclined tunnel whose entrance is to the right of the building in the middle. SFR and the harbour are furthest away in the picture.





Land for the deep repository's facilities is available from the entrance to the Forsmark plant (the present roundabout) eastward towards the barraks village. The need for temporary housing must then be solved in some other way. Nearest in the picture is a proposed stockpile for rock spoil that is hoisted via a shaft that discharges underneath the tall, narrow building. Further away is a shaft for a passenger elevator and ventilation

Figure 2-13. *Alternative locations for the deep repository's above-ground facilities – east of the roundabout at the entrance to the Forsmark plant or at SFR.*

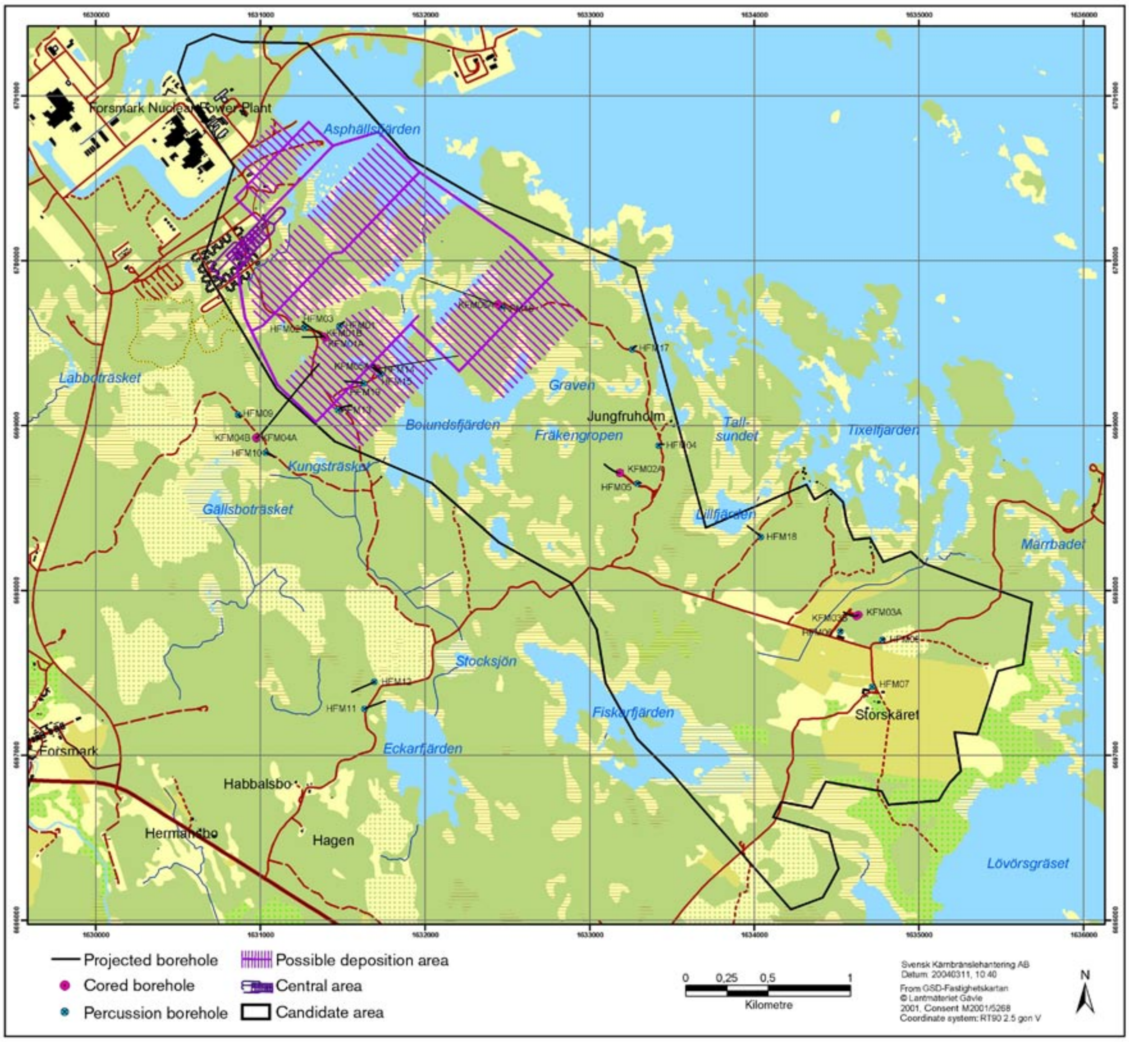


Figure 2-14. A possible layout for a deep repository situated at a depth of 400 metres in the northwestern part of the area.

2.4 Strategy for further investigations

2.4.1 Points of departure

SKB's strategy for the continued site investigation in Forsmark has been based on the following premises:

- The overall goal of the site investigation shall be achieved (section 2.1).
- The investigations shall provide supplementary data for the geoscientific key questions, according to section 2.3.2.
- The investigations shall be planned and executed so that time is available for the requisite coordination with, and feedback of facts and viewpoints from, other subprojects in the Deep Repository Project (section 1.2).
- The investigations shall be executed within the framework of the Deep Repository Project's overall planning (section 1.1).

2.4.2 Mode of working

The Deep Repository Project's organization and subprojects, and the stepwise mode of working are described in section 1.2. Besides the interaction between the subprojects, readiness must be maintained to deal with possible requirements and viewpoints from the regulatory authorities and their expert groups, as well as from the County Administrative Board, the municipality and local stakeholders via the established consultations. The programme must therefore allow for supplementary work at a late stage of the site investigation.

Moreover, there are a number of practical considerations. The site investigation ties up a site organization and large resources for drilling and investigations. A reasonable continuity in the work is necessary in order to make use of these resources in an efficient and economically defensible manner. Furthermore, the activities must be adapted in various ways to the area's valuable and to some extent protected nature, which also requires provision in the timetable.

2.4.3 Timing

According to the overall planning for the entire Deep Repository Project, a permit application will be submitted in 2008. In the final phase it is necessary to provide time for the analyses and evaluations that need to be done, both site-specific and more general, prior to site selection and application. For this reason the investigations should be finished and the results reported by mid-2007. Different types of monitoring are then planned, pending the results of evaluations and SKB's site selection.

Before that, results will be sent to the different subprojects in packages called "data freezes" timed so that the work with site description, facility design, safety assessment and environmental studies can go ahead. An important part of the strategy for accomplishing this is to decide as early as possible on preliminary locations for both the deep repository's deposition areas and other facilities under ground (central area, accesses), as well as the above-ground facilities. This is a prerequisite in order to:

- Optimize the positioning of boreholes and other investigation activities.
- Be able to present layouts and the consequences of the surface and underground facilities early on at EIA (environmental impact assessment) consultations so that any viewpoints can be taken into account in the continued work.
- Carry out safety assessments.

Another aspect that must be taken into consideration is that certain investigations require undisturbed conditions. This is true, for example, of measurements of natural groundwater conditions, interference tests between boreholes, and tracer tests. These measurements may be disturbed by nearby drilling. It is therefore an advantage if drilling in the preliminary repository area can be finished before these measurements begin.

2.4.4 Strategy

Taking into account the results obtained so far and the goals and requirements presented for the site investigation, a strategy in four points has been arrived at for the remainder of the site investigation in Forsmark:

1. Choose the northwestern part of the investigation area as a priority site. By "priority site" is meant the area that is of particular interest for the repository and on which further investigations will be focused.

2. Determine, for the priority site, the geological boundaries of the available rock volume at repository depth.
3. Characterize the available rock volume on this site to the required extent and level of detail.
4. Characterize the priority site's hydraulic boundary areas.

The reasons for this strategy are presented below point for point, along with a general discussion of what investigations may be necessary to implement the strategy.

1) Choose the northwestern part of the area as a priority site.

The candidate area can be divided into a northwestern and a southeastern part, situated on either side of the interpreted relatively wide fracture zone (zone A2) with elevated hydraulic transport properties which intersects the area at repository depth at the level of borehole KFM02A, see Figure 2-15. Both the northwestern and the southeastern part are judged to have bedrock that warrants further investigations. The difference noted is a higher frequency of gently-dipping, water-bearing fracture zones in the southeastern part.

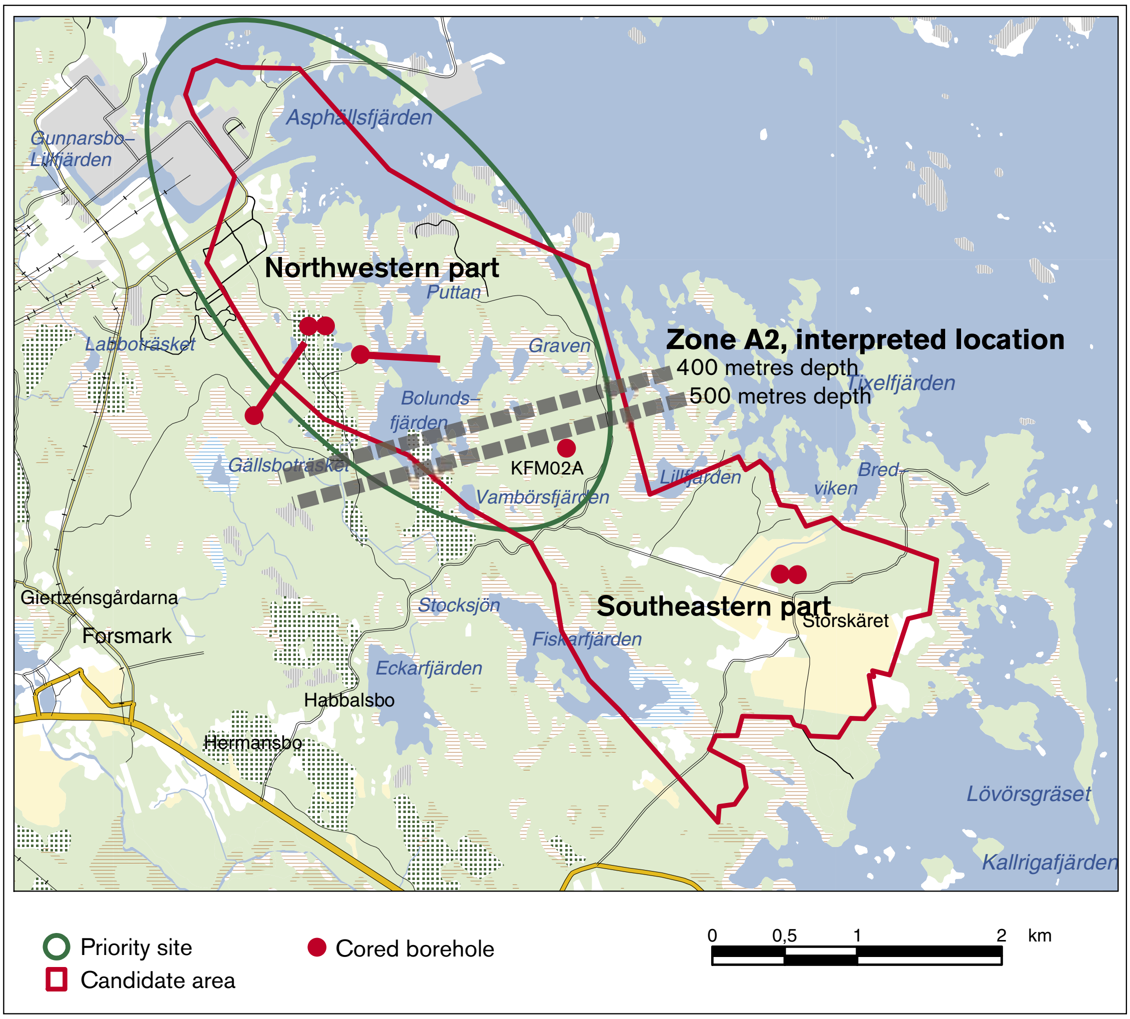


Figure 2-15. *The interpreted, dominant fracture zone A2 is judged to divide the candidate area into a northwestern and a southeastern part, from the viewpoint of a repository. The investigations are being focused on the northwestern part.*

The technical and environmental advantages of a location in the northwest are obvious: nearness to existing industrial facilities, roads, etc. The layout studies and underlying investigation results presented in section 2.3 show that a deep repository can in all probability be accommodated within the northwestern part. In view of this, SKB chooses the northwestern part of the candidate area as the priority site.

The strategy of focusing on the northwestern part of the tectonic lens has advantages, but is also associated with risks. The advantages include good prospects of achieving the goals of the site investigation with a reasonable input of resources and within the allotted time frame. The obvious risk is that the properties of the relatively limited rock volume that is investigated will not live up to expectations. If this should happen, a modified strategy will be required, with consequences in terms of both time and resources.

2) Determine, for the priority site, the geological boundaries of the available rock volume at repository depth.

The boundaries of the tectonic lens in the northwestern part are only partially known today (cf Table 2-1). Important questions remain to be answered, related to e.g. the fold hinge that has been identified by surface mapping in this part of the area, as well as lithological and tectonic boundaries on the northwest, north and northeast. There is therefore reason to continue the survey of the boundaries of the rock volume suitable for a deep repository that has been initiated with the completed or ongoing drilling work. Drilling of inclined boreholes from inside the lens out towards its margins is the most important method here. Geophysical ground surveys (seismic reflection) can also contribute, along with data from investigations conducted in conjunction with the construction of the NPP and SFR. Another question with a bearing on the available volume is the location and properties of the gently-dipping fracture zone (A2) that borders the priority site on the southeast. Additional drilling is required to determine this with greater precision.

3) Characterize the available rock volume to the required extent and level of detail.

The main tasks when it comes to characterizing the rock on the priority site are to clarify the properties and importance of already interpreted fracture zones at repository level, as well as the presence and importance of additional, as yet unknown zones. This includes examining the geological equivalents of interpreted lineaments and their importance at repository depth. Percussion and core drilling, in combination with surface-based investigations (seismic, excavation), are the most important methods. Other main tasks are continued characterization of rock stress conditions and groundwater chemistry at depth and of hydraulic connections in the horizontal and vertical directions, measurements of natural groundwater flow and tracer tests.

If the drilling indicates sufficient volumes of good rock on the priority site, the design of descents and the deep repository's central area will be pursued further, based on the current, preliminary placement of the central area. Boreholes are needed to obtain the requisite engineering geology data in the form of rock stresses, rock quality and groundwater conditions in locations for descents and the central area. The design of the deep repository's surface facilities will also require certain investigations (soil and foundation conditions).

4) Characterize the priority site's hydraulic boundary areas.

The hydraulic and hydrogeochemical models of the site that are constructed as a basis for the safety assessment require boundary conditions in the form of hydraulic properties of bounding structures. A fundamental question is whether the water-conducting zones that intersect the tectonic lens more or less transversely end against the dominant deformation zones that bound the lens along its long sides, i.e. the Singö Fault in the northeast and the Forsmark and Eckarfjärd zones in the southwest. This is tentatively judged to be the case, but it is also conceivable that the transverse zones cross the longitudinal ones, at least in a hydraulic sense. A special drilling and investigation programme is required to shed light on this question.

No drilling is planned at greater distances from the priority site. Data on geohydrological and hydrochemical conditions on other sites in the region are available from the study site investigations in Finnsjön, about 15 km west of the candidate area in Forsmark /Ahlbom et al. 1992/. Geological information is also available from an approximately 400 metre deep cored borehole about 3 km west of the Forsmark NPP. In view of the region's generally flat topography and the dominant role which the aforementioned hydraulic margins are deemed to have, it is difficult to see what additional investigations on a regional scale could add from a hydrogeological or hydrogeochemical viewpoint.

2.4.5 Programme

The four points above reflect the strategy based on the data need described in section 2.3.2. This must be combined with an execution sequence that meets the requirements on coordination between the different subprojects and that is furthermore suitable from a practical viewpoint. Figure 2-16 shows the main features of the work plan that has been devised. The starting point is the integrated account of results done in the summer of 2004 (data freeze 1.2) and the corresponding site description currently being prepared. The milestones for the remainder are three more data freezes, with the following main purposes:

- Data freeze 2.1, August 2005: The main purpose is **cross-checking of the investigation programme** at a stage when there is still sufficient flexibility to adapt the programme to results obtained. Analyses, modelling and reporting will be adapted to this purpose.
- Data freeze 2.2, May 2006: The main purpose is **basis for facility design**. According to the plan, all data with a primary bearing on the facility design produced during the site investigation phase will be available at this point. Analyses, modelling and reporting will be adapted to this purpose.
- Data freeze 2.3, March 2007: Pertains to **final reporting of data from the site investigation**, as a basis for corresponding comprehensive site description and safety assessment SR-Site.

As is evident from Figure 2-16, all planned core drilling on the priority site will be concluded during 2005. Data will thereby be available for data freezes 2.1 and 2.2. What will then be lacking from the priority site are data from the investigations that require undisturbed conditions. These will be done in 2006. The results are primarily of importance for the safety assessment.

During 2006, the focus will be on characterization of the site's hydraulic boundary areas, with a bearing on data freeze 2.3. The aforementioned tests under undisturbed conditions will then also be performed on the priority site, along with any supplementary work occasioned by feedback from, above all, data freeze 2.1.

Figure 2-17 shows a general timetable for the Deep Repository Project with subprojects and milestones for the site investigation in Forsmark.

2004	2005	2006	2007	2008
Focus on priority site		Focus on hydraulic boundary areas	Finish site investigation by mid-year	Waiting position
Conclude characterization on the surface	Finish drilling within priority site	Finish all drilling in hydraulic boundary areas	Conclude all field investigations	Surveillance monitoring
	Data freeze 2.1 Data for cross-checking of investigation programme	**Data freeze 2.2** Data for facility design	**Data freeze 2.3** All data from site investigation	
		Possible supplementary investigation		Site selection, application

Figure 2-16. Work plan for the site investigation in Forsmark.

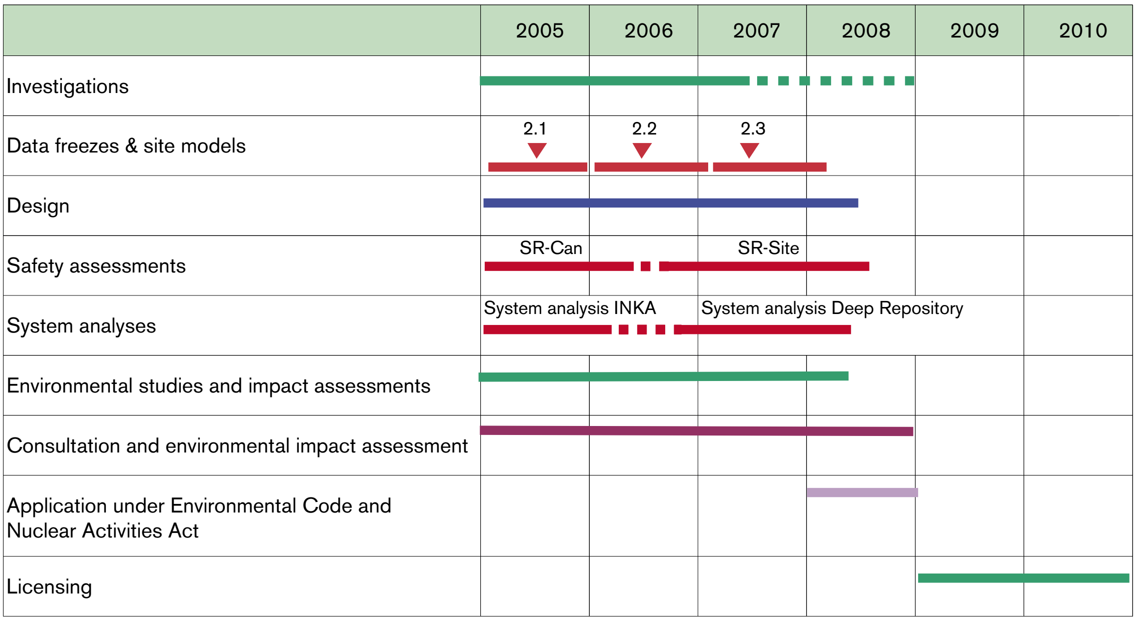


Figure 2-17. General timetable for the Deep Repository Project and the site investigation in Forsmark.

2.4.6 Drilling

Core drilling

Based on the chosen strategy, a drilling programme has been prepared. The programme is well defined for the first cored boreholes, after which it is necessarily more preliminary. It includes deep (700–1,000 m), medium-deep (200–700 m) and short (100–200 m) cored boreholes. The map in Figure 2-18 illustrates the programme with markings on a simplified geological map. Existing cored boreholes have also been marked. Two of the holes marked as planned (KFM06A and KFM06B) are currently being drilled. Table 2-2 describes the planned measures in greater detail and relates them to the above-mentioned purposes. The programme will employ two heavy core drilling machines instead of the one used so far.

The exact hole depths will in many cases be determined by the results obtained "along the way". However, most cored boreholes are planned to have a length of between 700 m and 1,000 m, according to Table 2-2. As before, a number of short holes are also needed to make up for the loss of core in the uppermost part of the holes drilled using the telescope technique. The drilling of different types of boreholes is described in section 3.8.

The majority of the planned boreholes will be documented and investigated with geological, geophysical and hydrogeological methods in roughly the same way as so far. Simplified procedures may be adopted, mainly for holes drilled for engineering geology reasons. Hydrogeochemical sampling at depth will be given particular priority to compensate for the current shortage of data for hydrogeochemical characterization of the site. This in turn affects how the boreholes are designed and what hydrogeological measurements are made. Rock mechanical investigations, in particular rock stress measurements, will also be accorded great attention in view of the fact that stress conditions have been identified as an incompletely resolved, site-specific key issue.

Percussion drilling

Percussion boreholes reach a maximum depth of about 300 metres and do not yield a core, but are much faster and less expensive to drill than the cored holes. They are suitable for investigating the importance of interpreted lineaments and for investigating near-surface,

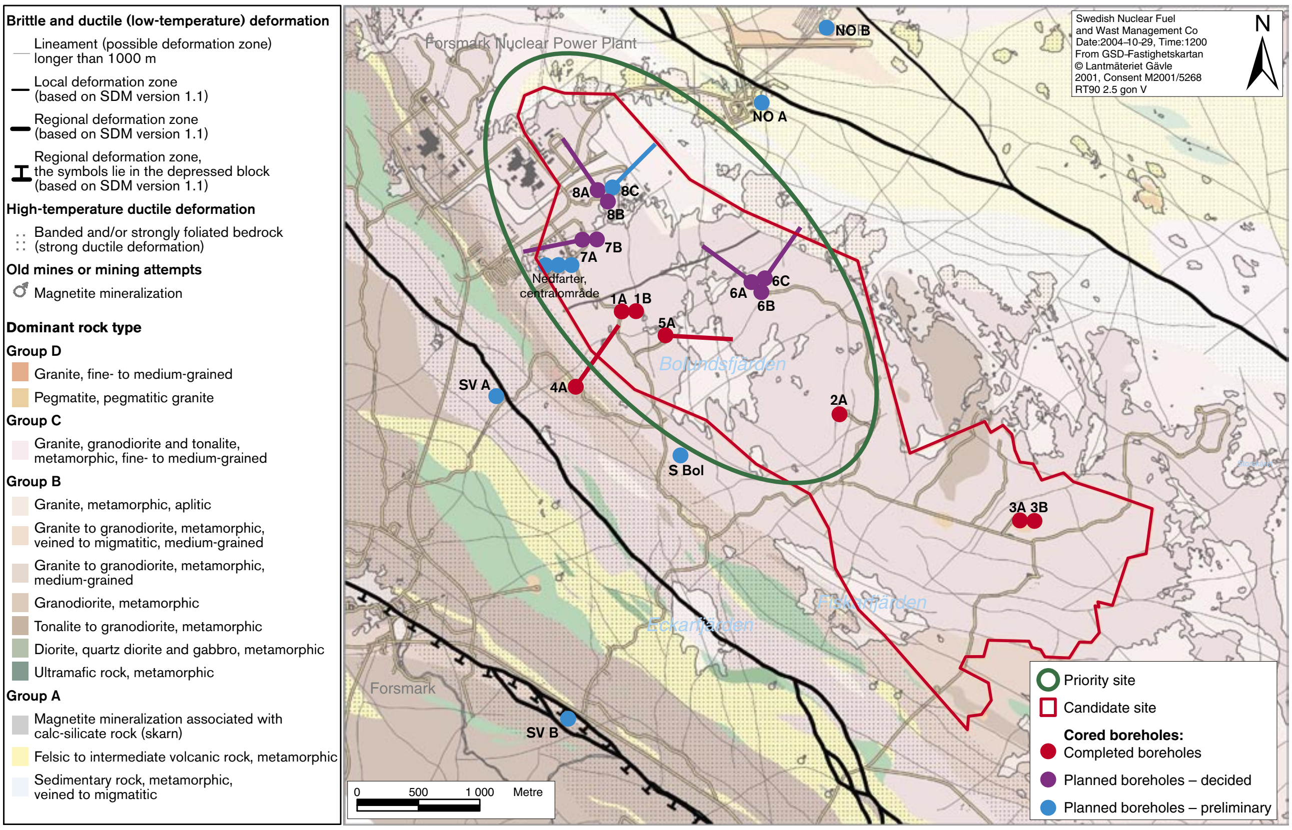


Figure 2-18. *Existing cored boreholes and planned core drilling during the remainder of the site investigation, see Table 2-2 for explanations.*

gently-dipping fracture zones. It is tentatively estimated that 10–15 percussion boreholes are needed, with a concentration to the priority site and the hydraulic margins. Most will probably be drilled to investigate the importance of interpreted lineaments. In the same way as previously, percussion boreholes will also be used as wells for flushing water for core drilling. The locations of the percussion boreholes have not been determined. In addition to feedback from analyses and site description version 1.2, data from ongoing seismic surveys will contribute important data for positioning the boreholes.

Table 2-2. Programme for remaining core drilling in Forsmark.

Designation (see Figure 2-18)	Planned work
Supplement the survey of the priority site's geological boundaries and features	
7A	A drilling site (DS 7) will be established at the residential area. A deep borehole (7A) is planned in a westerly direction, towards the interpreted geological boundary in this part of the area. The hole will be designed for complete chemical characterization.
8A, 8B, 8C	Another drilling site (DS 8) will be established at the inlet to the intake channel. A deep hole (8A) will be drilled in a northwesterly direction for the principal purpose of surveying the fold hinge in this area, plus a supplementary short hole (8B). Another deep hole is planned (8C), preliminarily in a northeasterly direction, to characterize the rock volume, investigate lineaments and possibly determine the northeastern geological boundary. 8A and 8C will be designed for complete chemical characterization.
6C	On existing drilling site 6, a deep hole will be drilled in a northwesterly direction (6A), plus a supplementary short hole (6B). Another deep hole is planned (6C), in a northwesterly direction and for the same purpose as 8C. 6A and 6C will be designed for complete chemical characterization.
S Bol	The information on the geology at depth in the southern corner of the priority site is incomplete. Among other things, better knowledge is needed of the gently-dipping fracture zone (A2) that separates the different parts of the candidate area. A new drilling site with a deep borehole (S Bol) is therefore planned in the area south of Bolundsfjärden. The location has not yet been determined; sensitive nature conservation interests must be taken into consideration. It is tentatively assumed that rock stress measurements by overcoring will be performed in this hole.
Collect data as a basis for placement and design of descents and central area	
7B	The deep borehole 7A will go through the rock volume that is tentatively prioritized for a deep repository's central area. After this a medium-deep, vertical hole (7B) is planned. The main purpose is rock stress measurements and other engineering geological characterization.
Descents	Additional drilling will be required later on as a basis for more exact design of descents and central area. Two or three medium-deep holes (max. 500 m) are tentatively planned. Locations and directions will be determined on the basis of the data and knowledge of rock conditions and sketched facilities available at any given time. Two more holes from drilling site 7 are a possibility, but another drilling site in the industrial area will probably be needed. Measurement programmes for the holes will be governed by design needs.
Characterize the priority site's hydraulic boundary areas	
NO A, NO B	The Singö Fault is judged to comprise the priority site's boundary area on the northeast. Detailed planning of drilling to characterize the Singö Fault remains. Preliminarily, two medium-deep holes (NO A, NO B) are being planned from sites adjacent to the SFR area. One of these can be drilled from the SFR repository, provided it doesn't affect the operation of SFR and that a permit can be obtained. Both boreholes will be designed for complete characterization; rock stress measurement by overcoring is also possible in the hole beneath the SFR repository.
SV A, SV B	There are two alternatives for investigation of the boundary area on the southwest: The Eckarfjärd Zone from a site west of drilling site 4, or the Forsmark Zone from a site near highway 76 east of Forsmarks Bruk. Two medium-deep holes are preliminarily planned on one of these sites. Another possibility, illustrated in Figure 2-18, is one hole at each zone (SV A and SV B). Results from seismic reflection and percussion drilling will be taken into consideration before the investigation strategy is finalized. Both boreholes will be designed for complete chemical characterization.

3 Investigations

Based on the strategy and the drilling programme presented in Chapter 2, a programme has been devised for further investigations of geosphere and biosphere in Forsmark. The programme is presented under the appropriate discipline headings, even though the investigations are often carried out jointly for several disciplines. For each discipline, first the purpose and then the goal of the investigations is presented, followed by important results from completed investigations and questions that remain to be answered. Finally, the investigation programme for the remainder of the site investigation is presented. The programme should be regarded as a best estimate based on SKB's current state of knowledge. As the programme is carried out, new knowledge will become available that may warrant changes in the continued investigation programme.

3.1 Surface ecosystems

3.1.1 Purpose and goal

The surface ecological investigations have several receivers and purposes. To enable the impact of the site investigation to be described and any effects minimized, knowledge is needed of where sensitive species and biotopes are located. This knowledge, together with information on ongoing and planned land use as well as protected and valuable areas, is also needed for environmental studies and assessment of impact for environment and human health stemming from construction and operation of the deep repository. Much more detailed information is required about the structure and functions of the different ecosystems for the safety assessment. The questions and parameters that are particularly important vary between the receivers. According to the calculations presented in the interim report for the safety assessment SR-Can /SKB, 2004d/, it is above all topographical low points (wetlands, lakes, sea) that are of great interest. Such areas can constitute discharge areas, which means they are potential release points for radionuclides. For environmental studies and assessment of impact for environment and human health, for example to judge the effects of increased traffic, it may be necessary to study a larger regional area. The size of the areas of interest also varies depending on what is being studied, for example different animal species. In the case of species that move over relatively small ranges (rodents etc), the focus area will be relatively limited, while the scale will be larger for species with larger ranges (moose etc).

Data from the site investigation will be used as input in the systems ecological models underlying the safety assessment. Systems ecological models need data in the form of quantity of biomass and range of the dominant functional groups (herbivores, predators, filter feeders, decomposers) in each type of ecosystem. The flow between the functional groups via processes such as production, consumption and decomposition must also be described. Similarly, the models need data on non-living material, such as Quaternary deposits, as well as flows of water and matter. Figure 3-1 shows an example of a systems ecological model.

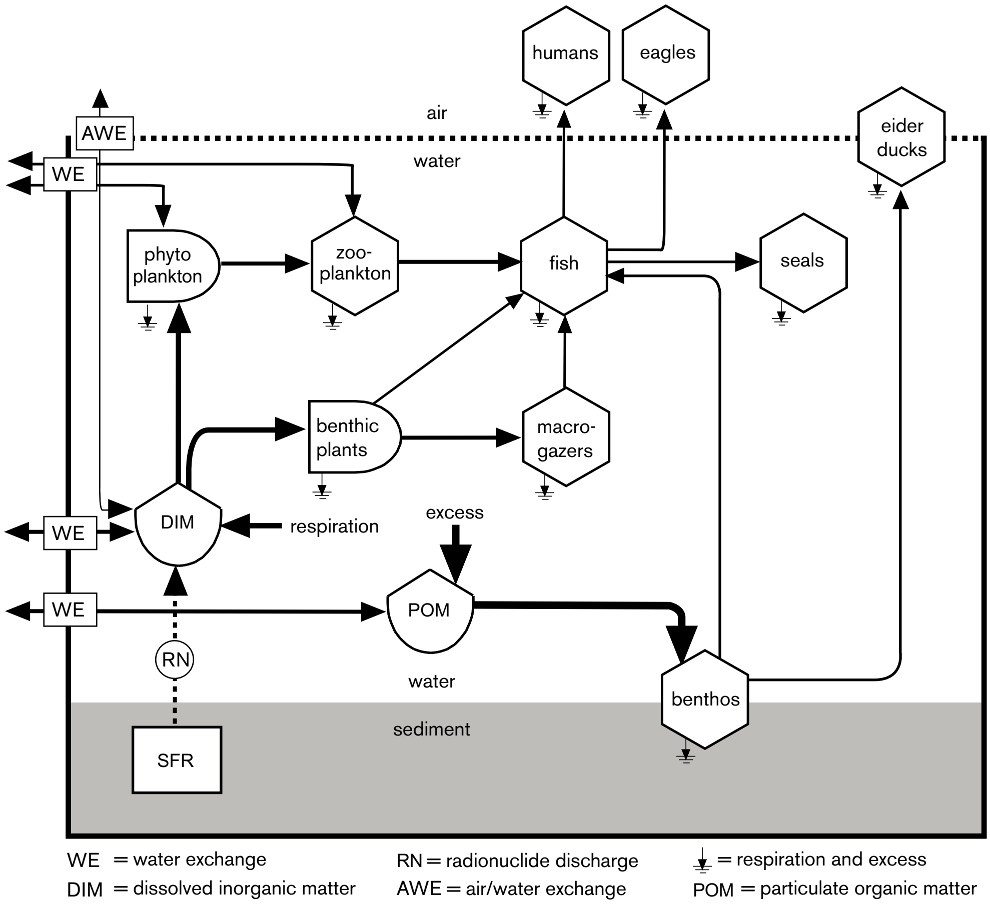


Figure 3-1. Example of systems ecological model: carbon budget and flows in an area in Öregrundsgrepen /Kumblad, 2004/.

3.1.2 Important results from completed investigations

During the initial stage of the site investigation, the investigations were concentrated on obtaining data for maps and spatial models of ecosystems in, above all, the regional model area. A large part of the ecosystem survey has now been completed. All investigations and their results are presented in reports, mainly SKB's P-report series.

Surveys have been conducted in the following areas:

- Flora and fauna on land:
  - Vegetation map /Boresjö Bronge and Wester, 2002/.
  - Dominant plant species and their biomass /Abrahamsson, 2003; Fridriksson and Öhr, 2003/.
  - Amount of dead wood /Andersson, 2004/.
  - Key habitats.
  - Game /Cederlund et al. 2003, 2004/.
  - Rodents (voles and mice).
  - Birds /Green, 2003, 2004/.
  - Amphibians and reptiles /Andrén, 2004/.
- Ecosystems in water:
  - Identification of catchment areas /Brunberg et al. 2004/.
  - The area's lakes and lake habitats /Brunberg et al. 2004/.
  - Chemical and physical parameters in surface water /Nilsson et al. 2003; Andersson et al. 2003/.

– Fish sampling in lakes /Borgiel, 2004b/.
– Surveying of underwater vegetation and benthic fauna in lakes and shallow sea bays /Tobiasson, 2003; Blomqvist et al. 2002; Nilsson et al. 2003/.

• Deposits:
  – Soil inventory /Lundin et al. 2004/.
  – Sediment sampling in lakes and shallow sea bays /Brunberg and Blomqvist, 2003; Borgiel, 2004a/.

Some supplementary work is needed, however (see section 3.1.4). In addition, knowledge gaps where supplementary data are needed may be identified in conjunction with preparation of the site model version 1.2.

Sampling points, results etc are entered in SKB's GIS database. Maps with virtually any theme and content can then be extracted from the database. As an example, Figure 3-2 shows the soil map for the Forsmark area /Lundin et al. 2004/.

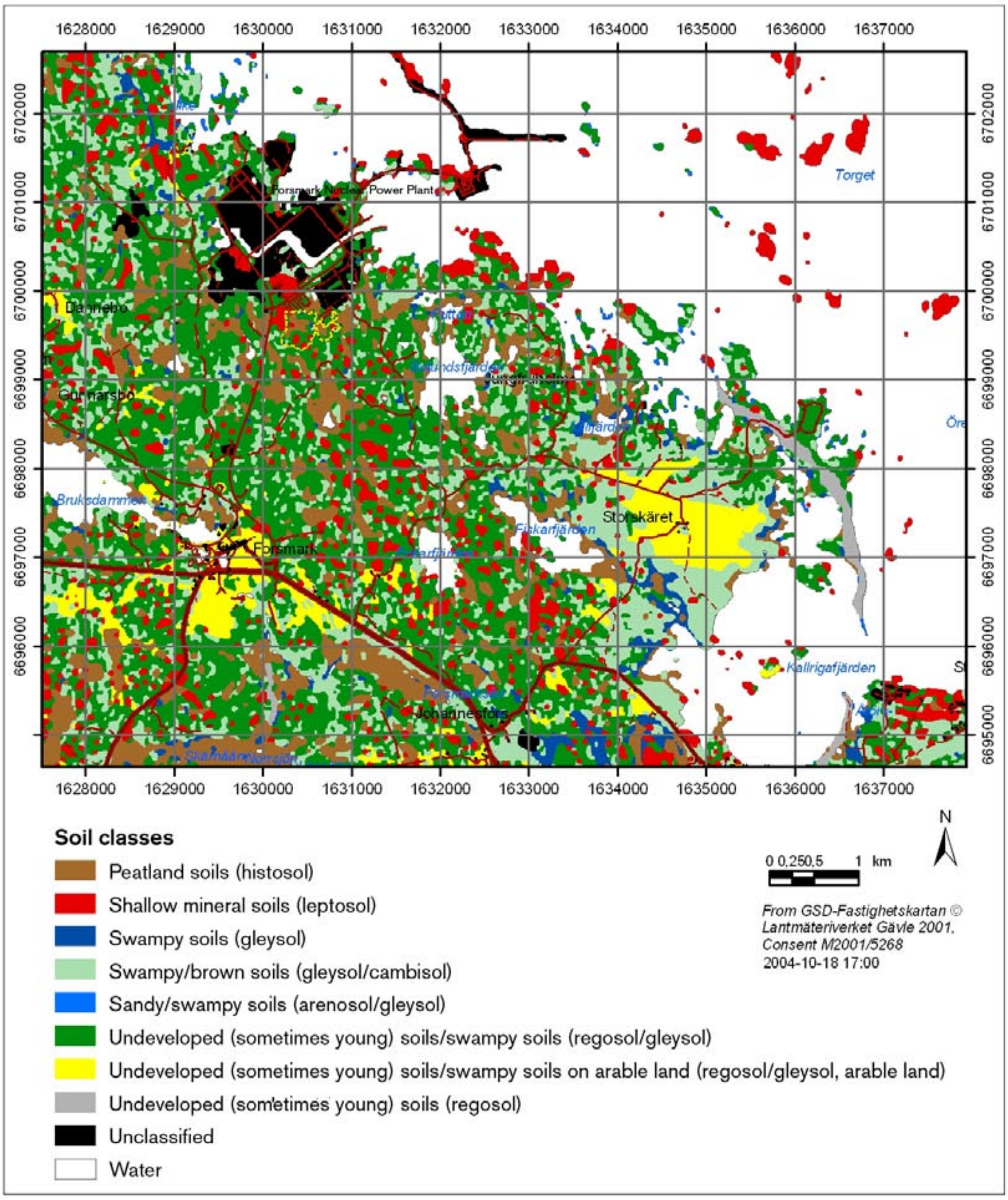


Figure 3-2. Soil map for Forsmark area.

3.1.3 Important questions remaining to be answered

The remainder of the site investigation will focus mainly on process measurements, in other words quantification of the most important ecosystem functions. The process measurements include surveying of primary production, consumption and decomposition as measured by respiration, transport of water or other substances, for example via plant transpiration, and immobilization of substances by, for example, sedimentation. Quantification of the ecosystem functions is as important as characterization of the different biomass and range of the subcomponents.

What happens in the boundary area between biosphere and geosphere is of great importance for an understanding of how the deep and superficial groundwater interact. A number of important processes that control what happens with radionuclides in this zone remain to be explored. These include fluctuations in the groundwater table as well as permeability and the variation of sorption properties with depth.

Another issue that needs to be explored is the hydrology of the wetlands in the Forsmark area. These ecosystems may be important recipients in the event of a leakage of radionuclides from the deep repository. They may also be affected by a lowering of the groundwater table.

3.1.4 Investigation programme[4]

Supplementary surveys on land

Deposit profiles

Excavations have been carried out in the autumn of 2004 in the discipline of geology in order to define and characterize lineaments. This makes it possible for other disciplines as well to conduct investigations in the trenches that are dug. For example, in the discipline of surface ecosystems, the extent of typical soils, various transitions and root depths have been documented. In order to characterize the soils chemically, samples that are representative of the most important soil types in the area have been collected.

Wetlands

Wetlands are probable recipients for radionuclides. Supplementary investigations are therefore planned, which will probably be conducted in campaign form. What needs to be clarified is what types of wetlands there are in the area and how they were formed. The hydrology of the wetlands (water flux) and how the elements flow also need to be investigated.

Fine roots

Today there is a large nationwide body of data describing the coarser fractions of tree roots. Based on this body of data, mathematical tools have been developed that can quantify the biomass content of the coarser root fractions. Corresponding knowledge is largely lacking on the fine roots, i.e. the smaller fractions. Knowledge of the quantity and extent of the fine roots in the soil profile is necessary in order to understand and quantify the cycling and accumulation of substances in ecosystems. These factors are important in modelling and analysis of radionuclide transport.

[4] See also sections 3.2 (Quaternary geology), 3.5.4 (Hydrology) and 3.6 (Hydrogeochemistry).

During 2005 we plan to conduct studies of the biomass and primary production of the fine roots on the same sites where we have carried out inventory and determination of plant biomass on land.

Vegetation

A small vegetation mapping may be carried out in order to obtain up-to-date knowledge of current conditions prior to licensing and monitoring.

Fauna

During the initial site investigation, a survey was made of the occurrence and range of the large mammals in the area, but not the occurrence of invertebrates. From a conservation viewpoint, it is sufficient to survey and follow the habitats in which sensitive invertebrates, mainly insects, live. This has been done via the inventories of biotopes and substrates, in particular the key habitat inventory conducted by the National Board of Forestry. What additional data would be needed to take into account the function of invertebrates in the ecosystems (i.e. what their importance is in terms of flows, pools of material, etc) will be clarified in conjunction with the site model, version 1.2.

Supplementary surveys in water

Flora and fauna

A large portion of the aquatic vegetation consists of reeds. Our quantitative knowledge of reeds and the fauna that lives in and around the reeds in the model area is not satisfactory. Data are probably of importance for site modelling and safety assessment, since they are needed to understand and quantify the cycling and accumulation of the substances in the ecosystems. A pilot study was conducted in Oskarshamn during 2004. The scope in the Forsmark area will be determined on the basis of the results of this study, where compilation is under way. The field work is planned to be done during the summer of 2005.

Fish

Data on the fish fauna may need to be updated as a basis for licensing and monitoring. In this case, it is possible that the National Board of Fisheries will add a point or two in the fish investigations which they conduct on behalf of the Forsmark NPP. This is planned as a one-off activity.

Oceanographic surveys

At present, current velocity and direction, as well as conductivity and temperature profiles, are being measured at a number of places in Öregrundsgrepen. This measurement series will continue for a year and will be used to calibrate the oceanographic model which SKB is constructing as a basis for the safety assessment. The model is based on the Forsmark NPP's extensive measurement programme with uniquely long measurement series. The model may also be used in the assessment of the environmental consequences of releases of drainage water from tunnels and rock caverns. There is a relatively heavy outflow of fresh water into Kallrigafjärden via the two rivers Forsmarksån and Olandsån. If discharge of groundwater in this part of the investigation area should prove to be a reasonable scenario, it is possible that the oceanographic model will need to be refined so that discharge to Kallrigafjärden is described in greater detail. In this case, supplementary measurements are needed, but the need and scope of these measurements will only be determined after the ongoing measurement series has been concluded and evaluated and further model calculations have been carried out.

Toxic pollutants, radionuclides and tracers

Work is under way on a programme for choice of materials and sampling and analysis of toxic pollutants, radionuclides and tracers. The programme is expected to be finished during the first half of 2005. Soil, peat and sediment samples, as well as biological material, including fish and rodents, have been saved and are available for analysis.

Process measurements – production and respiration measurements

Data from process measurements are mainly being collected as input to the systems ecological models underlying the safety assessment.

Terrestrial environment

Production and respiration on land was measured in the Oskarshamn area during 2004. Such measurements will also be carried out in Forsmark during 2005. The scope of the measurements has not yet been determined. The proposal is that production and respiration measurements should be done in forest, open land and wetland biotopes on 8–10 sites. The measurements will be made either once a month or four times a year in order to cover seasonal variations.

The measurements will be performed with the equipment shown in Figure 3-3. It consists of a glass hood from which a hose leads to a meter that registers the carbon dioxide concentration. Measurement in sunlight results in the sum of production and respiration in the investigation plot. In order to separate these two processes, a measurement is also performed where a dark hood is placed over the glass hood. The result then represents respiration alone, permitting the production fraction to be calculated.

Figure 3-3. *Measurement of terrestrial production and respiration.*

In order to investigate the water balance, a measurement system for estimating evapotranspiration will be obtained and placed on a suitable site within the area. The equipment measures wind speed, relative humidity and carbon dioxide concentration. The measurements are made at the stand level. The higher the meters are positioned, the greater the area that is covered. Evapotranspiration data are used for calculating the area's water balance, which is very important both for the hydrogeological modelling included in the safety assessment and for environmental impact assessment. However, the accuracy requirements of the two subjects probably differ. According to the plans, SKB will acquire and set up a meter in Forsmark during 2005. Measurements will be performed there for a year, after which the equipment will be moved to and used in Oskarshamn.

Aquatic environment

Direct production and respiration measurements for plants and animals in lakes and the sea will be done on 6–8 sites in four different biotopes (marine benthal, marine pelagial, lacustrine benthal and lacustrine pelagial). Measurements will be done four times a year in order to cover variations during the year.

The investigation setup can be seen in Figure 3-4. Plexiglas jars with a hole stoppered with a cork are placed on the bottoms of the various habitats. Oxygen is measured in the jar at the time of the measurement.

In addition to process measurements, measurements will also be done where net growth is determined, similar to what was done as a pilot study for bladder wrack (Fucus vesiculosus) in Oskarshamn in 2004. A number of bladder wrack plants were marked (using hole punches) before the growth season started, see Figure 3-5. When the growth season was over, the plants were taken up and growth was measured. In the Forsmark area, filamentous algae are important primary producers, and their annual dynamics will therefore be determined. Other species may also be studied, but the choice of species and the scope of the study have not yet been decided.

Figure 3-4. *Investigation setup for production and respiration estimation in aquatic environments.*

Figure 3-5. *Bladder wrack plant that was marked at the beginning of the growth season. The holes are 3 cm from the top of the shoot. The annual growth is obtained by measuring the length of the shoot again after the end of the growth season.*

3.2 Geology

3.2.1 Purpose and goal

The purpose of the geological investigations during the initial phase of the site investigation in Forsmark has been firstly to achieve a conceptual understanding on a regional scale of both the crystalline bedrock and the Quaternary deposits in the investigation area, and secondly to obtain a reliable body of data for a focusing of the investigations. The work has been pursued along two main lines: 1) detailed investigation of the extent of the bedrock and Quaternary deposits on the surface, and 2) characterization of rock volumes down to a depth of about 1,000 m by means of randomly drilled cored and percussion boreholes. Five strategically located cored boreholes (telescopic boreholes) to a depth of about 1,000 metres, one cored borehole to a depth of about 500 metres and 19 percussion boreholes to a depth of about 250 metres have been drilled to investigate the properties of the rock volume within the candidate area and document the occurrence of deformation zones. Brittle deformation zones are a key issue for the site description, since they can conduct groundwater and be of crucial importance for the possible configuration of a deep repository on the site.

The Quaternary deposits constitute a central part of the geosphere-biosphere interface and are also dealt with in the disciplinary programme for surface ecosystems, see section 3.1. A large portion of the superficial groundwater is transported through the Quaternary deposits, and knowledge of the three-dimensional extent of the different types of deposits is therefore essential for the surface hydrology modelling. The extent and properties of the Quaternary deposits (known as the regolith) are also of great importance for the radionuclide retention time.

All geological data collected has been, or is in the process of being, analyzed. Analyzed and processed data comprise the basis for the conceptual site-descriptive models. Model version 1.1 is finished /SKB, 2004c/ and version 1.2 is in preparation. The geological site models constitute the basis for rock mechanical, hydrological, hydrogeological and hydrogeochemical modelling, as well as for modelling of the transport properties of the bedrock. The geological site models thereby also comprise the basis for the assessment of long-term safety and for the layout of the deep repository's underground facilities.

3.2.2 Important results from completed investigations

Bedrock geology

A bedrock map was delivered in early May 2004, in good time before data freeze 1.2, see Figure 3-6. The map has been compiled from a large number of field observations /Stephens et al. 2003a; Bergman et al. 2004/ as well as analysis data from samples collected mainly during the field activities. In compiling this map, interpretation of geophysical data from airborne surveys has been integrated with bedrock geological field data. In addition to detailed determination of rock type boundaries, an important result has been the detection of large-scale folding within the tectonic lens comprising the candidate area, along with the occurrence of strong ductile deformation on both sides of this lens.

The body of data that describes the properties of the different rock types within the mapped area derives primarily from mineralogical, geochemical, petrophysical and geochronological analyses /Stephens et al. 2003b; Isaksson et al. 2004a; Page et al. 2004/. An important result is that all intrusive rock types in the candidate area have a high quartz content, which gives

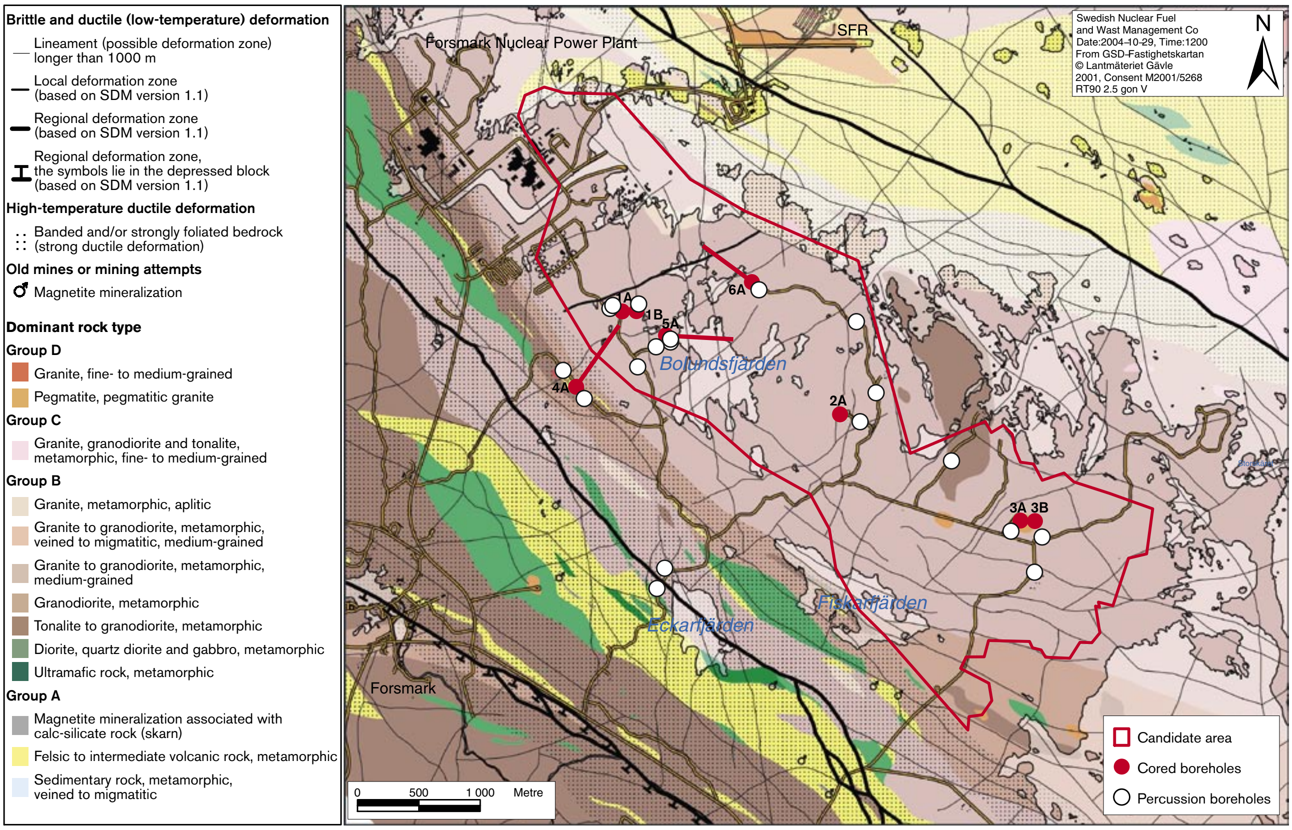


Figure 3-6. Geological map, version 1.2, of the investigation area in Forsmark.

the rock high thermal conductivity. The geochronological study reveals clear time intervals for the geological history of the Forsmark area. It shows that the cooling of the bedrock to a temperature below 300°C took place between about 1,630 and 1,700 million years ago. The results of datings with $^{40}Ar/^{39}Ar$- and (U-Th)/He technique provide different cooling ages for different blocks, which may indicate the oldest time for the movements and the relative direction of movement along the deformation zones between the blocks.

In an integrated effort with the discipline of Geophysics, a two-dimensional model of the occurrence of lineaments /Isaksson et al. 2004b/ in the investigation area was created by utilizing airborne geophysical, topographical and bathymetric data, as well as the results of older seismic refraction surveys, see Figure 3-7.

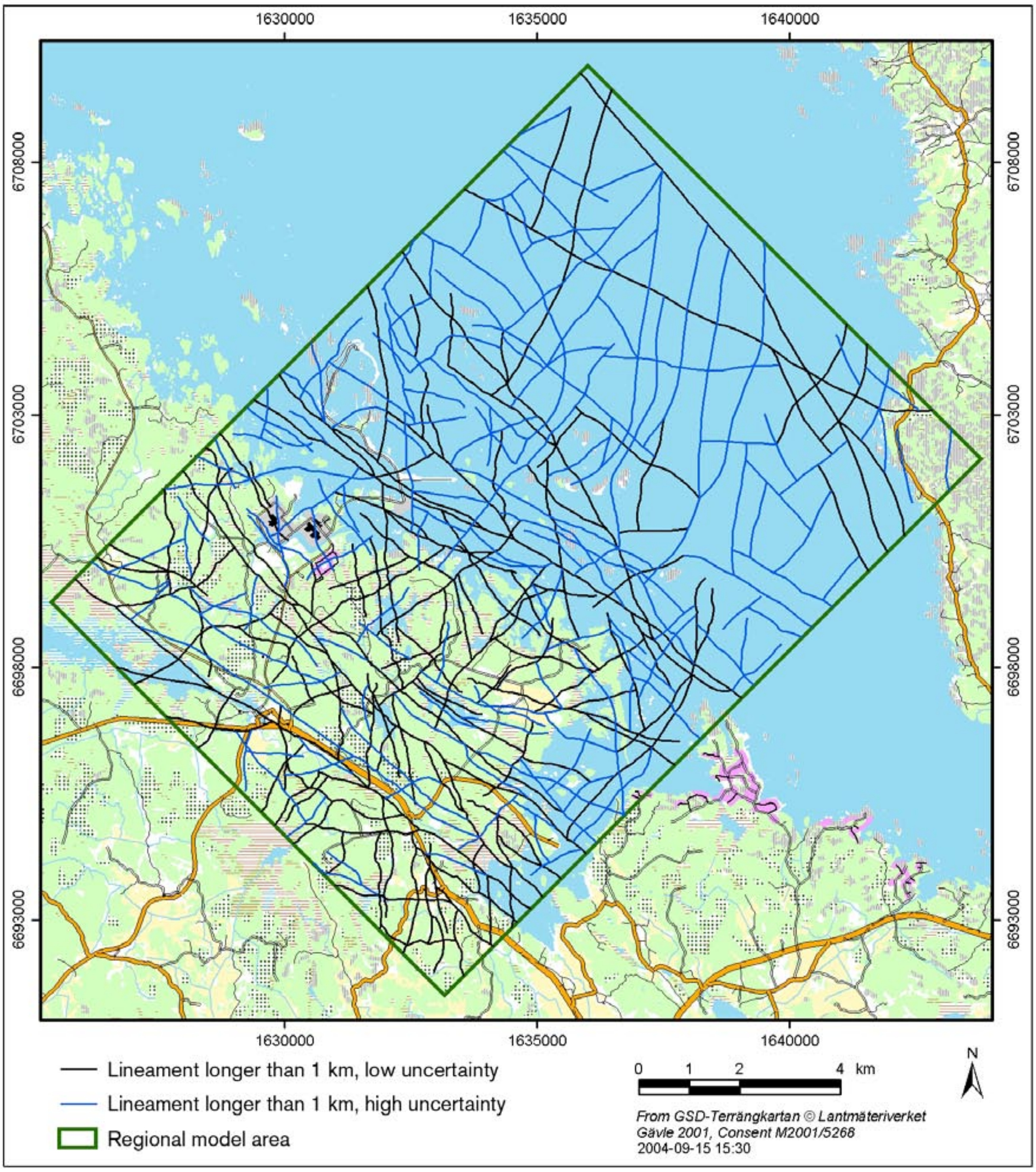


***Figure 3-7.** Lineament map of the investigation area in Forsmark.*

Detailed fracture mapping has been carried out on four drilling sites: DS2, DS3, DS4, DS5 and at a coastal location on Klubbudden. The sites represent three different rock domains. All drill cores and percussion boreholes have been mapped in detail with respect to rock types, alterations and fractures. The results of the fracture mapping, together with fracture data from the surface, are being used to construct a discrete fracture network model (DFN model) of the entire rock volume.

Geological single-hole interpretation has been performed of each individual cored borehole /e.g. Carlsten et al. 2004a/, based on data from core mapping /e.g. Petersson et al. 2003a/, geophysical borehole logging /e.g. Nielsen and Ringgaard, 2004/, including BIPS (borehole video) and radar logging /e.g. Gustafsson and Gustafsson, 2004/. The purpose of single-hole interpretation is to determine the vertical position of main lithological units and deformation zones by integrating existing measurement data, see Figure 3-8. Single-hole interpretations comprise a basis for the three-dimensional modelling of rock domains and deformation zones in the investigation area.

The drilling has verified that the character of the bedrock at a depth of 1,000 metres corresponds to what we see on the surface. It has also verified that many of the reflectors found in the candidate area in the early seismic reflection surveys (see section 3.3) corresponded to brittle deformation zones. These zones dip (incline) gently to the southeast and are most prominent in borehole KFM03A in the southeastern part of the candidate volume. The number of reflectors decreases in the northwestern part of the rock volume, which is interpreted to mean that gently-dipping brittle deformation zones are not as prevalent as in the southeast. On the other hand, the fracture frequency in the upper parts (down to a maximum depth of about 300 m) is relatively high in the northwestern cored boreholes KFM01A, KFM01B and KFM05A. The fractures are mainly subhorizontal or gently-dipping towards the southeast, in other words they exhibit roughly the same geometric pattern as the brittle, gently-dipping deformation zones in the southeastern part of the area. One of these zones (A2) probably emerges in or near the three aforementioned boreholes.

Mineralogical, geochemical and petrophysical data, similar to those obtained from the geological surface investigation, are currently available from the four cored boreholes KFM01A, KFM02A, KFM03A and KFM03B /Petersson et al. 2004/. The results with regard to the properties of the rock agree well with data from the surface investigation. Samples for geochronological investigations have been taken from one of the boreholes and show younger cooling age with depth. Furthermore, a special study has been made of fracture-filling minerals in boreholes. Six separate generations of fracture minerals, formed during different time periods and in conjunction with different geological events, have been found.

Quaternary geology

The Quaternary geological investigations have been focused on surveying the extent of the deposits on land and in lakes. The mapping has resulted in a detailed Quaternary deposit map that covers the central part of Forsmark's regional model area /Sohlenius et al. 2004/, see Figure 3-9. The smallest area that has been mapped is only 10×10 metres, so the map gives a detailed picture of the spatial distribution of different Quaternary deposits. Till is the most common Quaternary deposit in the area, covering 75% of the area.

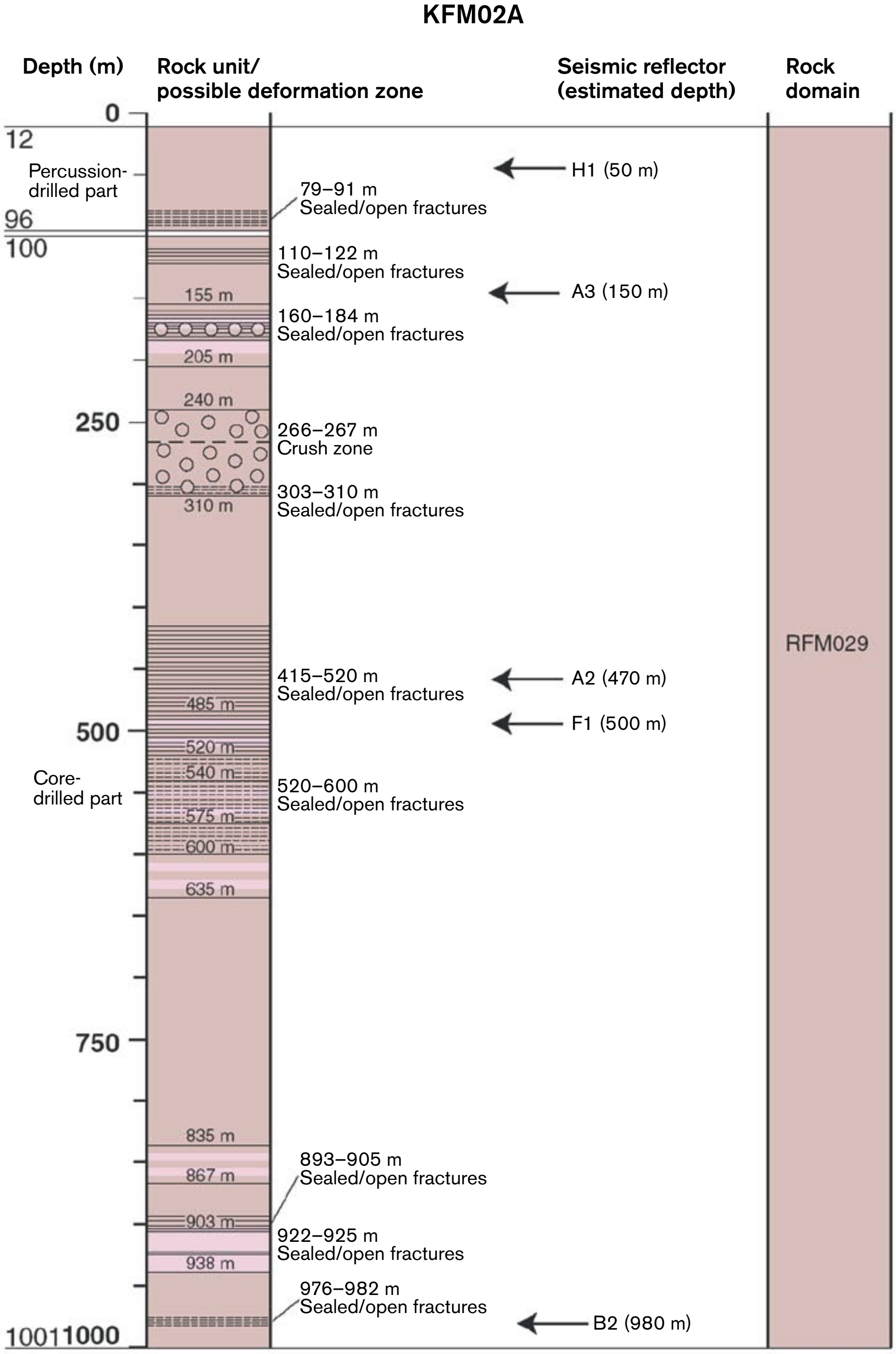


Figure 3-8. *Example of geological single-hole interpretation of borehole.*

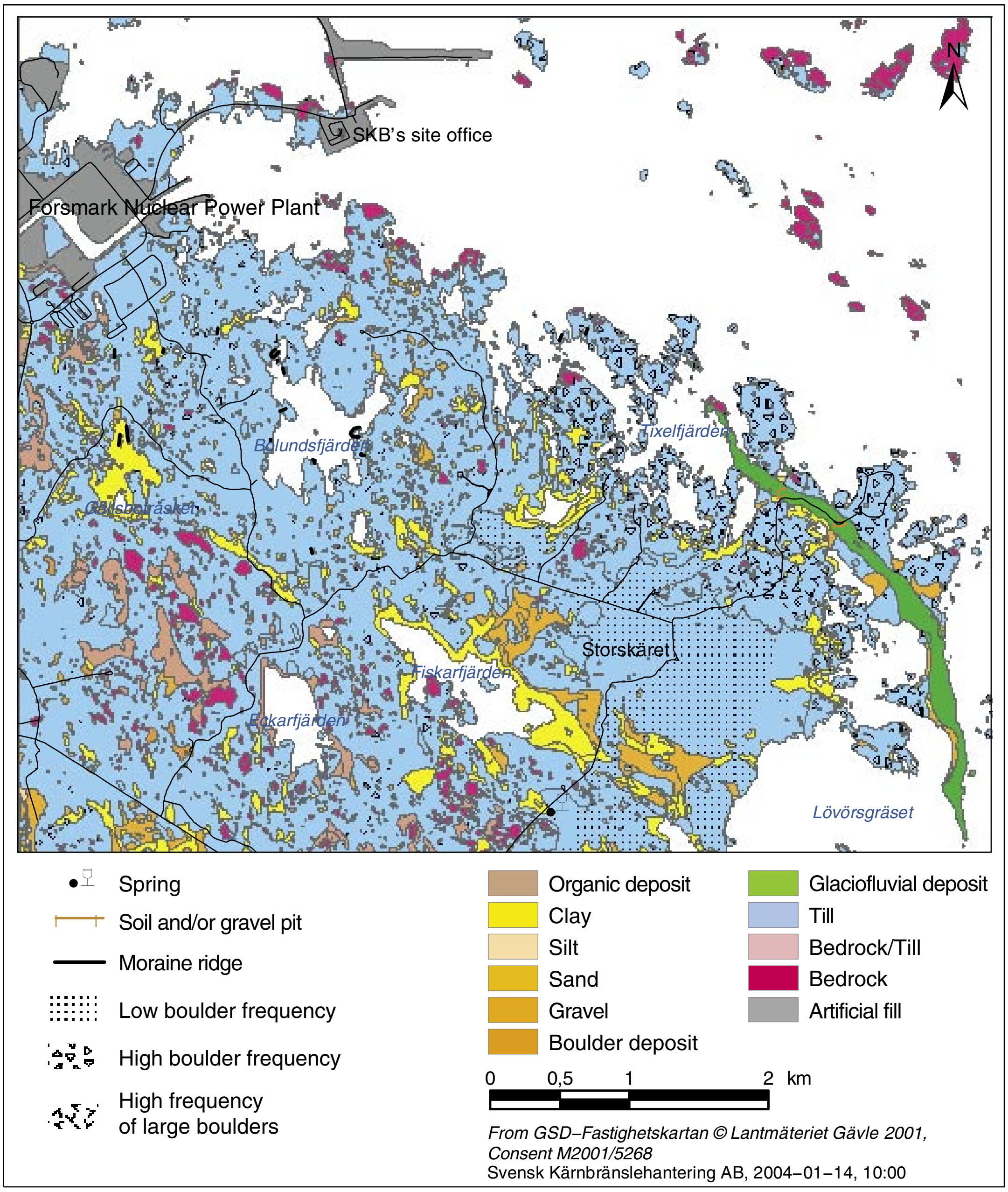


Figure 3-9. *Simplified version of Quaternary geological map of the investigation area in Forsmark. Till, which is the most common Quaternary deposit, is shown in blue.*

Marine geological investigations have resulted in a map showing the extent of the Quaternary deposits on the seafloor /Elhamre and Sandkvist, 2004/, see Figure 3-10. Moreover, a Quaternary deposit investigation has been done of the bottom of Kallrigafjärden /Bergkvist et al. 2003/. A comparison between the maps clearly shows that the seafloor is covered by a much larger proportion of clay and sand than the areas that have risen out of the sea. This may be due to the fact that the seafloor has been eroded and the sediments have been transported and deposited in topographic depressions.

Chemical analyses have shown that the till and the glacial clay are rich in calcium carbonate ($CaCO_3$) /e.g. Hedenström et al. 2004/. Its origin is paleozoic limestone, which forms parts of the seafloor north of the investigation area, in Gävlebukten and further north. The high lime content of the soil is an important prerequisite for the special flora in the area.

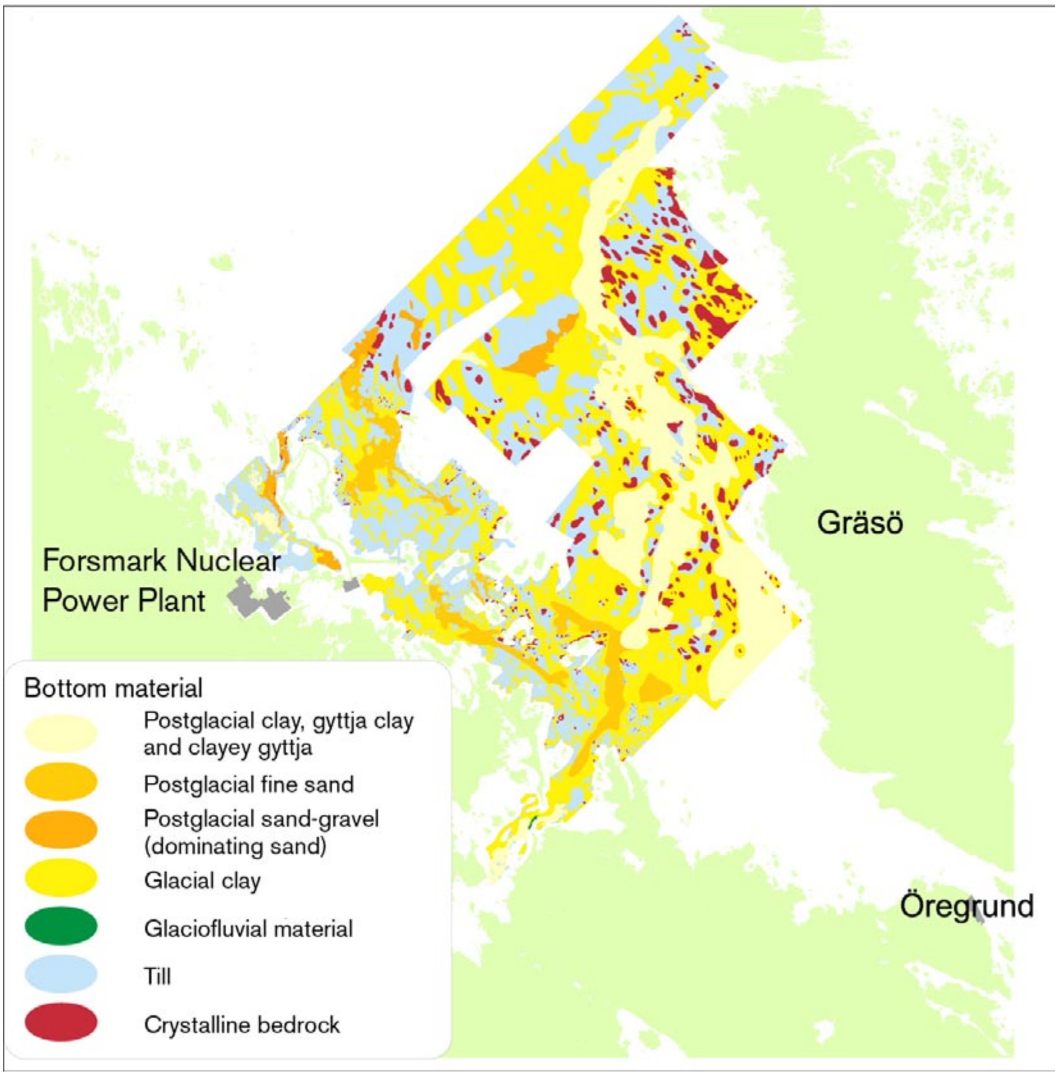


***Figure 3-10.** Marine geological map for parts of the bottom between Gräsö and the mainland based on the investigations conducted in 2002.*

Information on the extent of the Quaternary deposits at depth has been obtained from various types of drilling (auger drilling, percussion drilling and sampling with a Russian corer in sediments and peat) and from pit excavation /e.g. Hedenström, 2003; 2004; Johansson, 2003; Fredriksson, 2004/. The extensive documentation has resulted in a clarification of the complex extent of different types of till in the area and of the composition of the various till types. A sandy-silty till dominates in the northwest, while the southeastern parts, around Storskäret, are covered with clayey till and boulder clay. The results have also shown that the top surface of the rock is much more undulating than is suggested by the soil layers. Stratigraphic till studies with till fabric analyses were performed in deep excavated pits /Sundh et al. 2004/. These investigations have shown that the spatial distribution of the till is complex at depth as well. Among other things, a very hard clayey till was encountered under a porous sandy till at two places.

Investigations of sea and lake sediments have yielded good knowledge of the extent of water-deposited sediments and also show that the sediments in the area are of uniform composition /Hedenström, 2004/. Two peatlands have also been investigated /Fredriksson, 2004/. One of the findings is that the peat types are very young and therefore not very thick.

In the light of modern requirements, neither of the studied sites is suitable for extraction of fuel.

Furthermore, a special study has been conducted of the pollen content in glacial sediments, including material from the sediment-filled fractures encountered at drilling site 5 /Robertsson, 2004/. The pollen spectra indicate that the original deposition of the reworked pollen flora probably took place during the Eemian interglacial approximately 120,000 years ago. This means that the till was deposited during a stage of the most recent glaciation.

In another special study, the chemical composition of the till material was investigated. The study has confirmed that the probability of ore deposits in the candidate area is low /Nilsson, 2003c/.

Finally, investigations of indications of possible postglacial tectonics have been conducted during two field seasons and will be concluded during 2004/2005. So far, no conclusive traces of recent earthquakes have been found, but disturbed sediment layer sequences have been identified at several locations. Late- or post-glacial fault tectonics cannot, thus far, be ruled out /Lagerbäck et al. 2004/.

3.2.3 Important questions remaining to be answered

Bedrock geology

The main purpose of the planned drilling programme is to geologically define and characterize the rock volume on the priority site, as well as in surrounding hydraulic boundary areas, see sections 2.4 and 3.8. In addition, the investigations that have been conducted have given rise to questions that warrant a number of special studies.

Our understanding of the formation of the brittle deformation zones in Forsmark and their patterns of movement needs to be improved to enable models with higher confidence to be developed. Kinematic analysis of representative brittle deformation zones that have been verified both on the surface and at depth in boreholes therefore needs to be done. In this context it is important that studies of fracture filling minerals be coordinated with the structural characterization of fractures, particularly with regard to the orientation of different fracture sets.

Interpreted lineaments need to be investigated with respect to how representative they are as indicators of deformation zones. Studies of kinematics and other properties will be conducted on selected deformation zones. A lineament study is therefore planned during the autumn of 2004, where the plan is to dig pits across a number of representative and distinct lineaments for detailed study of the rock surface. In addition, a percussion drilling campaign will be carried out during the autumn of 2005. More pits will probably be dug then as well.

A supplementary geochronological investigation with $^{40}Ar/^{39}Ar$- and (U-Th)/He technique is planned for the purpose of arriving at a better chronological picture of the geological evolution of Forsmark under the temperature conditions when the brittle deformation zones were formed. This will provide important data as a basis for establishing the timescale for the oldest movements and the relative direction of movement along the deformation zones between the blocks. In connection with the study of fracture mineralizations and their relation to different fracture sets, a geochronological investigation is also planned. The purpose is to determine the chronological series of mineral growth for different fracture sets.

Supplementary bedrock geology mapping in the area southeast of Kallrigafjärden and in the northwestern part of Forsmark's tectonic lens is needed in order to confirm and gain a better understanding of the geometry of the large-scale folding in this part of the area. This study is of importance for the three-dimensional modelling of the rock domains in the Forsmark area.

Further, a detailed fracture mapping is planned to be done, if possible, in the area northwest of the emergence of the A2 reflector. The reason is that the fracture mapping that was done on drilling sites 2, 3, 4 and 5, as well as at Klubbudden, is not representative of the rock volume where the investigations will now be focused. The detailed mapping will serve as a basis for the discrete fracture network (DFN) model.

Data concerning the extent of the porous granite encountered in borehole KFM02A will presumably be obtained from the VSP surveys that are planned (see section 3.3). The result could possibly lead to further work that is impossible to predict today.

Finally, there is a need for a special study of the pretectonic alteration that has affected both the granite in the northwestern part of the candidate volume and the fine-grained granitic rocks in the adjacent rock domain in the northwest.

Quaternary geology[5]

Most of the Quaternary geology work within the site investigation has been done. What remains is to fill the geographic gaps and to answer certain key questions of importance for input data and boundary conditions for modelling of the surface ecosystems.

The Quaternary deposits on the bottom of sea areas with a water depth of less than 3 m have not yet been surveyed, but a mapping is planned. This will provide a complete Quaternary deposit map that includes both land and sea areas, and that will serve as an important basis for modelling of the future landscape.

Work has begun on constructing a first version of a three-dimensional soil layer model that shows both the depth to rock and the different soil layers. The results will constitute an important basis for the surface hydrology modelling as well as for the modelling of transport pathways for radionuclides. The soil layer model will be based on both data from drilling and excavation and results from ground-penetrating radar surveys, seismic and other investigations. In order for the model to fill its purpose, properties must be assigned to the different layers. This requires analyses of the parameters of the Quaternary deposits that are important for their transport properties, for example mineralogical composition and cation exchange capacity (CEC). The detailed planning of which and how many such analyses are to be performed remains to be done.

One knowledge gap that has been identified is how the many wetlands in the Forsmark area are structured geologically, and how they work hydrologically. An important question is what the properties of the Quaternary deposits at the bottom are, i.e. whether they are impervious (clay) or consist of coarse-grained material. This will be investigated in a broadly conceived campaign that is planned in collaboration with other concerned disciplines, for example surface ecology and surface hydrology (see sections 3.1 and 3.5).

The central questions surrounding the area's postglacial geological evolution, on land and at sea, have to do with the evolution of climate and vegetation, as well as sedimentation and erosion. This can be studied in sediment and peat cores. Pollen analyses of marine sediment and/or peat profiles can be done to describe the evolution of the regional area's

[5] See also sections 3.1 (Surface ecosystems), 3.4.4 (Hydrology) and 3.6 (Hydrogeochemistry).

postglacial vegetation. Since the Forsmark area does not have any peatlands older than about 1,500 years, two peat profiles from areas located further inland, but still as close to Forsmark as possible, can be studied. The results can provide information on climate variations and vegetation succession over a long period of time.

Sedimentation rates for the different Quaternary deposits will also be studied, and the erosive phases in marine and lake sediments, as well as peat sequences, will be dated. The marine environment can be studied in a sediment core that was taken in connection with the marine geological investigations in 2002. A key question that can then be answered is whether the Yoldia Sea was affected by brackish water in the Forsmark area. This is important information for defining the boundary conditions in the hydrogeological and hydrogeochemical modelling.

Questions relating to the glacial transport of rock material over long and short distances and the dynamics of the ice are important for our conceptual understanding of the site. Mapping of rock types in the large blocks encountered near the Börstilåsen esker can provide information on transport pathways. Rock type determination of the gravel fraction can also provide information on how long the till material has been transported.

3.2.4 Investigation programme

The work will primarily focus on collection and processing of data from the planned boreholes. The drilling programme for 2005 will primarily be concentrated on investigation of the rock volume in the prioritized northwestern part of the candidate area. During 2006, boreholes will be drilled towards the northeastern and southwestern boundary zones, see section 2.4.

The most important planned investigations in the disciplines of bedrock geology and Quaternary geology are summarized below.

Bedrock geology

- Borehole mapping (so-called Boremap mapping, where the drill core is mapped together with video images of the borehole wall (BIPS), alternatively for percussion boreholes – drill cuttings and BIPS images), along with geological single-hole interpretation, are among the most time- and resource-consuming activities in the bedrock geology programme.
- Kinematic analysis of structures in representative brittle deformation zones, from boreholes and on the surface. Together with geochronological investigation, this contributes to the conceptual model and an understanding of the brittle tectonic history of the area.
- Lineament studies in excavated trenches to determine whether the lineaments are representative as indicators of deformation zones, and if so conduct studies of kinematics and properties.
- Investigation of large-scale fold structures in the tectonic lens in Forsmark (rock domain 29). The purpose is to obtain a better understanding of the geometry of rock domain 29.
- Detailed fracture mapping of outcrops in the area northwest of the emergence of the A2 reflector. The purpose is to obtain more data as a basis for the three-dimensional site model.
- Studies of early alteration in the northwestern part of the granite within rock domain 29. The purpose is to gain an understanding of the mineralogical composition of the rock and its variation within the critical part of the candidate volume.

Quaternary geology

- Supplementary Quaternary geological investigation of the seafloor in areas with a water depth of less than three metres. The purpose of the investigation is to obtain a complete picture of the extent of the Quaternary deposits within the Forsmark area.
- Supplementary investigations of soil depth and stratigraphy in the Forsmark area. In the site-descriptive model 1.2, a soil layer model is presented that can provide an idea of where and how much new data are needed.
- Analysis of regolith properties that are important for modelling of transport properties, for example mineralogical composition and cation exchange capacity (CEC). At present there is no plan for exactly which and how many such analyses should be performed.
- Investigations of the extent and properties of organic sediments in and beneath wetlands are part of a campaign that is planned in consultation with other disciplines, such as surface ecology and surface hydrology. Dating of collected material to determine sedimentation rates, as well as to describe the erosion phases in the Forsmark area. Pollen analyses of marine and lake sediments, as well as peat sequences, to describe the area's postglacial vegetation succession and climate variations.
- Biostratigraphic analyses of marine sediment core from Forsmark to describe the area's evolutionary history since the most recent deglaciation. An important question to be answered is whether the Forsmark area was affected at all by brackish water during the Yoldia Sea phase.

Mapping of rock types in the large till boulders in order to obtain information on ice transport pathways. Rock type determination of the gravel fraction can also provide information on how far the till material has been transported. Conceptual understanding of the site's Quaternary evolution.

3.3 Geophysics

3.3.1 Purpose and goal

Geophysics is an "auxiliary science" to bedrock and Quaternary geology, so the purpose and goal of the geophysical investigations coincide with those of geology. In the presentation of investigation methods prior to the site investigation /SKB, 2001/, different types of surface geological and borehole geophysical methods are described in terms of execution and potential. From the perspective of the site investigation, important purposes of the geophysical investigations are to indicate the distribution of fractures and fracture zones, and of intervening potentially fracture-poor rock, to detect possible mineralizations, determine soil depth, measure salinity distribution in boreholes, characterize the rock properties in the formation surrounding boreholes, and to measure borehole geometric properties.

3.3.2 Important results from completed investigations

In the initial phase of the site investigation, three large and important geophysical investigations were conducted, whose results have served as a basis for the continued site investigation:

- Airborne geophysical surveys of the candidate area and a surrounding regional area, covering a total of about 100 km^2, see Figure 3-11.
- Seismic reflection surveys, totalling roughly 16 profile kilometres, in the candidate area, see Figure 3-12.
- Marine geophysical (and geological) surveys between Gräsö and the mainland.

The airborne geophysical surveys have provided important data for the lineament interpretations that have been done, as well as for large-scale rock type determinations /Isaksson et al. 2004b/. The lineament map has partly determined which rock volumes have been investigated by boreholes. The map of the magnetic anomaly field that resulted from the airborne geophysical surveys is shown in Figure 3-11.

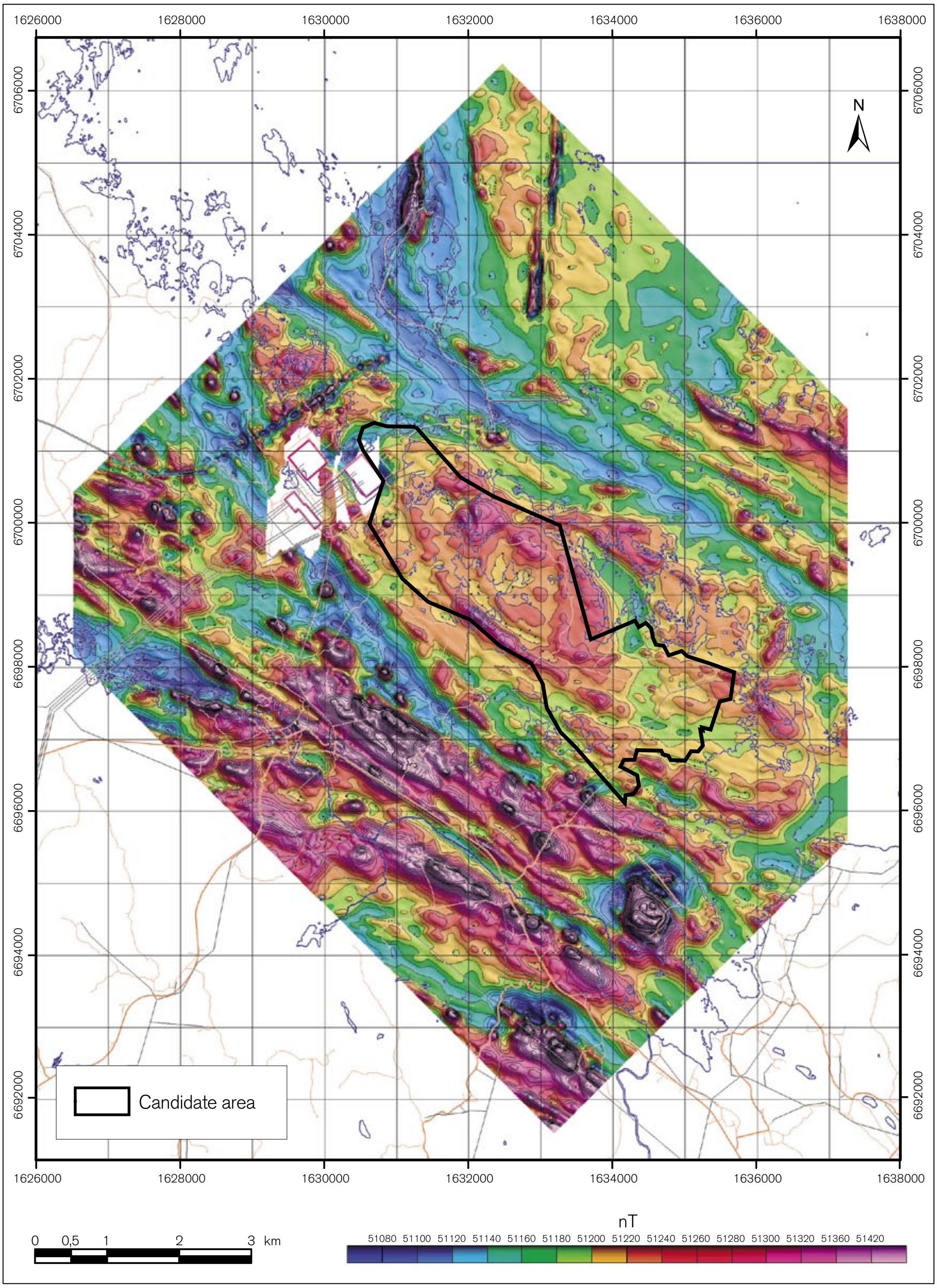


Figure 3-11. *Magnetic anomaly map of the Forsmark area from helicopter-borne surveys carried out during 2002.*

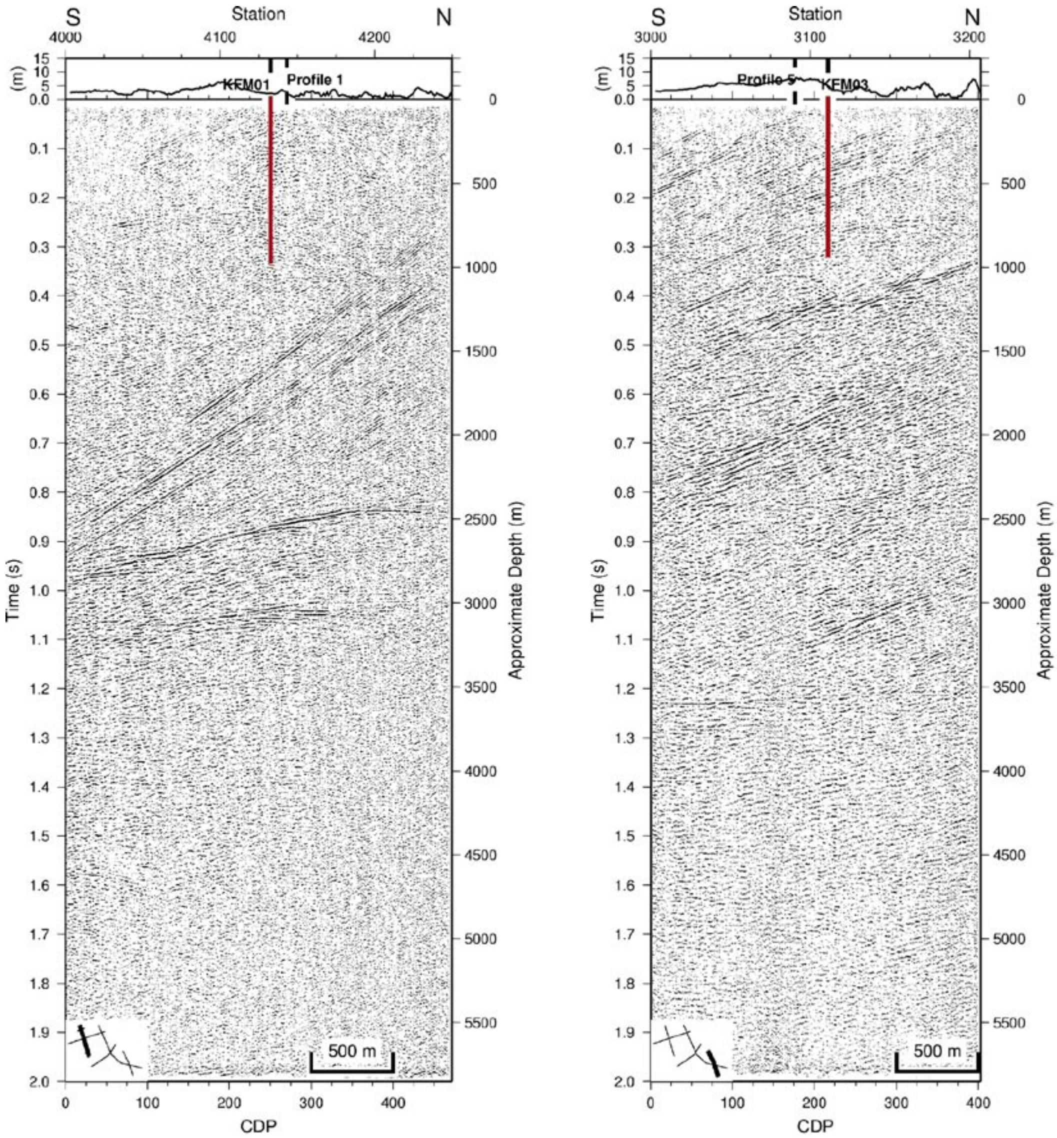


Figure 3-12. *Seismic reflection profile from the northwestern part of the candidate area with borehole KFM01A, and corresponding profile from the southeastern part with borehole KFM03A.*

With the aid of the seismic reflection surveys, it has been possible to explore the bedrock down to a depth of about 5 km /Juhlin et al. 2002/. The results have indicated gently-dipping fracture zones in the southeastern part of the candidate area, which have been verified by drilling. Seismic reflection also predicted the fracture-poor rock in the northwestern part of the candidate area, as well as between the gently-dipping fracture zones in other parts of the candidate area. Figure 3-12 shows a seismic reflection profile from the northwestern part of the candidate area, as well as a profile from the southeastern part of the candidate area. It can be seen that there are far less reflectors in the northwestern part of the candidate area down to a depth of about 1,000 m than in the southeastern part.

The marine geophysical surveys have mainly contributed information on bottom topography and rock surface topography, on which lineament interpretations have in turn been based. Otherwise the geophysical investigations have mainly focused on the candidate area itself, i.e. the tectonic lens. On the existing drilling sites, traditional geophysical logging has been carried out in all cored boreholes and in several percussion boreholes. The same applies to BIPS (Borehole Image Processing System = video photography of the borehole wall) and borehole radar logging with a dipole antenna and a directional antenna for determination of the direction and position in the borehole of fracture zones and other rock contacts. The geophysical borehole measurements have contributed data for single-hole interpretation of boreholes. The resistivity, density, magnetic susceptibility and gamma logs in particular have proved valuable.

A large number of ground geophysical surveys have been conducted. Besides the aforementioned seismic reflection surveys, magnetometer and slingram surveys have been conducted to indicate the locations of fracture zones for positioning of boreholes, ground-penetrating radar surveys for determination of soil depth, and CVES (Continuous Vertical Electrical Sounding) surveys for determining soil depth and zones of weakness in the rock /e.g. Marek, 2004/.

3.3.3 Important questions remaining to be answered

As before, the geophysical investigations will serve as support for the geological site description. Issues where geophysics is expected to make valuable contributions are:

- Verification of lineaments, particularly whether they can be linked to steeply-dipping fracture zones.
- Soil depth determinations.
- Determinations of the location and geometry of fracture zones.
- Vertical extent of quartz-poor rock types.

3.3.4 Investigation programme

From now on the site investigation will be focused on the northwestern part of the candidate area, as well as on the boundary areas northeast and northwest of the tectonic lens. The following work is planned for the priority site in the discipline of geophysics:

- Conventional borehole geophysical logging, plus BIPS and borehole radar logging in the new boreholes, just as in the old ones.
- Analyses of the large body of material from previous ground geophysical surveys, primarily seismic refraction surveys from the residential area, and based on this determine what supplementary ground geophysical surveys should be done, for example for the needs of design.
- Supplementary ground geophysical surveys on the priority site, primarily seismic refraction and ground-penetrating radar (GPR). This permits determinations of soil depth and P-wave velocity in rock.
- Vertical Seismic Profiling (VSP surveys), where boreholes are also used, for a more detailed determination of the three-dimensional geometry and orientation of fracture zones.
- Investigate the possibilities of modelling rock volumes based on gravimetric data, since gravimetry/microgravimetry can furnish valuable knowledge concerning the quartz-poor rocks west and south of the priority site. These rock types have sufficiently high contrast in density, compared with surrounding rocks with granitic-tonalitic composition, to enable their geometry and vertical extent to be modelled.

In addition to the above investigations, which primarily relate to the priority site, supplementary seismic reflection surveys are planned which also include the environs of the site and interpreted boundary zones. These measurements are important for the three-dimensional modelling of deformation zones and as a basis for groundwater flow models.

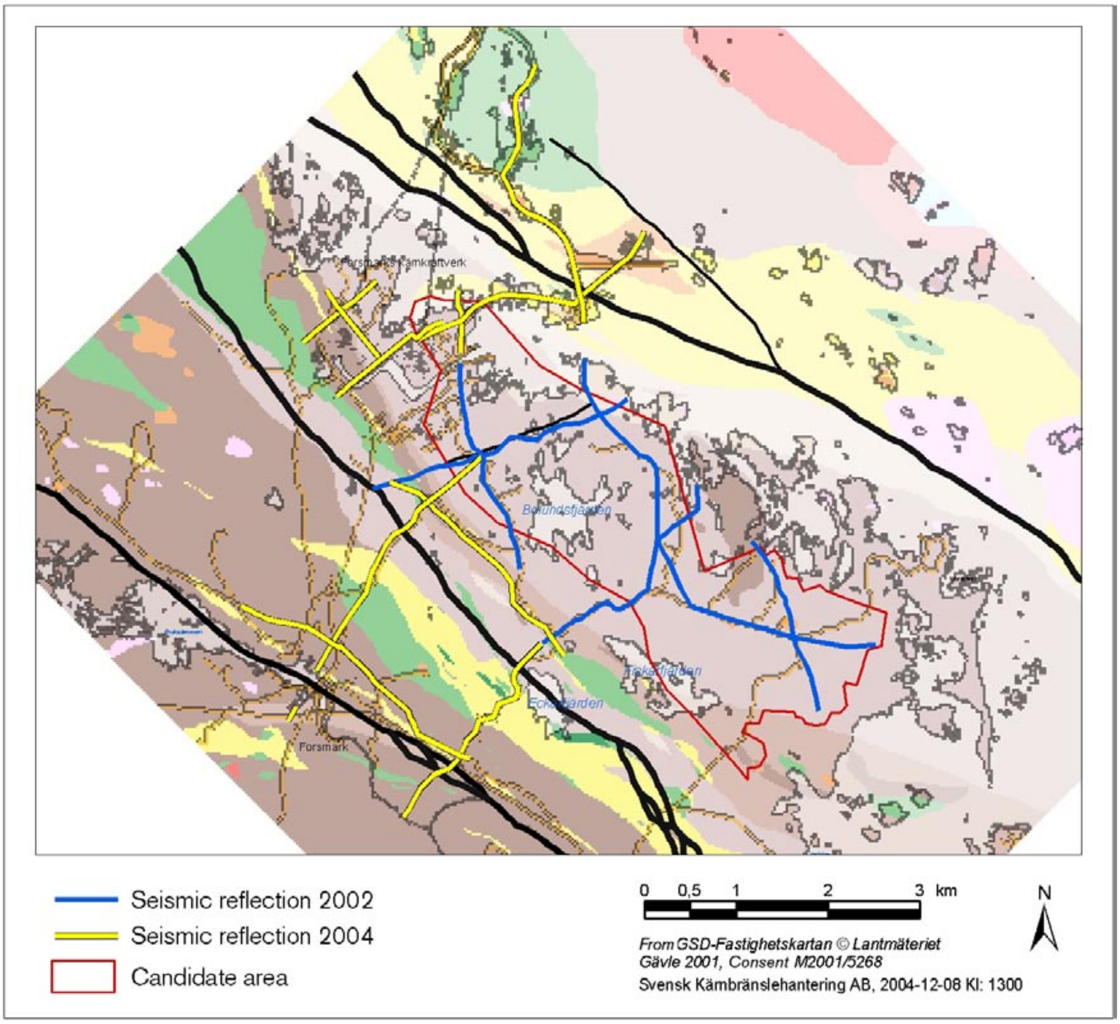


Figure 3-13. *Completed and planned seismic reflection profiles of the tectonic lens's hydraulic boundary areas.*

Figure 3-13 shows the supplementary seismic profiles that were performed in 2004. The measurements will be done where possible using a seismic vibrator (demolition hammer) as the source. Compared with using explosives as a source, this provides better data quality while reducing the environmental impact.

3.4 Rock mechanics and thermal properties

3.4.1 Purpose and goal

The rock mechanical conditions affect the isolating and retarding functions of the deep repository and also put constraints on how the repository can be configured and built. These conditions are governed by the prevailing loads – rock stresses – and the mechanical properties of the rock. The mechanical properties of a rock volume are dependent on the properties of the intact rock, as well as on the occurrence of fractures (frequency, length, orientation) and their mechanical properties. Different rock types have different strength and deformation properties. The strength and deformation parameters of intact rock samples, and to some extent also fractures, can be determined by laboratory tests, but there are scale effects that must be taken into consideration before data can be used for analyses that involve large rock masses. In the end it is the geometric distribution of fracture zones, fractures and rock types that determines the large-scale properties.

As regards the size and orientation of the rock stresses in a rock mass, experience shows that there is considerable regional and local variation. Determinations must therefore be done by in-situ measurements.

The discipline of rock mechanics includes measurement and analysis of the rock's strength, deformation and thermal properties, as well as measurement and analysis of the state of stress. With the support of these data, predictions are made of stability conditions as a basis for both facility design and safety assessment.

The goal of the rock mechanical investigations is to:

- Determine and assess the distribution of initial rock stresses within the priority area.
- Determine mechanical properties of intact rock and fractures within different lithological units.
- Determine whether the selected site is large enough (from a rock mechanical viewpoint) to accommodate a repository.
- Identify the risk of serious spalling or other stability problems in the deep repository's rock chambers.
- Identify possible problems where tunnels have to pass fracture zones.

The thermal properties of the rock have a bearing on the heat transport from a deep repository. This determines the minimum spacing between emplaced canisters, and thereby the area requirement for the whole repository. The rock's thermal conductivity is the crucial parameter in this context. This can be determined by means of laboratory tests, but scale-dependent variations and thermal anisotropy may have to be taken into consideration. In order to calculate thermomechanical effects (induced thermal stresses and deformations), data on the rock's thermal expansion properties are also needed, normally expressed as the coefficient of thermal expansion.

3.4.2 Important results from completed investigations

Rock stresses

Knowledge of rock stresses is necessary for the design of the deep repository (repository depth, orientation and configuration of tunnels, rock support), and for predictions regarding possible stress-related stability problems.

Data on rock stresses are available for Forsmark from investigations in conjunction with the expansion of the Forsmark NPP and SFR in the 1970s and 1980s /Carlsson and Christiansson, 1987/. At that time, measurements were made down to a depth of 500 metres in the boreholes DBT-1 and DBT-3, both situated near Unit F3. The results showed rock stresses that were relatively high for Swedish conditions. It was further found that the stress field was affected locally by a presumed gently-dipping fracture zone that intersected the borehole at a depth of about 320 metres. The influence led to an irregular stress gradient with depth.

The measurements now made in the candidate area have verified the existence of high stresses. The measurements have been made using two different methods: Overcoring measurement in cored borehole KFM01B and hydraulic methods in boreholes KFM01A, KFM01B, KFM02A and KFM04A. Figure 3-14 shows an early interpretation of data from the overcoring measurements in KFM01B, together with results from the older boreholes DBT-1 and DBT-3.

The stress magnitudes at depths between 230 and 475 m lie around or above the technical limitations of the measurement methods, creating method-related uncertainty in the interpretations. The results preliminarily indicate that the greatest stress may be between 45 and 55 MPa, which is relatively high for the depth interval in question. The measurements in borehole KFM01B in particular show unexpectedly high stress magnitudes relatively close to the surface (240 m); consequently, the stress gradient towards greater depth appears to be relatively flat. This is supported by the fact that the cores from the deep boreholes (down to 1,000 m) show few signs of core disking, which is a reliable indicator of very high loads. It is also worth noting that certain measurements with hydraulic methods at great depth indicate more normal stresses, at least locally.

As far as directions are concerned, the measurements confirm the picture from previous investigations that the dominant load has an orientation that largely coincides with the longitudinal direction of the tectonic lens, i.e. northwest–southeast.

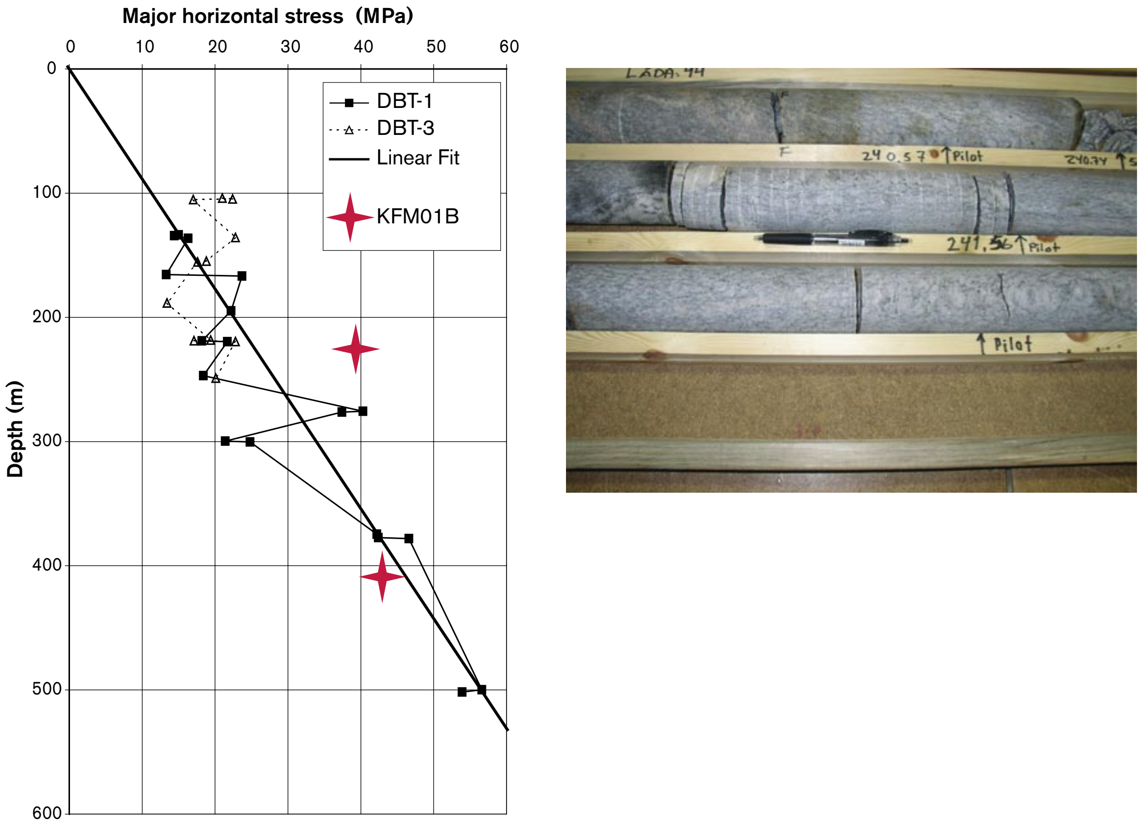


Figure 3-14. *Data from rock stress measurements: At left preliminary results from overcoring on two levels in KFM01B (red symbols). For comparison, results are shown from measurements made in the 1970s in boreholes DBT-1 and DBT-3 at the Forsmark NPP's Unit F3 (black symbols). At right a drill core from KFM01B showing core disking in conjunction with drilling. The core disking indicates stress levels at or above the measurement method's capacity limit.*

Stress data are being analyzed with regard to confidence in measurement results, heterogeneity in the stress field, and magnitudes. The results will be presented in version 1.2 of the site description. As a complement to the rock stress measurements, laboratory determinations have been made of P-wave velocities on samples from all cored boreholes. The method provides a rough picture of the depth at which the stress levels become so high that the drill core is affected by microfracture formation when it is taken up from the constrained rock. The results indicate that this occurs at a depth of 400–450 metres.

Mechanical and thermal properties – laboratory tests

The work with laboratory determination of rock mechanical and thermal properties has yielded the following lessons:

- Tensile strength (indirect testing) is very consistent in the granite within the tectonic lens.
- Uniaxial compressive strength is relatively consistent, but measurements are limited to cores from fairly vertical boreholes. Strength in different directions, i.e. possible anisotropy, has not yet been studied.
- Triaxial strength is as above, but the data have been obtained from relatively few samples.
- Tests with normal and shear loading of fractures have so far been performed on a limited scale, due to the very limited number of natural fractures in the mostly vertical drill cores.
- The granite exhibits high thermal conductivity, which is to be expected in view of its mineral composition (high quartz content). The data are consistent, but have exhibited unexpectedly high anisotropy in thermal conductivity, linked to foliation/lineation.
- Tests performed to date indicate that the coefficient of thermal expansion varies within an interval of approximately $5 \cdot 10^{-6}$ to $9 \cdot 10^{-6}$, which are normal values for granite.

3.4.3 Important questions remaining to be answered

In the geological environment that characterizes the investigated formation in Forsmark, with relatively high rock stresses and fracture-poor rock, it is important to be able to make reliable predictions of the stability conditions in a possible deep repository. This is particularly true if there is a risk of failure of intact rock nearest deposition tunnels or deposition holes. To make such predictions, knowledge is needed of prevailing rock stresses and the strength properties of the rock. More detailed data therefore needs to be obtained on these parameters.

The most important issue is the state of rock stress and its possible consequences for stability and rock support needs. In-depth and more detailed knowledge is needed about stress magnitudes in particular, including their distribution vertically and laterally. This requires further measurements, concentrating on the part of the area that has priority for further investigations, i.e. the northwestern part of the tectonic lens.

Further knowledge is needed about the strength of the rock within the priority area and at probable facility depth in order to confirm the current general picture and obtain more detailed data for the prediction work. Owing to the low fracture content of the granite, in combination with the vertical orientation of the first deep cored boreholes, there have been limited opportunities to determine the mechanical properties of natural fractures. Conditions for sampling are expected to be better when it is possible to take samples from holes drilled at an angle in different directions. These data are needed to determine the large-scale strength and deformation properties of the rock mass.

As far as thermal properties are concerned, measurements on drill cores in the manner performed to date provide expected and consistent data. The questions concern how these data are to be extrapolated to a scale that is relevant for the deep repository, taking into account the directional dependence that has been observed for thermal conductivity. Better knowledge is needed on this point.

3.4.4 Investigation programme

Rock stresses

The strategy for gaining more knowledge about rock stress conditions is to carry out additional rock stress measurements, concentrated to the prioritized northwestern part of the tectonic lens. However, if high stress levels exist here as well, there is a risk that the measurements will continue to be afflicted with uncertainties, given the limitations of available methods. In order to minimize uncertainty at depth, it is important to be familiar with the geological-structural conditions around the measurement sites. Modelling of the site's stress state can then be done as a complement to direct measurements /Hakami et al. 2002/.

Immediate plans call for measurements in a vertical hole at drilling site 7 at the residential area (hole 7B, see Figure 2-18 and Table 2-2). The purpose of the measurements there is to learn more about the stress profile in the northwestern part of the tectonic lens. This part of the priority site is moreover the preferred alternative for establishment of the surface part of the deep repository, as well as accesses to the underground part. The measurement results are therefore expected to provide a basis for proposed configurations for these facility parts.

In conjunction with the drilling of the hole, measurements will be performed with the overcoring method, starting relatively close to the surface, at a depth of about 50–100 metres. The exact position will be determined by data from hole 7A, which will be drilled first. The choice of the first measurement level will be determined by the presence and frequency of gently-dipping fractures or fracture zones. Measurements will be made on at least two additional measurement levels down to a depth of about 200 m, in part to determine the stress gradient and in part to ensure good results before the method approaches its limit. Below that, measurements will be made approximately every 50 metres down to a depth of about 500 metres, or until the stresses are so high that the measurements are no longer meaningful. After concluded overcoring measurements, the borehole will be finished down to a depth of about 500 metres. Rock stress measurements will then be performed by means of hydraulic methods as well, at depths corresponding to those of the overcorings.

Rock stress measurements are also included in the measurement programme for the deep borehole that is planned from a site not yet determined just south of Bolundsfjärden (S Bol), see Figure 2-18. The main purpose is to learn more about the stress profile through the dominant gently-dipping fracture zone A2 that bounds the priority site on the southeast. This is important for being able to model the stress field and as a basis for facility design. Details on borehole placement and measurement programme will be determined on the basis of site description version 1.2, and results from planned measurements in 7B. It is tentatively assumed that both overcoring and hydraulic methods will continue to be utilized.

The intention during 2006 is to concentrate the investigations on characterizing the boundary areas of the priority site, primarily from a hydrogeological and hydrogeochemical point of view. Rock stress measurements may also be considered in conjunction with these investigations. Knowledge of the stress profile in the boundary areas of the tectonic lens may underpin the models of stress distribution that are constructed.

Mechanical properties

Knowledge of the indirect tensile strength in the granite in the tectonic lens is judged to be adequate. Further measurements will be limited to cores from drilling in the adjacent rock domain (if it is reached by borehole 7A) and one or two measurement levels at a depth of approximately 400–500 m in the northern part of the tectonic lens.

Better knowledge of uniaxial and triaxial compressive strength in different directions, including at a higher stress level, is needed for rock mechanical modelling and stability analyses. Preliminarily, the frequency of uniaxial tests will be halved, while triaxial tests will have the same scope as before. Samples will mainly be taken within the depth interval 300–500 m.

Determinations of the normal and shear stiffness of fractures are planned. Samples will be taken from the metagranite in the priority area, and possibly from surrounding deformed bedrock as well. The purpose is to learn more about the properties of fractures that are representative of existing fracture sets deemed to be of importance for facility construction. The scope and choice of samples is determined by the fracture situation in the holes that are drilled, as well as the needs that emerge when the locations of the different parts of the deep repository are sketched.

The results of the so-called tilt tests that have been conducted, which provide an empirical estimate of the friction properties of fractures, have exhibited a relatively large spread. Further measurements will therefore be limited to a couple more drill cores from holes within the priority site (preliminarily 7A and 7B), as well as from one of the boreholes planned outside the tectonic lens.

Measurement of P-wave velocity for indication of microfracturing in conjunction with stress relief is planned to be done for all boreholes from now on as well.

Thermal properties – borehole tests

It is difficult to judge the consequences on a deep repository scale (a few metres at least) of the anisotropy in thermal conductivity observed on a drill core scale in the foliated and lineated rock. Field measurements are therefore planned in some ten or so points using the so-called multi-probe method /Sundberg, 2003/. In this method, a central heater is placed in a small-diameter borehole and temperature sensors are placed at a distance of about 30–50 cm from the heater in different directions. By measuring the change in temperature in different directions when the heat load is imposed in the central hole, the directionally dependent thermal conductivity can be determined on a large scale. Outcrops that are representative for the area are chosen as test sites. This scale may also give too large a spread in anisotropic properties. A large-scale field test is therefore planned for the purpose of determining the thermal conductivity in different directions. One of the above outcrops where a 5–10 m deep section can be found that is free of any soil-filled or water-conducting fractures will be chosen as the test site. There a central hole will be drilled for a heater. Around this central hole, at a distance of a metre or so, a number of holes will be drilled for temperature measurement.

The results from the different field tests will be cross-checked against each other and against laboratory data. It is also possible that technology for more large-scale determination of thermal conductivity by means of measurements in investigation boreholes will become available in the next few years. In this case, such measurements will also be considered.

Thermal properties – laboratory tests

A relatively large quantity of data is available on the thermal properties of the dominant rock type within the candidate area. However, the body of data is limited for certain secondary rock types. Supplementary determinations of the thermal conductivity of these rock types may therefore be done.

Laboratory tests of thermal conductivity and thermal expansion are done today on unloaded specimens. This can yield values that are systematically lower than for specimens under loads that correspond to conditions in situ. The difference may be of minor importance, but the effect of the pressure dependence should nevertheless be examined for some samples. For thermal expansion, tests are planned in a triaxial cell with temperature control equipment. For thermal conductivity, TPS measurements of pressurized specimens are being considered.

3.5 Hydrogeology

The hydrogeological programme includes meteorology, hydrology and hydrogeology in soil layers and bedrock. Like the meteorological measurements linked to water quantity, water flow rate and water level, the hydrological measurements are also utilized in the programmes for surface ecosystems and hydrogeochemistry. In a similar manner, measurements linked to the composition of the surface water and groundwater that are performed within surface ecosystems and hydrogeochemistry are also used in the hydrogeology programme as an aid to clarifying the area's water balance and the water's flow paths.

3.5.1 Purpose and goal

The purpose of the continued hydrogeological investigations is to secure a reliable and large enough set of hydrogeological data. These data will serve as a basis for a detailed hydrogeological description of the investigation area. In order to facilitate this description, a three-dimensional hydrogeological model of the area will be constructed. This model consists of three hydraulic domains: soil layers, deformation zones and the rock mass between the deformation zones. All three domains have to be characterized.

The body of data should include both geometric and physical properties, and the discipline of hydrogeology is dependent here on data from other disciplines. Examples of geometric properties are topography, water depth and the location and extent of the soil layers and fractures. Examples of physical properties are initial and boundary conditions for pressure and salinity, which in Forsmark are closely linked to the process of shoreline displacement, as well as material properties such as porosity and permeability.

Numerical modelling is used as an aid to a better understanding of the area's hydrogeology. By means of numerical simulation, aimed at describing the groundwater flow in terms of magnitude and flow paths, assumptions made in the conceptual hydrogeological model will be able to be demonstrated and tested. For example, what is the significance of the uncertainties in parameter values comprising the hydrogeological description? Can simulated results, for example with regard to pumping tests, be verified by measured data? The results of the simulation are expected to show whether supplementary field investigations are needed or whether the body of data already collected is sufficient. Moreover, modelling is an important tool in generating input data for repository design, safety assessment and environmental impact assessment.

Hydrogeological modelling is done on different scales, both a local scale around a hypothetical deep repository, and a regional scale within a larger area. The majority of the planned investigations will be concentrated to the northwestern part of the candidate area, but the hydraulic boundary areas will also be investigated. This means that the body of data underlying the local hydrogeological model for the northwestern part of the candidate area will be greatly improved, while the data in the southeastern part will not be changed to the same extent.

The regional hydrogeological model outside the local area will be supplied with data from the rock mass in and next to the boundary areas. The geological interpretation of the ongoing seismic reflection surveys in the southwest part of the regional area is expected to show whether supplementary hydrogeological field investigations are required within this area, or whether the assumptions made in model 1.2 and collected data are sufficient for a credible description of uncertainty. Data from previous investigations in e.g. the Finnsjö area are expected to be able to be utilized in the regional hydrogeological model. The safety assessment will be based on both the local and the regional hydrogeological model.

3.5.2 Important results from completed investigations

Generally speaking, the results from different types of hydrotests have shown good agreement. This strengthens our confidence in the investigation methodology as we continue our investigations.

The most important hydrogeological results included in data freeze 1.2 are those from the hydraulic characterization of the soil layers and the bedrock down to about 1,000 m. These results can be summarized in four points:

1. The Quaternary geological investigations have shown that the thickness of the soil layers varies from bare rock to a depth of about 17 m. Glacial till is the dominant type of deposit (cf section 3.1). In places it is overlain by a relatively thin layer of wave-washed sand and in topographical low points of clay and organic deposits. In the southeastern parts of the candidate area, especially at Storskäret, the till is clayey /Johansson, 2003; Werner et al. 2004; Werner and Lundholm, 2004/. The groundwater table in the soil layer is very close to the ground surface for much of the year. Artesian conditions prevail during certain periods in some of the groundwater monitoring wells. As far as the permeability of the soil layers is concerned, the results from the supplementary slug tests agree with the general picture presented in model version 1.1, with a surface layer with high permeability, underlain by less permeable till followed by higher permeability in the contact zone between soil and rock /Werner and Johansson, 2003; Werner, 2004/. It has not been clarified to what extent the relatively high permeability in the contact zone is associated with the actual till nearest the rock or whether it is at least partially due to fractured surface rock. It should, however, be emphasized that the variations in permeability between different measurement points are great.

2. The rock down to a depth of about 200 m (but usually above 100 m) contains a number of fractures with high or very high water flow rate. The fractures are gently-dipping and are hydraulically connected with each other /Ludvigson and Jönsson, 2003/. Between these water-conducting fractures, the rock exhibits a normal fracture frequency and a relatively low water flow rate.

3. The rock below a depth of about 200 m has proved to have a very low fracture frequency and a low water flow rate. However, a number of water-conducting fracture zones have been found at greater depth in the central to southeastern part of the candidate area /Carlsten et al. 2004b/. Figure 3-15 shows schematically a northwest-southeasterly

profile, with data from four cored boreholes situated more or less along the profile, plus an interpretation of the locations of the fracture zones. The zones appear to be very extensive and to dip gently towards the southeast (20–25° from the horizontal).

4. Hydraulic contact between different boreholes over large distances has been established in several tests. Hydraulic contact is demonstrated by pumping in one borehole and simultaneously recording pressure changes in another borehole. An example is shown in Figures 3-16 and 3-17: During drilling of the percussion borehole HFM16 at drilling site 6, pressure changes were observed in both HFM13 near drilling site 5 and KFM02A at drilling site 2. The distances in both cases are more than one kilometre. Data indicate that the hydraulic connections go via deformation zone A2.

Aside from the site-specific results that have been obtained, important method-related results have also emerged, especially when it comes to hydraulic detailed characterization of cored boreholes. The two standard methods that have been used for the detailed characterization are sectional injection tests (PSS, Pipe String System) and difference flow logging (PFL, Posiva Flow Log).

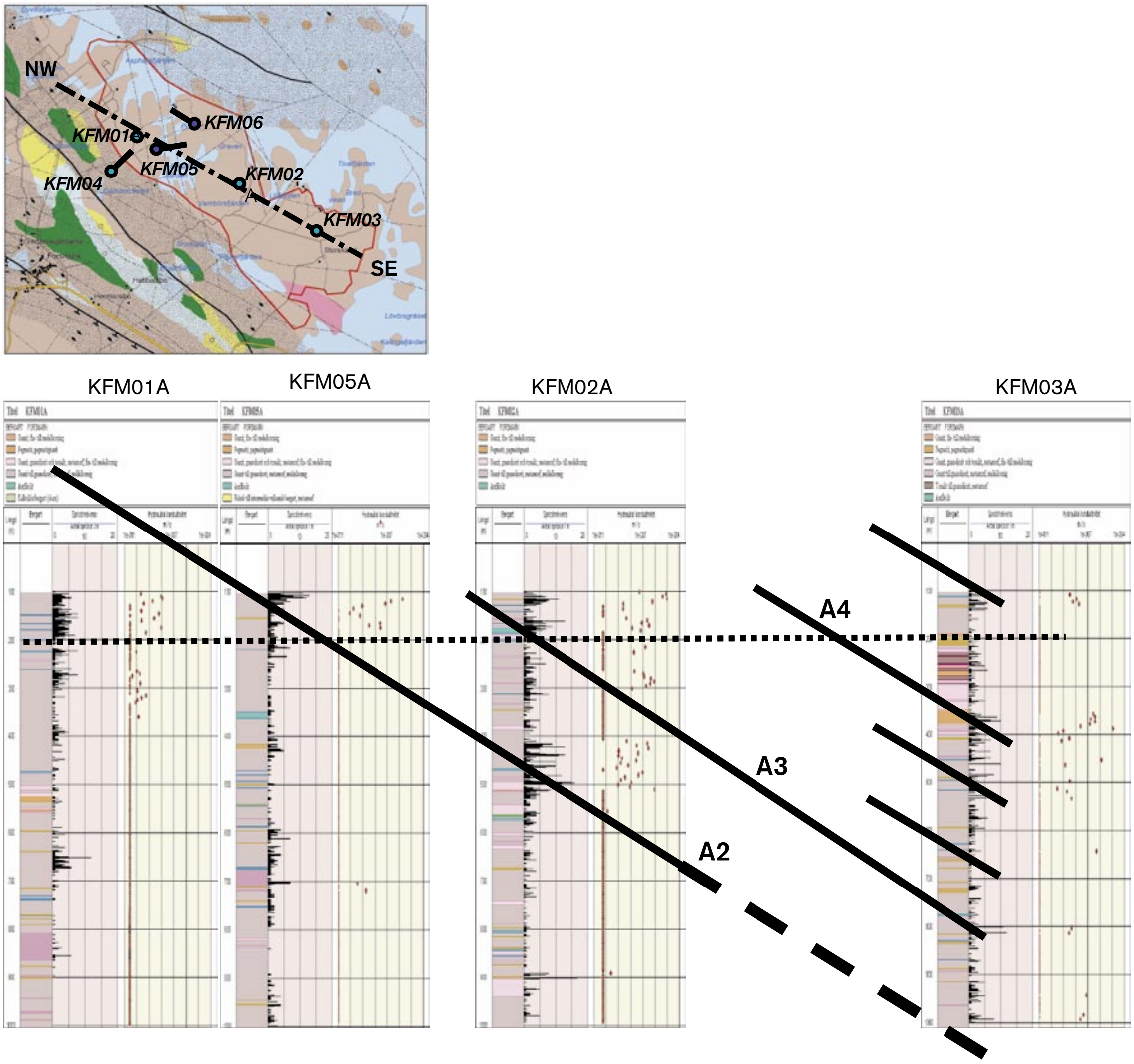


Figure 3-15. *Schematic profile, with data from four cored boreholes, plus deformation zone A2 and additional interpreted zones to the southeast. The deformation zones are estimated to dip 20–25° towards the southeast (the length scale has been compressed in the figure).*

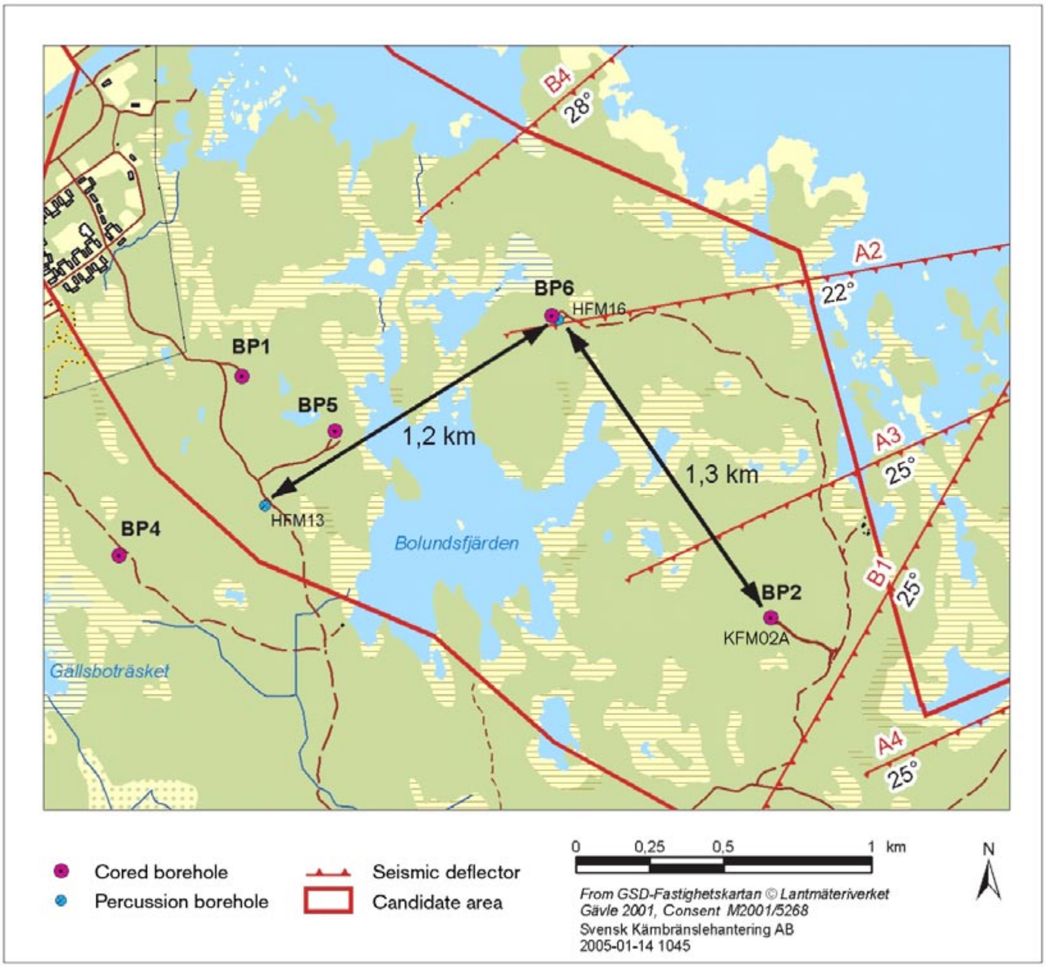


Figure 3-16. *Examples of observed hydraulic connections between boreholes. When percussion borehole HFM16 was drilled, pressure changes were noted in HFM13 and KFM02A (see Figure 3-17).*

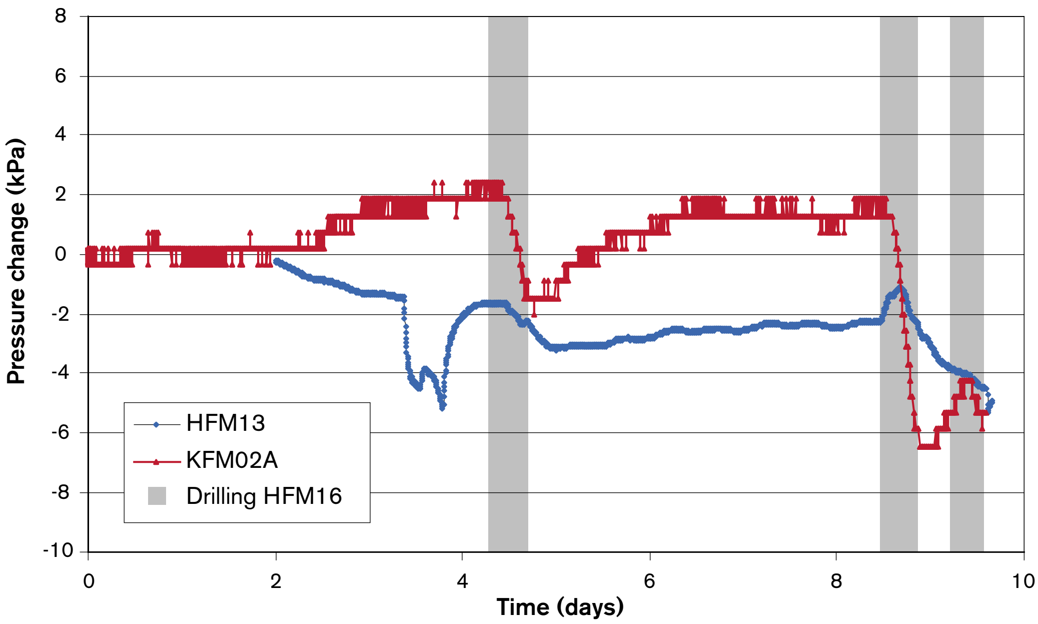


Figure 3-17. *Measured changes in water pressure (pressure responses) in HFM13 and KFM02A (see Figure 3-16) during the period when HFM16 was being drilled. Despite disturbances by other activities in the area before the start of drilling, it is clear that the drilling causes pressure responses.*

Experience from investigations of the three first cored boreholes (KFM01A, KFM02A and KFM03A) indicate that the two investigation methods overlap to some extent but yield different types of data. Data sets from both methods are important for evaluation of permeability in the analysis work. As an example, it can be mentioned that PSS has a larger measurement range with regard to permeability (hydraulic transmissivity) than PFL. Above all, low transmissivities can be quantified better by PSS than by PFL.

The disadvantage of PSS is that the minimum length of a measurement section in the borehole is five metres with the current design of the equipment. Consequently, PSS measures transmissivity with a maximum geometric resolution of five metres. The resolution of PFL measurements is, on the other hand, as high as 0.1 m. Fracture transmissivities can therefore be measured with PFL. Together with mapping of the drill core, Boremap data, and digitized TV logging of the borehole wall, BIPS, these methods provide useful information for the work with the fracture model of the area (the DFN model). PFL can also be used to measure electrical conductivity in specific fractures, which contributes to a better understanding of the hydrogeological and hydrogeochemical methods.

3.5.3 Important questions remaining to be answered

One of the most important remaining tasks is to further clarify the hydraulic contacts between surface water, soil groundwater and rock groundwater in the investigation area. The description of the hydraulic contact between surface water and groundwater is important. Lakes and wetlands can in principle be assumed to comprise discharge areas. However, the measurements performed so far indicate that certain lakes can comprise recharge areas during parts of the year. It is also important to clarify to what extent the wetlands are discharge areas with good groundwater contact and to what extent they are more or less isolated systems separated by impervious bottom sediments. Other questions relate to the properties of the soil-rock contact and how the large fracture zones are hydraulically connected. There are water-conducting fractures at great depth, and the question is how these connect hydraulically to nearby fracture zones.

A few deep-lying water-conducting fractures have been detected in several of the cored boreholes (KFM02A ~ 900 m, KFM05A ~ 720 m borehole length). These fractures do not have an extremely high water flow rate (transmissivities on the order of 10^{-9}–10^{-8} m^2/s), but sufficiently high to be regarded as deviating from the usual pattern and thereby particularly interesting. Individual water-conducting fractures could constitute a part of an otherwise sparse network of conductive fractures. What this fracture network looks like and whether it has contact with the water-conducting surface rock is one of the important questions that will be studied in the continued investigations.

The gently-dipping fracture zones should be further characterized. The zone that is most important to investigate from a repository perspective, for example with respect to hydraulic properties and lateral extent, is designated A2. Figure 3-15 shows data from boreholes through the zone, and Figure 3-18 shows its intersection with the ground surface interpreted from seismic reflection surveys. It is essential to survey permeability and its possible decrease with depth, as well as the natural water flow in the zone. It should also be clarified whether the A2 zone gives rise to hydraulic contact between the boreholes that intersect the zone (e.g. between KFM02A and KFM04A). It should also be investigated whether the gently-dipping fracture zones (including A2) are bounded by the Singö, Eckarfjärd and Forsmark zones, or continue on the other side of them as well. A new cored borehole (S Bol, see Figures 2-15 and 2-18) will probably penetrate the A2 zone at a depth of between 300 and 600 metres. It is expected to contribute to knowledge of the hydraulic properties of the zone and the surrounding rock, as well as the hydraulic connections along the zone and to the surrounding fracture network.

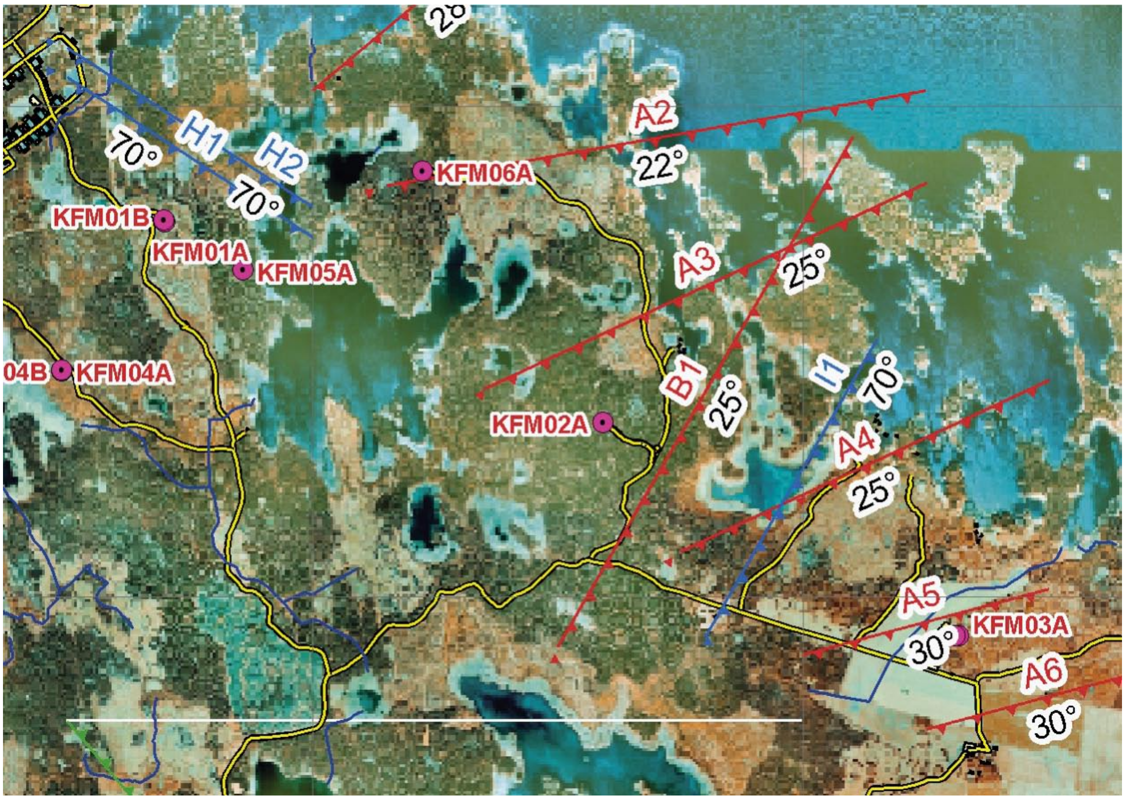


Figure 3-18. *Intersection of reflectors with the ground surface, interpreted from seismic reflection surveys. These reflectors, which probably represent fracture zones, are likely to be of crucial importance for water transport through the southeastern part of the investigation area in particular.*

The body of data for describing the permeability of the rock mass between the fracture zones must also be improved. It is of great importance for the safety assessment to quantify the number of fractures with low permeability and their properties. This particularly applies to Forsmark, where the rock between the fracture zones has very low conductivity.

3.5.4 Investigation programme

Hydraulic contact between surface water, soil groundwater and rock groundwater[6]

In order to find out more about the water flux in the area and refine the hydrological model on which the numerical simulations are based, it is important to further study the hydraulic contact between surface water, soil groundwater and rock groundwater. A number of soil pits to expose the rock are planned where lineaments have been observed. These investigations can yield important information about the transition between soil and rock and thereby shed light on the likelihood of hydraulic contact between soil and rock groundwater. The wetlands will be studied to find out to what extent they constitute discharge areas or largely separate hydrological systems.

The extensive monitoring that is being done in Forsmark with regard to meteorological data, water flows in streams and surface water and groundwater levels permits the effects of both natural changes and human activities to be studied. Examples of questions that can be illuminated are, for example, how soil and rock groundwater levels in different parts of the area are changed by heavy precipitation and sea level variations, how the groundwater level

[6] See also sections 3.1 (Surface ecosystems) and 3.6 (Hydrogeochemistry).

in soil and rock covaries, whether the lakes in the area always constitute discharge areas, how the water level in nearby soil boreholes changes due to pumping for interference tests in boreholes, etc.

Such analyses, which for the most part utilize information from already existing boreholes and observation and measurement systems, are expected, along with numerical modelling, to show the need for supplementary investigations in the form of additional boreholes for measurement of groundwater levels and for hydraulic tests. New cored and percussion boreholes are planned as described in section 3.8, while the strategy for setting-out of new soil boreholes, which are assumed to be relatively few, is primarily governed by needs in the discipline of Hydrogeology.

In order to study groundwater and runoff formation, special investigations in the form of measurement campaigns involving sampling and analysis of oxygen-18 and possibly other natural tracers as well are planned, in addition to water flow rate measurements and hydrochemical analyses.

Investigation of cored and percussion boreholes

The properties and positions of water-conducting fractures comprise very important information that is gathered for virtually all boreholes in the site investigation. The hydrogeological detailed characterization of deep cored boreholes is planned to include both injection tests (PSS) and difference flow logging (PFL). Certain short cored boreholes will also be characterized by means of injection tests. The reason the investigation methodology includes both methods is that both furnish information that is of importance for the analysis work. Focused investigation programmes for each method could possibly be applied in certain cored boreholes in the future.

Equivalent information from percussion boreholes is obtained by flow logging with SKB's equipment for hydrotests in percussion boreholes. In cases where flow logging cannot provide complete information, it is augmented by injection tests in the upper part of the hole, where flow logging cannot be done for practical reasons. Water samples are taken for chemical analysis during the long pumping test that coincides with flow logging. The results of the investigations will for most boreholes in the lens be presented at data freeze 2.2. At this time, data will also presumably be available from another borehole just south of Bolundsfjärden (S Bol) that intersects the hydraulically conductive gently-dipping fracture zone A2. Information on the boreholes in the boundary zones will be presented at data freeze 2.3.

Interference tests

Interference tests are used to "tie up the loose ends" and complete our understanding of the hydraulic contact in the investigation area. Information on how fracture zones and fracture networks are linked together is used, among other things, to support the hydrogeological model. Large-scale interference tests, in combination with tracer tests, will be an important part of the investigations in the final phase. A prerequisite for these tests to be carried out is that no other disturbing activity is going on in the immediate vicinity, for example drilling or cleanout pumping. In addition to these tests, a number of targeted interference tests will probably be carried out in order to clarify local hydraulic connections around future cored boreholes; single-hole interference tests may also be done. Within the candidate area, interference tests are planned to be done during the summer vacation of 2005 and the winter and spring of 2006. In the hydraulic boundary areas they may be done at the end of 2006. These times are chosen in view of the fact that other disturbing activities are then minimized. The results of the interference tests will be presented at data freezes 2.2 and 2.3.

3.6 Hydrogeochemistry[7]

3.6.1 Purpose and goal

The discipline of hydrogeochemistry includes investigations of chemical conditions in surface water and groundwater down to a depth of about 1,000 metres in the bedrock. The two principal purposes of the hydrogeochemical investigations are /SKB, 2001b/:

1. To characterize and describe the groundwater with respect to chemical composition, origin, evolution, principal flow paths and retention times, and to identify the chemical reactions and processes that have influenced the evolution of the groundwater up until today in order to be able to predict its future evolution.

2. To obtain representative and reliable values for certain chemical components that are important for designing a deep repository and for carrying out assessments of the long-term safety of the repository. The components referred to here are the ones which can, in very high or in some cases too low concentrations, influence the corrosion of the copper canisters in the deep repository, weaken the barrier of bentonite clay, or enable radionuclides to be transported in the water if a copper canister should begin to leak.

The primary purpose of the planned hydrogeochemical investigations is to provide a more complete picture of the groundwater situation in the area by augmenting, verifying and increasing the quantity of data, especially when it comes to deep groundwaters. Chemistry data obtained until present date have been used to describe e.g. the depth dependence of the groundwater chemistry. With additional data from more boreholes, the results can be interpolated to a three-dimensional distribution in the identified conductive structures within the candidate area.

A considerable quantity of hydrochemical data is needed for the continued evaluation and analysis work. Distributions of dissolved components, as well as isotope ratios, are needed to describe the origin and history of the groundwater. This information, linked to a groundwater flow model that describes the flow back in time in the Forsmark area (see Figure 3-19), provides support for the choice of the different type waters (original waters), such as meteoric water, Baltic Sea water, water from the Littorina Sea, glacial meltwater etc, which should be included in mixing calculations. Such calculations are done for the purpose of recreating water compositions in actual water samples with the aid of different proportions of the type waters. Differences between calculated and measured concentrations show to what extent chemical reactions and biological processes have occurred. Equilibrium calculations between chemically active rock minerals and chemical components dissolved in the groundwater show to what extent the hydrogeochemical system is stable or dynamic. The calculations are of importance for the interpretation of the groundwater's turnover times. The relatively limited quantity of data obtained from completed investigations will be supplemented with new data in order to obtain a higher resolution and so that the calculations and modelling can be refined.

Certain chemical components are important for the design and safety assessment work, and there are preferences and even requirements regarding groundwater concentrations if the site is to be considered suitable for a deep repository. It is, for example, important to show that anoxic (oxygen-free) conditions exist in the groundwater, since the presence of oxygen affects both the tendency of the copper canister to corrode and the solubility of radionuclides. Furthermore, total salinity and concentrations of divalent cations are important for the function of the bentonite. The groundwater's pH and content of colloids and microbes are of great importance for its ability to transport radionuclides. Colloids and microbes can act as carriers of radionuclides. For all these parameters, relatively few data

[7] See also sections 3.1 (Surface ecosystems) and 3.5.4 (Hydrology).

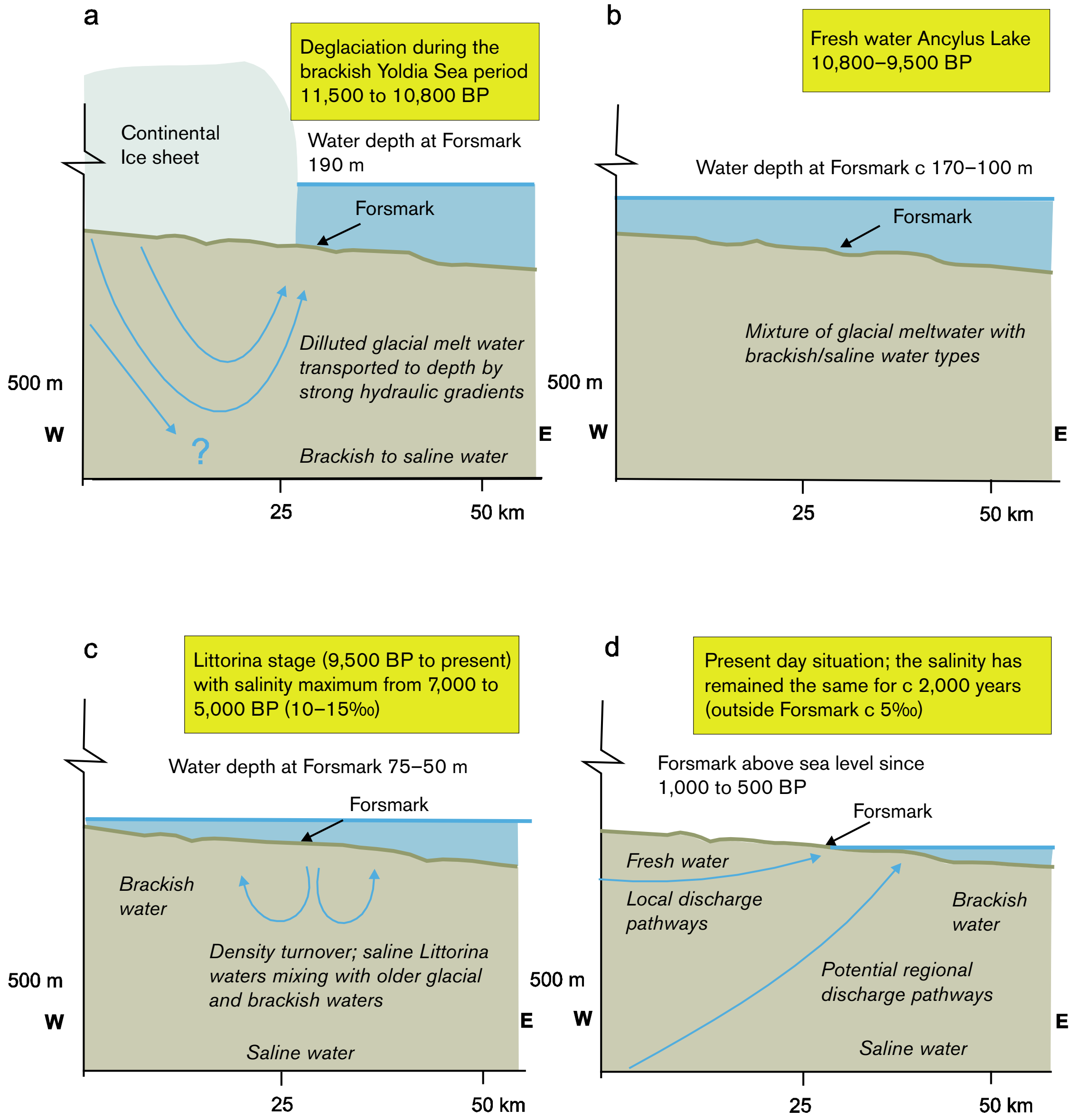


Figure 3-19. *Different stages in the history of the Baltic Sea at Forsmark since the most recent ice age: a) Ice age – Yoldia Sea, b) Ancylus Lake, c) Littorina Sea, d) Present-day Baltic Sea. These stages with alternating fresh and saline water, as well as the process of land uplift, have affected the evolution of the groundwater and resulted in today's groundwater composition /Laaksoharju et al. 2004/.*

of high quality are needed, but they must come from repository depth and from the planned location of the repository.

3.6.2 Important results from completed investigations

A two-year-long sampling campaign for surface water in sea bays, lakes and streams has been concluded and data from some 20-odd sampling points and 40 sampling occasions have been collected. The results show that the surface water in Forsmark has high alkalinity (often above 200 mg/l as hydrogen carbonate, with values reaching above 400 mg/l), high pH (values above 8.0 are common) and high calcium concentrations (on the order of 40–140 mg/l). The calcium concentration and the high alkalinity are caused by weathering of the calcareous till, which covers most of the candidate area in relatively thick layers. Furthermore, the time interval since the coastal area rose out of the sea is short, and the sampling points which were recently affected by brackish Baltic Sea water show high concentrations of sodium and chloride, see Figure 3-20. North of Bolundsfjärden, the threshold towards the sea is low, and from time to time more saline water can still enter the water system, which consists of a pinched-off former sea bay.

The results from the sampling of near-surface groundwaters include analyses of water samples from 20 soil pipes, three BAT pipes (special sampling pipes where the sample water is sucked into evacuated glass vials), six private wells and one spring. The two-year-long sampling campaigns for near-surface groundwaters will be concluded in the spring of 2005. The sampling points are presented in Figure 3-21. Some of them exhibit high salinities, which may indicate that deeper groundwaters are seeping up or that water of marine origin (perhaps the Littorina Sea) remains in pockets. For example, the sampling point beneath Bolundsfjärden exhibits a higher salinity than present-day Baltic Sea water.

Hydrochemical data have also been obtained from 19 percussion boreholes (HFM01 to HFM19) and four cored boreholes (KFM01A to KFM04A), see Figure 2-10. As a rule, the samples from the percussion boreholes represent the entire borehole, while the cored boreholes are investigated in a number of isolated sections /Nilsson, 2004; Wacker et al. 2004a,b,c/.

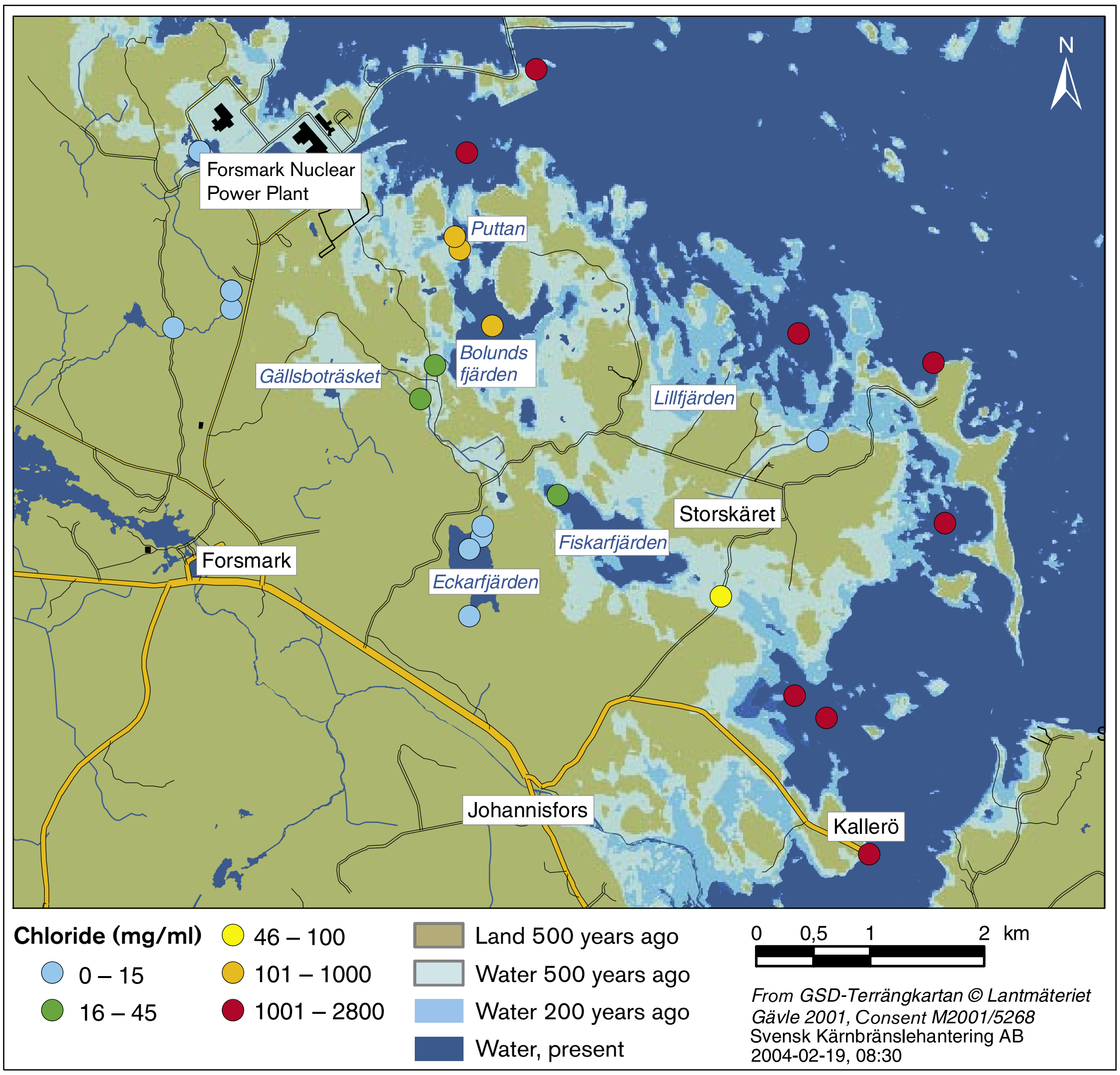


Figure 3-20. *Map with sampling points for surface water. The water type is indicated by means of a colour scale from blue to red for low to high chloride concentration. The location of the coastline at various points in time is also shown.*

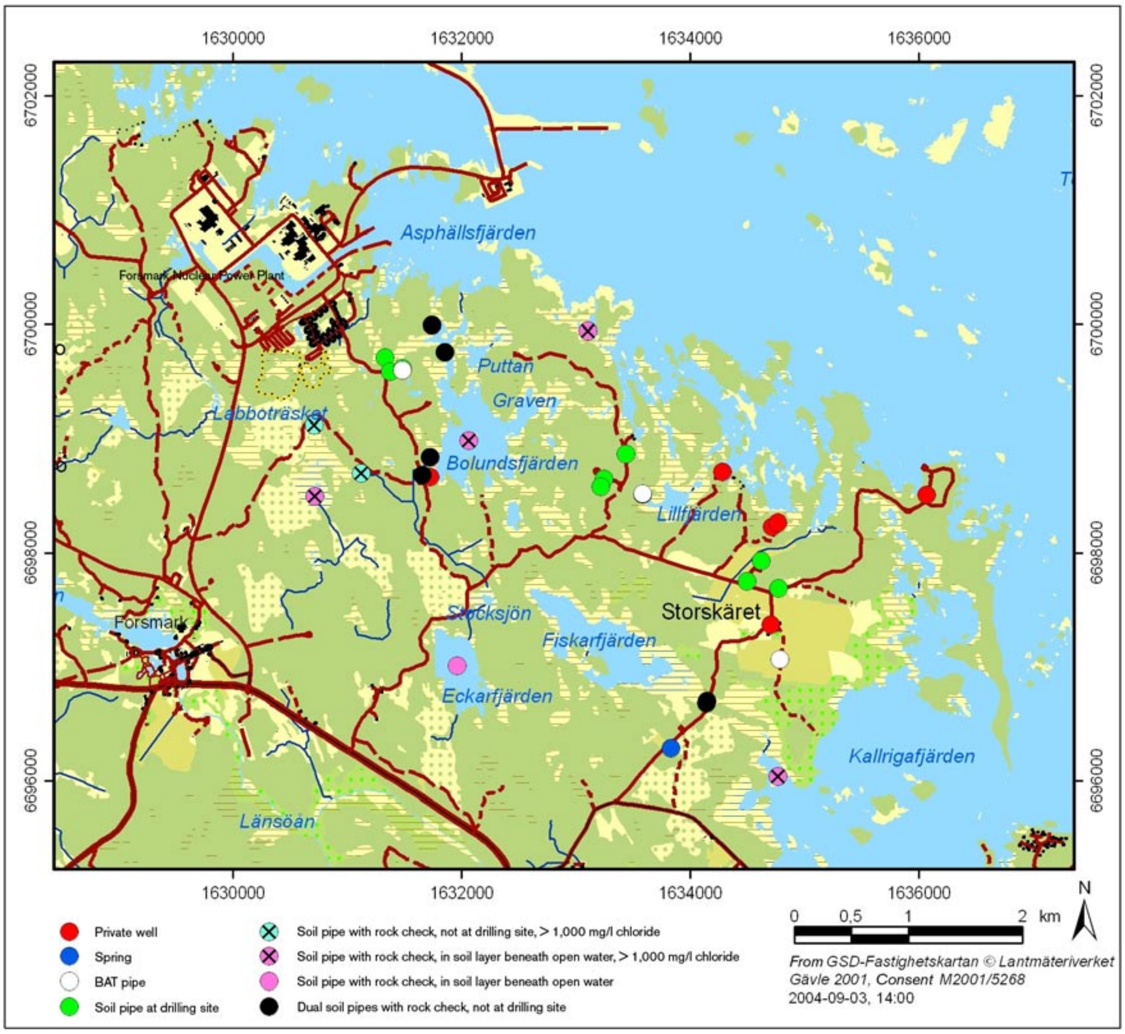


Figure 3-21. *Sampling points for near-surface groundwaters during the first two-year-long surveying campaign. The colour code indicates the type of sampling point. Sampling points that exhibit chloride concentrations consistently higher than 1,000 mg/l are marked with an x.*

A depth profile with the chloride concentrations from percussion boreholes and investigated sections in the cored boreholes plotted against depth is presented in Figure 3-22. For the percussion boreholes it is the depth at the most hydraulically conductive zone that is shown. The diagram clearly shows how the chloride concentration increases sharply with depth, levelling out at just over 5,000 mg/l in the depth interval between 150 and 600 metres. The chloride concentration increases again at greater depths.

In Olkiluoto, approximately 200 km from Forsmark on the Finnish side of the Bothnian Sea, similar investigations are being conducted for the Finnish repository for spent nuclear fuel. A similar concentration trend, with constant chloride concentration in a depth interval from about 150 m, has been observed there as well. However, the chloride concentration increases again from only 500 m, compared to 600 m at Forsmark. Like Forsmark, Olkiluoto is situated in a flat, near-coastal landscape at roughly the same latitude as Forsmark, and it is reasonable to assume that the groundwater there has a similar history to the groundwater in Forsmark. The ongoing evaluations of Forsmark data indicate that the plateau at 5,000 mg/l is created by two waters with the same chloride content but of different origins: water with marine content from the Littorina Sea (chloride concentration between 5,000 and 8,000 mg/l), and a brine from great depth that has been diluted with glacial meltwater, see Figure 3-23. The Littorina Sea occupied the Baltic basin some

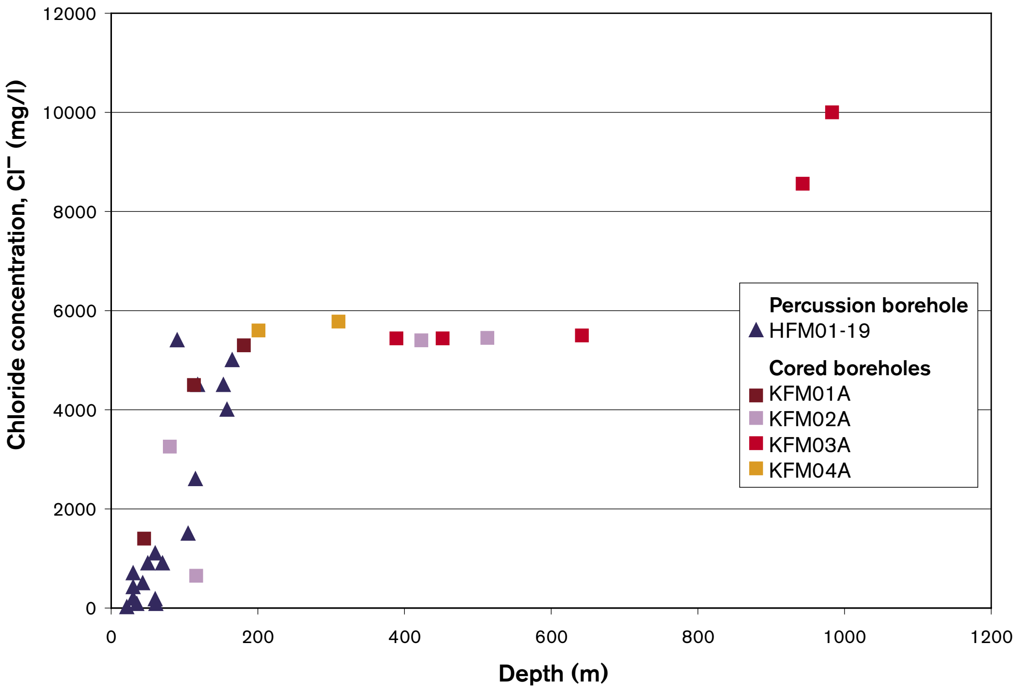


Figure 3-22. *Chloride concentrations at different depths in Forsmark. Red squares indicate water samples from 1,000 m long cored boreholes, while blue triangles indicate samples from percussion boreholes down to about 250 metres. For the percussion boreholes, the points have been plotted at the depth of the most conductive zone.*

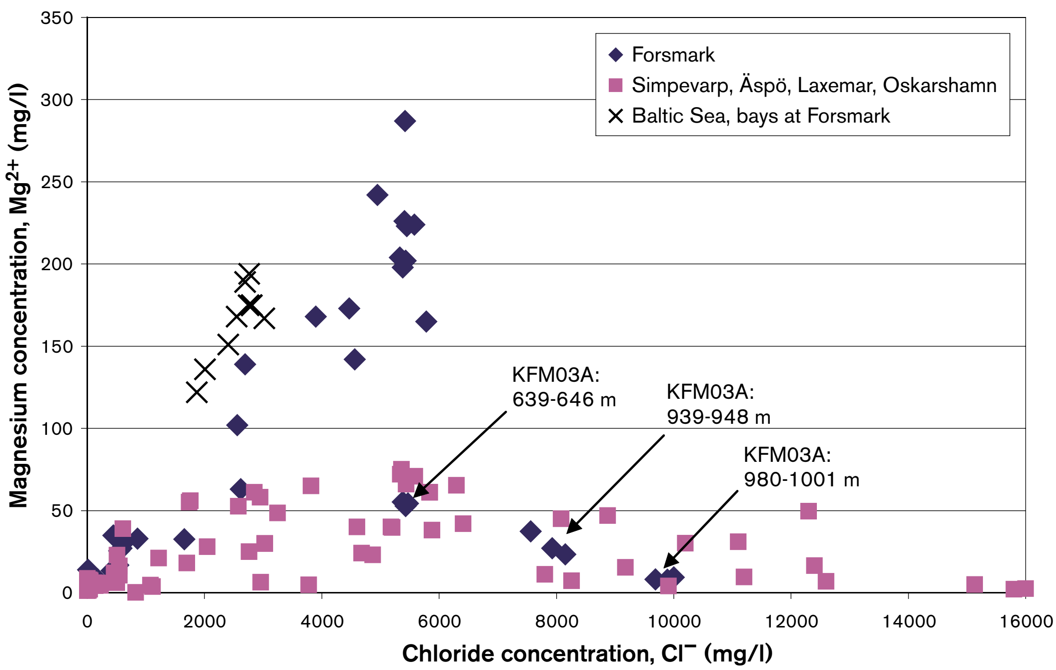


Figure 3-23. *Magnesium concentrations plotted against chloride concentrations for water samples from boreholes in Forsmark and Oskarshamn. Values for water samples from sea bays near Forsmark are given as comparison. The diagram shows that there are two types of deep groundwater in Forsmark's boreholes with different origins. Despite their different origins, the waters can have the same chloride content. The waters with a marine signature (Littorina) lie close to present-day Baltic Sea water, while the deep waters resemble many groundwaters in the Oskarshamn area.*

7,000 years ago and can be regarded as a precursor to the present-day Baltic Sea. Due to the flat topography at Forsmark, the hydraulic driving force is low, which means that old groundwater has not been circulated to the same degree as in hillier areas.

In order to show that reducing (anoxic) conditions prevail in the groundwater, redox potential measurements have been performed in three cored boreholes and a total of seven borehole sections at different depths. The redox measurements in Forsmark are stable and consistent, and the values obtained lie between –140 mV and –250 mV. The negative values confirm that there is no oxygen in the groundwater at these depths. Figure 3-24 shows an example of redox measurements where the value stabilizes at about –190 mV.

The discipline of hydrogeochemistry also includes microbiological investigations in groundwater, and the results obtained to date are from borehole sections in the cored boreholes KFM01A, KFM02A and KFM03A. Active microorganisms affect the composition and redox potential of the groundwater. The graph in Figure 3-25 shows how different types of microorganisms dominate in different redox intervals.

3.6.3 Important questions remaining to be answered

The northwestern part of the candidate area has been prioritized for further investigations. So far, no chemical data are available from depths greater than 200 m in this area. Experience from previous boreholes in the area indicates that water-conducting fracture zones will be very scarce at repository depth and thereunder, even in future boreholes. Every opportunity to perform chemical investigations at greater depths must therefore be taken.

Sediment pore water remains to be analyzed. The reason is that water that has passed through sediment contains high concentrations of waste products from organic degradation and therefore has a composition that deviates from that of other types of water. The sediment pore water may therefore be a type water that should be included in mixing calculations.

Since there are so few water-conducting fractures in large parts of the rock volume being investigated, the pore water in the rock matrix may be of great importance. The composition of the pore water is therefore an important issue.

The water's colloid content may be of importance for nuclide transport, since colloids can act as carriers of radionuclides. It is difficult to determine the colloid content of the groundwater, since the concentration can be affected by virtually every change in e.g. pressure, pH, concentration and temperature of the groundwater. Two methods for colloid determination are currently used: 1) fractionation through two cylindrical membrane filters with different permeabilities, i.e. molecules up to a given size pass, and 2) filtration through a series of filters with decreasing pore size. So far, no colloids have been found in the groundwater. In order to ensure that the colloid concentration in the groundwater is very low or non-existent, a third determination method will be tested based on laser technology.

The evaluation of chemistry data from data freeze 1.2 has scarcely started at the writing of this programme. Additional questions may therefore emerge, and other prioritizations may become necessary when the analysis has progressed further.

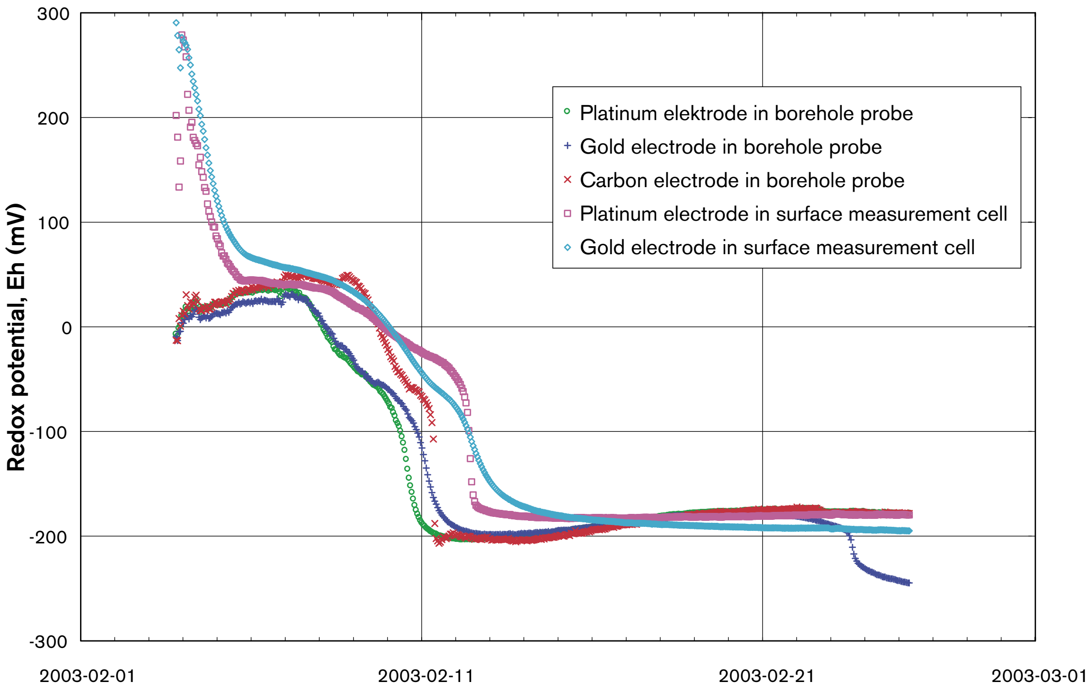


Figure 3-24. *Measurements of redox potential (Eh) in cored borehole KFM01A, section 110–117 m. The curves represent different measurement electrodes. The first period in the measurement with a sharp downward trend represents the process where the oxygen that accompanies the equipment down into the borehole is consumed.*

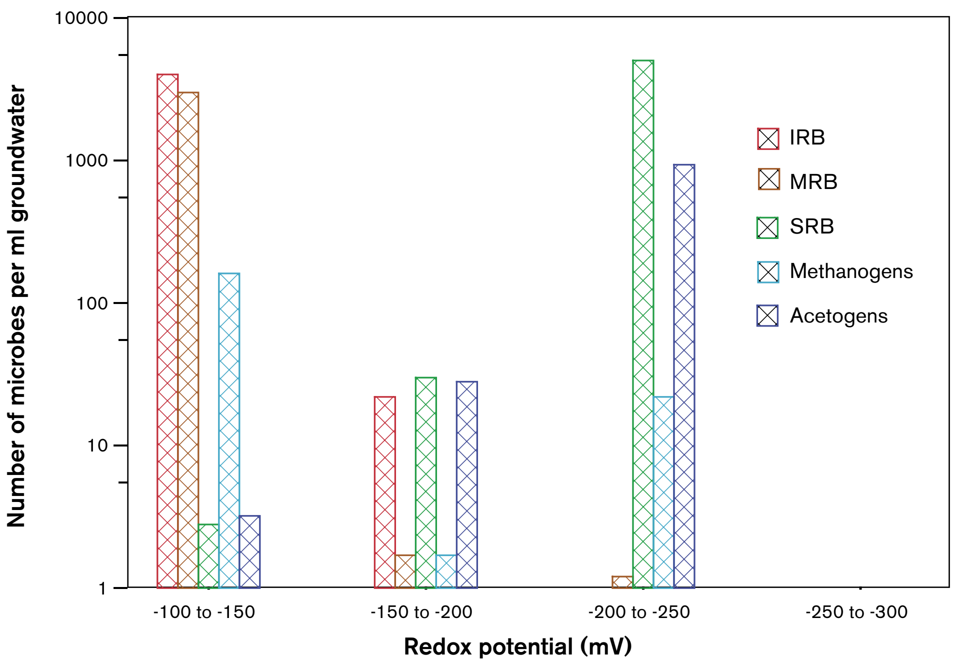


Figure 3-25. *Results from microbe investigations in different sections of the boreholes KFM01A, KFM02A and KFM03A in Forsmark, showing which microbes dominate in different redox intervals. Abbreviations: IRB (Iron Reducing Bacteria), MRB (Manganese Reducing Bacteria) and SRB (Sulphate Reducing Bacteria).*

3.6.4 Investigation programme

Investigations mainly of deep groundwaters are planned from now on. The two-year-long chemical surveys of surface water, precipitation and near-surface groundwaters in the candidate area are virtually finished, with the exception of sampling of precipitation and near-surface groundwaters, which will continue a bit into 2005. Water sampling in a few select sampling points will then phase into the monitoring programme, see section 3.9.

Planned hydrochemical investigations include cored boreholes, percussion boreholes and remaining activities regarding surface water and near-surface groundwaters. These investigations are presented below.

Hydrogeochemical investigations in cored boreholes

The hydrogeochemical investigations that are planned in cored boreholes, listed in chronological order from the time of drilling onward, are:

1. Extraction of water samples during drilling by Wireline probe or other technique is planned in all new cored boreholes. These so-called first strike samples are important for characterizing the groundwater before the borehole's short-circuiting effect has acted too long. Great efforts should be made to obtain samples of good quality, especially in the light of previous problems with equipment and certain difficulties in identifying water-conducting fracture zones when they are passed during drilling.

2. Hydrochemical logging (or hose sampling) immediately after completion of the cored borehole is carried out after an assessment of the flushing water situation in the hole. The flushing water is used during drilling of cored boreholes to cool the drill bit and is taken from a nearby percussion borehole. In many of the deep boreholes in Forsmark, the dominant water-conducting fracture zones are at depths of less than 200 metres, and below that the rock is more or less impervious. As a result, the water column in deeper sections of newly drilled boreholes often consists for the most part of flushing water. When this is suspected, hydrochemical logging is omitted from the investigation programme. Hydrochemical logging is planned in about five cored boreholes.

3. All long cored boreholes should be regarded as chemistry-prioritized (with the exception of the planned hole south of Bolundsfjärden) until it is shown whether they have suitable water-conducting fracture zones or not. For planning purposes, it is assumed that complete chemical characterization will be done in three boreholes and a total of nine borehole sections. Complete chemical characterization includes bacteria sampling. Fracture-filling mineral analyses are performed in the same borehole sections as chemical characterization of the groundwater.

4. Supplementary investigations of the water chemistry in cored boreholes can be conducted during pumping tests and dilution measurements. This may apply to cored boreholes with one or few water-conducting fracture zones in depth intervals of more limited interest, for example because a large quantity of data is already available from the depth in question in other boreholes. The investigations are then carried out mainly to supplement the three-dimensional model. There is no need here for advanced sampling methods and complicated analyses at specialized laboratories.

5. Pore water from core samples from borehole KFM06A will be analyzed. Depending on the outcome of the first sampling round, similar tests may be performed on samples from other cored boreholes.

Hydrochemical investigations in percussion boreholes

In the approximately ten percussion boreholes that are planned, flow logging will be done with equipment for hydrotests. These tests provide a good opportunity to sample groundwater for chemical analyses with little extra labour. The boreholes will be up to 300 m long. The most prevalent water-conducting fracture zones in Forsmark are located above a depth of 200 metres. The samples provide chemistry data with a good spread over the candidate area in the most conductive depth interval, especially within the priority site, and of sufficiently high quality for the three-dimensional model and for mixing calculations.

Hydrogeochemical investigations of surface water and near-surface groundwaters

The planned hydrogeochemical investigations of surface water and near-surface groundwaters are:

1. The two-year-long sampling campaign for precipitation and for near-surface groundwaters in soil pipes, BAT pipes, private wells and one natural spring will cease in the spring of 2005. Sampling of near-surface waters will then phase into long-term monitoring, see section 3.9. A number of soil pipes are placed in the sediments in lakes and sea bays. A couple of new pipes will be placed in wetlands and sampled in a special campaign.

2. Follow-up of water composition in nearby soil pipes during core drilling. The water composition needs to be followed up in any new soil pipes, as well as in old suitably placed soil pipes before, during and after core drilling, both with regard to environmental impact, for example from fuels and lubricants, and to keep track of any changes in water composition caused by hydraulic impact during drilling.

3. Sampling and analysis of sediment pore water will be carried out in the early spring of 2005 in approximately four sampling points, one in the sea and three in lakes.

3.7 Transport properties

3.7.1 Purpose and goal

The main purpose of the programme is to provide the safety assessment with data for calculations of radionuclide transport. The most important transport properties in this context are the rock's capacity to retard radionuclides by:

- Sorption (retention on fracture surfaces and in the pores of the rock).
- Diffusion (penetration into microfractures and pores).

In the case of reactive (sorbing) substances, some of the most important parameters are matrix diffusivity (a measure of how rapidly a substance can penetrate or diffuse through the rock matrix), matrix porosity and sorption coefficients (parameters that measure the rock's capacity to retain different substances on fracture surfaces and in pores). Matrix diffusivity can also be calculated on the basis of determinations of the formation factor (the ratio between diffusion in the rock matrix and in free water).

In the case of non-reactive (non-sorbing) substances, the most important parameters are flow porosity, dispersivity (measure of spread of flow velocities between fractures or in individual fractures), fracture aperture and travel time.

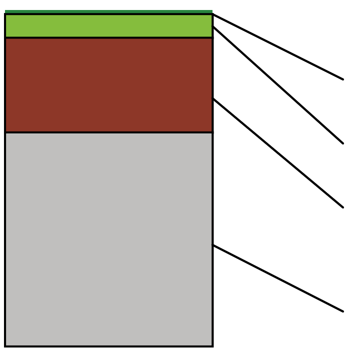
These parameters are determined primarily by laboratory measurements on pieces of drill cores, but also indirectly by means of tracer tests and interpretation of the rock's resistivity. Another vital parameter to determine is the groundwater flow, which affects radionuclide transport.

The advantage of laboratory measurements is that they can be conducted under controlled conditions, while the disadvantage is that they are conducted in a disturbed environment, where the samples have been depressurized and where the chemistry is different from that in the natural environment. An attempt is made to overcome this problem and obtain a better understanding of these processes by applying a combination of laboratory measurements and field methods (for example cross-hole and single-hole tracer tests).

The strategy that leads to the site-descriptive transport model consists of a strategy for laboratory measurements and their interpretation /Widestrand et al. 2003/, plus a modelling strategy /Berglund and Selroos, 2003/. In the former, the quantity of samples and the selection of typical rock types and fracture types to be investigated are specified. The strategy also includes a procedure for how samples that will undergo more extensive analyses of porosity distribution and sorption properties are to be selected, and it stipulates, together with the method descriptions, how data are to be evaluated.

The foundation of the modelling strategy is to combine the three-dimensional flow models of the area with the measured transport parameters. The former provide a statistical description of the spatial distribution of the flow paths, of the associated groundwater travel times, and of the transport resistances. The transport parameters are utilized to devise a site-descriptive retardation model that describes the retardation of radionuclides in the flow system. The flow models, in combination with the retardation models, constitute a basis for reactive transport modelling, whose result, the site-descriptive transport model, consists of breakthrough curves for tracers in tracer tests and dose curves in safety analysis modelling. In other words, the transport of both sorbing and non-sorbing substances on the repository site can be described with the aid of the transport model.

An example of what a description of a fracture type can look like is given in Figure 3-26. Co-interpretation between geology, mineralogy, hydrogeochemistry and transport properties is an important part of the site-specific retardation model.



Thickness	Mineral/rock	Mean porosity (-)	K_d(Cs) (m^3/kg)	D_e(Cs) (m^2/s)
0–1 mm	chlorite	0.05	$5x10^{-2}$	$5x10^{-12}$
1–10 mm	mylonite	0.02	$1x10^{-2}$	$1x10^{-12}$
10–30 mm	metamorphosed rock	0.01	$8x10^{-3}$	$5x10^{-13}$
30 mm –	fresh rock	0.005	$5x10^{-3}$	$2x10^{-13}$

Figure 3-26. *Example of description of the rock near a fracture surface with typical retention parameters, K_d (sorption coefficient) and D_e (matrix diffusivity) /Widestrand et al. 2003/.*

3.7.2 Important results from completed investigations

The goal to date has been to commence time-consuming laboratory measurements on core pieces and to conduct groundwater flow measurements in one of the first deep cored boreholes /SKB, 2001b/. This goal has been met with the start of batch sorption measurements in the autumn of 2004 and the performance of groundwater flow measurements and single-hole tracer tests (SWIW test = single-well injection-withdrawal tests of the type push and pull) in KFM01A, KFM02A and KFM03A/3B in the autumn of 2004.

Through-diffusion measurements (Figure 3-27) have been conducted since the spring of 2004 and determinations of the rock's diffusion properties (porosity and formation factor) have been performed on 100 or so core samples from KFM01A and KFM02A. The porosity measurements indicate low porosities, 0.1–0.3%, with the exception of a short section in KFM02A with highly metamorphosed granite, see section 2.3.2, where porosity is elevated, up to 20%. Data on diffusivities and formation factors are being delivered during the autumn of 2004. Based on the low porosity, the formation factors are also expected to be low, probably in the range 10^{-4}–10^{-6}. The timetable for all through-diffusion measurements has been delayed by about six months due to the fact that virtually none of the measurement methods used in the disciplinary programme are standard methods. A great deal of work has therefore been devoted to determining exactly how the method is to be executed and what strategy is to be used for taking samples.

A study regarding the feasibility of using data from similar rock in the Finnsjö area, situated about 15 km from Forsmark, shows that only a few data on diffusivity and formation factors can be used. The data that can be used represent a red granodiorite with porosity values around 0.5%, which would give formation factors on the order of 10^{-5}.

Other important input data for calculation of radionuclide transport are groundwater flow, fracture distribution and hydrogeochemical properties. The low fracture frequency and flat topography in the Forsmark area indicate that the groundwater flows are low, but no data from field measurements is yet available.

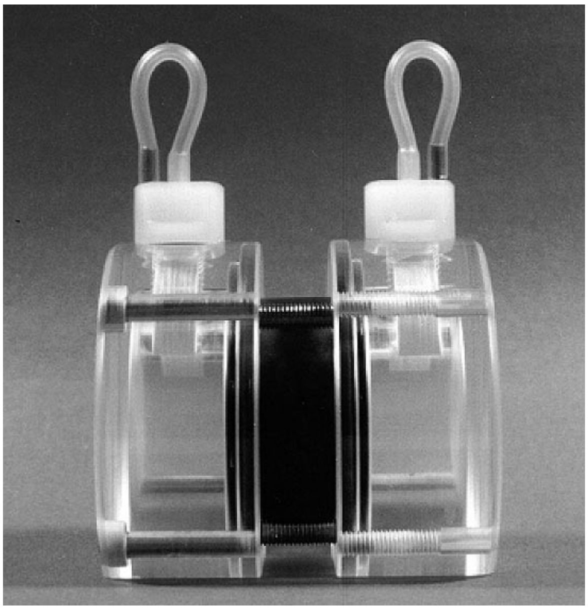


Figure 3-27. *Drill core piece mounted in diffusion cell for determination of diffusivity.*

3.7.3 Important questions remaining to be answered

Since only a few site-specific transport data have been obtained so far, a number of important questions remain to be answered.

The most important task will be to accumulate a solid body of data on the diffusion and sorption properties of the rock mass for the safety assessment. It is important to investigate the spatial variations in the parameter values for the intact rock and to collect data for an identification and description of "typical fractures", in accordance with the proposed strategy. It should be possible to obtain this information for the most part from ongoing laboratory experiments, augmented to some extent during the continued site investigation.

It is also important to clarify the natural movements of the groundwater within the candidate area and its boundary zones. How large are the water flows through the area? What are the most important zones from a flow viewpoint, and what are their flow properties? Such questions can be answered by measuring groundwater flows in fractures and fracture zones and by estimating the hydraulic gradient. Connections between fracture zones at depth and the highly transmissive superficial part of the bedrock are hereby of special interest, but connections between fracture zones are also important to establish, as well as how the water flow varies with depth along a fracture zone. Since no field tests have yet been performed, transport parameters from flow paths within the area are also lacking.

Other important questions for the disciplinary programme are the extent of the superficial, gently-dipping and highly transmissive fractures and fracture zones and their interconnections. The investigations have shown that these fractures are filled with sediment in places, but may nevertheless have "channels" with high permeability. Pumping tests in combination with tracer tests can provide more information on this. Since the soil layers are relatively thick within the area, their sorption properties may also play a role in the retardation of radionuclides. A study is currently under way concerning the best way to investigate the sorption properties of the soil layers. Certain batch sorption measurements will probably also be carried out.

3.7.4 Investigation programme

The laboratory programme will be intensified during 2005. Most of the through-diffusion measurements, batch sorption measurements and porosity distribution determinations by means of the PMMA method will be carried out that year. Besides the measurements already started on material from the central fracture-poor parts of the investigation area (i.e. from the candidate area), more energy will be devoted to fracture zones and deformation zones both within the priority site and in its hydraulic boundary zones. By "boundary zones" is meant here both the outer boundary of the tectonic lens consisting of inhomogeneous banded bedrock that has undergone ductile or, in parts, brittle deformation, and the regional hydraulic margins (the Forsmark and Eckarfjärd zones in the southwest and the Singö Fault in the northeast). The majority of the laboratory investigations are expected to be completed during 2006, after which only a few supplementary measurements will be performed.

Determinations of the formation factor will be carried out in the autumn of 2004 by an analysis of field data from resistivity measurements in the cored boreholes KFM01A and KFM02A. The results will serve as a basis for how future analyses will be done on the priority site. It is, however, likely that similar determinations will be performed in a number of additional boreholes, since preliminary results from the site investigation in Oskarshamn show good results. Groundwater flow measurements and single-hole tracer tests (SWIW tests), which are being conducted in the autumn of 2004 in the cored boreholes KFM01A, KFM02A, KFM03A and KFM03B, will be conducted in 2–3 additional cored boreholes during 2005–2007. The exact scope of such measurements is difficult to foresee, however, since no investigation results are available at present and experience is therefore lacking.

The large gently-dipping fracture zone A2 will probably be further surveyed in order to supplement the characterization of its depth-related properties. This can be accomplished by, for example, measuring water flows in the superficial part of the zone in percussion boreholes (HFM16 and HFM19) and at depth in the same zone in cored borehole KFM02A and the planned deep cored borehole just south of Bolundsfjärden (S Bol).

The open, sediment-filled and gently-dipping fractures in the superficial part of the bedrock can be investigated with regard to connections, persistence and water flux by means of groundwater flow measurements in combination with pumping and tracer tests. A suitable area in which this can be done may be the northwestern part of the investigation area in the percussion boreholes planned there.

Cross-hole tracer tests often require preparations in the form of an infrastructure with a number of instrumented boreholes. By "instrumentation" is meant in this case that the boreholes are divided into isolated sections, permitting pressure recording and tracer injection in individual fracture zones. These cross-hole tests, which are performed late when other disturbing activities have been concluded, are very important for providing a comprehensive picture of the magnitude of water transport and the transport pathways in the area. In addition to the above-mentioned proposal for the superficial, gently-dipping fractures, tracer tests along one of the major fracture zones, preferably A2, may be conducted when the borehole south of Bolundsfjärden (S Bol, about 1,400 m from KFM02A) is available.

It will be investigated whether it is possible, with the conditions prevailing in the deep rock in Forsmark, to conduct tracer tests with both sorbing and non-sorbing tracers. A possible candidate is the A2 zone at drilling site 2. This zone occurs in borehole KFM02A at a depth of 400–500 m. A second borehole, parallel to the first and ten or so metres away, could offer a suitable test setup. Since the usefulness of such a tracer test has not yet been investigated, the new borehole has not been included in the planning for the time being.

The transport properties of the boundary of the tectonic lens can be studied in one of the planned cored boreholes that will be oriented towards the northeastern boundary of the lens, e.g. KFM06C or KFM08C, or in the holes that have been or will be drilled through the southwestern boundary (KFM04A or KFM07A). Opportunities will also exist to study the transport properties of the regional boundary zones in the holes that are planned to be drilled through these zones.

3.8 Drilling

3.8.1 Purpose and goal

With the exception of excavation, drilling various kinds of holes is the only method available for directly investigating soil and rock beneath the observable surface. Drilling makes it possible to take samples of the material in the form of cuttings or cores, directly during drilling, and then provides access for a wide range of borehole-based methods for investigating the properties of the rock (such as mineral distribution, physical properties, fractures, loads) and the groundwater (permeability, flows, chemical composition). Drilling is a kind of random sampling of geological materials, with obvious limitations in that the material sampled exhibits wide spatial variation. The way to get around this is to combine the information from boreholes with knowledge of conditions on the surface (for example from geological mapping) and investigation methods able to "capture" properties over areas or volumes (for example airborne and ground geophysical surveys, borehole radar, seismic methods and hydraulic tests).

Three main types of boreholes are utilized in the site investigation:

- Cored boreholes, for investigating the rock down to a maximum depth of about 1,000 metres /e.g. Claesson and Nilsson, 2003b/.
- Percussion boreholes, drilled through soil layers and the superficial part of the bedrock, down to a maximum depth of about 300 metres /e.g. Claesson and Nilsson, 2003a/.
- Soil boreholes, drilled through the overburden and a short way into the surface rock.

The purpose and goal of cored and percussion boreholes follow directly from the overall strategy for the remainder of the site investigation, and are described in section 2.4. Auger drilling is used for environmental control at drill sites, and for investigations of Quaternary geological, hydrological and hydrogeochemical conditions.

3.8.2 Important results from completed investigations

The maps in Figure 2-10 and Figure 2-11 show locations and types of all boreholes drilled to date in the investigation area.

The investigations for which the boreholes are used sometimes make unique demands on borehole designs and quality of execution. These demands pertain, for example, to straightness and other geometric properties, cleanliness, flushing water handling and documentation of the drilling process. These demands have largely been met. The technical modifications that have been made have been aimed at simplifying and improving efficiency, without compromising quality.

This is not to say that the drilling work has proceeded entirely without mishap, since this would hardly be possible, especially when core drilling to great depths. But as a whole the disruptions have been surprisingly few and never serious. The successful drilling can be attributed to knowledge accumulated in earlier phases of the nuclear waste programme (study areas, Äspö HRL, preparations for the site investigations), the skill of the contractors, and favourable rock conditions.

Core drilling

The situation at the beginning of August 2004 is that five cored boreholes with lengths of just over 1,000 metres have been finished and a sixth is being drilled. In addition, one hole will be drilled to a depth of 100 metres and another to nearly 500 m. Six drilling sites have been established in the area. Figure 3-28 shows one of them. With the necessary drilling equipment, arrangements for flushing water handling, utility systems, peripheral equipment, storage areas and access road, a drilling site resembles a small building site.

Table 3-1 presents technical data on the boreholes. The holes are either nearly vertical or inclined at 60 degrees. Completely vertical holes, as well as holes with an inclination of less than 60 degrees, are avoided for measurement-related reasons, although they would not entail any drilling-related problems.

The deep cored boreholes are all of telescopic design, see Figure 3-29. This means that the first 100 metres are percussion-drilled with a diameter of 200 mm, or 250 mm if stabilization and/or sealing is needed. If this is the case, the borehole is lined with a stainless steel casing and the gap to the rock is sealed with cement. A loose support casing

Figure 3-28. Drilling site 1 during drilling of the site investigation's first deep cored boreholes.

Table 3-1. Technical data for cored boreholes.

Cored borehole	Type	Orientation (bearing/inclination)	Drilled length (m)	Vertical depth (m)	Comment
KFM01A, Drilling site 1	Telescopic borehole	318/85	1,001	982	Chemistry-characterized
KFM01B, Drilling site 1	Cored borehole	267/79	501	479	Rock stress measurements and complement to telescopic hole KFM01A as regards drill core 0–100 m
KFM02A, Drilling site 2	Telescopic borehole	275/85	1,002	989	Chemistry-characterized
Drilling site 3	Telescopic borehole	271/85	1,001	988	Chemistry-characterized
Drilling site 3	Cored borehole	264/85	102	93	Complement to telescopic hole KFM03A as regards drill core 0–100 m
KFM04A, Drilling site 4	Telescopic borehole	45/60	1,001	794	Chemistry-characterized
KFM05A, Drilling site 5	Telescopic borehole	81/60	1,003	825	Chemistry-characterized

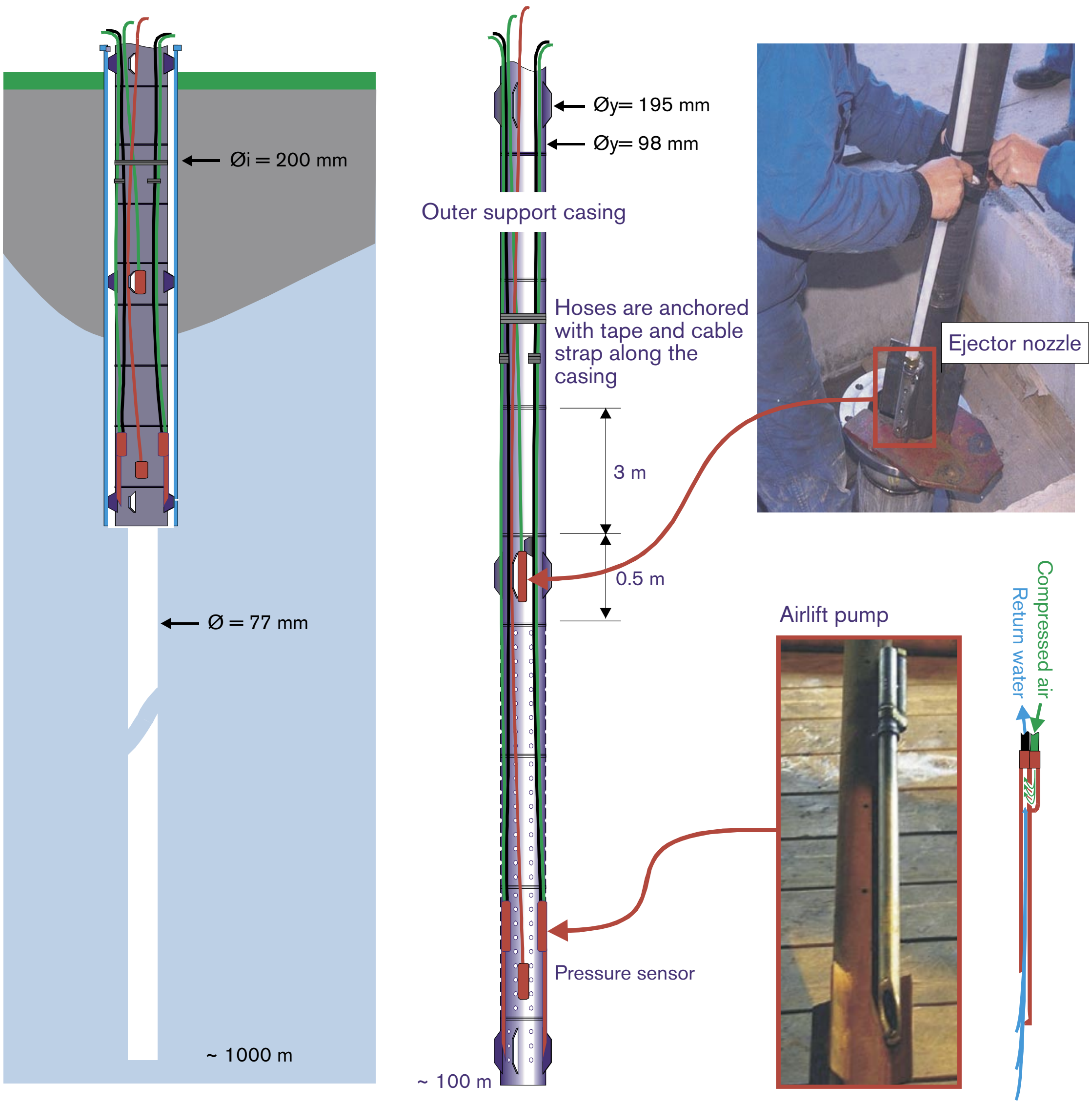


Figure 3-29. *Telescopic design for cored boreholes.*

is then installed together with pumping and measurement equipment. Finally, another casing is fitted to centre and support the drill string. When this has been done, core drilling of the 100–1,000 m section can begin.

The capacity for core drilling has been on average about 90 metres per week (four-day week with drilling round the clock). Including time for establishment etc, a deep cored borehole ties up equipment for about three months. The quartz-rich granitic bedrock causes heavy wear on the drill bits, and the frequent bit changes limit the rate of advance. On the other hand, the fracture-poor rock and efficient handling of cores increase the rate of advance.

The highly water-conducting fractures and fracture zones that are normally encountered at depths down to about 200 m are of importance for the drilling, even at greater depths. In cases where large water inflows occur at depths of less than 100 m, i.e. in the percussion-drilled part of the telescopic holes, they can as a rule be screened off by the installation of casing and grouting of the gap between the casing and the borehole wall. Figure 3-30 shows the water inflows, measured before the holes have been screened off in this manner. If, however, there are highly water-conducting fractures further down, in the core-drilled part, large inflows can make it more difficult to detect during drilling the much smaller inflows that may exist at greater depths.

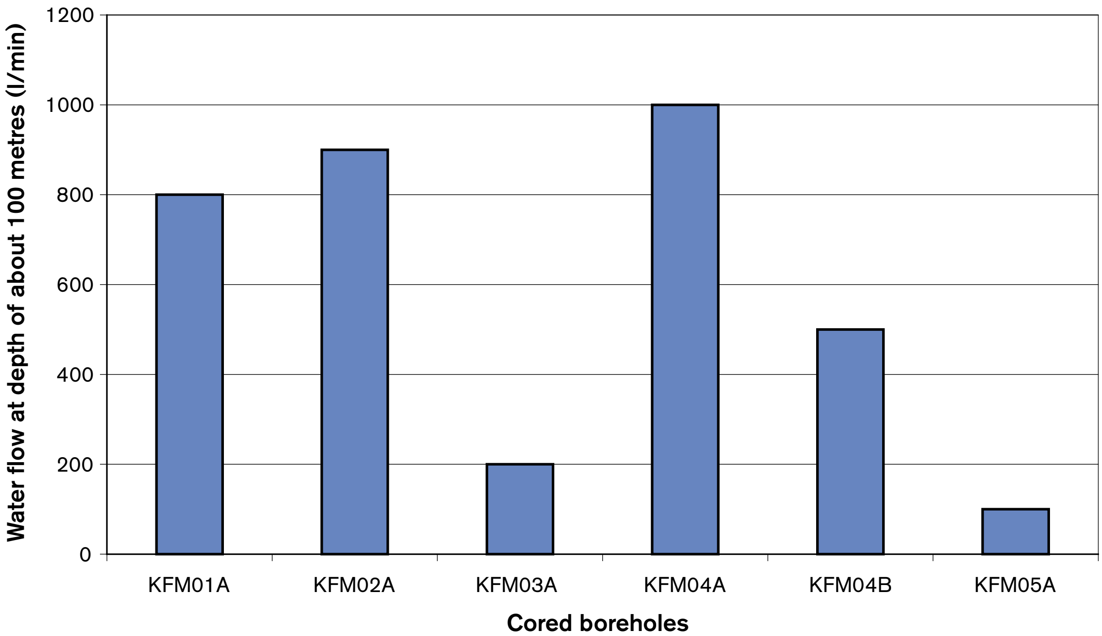


Figure 3-30. *Measured water inflows down to a depth of about 100 metres in telescopic cored boreholes. When casing is installed in the hole, these flows are usually screened off.*

Flushing water quality

Flushing water for core drilling is taken from nearby percussion-drilled holes. Before the water is used for flushing its quality is checked. The purposes of this quality check are:

- To make sure the water is good enough prior to use, particularly with regard to TOC (Total Organic Carbon) content. The concentration of organic components should be low. The reason is that hydrocarbons can affect the microbiological conditions in the borehole and thereby cause incorrect results in subsequent investigations of microbes in the borehole. A practical limit has been set at 5 mg/l.
- To check the microbe content for drilling of holes where hydrogeochemical investigations are planned.

The water is pumped from the approved well to the drilling site, where it is handled under pressurized nitrogen to minimize the concentration of dissolved oxygen in the water. After irradiation by UV light and marking with a tracer, the water is ready to be pumped down into the borehole. The purpose of UV irradiation is to eliminate microbes. Marking with a tracer (uranine) makes it possible to detect any residues of flushing water in water samples taken later on.

A summary of the analyses of microbes in flushing water performed to date is shown in Figure 3-31. The bars show the results of repeated tests of incoming water from the flushing water well and water after UV irradiation and tracer addition. What the graph reflects is a trend that has led to a current situation where the microbe content can be limited and checked much better than at the start of the site investigation phase. The concentrations are now so low that UV irradiation does not always lead to any improvement, partly because the addition of tracer, which has to be done after irradiation, can introduce microbes.

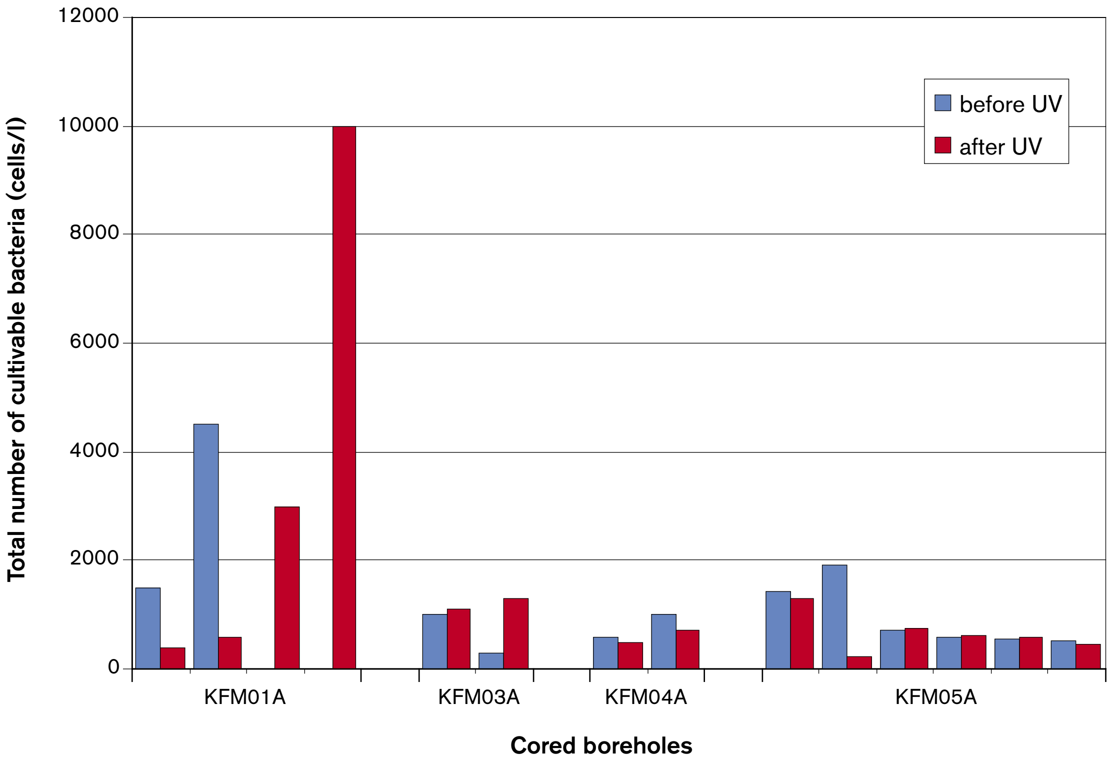


Figure 3-31. *Results of microbe analyses in flushing water for drilling of four cored boreholes. The concentrations are now so low that UV irradiation does not always lead to any improvement, partly because the addition of tracer, which has to be done after irradiation, can introduce microbes.*

Percussion drilling

The procedure for percussion drilling of holes through the overburden and the surface rock has been developed since the site investigation started, which has led to more efficient drilling. With the procedure that is currently used, a 200-metre borehole is finished in 3–4 days. A total of 19 percussion boreholes have been drilled. The majority are 100–200 m long. With few exceptions, the percussion boreholes have been drilled through highly conductive gently-dipping fractures or fracture zones, see Figure 3-32. Figure 3-33 shows depth and measured flows for all percussion boreholes drilled so far. As shown by the figure, the water flows cannot be correlated with hole depth.

Auger drilling

Auger drilling has been carried out for two main purposes. Firstly, wells (10) have been bored for environmental control at the drilling sites, and secondly holes have been bored to determine soil depth and Quaternary deposits, to measure the hydraulic transmissivity of the soil layers, and to take samples of groundwater (61 holes). All soil boreholes are included in the monitoring programme for groundwater levels, and some are used to monitor groundwater chemistry and ecosystems. Auger drilling is done using conventional technology. The boring rig is chosen based on requirements on capacity and off-road mobility. Figure A-6 Appendix A shows a auger drilling rig.

Figure 3-32. *Percussion drilling of HFM16, whereby an inflow of groundwater to the borehole of 1,200 l/min was measured.*

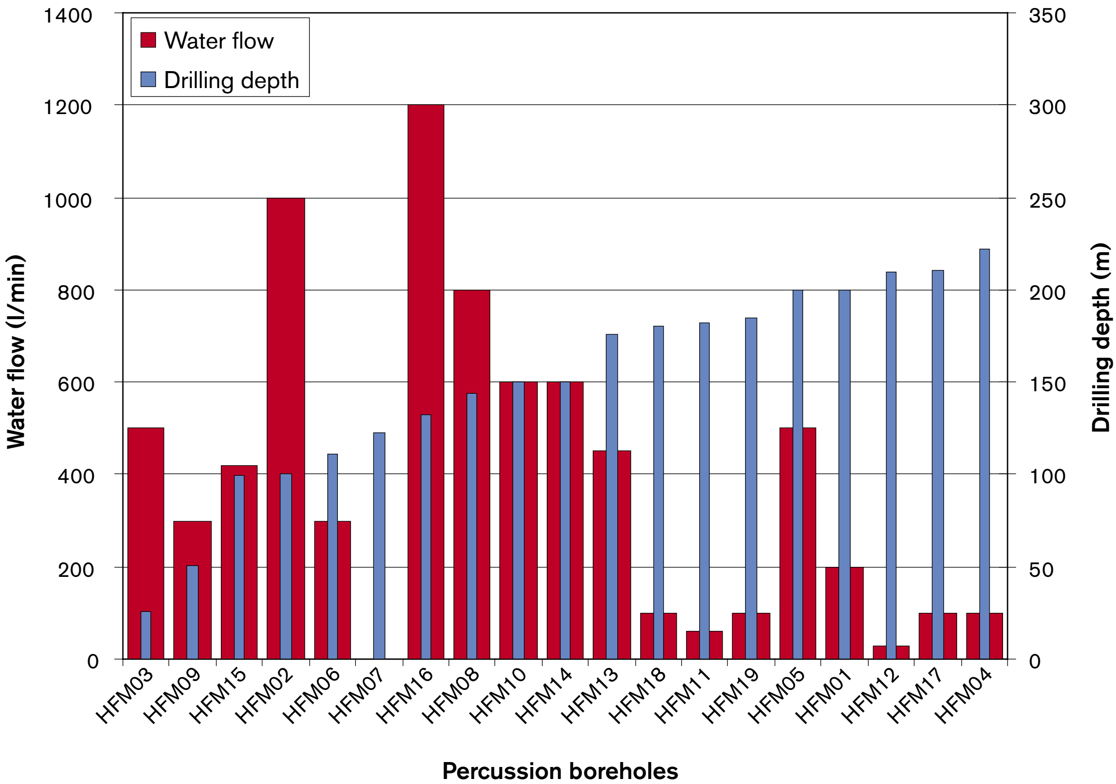


Figure 3-33. *Hole depth and measured water inflows for all percussion boreholes.*

3.8.3 Investigation programme

Core drilling

The programme for the remaining core drilling is reported in the context of investigation strategy in section 2.4. Table 3-2 shows the plan for the individual boreholes. The planning level varies from fixed specifications for the cored boreholes that are closest in time, to estimates of what activities are required in the final phase of the site investigation. The total hole length is estimated at about 9,500 metres. This assumes that another heavy drilling rig will be established, starting in the spring of 2005. Besides the new machine, no changes in technology or procedure are planned for the core drilling.

Table 3-2. Planned cored boreholes in Forsmark, cf Table 2-2.

Location, designation	Length (m)	Orientation (bearing/inclination)	Type of hole, comment
Survey the boundaries and properties of the priority site			
Drilling site 6			
KFM06A	about 1,000	NE/60	Cored borehole with telescopic part
KFM06B	about 100	Nearly vertical	Cored borehole without telescopic part
KFM06C	about 1,000	NE/60	Cored borehole with telescopic part
Drilling site 7			
KFM07A	about 1,000	~ W/60	Cored borehole with telescopic part
Drilling site 8			
KFM08A	about 1,000	~ NW/60	Cored borehole with telescopic part
KFM08B	about 200	~ W/60	Cored borehole without telescopic part
KFM08C	about 1,000	Probably NE	Cored borehole with telescopic part
S Bol			
KFMXX	about 700	Nearly vertical	Cored borehole without telescopic part, tentatively overcoring measurements
Data for planning of descents and central area			
Drilling site 7			
KFM07B	about 500	Nearly vertical	Cored borehole without telescopic part, overcoring measurements
Ramp			
KFMXX	about 600	Probably steep	Not decided
KFMXX	about 300	Not decided	Not decided
KFMXX	about 300	Not decided	Not decided
Characterize hydraulic boundary areas			
NE			
KFMXX	about 700	Not decided	Not decided
KFMXX	about 700	Not decided	Not decided
SW			
KFMXX	about 700	Not decided	Not decided
KFMXX	about 700	Not decided	Not decided

The timetable and sequence for remaining core drilling is shown in Figure 3-34. The timetable is judged to be tight but realistic, based on experience available from the initial site investigation. As before, delays can to some extent be made up by temporary increases in work intensity.

Percussion drilling

It is tentatively estimated that 10–15 percussion boreholes need to be drilled, with a concentration to the priority site and the hydraulic margins.

Auger drilling

Only a small number of supplementary soil boreholes, for environmental control among other things, are planned during the remainder of the site investigation.

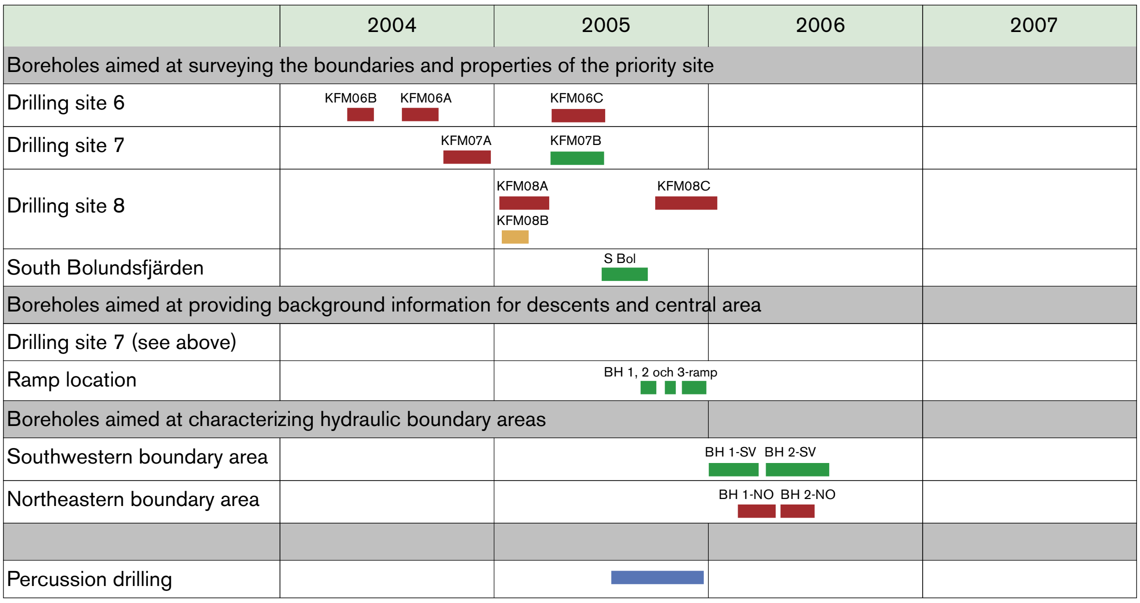


Figure 3-34. *Timetable and sequence for remaining core drilling. From the spring of 2005, the programme will engage two heavy core drilling rigs, and during brief periods a lighter rig as well. The different machines are marked with different colours.*

3.9 Monitoring[8]

Monitoring is important for many of the parameters included in the site investigation, not least to provide a frame of reference or baseline for both safety assessment and design, as well as for assessment of the impact on environment and health.

Many of the investigated parameters, such as precipitation and groundwater levels, will exhibit variations over time. One reason for this is seasonal variations in precipitation and temperature. There may also be other, more unpredictable causes, such as long-range variations or trends in meteorological parameters, as well as random events, which cause one or more parameters to vary over time. Furthermore, investigations and work in soil layers and in the bedrock may affect the parameters.

Being able to interpret and understand variations over time is an important part of the work of establishing primary baseline data for the site. Monitoring is therefore an important part of the site investigation. With the site's primary baseline data as a reference, it is possible to detect changes that are due to the construction of the deep repository, and differentiate between natural changes and variations in time and space that are due to human activities.

Time series are needed for parameters that exhibit clear variation over time, for at least two reasons. In the first place, the site investigation includes for many parameters an estimate of "typical" values (mean value, median value etc) or extreme values (minimum, maximum, etc), as well as a measure of how these values vary. Knowledge of patterns in and the scope of variations over time can be critical for our ability to describe site-specific conditions correctly and to model important processes. In the second place, many site-specific conditions will change during the construction and operation of the deep repository, both for natural reasons and as a consequence of the activities on the site. In order to be able to discover and quantify these changes, it is necessary to have a clear picture of "undisturbed" conditions on the site. Moreover, knowledge of undisturbed conditions, together with good reference data, can greatly improve our ability to distinguish between natural changes and changes caused by activities on the site.

The site investigation therefore includes collection of time series for all important parameters that show a clear variation over time, i.e. parameters for which an instantaneous "snapshot" is not enough to characterize undisturbed conditions or processes or processes that can be expected to change as a result of the construction and operation of a repository. Natural variations of this kind are mainly associated with ecological, hydrological, hydrogeological and hydrogeochemical parameters measured near the ground surface. But there may also be parameters, mainly hydrogeological ones, that exhibit considerable variation over time at great depth as well. The programme further includes recording of seismic activity.

In order to keep the monitoring programme from being of unreasonably or unnecessarily large scope, SKB will continuously evaluate results and experience from the programme. The choice of parameters, sampling points, and frequency of sampling and analysis will be based on evaluation and analysis of previously collected data. The current selection of parameters and sampling points for monitoring is thus based on the results of investigations conducted to date. Observed variations over both time and space have been important factors in this choice.

[8] Monitoring is defined in /Bäckblom and Almén, 2004/ as: "Continuous or repeated observations or measurements of parameters to increase the scientific understanding of the site and the repository, to show compliance with requirements or for adaptation of plans in the light of the monitoring results".

The site investigation will only yield time series covering a few years. To find out about more long-term trends, this information will therefore be supplemented with already available long-term measurements of e.g. meteorological data. Furthermore, the programme presented below is planned to be followed by a programme for monitoring during the entire construction and operating phase /Bäckblom and Almén, 2004; Andersson et al. 2004/.

The programme for monitoring during the site investigation phase is dealt with in the following sections. Even though the programme is primarily presented under headings for the different disciplines, several activities will be coordinated.

3.9.1 Meteorology

Meteorological measurements are necessary input parameters for calculation of an area's water balance and comprise an important basis for defining boundary conditions for the hydrological and hydrogeological calculation models. Meteorological statistics are also important input data for noise measurements and noise calculations, since the propagation of noise is greatly affected by the weather situation.

Completed investigations

Meteorological data in the form of precipitation, snow depth, temperature, wind, relative humidity, air pressure, cloud cover and global insolation can be obtained from existing monitoring stations operated by SMHI. In order to ensure high reliability in the data, however, the distance to the monitoring stations should not be too great. In Forsmark, SKB has chosen to set up its own meteorological monitoring stations. In the first place, an existing weather mast at the Forsmark NPP (the "high mast") has been utilized, and the measurement equipment there has been updated; in the second place, a new weather mast has been established in the southeastern part of the candidate area at Storskäret, see Figure 3-35. Snow depth and the water content of the snow have been measured at various selected localities within the candidate area.

The first year of the site investigation was devoted to planning and establishment of these systems. Meteorological data have therefore been collected over a period of about one year. Collected data are first sent to SMHI for quality control and are then stored in SKB's HMS (Hydro Monitoring System), which is a recording, data storage and display system for hydrogeological, surface hydrological and meteorological data /Lindell et al. 1999; Larsson-McCann et al. 2002; Aquilonius and Karlsson, 2003; Heneryd, 2004/.

Investigation programme

Data collection will continue according to the procedures and the technology established during the initial site investigation as a basis for the site description and as input data and for calibration and validation of the hydrological and hydrogeological models (local and regional) of the Forsmark area. The scope of the measurements is shown by Table 3-3.

Figure 3-35. *Meteorological monitoring station at Äspö HRL in Oskarshamn. A similar station has been established at Storskäret.*

Table 3-3. Meteorological measurements.

Parameter	Recording frequency	Storskäret	High mast
Wind direction and speed (at height of 10 m)	every 30 min (mean value)	x	x
Air temperature	every 30 min (mean value)	x	x
Relative humidity	every 30 min (mean value)	x	x
Precipitation	every 30 min (total)	x	x
Global insolation	every 30 min (mean value)	–	x

Reference data

A number of nearby SMHI stations serve as a reference and baseline for comparison with the data that will be collected at SKB's stations in the investigation, see /Larsson-McCann et al. 2002/. Data from some of these stations are already utilized today for comparisons with the site investigation data from the Forsmark area.

3.9.2 Hydrology

Most surface hydrological measurements, as well as hydrochemical data for surface water from lakes, streams and the sea off Forsmark are essential for the discipline of surface ecosystems as well and are therefore carried out in cooperation with this programme.

Completed investigations

A surface hydrological survey of topography, locations of streams, lakes and springs, and delineation of drainage basins was performed in the initial stage of the site investigation. Supplementary work has been done since, such as level determination of the fall line for the most important creeks inside and just outside the candidate area. Existing measurement series from some of the streams in the investigation area with surrounding area provide an initial body of data for determining runoff from the investigation area's drainage basins. In order to improve the body of data, a monitoring station with two measurement channels has been installed in one of the streams inside the candidate area, see Figure A-8 in Appendix A. Data collection was begun during the first quarter of 2004.

Investigation programme

Many of the environmental consequences that could potentially arise in conjunction with the construction and operation of the deep repository are associated with water. It is therefore of great importance that SKB monitors the groundwater and surface water on the site, both water levels and composition. Moreover, data on surface water is needed as input data to the hydrological and hydrogeological models, and for their calibration and validation. During the last quarter of 2004, three more stream discharge stations of the same type as the first will therefore be installed. Data collection from the stream discharge stations, which besides flow rate also includes continuous recording of temperature and conductivity, will continue throughout the site investigation in accordance with established procedures. In addition, the water level is recorded continuously at six points in lakes and three points in the sea. The location of the monitoring stations is shown on the map in Figure 3-36.

Reference data

There is no stream discharge station with regular long-term measurements in the immediate vicinity of the investigation area that could serve as a reference for the measurements that are being conducted within the site investigation. However, SKB believes that the present stream discharge stations in Forsmark are sufficient, since they can serve as references for each other. Depending somewhat on where the repository is eventually sited, it should be possible to use the stations at the outlets of the lakes Eckarfjärden and Gunnarboträsk as references. If some special aspect needs to be illuminated, it is also possible to use data from special investigations conducted in small investigation areas in different contexts, for example research projects and environmental monitoring programmes. In order to extend the relatively short time series collected within the limited time available in the project, stream discharge can be simulated from meteorological data.

The site investigation includes measurement of groundwater levels and groundwater chemistry in a large number of groundwater monitoring wells in soil. This permits comparative analyses to see whether the deep repository causes an impact at a given point. In order to be able to relate the measurements during the site investigation to the groundwater conditions over a longer period of time, data from SGU's groundwater grid can be used.

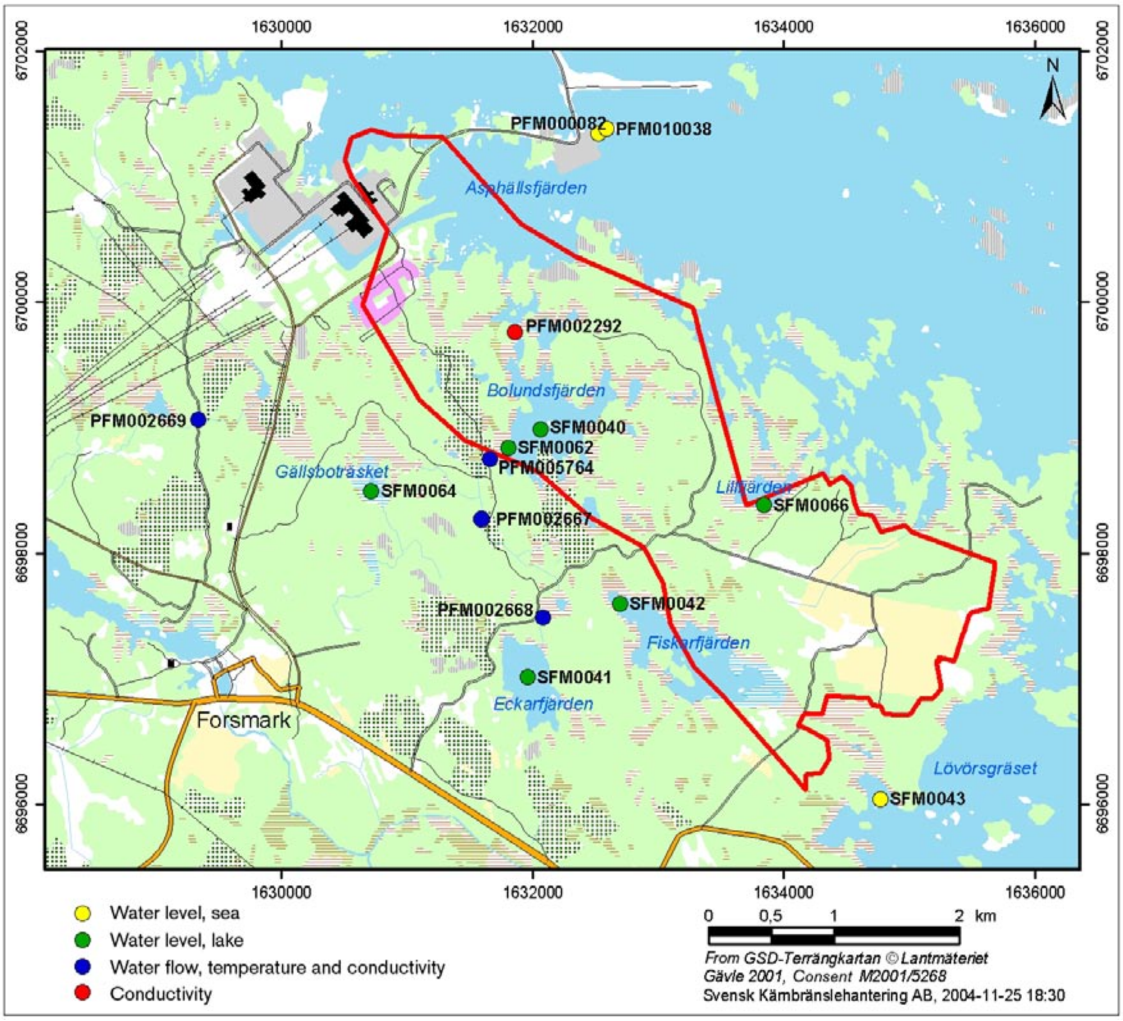


Figure 3-36. *Monitoring stations for continuous recording of water flow, water temperature, water level and conductivity.*

3.9.3 Hydrogeochemistry

Completed investigations

During the initial site investigation, a comprehensive chemical survey of the water in the area was performed, see section 3.6.2. In July 2004, the surface water programme then phased into a monitoring programme with a reduced number of sampling points and reduced sampling frequency.

Investigation programme

Long-term monitoring entails periodic measurement of the water composition in a number of monitoring points in surface water, soil pipes and sections of percussion boreholes and cored boreholes. The purpose is to use the results to help understand the area's hydrology and hydrogeology, to see whether and how the site investigation work affects the composition of the groundwater, and to obtain data in long time series for modelling purposes.

The monitoring programme for surface water, which is carried out in collaboration between the disciplines of hydrogeochemistry and surface ecosystems, includes sampling points in lakes, streams and the sea, see Figure 3-37. The points are situated in two drainage basins, the one that contains Bolundsfjärden, which is regarded as a potential "impact area", and the drainage basin just north of this, which is preliminarily regarded as a reference area. Sampling takes place once a month, and the scope of the analysis varies during the year, see Table 3-4. The sampling frequency may be changed after the evaluation of the programme that is planned in 2005.

Reference data

As far as surface water chemistry is concerned, SKB makes its own samplings in the Gunnarboträsk drainage basin just north of the investigation area. The lakes in the Forsmark area are oligotrophic hardwater lakes, which is a relatively unusual type of lake. This limits the options for choosing a reference area. However, two years of samplings have shown that the Gunnarboträsk drainage basin resembles the Bolundsfjärden drainage basin (which is situated in the investigation area) to such a high degree that Gunnarboträsk is relevant as a reference area for surface water chemistry. Reference data for near-surface groundwater chemistry, see section 3.9.2, and for groundwater in percussion boreholes, see section 3.9.5.

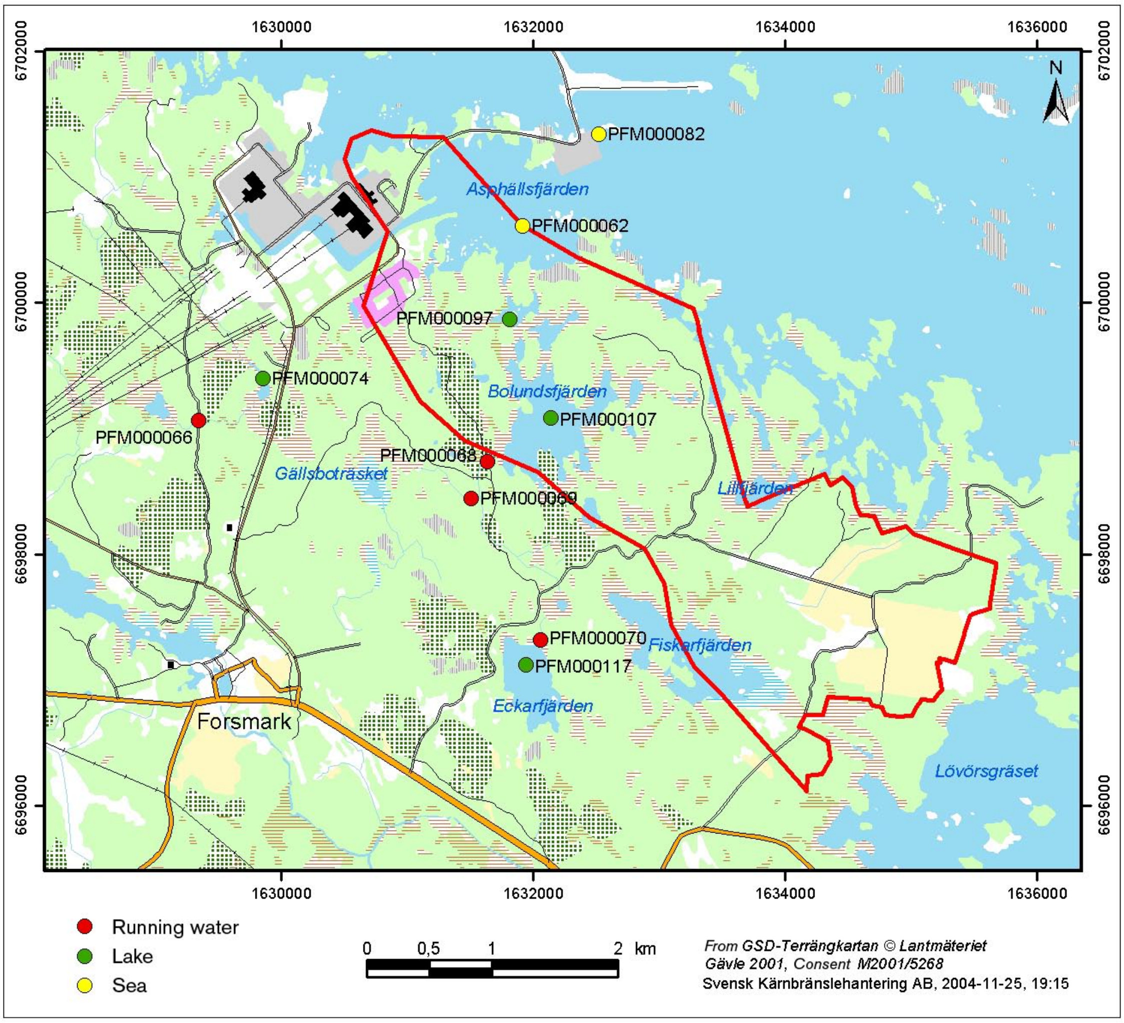


Figure 3-37. *Sampling points for monitoring of surface water.*

Table 3-4. Monitoring with regard to ecology, hydrology and hydrogeochemistry –- parameters that are measured and analyzed, sampling frequency and sampling points.

Parameter group	Sampling frequency [1]	Sampling point									
		lake				sea [2]	stream				
		PFM000074	PFM000097	PFM000107	PFM000117	PFM000062/ PFM000082	PFM000066	PFM002292	PFM000068	PFM000069	PFM000070
Nutrients etc, water flow, absorbance	12 times/yr	X	–	X	X	X	X	–	X	X	X
Main components (Na, Ca, K, Cl, SO_4 etc)	12 times/yr	X	–	X	X	X	X	–	X	X	X
Field measurements (measurement with probe of temp, pH, conductivity, turbidity, light, oxygen, chlorophyll and redox potential)	12 times/yr	X	X	X	X	X	X	–	X	X	X
Heavy metals (Cu, Zn, Pb, Cd, etc)	4 times/yr	X	–	X	X	X	–	–	–	–	–
Tritium, deuterium, O-18	4 times/yr	X	–	X	X	X	X	–	X	X	X
"Light isotopes" (Cl-36, C-13, C-14, Sr-87, S-34)	Once/yr (July)	X		X	X	X	–	–	–	–	–
"Heavy isotopes" (uranium, thorium, radium, radon)	Once/yr (July)	X	–	X	X	X	–	–	–	–	–
							PFM002669	PFM002292	PFM005764	PFM002667	PFM002668
Conductivity	continuously	–	–	–	–	–	X	X	X	X	X
Temperature	continuously	–	–	–	–	–	X	–	X	X	X
Water flow	continuously	–	–	–	–	–	X	–	X	X	X

[1] The sampling frequency may be changed after the evaluation of the programme that is planned in 2005.

[2] Normally, sampling is done at point PFM 000062. But when it is difficult or impossible (thin ice etc) to take samples at this point, sampling is done at point PFM 000082.

In addition to the investigations included in the programme for monitoring of surface water, current plans call for the continued hydrochemical monitoring programme to include:

- Samples of near-surface groundwaters in soil pipes, three monitoring points and four times per year.
- Water samples in percussion boreholes (the sampling is begun as soon as the instrumentation of the boreholes is finished; all boreholes will probably be instrumented by the end of 2006), approximately 15 boreholes, one section in each borehole, twice a year.
- Water samples in cored boreholes (the sampling is begun as soon as the instrumentation of the boreholes is finished; all boreholes will probably be instrumented by the end of 2006 or beginning of 2007), approximately 10 boreholes, two sections in each borehole, twice a year.
- Sampling for assessment of drinking water quality in private wells. Sampling and analysis are important for detecting any contamination caused by the activities during the site investigation. The drinking water test is done in private wells in or near the candidate area. The test includes sampling and analysis once a year.

3.9.4 Ecology

Within the discipline of surface ecosystems, monitoring is planned for surface water, game and birds, all three of which have parameters that exhibit variation over time and may be affected by the construction and operation of the deep repository.

Surface water

See section 3.9.2 Hydrology and 3.9.3 Hydrogeochemistry.

Game

SKB needs knowledge about possible changes in game populations of interest to man in the concerned area as well as in the reference area. Such knowledge comprises a basis for deciding if and how SKB's activities affect the game populations. For this, SKB has chosen to continue with the moose management programme, i.e. the collection and counting of moose carried out by the hunting parties, for which SKB pays the analysis costs. The inventory will be done annually, primarily during the period 2005–2008.

Birds

Birds are the part of the fauna of greatest interest to the public and can be sensitive to disturbances from SKB's activities. Keeping track of the bird life in the area is therefore an important part of monitoring. For this purpose, breeding success will be followed for a number of sensitive species (such as certain birds of prey). The territory mapping that has been done around drilling sites 1, 2 and 3 for two years will be followed up once during the continued site investigation. The monitoring will mainly be carried out during the period 2005–2008. The line and point count that was carried out earlier in the area will be repeated once during the continued site investigation.

Reference data

Data from investigations and monitoring within surface ecosystems can be compared with results from equivalent measurements in other areas in Sweden. The results of such measurements can be found in databases kept by, for example, the Swedish Environmental Protection Agency, the Swedish University of Agricultural Sciences (SLU) and Svensk Viltförvaltning. Figures from the annual bird survey in Forsmark are compared with data from the Swedish bird count that is carried out at several hundred locations all over Sweden. In a similar manner, comparisons are made between Forsmark's investigation area and Hållnäs north of the investigation area with regard to certain species of game.

3.9.5 Hydrogeology

Hydrogeological monitoring comprises a basis for describing groundwater pressure (actually hydraulic head) and flow distribution in the soil layers and in the rock mass. The purpose is to measure natural groundwater level variations prior to the construction of a deep repository, but the equipment is also used to measure pressure responses during single-hole pumping tests and interference tests. At a later stage, the monitoring system will also be used to measure pressure responses during tunnelling for the deep repository. Other hydraulic disturbances, for example from drilling, can be measured and in some cases contribute to the basis for the hydrogeological model /SKB, 2001b/.

Monitoring involves sectioning off deep cored boreholes by means of expandable rubber packers so that the pressure level in the groundwater can be measured in each section, see Figure 3-38. It is possible to isolate up to ten sections with packers and measure the pressure in them, but the number of sections in boreholes with few fractures and fracture zones may be considerably less. Of the ten pressure sections, two sections per borehole can be equipped so that sampling and/or circulation of the water in the section is possible by connecting two extra hoses and installing a portable pump. One of the hoses opens at the bottom of the section and the other at the top. The flow through the packered-off section is determined by adding a tracer and measuring its dilution with time. These sections also comprise injection points or sampling points in cross-hole tracer tests at later stages of the site investigation.

In percussion boreholes it is possible to use up to three packers, which means groundwater pressure can be measured in four sections, one of which can also be a dilution section. In soil pipes, only the groundwater level in one section is measured. Pressure sensors measure the groundwater pressure, which is converted to levels, and data is stored in the previously mentioned HMS system.

Monitoring of groundwater flows is done for the purpose of quantifying the impact of drilling and possible future tunnelling. Flows, and changes in flows, can furthermore be used to calibrate hydrological models.

An open borehole constitutes a short-circuited connection between fracture systems at different levels in the borehole. The monitoring equipment also serves to isolate these systems from each other and thereby prevent an uncontrolled mixing of groundwaters from different levels, and possibly with differing chemical composition. Long-term monitoring should be commenced as soon as all other borehole investigations are finished. On the other hand, since the installation work for monitoring in cored boreholes in particular is both extensive and costly, it is essential to be sure that the borehole does not need to be used for additional investigations before the monitoring installation is started.

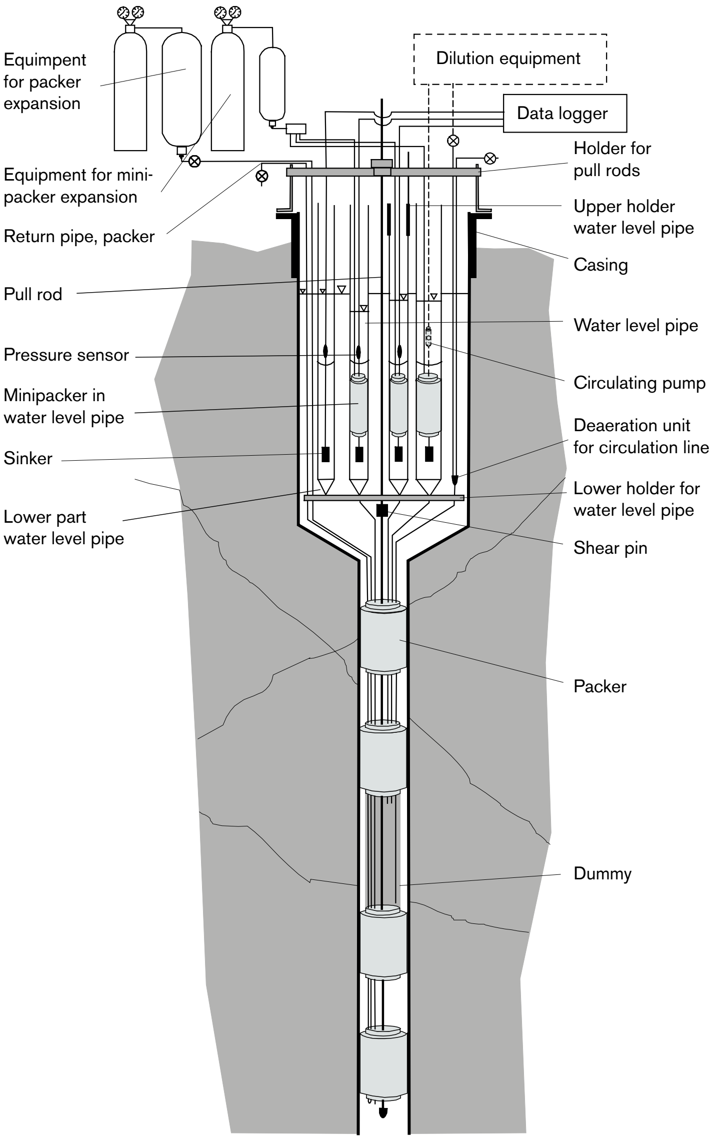


Figure 3-38. *Principle of monitoring of groundwater levels in sectioned boreholes.*

Completed investigations

Monitoring equipment for pressure recording has been installed in approximately 40 soil pipes and three percussion boreholes. All equipment is newly designed and manufactured, and there have been some running-in problems. Following solution of these problems, the pressure recordings have gone smoothly and are very valuable for recording of pressure responses to different types of disturbances (mainly drilling) that occur during the site investigation.

The groundwater level measurements in the soil pipes have provided important information on the position and variation of the groundwater levels in different parts of the investigation area as well as the groundwater's flow direction and gradients, and have, together with the measurements of levels in surface water and in rock, also provided information on recharge and discharge conditions.

Investigation programme

The timetable for further installations of monitoring equipment during the continued site investigation is completely dependent on when boreholes are drilled and investigations completed. Following is the preliminary scope and scheduling of the continued installations:

- Autumn 2004: one deep (about 1,000 m) cored borehole with telescopic part, one medium-deep (about 500 m) cored borehole (without telescopic part), one 100 m long cored borehole (without telescopic part), and two percussion boreholes.
- Spring 2005: Five deep cored boreholes with telescopic part and 12 percussion boreholes.
- Autumn 2005: One deep cored borehole with telescopic part, one medium-deep (about 500 m) cored borehole, one short cored borehole and three percussion boreholes.
- Spring 2006: Three deep cored boreholes with telescopic part, five medium-deep (about 700 m) cored boreholes, two short (100–200 m) cored boreholes and ten percussion boreholes.

Monitoring may be done in some additional boreholes at the initiative of subprojects or reviewers.

Reference data

Groundwater level and groundwater composition in the superficial part of the bedrock (down to at most about 300 m) are monitored in relatively many percussion boreholes in the site investigations. SGU's well archive constitutes a valuable database which can probably offer good reference material in terms of both groundwater level and groundwater composition.

3.9.6 Geological monitoring

Geological monitoring includes both measurements of slow creep movements along fracture zones in the rock and recording of earthquakes in the proximity of the investigation sites Oskarshamn and Forsmark, as well as all over Sweden /SKB, 2001b/.

Completed investigations

Movements in the rock

Tiny so-called creep movements can occur along major fracture zones. In order to get an idea of possible creep movements along fracture zones in the regional environs of the two investigation areas in Oskarshamn, a method study with GPS-based measurement technology was conducted there between 2000 and 2004. The method study shows that this technology is not feasible for studying small movements in the rock. Very long time series would be required to obtain useful results. SKB has therefore decided to discontinue the GPS measurements.

Other methods will be considered in order to find out more about conditions in the vicinity of the sites being investigated.

Earthquakes

A supplementary build-out of the national seismological network from Gävle in the north to Oskarshamn in the south was carried out during 2002, with financing from SKB. The goal of the seismological network is to record earthquakes down to a magnitude of near zero on the Richter scale. Figure 3-39 shows earthquakes in Scandinavia between 1375 and 2003, both experienced and recorded in the seismological network. Figure 3-40 shows earthquakes that occurred in 2003 and recorded explosions. Most of the recordings stemmed from explosions.

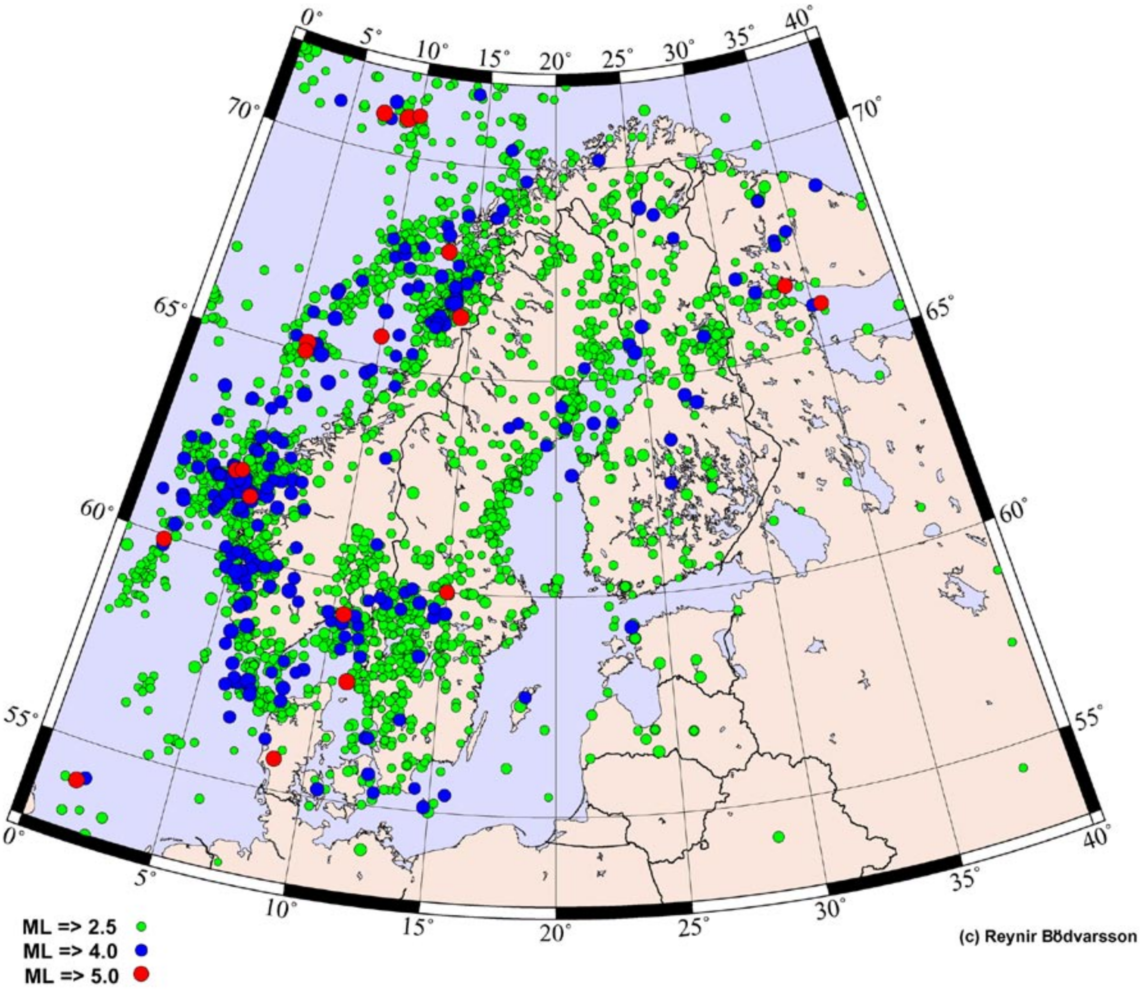


Figure 3-39. Observed earthquakes from 1375 to 2003. Red dots represent more powerful earthquakes (magnitude around 5 or more), blue dots magnitude around 4, and green dots magnitude 2–3.

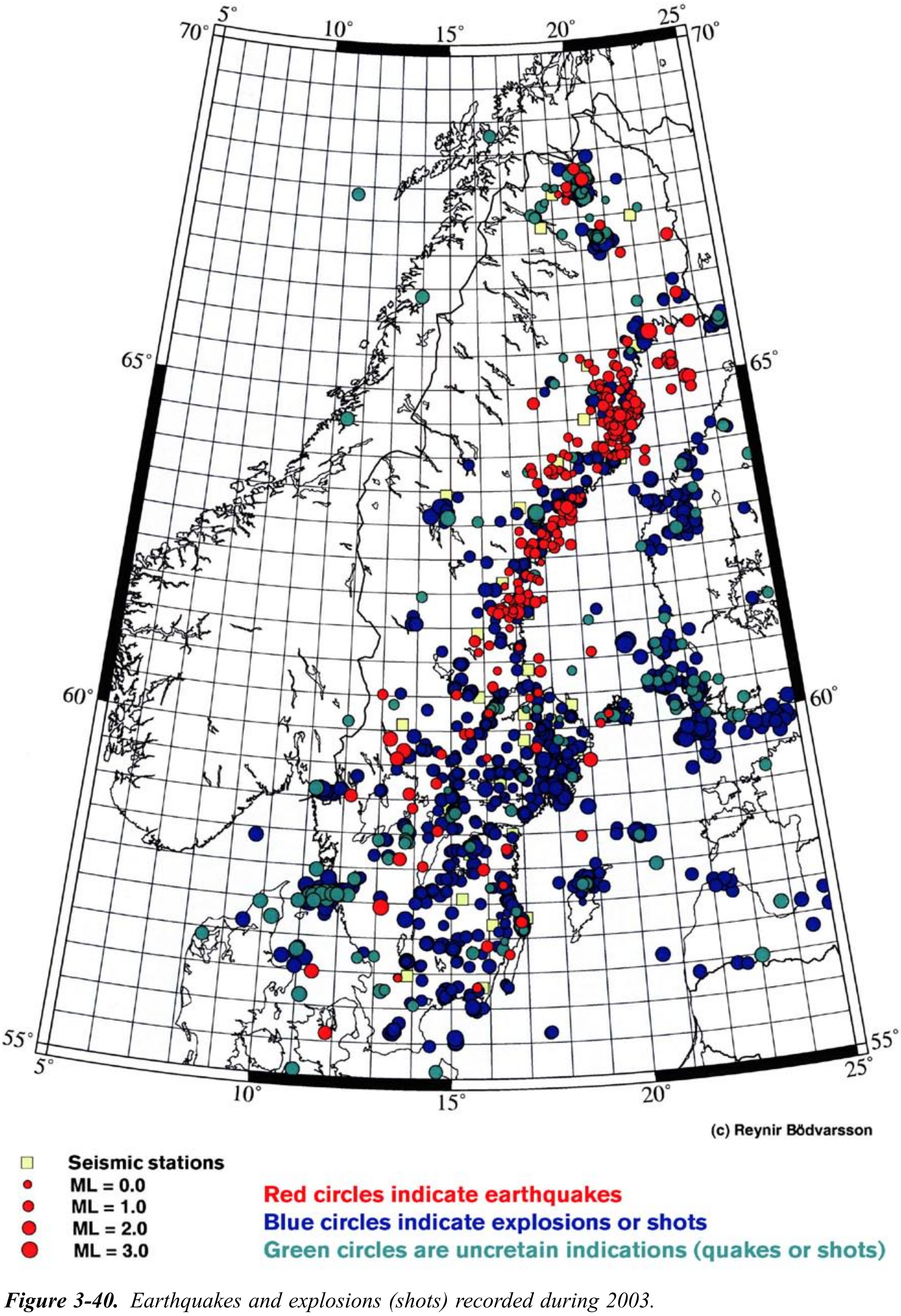


Figure 3-40. *Earthquakes and explosions (shots) recorded during 2003.*

Investigation programme

Movements in the rock

The method study with GPS-based measurement technology in Oskarshamn has been concluded. SKB will instead try other methods for registration of small rock movements, such as satellite-based radar interferometry (length measurement with radio waves).

Earthquakes

The goal of the seismological network is to be able to record earthquakes down to a magnitude near zero on the Richter scale and to be able to determine with greater accuracy the location, magnitude and direction of earthquakes. Measurements of earthquakes are expected to continue until at least 2011. The present-day national seismological network, see Figure 3-41, will be expanded with two stations, one in Forsmark and one in Oskarshamn. The station in Forsmark will be located at drilling site 4.

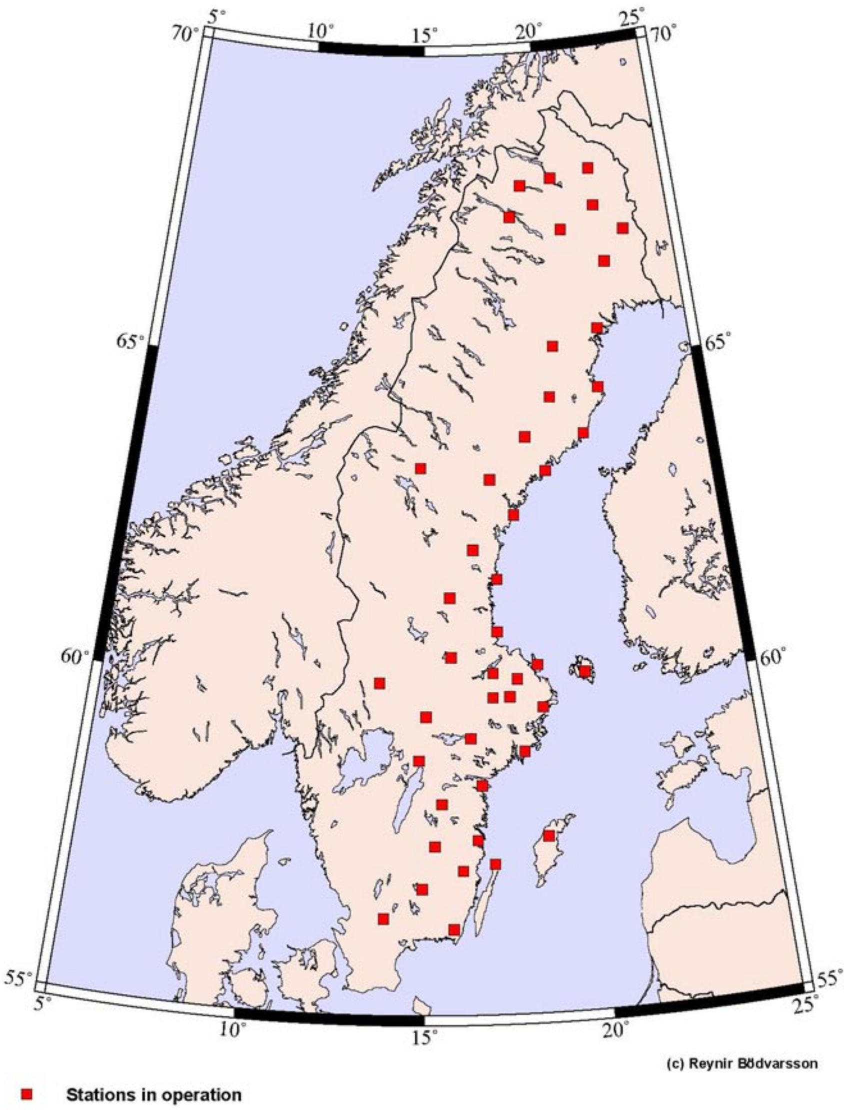


Figure 3-41. *The national seismological network as of 2004.*

3.10 Investigations for operating facilities above and below ground

3.10.1 Facilities above ground

Figure 2-13 gives an idea of the surface facilities a deep repository in Forsmark would require, and the alternative locations for them that have been designated. The preliminary proposals shown by the figure are for the most part based on information that was available when the site investigation commenced. The documentation of surface ecosystems, Quaternary and hydrogeological conditions that has been done since then has contributed additional data for further work with the alternatives.

On the whole, the foundation requirements for the deep repository's facilities do not differ from what is usual for industrial construction, but there are certain differences between different parts. Most of the area will be occupied by conventional buildings, roads and storage yards. The exceptions are production buildings and shaft superstructures, which may require more foundation work. Knowledge of soil and groundwater conditions is also required for the rock heaps that are planned.

The planned investigation programme includes the following points:

- Compile existing material from previous investigations that have been done in parts of the area.
- Roughly assess the geotechnical conditions for the entire area in question.
- Assess the foundation requirements for different parts of the deep repository's facilities.
- Identify the need for supplementary investigations, and perform them. It is expected that such investigations will be limited and can be performed using conventional technology.

Similar investigations may also be required for additional infrastructure.

3.10.2 Facilities under ground

Of the programme for investigation drilling that is presented in sections 2.4 and 3.8, the following parts are specifically aimed at obtaining rock construction-related data for descents and central area:

- Planned cored boreholes from drilling site 7 at the residential area.
- Supplementary drilling, tentatively three medium-deep holes at a later stage.

The currently planned cored borehole 7A on drilling site 7 (autumn 2004, tentatively 1,000 m towards the west) will provide the first direct information on rock conditions at depth in the area that has tentatively been given priority for the operating facilities. Another purpose is to locally determine the geological boundaries of the priority site, which can be of great importance for the placement and configuration of the facilities. Cored borehole 7B (spring 2005, 500 m, near-vertical) is primarily intended for rock stress measurements, see section 3.4.

The drilling of 7A and 7B is thereby expected to provide background information for an initial, site-adapted configuration of descents and central area. This will serve as a basis for the supplementary drilling planned at a later stage (autumn 2005). The facility design that is to be specified in the final phase of the site investigation is planned to include selected locations – and possible realizations – of ramp, shafts and central area. This imposes high demands on the body of geoscientific data on which the design is based. The supplementary drilling is therefore planned to include three cored boreholes, with depths in the interval 300–600 metres, see Table 2-2. The number, depths and locations of the holes have not yet been determined. These parameters must be determined when the main alternatives for the above-ground facilities have been chosen and the preliminary configuration has come farther. One or more additional holes from drilling site 7 is a possibility, but a new drilling site within the industrial area will probably also be needed.

In addition to core drilling, a number of studies of site-specific issues of particular importance with respect to the construction and operation of the operating facilities are planned:

- **Tunnel connection to SFR.** The alternative to locating the deep repository's above-ground facilities at SFR would entail an access tunnel from SFR to a repository on the priority site. The rock construction-related conditions for this are being studied, in support of the design work.

- **Consequences of near-surface water-conducting fractures and fracture zones.** The highly conductive structures detected in most boreholes must be taken into consideration in designing ramp and shafts. The study involves predictions of water leakage into these rock chambers, as well as methods for sealing and inspection.

- **Stability in rock chambers.** The combination of low fracture content and relatively high loads at depth creates different premises for stability than are found in most Swedish hard-rock facilities, which are located nearer the surface and usually in a more highly fractured rock. Special studies are being conducted to make use of knowledge gained from mines and foreign facilities with rock conditions comparable to those at Forsmark.

4 Investigations after the summer of 2007

According to SKB's plans, the site investigation in Forsmark will be concluded in the summer of 2007, see Figure 2-16. By that time, according to the objective for the site investigation phase, all investigations needed to prepare and submit applications under the Environmental Code and the Nuclear Activities Act will have been completed. During the period following the site investigation and up until SKB has selected one of the two sites, Forsmark or Oskarshamn, monitoring and also possibly some supplementary investigations will be carried out on both sites. Therefore, after the summer of 2007, in principle only follow-up and monitoring (see section 3.9) are planned in Forsmark.

The longer term planning naturally depends on which site is chosen for the deep repository. For the site not chosen, it is a reasonable assumption that SKB will wind down all field activities to a minimum. Some type of follow-up and monitoring activities will probably be carried out on this site as well, however.

For the site that is chosen, resources and infrastructure will probably be retained and certain preparations made, at the same time as follow-up and monitoring continue. When applications have been submitted and while they are being reviewed and considered, the reviewing bodies may request supplementary information requiring further investigations on the site. SKB does not find this very likely, but must nevertheless plan for this possibility. It is not possible to say in advance what types of investigations or work may be called for.

Once SKB has obtained permits to build and operate the final repository, extensive investigations will begin along with the construction activities. These investigations, often referred to as detailed characterization, will be conducted both from the surface and from the shafts and tunnels built in the initial part of the construction phase. SKB will present a programme for this detailed characterization along with the applications under the Environmental Code and the Nuclear Activities Act.

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Definitions

Abiotic	Used about non-living parts of our world, such as rock, air and water, and about processes not brought about by living creatures. Antonym: biotic.
Acetogenic	Acetogenic bacteria produce acetic acid from carbon dioxide and hydrogen.
Alkalinity	The water’s ability to neutralize acids, enabling it to better tolerate “acid rain” without the water becoming acidic.
Ancylus Lake	Fresh water stage in the evolutionary history of the Baltic Sea, about 9,500–8,000 years before present.
Anisotropy	Anisotropy is the state in which a physical property is different in different directions.
Aquatic	Relating to water (as opposed to terrestrial, relating to land).
Arenosols	Sandy soil, formed in coarse-grained, loose deposits such as dunes, sand banks, residual gravel and desert areas, also in coarse and mineralogically poor soils; an arenosol can evolve into a podzol.
Artesian	Term used about wells in a groundwater reservoir that is under pressure.
Banding	Alternating, more or less parallel layers in a rock with different colours, grain sizes or mineral compositions.
Benthal	The benthic zone, the biological bottom zone in seas and lakes. At great depths the only organisms are animals and bacteria, but in general benthal includes both plants and animals that are dependent for their existence on the bottom, even though some organisms spend parts of their life in the water above or live on plants attached to the bottom. The benthal is divided into the littoral, which includes most of the shore together with the wave-washed portion above the high-water level, the sublittoral, which extends down to the outer limit of the continental shelf, and the deep-sea zone thereunder.
Bentonite	Soft, plastic, light-coloured clay with high water absorbency. Swells when it absorbs water. Formed by chemical alteration of volcanic material, mainly ash and tuff. Transported and handled in powder form, can be compacted into blocks.
Biosphere	The parts of the earth and the atmosphere where living organisms are found. The biosphere can be divided into sea, fresh water, land and atmosphere.
Biota	Living fauna and flora.
Biotope	An ecological unit with uniform plant and animal life.
Bladder wrack	Fucus vesiculosus, species of brown algae, a perennial marine alga, that can grow to great heights, around 1 m or more. It usually has air-filled bladders attached in pairs on the flattened, branching fronds, and male and female reproductive organs in swollen tips on separate individuals.
Brittle deformation	Deformation in which the bedrock reacts by fracturing. In this kind of deformation, individual fractures and clusters of fractures form fracture zones.

C14	A radioactive isotope of carbon, used for dating (the C14 method) of long-dead organisms.
Cambisols	Large soil group. Includes all soils formed during a brief span of time. They may also have been recently formed on transported parent material and are found at all levels, in most climates and under most vegetation types. In Sweden, the soil has usually been called brown earth, which is interpreted differently in different parts of the world. Cambisols are topped by a blackish-brown layer of well-mixed organic matter and mineral soil called mull. The mixing is mainly caused by burrowing organisms, but may also be due to tillage. The soil is important for nearly all kinds of agricultural production. Forest production on cambisols is generally high. They are usually resistant to acidification.
Clab	Central interim storage facility for spent nuclear fuel. Spent nuclear fuel is stored at the facility, which is situated at the Oskarshamn Nuclear Power Plant, in water pools for about 30 years prior to encapsulation and deep disposal. Clab was commissioned in 1985.
Colloids	Finely divided particles that do not sediment due to their small size but remain freely suspended in the water; they range in size from 1 nanometre (10^{-9} metre) to 1 micrometre (10^{-6} metre).
Conductivity	Can refer to electrical conductivity (ability to conduct electric current), thermal conductivity (ability to conduct heat) or hydraulic conductivity (permeability of a rock to water).
Deformation zone	Collective term for folding and faulting of rocks due to stresses in the bedrock. The rock volumes on either side of a deformation zone have moved in relation to each other.
Detailed characterization	Investigations of the bedrock in conjunction with the construction and commissioning of the deep repository.
Diffusion	Transport (spreading) of one substance (e.g. salt) in another substance (e.g. water) due to concentration differences. Diffusion is substance-dependent and can take place in the rock via microfractures and pores.
Diorite	A plutonic rock (a rock formed at great depth) consisting of the minerals plagioclase, hornblende and biotite. Relatively quartz-poor. Dark grey to greyish-black and coarse- to medium-grained.
Dip	Angle of inclination of a planar structure, such as a bedding, a fracture zone or a fault plane, with the horizontal.
Dispersivity	Measure of spread of flow velocities between fractures or in individual fractures.
Dolerite/diabase	Basaltic, usually black and fine-grained hypabyssal rock that forms more or less steeply-dipping strata in the bedrock.
Ductile deformation	Deformation where the bedrock reacts plastically, i.e. like a viscous mass. Ductile deformation, which takes place at great depth and high temperature, can give rise to folding and ductile shear zones, with strong schistosity and linear structures.
Ecological succession	Gradual process of change in an ecosystem where new plant and animal communities take the place of old ones.
Ecosystem	Biological community (organisms and their habitat) that is relatively self-sufficient with regard to energy flows, e.g. forest, grassland.

Evapotranspiration	Evaporation of water from ground covered with vegetation. Evapotranspiration consists partly of evaporation from bare ground, open water (puddles, snow cover etc) and free water (rain or snow) on the vegetation, and partly of transpiration of water that passes through the plants from the soil. The term is also used, somewhat freely, as a synonym for evaporation.
Fold hinge	Line of maximum bending in a folded surface.
Folding	Deformation of the earth's crust due to compression by means of opposing forces.
Foliation	Most metamorphic rocks have a characteristic structure, foliation. This refers to the planar structure of a rock that allows it to be cleaved along parallel planes.
Fracture aperture	Fracture opening.
Fracture zone	Deformation zone formed as a result of brittle deformation, i.e. when the bedrock reacts by fracturing. See also brittle deformation.
Fucus	The scientific name of a genus of brown algae found in nearly all seas in the vegetation zone that starts directly beneath the higher green algae zone.
Gabbro	A plutonic rock (a rock formed at great depth) consisting primarily of the minerals plagioclase and pyroxene. It is coarse-grained, mafic (silica-poor) rock, normally dark grey to black in colour.
Geochronology	Dating and sequencing of events in the earth's history. In a general sense, geochronology refers to the determination of ages, absolute as well as relative, on a geological time scale.
Geophysical surveys	Measurements of magnetic fields, electrical resistivity and other physical parameters. By surveying variations in the physical properties of the rock or the soil layers, it is possible to determine soil depth, rock type boundaries, fracture zones and other geological parameters.
Gleysols	Formed in flat, low-lying areas with high water tables; found at depth of no more than 50 cm. The soil type is very common in Sweden around waterlogged seashores and is then often called gyttja clay. The gyttja clays have a characteristic hexagonal fracturing and high sulphide contents.
Gneiss	Highly metamorphosed rock type, often banded with more or less parallel mineral grains.
Granite	An igneous plutonic rock (a rock formed at great depth) consisting primarily of the minerals quartz, feldspar, mica and/or hornblende. The colour is usually grey or red.
Granitoid	Collective term for quartz-rich granite-like rocks, for example (besides granite) granodiorite and tonalite.
Granodiorite	Felsic igneous plutonic rock that outwardly resembles granite. Consists primarily of the minerals quartz (less quartz than in granite but more than in diorite), plagioclase, potassium feldspar and biotite (dark mica). It is medium- to coarse-grained and light to dark grey in colour.
Habitat	The setting in which a species normally lives; basically the same as its biotope.
Histosols	Soils that consist primarily of organic material; this category includes all peat soils in Sweden.

Hydraulic gradient	Difference in hydraulic head per unit length, i.e. the inclination of the water table.
Hypabyssal rock	Igneous plutonic rock in the form of an intrusion formed when magma (molten rock) has penetrated and solidified in fractures, usually in the superficial parts of the bedrock.
Igneous rock	Rock crystallized from molten rock (magma).
In situ	(Latin, 'in place'), technical term in a number of areas. Used in geology about a fossil or mineral that is in its original location; used in biology when an organism (especially a small or sedentary one) is studied in its natural habitat.
Intrusive	A plutonic rock (a rock formed at great depth) that has penetrated into and crystallized in the earth's crust as massifs or dykes.
Invertebrates	Animals without backbones.
Isotope	Atoms of the same element but with different atomic weights. Isotopes have identical electron shells and therefore almost identical chemical properties.
KBS-3 method	KBS is an abbreviation for **K**ärn**B**ränsle**S**äkerhet, which is Swedish for Nuclear Fuel Safety. Proposed method for deep disposal of spent nuclear fuel based on the concept of encapsulation of the fuel in canisters and emplacement of the canisters in crystalline bedrock at a depth of about 500 metres.
Kinematic	The field of mechanics that describes the motion of bodies regardless of the cause of the motion.
K value	Hydraulic conductivity, a measure of the permeability of (in this case) a geological stratum (soil layer or bedrock).
Lacustrine	Pertaining to or living in fresh water (lakes).
Lateral moraine	Side moraine, low moraine ridge deposited on a slope along the side margin of a glacier. A lateral moraine has a gentle inclination that reflects the gradient of the glacier surface when the moraine was deposited.
Leptosols	Shallow mineral soils found in high, hilly terrain, can merge continuously with the broken-up surface layer of the bedrock. Leptosols generally have a thin A horizon.
Lineament	More or less linear feature on the ground surface. May be a topographical structure (elongated depression) or a geophysical property, such as variations in the magnetic field. Lineaments may indicate faults or fracture zones in the bedrock. But they may also be caused by other geological phenomena.
Lineation	Linear structure of a rock.
Lithology	The description of Quaternary deposits or rocks with respect to characteristics visible to the naked eye, such as colour, mineral composition and grain size.
Littorina Sea	Salt water stage in the evolutionary history of the Baltic Sea, between about 8,000 and 3,000 years before present. It is named for the gastropod genus Littorina, periwinkles, which are found in the Littorina Sea's shore deposits up to the Stockholm region.
Magnetite	A black, strongly magnetic mineral (iron oxide). Important mineral for extraction of iron.

Magnitude	Measure of the strength of an earthquake.
Marine	Relating to the sea.
Matrix diffusivity	A measure of how quickly a substance can penetrate (diffuse) through the rock matrix.
Meta-	Prefix used in front of the name of a rock to indicate that the rock has been metamorphosed.
Metamorphic	A metamorphic rock is one that has been altered in the earth's crust due to changed pressure and temperature conditions.
Metavolcanics, metavolcanic rocks	Rocks formed by volcanic activity (lava or volcanic ash) which have subsequently undergone metamorphism.
Meteoric water	Water that originates from rain.
Methanogenic	Methanogenic bacteria produce methane from carbon dioxide and hydrogen.
Monitoring	Surveillance of groundwater level, air pressure, etc by means of continuous or repeated observations and measurements.
National interest	Area designated by a municipality, county administrative board, national agency or authority as being particularly suited for a given activity, for example outdoor recreation, professional fishing, extraction of mineral deposits, industrial production, energy production, waste management or water supply. According to the Environmental Code, areas of national interest shall be protected as far as possible against measures that may be prejudicial to their utilization according to this interest.
Nuclear installation	Plant where nuclear materials are handled. The present-day nuclear installations in Sweden are the nuclear power plants in Ringhals, Barsebäck, Oskarshamn (including Clab) and Forsmark (including SFR), Studsvik, Westinghouse Atom's fuel factory and Ranstad Mineral.
Pegmatite	Coarse-grained rock of granitic composition that usually forms dykes of small massifs.
Pelagial	Pelagic zone, the open water in seas and lakes (in lakes also called the lacustrine zone), but normally not the top and bottom levels of the water. The organisms of the pelagial include the bacteria, algae, plants and animals that spend their entire lives (holoplankton) or only a portion of their lives (meroplankton) in this zone. They also include active swimmers, such as fish.
Permeability	Capacity of porous media, such as soil or fractured rock, to transmit gas or water.
pH	Value that indicates how acidic or basic (alkaline) a solution is. It is often used in e.g. chemistry, biology and environmental science. At room temperature, pH=7.0 corresponds to a completely neutral solution (no excess of either hydrogen ions or hydroxide ions). A lower value indicates that the solution is acidic (excess of hydrogen ions) and a higher that the solution is basic (excess of hydroxide ions).
Podzols	Have a well-developed illuvial horizon consisting of organic matter, aluminium, iron, manganese and above that a bleached horizon. This type of soil is the most common in Sweden. Podzols are principal soils within the boreal and temperate parts of the northern hemisphere.
Porosity	Porosity is defined as the volume of void space per unit volume of the entire material.

Postglacial	Following the most recent ice age.
P-wave	P-wave (= **p**rimary wave) compressional wave during earthquake. The name derives from the fact that it is the first wave to arrive at a seismograph after an earthquake. Primary waves are longitudinal waves.
Quartz	Light and very hard, sometimes translucent mineral consisting of silica (SiO_2). The more silica a rock contains, the more felsic it is. The less quartz it contains, the more mafic it is.
Quartzite	Even-grained, usually white or grey, metamorphic rock that consists mainly of quartz.
Radar interferometry	Length measurement using radio waves.
RD&D-Programme	The programme of **R**esearch, **D**evelopment and **D**emonstration which SKB is required by the Nuclear Activities Act to present every third year.
Redox potential	Can be compared to a measure of "electron pressure". At a negative redox potential and high "electron pressure", oxygen-free conditions prevail. At a positive redox potential, oxygen is present. The redox potential determines which reactions can take place and which chemical components can occur in e.g. groundwater.
Regolith	The layer of unconsolidated overburden covering the unweathered bedrock. In areas that have not been covered by ice sheets, it includes the weathered bedrock (saprolith) and transported material on top of it. In areas that have been glaciated, the regolith consists primarily of glacial and postglacial deposits, but also a small portion of deeply weathered bedrock.
Regosols	Group of immature soils formed in fine-grained unconsolidated minerogenic materials that have no other horizons than a weakly formed A horizon; found within high-lying, hilly terrain; regosols are found in all climates all over the world; in Sweden, regosols may possibly phase into weakly formed podzols or cambisols.
Respiration	Scientific term for breathing.
SFR	Final repository for radioactive operational waste. SKB's facility for final disposal of low- and intermediate-level operational waste situated approximately 50 metres down in the rock, beneath the seafloor, at the Forsmark Nuclear Power Plant. The repository has been in operation since 1988.
Shear zone	Deformation zone formed as a result of ductile deformation, i.e. under high pressure and temperature. See also "Ductile deformation".
Sheeting	The structure near the surface of the bedrock in which fracturing has divided the rock into tabular bodies, or sheets, that are parallel or nearly parallel to the surface of the bedrock. Common in otherwise fracture-poor crystalline bedrock and can be seen in many road cuts around the country.
SKI	Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate). Authority whose mission is to exercise supervision of the safety of the nuclear installations according to the Nuclear Activities Act.
Sorption	Physical and/or chemical bonding of atoms or molecules to a surface, includes both adsorption and absorption.
Sorption coefficient	Measure that indicates the ability of a rock to retain different substances on fracture surfaces and in pores.
Spatial	Having to do with extent in space, e.g. the shape of an object.

SSI	Statens strålskyddsinstitut (Swedish Radiation Protection Authority). Authority whose mission is to protect humans, animals and the environment against the harmful effects of radiation in accordance with the Radiation Protection Act.
Strike	The direction taken by a planar structure, such as a bedding, a fracture zone or a fault plane, as it intersects the horizontal.
Subhorizontal	Close to horizontal.
Substrate	The surface or material (soil, water) on which plants, fungi, lichens, bacteria and certain invertebrate animals grow or live.
Supracrustal rock	Rock formed on or near the surface of the earth by sedimentary or volcanic processes.
Tectonic lens	Bedrock unit enclosed in a ductile deformation zone which is unaffected, or much less affected, by ductile deformation than the deformation zone as a whole.
Terrestrial	Relating to land. Land-based as opposed to aquatic (in water). Habitat on the surface of the earth.
Till	Unsorted, unconsolidated material deposited by glaciers and inland ice sheets, consisting of pulverized rock fragments of varying size from boulders to clay particles.
Tonalite	Igneous plutonic rock (a rock formed at great depth) related to granite. Tonalite is usually grey and consists primarily of the minerals quartz and plagioclase, plus biotite and amphibole.
Transmissivity	Ability of a soil or rock layer to conduct water. Groundwater flow rate unit width is given by the transmissivity (m^2/s) multiplied by the hydraulic gradient (m/m). Transmissivity can be determined by test pumping.
Transpiration	Loss of water vapour from plants by evaporation.
Veined gneiss	A very common type of gneiss in Sweden, characterized by light and dark layers, parallel to the rock's plane of schistosity. The light layers are dominated by quartz and/or feldspar, while the dark layers contain dark mica and possibly amphibole.
Volcanic rock	Rock formed by volcanic processes, i.e. extrusion of magma (molten rock) on the earth's surface, which forms lava or layers of volcanic ash.
Weathering	In geology, decomposition and disintegration of solid rock, stones and boulders to a gravely, sandy or clayey mass by mechanical, chemical and biological processes.
Yoldia Sea	Stage in the evolutionary history of the Baltic Sea falling between the Baltic Ice Lake and the Ancylus Lake. The Yoldia Sea was named for the marine arctic bivalve Yoldia arctica (now Portlandia arctica), which has been found in deposits from this stage. The Yoldia Sea existed between approximately 10,300 and 9,500 carbon-14 years before present. According to the classical picture of the history of the Baltic Sea, the water in the Yoldia Sea was brackish, but more recent investigations show that the actual brackish water phase only spanned 100 years around 10,000 carbon-14 years before present (i.e. about 9,400 BC).
Younger granite	Granite that was formed after the most recent major ductile deformation of the bedrock. In Sweden, these granites are normally 1,800 million years old or younger.

Äspö HRL	SKB's Hard Rock Laboratory on the island of Äspö north of Simpevarp, intended for geological research and technical development and demonstration of methods for deposition and retrieval of canisters with spent nuclear fuel.

Appendix A

Environmental impact of the site investigation

This appendix examines the environmental impact to which the planned investigation activities can give rise during the continued site investigation in Forsmark and what measures are planned to minimize this impact. Experience from the first years of the site investigation with application and development of the environmental management and environmental optimization of the activities that was presented in /SKB, 2001a/ comprises an important basis for this account. At the end of the appendix, the activities deemed to cause potential impact to the environment are presented in a table. The table also shows SKB's preliminary assessment of which activities will be notified to the County Administrative Board for supplementary consultation.

A.1 Environmental management of the site investigation

SKB's objective is that the site investigations should be executed in such a manner that they cause as little environmental impact as possible. In order to achieve this, we are integrating environmental aspects in the planning so that the work can be done with minimal environmental impact. This is done with the aid of an environmental control programme for the activities performed in the field. The environmental control programme has been developed continuously during the course of the site investigations and includes checklists for different types of activities, such as excavations, samplings in the field, drilling and seismic investigations.

All field activities are preceded by cross-checking against SKB's so-called accessibility map and checking in the field of natural and cultural values. This field check is carried out either by SKB's site ecologist or, in the case of more complicated checks, by contracted experts. The results of these checks may indicate that special precautions need to be taken. The mode of operation is illustrated in Figure A-1. The accessibility map is updated as information is received from field checks and investigations, especially in the discipline of surface ecosystems. The accessibility map provides guidance with regard to whether the investigations can be conducted on the intended site or must be relocated or adapted to local conditions. The map shows the location of sensitive areas or species worthy of protection, or other features that must be taken into consideration. After the initial site investigations, this map is very extensive and comprises a valuable document for management of the activities so that environmental impact can be avoided or minimized. The information on which the map is based is to some extent seasonally dependent and also includes plant and animal species that are sensitive and/or worthy of protection. Due to these factors, along with the very large quantity of information, the map cannot be presented in this appendix.

In December 2001, SKB gave notice of consultation for the site investigation in Forsmark to the Uppsala County Administrative Board, pursuant to Chapter 12 of the Environmental Code. The County Administrative Board stipulated in its decision in February 2002 that the investigations could be conducted in accordance with the notice, provided the precautionary measures presented in the notice were adopted. SKB has since maintained an active and open dialogue with the County Administrative Board regarding the environmental impact of the site investigation and how it can be avoided or minimized. Among other things, we have submitted supplementary notices for consultation regarding additional activities with environmental impact.

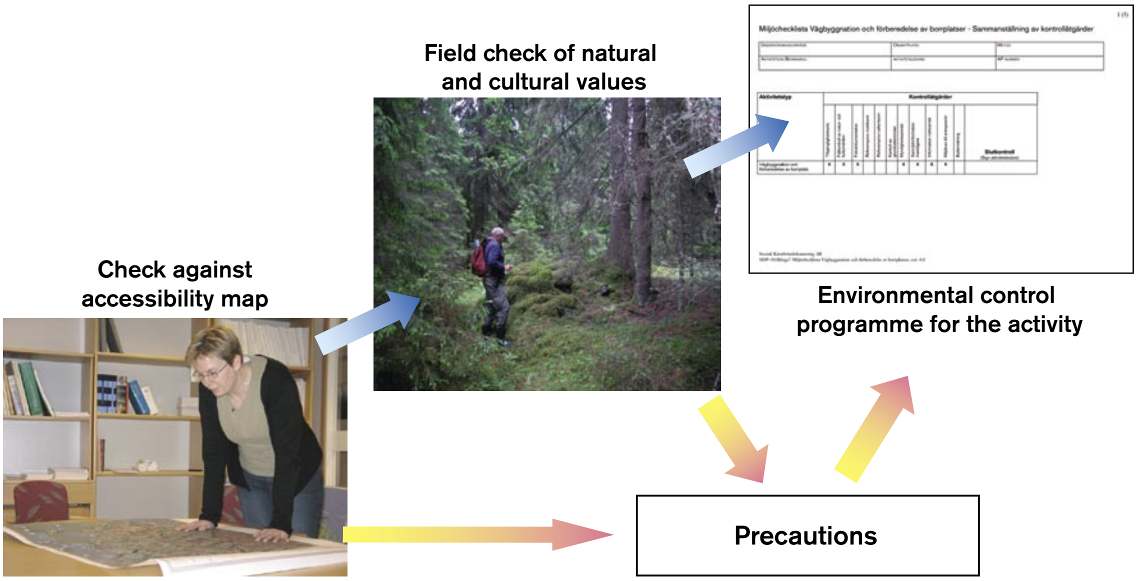

Figure A-1. Description of how SKB proceeds in planning and managing activities in the field so that environmental impact can be avoided or minimized. The environmental control programme describes all precautions that are to be taken when an activity is planned and executed.

Certain activities in the field require a good dialogue with nearby residents and other concerned parties, and in some cases the consent of landowners in the area is required. These consultations and contacts are included in the environmental checklists for the various activities, which are an important part of SKB's environmental control programme.

Many of the investigations are conducted by consultants and contractors. To minimize risks and limit the negative consequences for human health and the environment, SKB requires suppliers to comply with SKB's environmental policy and overall goals. All contractors and consultants who carry out assignments in the site investigation area undergo special training before they are allowed to start work. On completion of this training, they get a car pass that must be clearly displayed while they are working in the area. SKB has also issued local safety and environmental regulations that govern work within the site investigation. They require all contractors to report any environmentally hazardous substances and products they intend to use. All products must be approved for use by SKB. These so-called SHM protocols (SHM = Säkerhet, Hälsa, Miljö = Safety, Health, Environment) also describe occupational safety and environmental risks and how they can be managed.

A.2 Experience from the initial site investigation

Early in the site investigation, inventories were made of vegetation, key habitats, game, birds etc in order to get a good picture of the area before road construction, drilling and other more disturbing activities were commenced. In this way, SKB found out early on where in the area sensitive species and environments worthy of protection are located. The accessibility map has been continuously updated with this information and comprises a very important planning document for the continued investigations. A certain running-in period was needed to achieve effective environmental control of all field activities, partly because the organization was growing and partly because a lot of activities were being started up during a relatively short period of time. As the organization has become established and the work has taken on more routine forms, accessibility and field checks have become a natural part of the planning of the field activities. SKB's site ecologist is in charge of performing and documenting these checks, but the checks themselves are initiated by the relevant activity leader based on SKB's environmental control programme. After completed checks, any precautions and necessary changes in the timetable are introduced in the planning of the activity in consultation between the site ecologist and the concerned activity leader. In this way, it has been possible to protect sensitive environments from serious impact and unnecessary disturbances.

As the investigations have progressed and we have gained more experience, we have made some changes and additions to SKB's environmental control programme. For example, environmental checklists have been added and control steps have been reformulated. The environmental control programme underwent extensive review and modification during the autumn of 2004.

SKB has notified a number of activities and investigations to the County Administrative Board for supplementary consultation in accordance with Chapter 12 of the Environmental Code. This includes establishment of drilling sites, excavation of pits for determination of Quaternary deposits and location of seismic profiles. In most cases, SKB's records from accessibility and field checks have been appended to these notices. Some of the County Administrative Board's decisions have included conditions, for example measurement and reporting of the chloride content of the return water in connection with core drilling, temporal restrictions for access to nature reserves, and noise limits. All conditions have been met during the initial site investigation, and feedback and information have been given to the County Administrative Board. During the remaining site investigation, feedback reports will be sent to the County Administrative Board at least once a year, depending somewhat on the number of matters that require supplementary consultation.

Experience from the excavation of pits shows that the method of setting aside the top organic soil layers and then placing them back on top during remediation has been successful and led to a rapid return of the vegetation on these sites. Figure A-3 shows pictures of pit excavation and the same site after remediation. This approach will be applied in connection with future excavation work, for example the excavation planned for investigating lineaments.

The seismic surveys have left very few traces in nature. In these surveys, very small dynamite charges (shots) are placed in shallow boreholes drilled through the soil layer or in rock and then detonated so that the sound wave's velocity and reflection from fracture zones or rock type boundaries can be recorded. Depending on where the profiles are located, however, cross-country transport of equipment and personnel is sometimes necessary. For this reason, planned seismic surveys, like previous ones, will be preceded by a cross-check against the accessibility map and a field check of natural values so that sensitive areas can be avoided.

The objective has been to limit the construction of new roads and wherever possible try to locate drilling sites and percussion boreholes along existing roads. This has been possible thanks to the fact that much of the candidate area can be reached from existing roads and drilling sites if 1,000 m long boreholes are drilled at an angle of 60° from the vertical. In order to reach the central part of the area under Bolundsfjärden, however, drilling site 5 had to be built some distance into the forest. Construction of road and drilling site was preceded by an accessibility check and a field check of natural values, which guided the routing of the road and the final location of the drilling site. The drilling site and the road will be removed and the area remediated in keeping with the decision of the County Administrative Board when the site investigation has been completed.

Another strategy for reducing detriment and environmental impact has been to plan the drilling sites in such a way that their location and design permits boreholes to be drilled in different directions so that different questions can be answered. This has necessitated making the drilling sites a little bigger than originally planned, but has also permitted the number of drilling sites to be reduced.

The return water from core drilling has been discharged through a pipe to the sea wherever possible. However, sometimes the return water has been collected during a short period and driven by road tanker to the sea. Discharge of return water via a pipe may be problematic in the wintertime, since the pipe can easily freeze, causing a blockage. Electrically heated pipes have been used over short distances (< 600 m), but the water from drilling site 5 was discharged to Bolundsfjärden, since the distance to the sea was too great for heated pipes to be used. This was done with the permission of the County Administrative Board. Furthermore, hauling away the return water by road tanker would lead to heavy traffic in the area, resulting in noise and exhaust emissions. Sampling of the water in Bolundsfjärden within the framework of SKB's surface water programme shows that the release of return water has caused less of a change in the chloride concentration in the lake than the recurrent influxes of sea water do. For practical reasons, return water from future drilling in the wintertime at drilling sites 5 and 6 will be discharged to Bolundsfjärden. The same may also be true for other drilling sites located far away from the sea with a suitable receiving body of water nearby. Discharging water in this way requires the approval of the site ecologist and a permit from the County Administrative Board. In addition, it may be necessary to monitor flora and fauna by sampling before and after the release of return water.

A.3 Investigations with potential environmental impact

The following sections describe which activities in the field that can lead to environmental impact. The measures that will be adopted to minimize the impact of the various activities are described below, along with what types of investigations that will be notified for supplementary consultation in accordance with Chapter 12 of the Environmental Code.

A.3.1 Roads and infrastructure

Description

Early during the site investigation in Forsmark, a new service road into the area was built from the residential area in the northwestern part of the area. Altogether, less than 1 km of gravel road has been built and about 6 km of existing road has been reinforced in the area. The objective in the future is to position drilling sites and boreholes along existing roads and to make use of existing drilling sites to drill additional holes in other directions. There is deemed to be very little need for additional roads beyond the short branch roads that may be needed to reach new drilling sites. But it may be necessary to build drilling sites that are not located along the existing road network, in which case short roads will be required to these drilling sites.

The roads must be negotiable by cars and trucks with trailers (length 24 metres, width 2.6 metres, height 4.5 metres, gross vehicle weight 50 tonnes). The loadbearing capacity of the road must permit heavy traffic year-round. The roadway is designed so that haulage and use of aggregate material to build the road are minimized. If possible, dewatered drill cuttings are used as fill when building drilling sites and branch roads.

Since investigations at the cored borehole sites are conducted for several years, permanent power supply and telephone lines are needed. Power cable (400 V/63 A, underground cable or overhead line on temporary poles) plus signal cable is run to all cored boreholes. Signal cable is enough for most percussion boreholes.

Installations are also made for monitoring. The permanent installations that will be made during the continued site investigation comprise three stations for measurement of flow rates in streams plus a number of soil holes for monitoring of the groundwater level. A mast for measurement of evapotranspiration from the vegetation may also be erected. Small sheds such as freight containers or the like are required for some of the installations. Low-energy technology is preferred for these installations. Meteorological monitoring is done by equipment mounted in two masts, one at drilling site 3, which was established by SKB during the initial site investigation, and the Forsmark NPP's mast near the cooling water channel. A monitoring station for recording movements in the earth (seismic activity) will also be installed in the area at drilling site 4.

Operation of the monitoring installations requires visits by personnel for maintenance and service, as well as to retrieve collected data. Some of the monitoring and measurement equipment communicates via the GSM network, reducing the need to visit the sites.

Environmental impact

Construction of new roads, storage sites and fixed installations gives rise to noise, dust and exhaust emissions. Mobile machinery can leak hydraulic and lubricating oil. In some cases off-road operation may be required, which gives rise to ground damage.

The scope of the environmental impact in conjunction with roadbuilding can be compared to the damage caused by logging or the impact caused by the earlier building of logging roads in the area. The roads remain in the area throughout the site investigation phase, possibly even longer, and therefore take up land. They also change the landscape to some extent. Additional roadbuilding increases accessibility in the area, which can affect sensitive landscapes and species.

Power and telephone lines will be run as underground cable or temporary overhead cables. The lines will be harmonized to the existing local network in the area. All-terrain vehicles will be used for the erection of temporary poles. Branches and some trees may need to be removed. Cable trenches are dug for underground cable. Overhead line and underground cable are preferably laid along existing and additional roads.

To permit monitoring of the groundwater level in soil pipes in the wintertime as well, they are provided with protective hoods to prevent freezing in the pipe, see Figure A-2 below.

Regarding environmental impact in connection with the construction of monitoring stations in streams, see section A.3.7 below.

Measures

In planning roads, natural values and the landscape are taken into consideration in that an attempt is made to find routes that avoid streams, mires and swampy ground. All routes are cross-checked against the accessibility map and preceded by a field check of natural and cultural values. Routes are documented by photography before the roadbuilding begins.

In order to make it easy for vehicles to cross the road, and so that the natural water flows in the soil will not be affected more than necessary, roads will if possible be built without open ditches. Where there is a risk of wash problems, plastic drums will be used. Arches will be used in permanent streams so that the aquatic fauna is not affected, but crossing streams will be avoided wherever possible.

Figure A-2. *Preparations for measurement of groundwater level in soil boreholes.*

After conclusion of the site investigation and if the area is then no longer being considered for a repository, roads, drilling sites and other places where incursions have been made will be remediated. Power and signal lines as well as other fixed installations will be removed. The remediation work will be carried out in consultation with landowners and the County Administrative Board. Certain roads and gravelled surfaces may be left in place if that is the wish of the landowner.

Construction of roads, drilling sites and fixed installations that can affect the natural environment will be preceded by supplementary consultation with the County Administrative Board.

A.3.2 Excavation in conjunction with mapping work

Description

The mapping work that requires some form of mechanized excavation is geological bedrock mapping to investigate lineaments. This is planned on two or three sites, but more are possible. The trenches are 50–100 metres long and three metres wide at the bottom, see Figure A-3. They are wider at ground level since the sides need to be sloped to avoid the risk of cave-in. For trench digging to be practically feasible, the soil depth may not exceed five metres. According to current plans, excavations will be carried out during the autumn of 2004. Further excavations may take place in the autumn of 2005.

Figure A-3. *Trench for Quaternary deposit mapping during and after excavation.*

The trenches are dug by crawler excavators. The objective is to carry out the excavations alongside existing roads, but it may also be necessary to do them further from the road. It may be necessary to fell trees and move large boulders.

Compressed air or high-pressure water sprays are used to clean rock surfaces. Water is taken from a nearby stream or a tank. Small quantities of seepage water are pumped away by an electric drainage pump. A generator set may be needed to power the pump and any lighting needed on the site. Large groundwater inflows may necessitate interruption of the excavation work and relocation to another site.

When the soil is deep, stripping the soil gives rise to large quantities of excavation spoil. The excavation spoil is heaped up next to the pit or trench and later used for backfilling. In some cases, the spoil may need to be placed on another site temporarily if the pit is dug near a sensitive natural area. The trenches are refilled after the survey.

Environmental impact

Excavators, compressors and power generators as well as vehicles for transport of personnel and equipment give rise to noise, dust and exhaust emissions. Excavators may leak hydraulic oil and lubricating oil.

The sites where excavation is done will take up land for between several weeks and several months. The area immediately surrounding the excavation area is temporarily altered by the excavated spoil. Local impact to the vegetation will occur, and possibly a temporary lowering of the water table.

The soil stripping work emits noise from small machines and pumps, as well as from excavation and handling of excavated spoil. There may also be some vibration. The work is similar to that that occurs in conjunction with small construction jobs. Any disturbances will be of short duration, a few weeks per excavation site.

Measures

The excavation site should be designed to minimize the impact on the natural environment. All excavations are cross-checked against the accessibility map and preceded by a field check of natural and cultural values, and must be approved by the site ecologist before they may be commenced. Selected sites are documented by photography before the excavation begins.

Pits and trenches are sloped to prevent the risk of cave-in. The excavation is cordoned off in the field. Spilled oil is collected wherever possible.

The excavation work is done in the autumn when the water table is at its lowest so that drainage effects are minimized. This time is also favourable for the natural environment, since the sensitive nesting season is over.

After completion of the investigations the excavation spoil will be put back. The top soil layer with vegetation is separated so that it can be put back intact afterwards. The site is photographed once again, and remediation measures are documented.

Excavations that can cause impact to the natural environment will be preceded by supplementary consultation with the County Administrative Board.

A.3.3 Core drilling

Description

During the complete site investigation in the Forsmark area, an additional 12 or so cored boreholes are planned down to a depth of at most about 1,000 metres. What mainly determines the choice of drilling site is the geoscientific question which the borehole is intended to answer. Since the geoscientific goals can usually be achieved with inclined boreholes, the drilling sites can in most cases be chosen with consideration for the area's natural values as well. It is also possible to drill several boreholes from the same drilling site. SKB plans to build 7 new drilling sites (see Figure 2-18) during the remainder of the site investigation. The remaining cored boreholes can probably be drilled from these and existing drilling sites.

Core drilling entails that a cylindrical drill core is retrieved and evaluated along the entire length of the hole. Larger and heavier drilling machines are used for core drilling to great depth than for the more common types of boreholes. Core drilling of a 1,000-metre deep hole normally takes 2–3 months, but may take nearly 4–6 months if the drilling is interrupted for measurements. Drilling is usually done 24 hours a day, Monday–Thursday. Drilling may be done on weekends as well during certain periods, however. When the position of a cored borehole has been determined, the transport road and drilling site are built. The drilling machine is transported – along with the drilling rig, compressors, cooling water pumps, hoses and containers etc – to the drilling site on a trailer. At the drilling site (see Figure A-4), a rest shed, toilet and temporary storage building for equipment are also built. The fenced-in drilling site is estimated to occupy an area of about 30×40 metres. During the wintertime, or if special reasons exist, core drilling is done under the shelter of a large tent.

During core drilling, clean groundwater (called flushing water) is pumped down into the hole to cool the drill bit and remove the drill cuttings. This water is pumped from one of the nearby percussion boreholes; sometimes it has to be hauled to the drilling site by road

Figure A-4. *Drilling site in Forsmark.*

tanker. The water is marked with the tracer uranine so that contamination with flushing water can later be determined by water sampling. Most of the flushing water is pumped up out of the borehole by compressed air. Relatively large quantities of slurried drill cuttings are brought up with the return water, which therefore passes through settling tanks before being discharged to a receiving body.

If the return water is saline it is discharged to the sea, an alternative is to haul it away in road tankers. Experience from the drilling during the site investigation shows that the deep groundwater is saline (from a depth of about 150 metres and downward, with a salinity on the order of 5,000 mg chloride/l). The return water has therefore, with one exception, been discharged to the sea. The return water pipe (and sometimes the flushing water pipe as well) is laid by an all-terrain vehicle, which can cause ground damage. Pipe laying must therefore be planned in consultation with the site ecologist.

Environmental impact

The core drilling equipment requires a gravelled surface and a road for transport of the drilling machine and measurement equipment. Trees need to be felled and the ground gravelled for the road and the drilling site. Land is occupied for a long time.

The activities on the drilling site require electricity. Power supply to measurement equipment and operation requires 400 V/63 A. Powering the actual drilling rig and compressor requires 400 V/250 A. For these purposes, underground cable has been laid to all drilling sites except drilling site 3, where the power supply is 63 A and where signal transmission takes place via a mast. The Forsmark NPP's existing infrastructure for electricity, telephone and roads is used at drilling sites within the Forsmark industrial area. Here the electrical system is only fused for 63A, so electric power for core drilling on these drilling sites, like before on drilling site 3, will be supplied by a diesel-powered generator set. For other drilling sites, a decision on what type of power supply is to be used will be made when the exact location of the drilling site has been determined.

The drilling machine makes noise, which has a disturbing impact in the area around a drilling site. Noise-sensitive and timid animals may be temporarily disturbed in a larger area during the actual drilling. Noise will also be caused by vehicular traffic during the drilling work. Furthermore, some limited ground vibrations will occur in the immediate environs of a drilling site. The lighting on the drilling site in the evening and at night is also of relatively limited intensity and range.

Some environmentally harmful substances are used during core drilling, such as hydraulic oil, lubricating oil and thread grease, as well as diesel oil when diesel generators are used. Since the investigations of bacteria in the bedrock are very sensitive to different types of disturbances, biodegradable oils cannot be used for equipment that is lowered into the boreholes. The drilling contractor is obligated to use as little oil and grease as possible. When it comes to other substances that do not come into contact with the borehole, environmentally friendly alternatives are preferred, such as biodegradable oils.

In all cored boreholes, stainless steel casing is installed through the soil layers and a short distance, no more than 100 m, into the rock. To prevent superficial water from leaking down and mixing with deeper-lying groundwater, the gap between the casing and the borehole wall is generally grouted. Only low-alkaline so-called white cement may be used for this grouting. The grout also penetrates out into the fracture system around the borehole. Consumption can be around 2,000–3,000 kg per borehole. Theoretically, the grout could be transported to e.g. a stream, where it could cause some pH increase. Some pH change in the groundwater in the immediate vicinity of the borehole can also be expected as a result of grouting.

During the drilling (as well as later during test pumping of boreholes), a temporary lowering of the groundwater level occurs due to the continuous pumping-out of flushing water and groundwater. Groundwater lowering or “drawdown” is normally measurable within several hundred metres of the drilling site, but may be considerably greater along a water-conducting fracture zone. The size of the drawdown declines with the distance from the drilling site at a rate that is dependent on the hydraulic properties of the bedrock and the soil layers. The drawdown is recorded by equipment installed in both nearby and more faraway soil and percussion boreholes. Experience from the initial site investigation is that the drawdown of the groundwater level in the borehole being drilled is 30–60 m during the actual drilling period (10–12 weeks). Due to the large flows in the superficial rock, recovery takes place very quickly, usually within a few hours, after pumping has been discontinued. Another observation made during the initial site investigation is that there is usually no measurable lowering of the groundwater level in the soil layers during core drilling.

If slurried drill cuttings were released, this could have some environmental impact. Return water with a high salinity that is unintentionally released can also and cause harm, mainly to animal and plant life. Unintentional releases of flushing water marked with uranine leave coloured stains in the surroundings for a short time. However, the dye is quickly broken down by sunlight. Passenger and equipment traffic, as well as haulage of e.g. flushing water and drill cuttings, may be substantial during the drilling work, along with visits to the drilling site.

Measures

Times and places for drilling are checked against the accessibility map and new construction of drilling sites is preceded by a field check of natural and cultural values.

When suitable drilling sites are to be chosen, their location, transport roads to and from the sites, and the time of the drilling will be planned and approved by SKB’s site organization, which also judges whether there is a need for consultations with the County Administrative Board, landowners and other concerned parties. SKB must ascertain what consideration needs to be taken, for example under the terms of the Environmental Code and the Cultural Monuments Act. Prior to the construction work, the surface ecosystems at the drilling site must also be documented. To minimize the environmental impact, we try whenever possible to direct groups of visitors to those drilling sites that are least sensitive from an environmental standpoint.

In cases where it is technically and economically feasible, we will lay underground power supply lines for drilling rigs and air compressors to future drilling sites as well.

By building a tent over the core drilling machine with appurtenant equipment, a more weatherproof and manageable workplace can be obtained. At the same time, the tent provides some noise attenuation.

Sedimented drill cuttings (about six cubic metres per hole), as well as cuttings from the percussion boreholes (see below), have been used in the construction of drilling sites and branch roads. An attempt will be made to do this when possible during the continued site investigation as well. If there is a surplus, the cuttings may have to be disposed of in a suitable manner within the area or be hauled to a landfill.

The groundwater level in nearby soil and percussion boreholes will be checked before, during and after core drilling. The water chemistry will also be checked. So far no changes in water chemistry have been observed.

When the gap between casing and hole wall is grouted, injection flows and pressures are carefully monitored.

In case of oil leakage (mainly hydraulic and lubricating oil), a concrete slab with a raised rim is cast on which the core drilling machine is placed. This keeps any fluids spilled by the drilling machine from running into the ground. It also enables the personnel to detect even small leakages of, for example, hydraulic oil very quickly. The drilling personnel also follow a special environmental control programme that includes daily inspection of hoses and couplings as well as replacement of worn equipment. Equipment for cleanup of oil spills is also available on the drilling site. Drilling under a tent provides extra pollution protection since precipitation is prevented from reaching the drilling area. Without a tent, in the event of rain any spilled oil might overflow the rim of the concrete slab and contaminate the ground.

Waste will be collected and taken to environmental stations. Free-standing oil tanks will be dyked-in so that the whole volume is within the dyke, and will also be provided with a rain collar.

During the initial site investigation, a spill of diesel oil took place at drilling site 3, when a total of 20 litres ran out onto the ground. A diesel generator set was being used at this drilling site to power the equipment. The spill occurred while the generator was being fuelled. The leak was discovered immediately and the rescue services cleaned up the site. The contaminated soil was dug up and removed. A few minor leaks have occurred, all less than one litre. Most have involved hose rupture. These leaks all ran out on the concrete slab and could therefore be dealt with easily with the cleanup equipment available on every drilling site where drilling is being done.

After completion of drilling, the work site is given a final cleaning and any ground damage outside the gravelled surface is remediated.

The location of future drilling sites will be subject to supplementary consultation with the County Administrative Board.

A.3.4 Percussion drilling

Description

An additional 10–15 percussion boreholes are planned to be drilled during the continued site investigation in the Forsmark area. The boreholes are normally 100–200 metres long. Percussion boreholes are drilled to obtain flushing water for core drilling, to investigate fracture zones and to investigate the bedrock between fracture zones. Many of the percussion boreholes are moreover intended for long-term monitoring of the groundwater level and groundwater chemistry.

Drilling of a percussion borehole takes about three days. Percussion drilling can be done at all times of the year and in multiple shifts. Percussion boreholes are drilled with a pneumatic drilling rig similar to those used for drilling wells (see Figure A-5) and must comply with the same purity requirements as well bores for drinking water. The drill bit fragments the rock and the cuttings are blown up out of the hole by compressed air. A 200-metre deep percussion borehole produces approximately three cubic metres of cuttings. During the initial site investigation, all cuttings that were not collected for examination were used in the construction of drilling sites and branch roads. If there is a surplus, the cuttings may have to be disposed of in a suitable manner within the area or be hauled to a landfill.

Figure A-5. *Percussion drilling machine set up on protective ground cloth that prevents ground contamination and permits any leakage to be collected.*

The cuttings are blown up together with the water that seeps into the borehole while it is being drilled. It is superficial groundwater, which in the Forsmark area is generally fresh to brackish. The water is collected in a container, where the cuttings are allowed to settle. The water is then released into the nearest ditch.

Except during setup and removal of the drilling equipment, virtually no vehicles are used for transport to and from the percussion drilling site. An exception is if heavy measurement equipment is needed on a later occasion. During the drilling work, the personnel can get in on foot in cases where no roads are built. After completion of drilling, the drilling site is cleaned, the borehole is instrumented and a measurement hood is placed over it. After concluded geophysical and hydraulic borehole measurements, the borehole is instrumented for long-term monitoring of groundwater levels and groundwater chemistry, and the measurement instruments are covered by a lockable measurement hood. Signal cable is run to the measurement hood.

Environmental impact

The drilling machine and thereby the sound level are the same as during ordinary well drilling in rock. The diesel-powered compressors used to generate the compressed air, as well as the drilling machine's diesel engine, produce both noise and exhaust gas emissions. Percussion drilling makes more noise than core drilling and can be heard at a great distance (a kilometre or so), especially in the beginning of the drilling when the bit is near the ground surface. However, the noise does not last long (about three days). Noise is also created by vehicular traffic associated with the drilling. Noise-sensitive and timid animals in a large area may be temporarily disturbed during the drilling work. Vibration is limited, as is the light from electric lighting in the evenings and at night.

Since new roads and gravelled areas are avoided at most percussion drilling sites, land needs are modest. Off-road driving in connection with drilling and subsequent measurements can cause damage to the ground and vegetation. The groundwater table is lowered (drawdown) during drilling. Groundwater of elevated salinity may be released to the environment during drilling.

Both percussion boreholes and cored boreholes are lined with stainless steel casing, and the casing-wall gap is grouted with white cement. The quantity of grout is generally much less than in the case of core drilling, but the potential environmental risks are of the same kind as for grouting of cored boreholes.

Measures

As in the case of core drilling, the choice of drilling site will be determined by the geoscientific question which the borehole is intended to answer. Consideration can nevertheless be given to natural values by locating the investigation holes where the fracture zones to be studied intersect existing roads. Some holes may end up being located relatively far from the nearest road, however. Since the drilling is of short duration, and because an attempt is made to avoid building roads and a drilling site, the impact is judged to be limited. However, off-road driving will be necessary during drilling, as well as later when measurements are made. Off-road driving must be approved by the site ecologist after the travel route is checked.

The drilling equipment is placed on a waterproof geotextile sheet so that any oil spilled by the drilling machine won't reach the ground immediately and so that the spill can be quickly discovered and remediated.

The air compressor's diesel engine must have a silencer that is approved for use in an urban environment.

The electrical conductivity of the water that is pumped up from the borehole is measured during drilling. If groundwater with elevated salinity comes up from the hole during drilling, no measures are taken since the impact is of short duration. Due to the very high water-generating capacity of the upper part of the bedrock, the flow rate during percussion drilling has generally been high, up to around 1,200 l/min.

A.3.5 Auger drilling

Description

During the initial site investigation, just over 70 soil boreholes were drilled in the Forsmark area. The purpose was to take soil samples and to set up groundwater monitoring wells for measurement of groundwater levels in soil layers and for water sampling to check for possible spread of chemicals from core drilling. During the continued site investigation, auger drilling is planned mainly for the installation of soil pipes next to new drilling sites. But a few holes may also be drilled to answer special questions. Auger drilling is done with a lightweight crawler machine (type Geotech), see Figure A-6; it takes two persons about one day per hole.

Environmental impact

Since light equipment is used for the majority of soil boreholes, the environmental impact of the auger drilling is judged to be small. Only small amounts of cuttings or augured-up soil ends up on the ground and the groundwater is only affected to a limited extent. The

Figure A-6. *Auger drilling machine.*

main impact comes from off-road driving, some noise and minor exhaust emissions, passenger transport and a general increased presence in the area.

Measures

Off-road driving in sensitive areas will be limited and will be preceded by a cross-check against the accessibility map and a field check of natural and cultural values.

A.3.6 Investigations in boreholes

The group includes:
- Hydraulic tests and water samplings in wells and boreholes.
- Tracer tests.
- Thermal borehole tests.

Description

Heavier lifting and measuring equipment is used for hydraulic testing and water sampling. Equipment for hydraulic testing is often installed in freight containers or mobile work wagons that are positioned directly above the borehole. The investigations can be conducted year-round.

During water injection tests and pumping tests, water is handled in a way that resembles flushing and return water handling during drilling. Owing to the large water-conducting zones in the upper bedrock, the water quantities that are handled in test pumping are

Figure A-7. *Borehole investigation in Forsmark.*

relatively great if the pumping is of long duration. Most boreholes are test-pumped for one to several hours. In some boreholes, one or more tests are performed with a duration of around a week. But the water flows are much less than during core drilling and percussion drilling.

Interference tests will be performed during the continued site investigation. This entails investigating the hydraulic contact between different boreholes by pumping water out of one hole and measuring responses in others. These tests will have a duration of several months. Depending on the amount of water flowing into the holes and depending on the nature of the soil layers and the contact between rock and soil, there may be some impact on the vegetation due to lowered groundwater level. The insignificant impact on the soil layers observed so far in conjunction with core drilling indicates that there is little risk of this, however.

Dilution tests and other types of tracer tests have not been conducted during the initial site investigation but are planned during the continued investigation. In a dilution test, a tracer is injected into a borehole and the dilution of the tracer is then observed. The tests are done under undisturbed conditions or during pumping in a nearby borehole and enable the rock's hydraulic and transport properties to be evaluated. Probable tracers are dyes (biodegradable) and some salts (NaI, NaBr, CsI). Some metal complexes (EDTA or DTPA) may also be used. If so, they must be used in extremely low concentrations, since they are rare earth metals (erbium, terbium, gadolinium). The tracers are not expected to have any environmental impact in themselves, since they are harmless and the concentrations are so low. As in other borehole tests, some water will be pumped up.

Thermal borehole tests are performed in short (< 10 m) boreholes where the soil depth is low, preferably on a suitable outcrop. Heat is generated electrically. Heating is done for roughly one week. The heat only reaches a metre or so from the heater. Cooling takes about the same length of time (may depend on season).

Thermal borehole tests may also be performed in deeper boreholes. Either a borehole instrument that emits heat very briefly is used, or a "pumping test" is performed with heat or cold.

Other borehole investigations: geophysical logging, videotaping and borehole radar measurements are not expected to give rise to environmental disturbances.

Environmental impact

Pumping tests lead to a lowering of the groundwater table (drawdown). The amount depends on the pump flow and the duration of the pumping. The groundwater level in the bedrock can be affected within a range of 200–400 metres from a borehole, or more than a kilometre in a water-conducting fracture zone. The drawdown is greatest (about 40–60 metres) around the hole itself. The tests we have done so far have lasted several weeks, and as mentioned previously the groundwater table returns to its original level only a few hours after pumping has stopped.

Wells, especially ones drilled in rock, in the vicinity of the pumping test may be affected mainly by drawdown while the pumping test is under way, but the groundwater's salinity can also increase due to the fact that deeper groundwater seeps up in the well.

The impact in overlying soil layers is entirely dependent on the composition of the soil layers and the nature of the interface between soil and rock. If the overburden deposits are impervious and the hydraulic connection between soil and rock is poor, the drawdown in the soil layers is reduced or eliminated entirely. Permeable overburden deposits such as gravel are affected more by pumping, but due to its brief duration, test pumping will probably not have any effect on the vegetation. On the other hand, the interference tests may have some impact on the vegetation depending on how sensitive the vegetation around the boreholes is. Areas that are wet in their natural state are most sensitive to drying-out. The effect will be temporary, however, so no effects are expected to persist into the next season.

The environmental impact of the heat in the thermal borehole investigations is assumed to be negligible. However, the use of the rig gives rise to exhaust and noise emissions.

Measures

The water that is pumped up is normally discharged to the nearest stream or ditch. If there are large quantities or if the water is saline, however, it may have to be collected in a tank to be hauled to the sea or be pumped out to sea through a pipe.

Nearby private wells are checked for any impact, and if the impact is permanent measures are taken, for example a new well.

As with other boreholes, the location of the thermal boreholes is determined by the geoscientific question the borehole is intended to answer. Consideration should nevertheless be given to natural values by locating the boreholes close to existing infrastructure so that off-road driving is avoided and power can be taken from the grid.

A.3.7 Flow and level monitoring in streams

Description

Since the most common means of measuring water flow in small streams – a measuring weir with a small pond upstream of the weir – is an obstacle to the migration of fish and other aquatic organisms, another solution has been chosen in Forsmark. A measurement channel of a special design is built on the bottom of the stream so that the flow can be calculated based on the water level in the channel (measured with a pressure sensor). The channel must be kept ice-free to work in the wintertime, so heating coils are placed underneath the channel. In order to get reliable values, the downstream section may not be too flat and weedy, since this will slow down the flow and affect the measurement result.

Pressure probes positioned next to a groundwater monitoring well are used to measure the water level in lakes and bays. The pressure levels are stored by a battery-powered logger mounted on the well. The loggers are connected to a GSM system that phones up and transmits data several times a week. The stations are visited roughly every fourth month when the batteries need to be changed.

Figure A-8. *Flow monitoring station upstream of Bolundsfjärden.*

The first monitoring station (upstream of Bolundsfjärden) has been operating for about one year and its operation has been evaluated. To get reliable data the channel has been raised more than a decimetre. Three new monitoring stations of the same type are being installed in the autumn of 2004, downstream of Gunnarboträsk, downstream of Eckarfjärden and between the latter and the existing monitoring station, see map in Figure A-9.

Equipment for level monitoring has been installed in five of the area's lakes, in a shallow sea bay and in the Forsmark harbour. Their locations are shown in the map in Figure A-9. No more level monitors are planned at present.

Environmental impact

To permit construction of the monitoring station, the stream needs to be dredged by an excavator along a 30 m section. To clear the way for the excavator, trees need to be felled. During the excavating work the water in the stream must either be pumped past the construction section or diverted in a temporary side channel. The former alternative will be the main option in order to minimize the amount of land that needs to be occupied.

To minimize the damming effect, it may be necessary to clear the stream downstream of the monitoring station by removing some small trees growing in the streambed as well as fallen branches and the like.

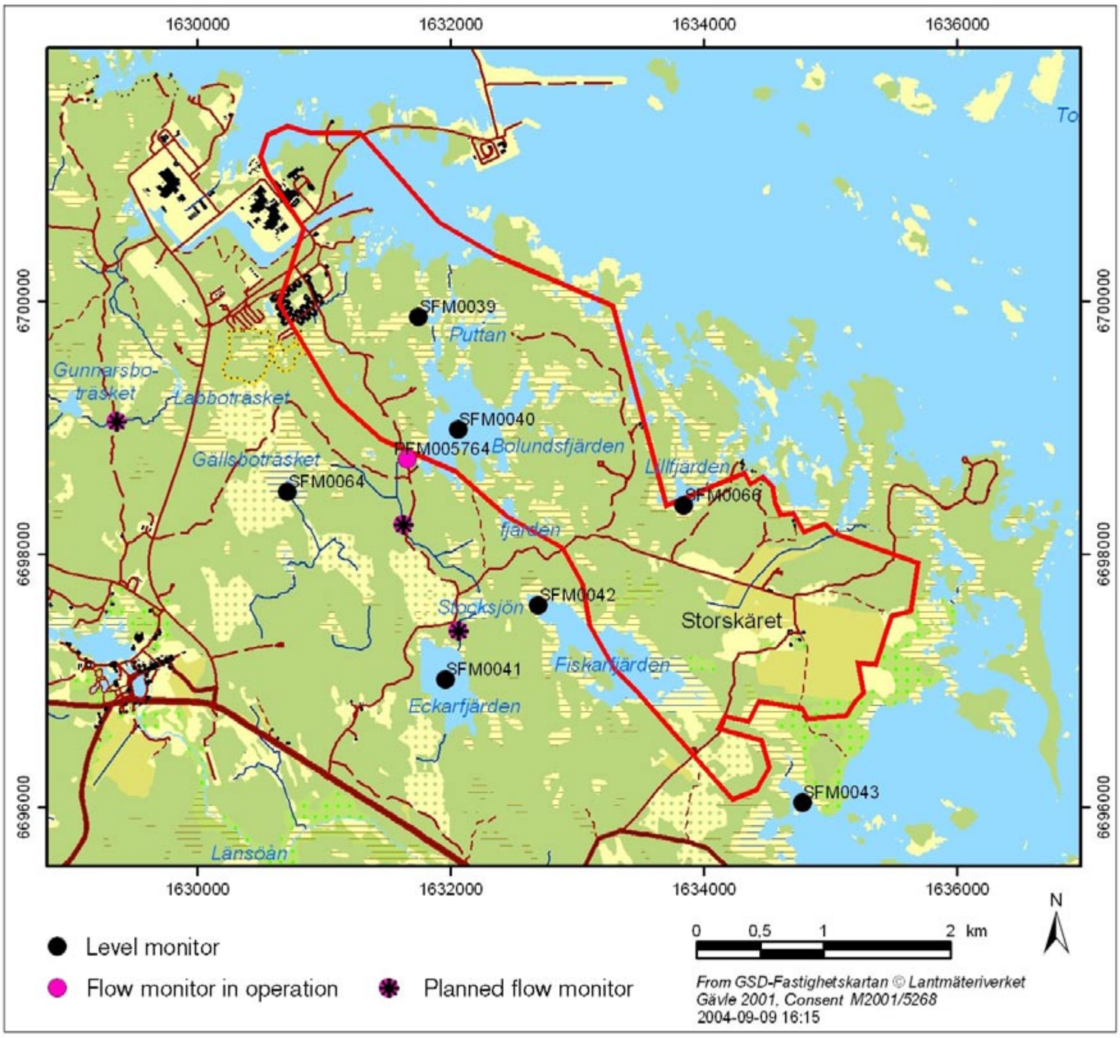

Figure A-9. *Location of level monitors and flow monitoring stations.*

Measures

To prevent mobile machinery from having to be driven long distances off-road, the monitoring stations have been located close to existing roads. This location has been determined in consultation with the site ecologist and has been preceded by a cross-check against the accessibility map and a field check of natural and cultural values. Furthermore, the location and design of the flow monitoring stations has been approved by the County Administrative Board. No more flow monitoring stations are planned at present. But if more should need to be built in the future, they will be installed at times when nature is less sensitive to disturbance, i.e. late summer or autumn. In early autumn the water levels are often at their lowest, making it simpler to work in the streams.

The locations of the level monitoring stations in the lakes and sea bays have also been chosen in consultation with the site ecologist.

A.3.8 Seismic surveys

Description

The seismic surveys consist of three different methods: seismic refraction, seismic reflection and Vertical Seismic Profiling (VSP). Seismic refraction will be used to determine soil depth and to study superficial structures in the rock, for example as a basis for the lineament excavations that are planned. Seismic reflection is used to determine the location and orientation of rock type boundaries and fracture zones down to great depths in the bedrock, while VSP allows a more detailed determination of the geometry and orientation of fracture zones in the vicinity of the investigated boreholes.

Normally, seismic surveys are carried out by detonating small explosive charges ("shots") in the ground and recording the sound wave's propagation and reflection from structures in soil or bedrock with geophones, which are like sensitive microphones. An alternative method has also been used with good results during the site investigation. Here the charges are replaced by vibration from an impact hammer mounted on an excavator. This reduces the environmental impact and, since no holes need to be drilled for charges, it also reduces

Figure A-10. *Seismic survey with impact hammer.*

the costs of the investigations. The impact hammer method is only employed near existing roads, however. When the profiles go through the terrain, conventional methodology with explosive charges will be used, since a tractor would cause major ground damage in such cases.

In seismic refraction, a charge of no more than a couple of hundred grams is used. In seismic reflection the charge is even smaller, generally between 15 and 100 grams.

The size of the shot holes in seismic reflection is dependent on the soil depth. When the soil is deep, the shot holes are drilled in with a handheld drilling machine or a Geotech-type crawler drill, see Figure A-6. The drilling machine is powered by compressed air from a compressor that is towed by some kind of all-terrain vehicle, see Figure A-11 below. If the overburden is thin, it is stripped from the rock surface and a Hilti electric handheld drill is used. The electric power is supplied by a generator.

Figure A-11. *Preparations for drilling and charging for seismic reflection.*

Other ground geophysical surveys, such as ground-penetrating radar surveys or gravimetric surveys, that may be carried out during the continued site investigation do not give rise to any other disturbances but the movement of people within the investigation area.

Environmental impact

In connection with seismic surveys, the compressor used for drilling of shot holes emits exhaust emissions. If a motorized crawler drill carriage is used, it also gives rise to exhaust emissions. The explosive charges emit explosion gases when detonated.

The noise levels from the seismic reflection surveys are low. Seismic refraction shots are slightly louder. They cause a report that can be perceived a couple of hundred metres away. The report from the shots located furthest from the geophones in seismic refraction is even louder. The noise is of short duration, but the shots can disturb birds and mammals.

The impact on the ground is judged to be very little after a seismic reflection survey. However, individual shots directly on exposed outcrops can result in some fracturing of the rock surface. A normal shot for seismic refraction on soil layers creates a mound in the ground surface with a diameter of about a half a metre, where the soil is loosened under the mound. The mound is levelled before the site is abandoned, so the impact is judged to be insignificant. Shots at greater distances from the geophones require larger charges, causing bigger pits and eruptions of soil and stones. The craters may be a metre in diameter, with a depth of a couple of decimetres. The most long-lasting changes in the terrain are the tracks left by all-terrain vehicles when they have to leave the logging roads for compressor transport.

Shots in water affect fish near the shot. The nearest fish die, while fish further away from the shot are stunned. The range of impact is difficult to estimate. If seismic surveys are done in water, this effect will be taken advantage of to record the fish fauna in the affected areas.

When impact hammers are used, a sharp chattering sound results that is only audible a few hundred metres from the tractor. The tractor emits exhaust gases.

Measures

The route taken by all profiles is cross-checked against the accessibility map. In cases where the profiles do not follow existing roads but strike out into the countryside, natural and cultural values in the field are also checked. The purpose is to guide the choice of route for all-terrain vehicles and the location of shot points so that the risk of damage to sensitive environments is minimized. Based on the accessibility map, the locations of the survey profiles can be adjusted and the time of the year can be chosen so that disturbances to sensitive nature are limited. Craters created in the ground are backfilled with debris and levelled off.

Compressors and crawler-mounted drilling machines are set up on fibre-reinforced cloth to collect and oil spills. In order to avoid cross-country transport, equipment is set up alongside roads wherever possible.

Guards are stationed to warn of ongoing blasting work. Storage, transport and handling of explosives complies with laws and regulations. For example, the seismic contractor must have a blasting licence and a permit for the blasting work.

Seismic surveys that entail off-road driving and profiles through virgin terrain will be preceded by supplementary consultation with the County Administrative Board.

A.3.9 Field inventories and other investigations in sensitive areas

Description

The big field investigations such as surface mapping of rock types, soil inventories, Quaternary deposit mapping and mapping of watercourses were carried out during the initial site investigation. But some field investigations will also be carried out during the continued site investigation as well. Most investigations – respiration measurements on land and in water and continued monitoring of the bird fauna in the area – entail minimal environmental impact. Other investigations that will be conducted are supplementary bedrock geological mapping southeast of Kallrigafjärden and detailed fracture mapping in the northwestern part of the candidate area. The bedrock geological mapping is being done on outcrops in the area. In detailed fracture mapping, outcrops are exposed by stripping the overburden and the rock surface is cleaned with a high-pressure spray. Some of the investigations that are planned may also affect sensitive or protected areas, such as the Kallriga Reserve. Furthermore, supplementary marine geological investigations will be conducted on seafloor in marine areas with a water depth of less than three metres. These investigations are conducted from a boat, whereby sediment plugs are taken from the bottom. An investigation of fine roots will also be conducted in the area, requiring digging of small pits.

Environmental impact

Most of the remaining field inventories and investigations have very little environmental impact, in principle only the disturbance caused by the presence of the personnel in the field. In some cases, small pits will be dug for an inventory of the fine root fraction. These pits are dug with a shovel and are around a half metre or so in diameter. The pits are refilled after sampling.

Bedrock geological mapping of outcrops may require the temporary removal of moss and lichens within small areas. The areas, around 0.5–1 m in diameter, are remediated after completed mapping.

Detailed fracture mapping requires that the overburden be stripped down to the rock surface by an excavator. Outcrops that are already bare or have little soil cover are preferred, however. The outcrops are then cleaned with a high-pressure spray or compressed air. Excavation gives rise to noise, dust and exhaust emissions, and excavators can leak lubricating and/or hydraulic oil. Compressors for powering high-pressure equipment also give rise to noise and exhaust emissions.

The animal and bird life is particularly sensitive during certain times of the year, and presence in the field may cause disturbances.

A boat is needed for mapping of Quaternary deposits in marine areas with depths of less than three metres, which gives rise to noise and exhaust emissions. The investigation may also require the presence of personnel in Kallriga Reserve.

Measures

All field activities are preceded by a cross-check against the accessibility map and a field check of natural and cultural values. The investigations are scheduled to minimize disturbance of the animal life. If the investigations need to be conducted in the Kallriga Reserve during periods of prohibited access, an exemption from the regulations will be applied for from the County Administrative Board.

Thanks to the monitoring of birds and game conducted by SKB, there are good opportunities to plan activities so that disturbances are minimized.

Field investigations that impact the natural environment will be preceded by supplementary consultation with the County Administrative Board.

A.3.10 Summary

The table below summarizes the investigations that are judged to have a possible impact on the environment and that in certain cases will be preceded by supplementary consultation for further specification of dates, implementation and siting.

Activities that can lead to environmental impact	**Estimated scope**	**Comment**
Construction of roads	New roads may have to be built in conjunction with the construction of new drilling sites, see below. Otherwise, however, no additional roads are planned in the area. The roads must be negotiable by cars and trucks with trailers (length 24 metres, width 2.6 metres, height 4.5 metres, gross vehicle weight 50 tonnes)and the loadbearing capacity of the road must permit heavy traffic year-round.	During the initial site investigation, approx. 1 km of road has been built and approx. 6 km of existing road has been strengthened. Construction of roads will be preceded by supplementary consultation with the County Administrative Board.
Construction of branch roads and drilling sites	Short roads may need to be built to new drilling sites. The road may need to be made wider at the drilling site. The extra width is used as a loading and unloading area and a parking place. The road can be widened on one or both sides. Core drilling sites require a gravelled surface of about 30×40 m and will be fenced in.	The notice of supplementary consultation regarding additional drilling sites will include an integrated account of roads, design and additional infrastructure.
Construction of other infrastructure	The need for additional power and signal lines is determined by the number of additional drilling sites and their location in relation to existing infrastructure. Lines are installed alongside roads, mainly underground in conduits. For infrastructure related to measurement and monitoring equipment, see below.	Power and signal lines have been laid to all core drilling sites, with the exception of signal line to drilling site 3. At drilling sites 7 and 8 we will make use of existing infrastructure, which does not permit electric drilling.

Activities that can lead to environmental impact	Estimated scope	Comment
Core drilling	Approx. 12 cored boreholes, 3–6 months per borehole. 2–5 additional drilling sites. A 1,000 m hole requires at least 1,000 m^3 of flushing water for cooling of the drill bit and removal of drill cuttings. Flushing water is supplied from nearby percussion boreholes. Return water is conducted via settling tanks to a receiving body of water.	Alternative receiving bodies may have to be used in the wintertime due to the risk of freezing if the return water line is too long. Construction of new drilling sites in the terrain and discharge of return water to alternative receiving bodies will be preceded by supplementary consultation with the County Administrative Board.
Percussion drilling and auger drilling	Approx. 10–15 percussion boreholes, 100–200 m deep, and 5–10 soil boreholes. Do not normally require construction of road or gravelled surface, which means insignificant occupation of land. Drilling takes about 3 days per hole for percussion drilling and 1 day per hole for auger drilling.	Will not normally be preceded by consultation with the County Administrative Board, unless accessibility check or field check of natural and cultural values warrants this.
Excavations for mapping of bedrock etc	Excavation of pits or trenches for examination of the rock surface at suspected fracture zones is planned at 3–6 places in the area. Two trenches will be dug during the autumn of 2004. An additional 2–3 trenches are planned to be dug during 2005. The trenches are 50–100 m long with a bottom width of about 3 m. For excavation to be feasible, the soil depth should not exceed 5 m.	The locations where excavation will be done in the autumn of 2004 have been notified for consultation with the County Administrative Board. Additional locations will also be preceded by consultation.
	Excavation to expose outcrops – on an area of about 30×30 m – may be done in conjunction with detailed fracture mapping in the northwestern part of the area. Such soil stripping is being planned at present.	Major excavations will be preceded by consultation with the County Administrative Board regarding siting and scope.
Seismic surveys	Seismic refraction surveys will be conducted in the autumn of 2004 to determine soil depth at the locations where excavations will be made to examine lineaments. Seismic reflection surveys will also be conducted during 2004 to investigate the area southwest and northeast of the candidate area. The scope of other seismic surveys cannot be estimated at present.	The planned seismic surveys have been notified for consultation with the County Administrative Board. Future seismic surveys will be preceded by consultation with the County Administrative Board if profiles are to be located in untracked terrain or in water.
Field inventories and investigations in sensitive areas	A number of minor field investigations will be conducted during the continued site investigation. Among other things, marine geological investigations will be conducted in marine areas with a water depth of less than 3 m. Furthermore, supplementary bedrock geological mapping will be conducted in the area southeast of Kallrigafjärden.	If the investigations are judged to have a possible impact on the environment or need to be conducted in sensitive or protected areas, they will be preceded by supplementary consultation with the County Administrative Board.