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Finnsjön study site. Scope of activities and main results

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ABSTRACT (ENGLISH)

The Finnsjön study site was selected in 1977 to provide input to the KBS-1 and KBS-2 performance assessments. The site was later used as a test site for testing new instruments and new site characterization methods, as well as a research site for studying mainly groundwater flow and groundwater transport. All together, the Finnsjön studies have involved 11 cored boreholes, down to max. 700 m depth, and extensive borehole geophysical, geochemical and geohydraulical measurements, as well as rock stress measurements and tracer tests.

This report presents the scope of the Finnsjön studies together with main results. Conceptual uncertainties in assumptions and models are discussed with emphasis on the models used for the performance assessment SKB91. Of special interest for the Finnsjön study site is the strong influence caused by a subhorizontal fracture zone on groundwater flow, transport and chemistry.

ABSTRACT (SWEDISH)

Typområdet Finnsjön valdes 1977 för att få platsspecifika data till KBS-1 och KBS-2 säkerhetsanalyser. Området har sedan dess använts som ett försöksområde för nya mätutrustningar och nya metoder för att karaktärisera berggrunden, speciellt med avseende på grundvattenflöde och grundvattentransport. Sammantaget har studierna i Finnsjön inkluderat undersökningar i 11 kärnborrhål, ner till max. 700 m djup, och ett omfattande material från geofysiska, geokemiska och hydrauliska borrhålsmätningar samt bergsspänningsmätningar och spårförsök.

Denna rapport beskriver vilka undersökningar som har gjorts i Finnsjöområdet, vilka huvudresultaten är och kvarstående konceptuella osäkerheter. Rapporten beskriver även till viss del de omfattande konceptuella och numeriska modelleringar som har gjorts i samband med SKB91. Finnsjöområdet är speciellt intressant pga den stora inverkan som en subhorisontell zon har på de vattenkemiska förhållandena samt på grundvattenflöden och grundvattentransport.

PREFACE

During the period from 1977-1986 SKB (Swedish Nuclear Fuel and Waste Management Co) performed surface and borehole investigations of 14 study sites for the purpose of assessing their suitability for a repository of spent nuclear fuel. The next phase in the SKB site selection programme will be to perform detailed characterization, including characterization from shafts and/or tunnels, of two or three sites. The detailed investigations will continue over several years to provide all the data needed for a licensing application to build a repository. Such an application is foreseen to be given to the authorities around the year 2003.

It is presently not clear if anyone of the study sites will be selected as a site for detailed characterization. Other sites with geological and/or socio-economical characteristics judged more favourable may very well be selected. However, as a part of the background documentation needed for the site selection studies to come, summary reports will be prepared for most study sites. These reports will include scope of activities, main results, uncertainties and need of complementary investigations.

This report concerns the Finnsjön study site. The report has been written by the following authors; Kaj Ahlbom and Sven Tirén (scope of activities and geologic model), Jan-Erik Andersson (geohydrological model), Thomas Ittner (groundwater chemistry), Peter Andersson (solute transport) and Christer Ljunggren (rock mechanics).

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1. ASSESSMENT OF THE FINNSJÖN STUDY SITE

This chapter summarizes characteristics and uncertainties of the Finnsjön study site, Figure 1. Based on these descriptions the needs for complementary site characterization studies are outlined.

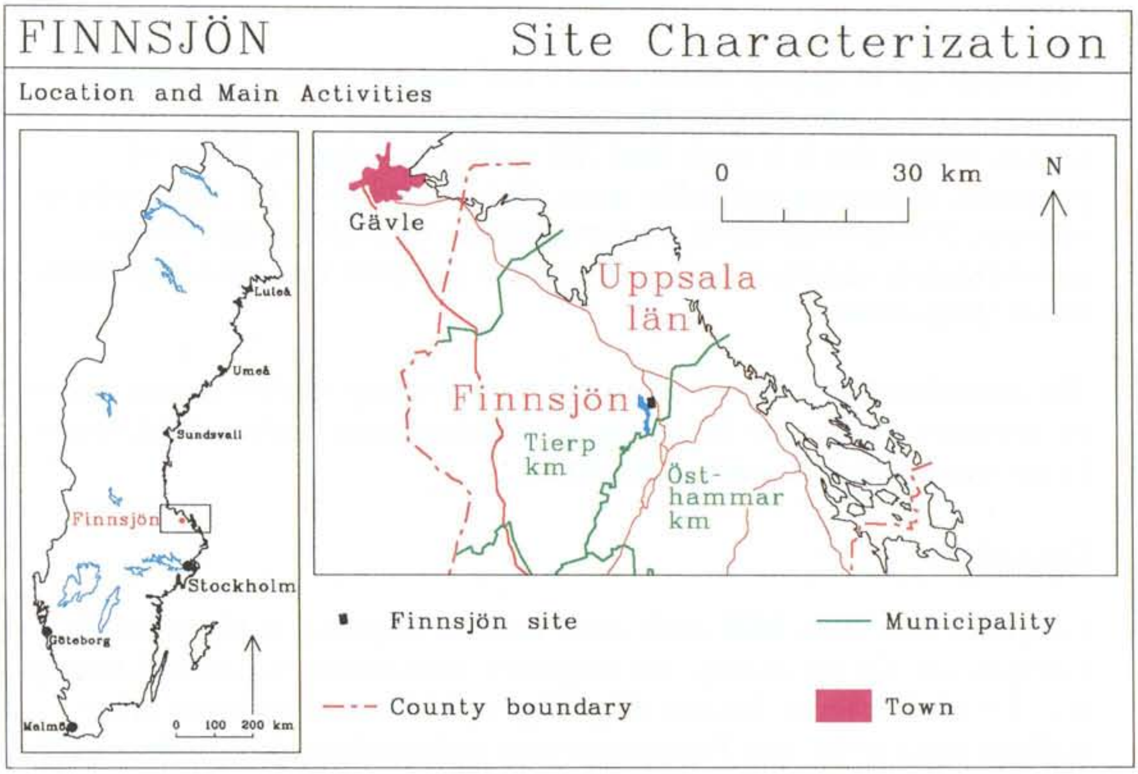


Figure 1. Location of the Finnsjön study site.

1.1 Main characteristics and uncertainties

General

The Finnsjön site is located in northern Uppland, a region of low topographical relief constituting the sub-Cambrian peneplain. The altitude varies less than 15 m within the site. Although outcrops are common, the degree of exposed rock is ca 15 %. The cover is composed of Quaternary sediments, mainly moraine and peat.

Rock type distribution

The rocks comprising the bedrock of northern Uppland are between 2,200 to 1,600 million years old. The oldest rock are supracrustal rocks and comprises acid volcanics (leptites) and metasediments. During the Svecokarelian orogeny, which culminated c. 1,850 million years ago, huge amounts of granitoids belonging to a magmatic suite of gabbroic to granodioritic (youngest) rocks intruded the bedrock. The penetrative deformation during the Svecokarelian orogeny transformed the granitic rocks into a gneiss. character. After the culmination of the semi-ductile deformation emplacements of reddish to greyish-red granites occurred, c. 1,700 million years ago. These granites constitute the youngest rock type.

The study site is located within a c. 12 km^2 large rock body consisting of greyish foliated granodiorite. The vertical extension of the granodiorite is not known, except that it is more than 700 m (borehole depth). Dykes of pegmatite, metabasite and aplite occur. The orientation of the gneissosity is uniform, N50-60W/80-90NE. The granodiorite is locally altered due to mylonitization, cataclasis, and hydrothermal alteration (red colouring) along minor shear zones.

The granodiorite is bordered to the east by the young reddish granite and to the northeast by an older layered gabbro. Metavolcanic rocks (oldest) occur to the west and to the south of the site.

Fractures

Compared with other SKB study sites, fracture frequency is higher in the Finnsjön site. On the average the frequency, determined on exposed outcrops, is c. 2.9 fr/m. A lower fracture frequency, c. 1.5 fr/m, is observed in the northern parts of the site. Fracture surveys performed along scan-lines on the ground surface and on cores show the same fracture frequency. The average fracture frequency of the upper 100 m of boreholes KFI03, 04 and 05 is 3.0 fr/m (excluding crushed sections). No decrease in fracture frequency with depth in these boreholes (0-600 m) have been observed.

Fracture surveys on outcrops in the northern part of the site have defined three main fracture groups (ordered according to their relative occurrence):

* Northeast (N10-70E) fractures with a steep dip towards SE
* Northwest (N25-80W) fractures with a steep dip towards SW
* Flat lying fractures dipping predominantly to the SW

Most of the fractures are considered to be initiated early in the geologic history and reactivated several times. Geological dating of fractures outside the site, using Rb-Sr, indicate ages of 1,600-1,500 million years for epidote and 1,250-1,100 million years for prehnite.

Uncertainties: The Finnsjön site is located in a large and homogenous granodioritic rock body. In spite of a large number of boreholes down to depths of 500-700 m, no change in main rock type has been observed. Data regarding locations, extensions and characteristics of the pegmatite, metabasite and aplite dykes are however scarce.

Fracture zones

Interpretation of the regional tectonic character of northern Uppland suggests that the Finnsjön study site is located within a 50 km^2 large shear lens, developed within a, c. 20-30 km wide, WNW trending shear belt. This belt has a regional extension and was formed 1,600 - 1,800 million years ago.

The Finnsjön Rock Block, bounded by regional and semi-regional fracture zones, constitute the main part of the Finnsjön site. The size of the block is about 6 km^2. A northeasterly trending fracture zone, Zone 1, divides this block into two lower order blocks, the northern and the southern block.

All together 14 fracture zones are interpreted at the Finnsjön site. All zones are correlated to lineaments, but borehole data are only available for eight fracture zones. Eleven fracture zones dips steeply (60-90° from horizontal) while the remaining three have a gently dip (15-35°).

Due to the Fracture Zone Project a large amount of data are available for the above mentioned Zone 1 and even more so for a subhorizontal-gently dipping zone, Zone 2. These zones appears to have a strong influence of the overall hydraulic and water chemistry conditions in the northern part of the site.

Zone 1, the Brändan fracture zone, is oriented N30E/75SE and has a minimum length of 5 km. The width is estimated to 20 m. In addition to its lineament expression, the zone is also indicated on geophysical maps and identified in the cores from boreholes KFI05 and KFI10. The cores are altered and red coloured. The fracture frequency in the zone is strongly increased compared to the host rock high, ranging between 8-20 fr/m. Characteristic fracture infillings are ironoxyhydroxides, hematite and asphaltite.

Zone 2 , a 100 m wide subhorizontal-gently dipping zone, occurs in the northern block. Its upper boundary is defined in nine boreholes at 100 to 295 m below the ground surface. There is no indication that Zone 2 extends across the Brändan fracture zone, into the southern block, nor has any outcropping parts of the zone been identified. Zone 2 is oriented N28W/16SW and with a estimated lateral extension of at least 1.5 km. The zone was formed more than 1600-1700 million years ago as a some hundred meters wide ductile shear zone at a depth of c. 10 km. Zone 2 is a product of repeated shear movement along the zone. The deformation has resulted in the frequent occurrence of mylonites and cataclastic rocks. A high frequency of fractures in Zone 2 are sealed.

The fracture frequency is generally low within Zone 2, except for two or three fractured sections in each borehole. These sections are narrow, 2-30 m wide (often 2-5 m wide) and are mainly located at the upper and lower boundaries of the zone. The hydraulically conductive parts of these sections are even more narrow, in some boreholes the widths of these parts are in the order of 0.5-1 m. Narrow fractured parts in the central part of the zone also occur in some boreholes. Late reactivation of Zone 2 seems to occur preferentially along the upper boundary of the zone. The average fracture frequency for Zone 2 is 5 fr/m.

Other fracture zones, located within the interior part of the Finnsjön site are less obvious as lineaments or in the drill cores. Although, much remains to be done regarding interpretation of fracture zones, especially in the southern part of the site. According to the present interpretation, characteristic for the interior parts of the site are minor N60W shear zones dipping of 60^0 and occurring at regular intervals with spacings of 40-400 m.

Uncertainties: The general control of the geologic conditions of the northern block is far better known compared to the southern block, due to the detailed studies that has been conducted within the Fracture Zone Project. This difference also implies a general higher reliability of interpreted fracture zones in the northern block compared to the southern block.

Apart from this general difference in reliability between the two blocks, the only zones that can be regarded as well established, with respect to location and character, are Zone 1 and Zone 2 (in areas where these zones are intersected by boreholes). Other interpreted fracture zones must be regarded as more or less uncertain. For zones interpreted from lineaments, there are normally no information regarding degree of fracturing nor the dip and even if a single borehole intersects a zone there might be several alternative interpretations regarding its orientation. Thus, the lack of borehole data implies that many of interpreted fracture zones, especially in the southern block and outside the Finnsjön site, should be regarded as tentative.

Hydrology

A (semi)regional area in the order of 100 km^2 bounded by major lineaments was defined prior to the geohydraulical modelling. The groundwater level in this area ranges from about 46 and 38 m (above sea level) in the southwest and the southeast, respectively, to about 12 m in the northeast. The regional shallow groundwater flow is mainly directed towards north and northeast.

The Imundbo fracture zone is a presumed major discharge area. Local, minor discharge areas are found in low-lying parts within the area. A regional geohydraulical domain was subsequently defined within this area.

Within the Finnsjön rock block the elevation of the shallow groundwater table ranges from about 33 m to 22 m. The shallow groundwater flow is directed from the local elevation in the central part in all directions with the main flow directed towards northeast. Outside the local area discharge areas (swamps) are found in low-lying parts in northeast.

Uncertainties: The regional groundwater table map was largely based on topographical maps with some adjustments and must therefore be regarded as uncertain. This map was utilized in defining the upper boundary condition of the regional geohydraulical model.

Hydraulic units

The hydraulic units included in the regional, deterministic geohydraulic model were 1., the rock mass (excluding all fracture zones) and 2., the regional fracture zones bounding the model domain together with the semiregional fracture zones within the model domain. In addition, a generic subhorizontal zone located below Zone 2 was included in a few cases. In the local, stochastic model the fracture zones were included as trends in the reference case.

Uncertainties: The interpretation and conceptualization of the fracture zones is uncertain both in the regional and local models.

Hydraulic conductivity

Due to lack of data on a larger scale, the hydraulic conductivity versus depth functions applied to the rock mass and fracture zones in the regional and local model were based on data from boreholes within the Finnsjön rock block.

The hydraulic conductivity of the rock mass, calculated from statistical analysis (regularization) of data from 2 m and 3 m sections to 36 m sections, is significantly higher than those calculated from other study sites. The applied hydraulic conductivity function of the rock mass was about 10^{-9} m/s at 500-600 m depth. This is 40-50 times higher than the corresponding value of Fjällveden, Gideå and Svartboberget and about 80 times higher than that of Kamlunge.

The number of measurements in fracture zones are limited but available data also suggest an increased hydraulic conductivity compared to other sites. The applied hydraulic conductivity functions to the subvertical fracture zones in the regional modelling correspond to hydraulic conductivities of about $1\text{-}3 \cdot 10^{-7}$ m/s at 500-600 m depth. The applied hydraulic conductivity of Zone 2 ranges from about $1\text{-}5 \cdot 10^{-6}$ m/s in the regional model, whereas the applied hydraulic conductivity of the generic, subhorizontal zone was about 10^{-7} m/s at 800 m depth.

The conductive fracture frequency in Zone 2, in the rock mass above and below the zone, was estimated to about 0.90-1.15 fr/m, 0.47-1.44 fr/m and 0.56-0.76 fr/m, respectively, based on 2 m and 3 m sections in selected boreholes.

Uncertainties: The applied hydraulic conductivity functions versus depth for both the rock mass and fracture zones in the regional and local model are uncertain, partly due to uncertainties in the geological interpretation and partly due to the analysis technique based on regression analysis. For most of the fracture zones (except Zone 2) few or no data are available.

An alternative interpretation of the hydraulic conductivity data, both in the rock mass and fracture zones, is that the upper 100-200 m of the bedrock has higher conductivity than the deeper bedrock and that no significant depth trend exists in neither upper or lower parts of the bedrock.

Groundwater flow rates at repository depth

Consistent results were obtained from the regional and local models regarding the calculated fluxes at the repository depth (600 m). Fluxes of about 0.001 m^3/m^2/year were calculated in the rock mass with a significant increase in the vicinity of fracture zones. This value is considerably higher than those calculated from other study sites, e.g. Fjällveden, Gideå and Kamlunge. This is a result of the high hydraulic conductivity applied for the rock mass and fracture zones measured at Finnsjön.

The groundwater flow calculations were made without any consideration regarding the occurrence of saline groundwater below the upper boundary of Zone 2. Some scooping calculations were however made. These showed that the saline water would strongly decrease the groundwater flow below the non-saline/saline interface (which is also suggested by in situ flow measurements). However, since the long-time stability of this situation could not be proven it was decided to model the site and the surrounding region assuming non-saline groundwater throughout the modelled domain.

Uncertainties: The above mentioned uncertainties in the conceptual geological models, the hydraulic properties of the hydraulic units and the assumption of non-saline groundwater at depth, implies a corresponding uncertainty in the calculated groundwater flow rates. Also the applied lateral and upper boundary conditions are uncertain.

Solute transport

There are a number of different solute transport models applied to Finnsjön data. However, most of the models have been applied to tracer tests performed in artificial flow regimes, and they have not or can not be transferred to predicting the transport from a repository at 600 m depth. However, within the SKB 91 study, both a deterministic and a stochastic continuum model has been used to describe the flow field and travel times from a repository. Travel times are determined to vary between ten and ten thousands of years. The most important factors that affect the travel times and flow pattern at the site are; the conductivity contrast between fracture zones and rock mass, the location and connectivity of fracture zones, the magnitude and direction of the local and regional gradient, and the presence of saline water. Low angle fracture zones, like Zone 2, have been found to be particularly important for flow and transport at the Finnsjön site.

Uncertainties: The boundary conditions are of great importance for the solute transport. Only a few variations of the boundary conditions for the deterministic model has been made and no variations for the stochastic model. Also, the existence, location and connectivity of fracture zones are important for the solute transport. These factors have not been varied to any large extent in the Finnsjön models. The magnitude and direction of the natural gradient is also important in a flat topography area like Finnsjön. This was shown by the deterministic modelling but no variations were made in the stochastic modelling. Lastly, to determine the actual fluid velocity through the Finnsjön site, knowledge of the flow porosity is important and only a few data exist from fracture zones at the site.

Groundwater chemistry

Groundwater sampling for chemical analyses have intermittently been carried out in 19 boreholes over a period of 12 years. During this time the sampling techniques and the chemical analyses have developed significantly. Also the number of investigated parameters have been increased.

The main types of groundwaters can be distinguished, one old saline and one younger non-saline type. Samples taken below Zone 2, represents the deep old groundwater, which is of reducing character and with high chloride content. Non-saline groundwater are found above Zone 2 and in the southern block down to the maximum borehole depth.

Uncertainties: Only five of the sampled boreholes were considered representative for the depth sampled. With the exception of borehole KFI08, located at the eastern boundary of the site, all "representative" boreholes are located in the northern block. The groundwater chemistry conditions in the southern block are therefore uncertain.

Rock mechanics

Stress measurements using hydraulic fracturing technique have been carried out in borehole KFI06 down to 500 m depth. The results showed normal conditions for Sweden regarding stress magnitudes and stress orientations. No obvious stress anomalies was associated with Zone 2. Rock mechanical tests on core samples from three depths in borehole KFI01 also reports normal conditions, indicating a "average quality designation" for the intact rock.. A special study of Zone 2 indicate a deformation modulus of no less than 25 GPa for the complete zone.

Taking into account the state of stress and the mechanical properties of the rock mass and fracture zones at Finnsjön, there should not be any stability problems in the construction of a repository at 600 m depth.

Distinct element modelling of the rock mass response to glaciation have also been made. This study indicate that reactivation of existing fracture zones are likely to occur and that any repository should be located at least 100 m from fracture zones.

1.2 Suggestions for complementary studies

Conceptual geologic models

The distribution of rock types at the Finnsjön site and its surroundings is well known and there is no need for any complementary studies. The opposite applies for the distribution of fracture zones. The present model of fracture zones should be regarded as tentative and should be thoroughly tested with trenches, boreholes and borehole measurements. In particular, this should be made for fracture zones interpreted from lineament studies only.

Also, existing drill cores could be used to a greater extent to improve the reliability of interpreted zones, including their location, extension and hydraulic properties and depth dependence. It should also be noted that further work on detailed correlation between surface and borehole, or between boreholes, would probably identify additional fracture zones. Since the occurrence of subhorizontal fracture zones is of great importance for the performance of a repository, the possible existence of additional such zones should be investigated.

Conceptual geohydrological models and data sampling

The regional distribution of saline groundwater should be further studied, possibly by drilling one borehole in the farmland area covered by clay to the east of the Finnsjön rock block and deepening one borehole in the Finnsjön southern block. By determining groundwater flow and chemistry in these and other boreholes, in situ data will be available to calibrate and/or validate groundwater flow models. In parallel, modelling studies should be made on the rate of exchange of saline water to non-saline water due to the land uplift/sea level changes, as well as the possible influence of regional flow on the deep groundwater.

Groundwater chemical conditions

As discussed above there is a need to map the extent of the saline groundwater and to quantify the amount of regional groundwater flow at various locations and depths. To resolve these questions additional groundwater sampling is needed, especially in new boreholes in the southern Finnsjön block where reliable chemical data is more or less lacking. Chemical sampling will also be important if new boreholes are drilled outside the site, as discussed above. The new sampling rounds should be designed to meet three objectives; 1.) to characterize the groundwater chemistry at depth, 2.) to assist in the interpretation of regional hydrology, and 3.) to assist in the interpretation of local hydrology.

Although the available chemistry data at Finnsjön has been evaluated thoroughly, at the time of writing the most evaluated test site in Sweden, it is possible to gain some further hints about hydrological conditions by complementary evaluation of existing data. One attempt to compare the general chemistry characteristics of the different sections for all the boreholes would show to what extent the sampled sections can be categorized into distinct groups, and thereby possibly provide clues that can be used to interpret the geohydrology. It is possible that such additional analysis would help in the interpretation of where local or regional flow conditions prevails.

The groundwater flow model within the area could be used to investigate the possible connection between the Zone 2 and Lake Finnsjön. Natural tracers such as organic material could be used to study the potential link between the two water systems.

Solute transport

To improve knowledge of transport at the Finnsjön site, the following factors would be most important; 1.) investigation of the deep groundwater system (what boundary conditions would be appropriate for a local site model predicting flow and transport?), 2.) investigation of connectivity, transmissivity, and extension of fracture zones close to the repository area as well as close to regional zones, and 3.) investigation of the lateral extension of the saline water below Zone 2. Once these facts are established, the point of next greatest importance would be determination of hydraulic conductivity distribution including possible depth dependence.

Sorption coefficients, including estimates of surface available for sorption, and reaction coefficients, are of next greatest importance to improving knowledge of nuclide transport in both the conductive fractures and in bedrock blocks. In-situ tests to determine effective sorption coefficients, effective area and importance of matrix diffusion should be carried out.

Of least importance to a safety analysis is knowledge of pure parameters of transport, the flow porosity and the dispersivity, which only change the timing of nuclide mass arrival in the biosphere. Uncertainty in these parameters would likely be overshadowed by uncertainties in the boundary conditions, structures, conductivity distribution and sorptivity of nuclides.

Rock Mechanics

The rock stresses have only been measured down to 500 m below surface. It might be suggested to investigate the stress state from 500 m depth down to the bottom of borehole KFI06 at 700 m. Furthermore it is recommended to determine the thermal properties (conductivity, diffusivity and specific heat).

2. BACKGROUND

2.1 Objectives

Geological investigations of study sites in the Swedish programme for disposal of spent nuclear fuel has until 1990 involved a total of 14 sites. For some of these sites, investigations has been limited to surface studies and/or only one deep borehole. Relatively extensive investigations have been carried out at eight sites. The investigations in these later sites have involved an extensive programme of surface geophysical surveys and geological mapping and several deep boreholes down to 700-1000 m depth.

Over the years the scope of investigations at the study sites has gradually extended due to a steady increasing demand of data for performance assessments. The amount of data available from the later investigated sites are therefore greater compared to the earlier sites.

2.2 Selection of the Finnsjön study site

The Finnsjön study site was selected in 1977 to provide input to the KBS-1 performance assessment. The time-constraint of this assessment made it necessary to select easy assessable sites, preferable located close to existing power stations. Such a location was also recommended in an earlier report to the government (Aka utredningen, 1976).

The first reconnaissance borehole was drilled close to the Forsmark nuclear power station. However, because of unfavourable rock conditions in this borehole, the investigation area was moved 15 km eastwards to a large, well exposed and homogenous rock block, later named the Finnsjön rock block.

The first main period of site investigations at Finnsjön took place between 1977 and 1979. The results are summarized in the KBS-1 and KBS-2 reports (SKBF, 1977 and 1978). The investigations were a result of the "Stipulation Act" which, among else, demanded the reactor owners to demonstrate how and where an "absolutely safe" final storage of high level waste and/or spent nuclear fuel can be effected. During the early parts of the KBS-1 studies three deep cored boreholes were drilled down to 500 m depth and tested hydraulically.

The government resolution, concerning the application to fuel two nuclear reactors, required that supplementary geological studies should be carried out to ensure that all provisions of the "Nuclear Power Stipulation Act" were fulfilled.

SKB responded to this demand by drilling four additional boreholes at the Finnsjön study site down to depths of about c. 500 m. Hydraulic tests, were made in all boreholes. For some boreholes also geophysical logging and groundwater sampling were made. Although it was stated in the KBS-1 and 2 reports that the Finnsjön site could be used for a repository, the site was ranked lower than the Sternö site because of "..water-bearing fracture zones ...which must be carefully considered in the design of a rock repository".

2.3 Investigation periods

The Finnsjön site has been studied more or less continuously from 1977 until today. The studies have included site characterizing activities as well as testing new instruments and characterization methods. Ekman (1989) briefly presents all studies before 1989 in the Finnsjön region including scope of work and references. Figure 2 presents a time schedule for the main present and past activities at Finnsjön.

Although main objectives and corresponding activities have changed over the years this report arrange the activities into two main periods:

- Site investigation activities (1977-1983)
- Fracture Zone Project (1985-1992)

The site investigation activities includes two main studies. The first concerned the KBS-1 and 2 studies. This investigation included 7 cored boreholes, down to 700 m depth, and extensive borehole geophysical, geochemical and hydraulic measurements. The second study was performed during 1979-1983 with the main purpose to study the water balance of a local drainage area and particular the groundwater recharge in different subareas within the drainage area. This study involved extensive surface mapping and drilling of one cored borehole and several shallow percussion boreholes. Main results is reported in Carlsson and Gidlund (1983).

During 1985, the Fracture Zone Project started, a detailed study concerning the geologic, hydraulic and geochemical characteristics of a gently dipping fracture zone in the northern part of the site. This study has included some ancillary surface bedrock mapping, including some geophysical surveys, but the main scope of work concerned borehole studies. Three cored boreholes and three percussion boreholes were drilled. Subsequent borehole surveys involved geological, geophysical, hydrological and geochemical characterization. Main results are reported in Ahlbom and Smellie (eds, 1989).

During 1989-1991 a major safety assessment, SKB 91, were made on data from the Finnsjön site. This assessment involved a large number of studies in where data were compiled and evaluated. Based on these studies hydraulic modelling, using both deterministic and stochastic approaches, were made. Main results are presented in the SKB 91 report. All studies were made on existing data and therefore no additional field activities was made.

The only study presently on-going at Finnsjön concerns a programme for monitoring groundwater nuclide transport from the Chernobyl fallout.

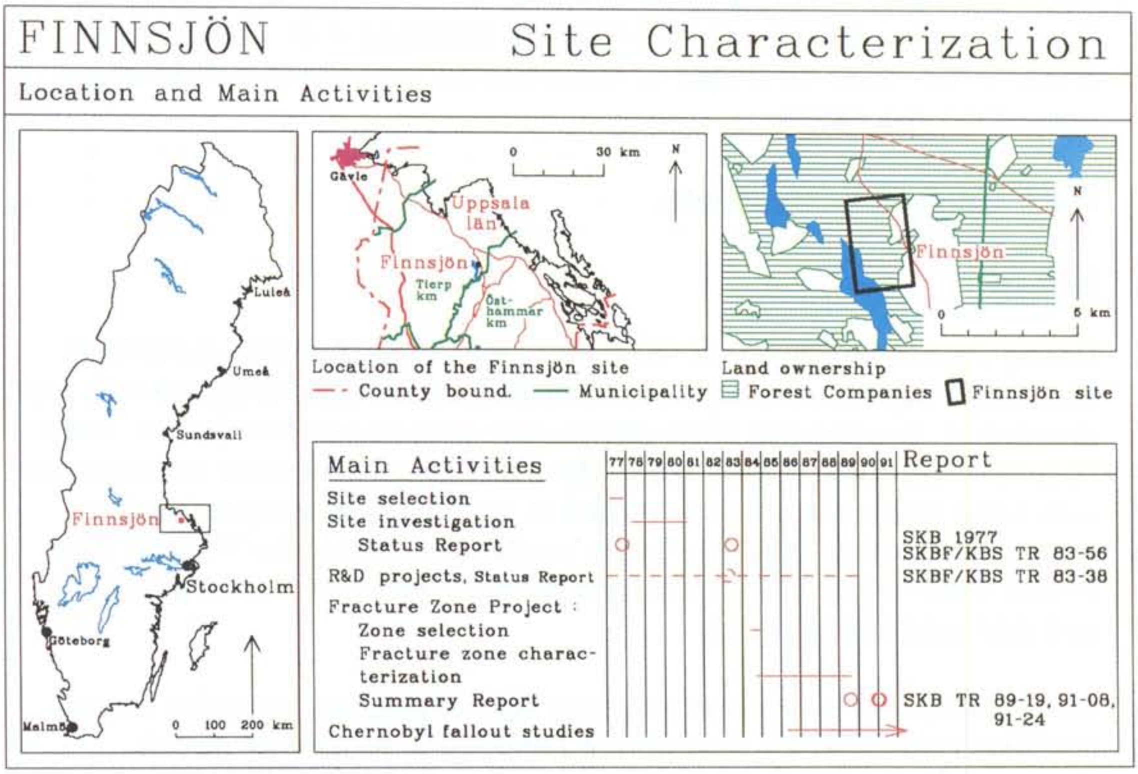


Figure 2. Location of the Finnsjön study site. Administrative borders and land ownership are shown. Site investigation refers to the KBS-1 and KBS-2 studies and the subsequent water balance studies.

3. SCOPE OF ACTIVITIES

3.1 Reconnaissance

The Finnsjön study site was selected because of its geological characteristics (large homogenous and well exposed rock block) in combination with its favourable location close to a nuclear power plant. However, there is no report describing the reconnaissance activities involved in the selection of the Finnsjön study site, although it is stated in Scherman et al. (1978) that the selection was based on studies of topographical, economical and geological maps and aerial photos.

3.2 Surface investigations

General

During the site investigations 1977-1983 maps were produced showing the Quaternary deposits, drainage basins, hydrobotanical conditions and rock type distribution. Satellite and aerial photos were used to interpret fracture zones both on a regional and local scale. The hydrological conditions in connection with some fracture zones were studied in more detailed using refraction seismic and shallow boreholes in the overburden. During the Fracture Zone Project some additional detailed mapping were made concerning geological and tectonical characteristics.

Areas covered by the various mappings and compilations of earlier studies, including references, are presented in Figures 3 to 8. Activity periods showing when studies were made are presented in Figures 9 to 12.

Geological mapping

The Finnsjön studies have not involved any mapping of the rock type distribution in the regional scale. Instead available maps have been used, e.g. Söderholm et al. (1983) in the scale 1:250 000, for the north Uppland region, and Stålhös (1988, 1991) in the scale 1:50 000 for the region surrounding the Finnsjön study site.

Generalized maps of the rock type distribution of the Finnsjön site, including its closest surroundings, are presented in Scherman (1978) and in Almén et al. (1978). The results from a more detailed study, in where all outcrops were mapped, is presented in Olkiewicz and Arnefors (1981) and in Carlsson and Gidlund (1983). During the Fracture Zone Project detailed geologic bedrock mapping were made in the northern part of the Finnsjön site, Ahlbom et al. (1988). Areas covered by the various maps are shown in Figure 3.

Fractures

A scan-line fracture survey was made on 73 outcrops in two orthogonal profiles (Figure 3). The survey was made as a part of a programme for testing investigation techniques for site investigations. The results are therefore preliminary in nature. The results is published in Olkiewicz and Arnefors (1981).

As a part of the Fracture Zone Project comprehensive fracture surveys was made in the northern part of the site (Tirén 1989). These surveys included mapping of prominent fractures in a ca 2 km^2 large area, as well as a detailed survey of all fractures in a 90 m x 5 m area, in where all soil was removed.

Variations in directions of paleostresses have been determined by analysing fracture configurations (Munier and Tirén 1989). Summaries of fracture studies at Finnsjön are presented in Ahlbom and Tirén (1991) and in Andersson et al. (1991).

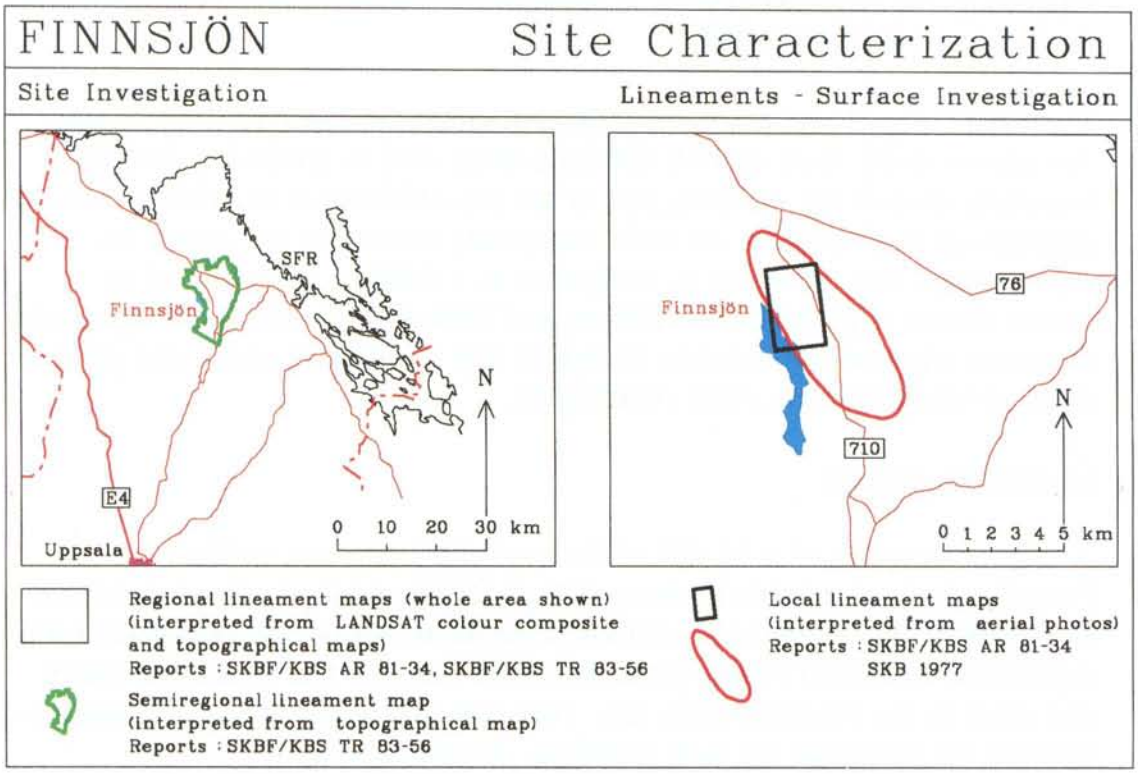


Figure 3. Left, extent of bedrock and fracture mappings made during the site investigation period. Right, extent of bedrock and fracture mappings made during the Fracture Zone Project.

Lineament analyses

Since 1977 several lineament interpretations and tectonical analyses have been made of the northern Uppland region, including the Finnsjön study site (Figures 4 and 5). Lineament interpretation of northern Uppland in the scale of 1:250 000 using satellite images is presented in Olkiewicz (1981). A somewhat modified version of this map is presented in Carlsson and Gidlund (1983). A description of the regional tectonic setting is presented in Ahlbom et al. (1988). This study describes the geologic history of the region and presents regional lineament maps in different scales interpreted from topographical relief and contoured maps. Some results of the latter study are presented in the summary report by Ahlbom and Tirén (1991).

There has also been several local lineament maps published for the Finnsjön site and its surroundings. The first was made in connection with the KBS-1 and 2 investigations (Olkiewicz et al., 1979). A more detailed lineament map in the scale of 1:20 000, based on air-photo interpretation, was presented in Olkiewicz and Arnefors (1981). A generalized lineament map is presented in Carlsson and Gidlund (1983).

Lineament maps have also been produced within the Fracture Zone Project. Air-photos in the scale of 1:10 000 have been used to produce a detailed lineament map of the northern part of the site (Ahlbom et al., 1986). A more generalized map showing the main lineaments within the site and in its surroundings was presented in Ahlbom et al. (1988). A summary of all earlier studies is presented in Ahlbom and Tirén (1991). The latter report also discusses relationships between lineament sets in different scales and presents maps showing different order rock blocks.

Quaternary geology

A map in the scale of 1:25 000 of the quaternary deposits within the Finnsjön study site and in its surroundings (Figure 6) is presented in Almén et al. (1978). This report also discusses the ice-recession and post-glacial sea regression. Jacobsson (1980) presents results from 57 soil soundings within and close to the Finnsjön study site. Type and width of deposits and depth to bedrock are presented for each sounding. A summary of all previous quaternary studies is presented in Gidlund and Carlsson (1983). Ahlbom (1991) discusses the postglacial sea that covered the Finnsjön site until c. 3 000-5 000 years ago and its influence on the occurrence of deep saline groundwaters at the Finnsjön site.

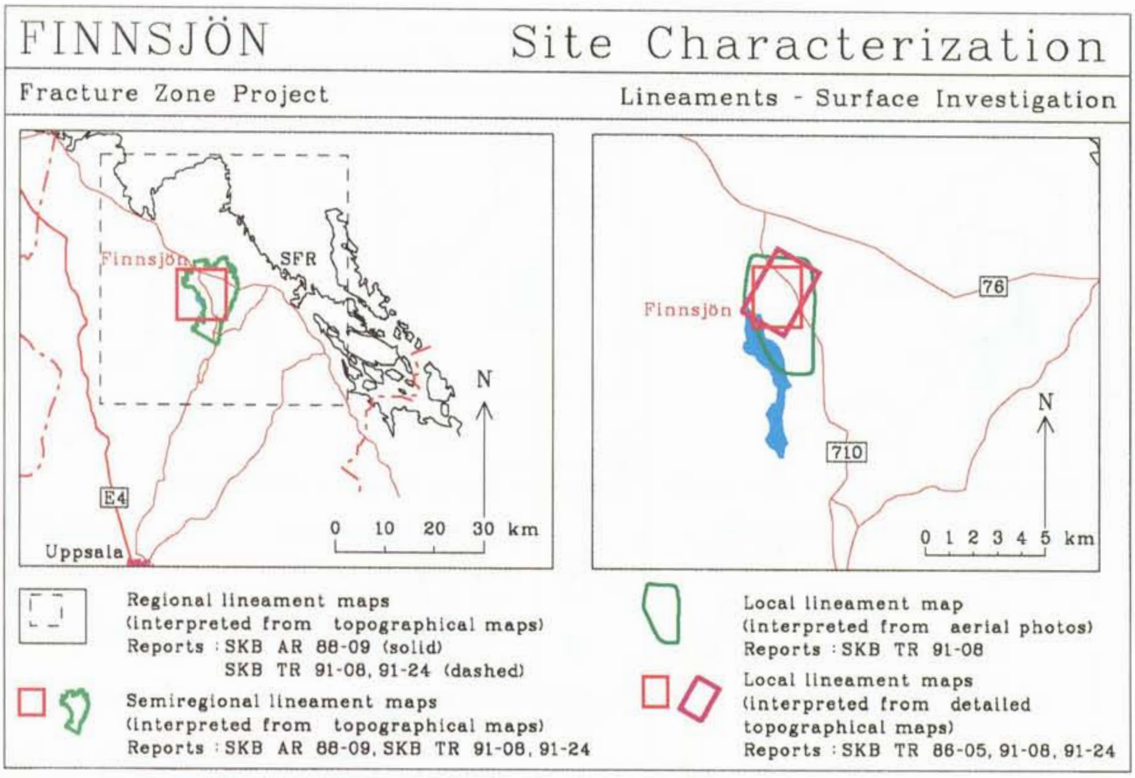


Figure 4. Extent of areas for regional and local lineament analyses during the site investigation period (1977-1983).

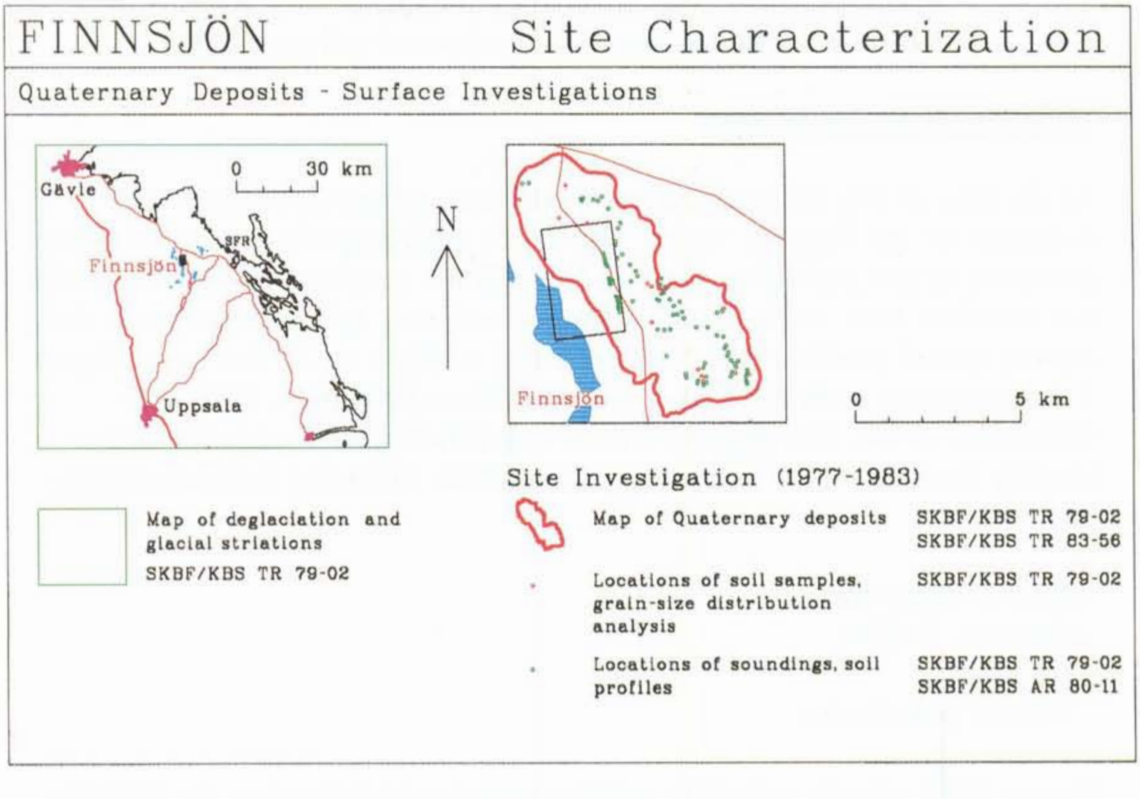


Figure 5. Extent of areas for regional and local lineament analyses during the Fracture Zone Project (1985-1991).

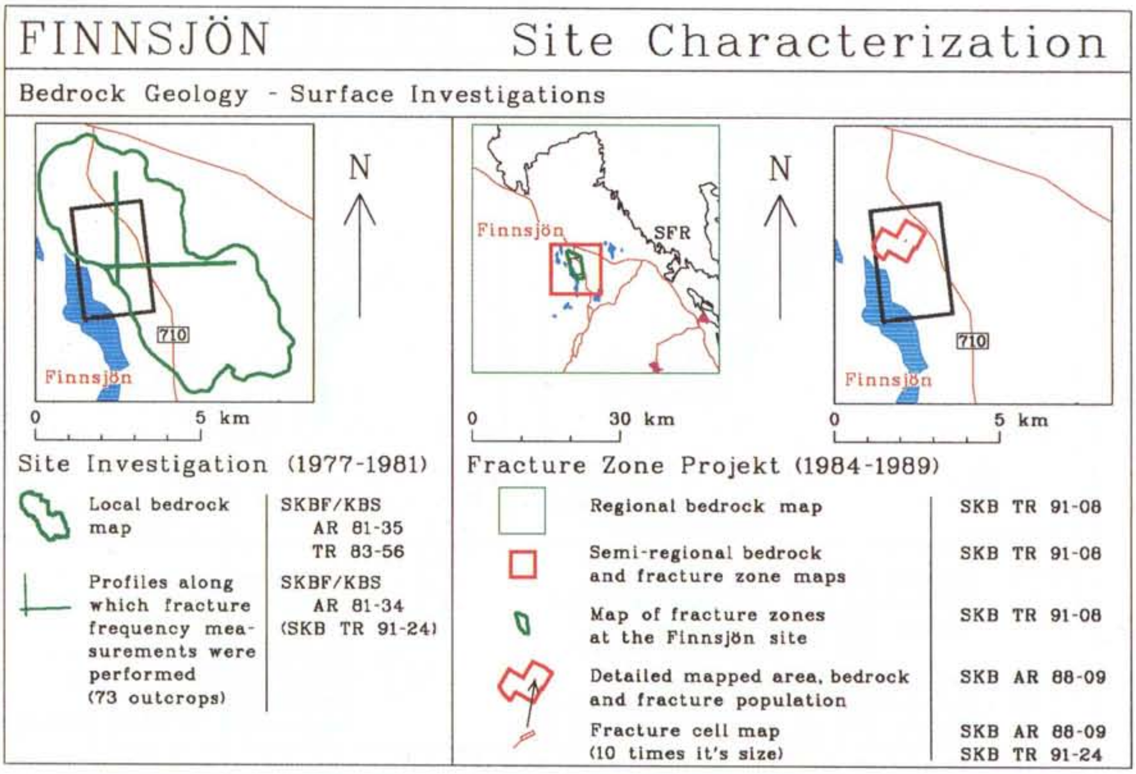


Figure 6. Left, extent of regional map of ice-sheet recession and glacial striations. Right, area covered by the Quaternary deposits map, location of soil samples and locations of soil soundings.

Geophysical surface surveys

At the time of site characterization no airborne geophysical data were available for the Finnsjön region. (However, such maps have recently been produced by the geological survey). No regional geophysical characterization has therefore been made. Detailed studies involving grid measurements along closely spaced profiles were however made within a ca 2.5 km^2 area, Figure 7, in connection with the KBS-1 and -2 studies (Scherman, 1978 and Olkiewicz, 1979). The purpose was to map lithological boundaries and to identify fracture zones. The survey included the following methods (Figure 7):

- protonmagnetometer
- slingram 18 Khz
- resistivity
- induced polarization

During 1979 seismic refraction profiles were conducted across the Brändan fracture zone (Zone 1). This zone was further geophysically surveyed in connection with the Fracture Zone Project, involving 10 slingram and VLF profiles. Locations of profiles and references are presented in Figure 7.

Over the years there has also been several geophysical surveys to study the potential of various methods for site characterization in general. These supplementary surveys included the following (see Figures 7 and 12):

- applicability of mise-à-la-masse measurements (cross-hole and hole-surface electrical method) in site characterization (Jämtlid et al., 1981),
- applicability of radon, methane and helium gas monitoring in the overburden above a fracture zone for studies regarding gas transport in fracture zones (Lindén et al., 1987),
- seismological monitoring using mobile stations (Holmqvist, 1987),
- applicability of reflection seismic surveys for detecting subhorizontal fracture zones (Dahl-Jensen and Lindgren, 1987).

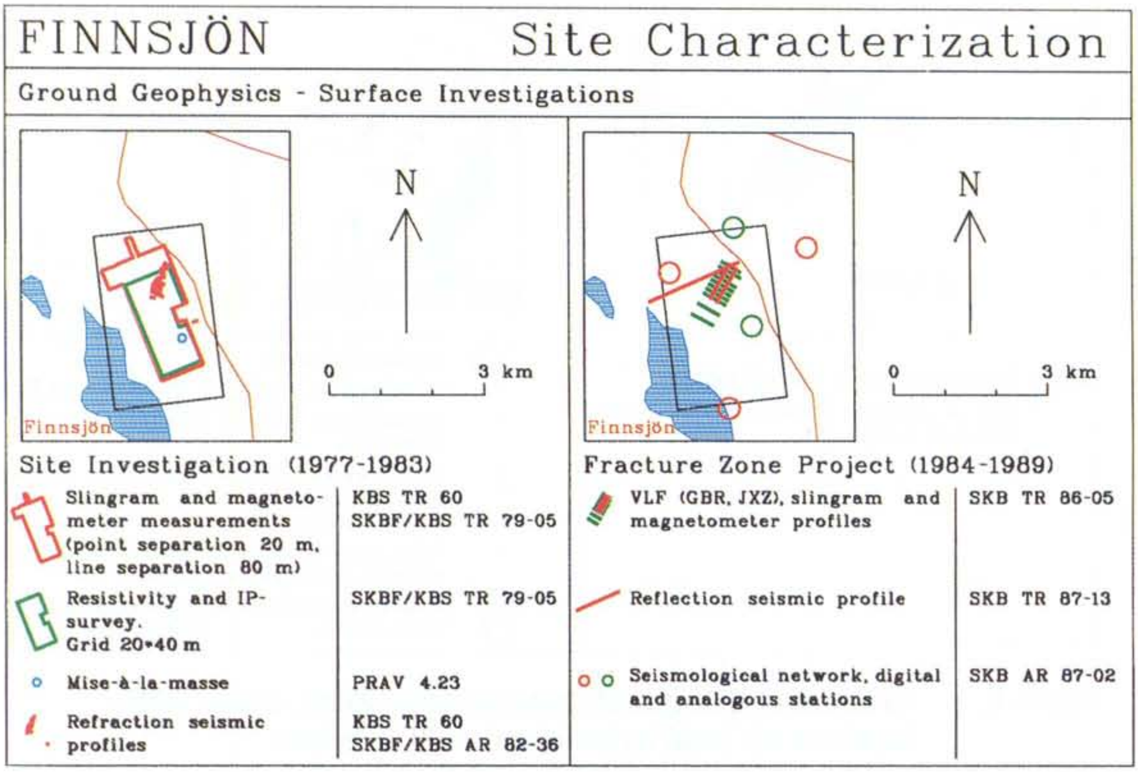


Figure 7. Left, extent of geophysical surveys made during the site investigation period. Right, extent of geophysical surveys made during the Fracture Zone Project.

Hydrology

The surface hydrological part of the water balance studies, 1979-1983, included the following activities:

- a well survey, including chemical sampling (Jacobsson, 1980),
- mapping of local drainage system (Jacobsson and Larsson, 1980),
- hydrobotanical mapping of discharge areas (Svensson 1981),
- stations for meterologic monitoring (Larsson and Svensson, 1980),
- stations for run-off measurements (unpublished).

The results are summarized, evaluated and discussed in Carlsson and Gidlund (1983). This report also includes a map of regional drainage basins and regional hydrometerological data. Areas covered by the various mappings and compilations including references are presented in Figure 8.

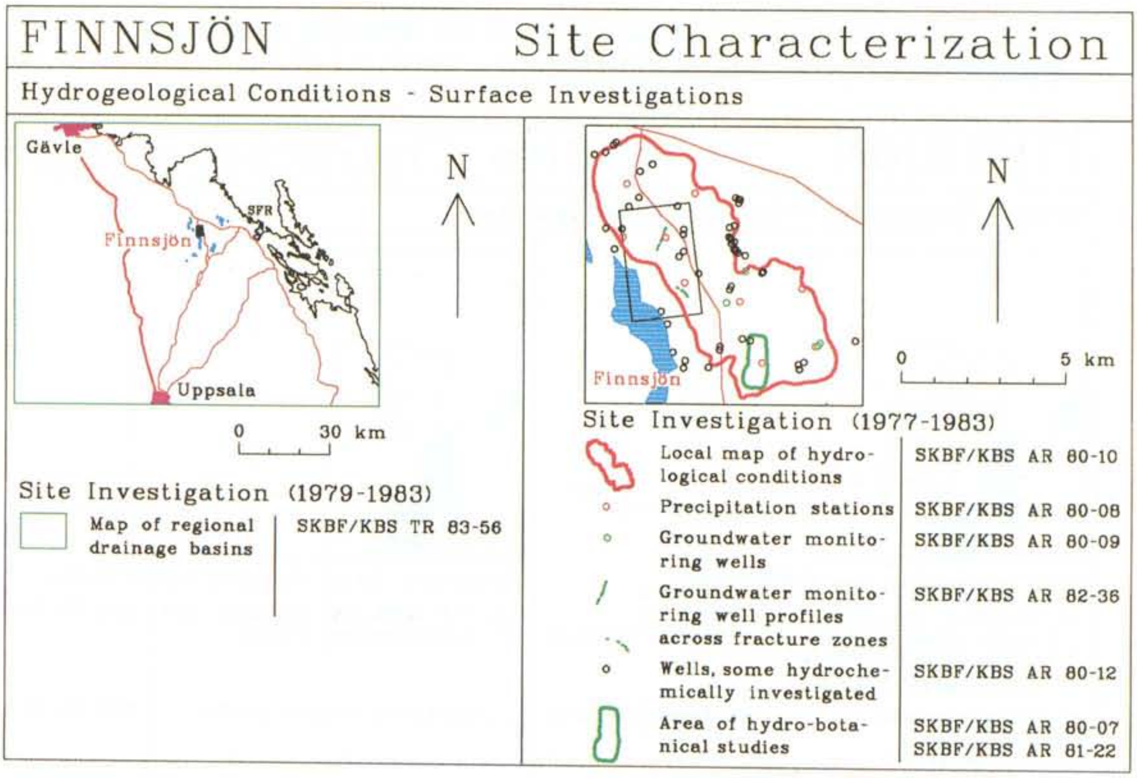


Figure 8. Left, extent of regional drainage map. Right, extent and/or locations for local hydrological field activities.

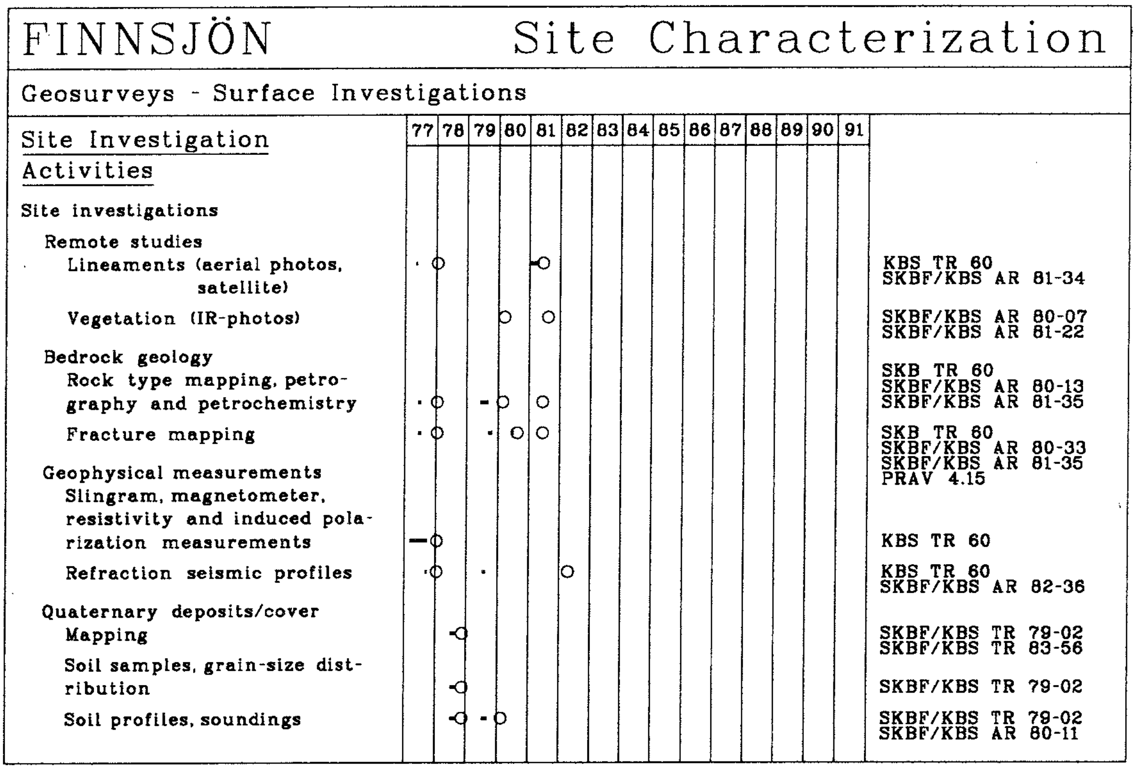


Figure 9. Activity periods - geological and geophysical surface mappings during the site investigation phase.

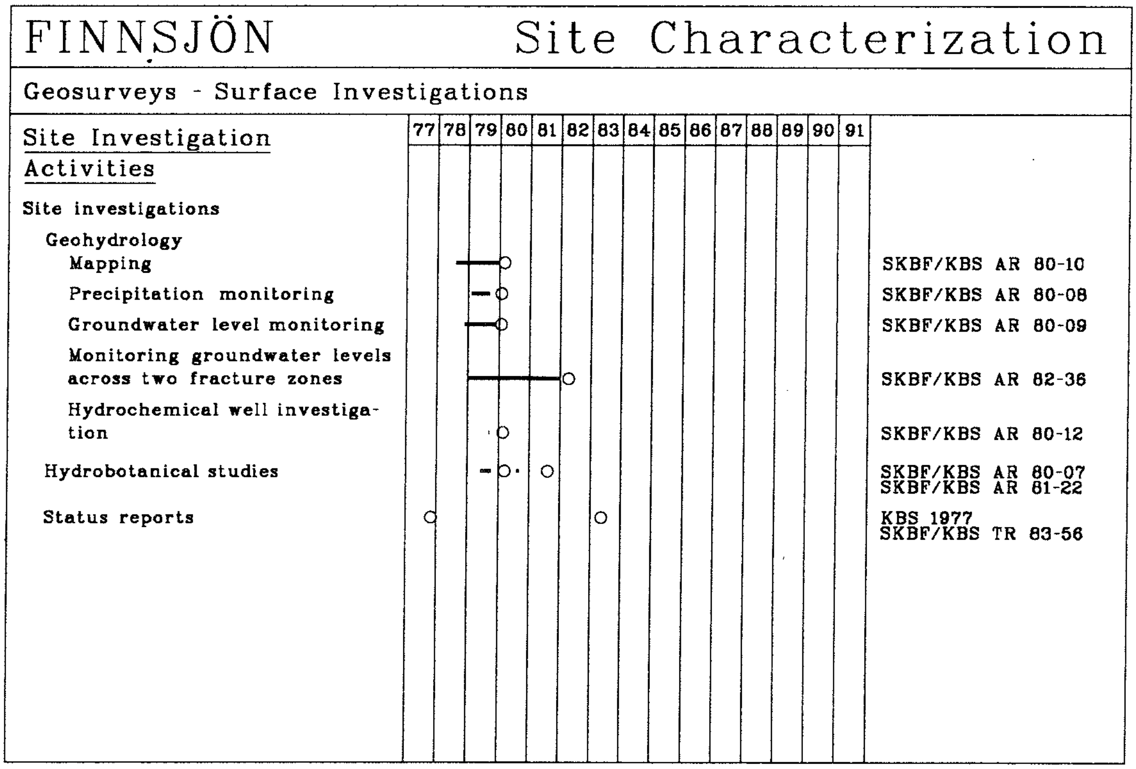


Figure 10. Activity periods - geohydrological and hydrobotanical studies during the site investigation phase.

FINNSJÖN Site Characterization

Geosurveys - Surface Investigation Fracture Zone Project

Fracture Zone Project Activities	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	
Selection of a fracture zone																
Reported									○							SKBF/KBS AR 85-05
Established stake system									·							
Remote studies (detailed and ordinary topographical maps)																
Lineaments																
Reported										○	○		○ ○		○	SKB TR 86-05 SKB AR 88-09 SKB AR 89-08 SKB AR 89-24 SKB TR 91-08 SKB TR 91-24
Geophysical profile measurements																
Slingram, VLF (GBR, JXZ) and magnetometer									·							
Reported										○						SKB TR 86-05
Shallow drilling profile, cored boreholes across covered fracture zone																
Reported										○						SKB TR 86-05
Bedrock geology																
Structural mapping									-							
Reported											○					SKB AR 88-09
Fracture cell and scan-line mapping				-					·							
Reported											○		○		○	SKB AR 88-09 SKB AR 89-24 SKB TR 91-24

Figure 11. Activity periods - geological and geophysical surface surveys during the Fracture Zone Project.

FINNSJÖN Site Characterization

Geosurveys - Surface Investigation

Supplementary Studies 1981 - 1988	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	
Mise-à-la-masse					○											PRAV 4.23
Transport of radon, methane and helium in a fracture zone										-						
Reported											○					SKB AR 87-32
Registration of micro-earthquakes										-						
Reported											○					SKB AR 87-02
Shallow reflection seismic investigation											·					
Reported												○				SKB AR 87-15 SKB AR 87-19 SKB TR 87-13
Paleo-stress interpretations													○			Munier and Tirén Upps. Univ. UUDMP, P.R.59

Figure 12. Activity periods - supplementary studies.

3.3 Percussion boreholes

Contrary to other SKB sites the primary objective with the percussion drillings at Finnsjön have not been to investigate the existence and dip of interpreted fracture zones. Instead they have been drilled for the following purposes; for monitoring the groundwater table, for tracer experiments and to provide flushing groundwater for the core drillings. In addition, some boreholes have been used in hydraulic single or multi borehole tests or for groundwater chemical sampling.

In total there are 18 conventional percussion boreholes and 2 large-diameter percussion boreholes, drilled with the so called booster drilling techniques (Table 1). In addition, some short boreholes were drilled for studying the composition and depth of the overburden and the upper few meters of the bedrock (e.g. Lindén et al., 1987).

The locations of the percussion boreholes are presented in Figure 13 and Table 1 describes some data for each borehole. Activity periods involving the percussion boreholes are shown in Figures 14-17.

17 of the total 20 percussion boreholes were drilled early in the site characterization program and are located in the southeastern part of the site. These holes, named HGB 01-17, have been used for either measuring fluctuations in the groundwater level or for various tracer tests. Results from the latter tests are reported in Klockars and Persson (1978), Gustafsson and Klockars (1981, 1983 and 1984). No data exist from these boreholes on groundwater inflows during drilling nor drilling rates. During 1977 single-hole water injection tests in 2 m sections were made in these boreholes, however only tests in boreholes HGB01-07 have been reported (Klockars and Persson, 1978). This latter report also presents results of an early interference test using the percussion boreholes HGB01-07.

The boreholes HFI01, BF01 and BFI02, drilled within the Fracture Zone Project, are all located in the northern part of the Finnsjön site. They all partly or fully penetrate the subhorizontal Zone 2. These boreholes have been subjected to extensive hydraulical single-hole and interference tests, as well as chemical groundwater sampling. The drilling and sampling activities are reported in Ahlbom et al. (1986), Smellie et al. (1987) and Ekman et al. (1988). A summary of results from hydraulic tests are presented in Andersson et al. (1991). Detailed descriptions of activities in these three boreholes are presented in Appendix A.

According to researchers that have been involved in the Finnsjön site characterization activities all percussion boreholes are probably still open for borehole surveys, with the exception of borehole HGB16, which is blocked by a hydraulic test equipment.

Table 1. Geometric and hydraulic data for percussion boreholes in the Finnsjön study site.

	Length (m)	Diameter (mm)	Incl°/Decl°	Casing (m)	Inflow* (l/h)
HBG01	105	115	60/275	?	?
HBG02	94	115	90/-	?	?
HBG03	99	115	90/-	?	?
HBG04	98	115	90/-	?	?
HBG05	95	115	90/-	?	?
HBG06	95	115	90/-	?	?
HBG07	99	115	90/-	?	?
HBG08	100	115	90/-	3.0	?
HBG09	100	115	90/-	6.0	?
HBG10	97	115	90/-	5.0	?
HBG11	100	115	90/-	3.1	?
HBG12	100	115	90/-	3.0	?
HBG13	100	115	90/-	0.3	?
HBG14	100	115	90/-	1.0	?
HBG15	98	115	90/-	3.0	?
HBG16	100	115	90/-	2.0	?
HBG17	100	115	90/-	?	?
HFI01	129	115	90/-	1.2	20 000
BFI01	459	160-171	90/-	7.9	50 000
BFI02	288	152-183	90/-	4.2	200 000

*estimated total groundwater inflow immediately after stop of drilling.

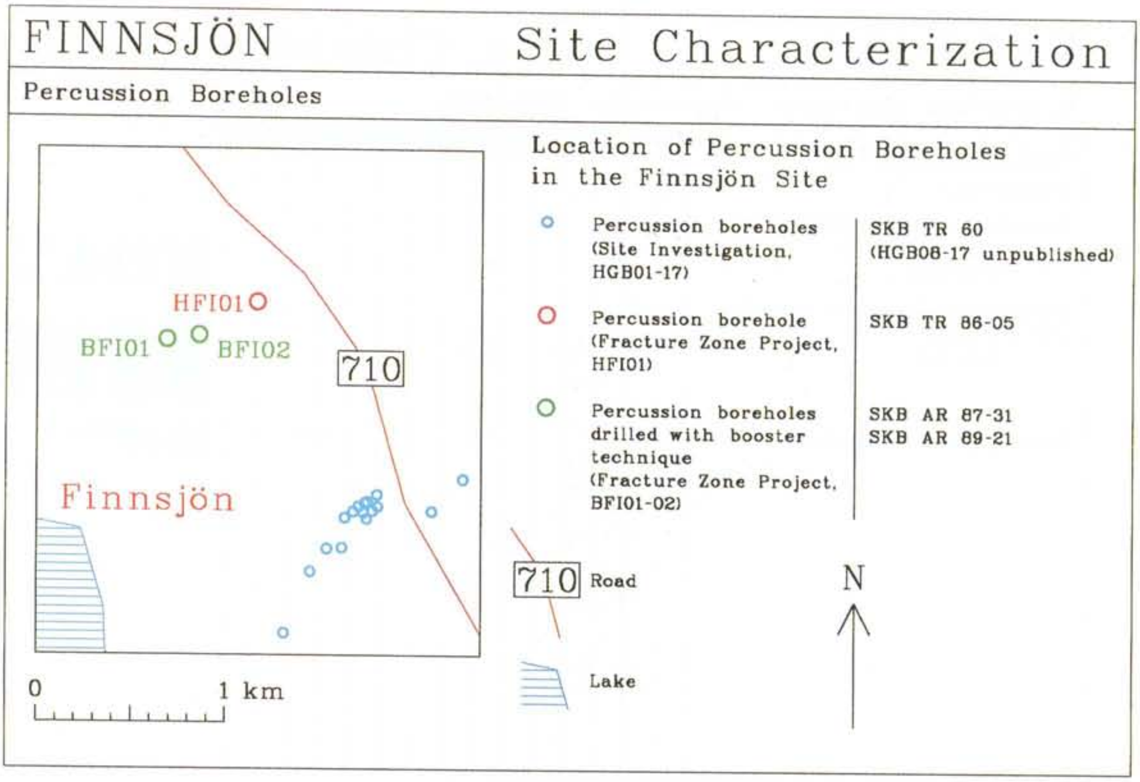


Figure 13. Location of percussion boreholes at Finnsjön.

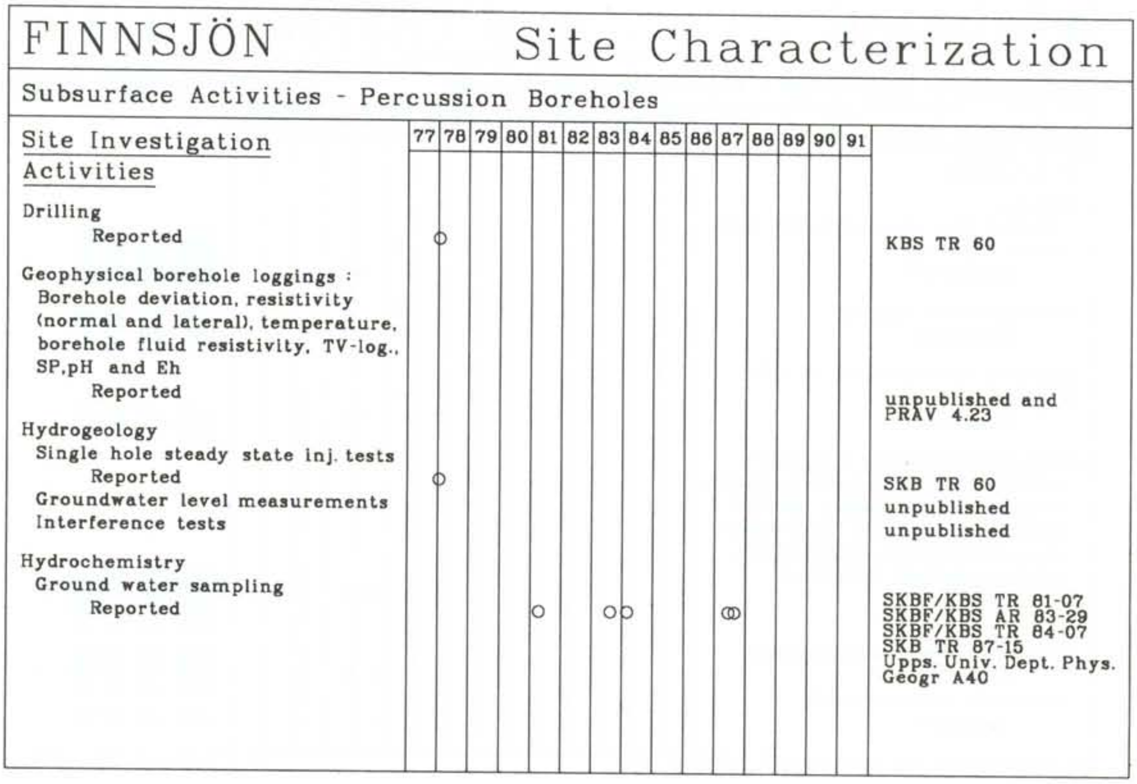


Figure 14. Activities in the percussion boreholes - site investigation.

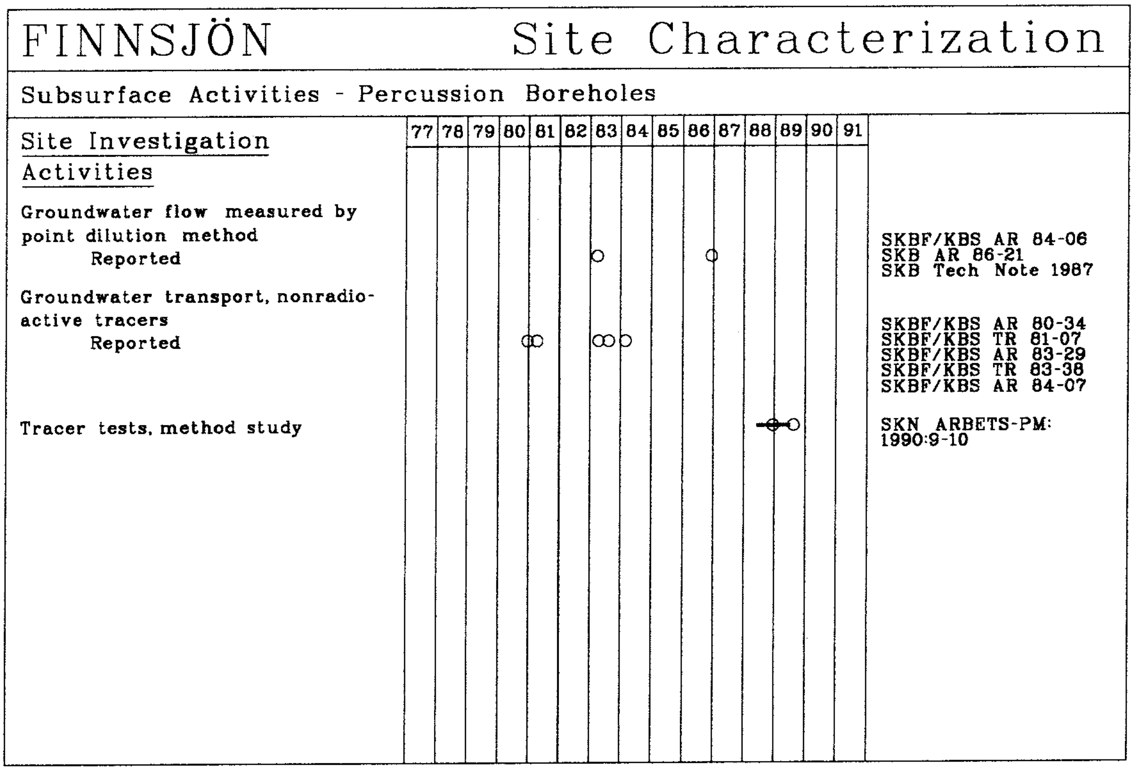


Figure 15. Activities in the percussion boreholes - site investigation, cont.

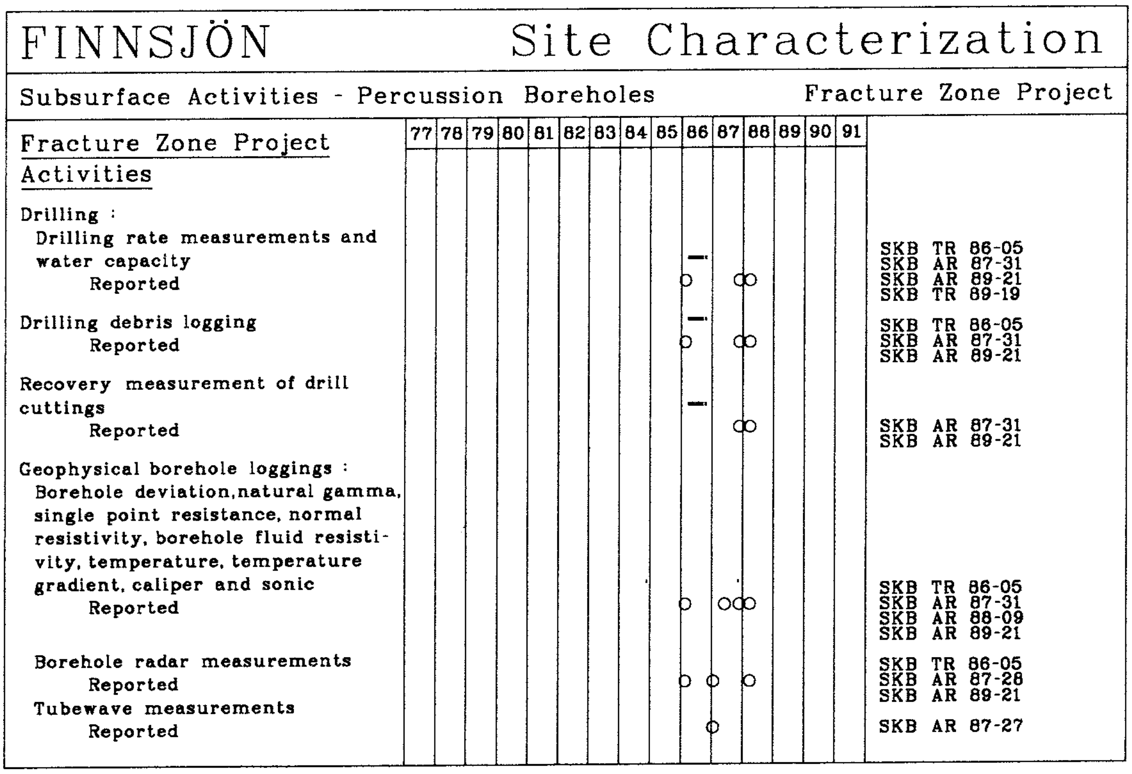


Figure 16. Activities in the percussion boreholes - Fracture Zone Project.

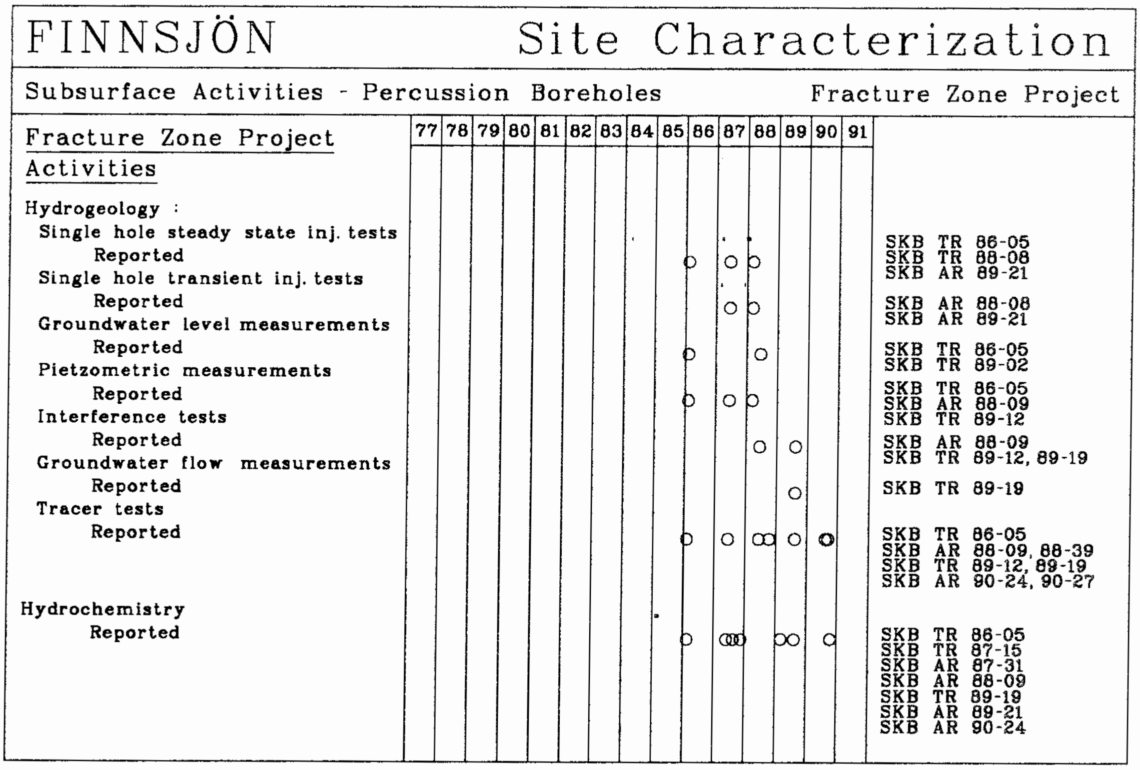


Figure 17. Activities in the percussion boreholes - Fracture Zone Project, cont.

3.4 Cored boreholes

A total number of 11 cored boreholes have been drilled at the Finnsjön site down to a maximum vertical depth of 691 m (Figure 18). Six boreholes are inclined, 50-60 degrees from the horizontal, while the other are more or less vertical. The borehole lengths varies between 255-751 m (Table 2).

The main objectives with boreholes KFI01-KFI07, drilled during the KBS 1 and 2, were to obtain data regarding bedrock conditions at depth, with emphasis on hydraulic characteristics (Scherman 1978, Hult et al. 1978, Olkiewicz et al. 1979, Carlsson et al. 1980). Borehole KFI08 were drilled to provide geometrical and hydraulical data of the Gåvastbo fracture zone for evaluation of tracer tests. Boreholes KFI09-11 were drilled to provide data for the Fracture Zone Project (Ahlbom and Smellie 1991).

Table 2. Cored boreholes at the Finnsjön site. Depth estimates is obtained from borehole deviation surveys for all boreholes except KFI02 and KFI03 where such survyes are missing.

No (KFI)	Dekl° / Dip°		Length (m)	Depth (m)
01	-	90	500.9	500
02	345	50	698.7	535*
03	180	50	730.7	560*
04	50	80	602.9	596
05	296	50	751.5	558
06	-	90	691.4	691
07	335	85	552.7	549
08	75	60	464.4	399
09	106	60	375.8	322
10	276	50	255.6	193
11	-	90	389.9	389

*Calculated from borehole dip at ground surface.

Activity periods in the cored boreholes are shown in Figures 19-23. Detailed break-downs of activities in each borehole are presented in Appendix B.

3.5 Core logging

The drill cores were mapped with respect to rock types, fractures and fracture minerals. However, over the years the level of detail in the mapping has considerable been increased. Also in what way the data is stored have changed.

For example, for the early boreholes, KFI01-07, drilled during 1977-78, fractured sections exceeding 10 fr/m are mapped as "fracture zones" or "crushed zones". There is no quantitative information, such as actual number of fractures per unit length or percentage of crushed material for these sections, nor is there any information regarding fracture intersection angles relative to the core axis. Only drawings are available (Scherman 1978, Olkiewicz et al. 1979). With the exception of some remapped parts, no data from these boreholes are stored in the SKB database.

For boreholes KFI09-11, drilled 1984 and later, the core mapping was made using a computerized system (Almén et al., 1983). The core mapping data, except for descriptions of rock types, was stored on discs and later transferred to SKB database. Detailed print-outs in a scale of roughly 1:40 is available in Ahlbom et al. (1985) for boreholes KFI09 and KFI10. This report also contains some remapped sections of boreholes KFI05 and KFI06. The locations of the remapped sections are shown in Figures B6-B8, Appendix B.

The SKB database of boreholes KFI09-11 and parts of KFI05-07 include data on:

- rock type
- intersection angle between lithological contact and core axis
- type of fracture (sealed, fresh or coated)
- intersection angle between fracture and core axis
- fractured section (more than 10 fr/m)
- crushed section
- core loss
- fracture mineral
- short comment

No print-out regarding the core mapping of borehole KFI08, drilled during 1980, is available because of early termination of a research project. Also, no print-outs of the core logging of KFI11 and remapped parts of KFI07 are available, although data from these boreholes is stored in the SKB database.

Core samples for petrophysical measurements were taken from borehole KFI05 (6 samples between 261-538 m) and KFI08 (14 samples between 115-322 m). The results are reported in Jämtlid and Tullborg (1982) and Öqvist and Jämtlid (1984). The samples were measured with respect to:

- density
- porosity
- resistivity
- induced polarization

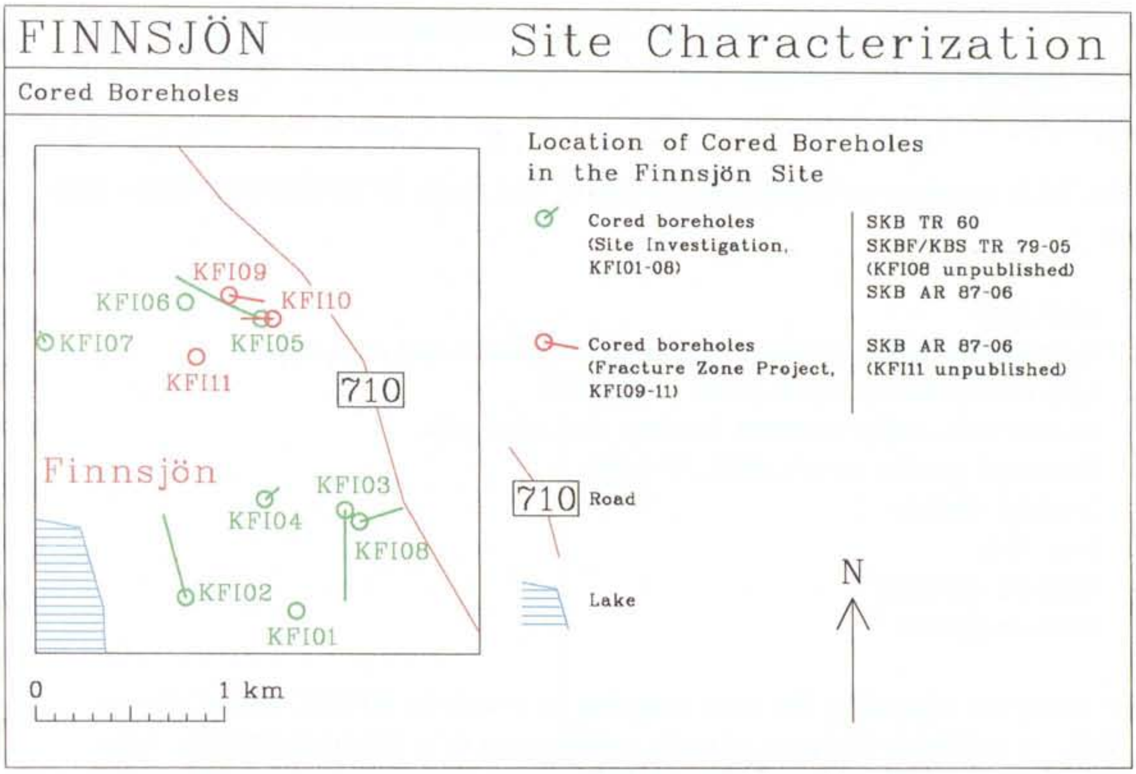


Figure 18. Location of cored boreholes at the Finnsjön study site.

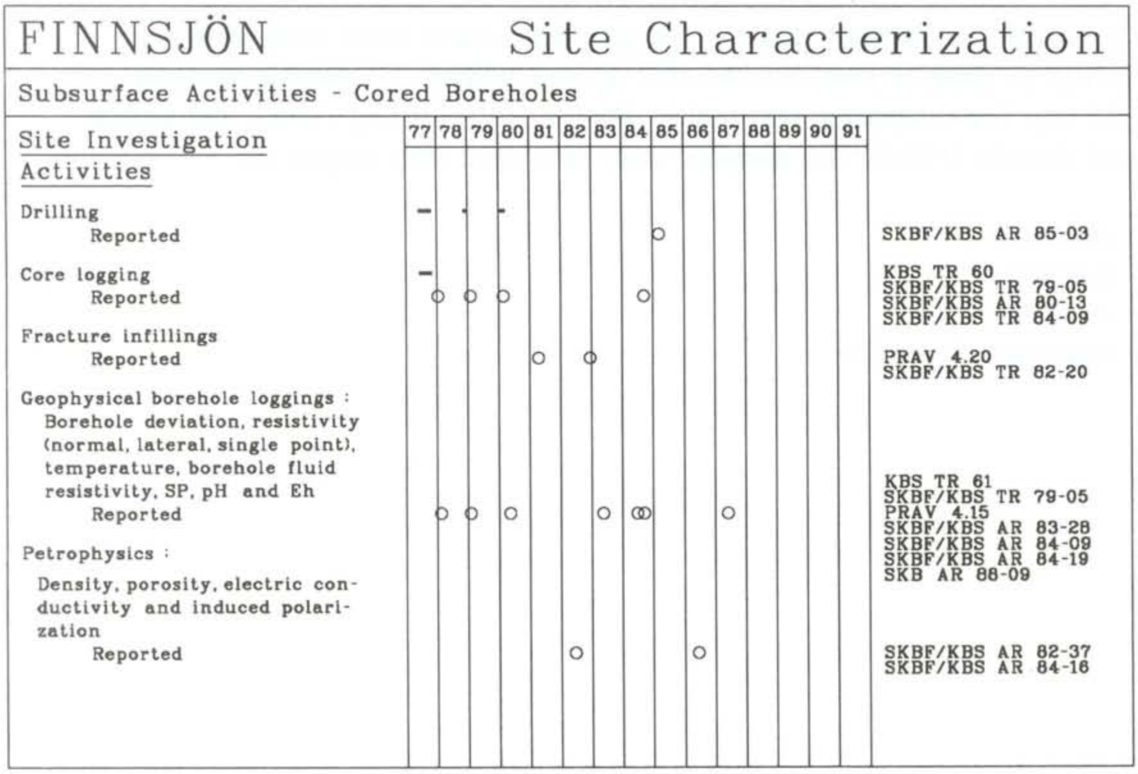


Figure 19. Activities in the cored boreholes - site investigation.

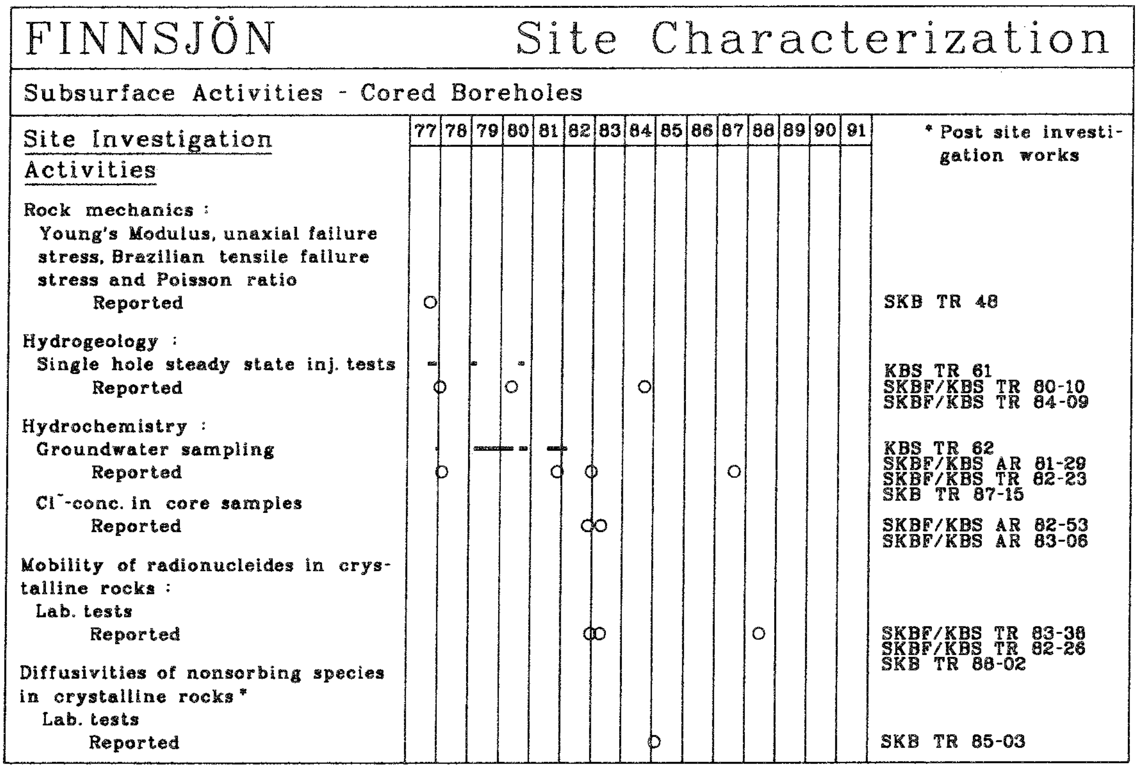


Figure 20. Activities in the cored boreholes - site investigation, cont.

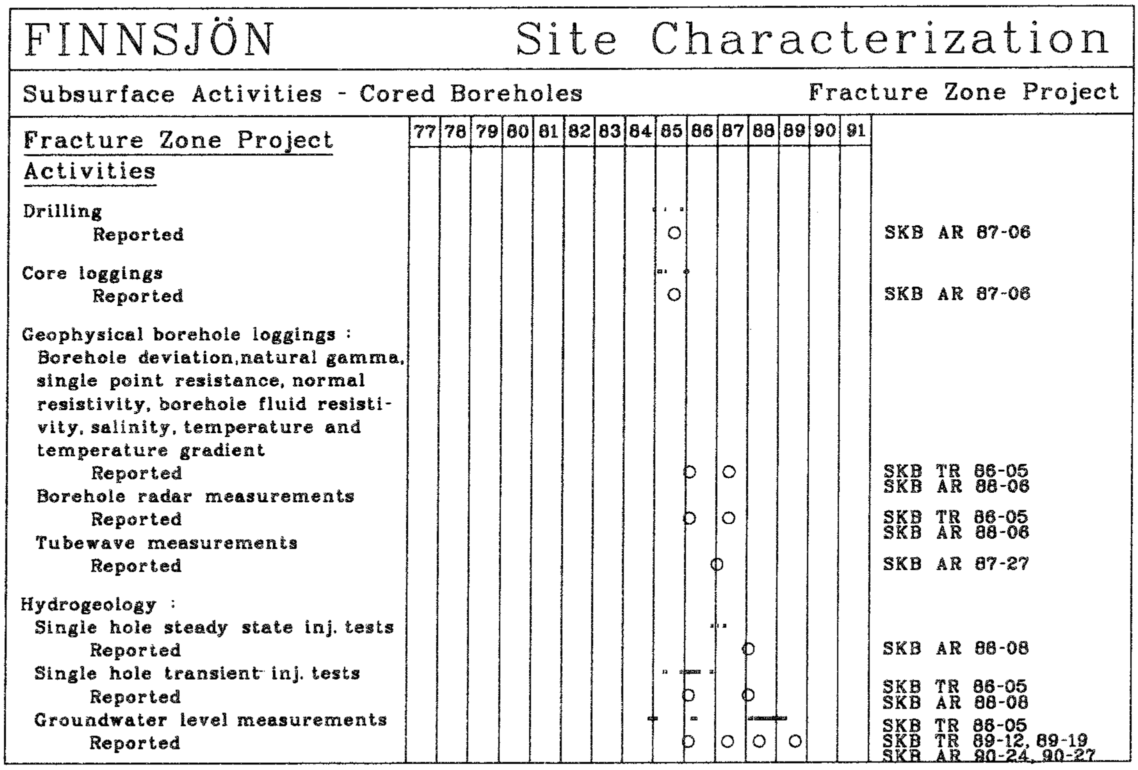
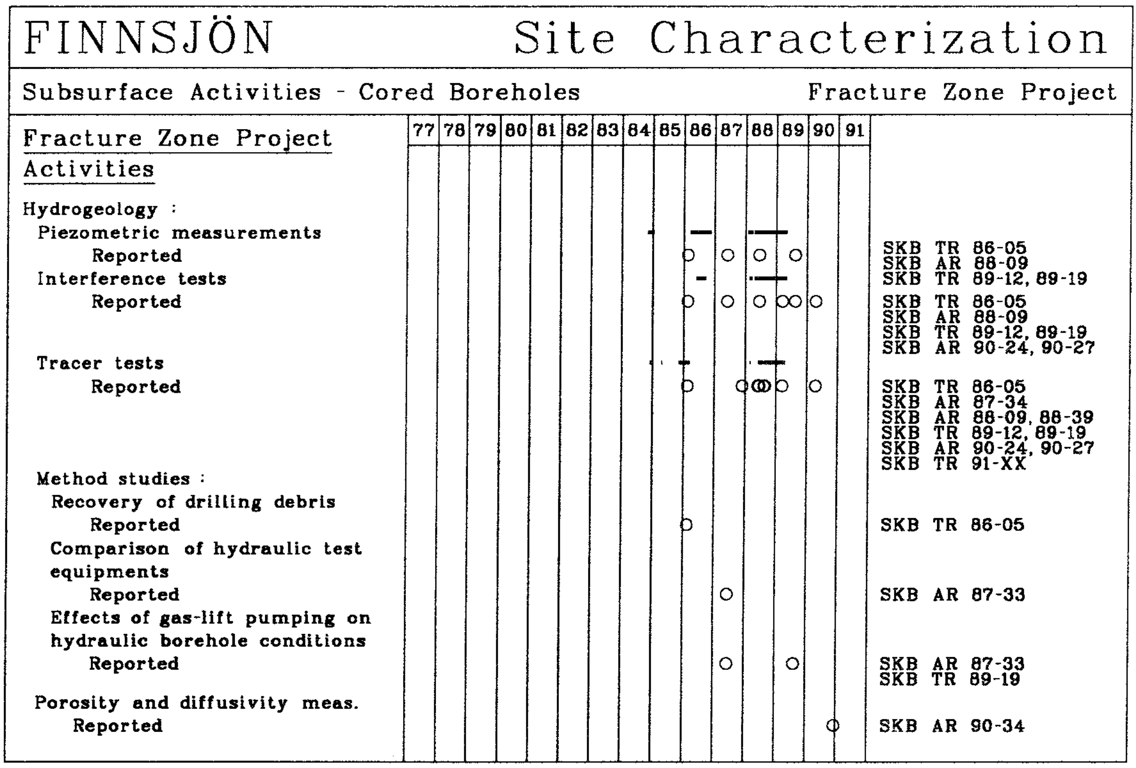


Figure 21. Activities in the cored boreholes - Fracture Zone Project.

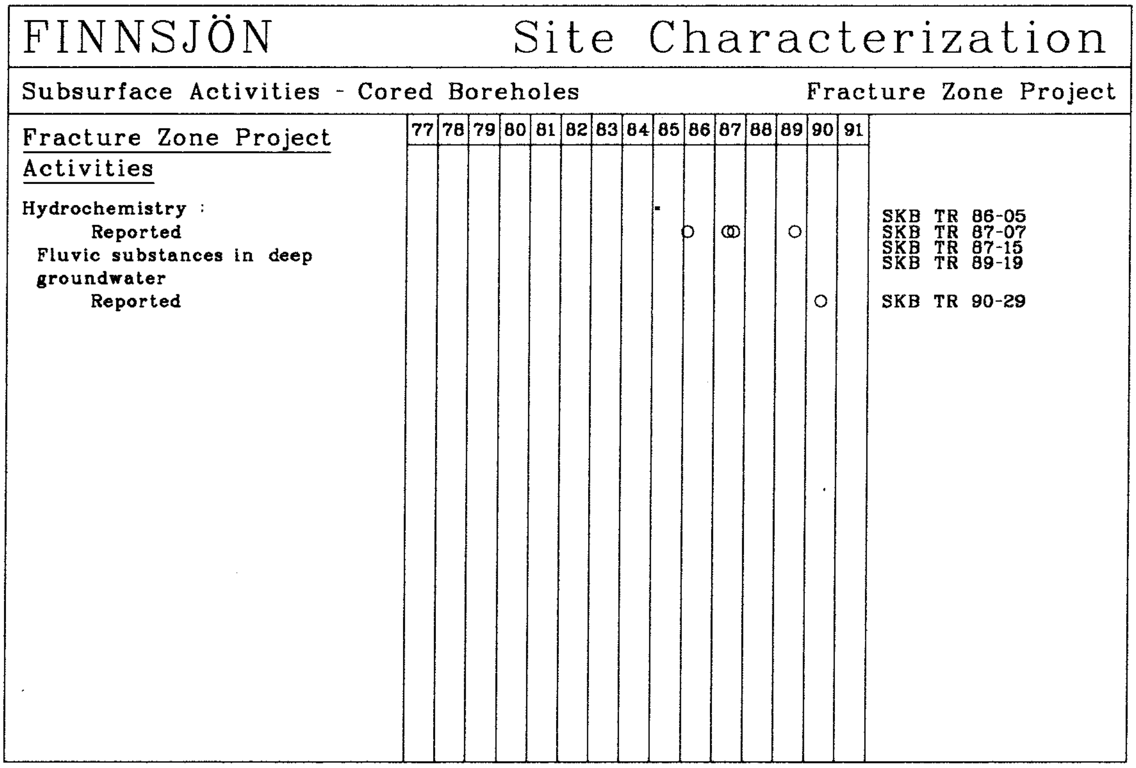


FINNSJÖN Site Characterization

Subsurface Activities - Cored Boreholes — Fracture Zone Project

Fracture Zone Project Activities	
Hydrogeology :	
Piezometric measurements	
Reported	SKB TR 86-05 SKB AR 88-09 SKB TR 89-12, 89-19
Interference tests	
Reported	SKB TR 86-05 SKB AR 88-09 SKB TR 89-12, 89-19 SKB AR 90-24, 90-27
Tracer tests	
Reported	SKB TR 86-05 SKB AR 87-34 SKB AR 88-09, 88-39 SKB TR 89-12, 89-19 SKB AR 90-24, 90-27 SKB TR 91-XX
Method studies :	
Recovery of drilling debris	
Reported	SKB TR 86-05
Comparison of hydraulic test equipments	
Reported	SKB AR 87-33
Effects of gas-lift pumping on hydraulic borehole conditions	
Reported	SKB AR 87-33 SKB TR 89-19
Porosity and diffusivity meas.	
Reported	SKB AR 90-34

Figure 22. Activities in the cored boreholes - Fracture Zone Project, cont.



FINNSJÖN Site Characterization

Subsurface Activities - Cored Boreholes — Fracture Zone Project

Fracture Zone Project Activities	
Hydrochemistry :	
Reported	SKB TR 86-05 SKB TR 87-07 SKB TR 87-15 SKB TR 89-19
Fluvic substances in deep groundwater	
Reported	SKB TR 90-29

Figure 23. Activities in the cored boreholes - Fracture Zone Project, cont.

3.6 Geophysical logging

During the early characterization much of the logging activities were made to test the applicability of various instruments and methods. This has resulted in a large amount of logging data for borehole KFI01 (Appendix B, Figure B2), (Magnusson and Duran, 1978 and 1984) while logging data from boreholes KFI02, 03 and 04 are lacking or very limited. Some early tests were also made in boreholes KFI01, 06 and 07 with a prototype geochemical log for determining the redox-conditions of the deep groundwater (Magnusson and Duran, 1980).

For all boreholes drilled in connection with the Fracture Zone Project (KFI09-11, BFI01-02 and HFI01), the following "standard" set of geophysical logs were used (see Appendixes A and B):

- borehole deviation
- natural gamma radiation
- point resistance
- resistivity, normal 1.6 m
- temperature
- resistivity (salinity) of borehole water
- borehole radar

The results are reported in Ahlbom et al. (1986) and Ahlbom et al. (1988). In addition to the above set of logs, tube-wave measurements were made for boreholes KFI06 and BFI01 (Stenberg 1987a), and caliper and sonic methods in borehole BFI02 (Stenberg 1987b). The results from the geophysical logging are reported as so called complot diagrams in the scale 1:5 000. The geophysical loggings made in each of the cored borehole are presented in Appendix B.

The logging activities during the Fracture Zone Project also included logging of the older boreholes KFI05-08 with the methods (Ahlbom et al., 1986):

- normal resistivity
- resistivity (salinity) of borehole water
- temperature
- borehole radar

The percussion boreholes HBG01-10, drilled during 1977, were logged using TV-log, lateral and normal resistivity. Some boreholes were also logged with salinity, temperature and redox-log. Only TV-logging were used in boreholes HGB11-17. With a few exceptions (Jämtlid et al., 1982), these early logging data were never reported.

3.7 Hydraulic tests and monitoring

Water injection single-hole tests

Single-hole water injection tests have been carried out since 1977 at the Finnsjön study site. Information on boreholes tested, actual packer spacing, intervals measured, lower measurement limits and year of testing is compiled in Table 3. The oldest tests (boreholes KFI01-08) were normally performed in 3 m-sections, covering almost the entire boreholes. These tests, which were carried out as short-time steady-state tests, are reported by Hult et al. (1978) and Carlsson et al. (1980). In the deepest parts of boreholes KFI02 and KFI03 no hydraulic tests were performed due to intense fracturing.

The Fracture Zone Project was initiated 1984. In this project the hydraulic single-hole tests were generally performed in 2 m-sections covering Zone 2 and its immediate surroundings. Tests in 20 m-sections were generally performed above Zone 2 and in some cases along the entire boreholes. Single-packer tests were generally carried out in the lower parts of the boreholes.

The 2 m-tests were performed as short steady-state tests whereas the 20 m-tests were transient tests of 2 hours of injection followed by 2 hours of pressure recovery. Finally, very detailed tests in 0.11m-sections were carried out in segments of Zone 2 in borehole BFI02. Results are reported in Ahlbom et al. (1986), Ahlbom et al. (1988), Andersson et al. (1988) and Ekman et al. (1988). The performance and interpretation of the single-hole tests are described in Almén et al. (1986). A comparison of results from old 3 m-tests and new 2 m-tests in boreholes KFI05-07 is reported in Andersson et al. (1988). The activity periods for the hydraulic tests are presented in Figure 21. Scope of water injection tests in the different boreholes is presented in Appendixes A and B.

Interference tests

During drilling of borehole BFI01 the groundwater head was registered in isolated sections in several other boreholes. Since water was flushed out of borehole BFI01 by compressed air at a fairly constant rate, the drilling periods could be regarded as (preliminary) drawdown tests. Between the drilling periods the groundwater heads were allowed to recover. These tests are reported in Ahlbom et al. (1988). Subsequently, more sophisticated hydraulic interference tests were carried out by pumping from different parts of Zone 2 in borehole BFI02 and monitoring the head changes in isolated multiple-borehole sections within Zone 2 and in a few boreholes outside the zone. The detailed interference tests were analysed both qualitatively and quantitatively by Andersson et al. (1989).

Table 3. Compilation of data from hydraulic single-hole tests at Finnsjön.

Borehole	Dip	Borehole length (m)	Section length (m)	Interval measured (m)	Lower meas. limit K (m/s)	Year of testing
KFI01	90°	500	2	14-494	$2.4 \cdot 10^{-9}$	1977
KFI02	50°	698	3	16-673	$2.0 \cdot 10^{-9}$	1977
KFI03	50°	730	3	8-677	$3.3 \cdot 10^{-10}$	1977
KFI04	80°	602	3	50-596	$1.9 \cdot 10^{-10}$	1979
KFI05	50°	750	3	50-743	$1.9 \cdot 10^{-10}$	1979
			2	141-320	$7.5 \cdot 10^{-10}$	1986
KFI06	90°	691	3	58-679	$1.9 \cdot 10^{-10}$	1979
			2	192-293	$7.5 \cdot 10^{-10}$	1987
KFI07	85°	552	3	18-543	$1.9 \cdot 10^{-10}$	1979
			2	263-364	$7.5 \cdot 10^{-10}$	1987
KFI08	60°	464	3	40-460	$1.6 \cdot 10^{-10}$	1980
KFI09	60°	375	20	10-350	$1.0 \cdot 10^{-11}$	1985
			2	109-263	$1.0 \cdot 10^{-10}$	1986
KFI10	50°	255	20*	10-230	$1.0 \cdot 10^{-11}$	1985
			5*	75-105	$4.0 \cdot 10^{-11}$	1985
			5*	205-235	$4.0 \cdot 10^{-11}$	1985
			2	60-224	$1.0 \cdot 10^{-10}$	1986
KFI11	90°	389	20	6-386	$1.0 \cdot 10^{-11}$	1986
			2	210-360	$1.0 \cdot 10^{-10}$	1986/87
HFI01	90°	129	10	4-124	$1.0 \cdot 10^{-10}$	1985
			2	34-44	$2.0 \cdot 10^{-9}$	1985
			2	104-114	$2.0 \cdot 10^{-9}$	1985
BFI01	90°	460	20	30-450	$1.0 \cdot 10^{-11}$	1987
			2	220-450	$1.0 \cdot 10^{-10}$	1987
BFI02	90°	289	20	10-200	$1.0 \cdot 10^{-11}$	1987
			2	200-284	$1.0 \cdot 10^{-10}$	1987
			0.11	201.89-206.07	$5.0 \cdot 10^{-9}$	1988
			0.11	211.89-214.09	$5.0 \cdot 10^{-9}$	1988
			0.11	257.89-262.18	$5.0 \cdot 10^{-9}$	1988

* The tests were repeated at three different occasions before and after gas-lift pumping.

Groundwater head measurements

Groundwater head measurements were made both during undisturbed conditions and during drilling of BFI01 (Ahlbom et al., 1988). The measurements were made in 3-5 isolated sections in the cored boreholes KFI05-11 and in three sections of borehole HFI01. The measurements were made intermittently during most part of 1986. Undisturbed head measurements in the borehole sections were obtained before the pumping and after the recovery periods of the drilling. To calculate the groundwater potentials, the pressures were corrected for the varying salinity along the boreholes.

Groundwater head estimates were also obtained during the single hole water injection tests, before and after the test sequence, in boreholes KFI09-11 and BFI01. Only head estimates in sections higher than 10^{-10} m/s were considered reliable.

Tracer tests

Preliminary tracer tests

Several parameters were determined from preliminary tracer tests in the upper part of Zone 2 by injecting tracers in boreholes KFI06, KFI11 and BFI01 and monitoring the break-through of tracers in the pumping borehole BFI02 during an interference test (Andersson et al. 1989).

Radially converging tracer test

The objective of the radially converging tracer test was primarily to determine the transport parameters of Zone 2 and to utilize the experimental results for validation and verification of radionuclide transport. In a radial geometry of a central pumping borehole (BFI02) and three peripheral injection boreholes (KFI06, KFI11 and BFI01), tracers were injected in three packed-off intervals in each borehole in totally nine injection points at distances of c. 150 m from the pumping borehole.

The central borehole was pumped from a packed-off interval enclosing the entire Zone 2. Totally eleven different tracers were injected, eight of them continuously for 5-7 weeks and three were injected as pulses.

Tracer breakthrough was registered from all nine injection intervals, with first arrivals ranging between 24 - 3500 hours. An analytical evaluation of transport parameters was made including hydraulic conductivity, fracture aperture, flow porosity and dispersivity. Possible interconnections between highly conductive intervals were also studied by detailed sampling in the pumping borehole. In addition, a comparison was performed. between predictions of the tracer breakthroughs, based on a numerical model that was calibrated by the hydraulic interference tests and the experimental results. The radially converging tracer tests are reported by Gustafsson et al. (1990).

Dipole tracer test

A tracer test was also performed in a dipole flow field created in the upper part of Zone 2 between borehole BFI01 (injection) and BFI02 (withdrawal). The main objective of the test was to verify the results from the radially converging test and to test the applicability of the method in a large scale in high conductive rock, using short-lived radioisotopes. Totally 15 tracer injections were made including 14 radioactive tracers and 5 non-active. Tracer breakthrough was monitored both in the pumping hole BFI02 and in two observation boreholes, KFI06 and KFI11. The results indicated that the transport in the upper part of Zone 2 is highly heterogenous. The dipole tracer test is reported by Andersson et al. (1990).

Tracer dilution tests

Tracer dilution tests were performed in boreholes BFI01 and HFI01 to determine the natural groundwater flow rate in Zone 2, and secondly to establish the flow rate in the rock and fracture zones adjacent to Zone 2. The dilution measurements were successful in 10 of the 12 selected borehole sections (Gustafsson and Andersson, 1991).

Other tracer tests

During drilling of borehole KFI11 the flushing water was recovered from the existing borehole HFI01, located at a distance of about 440 m from KFI11. Both boreholes intersects the upper part of Zone 2.The flushing water was labelled with a tracer at the surface before it was pumped down in borehole KFI11. A total loss of flushing water occurred when borehole KFI11 penetrated the upper boundary of Zone 2 (Gustafsson and Andersson 1991). By continuously monitoring the tracer content of the water pumped up from borehole HFI01 the first breakthrough of tracer (Uranine) from borehole KFI11 was recorded in borehole HFI01 about one month after penetration of Zone 2.

This test was used to estimate the hydraulic fracture conductivity, firstly based on the assumption of radial flow in a single fracture between boreholes KFI11 and HFI01 and secondly, assuming linear flow in the fracture between the boreholes. In addition, the flow porosity was estimated assuming a 1 m thick hydraulically active zone. The results are shown in Table 12. The same parameters were latter re-calculated including the effect of the radius of influence (r_e) and finally, including the combined effects of both radius of influence and enhanced transport velocity in the vicinity of the pumping borehole.

Early tracer tests were made in a minor fracture zone at the Gåvastbo area between boreholes HGB01 and HGB02 (Gustafsson and Klockars, 1981). The equivalent hydraulic fracture conductivity and flow porosity were calculated. The tests also included studies of sorbing tracers (Cs and Sr) (Gustafsson and Klockars 1984).

3.8 Groundwater sampling

Groundwater sampling has been made in 12 deep boreholes. Sampled depths varies between 100-700 m. Results are presented in Laurent (1982), Ahlbom et al. (1986), Smellie and Wikberg (1989) and Andersson et al. (1991). In an early study geochemical associations between the groundwater and the fracture minerals were discussed by Tullborg and Larson (1982).

Methods for groundwater sampling and chemical analyses have developed considerable since the first investigations in 1977. Instruments used in the first years was prototypes. The quality of sampling increased considerable during 1984 when the SKB mobile laboratory was introduced, which among other improvements made it possible to measure pH and Eh down-hole during sampling. Only chemical analyses from the two last sampled boreholes, KFI09 and BFI01, should be regarded as fully representative.

3.9 Studies at the Finnsjön site after 1988

After the main investigation period of the Fracture Zone Project was terminated in 1988, the Finnsjön site have been used for studying radionuclide migration in connection with the Chernobyl fallout. The scope of work and the corresponding references are presented in Figure 24. Apart from these studies no field activities have been performed at the Finnsjön site since 1988.

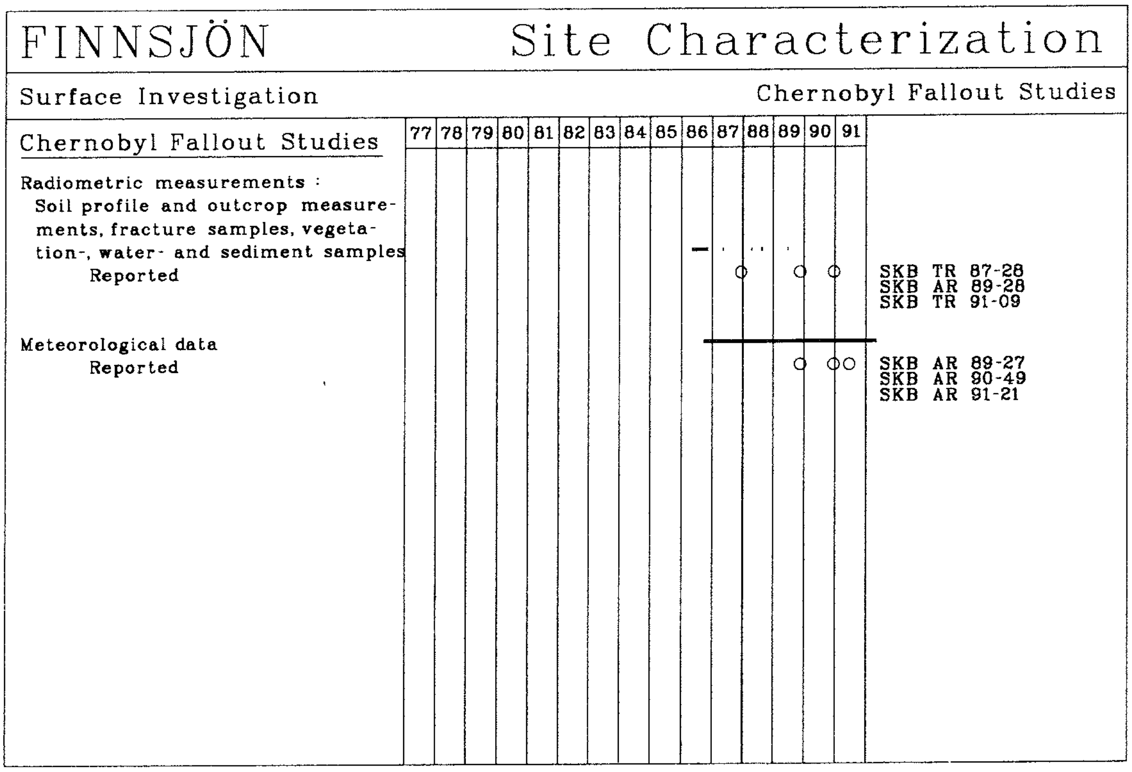


Figure 24. Studies in connection with the Chernobyl fallout at the Finnsjön study site.

4. STORAGE OF INFORMATION IN THE SKB DATABASE

Data from surface surveys

With the exception of the refraction seismic survey, all geophysical surface measurements are stored in the SKB database GEOTAB. "Surface data", such as geological maps, lineament interpretations, surface fracture surveys, depth of overburden, hydrometerological data and groundwater level maps, are not stored.

Data from borehole surveys/tests

Most data from the geological and geophysical surveys, hydrological tests and water sampling in the cored boreholes are stored in GEOTAB. This includes borehole geometrical data (coordinates, length, dip, deviation etc), core logging, "standard" geophysical logs and single hole hydraulic packer tests. Also stored are chemical analyses of sampled groundwater from the cored boreholes, as well as from the Booster borehole BFI01.

For the percussion boreholes the database includes geometrical data, geophysical logs, borehole deviation measurements, groundwater level monitoring and some interference tests. A description of stored data from surveys in each borehole are presented in Appendix A and Appendix B (under the heading GEOTAB).

The following borehole measurements/sampling/analysis are **not stored** in the database:

Percussion boreholes. No drilling rates or data regarding drilling debris are stored. Furthermore, the data base does not contain any information regarding the locations of major inflows and total water capacities.

Geological analyses. No chemical analysis of whole rock samples nor analyses of fracture minerals is stored. This also applies to data concerning mineralogical compositions (thin sections).

Geophysical/mechanical measurements. No petrophysical nor mechanical parameters determined from tests on core samples are stored. This also applies to results from the mise-à-la-masse and tube-wave surveys, as well as the borehole radar and rock stress measurements.

5. GEOLOGIC MODELS

5.1 Regional geologic models

Geology

The rocks comprising the bedrock of northern Uppland are between 2,200 to 1,600 million years old. The oldest rock are deposited at the surface of the crust (supracrustal rocks) and comprises acid volcanics (leptites) and metasediments with intercalated mineralized beds (eg. Dannemora Iron Mine). A basement, on which these rocks were deposited, has not been identified.

The supracrustal rocks were later deformed and altered during a period of mountain building, the Svecokarelian orogeny, which culminated c. 1,850 million years ago. Huge amounts of granitoids, a magmatic suite of gabbroic to granodioritic (youngest) rocks, were at this time emplaced in the supracrustal sequence. The culmination of the ductile deformation during the Svecokarelian orogeny occurred just after the intrusion of the granitoids. The deformation resulted in a regional foliation and shearing along contacts of major lithological boundaries. The mineralogy of the bedrock indicate that this deformation occurred at a temperature of c. 400-600 °C and a pressure of c. 4-8 kbar (middle amphibolite facies).

The deformation ceased, but before the deformation changed character from ductile to semi-ductile the bedrock was intruded by doloritic Herräng dykes (c. 1,800 million years ago), and the deformation become more linked to regional shear zones, forming regional lens-shaped (anastomosing) patterns. These shear zones have a N-S trend in central Uppland, while they form a c. 20-30 km wide, WNW trending belt along the northeastern coastline of Uppland deforming the Herräng dykes.

After the culmination of the semi-ductile deformation, emplacements of reddish to greyish-red granites occurred, c. 1,700 million years ago. These granites overprinted the semi-ductile shear pattern and brecciated the bedrock. The bedrock was affected by thermal alteration and deformation at the contacts to the late granites. The deformation was locally intensive.

Younger intrusive rocks, younger than 1,700 million years old, have not been recognized at the Finnsjön site nor at its surroundings. However, the record of younger doleritic and alkaline intrusions just outside this area are numerous. The region was affected by block faulting during a long period, more than 800 million years. This block faulting declined and erosion resulted in the formation of the sub-Cambrian peneplain for more than 600 million years ago. A sequence of Cambro-Silurian sediments were deposited on the peneplained surface, which was distorted by minor faulting. The sediments are now eroded away, except for some few remnants, and the present ground surface of northern Uppland coincide roughly with the sub-Cambrian peneplain.

A generalized map showing the rock distribution in a 50x50 km^2 regional area, with the Finnsjön study site in its center, is presented in Figure 25. The oldest rocks, the 2,200-1,850 million years old meta-volcanics and meta-sediments (supracrustals), occur now along regional shear zones or downfolded in tight synformal structures. These rocks have irregular boundaries and constitute c. 25% of the bedrock.

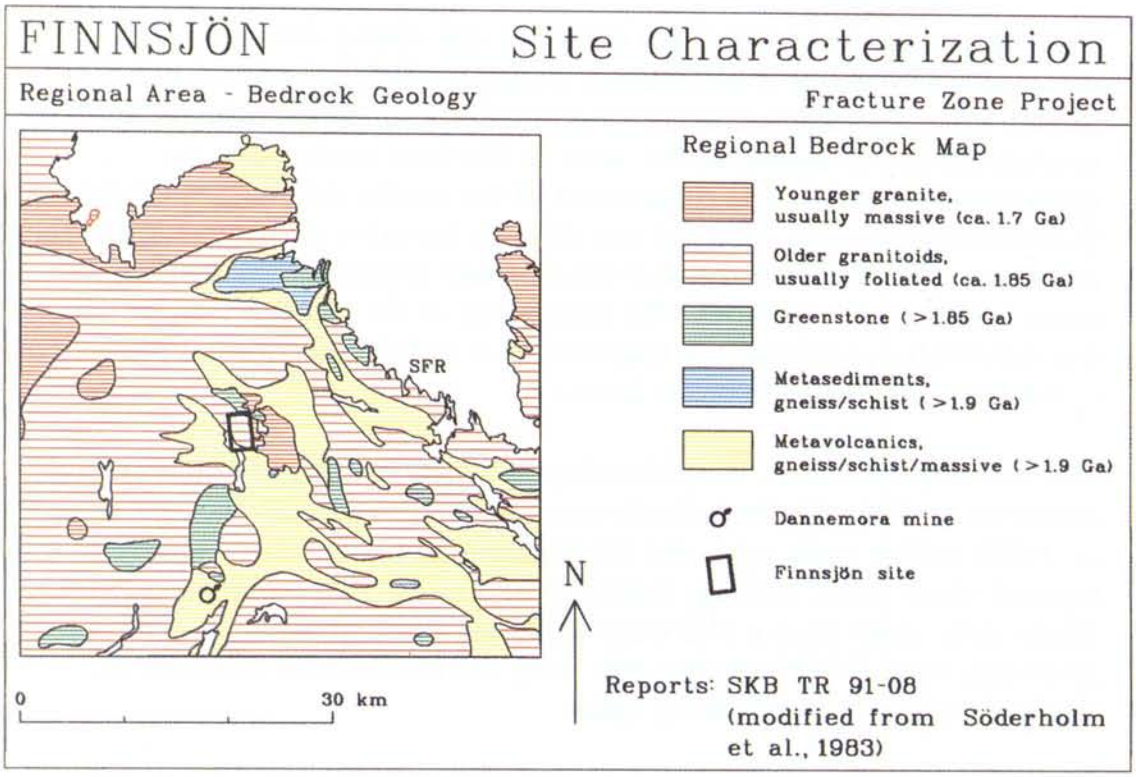


Figure 25. Distribution of rock types in the northeastern Uppland (modified from Söderholm et al. 1983).

Notable is the pronounced NW-SE orientations of these rocks in the northern part of the map, i.e. parallel to the Singö fault (see below). At the Dannemora Mine these old supracrustals are downfolded to great depths, c. 500 m in the southern part of the mine to more than 1 100 m north of the mine, along a N30E fold axis plunging gently. The folding is argued to be caused by intruding Svecokarelian granitoids (c. 1,850 million years old).

More than 50% of the present bedrock consist of major intrusions of granodiorite-granitic rocks of Svecokarelian age. These granitoids deformed earlier intruded basic rocks. The penetrative deformation during the Svecokarelian orogeny uniformed the structure of the bedrock, giving the granitoid rocks a shear gneiss character on a regional scale. The Finnsjön study site is located within a granodioritic intrusion.

Large intrusions of younger granites (post-Svecokarelian, c. 1,700 million years), occur preferable in the northern part of the map. These are accompanied by pegmatite and aplite dykes.

Lineaments

The lineaments in the region surrounding the Finnsjön study site have been interpreted from an altitude map in scale 1:250 000 with contour lines drawn for every 12.5 m (Carlsson and Gidlund, 1983). Within this region the altitude changes from sea level to a maximum altitude of 62 m. The relief reflects the surface of the bedrock since the thickness of the Quaternary cover (mainly moraine and clay) for most areas is not more than a few metres thick. The direction of the movement of the last inland ice was predominately toward the south. The interpreted lineaments are presented in Figure 26.

The lineaments are in general curved, forming a network of linsoidal blocks. At least two sets of lineaments are present, one trending north to northeast and the other with a northwesterly trend. The linsoidal shape of the rock blocks indicate that the lineaments reflect shear structures. It is not clarified if these two shear sets have been active at the same time, forming a conjugate shear configuration.

An interesting feature of this region is the systematic tilting of major blocks (up to 2 degrees), as indicated in Figure 26. The ground surface of the north-northeast trending rock blocks are tilted towards the east and southeast while the ground surface of northwest trending rock blocks dips towards the north-east. The tilting is interpreted to be caused by listric faults (spoon shaped). Close to the ground surface these faults are probably steeply dipping.

Only one of the lineaments on the regional map has been investigated in detail. This is the northwesterly trending Singö fault, Figure 26. This fault has been studied in connection with the construction of the final repository for reactor waste (SFR) at Forsmark (SFR1, 1987). At this location the fault is 100-200 m wide and subvertical. The zone exhibit a complex tectonic structure with about c. 100 m of altered and mylonitized bedrock and c. 15 m of crushed bedrock in the central part of the fault. The hydraulic conductivity, estimated from borehole tests, varies strongly between different boreholes. In the central (core) part of the fault the average conductivity value is $4 \cdot 10^{-6}$ m/s, while the conductivity in its peripheral parts is $5 \cdot 10^{-7}$ m/s (SFR1, 1987).

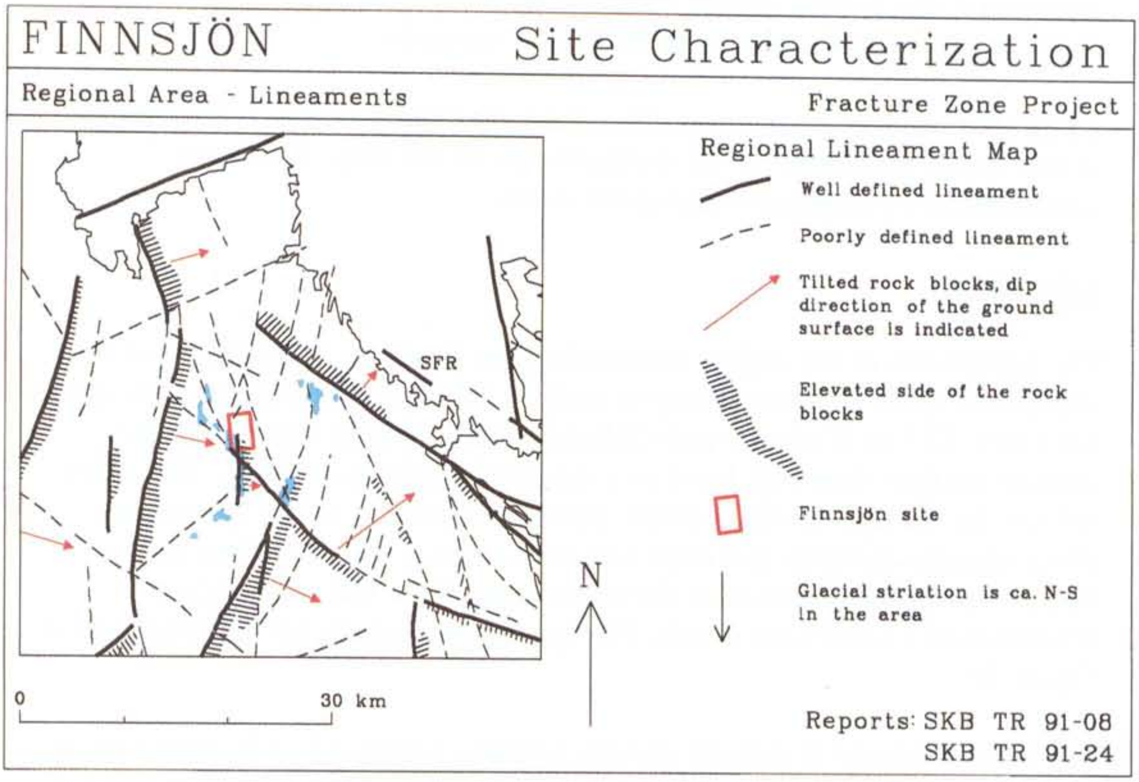


Figure 26. Lineaments in northeastern Uppland interpreted from topographical maps in scale 1:250 000.

5.2 Geological characteristics of the Finnsjön site

General

The site has a flat topography with differences in altitude of less than 15 m. Although outcrops are common, the area is covered to 85% by Quaternary sediments, mainly moraine and peat. The main part of the Finnsjön site is located within a 6 km^2 large block, the Finnsjön rock block, bounded by lineaments of regional or subregional in length. Zone 1 divides the Finnsjön rock block into a northern and a southern block, Figure 27.

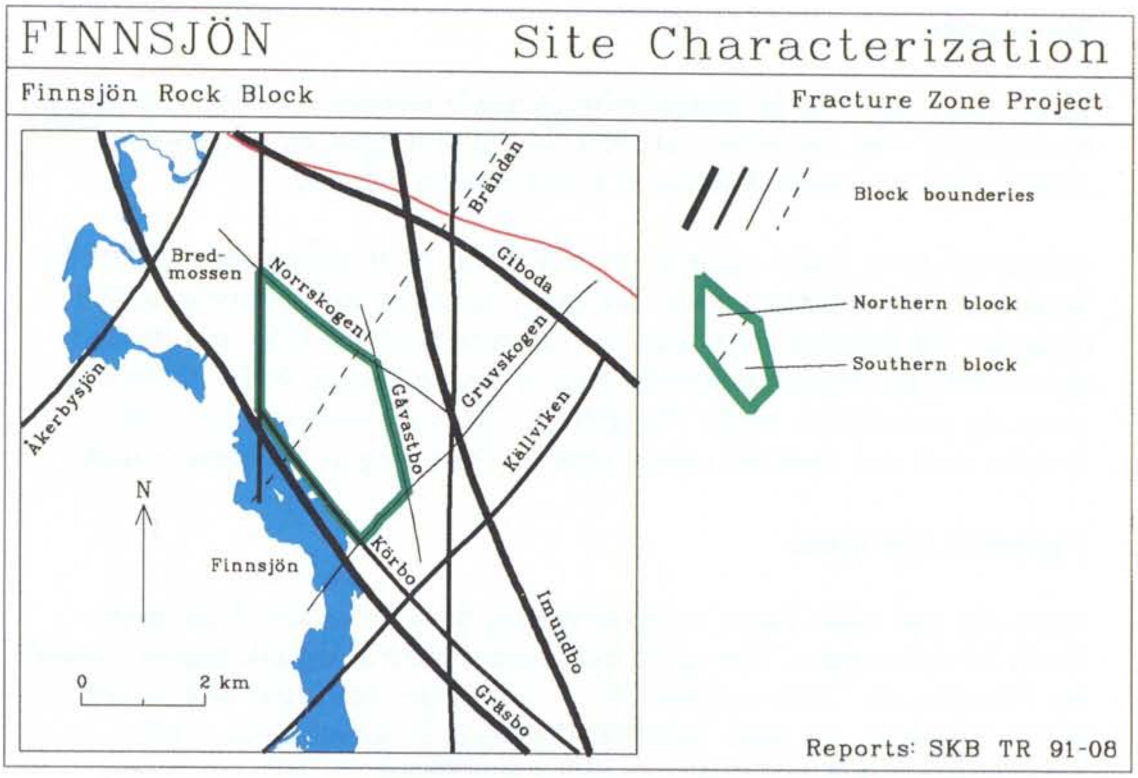


Figure 27. The Finnsjön rock block (rastered area). The Brändan fracture zone (Zone 2) divides it into a northern and a southern block.

Rock types

The site is located within c.12 km^2 large rock body consisting of greyish foliated granodiorite, Figure 28. The depth of the rock body is not known, except that it is more than 700 m (borehole depth). Dykes of pegmatite, metabasite and aplite intersects the granodiorite. The granodiorite is bordered to the east by a reddish young granite and to the northeast by a layered gabbro. Metavolcanic rocks occur to the west and to the south of the site.

Granodiorite

The granodiorite, which is greyish, medium grained and uniform, was thoroughly deformed during the Svecokarelian orogeny (c. 1,800 millon years ago) and transformed into a gneiss. The gneissosity is defined by a parallel arrangement of minerals (hornblende and biotite) or mineral aggregates (flakes of recrystallized quartz). The orientation of the gneissosity is uniform, N50-60W/80-90NE. The foliation, character and colour of the granodiorite is locally changed due to mylonitization, cataclasis, and hydrothermal alteration (red colouring) along minor shear zones and fractures.

Metabasites

Basic rocks occur in the granodiorite as minor elongated xenoliths laying in the foliation. The xenoliths (less than 23 cm in length) are of gabbroic affinity and are evenly distributed within the granodiorite.

Inlayers of basic rocks occur as dolerite dykes or as amphibolite sheets. The latter lying within shear zones. The dykes are some decimeters wide and cross-cut the foliation. The dykes are oriented N-S and E-W, but sheared dykes, metadolorites/amphibolites have a predominating WNW trend with a steep dip towards the south. The dolerite dykes are well welded to the country rock and have the same degree of fracturing as the country rock.

Pegmatite and aplite

Pegmatite and aplite occur as dykes cutting the gneissosity of the granodiorite at right angles. The aplite dykes are related to the late granite outside the Finnsjön site. They are pink, 0.1 -1.0 m wide, and often very extensive, locally mappable for more than 500. Two sets of aplite dykes occur; N40-60E/steep and subhorizontal with a southward dip. The commonly occurring pegmatites are grey up to 0.2 m wide and traceable for some 10 m. Fractures within these dykes are often oblique to the trend of the dykes.

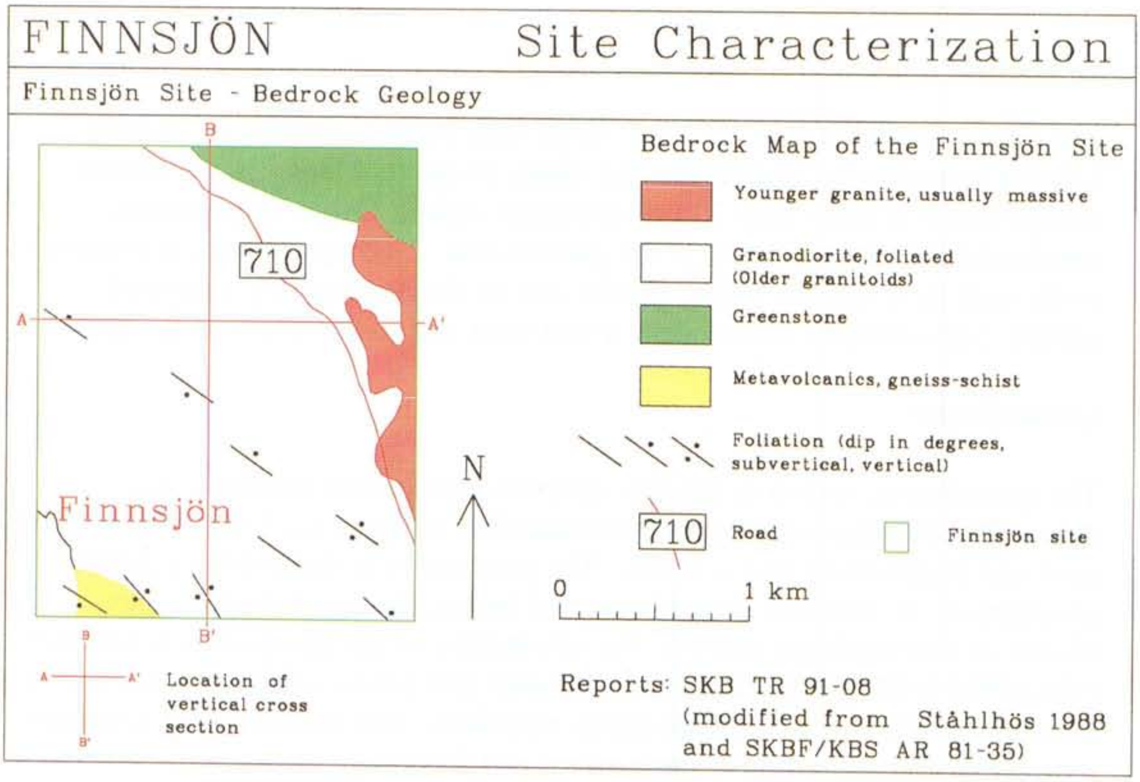


Figure 28. Bedrock map of the Finnsjön site.

Fractures

The fracture frequencies measured on outcrops in the Finnsjön study site do not indicate an uniform fracturing. A fracture survey performed along two orthogonal profiles (Figure 3) during the early site characterization reflects the fracturing in the southern block and in the bedrock surrounding Zone 1, 3 and 4. The result of this survey indicates, compared to other SKB study sites, a fracture frequency which is relatively high. On the average the frequency, determined on exposed outcrops, is c. 2.9 fr/m (Olkiewicz, 1981). For comparison, the Sternö and Gideå sites display fracture frequencies of c. 0.9 and c. 1.2 fr/m, respectively.

The fracture surveys performed along scan-lines on the ground surface and on cores show the same fracture frequency. This suggests a homogeneous configuration of fractures. The average fracture frequency in the cores from the upper 100 m in the boreholes KFI03, 04 and 05 is 3.0 fr/m (excluding crushed sections). No decrease in fracture frequency with depth (0-600 m) have been observed in these boreholes. The locations of sections with high fracture frequency in each cored borehole are presented in Appendix C.

Fracture surveys performed along an excavated trench, ca 5 x 90 m large, in the northern block indicates a lower average fracture frequency, c. 1.5 fr/m. This is also apparent in the cores from boreholes in this block. For example, borehole KFI11 display a fracture frequency of about 1 fr/m in the bedrock above Zone 2.

Fracture surveys on outcrops in the northern block have defined three main fracture sets (ordered according to their relative occurrence):

* Northeast (N10-70E) fractures with a steep dip towards SE
* Northwest (N25-80W) fractures with a steep dip towards SW
* Flat lying fractures dipping predominantly to the SW

This configuration of fractures resembles the fracture configuration at Forsmark (SFR1, 1987).

Northeast fractures

Northeast trending fractures are the most frequent occurring fractures. The fracture walls are altered, reddened by hydrothermal fluids. A common infilling in these fractures is iron-rich prehnite, which has, outside this area, been dated to 1,250-1,100 Ma (Wickman et al. 1983). The northeast fractures often occur en echelon (stepped configuration). This fracture set is interpreted to have been formed by a regional ENE left lateral shearing with a compression component in NNE.

Northwest fractures

The northwest fracture set is older than the northeast fractures and has been formed by a ductile-brittle deformation. This is evident by the common occurring ductile deformation of the wall rock (flexures and mylonites). The northwest fractures are oriented more or less parallel to the foliation in the granodiorite. Regarding the frequency of "open fractures" mapped on outcrops, there is an equal relative occurrence for the two steeply dipping fracture sets, but the northwest fractures are the most extensive.

Flat lying fractures

Flat lying, horizontal to gently dipping, fractures are relatively scarce in outcrops. Although they are well expressed as planar structures forming the morphology of outcrops. Most dips towards the SW. Some of the southwest dipping fractures show a wall rock alteration similar to the northeast trending fracture set, indicating that these two fracture sets were connected.

Fracture infillings

The fracture infillings are mostly of hydrothermal origin. According to Tullborg and Larson (1982) and Tirén (1989), the sequence of fracture infilling, from oldest to youngest, is:

- Epidote and calcite (associated with mylonitic and cataclastic processes).
- Prehnite and calcite/quartz.
- Hematite, laumontite, prismatic calcite and quartz.
- Chlorite and calcite.
- Amorph. Fe^{3+} oxy-hydroxid precipitates (rust)

Most of the fractures are considered to be initiated early in the geologic history and reactivated several times. Geological dating using Rb-Sr indicate ages of 1,600-1,500 million years for epidote and 1,250-1,100 million years for prehnite (Wickman et al., 1983).

5.3 Fracture zones

General

The results from the KBS 1 and 2 investigations (1977-79) of the Finnsjön site was never compiled into a 3D tectonic model of fracture zones. Only very generalized models for the northeastern Uppland region was presented, in which all main lineaments were supposed to represent vertically dipping fracture zones (Carlsson and Gidlund, 1980).

The first detailed model of fracture zones at the Finnsjön site was presented in connection with the Fracture Zone Project (Ahlbom et al. 1986, 1988). However, this model only covered the northern Finnsjön block. A 3D tectonic model (Ahlbom and Tirén, 1991) covering the whole site was however presented as a part of the SKB-91 safety assessment. The model is based on lineament interpretations, field studies and, where available, on core logs and geophysical logs. Interpreted fracture zones are presented in Table 4 and in Figure 29. A detailed map of interpreted fracture zones at the ground surface and at 500 m depth is presented in Figure 30, while vertical cross-sections are presented in Figure 31. Descriptions of each fracture zone are presented in Appendix D. Interpreted locations of fracture zones in boreholes are presented in Appendix C.

Table 4. Geometrical data for interpreted fracture zones at Finnsjön.

Zone	Strike	Dip	Length (km)	Width (m)
1	N30E	75SE	5	20
2	N28W	16SW	1.5	100
3	N15W	80W	5	50
4	N50W	65SW	1	10
5	N50W	60SW	5	5
6	N55-65W	60SW	2	5
7	N55W	60SW	2	5
8	N50W	90	3	5
9	N10W	15W	2	50
10	NW	85SW	2.5	5
11	N5W	35W	2	100
12	N-S	90	6	25
13	N30E	75SE	7	20
14	NW	90	>50	100

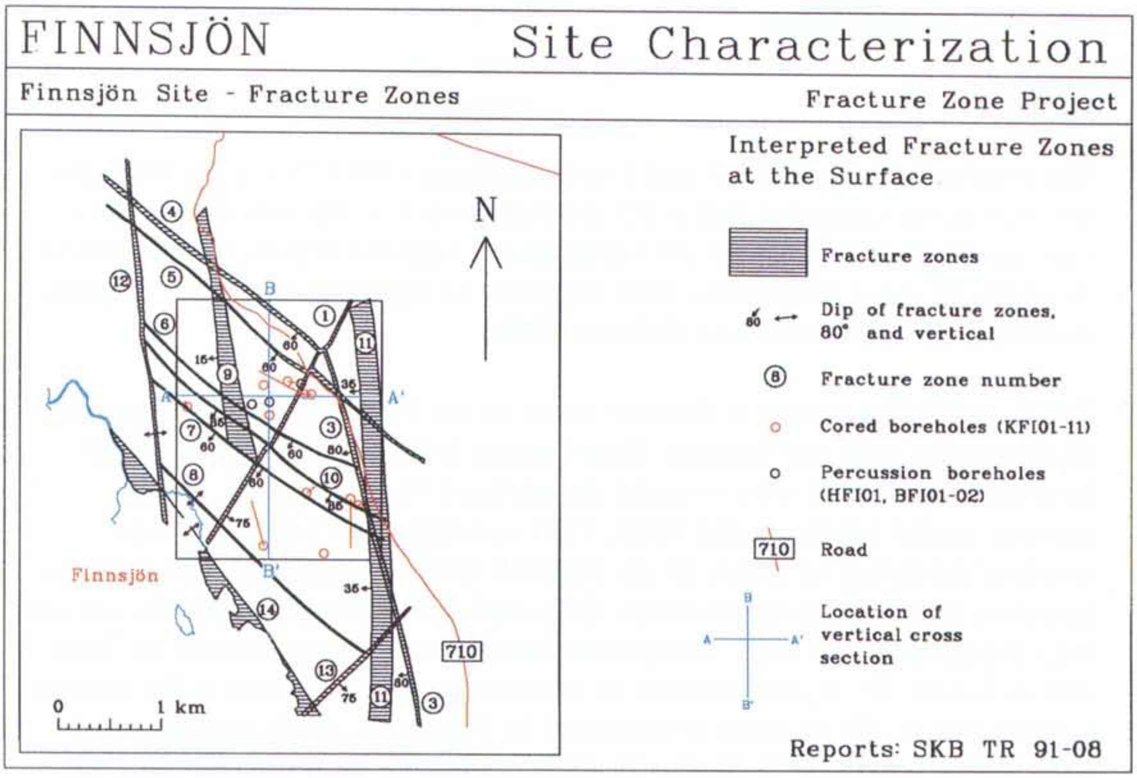


Figure 29. Interpreted fracture zones at the ground surface.

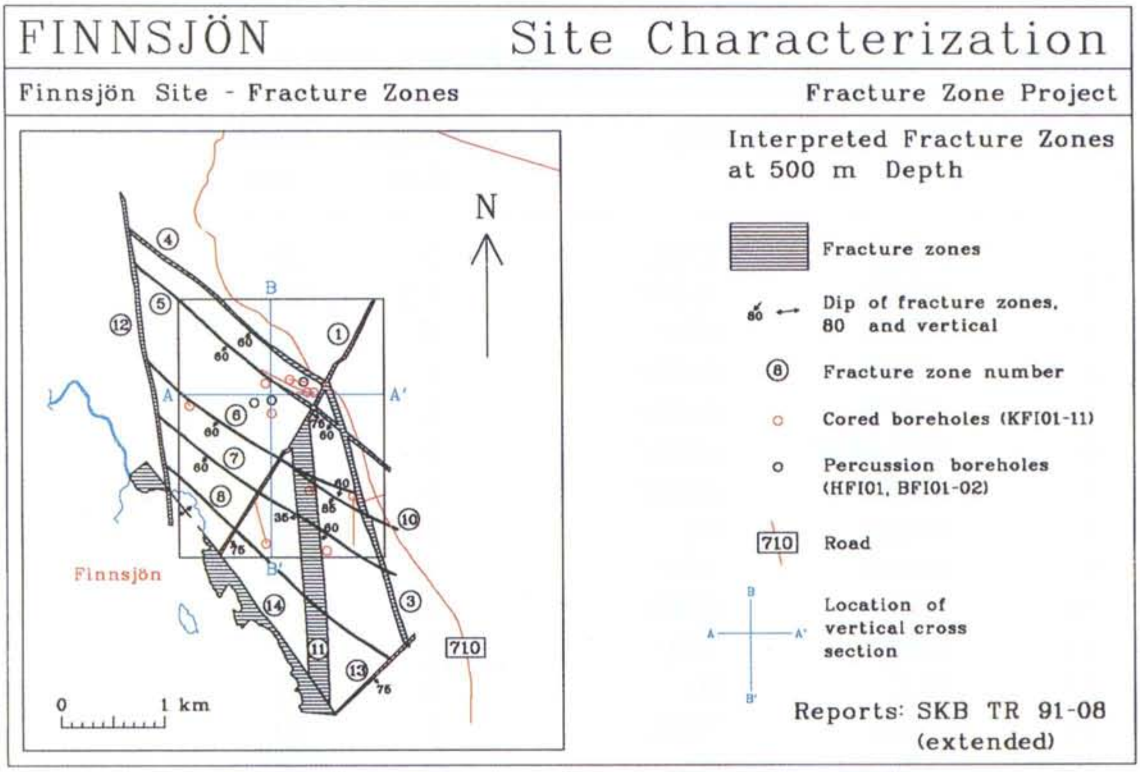


Figure 30. Interpreted fracture zones at 500 m depth.

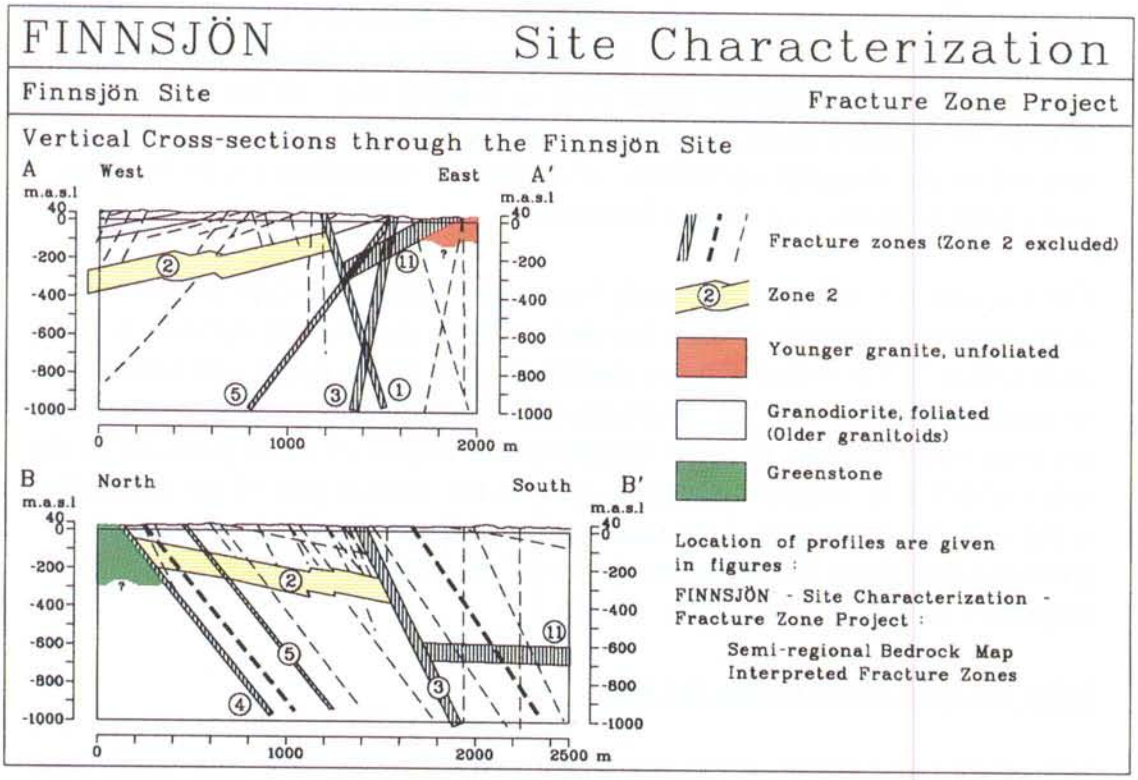


Figure 31. Vertical cross-sections through the Finnsjön study site. The locations of the sections are shown in Figure 29.

Main fracture zones

Two main fracture zones, Zone 1 and Zone 2, have been identified within the interior part of the site. Detailed descriptions of these and other fracture zones are presented in Appendix D. A summary is presented below.

Zone 1, the Brändan fracture zone, is oriented N30E/75SE and has a length of c. 5 km. The width is estimated to 20 m. In addition to its lineament expression, the zone is also indicated on geophysical maps and identified in the cores from borehole KFI05 and KFI10. The cores are altered and red coloured. The fracture frequency in the zone is high, ranging between 8-20 fr/m. Characteristic fracture infillings are iron oxyhydroxides, hematite and asphaltite.

Zone 2, a 100 m wide subhorizontal-gently dipping zone, occurs in the northern block. Its upper boundary is defined in nine boreholes at 100 to 295 m below the ground surface. There is no indication that Zone 2 extends across the Brändan fracture zone, into the southern block, nor has any outcropping parts of the zone been identified. Zone 2 is oriented

N28W/16SW and with a estimated lateral E-W extension of at least 1.5 km. The zone was formed more than 1600-1700 million years ago as a some hundred meters wide ductile shear zone at a depth of c. 10 km. Zone 2 is a product of repeated shear movement along the zone. The deformation has resulted in the frequent occurrence of mylonites, cataclastic rocks, breccias, and a high frequency of sealed fractures.

The fracture frequency is generally low within Zone 2, except for two or three fractured sections in each borehole. These sections are narrow, 2-30 m wide (often 2-5 m wide) and are mainly located at the upper and lower boundaries of the zone. The hydraulically conductive parts of these sections are even more narrow, in some boreholes the widths of these parts are in the order of 0.5-1 m. Narrow fractured parts in the central part of the zone also occur in some boreholes. Late reactivation of Zone 2 seems to occur preferentially along the upper boundary of the zone. The average fracture frequency for Zone 2 is approx. 5 fr/m.

Other fracture zones within the site

The general knowledge about other interpreted fracture zones are much less. The interpretations should therefore be regarded as tentative and should be further tested. This specially applies for fracture zones in the southern block where not much analyses regarding tectonical conditions have been made. For example, a study should be made on Zone 11, a 100 m wide and gently dipping zone, interpreted to occur in four boreholes, to determine its origin and its relationship to Zone 2.

Within the northern block area, minor N60W shear zones occur at regular intervals, with estimated spacings of 40-400 m. These zones are interpreted to dip 60-90° towards SW. The most common fracture orientation within the zones is N60W/80-90SW. The fracture frequency varies between 0.5-5 fr/m. The zones are commonly between 1-5 m wide (up to 20 m) and have an extension of several hundred meters or more. Some of the zones appear to have blind terminations. The wall rock is commonly red coloured. The shear zones are often associated with mylonites or sheared amphibolites/-metadolorites.

Intersections with boreholes

The intersections between boreholes and fracture zones is presented in Table 5, both as borehole length and as depth below ground surface. The depths below ground surface are calculated from borehole deviation data in SKB database GEOTAB.

Table 5. Location of fracture zones in boreholes.

Fracture zone	Borehole	Borehole length (m)	Depth below ground surface (m)
1	KFI05	10-48	8-38
	KFI10	75-105	57-80
2	KFI05	166-305	124-235
	KFI06	201-305	201-305
	KFI07	295-380	295-380
	KFI09	130-212	112-183
	KFI10	152-256*	116-193*
	KFI11	221-338	221-338
	BFI01	240-365	238-362
	BFI02	204-289*	204-289*
	HFI01	105-125*	105-125*
3	KFI08	20-150	17-129
5	KFI05	485-498	370-379
	KFI06	554-557	554-557
	KFI09	212-216	184-187
6	KFI07	530-537	527-535
9	KFI07	109-154	109-154
10	KFI03	57-62	42-48
11	KFI01	332-436	332-436
	KFI03	107-245	82-188
	KFI04	368-440	365-436
	KFI08	20-125	17-107

*does not fully penetrate Zone 2

5.4 Validity of models

Rock type distribution

The homogeneity of the granodioritic bedrock at the Finnsjön study site, in combination with the well exposed bedrock and the large amount of borehole data, implies a high degree of certainty in the distribution of the main rock types for most part of the site. However, this is not the case for the easternmost part of the site where a high frequency of granitic dykes occurs in the deeper parts of the boreholes. This probably implies a closeness at depth to the large body of younger granite which outcrops outside the site to the east.

There are also large uncertainties in the occurrence and in the continuations of amphibolitic, granitic and pegmatitic dykes. In fact, with some exception no attempt was made in the geological mapping to study their lateral and vertical continuations.

Interpreted fracture zones

The general control of the geologic conditions of the northern block is far better known compared to the southern block (Figure 27), due to the detailed studies that has been conducted within the Fracture Zone Project (Chapter 1) in the southeastern part of the northern block. This difference also implies a general higher reliability of interpreted fracture zones in the northern block compared to the southern block.

Apart from this general difference in reliability between the two blocks, the only zones that can be regarded as well established, with respect to location and character, are Zone 1 and Zone 2 (in areas where these zones are intersected by boreholes). Other interpreted fracture zones must be regarded as more or less uncertain. For zones interpreted from lineaments, there are normally no information regarding degree of fracturing nor the dip and even if a single borehole intersects a zone there might be several alternative interpretations regarding its orientation. It is probable that further work on detailed correlation between surface and borehole data would identify additional fracture zones.

Appendix D describes on what grounds each fracture zone has been interpreted, including an judgment regarding the reliability in the interpretation, mainly based on the nomenclature suggested by Bäckblom (1989). Also intersections with interpreted fracture zones and boreholes are presented, including main geologic and tectonic characteristics in the cores.

Three levels of reliability regarding the existence of each fracture zone are identified (from low to high reliability), possible, probable and certain. As seen in Table 6 there are five fracture zones that are "certain" or "probable" and nine zones that should be regarded as "possible", thus implying a large uncertainty in the interpretation of fracture zones.

Table 6. Reliability of interpreted fracture zones mainly according to the nomenclature of Bäckblom (1989).

Fracture zone	Reliability
Zone 1	Certain
Zone 2	Certain
Zone 3	Probable
Zone 4	Possible
Zone 5	Probable
Zone 6	Possible
Zone 7	Possible
Zone 8	Possible
Zone 9	Possible
Zone 10	Possible
Zone 11	Probable
Zone 12	Possible
Zone 13	Possible
Zone 14	Possible

The main reason for the low reliability for many interpreted fracture zones is that they are interpreted from lineaments only and thus no boreholes have been drilled to test their existence.

This also applies for Zone 14. However, based on the well expressed and regional extension of the lineament, together with the faulting associated with the zone (Appendix D), it could be argued that the zone should be denoted as "certain".

6. GEOHYDROLOGICAL MODELS

6.1 General

Groundwater flow modelling of the Finnsjön site and its surroundings has been performed on two different occasions. Preliminary modelling was performed by Carlsson et al. (1983) using a more or less generic approach. Since then, the knowledge of the geological and hydrogeological conditions at Finnsjön has been greatly improved by the Fracture Zone Project (Ahlbom et al., 1988) and the SKB 91 project (SKB, 1992). The latter project involved comprehensive modelling efforts, including both deterministic and stochastic continuum modelling and discrete fracture modelling (Table 7). Scoping calculations were also carried out to study the effects of saline groundwater and the influence of permafrost.

The basic strategy in the SKB 91 project was to perform deterministic continuum modelling in the regional area and subsequent stochastic continuum modelling in the local area. The main results of this modelling are described in this chapter.

The geohydrological deterministic continuum modelling in the regional area at Finnsjön within the SKB 91 project was performed using a model code based on the finite element method (NAMMU) together with a modified version of the program package HYPAC. Subsequently, stochastic continuum modelling was carried out in the local area using the program package HYDRASTAR. In addition, the code PHOENICS was used to model saline groundwater flow and FRACMAN/MAFIC for discrete fracture modelling as an alternative description of the groundwater flow pattern in the rock.

6.2 Available data

The geoinformation used in SKB 91 for the hydraulic modelling consist of conceptual models of fracture zones on different scales, hydrological and hydrometeorological data, contour maps of the groundwater table and hydraulic conductivity data from hydraulic single hole tests. Measurements of the natural groundwater flow through isolated sections of two boreholes were also used for model validation.

All background data for the hydraulic modelling are presented in Andersson et al. (1989). Subsequently, the geological interpretation of a few of the fracture zones was slightly modified by Ahlbom and Tirén (1991) followed by a corresponding updating of the background data report (Andersson et al., 1991). The hydraulic modelling was mainly based on the information in the original data report by Andersson et al. (1989). However, in some of the subsequent variation analyses the effects of the updating were studied.

Table 7. Groundwater flow modelling related to the SKB 91 project.

Item	Reference
Deterministic continuum modelling	
Initial groundwater flow calculations	Lindbom et al. (1991)
Variation analyses of groundwater flow	Lindbom and Lindberg (1991)
Complementary calculations	Lindbom and Boghammar (1991a)
Extended regional area	Lindbom and Boghammar (1992a)
Influence of the regional gradient	Lindbom and Boghammar (1992b)
Sensitivity analysis of groundwater flow	Yung-Bing Bao and Thunvik (1991)
Effects on dilution in a domestic well	Axelsson et al., (1991)
Impact of fluid density gradients	Ahlbom and Svensson (1991)
Influence of glaciation and permafrost	Lindbom and Boghammar (1991b)
Stochastic continuum modelling	
Reference case	SKB 91, SKB AR 92-33, 92-01
Variations	SKB 91, SKB AR 92-27, 92-28, 92-29, 92-30, 92-31, 92-32
Validation of flux calculation	Boghammar (1992)
Discrete fracture modelling	
Feasibility study	Geier and Axelsson (1991)
Discrete fracture model	Geier et al., (1992)

Table 8 presents the number of single hole water injection tests performed at Finnsjön (excluding early tests in the percussion boreholes HGB01-17). To provide an estimate on the "investigation density" also the number of tests per km^2 of the Finnsjön Rock Block (c. 6.6 km^2) is presented. In total, 11 cored boreholes with vertical depths ranging from 193 m to 691 m (Table 2) and three percussion boreholes (129-459 m vertical depths) have been tested hydraulically during the time period 1977-1987 (cf. Appendixes A and B). Table 8 shows that the total number of tests performed at Finnsjön is considerably higher in comparison to the other study sites, particularly in short borehole sections.

In the early testing campaigns a test section length of 3 m was normally used throughout the boreholes (Table 3). In the Fracture Zone Project, the intervals of Zone 2 were generally tested in 2 m sections and a few boreholes in 20 m sections. A few tests with 5 m and 10 m have also been performed. Finally, a special survey was made over a total length of 10 m in borehole BFI02 using injection tests in 0.11 m borehole sections. The total borehole length covered by continuous double-packer tests with a section length of 20 m at Finnsjön is 1550 m, with 2 m length 1660 m and with 3 m length 4131 m.

Table 8. Number of borehole sections tested with different length together with number of tests per km^2 at Finnsjön.

Number of sections	Section length (m)	No of tests/km^{2*}	Test type
78	20	12	double-packer
12	10	2	double-packer
12	5	2	double-packer
1377	3	209	double-packer
830	2	126	double-packer
97	0.11	15	double-packer
2406		365	all sections

* area of the Finnsjön Rock Block (6.6 km^2)

6.3 Regional scale

Hydrological conditions and groundwater table

A (semi)regional area at Finnsjön was delineated in Andersson et al. (1989, 1991). A contour map of the (mean) groundwater table within this area is shown in Figure 32. Subsequently, a regional model domain was selected within this area (Figure 33). The topography of the groundwater table is relatively flat, ranging from about 45 m (metres above sea level) in southwest to about 12 m in northeast. Based on the groundwater table map the regional, shallow groundwater flow is primarily directed from southwest to northeast with local deviations. Local, minor discharge areas are found in low-lying parts within the area.The regional hydraulic gradient is about 0.2-0.3% for the shallow groundwater.

The average precipitation in northern Uppland is 670 mm/year. The potential and actual evaporation is estimated to 540 mm/year and 430 mm/year, respectively. The run-off is 240 mm/year.

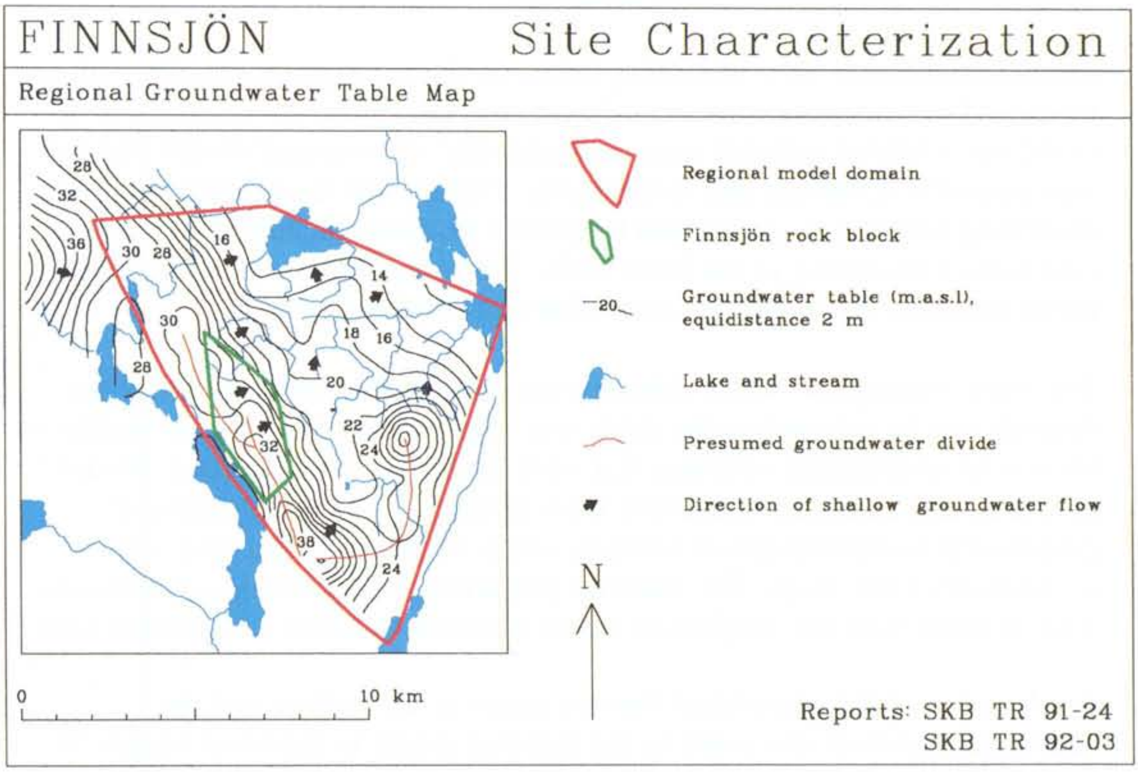


Figure 32. Map of groundwater table for the regional area.

Occurrence of saline groundwater

According to a nationwide compilation of saline wells by the Swedish Geological Survey, saline groundwater (>300 mg/l of chloride) is commonly found in shallow wells (up to 100 m deep) in northeastern Uppland where the Finnsjön site is located. It is estimated that at least 10% of all shallow water wells (50-100 m deep) in this region encounter saline water. Most of the saline wells are located near the coast of the Bottnian Sea but many saline wells are also encountered inland.

In the Dannemora Mine, located 17 km to the south of Finnsjön site, saline groundwater of 7000 mg/l of chloride occurs at 420 m depth. In the SFR repository, located beneath the Bottnian Sea, saline groundwater of up to 6000 mg/l of chloride has been encountered. The chloride content of the brackish water of the Bottnian Sea at SFR is 3000-4000 mg/l (Ahlbom and Svennson 1991). Saline groundwater is present in several boreholes in the Finnsjön site. The salinity is about 0.8%, or 5000-6000 mg/l of chloride, at depths ranging from 90-300 m (Figure 38). The Finnsjön study site is located 13 km from the Bottnian Sea.

Deterministic groundwater flow modelling

Initial groundwater flow modelling based on the assumption that the rock can be treated as a (deterministic) continuum was performed by Lindbom et al. (1991) in a limited regional area. Subsequently, the regional model domain was extended (Lindbom and Boghammar 1992a). The latter (deterministic) modelling was mainly performed to provide boundary conditions to the (stochastic) modelling in the local scale. The deterministic modelling was performed with the NAMMU code (Rae and Robinson 1979).

The basic assumption in the deterministic continuum modelling is that the bedrock can be represented by either one single continuum (porous media) or by several overlapping continua, e.g. rock mass and fracture zones. Model geometry and boundary conditions were obtained using geological and geophysical interpretations of fracture zones, hydrogeological data and groundwater table maps. The material properties, i.e. hydraulic conductivity, were derived from the single hole water injection tests and interference tests.

The location of the interpreted fracture zones at the surface and the conceptualization of the zones in the regional model is shown in Figure 33. The areal coverage of the regional model domain is about 80 km^2. The outer boundaries of the domain (except the northern) approximately coincide with regional lineaments interpreted in the simplified rock block map (Figure 33). The western part of the northern boundary aligns with the main hydraulic gradient at that location. The groundwater table within the regional domain (Figure 32) was digitized and used as the upper boundary condition in the model (zero prescribed head). The outer boundaries of the regional model domain were all treated as vertical no-flow boundaries. The lower boundary was modelled as a horizontal no-flow boundary at 1500 m depth.

The hydraulic units included in the regional model were 1.) the rock mass (excluding all interpreted fracture zones) and 2.) the fracture zones delimiting the regional model domain together with the semiregional fracture zones within the model domain (Table 9). In addition, the influence of a generic subhorizontal zone (2u), located 600 m below and parallel to Zone 2, was studied. Zone 2 was assumed to be confined between Zones 1, 4 and 12, while Zone 2u was assumed to extend to the confinements of the modelled domain. The position of its modelled outcropping is shown in Figure 33.

The modelled geometry (width and orientation) of the fracture zones (including Zone 2u) is presented in Table 9. The fracture zones within the regional domain were implicitly modelled. The finite element mesh consisted of roughly 18 400 eight-noded brick elements with totally about 20 700 nodes.

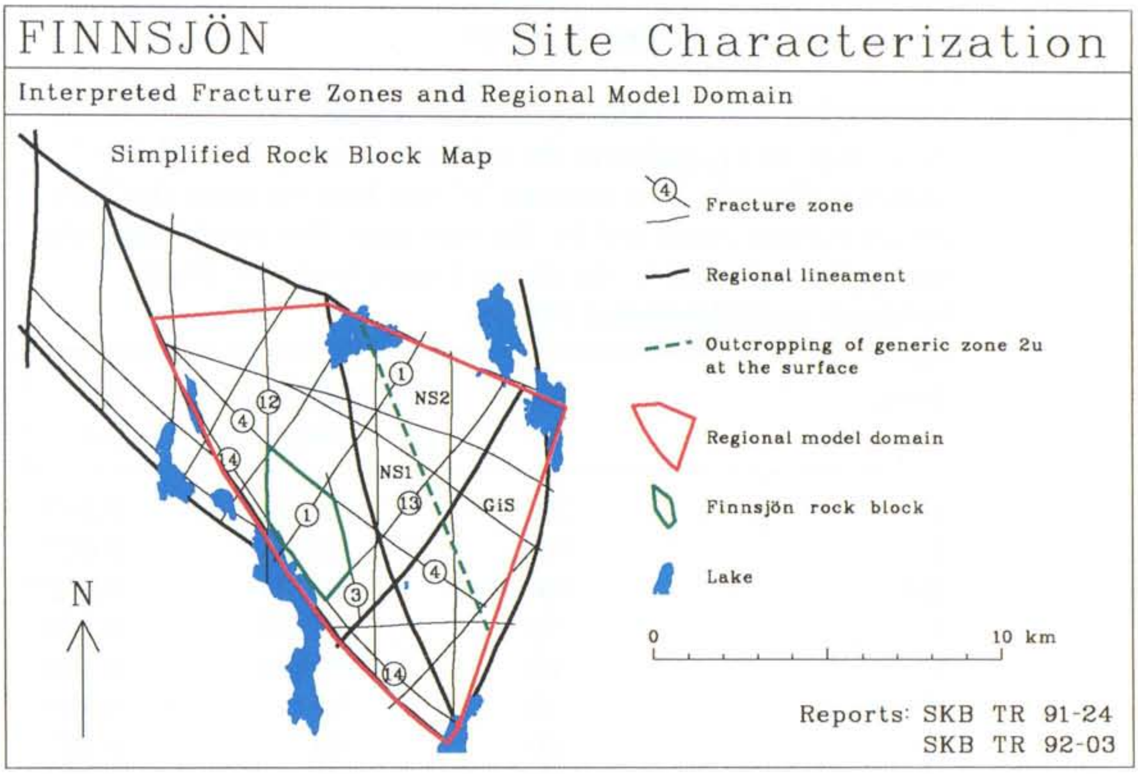


Figure 33. Interpreted and modelled fracture zones at the surface in the regional model at Finnsjön.

The hydraulic conductivity versus depth functions assigned to the rock mass and fracture zones in the regional model were based on regression analyses of (the logarithms of) upscaled conductivity data from 2 m and 3 m long borehole sections to an averaging length of 36 m. This procedure is described by Norman (1992). The regression curves were based on a power function of the following form:

$$K = a \cdot z^{-b} \qquad (z > 0) \qquad (6.1)$$

where K is hydraulic conductivity, z is vertical depth below ground surface and a and b are constants. Measured data below the lower measurement limit were assigned the actual value of this limit in the regression analyses (Table 3).

The hydraulic conductivities for both the rock mass and the fracture zones were assumed to obey Eqn. (6.1) with the same value of the constant 'b' in this equation (b=2.23) for the rock mass and fracture zones. The values of the constant 'a' for the fracture zones applied in the reference case are shown in Table 9. The value of 'a' in the depth functions for the rock mass was 0.0121 in all cases except one, in which the hydraulic properties of the rock mass was decreased by one order of magnitude to increase the contrast between the rock mass and the fracture zones.

Table 9. Geometrical data of the fracture zones together with the constant 'a' in Eqn. (6.1) applied in the reference case of the regional model at Finnsjön. The constant 'b' was kept the same (b=2.23) for all fracture zones and for the rock mass. For comparison, also the applied value of 'a' for the rock mass is shown. From Lindbom and Boghammar (1992a).

Zone	Width (m)	Inclination (degrees)	a (-)
1	20	75 SE	0.187
2	100	16 SW	0.427
2u[1]	100	16 SW	(0.427)
3	50	80 SW	0.140
4	10	60 SW	0.118
12	50	90	0.118
13	50	90	0.187
14	50	90	0.118
Skogsbo (Sk)	100	90	0.270
Giboda (Gi)	100	90	0.270
Imundbo (Im)[2]	100	90	0.270
Gräsbo (Gr)	100	90	0.118
Dannemora (Da)	100	90	0.118
Källviken (Kä)	100	90	0.187
Giboda S (GiS)[3]	50	90	0.270
NS1	50	90	0.118
NS2[4]	25	90	0.118
Rock mass			0.012

1) Generic zone (only in Cases X36V3 and X36V4).
2) Inclined 45° SW in Case 36V4.
3) The zone is assumed to have the same hydraulic properties as the zone Giboda but with an intermediate width between this zone and Zone 4
4) The zone is assumed to have the same hydraulic properties as Zone 12 but a different width.

Due to the lack of measured data in the rock mass and from several of the fracture zones in the regional scale the hydraulic conductivity functions applied in the regional model were based on regression analyses of data from boreholes within the Finnsjön Rock Block. Figure 34 shows all measured hydraulic conductivity data from 3 m sections in the rock mass in selected boreholes in the southern and northern part of the Finnsjön Rock Block together with the calculated conductivity functions.

Regression curves based on measured data in 3 m sections are shown for the northern and southern parts of the site. The lower measurement limit for these sections corresponds to a hydraulic conductivity of about $2 \cdot 10^{-10}$ m/s. Also shown is a regression curve based on statistical analyses of upscaled data in 36 m sections. This depth function was applied to the rock mass in the regional (deterministic) modelling. It should be observed that the underlying data sets were not identical in the derivation of the two types of regression curves. The former curves were based on selected data in 3 m sections solely, while the latter curve was based on data in both 2 m and 3 m sections (upscaled to 36 m).

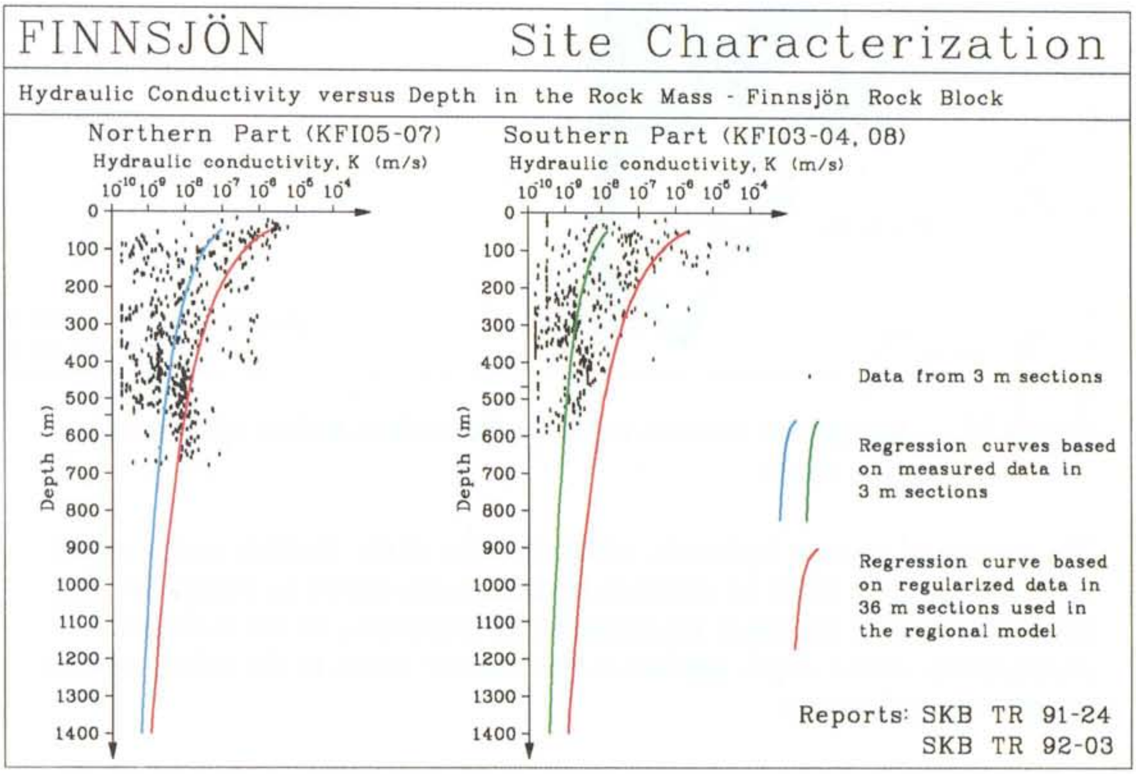


Figure 34. Measured hydraulic conductivity in 3 m sections in the rock mass in the southern and northern parts of the Finnsjön Rock Block together with calculated regression curves. For comparison, the regression curve based on upscaled data used in the geohydrological modelling, is also shown.

Due to lack of data, the hydraulic conductivity of most regional fracture zones (Table 9) were estimated using a combination of known hydrogeological information from similar structures outside the Finnsjön area, together with upscaled data from single-hole hydraulic tests in 2 m and 3 m sections of local fracture zones at the Finnsjön site. The interpreted fracture zones within the site is shown in Figure 35.

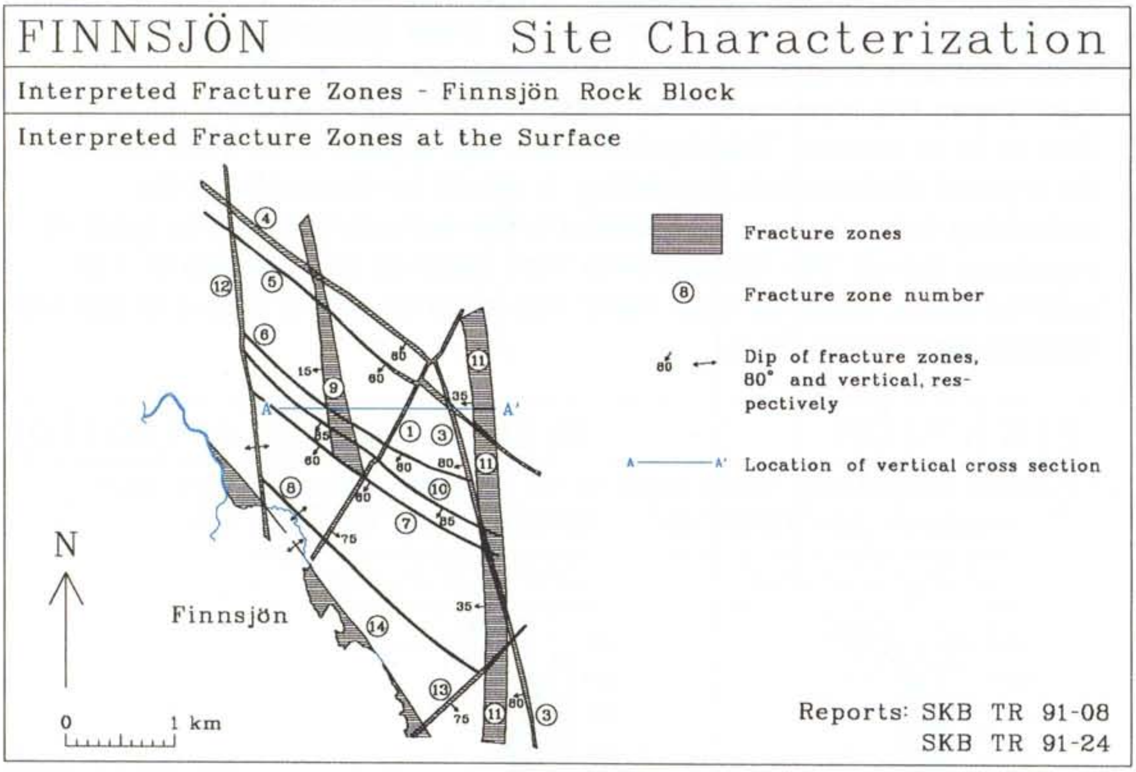


Figure 35. Interpreted fracture zones at the surface within the Finnsjön rock block.

The measured average hydraulic conductivities of the fracture zones within the Finnsjön rock block in different boreholes are shown in Figure 36. The figure also shows the range (maximum and minimum) of the hydraulic conductivity versus depth applied to the fracture zones in the reference case for the regional model.

According to Eqn (6.1) and Table 9 the applied hydraulic conductivity of Zone 2 at 200 m depth is about $3 \cdot 10^{-6}$ m/s, i.e about 35 times higher than that of the rock mass at that depth. Similarly, the applied conductivity of the generic subhorizontal zone (Zone 2u) at 800 m depth was about 10^{-7} m/s, which again is about 35 times higher than the adjacent rock mass.

In total, one reference case and seven variation cases were modelled on the regional scale. The reference case was aimed at providing boundary pressure conditions to the local (stochastic model). The variation cases were aimed at elucidating the sensitivity of the hydraulic conductivity contrast between the rock mass and fracture zones, the presence of a subhorizontal zone at depth and the degree of confidence in the location of the discharge area.

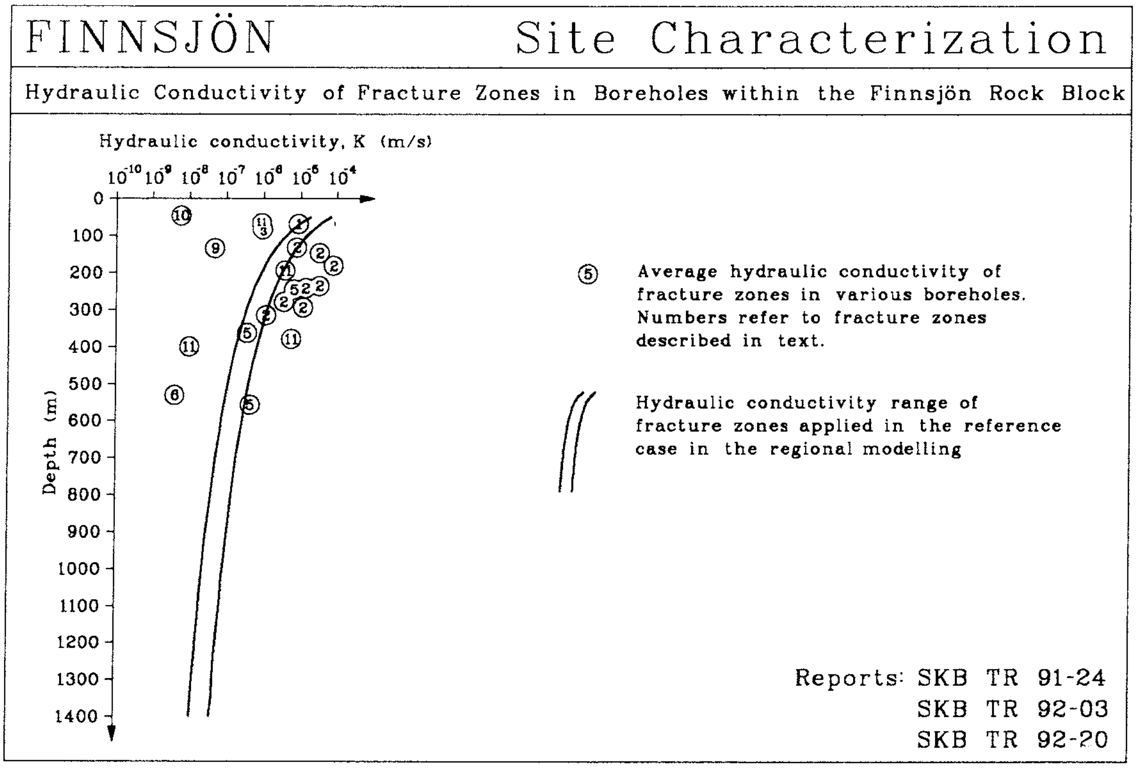


Figure 36. Average hydraulic conductivities of the fracture zones within the Finnsjön Rock Block measured in different boreholes together with the range of hydraulic conductivities applied to fracture zones in the reference case in the regional model. Locations of fracture zones are presented in Figure 35.

In the reference case the applied hydraulic conductivities of the subvertical fracture zones were about 1.5 order of magnitude higher than that of the rock mass. The groundwater fluxes at repository level (600 m) in the local scale block were calculated to about 0.001 m^3/m^2/year (1000 ml/m^2/year) as a median value with a tendency to higher values in the vicinity of Zone 4. The upper quartile value was almost 0.002 m^3/m^2/year.

In the first two variation cases the hydraulic conductivity contrast between the rock mass and fracture zones was increased to between two and three orders of magnitude by increasing the fracture zone conductivity or by decreasing the rock mass conductivity. As expected, an increase in the conductivity of the fracture zones resulted in an increase in groundwater flux at repository level (by maximum one order of magnitude). A decrease of the rock mass conductivity resulted in a decrease of the fluxes at repository level in proportion to the reduction of the rock mass conductivity.

The next three variation cases intended to study the influence by Zone 2 and the influence of a high-conductive subhorizontal fracture zone below Zone 2. In the first case, Zone 2 was assigned the same hydraulic conductivity as that of the rock mass, i.e. the zone was neglected. In the next case both Zone 2 and the generic subhorizontal zone (Zone 2u) were modelled according to the geometry given in Table 9. The two zones were assigned the same hydraulic conductivity versus depth functions (Table 9). In the third case Zone 2 was again modelled as the rock mass, while Zone 2u was modelled as before.

The presence of high-conductive fracture zones had a strong influence on the results, particularly the situation with such a zone located below the repository without the presence of a similar zone above the repository. The two cases with the generic, deep zone included, resulted in median values of the fluxes at repository level of about 0.002 m^3/m^2/year, being roughly twice as high as the other cases.

The last two variation cases were aimed at studying the confidence in the location of the discharge area in the regional model. The initial study by Lindbom et al. (1991) indicated that the Imundbo fracture zone (Figure 33) acted as the major discharge area for particles released within the potential repository. Both the geometry and hydraulic properties of the Imundbo zone are highly uncertain (Andersson et al.,1989, 1991). Because of this fact the Imundbo zone was assigned hydraulic properties as the rock mass in the first variation case. Hereby it was possible to analyzing whether the topography of the area around the zone was pronounced enough to act as a discharge area without the presence of the Imundbo zone. In the second variation case the sensitivity to the inclination of the Imundbo zone was studied by changing the dip of the zone to 45° SW, which means that the zone approaches the potential repository with depth.

The variation analyses showed that the discharge point for released water particles was rather well-defined. The major discharge collector was located at the Imundbo zone, both when this zone was assigned rock mass properties and when the zone was assumed to be inclined towards the repository.

No specific calculations (e.g. recharge rate or groundwater flow in Zone 2) were made to assess the validity of the regional model. Compared to the modelling by Lindbom et al. (1991), the conductivities used for the fracture zones in Lindbom and Boghammar (1992a) study were significantly lower and based on more relevant statistical analyses (regularisation). On the other hand, the applied conductivity of the rock mass was slightly higher. The combined effect resulted in increased flux values in the rock mass at repository level by about one order of magnitude.

6.4 Local scale

Geohydrological conditions

A contour map of the (mean) groundwater table within the Finnsjön Rock Block is shown in Figure 37. The topography of the groundwater table is flat, ranging from about 33 m (above sea level) in the central part to about 28 and 22 m in southwest and northeast, respectively. Based on the groundwater table map the shallow groundwater flow is directed from the local elevation in the central part in all directions with the main flow towards northeast. Outside the local domain, discharge areas (swamps) are found in low-lying parts in northeast.

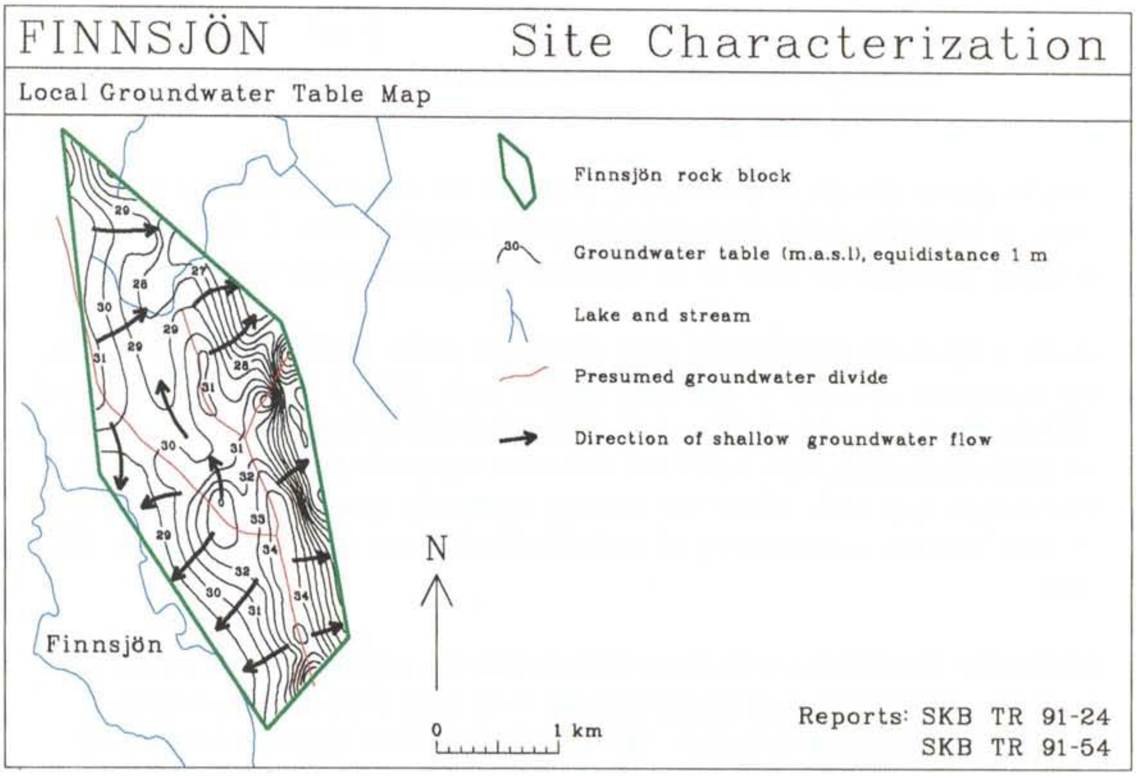


Figure 37. Groundwater table within the Finnsjön Rock Block.

Fracture zones with emphasis on Zone 2

Interpreted width, transmissivity and average hydraulic conductivity of those fracture zones where hydraulic data are available are shown in Table 10. The hydraulic parameters are calculated from hydraulic single-hole tests in 2 m and 3 m sections and interference tests (Zone 2).

Table 10. Estimated width, transmissivity and average hydraulic conductivity of the fracture zones within the Finnsjön Rock Block.

Fracture zone	Number of boreholes	Width (m)	T (m^2/s)	K (m/s)
1	1	20	$2 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
2	8*	100	$2\text{-}3 \cdot 10^{-3}$	$2\text{-}3 \cdot 10^{-5}$
3	1	50	$1 \cdot 10^{-4}$	$2 \cdot 10^{-6}$
5	3	5	$4 \cdot 10^{-5}$	$8 \cdot 10^{-6}$
6	1	5	$3 \cdot 10^{-8}$	$6 \cdot 10^{-9}$
9	1	50	$3 \cdot 10^{-6}$	$5 \cdot 10^{-8}$
10	1	5	$3 \cdot 10^{-8}$	$6 \cdot 10^{-9}$
11	4	100	$2 \cdot 10^{-4}$	$2 \cdot 10^{-6}$

* borehole HFI01 not included.

The hydraulically most dominating and also the most investigated fracture zone at Finnsjön is the subhorizontal-gently dipping Zone 2. Because of this, a rather thorough account of its hydraulic properties is presented below.

Zone 2 has been identified in nine boreholes in the northern part of the site, i.e. northwest of Zone 1. The total thickness of Zone 2 is estimated to about 100 m. Hydraulic single-hole tests shows that the zone consists of a number of high-conductive, thin (<0.5 m) subzones separated by long intervals of low-conductive rock. While the average hydraulic conductivity of Zone 2 is $2\text{-}3 \cdot 10^{-5}$ m/s the conductivity of individual subzones may be as high as 10^{-3} m/s.

Hydraulic interference tests have shown that the uppermost part of the zone is highly conductive and interconnected over long distances (hundreds of meters) in the lateral direction. The interference tests together with tracer tests have also shown that the subzones within Zone 2 are hydraulically interconnected. A schematic cross section (A-A') showing the extent of Zone 2 and the groundwater flow conditions in and adjacent to the zone is presented in Figure 38. The location of the cross section is shown in Figure 35.

Measurements of the natural groundwater flow through isolated sections in one borehole indicated a high flow rate in the uppermost high-conductive part of Zone 2 whereas no measurable flow was observed in a similar, high-conductive subzone at the bottom of the zone. This fact is probably due to the lack of a sufficient driving force (hydraulic gradient) in this part. It is assumed that the uppermost part of the zone acts as a "hydraulic barrier" thus shortcircuiting the topographically induced hydraulic gradient. Also the occurrence of relict saline groundwater below the uppermost part of Zone 2 indicates stagnant groundwater flow conditions.

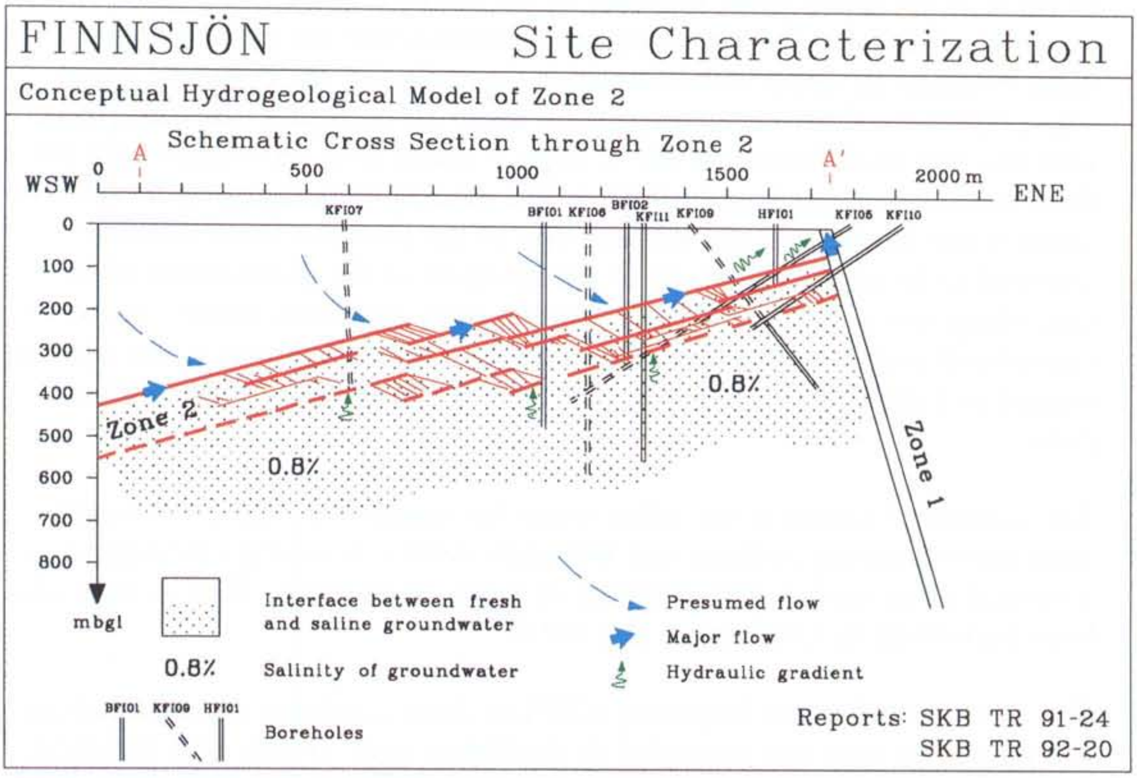


Figure 38. Schematic illustration of groundwater movements in and around Zone 2.

The natural groundwater flow in the upper part of Zone 2 through a 1000 m wide cross section is estimated to be in the order of 150 000-370 000 m^3/year (5-12 l/s) Gustafsson and Andersson (1991). Such high flow rates can probably not solely be explained by local recharge through the overlying rock, instead a major part of the recharge (and drainage) is likely to take place via fracture zones outside the Finnsjön Rock Block. Recharge may possibly occur below Lake Finnsjön (via the regional Zone 14) while the drainage probably occurs via several fracture zones (1, 5 and 11), located just outside the northeastern part of the Finnsjön Rock Block (Figure 35).

Saline groundwater is found in all (nine) boreholes in the northern part of the Finnsjön Rock Block at depths ranging from 90-300 m, corresponding to the upper boundary of Zone 2. In the southern part no saline water has been encountered in any of the four cored boreholes drilled to depths of 500-600

m. Apart from the northern block, saline groundwater has also been encountered in borehole (KFI08), penetrating the eastern boundary of the Finnsjön Rock Block, and continuing under farmland to the east. The farmland is covered by a thick layer of glacial clay (7-8 m thickness).

According to a tentative model presented in Ahlbom and Svensson (1991) the location of the saline water interface in the northern block is governed by the presence of Zone 2, which is assumed to shortcircuite the saline water below Lake Finnsjön (at about 370 m depth) in the west and the presumed saline water below the farmland in the east (at about 10 m depth). The saline water interface will thus follow the dip of Zone 2 which is in accordance with the field observations (Andersson et al. 1991). According to the same model, the saline water interface in the southern part of the Finnsjön Rock Block is assumed to be an inverse image of the elevation of the groundwater table (according to a certain depth ratio between fresh and saline water). In the central and southern parts the saline interface would according to this ratio be located at a depth of 700-1000 m, i.e below the boreholes drilled in these parts.

The conceptual model of the saline water has tentatively been confirmed by numerical modelling Ahlbom and Svensson (1991). Scooping calculations in a vertical cross section with presence of saline water below Zone 2, have also been performed by Lindbom et al. (1991).

The conductive fracture frequency (CFF) in Zone 2 and the rock mass above and below the zone was estimated in Andersson et al. (1988) by a statistical method using hydraulic conductivity data from 2 m and 3 m sections in selected boreholes. The estimated range of average CFF in Zone 2 was 0.90-1.15, whereas the average CFF in the rock mass above and below the zone was 0.47-1.44 and 0.56-0.76, respectively. It should be pointed out that these values are based on shorter test sections than the values reported from other study sites, e.g. Fjällveden and Gideå, and thus not directly comparable.

Stochastic groundwater flow modelling

In the local scale, stochastic groundwater flow modelling was performed in SKB 91 using the code HYDRASTAR. This code carries out Monte Carlo simulation of the steady-state form of the hydrology equation in a rectilinear block. The rock is assumed to be a stochastic continuum. The modelled block is shown in Figure 39. The block is about 5 x 3 x 1.5 km in size.

The simulation of groundwater flow with HYDRASTAR is preceeded by geostatistical analyses of available hydraulic conductivity data from single-hole tests with different packer spacing. Prior to the analyses these data are first scaled up to the desired averaging scale to be used in the simulation. The analyses result in a statistical description (model) of the data with a given variance, correlation length and, where applicable, trend. These values are then used as input data in HYDRASTAR to reproduce the spatial variability of the rock in the stochastic modelling. Based on the statistical model different realizations of the conductivity field are generated. The actual hydrology equation is then solved and the resulting hydraulic head and flux distributions are calculated.

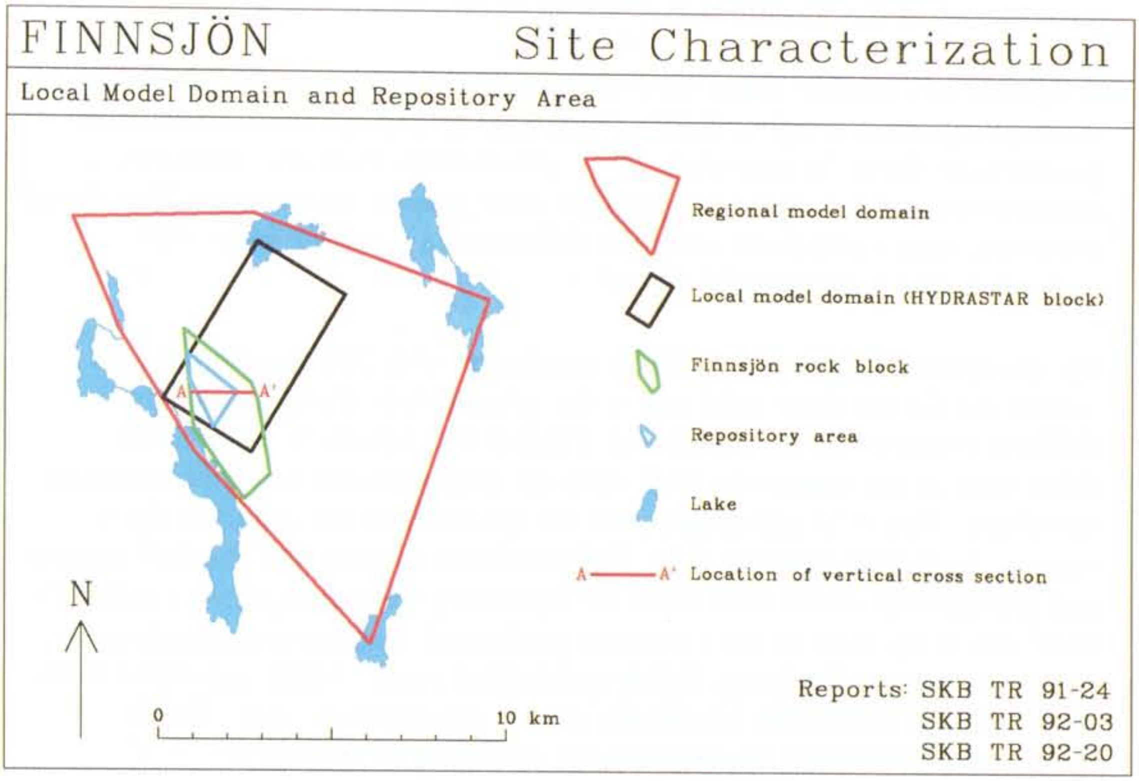


Figure 39. Location of the local model domain (HYDRASTAR block) and the repository area within the regional model domain.

In order to get consistency between the regional (deterministic) and the local stochastic modelling the same averaging scale, i.e. 36 m, was used in the reference case in the stochastic modelling. Hydraulic conductivity data from 2 m and 3 m sections were scaled up to this averaging scale (Norman 1992). Boundary conditions were imposed on the outer boundaries of the modelled block by transferring the calculated potential field from the regional modelling, described in Section 6.3. This means that the influence of the groundwater table is also included via the regional model. Repository drifts and canister positions were inserted in the model according to a specific repository description. A disturbed zone around the deposition drifts was also introduced with certain hydraulic properties.

The SKB 91 reference case in the stochastic modelling was based on a statistical model with trends based on a spherically isotropic variogram functions. The trend was according to the regression curves of hydraulic conductivity, based on upscaled data for the rock mass is shown in Figure 34. The reference case model was based on the averaging scale of 36 m with a variance of 1.25 and a correlation length of 106 m for the logarithm of the hydraulic conductivity. The extent of the disturbed zone was assumed to be 1 m around the deposition drifts with a hydraulic conductivity of 10^{-6} m/s. The conductivity of the backfill was assumed to 10^{-9} m/s.

A number of variation cases were also carried out to assess the sensitivity of varying, e.g. the averaging scale or hydraulic properties, on the calculated groundwater fluxes at repository level, travel times from the repository, conductivity fields and the groundwater flow pattern, respectively. The model variations were carried out with two different-sized model areas, the "reference case" and "smaller block".

For the reference case Monte Carlo simulation with 500 realizations was carried out for the flow field and of the groundwater travel times from different positions in the repository. Typical flux values of about 0.001 m^3/m^2/year at the repository level (600 m) were obtained from the stochastic modelling. This is in agreement with the results from the regional, deterministic modelling (Section 6.3). The variations showed that the flow pattern and groundwater travel time from the repository were changed to a relatively small extent by most of the variations performed. Significant changes are mainly caused by flat-lying, highly conductive zones, which can create both more and less favourable conditions than in the reference case. The calculated groundwater travel times are presented in Chapter 8.

The validity of the results from the stochastic modelling was assessed by simulations of the natural groundwater flow in different boreholes at Finnsjön. The modelled flows were compared with results from field measurements of the natural flow with a point dilution probe presented in Andersson et al. (1991). Comparisons in one borehole (BFI01) showed that the extremely high fluxes measured on a metre scale at the upper interface of Zone 2 could not be recreated by the stochastic model. However, there is a good agreement when considering the total flow. The simulated fluxes above the zone are also in reasonably good agreement with the measured.

In the lower, high-conductive part of Zone 2 the groundwater is more or less stagnant. This situation was not reproduced in the stochastic modelling (nor the deterministic modelling), probably because the modelling did not take into account the presence of a more saline and heavier groundwater at this level.

7. GROUNDWATER CHEMISTRY

7.1 Scope and reliability of samples

Sampling of groundwater for chemical analyses have been made intermittently from 1977 to 1989. All together, 19 boreholes have been sampled. The results, including sampling methods, are presented by Hultberg et al (1981), Gustafsson and Klockars (1981), Laurent (1982), Ahlbom et al. (1986), Smellie et al. (1987), Smellie and Wikberg (1989) and Andersson et al. (1991). In Ekman (1989) a compilation of investigated parameters of all boreholes at Finnsjön up till 1988 are presented.

The results and reliability of the early groundwater samples are discussed in Allard et al. (1983), Nordstrom and Puigdomenech (1986), Puigdomenech and Nordstrom (1987). By considering various sources of contamination it was concluded that boreholes KFI05, KFI06, KFI08, KFI09 and BFI01 can be regarded as relatively free from contamination during groundwater sampling procedures and thus representative for the depth sampled. Boreholes KFI04 and KFI07 show varying degree of contamination. Boreholes KFI01 and KFI02 are contaminated by near-surface and/or flushing water during sampling.

The methodology for sampling analysis of borehole water was developed considerable with the introduction of the mobile laboratory in 1984. This made it possible to analyze the most sensitive components immediately and to carry out sampling under well-controlled conditions. These improvements mean that the most reliable analyses of deep groundwater are from the most recently sampled boreholes, manly KFI09 and BFI01.

This chapter review some of the most important results with emphasis on the sampling performed by the mobile laboratory. A division is made into general chemistry, redox-sensitive parameters, uranium chemistry and environmental isotopes. Such a division is somewhat arbitrary, and obviously some of the parameters overlap. Where not specifically referenced, the comments made are generally based on the extensive data analysis carried out by Ahlbom et al. (1986), Smellie and Wikberg (1989) and Andersson et al. (1991).

7.2 Results

General chemistry

Groundwater sampling in the two boreholes KFI09 and BFI01 shows the three main types of groundwaters that are present at the Finnsjön study site,

Table 11. These waters are; near-surface and shallow groundwaters, intermediate to deep non-saline groundwater and deep saline groundwater of old age.

The groundwater chemistries in the various boreholes show the following characteristics:

- Saline groundwater occurs in boreholes KFI05, KFI06 and KFI08, where the chloride concentrations range from 2500 - 5900 mg/l. Low tritium content and relatively old ^{14}C ages also typify these waters thus establish them as representative and free from major contamination.
- Groundwaters from boreholes KFI04 and KFI07 exhibit higher tritium and younger relative ^{14}C ages which, together with smaller concentrations of chloride indicates varying degree of contamination from other sources.
- Non-saline water in KFI01 and KFI02 are characterized by high or very high tritium content and correspondingly low ^{14}C ages. These waters are not representative for the measured holes.
- Boreholes KFI09 and BFI01 show the transition of non-saline to saline groundwater with depth. The boundary occurs at Zone 2. Vertical trends in groundwater chemistry from these boreholes show the clear distinction between non-saline groundwater (calcium-bicarbonate type) and saline groundwater. The pH, in contrast, shows a decrease with depth from just above Zone 2, which is contrary to that normally indicated by Swedish groundwaters at increasing depths.
- Of the cations, calcium, sodium and magnesium show marked increases with depth, potassium is less emphasized. Of the anions, bicarbonate decreases with depths accompanied by a sympathetic increases of chloride and sulfate, increases on bromide, iodine and fluoride are also present.

The origin of the Finnsjön saline water and of saline water in general, in deep crystalline aquifers in Fennoscandia, have been debated by several authors such as Allard et al. 1983, Ahlbom et al. 1986 and Puigdomenech and Nordstrom 1987. Wikberg et al. (1987) suggests that the Finnsjön groundwaters can be considered as a mixture of water derived from the Yoldia/Litorina marine transgressions, residual fluids (igneous/metamorphic) and fluids derived from the mechanical breakdown of fluid inclusions.

Redox-sensitive parameters

Some of the redox-sensitive parameters are presented in Table 11. Generally, the samples are reducing, as indicated by negative Eh-values. There are no apparent trends with depth in any of the redox parameters. However, the most striking feature is the highly oxidizing character of the groundwaters sampled from Zone 2 in borehole BFI01. This is attributed to perturbations caused by the percussion drilling when air at high pressure was forced into Zone 2. Borehole KFI09, drilled using conventional core drilling techniques, provides a more normal situation with negative Eh readings.

Uranium geochemistry

The measurements of uranium content and the activity ratio $^{234}U/^{238}U$ were performed in boreholes BFI01 and KFI09, Table 11. There is a tendency to find relatively high uranium contents closer to the surface and relatively low concentrations in the deeper sections (Smellie et al. 1987). The uranium isotope contents indicate widespread disequilibrium in the groundwaters. For example, the isotope ratios lacks the relatively high values (except for BFI01, 284 m), indicating that the groundwaters have had medium-long residence times in contact with the bedrock. The high value for BFI01, 284 m may be explained by the positive Eh value.

Environmental isotopes

A summary of the analyses of the environmental isotopes are presented in Andersson et al. (1991). The stable isotope data show very little variation with depth and can be considered to be meteoric origin. Radioisotope data, i.e. percentage modern carbon and tritium content, clearly indicate the extent of the young, near-surface derived fresh water component characterized by high amounts of modern-derived carbon and significant tritium contents. With increasing depths and salinity the groundwaters rapidly exhibit a reduction in the modern-derived carbon with an minima at the lower horizons at Zone 2. At these depths no significant tritium has been detected.

Trace elements

During two tracer tests in 1988 and 1989 chemical analyses to cover background concentrations of trace elements, as c.f REE, in groundwater were performed. The tracer tests were made where Zone 2 intersects boreholes BFI01, BFI02, KFI06 and KFI11. For further information see Gustafsson et al., (in manuscript) and Andersson et al. (1990).

Table 11. Chemical groundwater composition from boreholes KFI09 and BFI01, Finnsjön.

Borehole		KFI09	KFI09	KFI09	KFI09	BFI01	BFI01	BFI01	BFI01	BFI01	BFI01
Level	(m)	94	114	182	360	71-85	169-191	234-247	284-294	335-385	439-459
pH		7.3	7.5	7.4	7.6	6.9	7.7	7.7	***	***	***
Eh	(mV)	-245	-300	-212	-	+40	-320	-270	***	***	***
Alkalinity (mg/l bicarbonate)		285	116	160	32	220	200	260	***	***	***
Calcium	(mg/l)	115	-	700	1700	76	270	320	1500	1500	1600
Magnesium	(mg/l)	16	-	91	84	6.3	36	40	126	140	140
Sodium	(mg/l)	415	-	960	1500	23	610	650	1600	1700	1700
Potassium	(mg/l)	5.8	-	15	7.4	3.2	6.5	8.7	15	15	13
Iron(II)	(mg/l)	0.56	0.36	1.07	0.34	8.86	0.50	0.87	***	***	***
Iron(Tot)	(mg/l)	0.56	0.35	1.08	0.35	9.01	0.51	0.90	***	***	***
Manganese	(mg/l)	0.19	0.45	0.82	0.36	0.50	0.37	0.42	***	***	***
Sulfide	(mg/l)	0.22	-	0.44	0.03	<0.01	0.01	<0.01	***	***	***
Sulfate	(mg/l)	175	-	210	340	8.3	150	140	380	400	380
Chloride	(mg/l)	680	2100	2800	5200	61	1300	1500	5200	5500	5500
Bromide	(mg/l)	2.0	-	14	27	0.3	4.5	7.0	26	29	29
Iodine	(mg/l)	0.01	-	0.03	0.07	<0.002	0.02	0.04	0.07	0.12	0.12
Silica	(mg/l)	7.6	1.8	4.6	7.6	6.2	8.3	7.5	5.5	6	5.4
TOC	(mg/l)	18	-	7.5	1.0	16	12	6.9	***	***	***
Ammonium	(mg/l)	-	-	1.1	-	0.15	0.34	0.63	0.46	0.71	0.35
Nitrate	(µg/l)	20	-	19	10	6	<5	5	<5	<5	<5
Phosphate	(µg/l)	1	2	3	4	1	1	<2	<5	2	<5
Uranium	(µg/l)	2.1	-	1.6	8.2	4.6	13	3.9	***	***	***

*** The values of these parameters are affected by the drilling and therefore not presented

\- Not determined TOC= Total organic carbon

7.3 Summary and relevance of results

A total of 19 boreholes have been sampled at Finnsjön. In general, the overall picture from these boreholes is fairly simple with Zone 2 as a structural/hydraulic barrier to vertical groundwater movement. Downward moving non-saline groundwater flow will preferentially spread out along Zone 2 rather than continue to deeper levels. Thus preventing or considerably delaying the process of mixing and flushing out the older saline water below the zone. Similarity, the more sluggish upward moving salt water will do likewise. Zone 2 will therefore be a horizon along which groundwaters of considerably age differences will come into contact and mix with one another.

The groundwater chemistry at the Finnsjön study site is similar to other studied areas in Sweden. A special characteristic is the high content of carbonate in the non-saline water.

8. ASSESSMENT OF SOLUTE TRANSPORT

8.1 Review of earlier work

Finnsjön is the most investigated and modelled region so far within the SKB programme. Several modelling efforts have been made over the years. The first modelling efforts was made by Carlsson et al. (1983) with the purpose to test the program package later used for modelling of the Fjällveden, Gideå and Kamlunge sites. The modelling did not include any transport calculations for the Finnsjön site. A similar finite-element code was later used in the SKB 91-study but then also including transport calculations (Lindbom et al., 1991; Lindbom and Boghammar 1991a, 1992a, 1992b). This model is further described below.

Finnsjön has also been used as test location for development of various tracer test methods and therefore a number of tracer tests have been performed in the area. In the Gåvastbo area a series of converging tracer tests with both conservative and sorbing tracers were performed by Gustafsson and Klockars (1981, 1984). These tests were modelled using one-dimensional transport models in order to determine transport properties of the Finnsjön bedrock such as flow porosity, dispersivity and hydraulic fracture conductivity. These tests were also incorporated in the INTRACOIN study (SKI, 1986) where three different modelling teams used the tracer tests to test their model concepts. All three teams used one-dimensional approaches. The processes and phenomena included in the modelling were: advection, dispersion, channeling, matrix diffusion, diffusion into stagnant water, several pathways, surface sorption and sorption in rock matrix. No attempts were made to model the groundwater flow at the site.

Studies of the transport processes were also performed as a part of the Fracture Zone Project. A series of interference tests and tracer tests were made to determine the transport properties of Zone 2. The study involved simulations of both flow and transport (Nordqvist and Andersson, 1987; Andersson et al., 1990; Gustafsson et al., 1990) using a 2D finite element code, SUTRA (Voss, 1984). The modelling procedure was made in a series of steps by using the data from the early phases of the project as calibration measurements and then make predictions for the following phase. After the calibration and verification of the flow model, the transport for the radially converging tracer test was predicted and the experimental results were compared to the prediction (Gustafsson et al., 1990). The tracer tests were also modelled with one-dimensional advection-dispersion models in order to determine transport properties of Zone 2.

The interference tests and tracer tests within the Fracture Zone Project were also used as a test case in the INTRAVAL study (NEA/SKI, 1990). Seven different modelling teams have analyzed the radially converging test and the dipole tracer test using different modelling concepts. The modelling was mainly concentrated on one of the tracer tests and none of the teams used the whole sequence of tests including the interference tests. The modelling concepts are summarized below.

At the Finnsjön site tracer tests have been made at two main locations. The Gåvastbo area, located in the eastern part of the site (where the percussion boreholes HGB01-17 cluster in Figure 13) and at Zone 2, located in the northern part of the site.

8.2 Main results

Conceptual model of flow and transport

The investigations within the Fracture Zone Project have resulted in a large number of geological, hydrological, and geochemical data. Based on these data a conceptual model of flow and transport has been established for the northern part of the site. The most important feature regarding flow and transport in this part is the subhorizontal-gently dipping Zone 2, see Figure 38.

Gustafsson and Andersson (1991) present a conceptual model of flow and transport within Zone 2 based on measurements of natural head conditions, a series of tracer tests, and in-situ groundwater flow measurements.

Hydraulic head measurements and groundwater sampling indicate that in the deeper lying western parts of Zone 2, saline water from below and non-saline water from above, is recharged into the zone. Water is then transported upwards along Zone 2 and eventually discharged into Zone 1 or close to the intersection with Zone 1. As discussed in Section 6.4, water balance calculations indicate that regional groundwater flow is dominating the recharge to Zone 2. In the lower parts of Zone 2 water sampling and flow measurements indicate near stagnant conditions, while high groundwater flow is measured in the upper part.

This conceptual model was partly confirmed by studies of the movement of labelled drilling fluid from borehole KFI11. The drilling fluid was transported within Zone 2, mainly under natural gradient conditions, a distance of 440 m to borehole HFI01. The mean transport time was 37 days which indicate that both magnitude and direction of the natural gradient is correctly estimated from the measurements of hydraulic head. The hydraulic tests and tracer tests indicate that the upper part of Zone 2 is fairly homogeneous and that tracer transport in the flow paths studied, and at the distances involved (150-400 m), is dominated by advection whereas dispersion is of minor importance.

Hydraulic and transport parameter values

Knowledge of both hydraulic conductivity and flow porosity ("kinematic porosity") is important to determine actual fluid velocity through a repository region. The flow porosity is important for transport of radionuclides that do not undergo strong chemical or surface retardation processes along flow paths to the surface, and together with hydraulic conductivity, controls travel times of such nuclides. The flow porosity is a scale dependent value and the use of a single value for the entire rock mass and fracture zones may be questioned.

Some flow porosities that have been determined in tracer tests in the Gåvastbo area and in Zone 2 are presented in Table 12.

Table 12. Flow porosities (1 m-section) determined at Finnsjön.

Flow porosity	Reference
$2 \cdot 10^{-3}$	Gustafsson and Klockars (1981)
$1\text{-}9 \cdot 10^{-3}$	Gustafsson and Andersson (1991)
$1\text{-}12 \cdot 10^{-3}$	Gustafsson et al. (1990)

The higher values were determined in the upper highly conductive part of the Zone 2. The values are determined assuming a "flowing width" of the fractures/fracture zones of 1 m.

The dispersivity has been determined from several tracer tests, see Table 13. The values varies very much due to the different conceptual models applied for the evaluation of the tests. The lower values are in most cases determined by assuming that several flow paths are involved in the transport and the low value is the contribution from the fastest flow path. The high values are resulting from trying to fit the data to a single flow path and/or including other phenomena such as matrix diffusion.

Table 13. Dispersivities determined from field tracer test at Finnsjön.

Dispersivity (m)	Scale (m)	Reference
0.9-1.5	30	Gustafsson and Klockars (1981)
1.0-6	30	Moreno et al. (1983)
0.2-16	30	SKI (1986) (INTRACOIN)
1.3-3.9	155-189	Gustafsson and Andersson (1991)
5.0-28	155-189	Gustafsson et al. (1990)
0.3-111	155-189	Tsang and Neuman (in prep) (INTRAVAL)

There are several modelling efforts with solute transport models using Finnsjön data including the matrix diffusion. Moreno (1983) and SKI (1986) concludes that the matrix diffusion is an important mechanism which cannot be neglected in order to explain the tracer breakthrough curves in the Gåvastbo tests. Other authors like Gustafsson and Klockars (1981) could explain the breakthrough by applying a multi-pathway advection-dispersion model.

Laboratory measurements of porosity and diffusivity on rock samples from Finnsjön are reported by Skagius and Neretnieks (1982, 1985) and Gidlund et al. (1990). The porosity values are determined both from fracture zones and from the rock mass. For fracture material the porosity ranges between 1-5% and for the rock mass, 0.5-3% (Gidlund et al. 1990).

The retardation of solutes due to sorption has also been studied at Finnsjön. Gustafsson and Klockars (1984) performed a converging tracer test with the sorbing tracers Strontium and Cesium. The Strontium run was also used in the INTRACOIN study. Andersson et al., (1990) used a large number of different tracers in a dipole flow geometry in the upper part of Zone 2. Sorbing tracers like Tc-99, Co-58, Rb-86, Na-24, and Tl-201 were used but only Na-24 could be detected whereas the others were completely sorbed. Besides the tracer test, some laboratory determinations of distribution coefficients (K_d) for Strontium and Cesium on Finnsjön granite, or fracture infillings from Finnsjön, have been made by Skagius et al. (1981), Torstenfeldt et al. (1981), and Landström et al. (1983).

Deterministic groundwater flow modelling

The modelling concepts used for modelling the tracer tests at Finnsjön, briefly described in Section 8.1, are mainly concerned with the determination of transport properties of either individual fractures or fracture zones but none of these approaches considers the transport from a hypothetical repository to the surface. However, in the SKB-91 study the 3D finite element code NAMMU (Rae and Robinson, 1979) was used to model the groundwater system. Lindbom and Boghammar, (1992a) describes a model of the groundwater system in which both a three-dimensional flow field and groundwater travel times from a repository at 600 m depth are shown. Parameter variations and boundary conditions for eight different cases are presented, c.f. Chapter 6.

The main objective of performing the deterministic modelling was to use the model results as boundary conditions for the stochastic continuum modelling performed as a part of the SKB 91 study (SKB, 1992), cf below.

Groundwater flux distributions in a horizontal cut at 600 m depth are presented for eight variations. A median value for the Base Case amounted to about 0.001 $m^3/m^2/year$, c.f. Chapter 6.

Travel times for particles released at eight different points at 600 m depth are given. The travel times ranges between 40-2400 years. The shortest travel times are determined for the case with a fracture zone below the repository and without the presence of Zone 2, i.e an entirely generic case. Considerable reduction of travel times was also achieved for the case with an increased conductivity contrast between rock mass and fracture zones.

The discharge point for all particles was the Imundbo zone, which is a regional lineament with hydraulic properties assumed to be similar to Zone 5.

One variation assigning rock mass properties to the Imundbo zone (i.e. no fracture zone) showed only minor differences regarding flow and transport.

Lindbom and Boghammar (1992b) performed six calculations in order to check the model sensitivity of an altered regional gradient by imposing a regional gradient along the top surface of the model. The resulting travel times showed no substantial difference compared to the Base Case whereas the flow paths were considerably different for some of the variations. The reason for this was that the imposed gradient changed the direction of the local natural gradient.

Stochastic groundwater flow modelling

For the SKB 91 study, the main part of the modelling work was focused on conditional stochastic simulation of the flow conditions in the Finnsjön block. The computer program HYDRASTAR was used for the stochastic simulations of the groundwater head and flow field at Finnsjön, c.f. Chapter 6. In addition, particle tracking was performed in 500 realizations for the base case and in 50 realizations for 16 variations of the base case. Travel times were calculated using a fixed value for the flow porosity of 0.0001.

The results from the HYDRASTAR simulations are presented as head and conductivity fields in three different vertical cross-sections and one horizontal section at 600 m depth (repository level). Due to the large number of realizations, only a few have been presented in the report. The groundwater travel times and Darcy fluxes from the different realizations have also been analyzed statistically and are presented in histograms.

The distribution of travel times shows that nearly half of the travel times are longer than 10 000 years and that the other half is centered around 100 years. The statistical analysis of the travel times shows that they are very dependent on the location of the release point within the repository.

The variations made include; altering of repository depth (± 100m), altering of repository position (closer to major fracture zones), changed repository layout, altered conductivity contrast, and exclusion and introduction of zones. Also, combination of the variations have been made so that totally 16 different cases have been considered.

In summary, the variations shows that:

- a reduction of the rock mass conductivity alters the flow pattern so that Zones 4 and 5 becomes more important. Travel times are not increased,

- the influence of increasing the conductivity of the steeply dipping fracture zones is small,

- the exclusion of Zone 2 has very little effect on flow paths and travel times due to the fact that the flow is downward-directed from Zone 2,

- the introduction of a low angle fracture zone beneath the repository gives much shorter travel times.

In addition to the particle tracking, transport modelling has been performed both for the near field and the far field. The near field modelling includes the radionuclide transport through the engineered barriers and will not be treated in this report. The far field modelling is performed by studying the transport in stream tubes by means of the far field model FARF31 (Norman and Kjellbert, 1990). The transport equation is solved for 88 different streamtubes emerging from the repository. The processes included in the model are advection, dispersion, matrix diffusion, matrix sorption, and chain decay. The most important input parameters for the model are the travel time (obtained from particle tracking with HYDRASTAR), the Peclet Number (dispersion), the matrix sorption coefficients for the different elements (K_d), and the specific surface area per unit volume of rock (or water) that is available for sorption and diffusion into the rock matrix.

The input data for the model are based on both field and laboratory experiments, not only at the Finnsjön site, but also from Stripa and other sites. The input data are discussed by Elert et al. (1992).

The results of the transport calculations are presented as histograms and diagrams of maximum doses and doses as a function of time for the long-lived fission products. A few variations of the input data are also presented. The combined results from the near field and far field transport modelling showed that only the long-lived nuclides carbon-14, iodine-129, cesium-135, radium-226, and protactinium-231 can escape from the near field and that the doses are more than a factor 1000 lower than the individual dose limit suggested by the authorities.

Other calculations

As earlier described a number of different transport models have been applied to some of the tracer tests performed at Finnsjön. Most of the models have been applied in order to determine transport parameters or trying to distinguish between different transport phenomena. However, Andersson et al. (1989) presents simulations of both flow and transport in a horizontal plane of Zone 2 using the SUTRA-code. The model was used to simulate the interference tests and to predict the tracer breakthrough in the radially converging tracer test by Gustafsson et al. (1990). Parameter sensitivity analysis showed that the model was rather insensitive to changes in the transmissivity values whereas the choice of boundaries is important. The model managed to simulate the more distant pressure responses very well but the near-field responses could not be fitted so well. This shows the anisotropic nature of the zone but also that the zone may be treated as a porous media in scales exceeding 500 m. The anisotropy or rather heterogeneity of the zone was also demonstrated by the large scale tracer tests (Gustafsson et al., 1990; Andersson et al., 1990). No transport calculations were made under natural gradient conditions and very few variations of boundary conditions.

The transport within Zone 2 has also been studied by several teams in the INTRAVAL study (NEA/SKI, 1990). The approaches are all directed towards explaining the pure solute transport using different conceptual models. The concepts used include a porous medium model, a channel model, a variable channel aperture model, and a fracture network model. All of these models seem to be able to reproduce the tracer breakthrough during these artificial conditions. However, no attempts have been made to predict the transport under natural conditions.

A specific feature of the Finnsjön site is the presence of saline water. Ahlbom and Svensson (1991) presents a simple steady-state model which may explain the presence of saline water in the northern Finnsjön block and also the lack of saline water in the southern block. According to the model, the main reason for the presence of saline water is the clay cover to the east of the Finnsjön Rock Block. However, the model is built upon some non-tested assumptions and rough estimates. There is currently no field data available to validate the model. Ahlbom and Svensson (1991) also presents another conceptual model where the presence of saline water can be explained by the presence of Zone 2. They also examines the impact of saline water on travel times and flow distribution using the PHOENICS code. Travel times were found to be considerably increased due to the presence of saline water below Zone 2, from 450 to 13 500 years (average values).

8.3 Discussion

Comparison of field data to modelled results

The transport modelling performed for the SKB 91 study included both deterministic and stochastic approaches. However, both approaches are based on the same conceptual model of the Finnsjön area and there are large uncertainties regarding connectivity and transmissivity of the fracture zones.

Only 8 of the total 14 interpreted fracture zones has been investigated with boreholes and of the 11 regional zones only 2 have been investigated. This is also one of the reasons for a stochastic modelling approach for Finnsjön.

It is also difficult to compare the modelling results with experimental results regarding flow and transport in the Finnsjön Rock Block due to the fact that most of the modelling efforts have been made neglecting the presence of saline water. However, the calculations including saline water with the PHOENICS code (Ahlbom and Svensson, 1991) shows that the presence of saline water changes the flow pattern and travel times drastically. Flow direction and magnitude are then consistent with the conceptual model presented by Gustafsson and Andersson (1991), i.e. a very slow transport of saline water upwards to Zone 2. The exclusion of saline water leads to a transport that is governed by the topographical gradient, which means that the area where Zone 2 is located is a recharge area and water moves downwards below the zone and discharges in the Imundbo zone, which is the case for the deterministic modelling (Lindbom and Boghammar, 1992a, b) and the stochastic modelling (SKB 91, 1992).

Implications of existing information for solute transport

The modelled groundwater system is the primary basis for this evaluation of solute transport. In detail, little is actually known about transport paths or travel times from a repository at 600 m depth. Under the conditions studied, travel times for conservative solutes are predicted within large ranges, from as little as ten to as much as a ten thousands of years. Travel times and paths are found to be most dependent on the existence of conductive fracture zones, especially low angle fracture zones below the repository, but only a few tests varying structure and connectivity was carried out.

Boundary conditions are equally important to the transport predicted by the model analysis. It was shown that the use of major fracture zones as boundaries may lead to errors, especially when pressure distributions are transferred from regional scale to local scale. In fact, it is entirely possible and even likely that the 600 m depth is within the realm of a deep regional groundwater system. The groundwater flow and transport through the repository may have little, if anything, to do with the water-table topography within the site area. Flows at depth may be driven by a more regional water-table gradient. The direction and magnitude of the gradient becomes very important in a flat topography area like Finnsjön. A reduction of the gradient with 50% was shown to alter flow paths and travel times considerably.

Considerations towards improving the transport predictions of the Finnsjön site model must begin with improvements in the conceptual model of the groundwater system. Of particular importance is a clarification of flow regimes in the deeper regions of the site wherein a repository would be situated. Boundary conditions appropriate to the surficial groundwater may not simply be projected downward to apply to deeper systems. Such an assumption, even when inappropriate, is decisive for the groundwater flow and transport that occurs at depth, and essentially overrides other considerations such as conductivity distribution. Further, information on conductive structures which control flow and transport that depends on structures which strike the ground surface is not likely sufficient to describe the connectivity at depth which may depend also on possible but not yet identified additional low-angle zones that do no outcrop.

9. ROCK MECHANICAL CONDITIONS

Compared to other study sites there has been quite an extensive programme of rock mechanical studies at Finnsjön. These studies includes mechanical tests on rock samples, borehole stress measurements, response of Zone 2 to various loadings and mechanical modelling of bedrock response to glaciation.

9.1 Mechanical properties of the rock

Uniaxial compression tests and brazilian tests have been made on twelve core samples from borehole KFI01 to determine mechanical properties (Swan, 1977). All samples were granodiorite. Samples were taken from 50 m, 200 m and 400 m depth.

Uniaxial compression tests

The uniaxial compression tests gave a uniaxial compressive strength of 240.6 ± 15.2 MPa, a static Young's modulus of 82.5 ± 3.2 GPa and a static Poisson's ratio of 0.20 ± 0.02. No difference could be found between the different depths. The reported results of the Young's modulus and Poisson's ratio were evaluated from secants drawn from the origin to intersect the load-deformation curves at points that correspond to 50% of the failure load of the specimens.

Brazilian disc tests

The brazilian disc tests gave a tensile strength of 13.5 ±+ 1.9 MPa. The results did not show any differences with depth.

9.2 Rock stress measurements

Rock stress measurements were conducted in the vertical borehole KFI06 (Bjarnason and Stephansson, 1988). Successful measurements were conducted at 14 test sections, from 80 m depth down to a maximum depth of 500 m. Due to casing no measurements could be conducted above 56 m depth. The results are presented in Figure 40. The location of Fracture Zone 2 is indicated in the figure. The results show moderate rock stresses with no extreme values. At 80 m depth, the minimum horizontal stress is around 4.5 MPa and at 500 m depth 14.5 MPa.

The magnitude of the minimum horizontal stress is larger than the theoretical vertical stress for the entire measurement interval. Hence, the stress situation for the upper 500 m of the crust represents thrust fault conditions. The minimum horizontal stress increase with depth at a rate slightly less than that of the theoretical vertical stress. This indicates, based on the assumption of linear stress increase, that strike-slip conditions will begin to prevail at 700 - 800 m depth.

The magnitude of the maximum horizontal stress shows a steady increase with depth. The maximum horizontal stress is around 6 MPa at 80 m depth and 23 MPa at 500 m depth. However, there is a large scatter in magnitudes between 400-500 m depth, as can be seen Figure 40.

The ratio of the maximum to the minimum horizontal stress increases from approximately 1.1 at 100 m depth to 1.5 at 500 m depth. Single horizontal fractures were recorded in three test sections. The recorded shut-in pressures, Figure 40, were almost identical to the theoretical vertical stress (rgz).

The results in Figure 40 do not show any evidence for significant stress anomalies as Zone 2 is passed. Due to intense fracturing, data from within the zone is restricted to one measuring point. Also this point did not show any significant stress anomaly.

The maximum horizontal stress is oriented N48 W, with a standard deviation of ±10°. This is based on a total of 16 reliable imprints of initiated hydrofractures. No rotation with depth is observed.

9.3 Deformational characteristics of Zone 2

The deformational characteristics of Zone 2 were estimated as a part of the Fracture Zone Project (Leijon and Ljunggren, 1992). Three methods were used to estimate the deformation modulus of the zone; (i) RQD, (ii) the Q-system and (iii) the JRC and JCS. For all methods, information from borehole KFI06 were used. For the complete zone (between 200 m - 300 m depth in the borehole) the analyses indicate a deformation modulus of no less than 25 GPa (30% of Young's modulus).

9.4 Distinct element modelling of the rock mass response to glaciation

The rock mass response to glaciation, deglaciation, isostatic movements and water pressure from an ice lake have been simulated for a cross section of the Finnsjön study site (Rosengren & Stephansson, 1990). A total of six models have been simulated. Four of the models use a boundary condition with boundary elements at the bottom and sides of the model. Roller boundaries were applied to two models.

Simulation of isostatic movements, in combination with ice loading and melting, resulted in large displacements in the major fracture zones. The effect was greatest during deglaciation. At this time the model predicts failure in Zone 2 and other major fracture zones down to approximately 1000 m depth.

Two different geometries of Zone 2 were simulated in where Zone 2 was represented as a continuous plane and as a faulted, discontinued plane. Results from modelling showed however only minor changes between the two geometries.

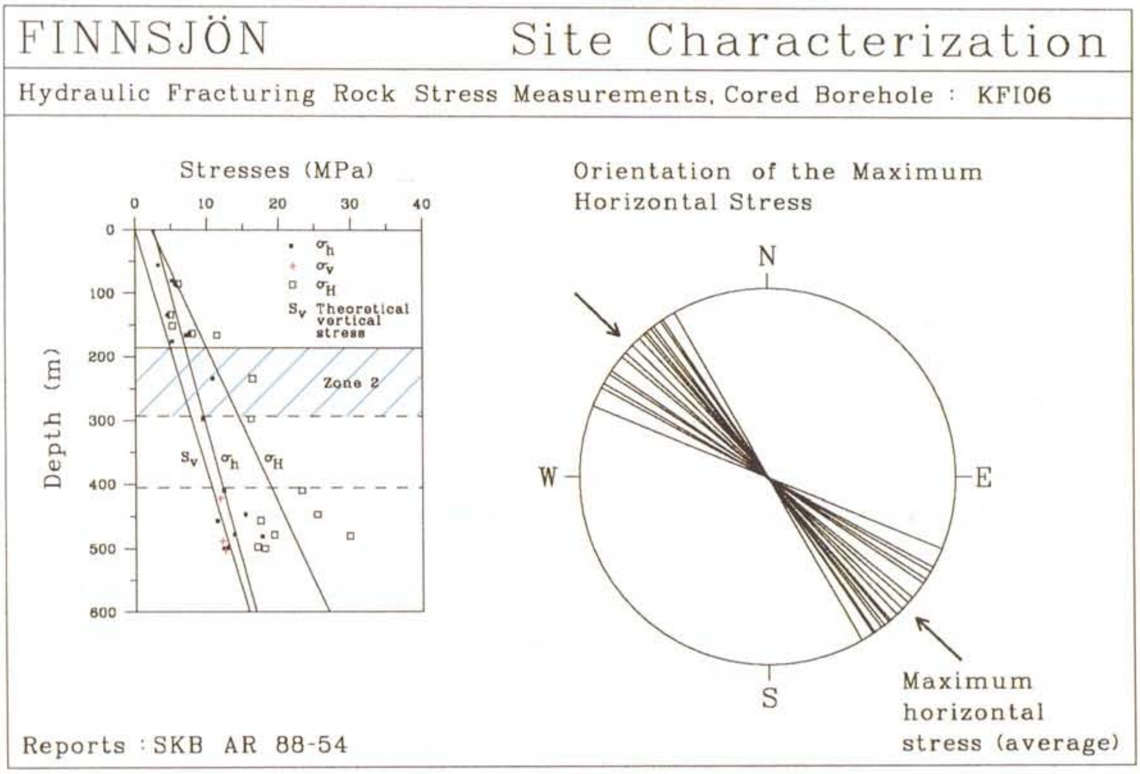


Figure 40. Results from stress measurements using hydraulic fracturing in borehole KFI06.

9.5 Evaluation

The mechanical testing of the rock at Finnsjön do not report anything anomalous. The results show that the intact rock is competent in both compression and tension. The majority of the mechanical parameters have to be considered as normal when compared to the compilation of rock properties on crystalline rocks by Tammemagi and Chieslar (1985). The exception is the result for the Young's modulus, which must be considered as a high value, i.e. a stiff rock. When compared to the strength- and modulus ratio classification by Deere and Miller (1966) an average quality designation is obtained for the Finnsjön granodiorite.

The rock stresses are moderate and the difference in magnitude between the maximum and minimum horizontal stress is normal for Sweden. The standard deviation on the orientation is fully acceptable and can be considered as normal for hydrofracturing measurements. The orientation of the maximum horizontal stress coincide with the NW-SE trend found in Sweden, (Müller at al., 1991, Stephansson and Ljunggren, 1988). Between depths 400 m - 500 m three single horizontal fractures were recorded. The shut-in pressures from these are almost identical to the theoretical vertical stress. Thus, at that depth, the assumption of the vertical stress being controlled by the overburden pressure, is valid.

The rock mechanics study of Zone 2 indicate a deformation modulus of no less than 25 GPa for the complete zone. For the poorest parts of the zone a deformation modulus of 10 GPa is indicated. Despite the high fracture frequency of the zone, the rock mass deformation modulus is on the order of 30% of Young's modulus. Such a value do not in any way contradict the existing bank of large-scale field data, as obtained from various case studies, (Bieniawski (1978), Heuze (1980)).

The risk of spalling, or rock bursts have been estimated by use of the empirical relationships by Hoek & Brown (1980) and Russenes (1974). Taking into account the stress state at Finnsjön and the uniaxial compressive strength of the granodiorite no spalling should occur above 400 m depth. Between 400 m - 500 m depth minor spalling may occur. The brittleness of the rock has not been considered.

No low quality mechanical parameter has been discovered for the intact rock, and taking into account the stress state, the rock shouldn't create any stability problems in the construction of a repository at 600 m depth.

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APPENDIX A

ACTIVITIES IN BOOSTER BOREHOLES

This appendix presents all activities that have been performed in the booster boreholes BFI01 and BFI02 and the percussion borehole HFI01, all drilled during the Fracture Zone Project. The activities are presented as separate activity schemes for each borehole. Each scheme contains information on activities/surveys for the particular borehole with reference to depths or intervals. Also borehole coordinates, survey periods, references to reports and information on storage in the SKB database GEOTAB is presented.

Locations of the three boreholes are presented below in Figure A1. Intersections of fracture zones with boreholes are summarized in Table 3 and in Appendix C, Figures C1-C3. Location of interpreted fracture zones are presented in Appendix D, Figure D1. All three boreholes are intact.

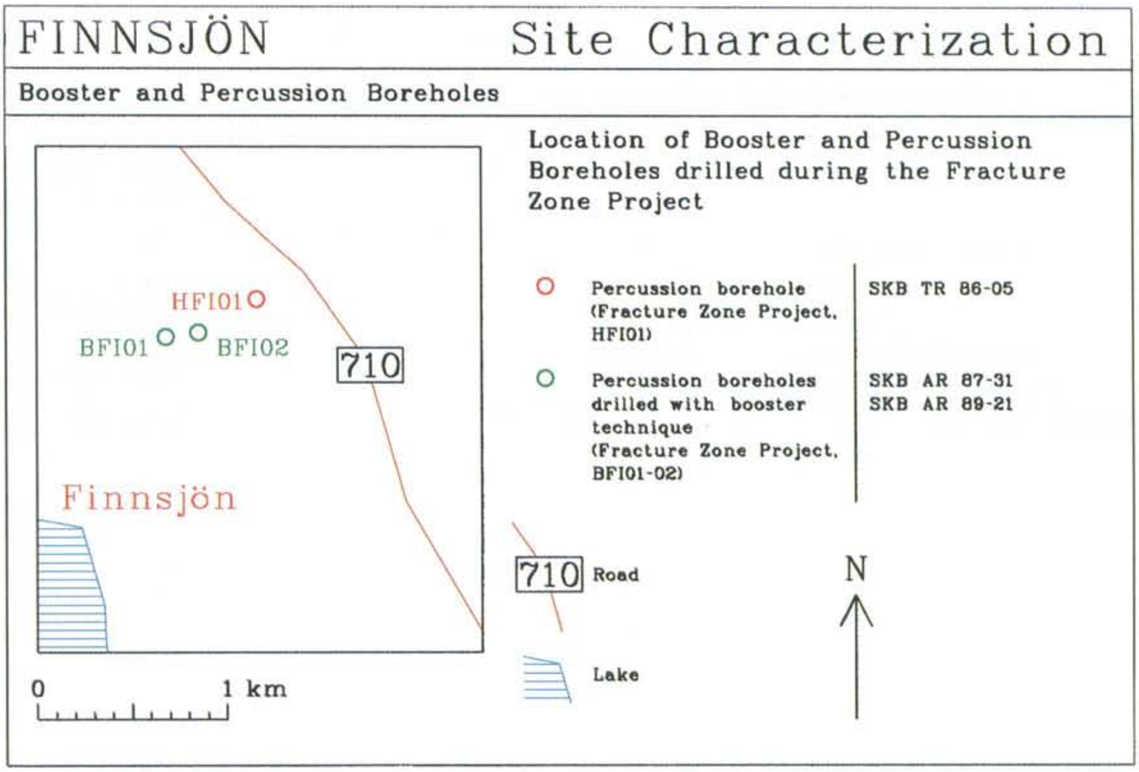
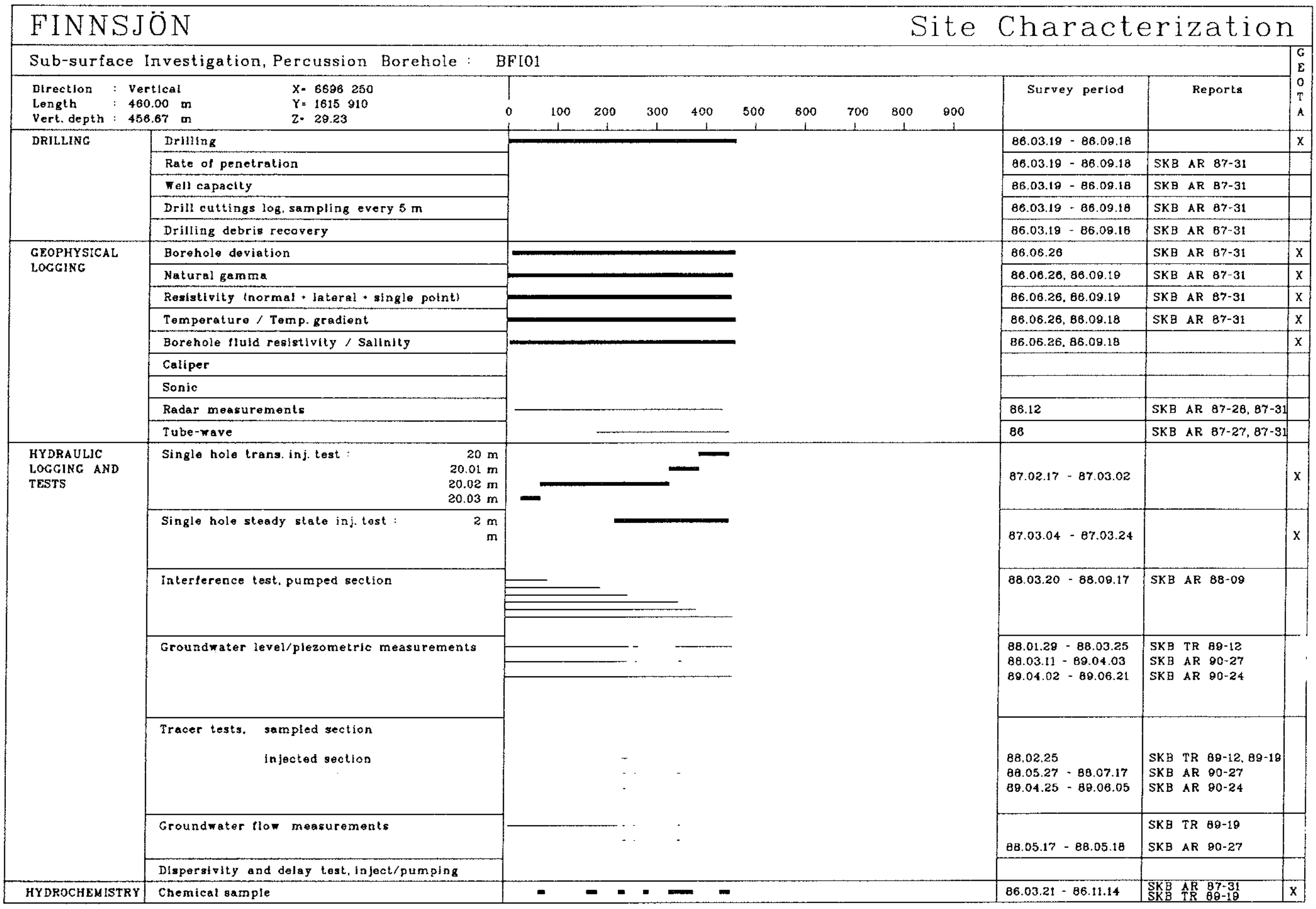


Figure A1. Locations of booster boreholes and a percussion borehole drilled during the Fracture Zone Project at Finnsjön study site.



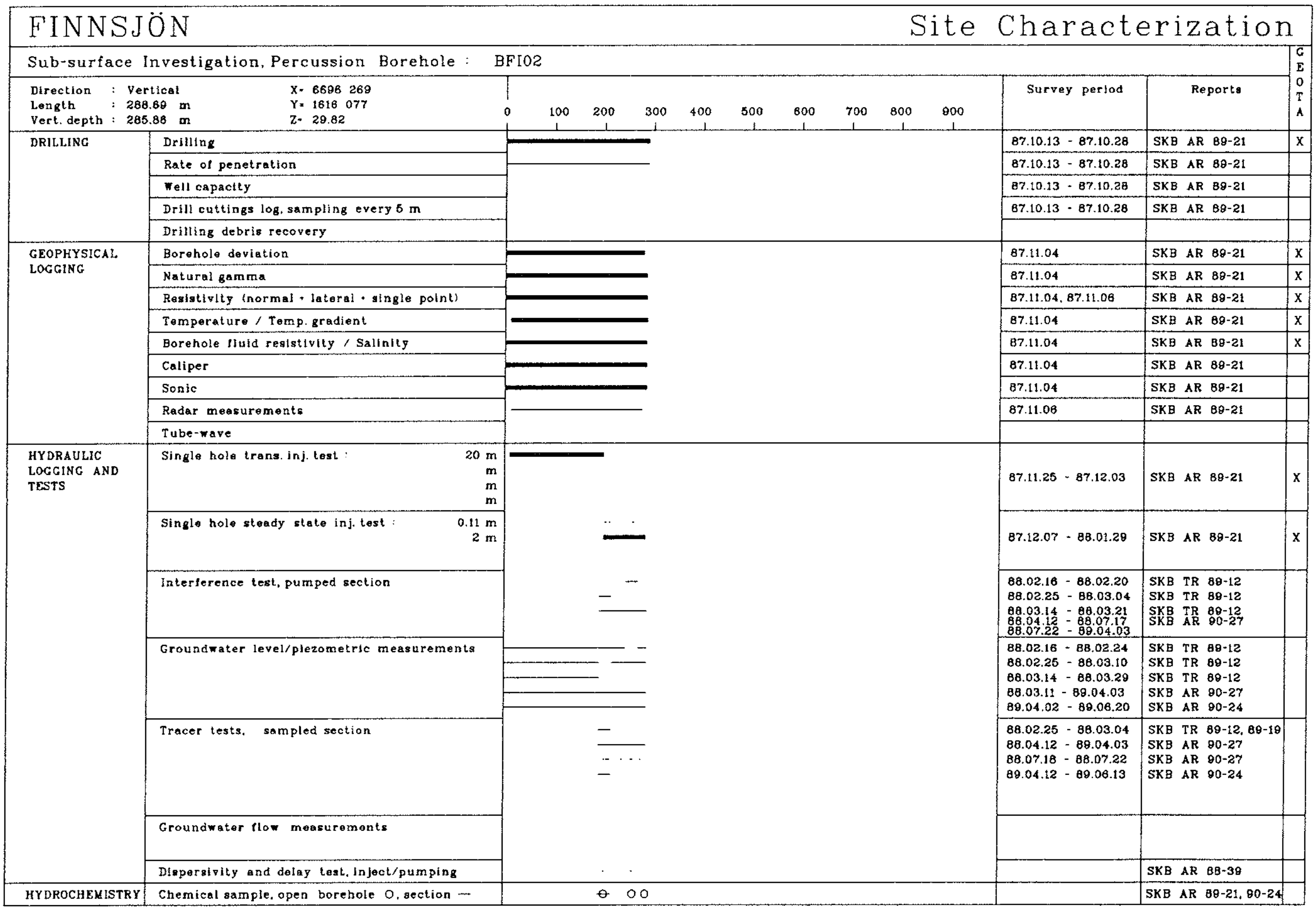
FINNSJÖN Site Characterization

Sub-surface Investigation, Percussion Borehole : BFI01

Direction : Vertical X= 6696 250
Length : 460.00 m Y= 1615 910
Vert. depth : 456.67 m Z= 29.23

		Survey period	Reports	GEOTA
DRILLING	Drilling	86.03.19 - 86.09.18		X
	Rate of penetration	86.03.19 - 86.09.18	SKB AR 87-31	
	Well capacity	86.03.19 - 86.09.18	SKB AR 87-31	
	Drill cuttings log, sampling every 5 m	86.03.19 - 86.09.18	SKB AR 87-31	
	Drilling debris recovery	86.03.19 - 86.09.18	SKB AR 87-31	
GEOPHYSICAL LOGGING	Borehole deviation	86.06.26	SKB AR 87-31	X
	Natural gamma	86.06.26, 86.09.19	SKB AR 87-31	X
	Resistivity (normal + lateral + single point)	86.06.26, 86.09.19	SKB AR 87-31	X
	Temperature / Temp. gradient	86.06.26, 86.09.18	SKB AR 87-31	X
	Borehole fluid resistivity / Salinity	86.06.26, 86.09.18		X
	Caliper			
	Sonic			
	Radar measurements	86.12	SKB AR 87-28, 87-31	
	Tube-wave	86	SKB AR 87-27, 87-31	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 20 m 20.01 m 20.02 m 20.03 m	87.02.17 - 87.03.02		X
	Single hole steady state inj. test : 2 m m	87.03.04 - 87.03.24		X
	Interference test, pumped section	88.03.20 - 88.09.17	SKB AR 88-09	
	Groundwater level/piezometric measurements	88.01.29 - 88.03.25 88.03.11 - 89.04.03 89.04.02 - 89.06.21	SKB TR 89-12 SKB AR 90-27 SKB AR 90-24	
	Tracer tests, sampled section injected section	88.02.25 88.05.27 - 88.07.17 89.04.25 - 89.06.05	SKB TR 89-12, 89-19 SKB AR 90-27 SKB AR 90-24	
	Groundwater flow measurements	88.05.17 - 88.05.18	SKB TR 89-19 SKB AR 90-27	
	Dispersivity and delay test, inject/pumping			
HYDROCHEMISTRY	Chemical sample	86.03.21 - 86.11.14	SKB AR 87-31 SKB TR 89-19	X

Figure A2. Activities in borehole BFI01. Data from borehole sections stored in GEOTAB have thick lines.



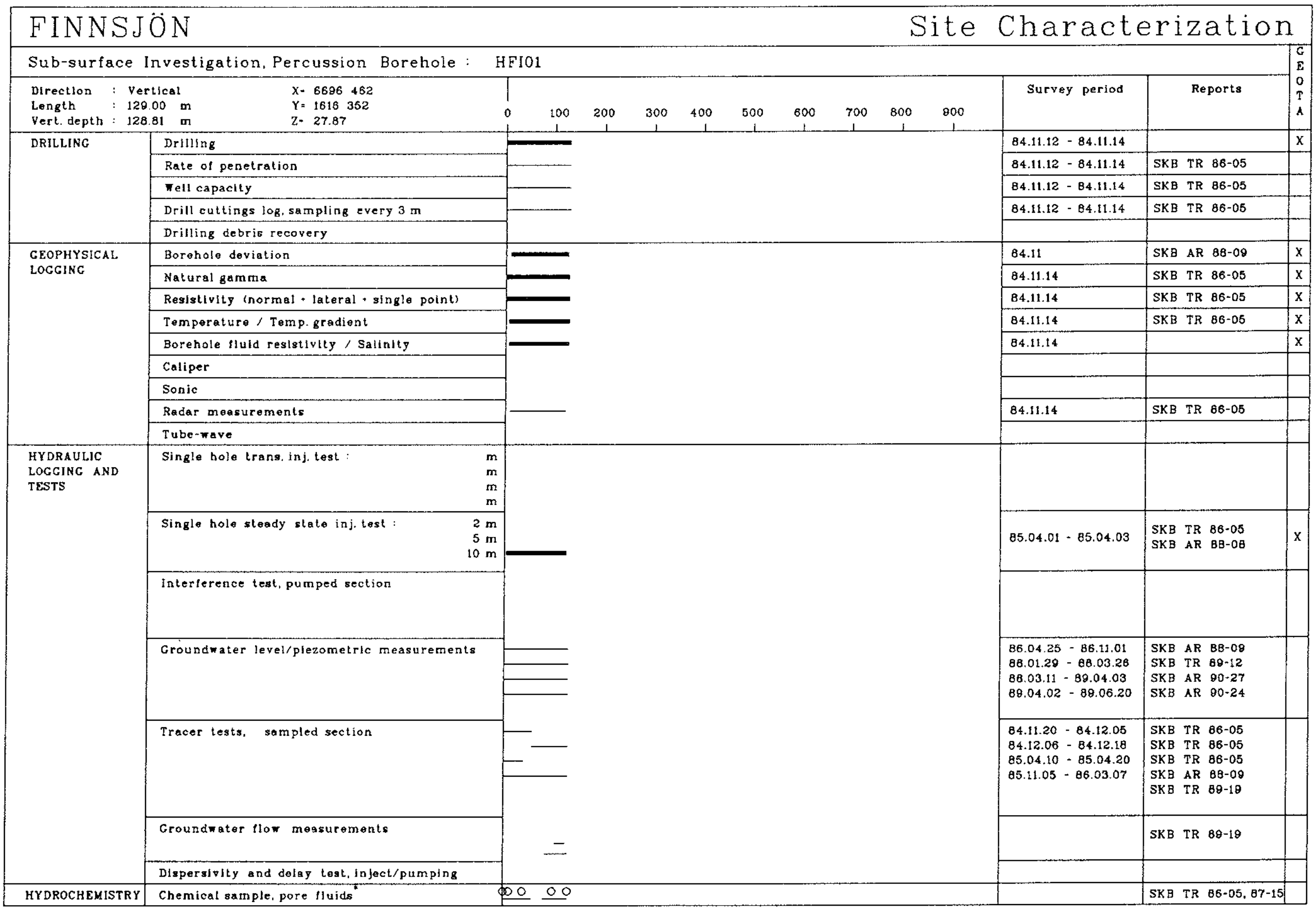
FINNSJÖN Site Characterization

Sub-surface Investigation, Percussion Borehole : BFI02

Direction : Vertical X- 6696 269
Length : 288.69 m Y- 1616 077
Vert. depth : 285.86 m Z- 29.82

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTA
DRILLING	Drilling		87.10.13 - 87.10.28	SKB AR 89-21	X
	Rate of penetration		87.10.13 - 87.10.28	SKB AR 89-21	
	Well capacity		87.10.13 - 87.10.28	SKB AR 89-21	
	Drill cuttings log, sampling every 5 m		87.10.13 - 87.10.28	SKB AR 89-21	
	Drilling debris recovery				
GEOPHYSICAL LOGGING	Borehole deviation		87.11.04	SKB AR 89-21	X
	Natural gamma		87.11.04	SKB AR 89-21	X
	Resistivity (normal + lateral + single point)		87.11.04, 87.11.06	SKB AR 89-21	X
	Temperature / Temp. gradient		87.11.04	SKB AR 89-21	X
	Borehole fluid resistivity / Salinity		87.11.04	SKB AR 89-21	X
	Caliper		87.11.04	SKB AR 89-21	
	Sonic		87.11.04	SKB AR 89-21	
	Radar measurements		87.11.06	SKB AR 89-21	
	Tube-wave				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 20 m m m m		87.11.25 - 87.12.03	SKB AR 89-21	X
	Single hole steady state inj. test : 0.11 m 2 m		87.12.07 - 88.01.29	SKB AR 89-21	X
	Interference test, pumped section		88.02.16 - 88.02.20 88.02.25 - 88.03.04 88.03.14 - 88.03.21 88.04.12 - 88.07.17 88.07.22 - 89.04.03	SKB TR 89-12 SKB TR 89-12 SKB TR 89-12 SKB AR 90-27	
	Groundwater level/piezometric measurements		88.02.16 - 88.02.24 88.02.25 - 88.03.10 88.03.14 - 88.03.29 88.03.11 - 89.04.03 89.04.02 - 89.06.20	SKB TR 89-12 SKB TR 89-12 SKB TR 89-12 SKB AR 90-27 SKB AR 90-24	
	Tracer tests, sampled section		88.02.25 - 88.03.04 88.04.12 - 89.04.03 88.07.18 - 88.07.22 89.04.12 - 89.06.13	SKB TR 89-12, 89-19 SKB AR 90-27 SKB AR 90-27 SKB AR 90-24	
	Groundwater flow measurements				
	Dispersivity and delay test, inject/pumping			SKB AR 88-39	
HYDROCHEMISTRY	Chemical sample, open borehole O, section —	⊖ O O		SKB AR 89-21, 90-24	

Figure A3. Activities in borehole BFI02. Data from borehole sections stored in GEOTAB have thick lines.



FINNSJÖN Site Characterization

Sub-surface Investigation, Percussion Borehole : HFI01

Direction : Vertical
Length : 129.00 m
Vert. depth : 128.81 m

X- 6696 462
Y= 1616 352
Z- 27.87

		Survey period	Reports	GEOTA
DRILLING	Drilling	84.11.12 - 84.11.14		X
	Rate of penetration	84.11.12 - 84.11.14	SKB TR 86-05	
	Well capacity	84.11.12 - 84.11.14	SKB TR 86-05	
	Drill cuttings log, sampling every 3 m	84.11.12 - 84.11.14	SKB TR 86-05	
	Drilling debris recovery			
GEOPHYSICAL LOGGING	Borehole deviation	84.11	SKB AR 88-09	X
	Natural gamma	84.11.14	SKB TR 86-05	X
	Resistivity (normal + lateral + single point)	84.11.14	SKB TR 86-05	X
	Temperature / Temp. gradient	84.11.14	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity	84.11.14		X
	Caliper			
	Sonic			
	Radar measurements	84.11.14	SKB TR 86-05	
	Tube-wave			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m m			
	Single hole steady state inj. test : 2 m 5 m 10 m	85.04.01 - 85.04.03	SKB TR 86-05 SKB AR 88-08	X
	Interference test, pumped section			
	Groundwater level/piezometric measurements	86.04.25 - 86.11.01 88.01.29 - 88.03.26 88.03.11 - 89.04.03 89.04.02 - 89.06.20	SKB AR 88-09 SKB TR 89-12 SKB AR 90-27 SKB AR 90-24	
	Tracer tests, sampled section	84.11.20 - 84.12.05 84.12.06 - 84.12.18 85.04.10 - 85.04.20 85.11.05 - 86.03.07	SKB TR 86-05 SKB TR 86-05 SKB TR 86-05 SKB AR 88-09 SKB TR 89-19	
	Groundwater flow measurements		SKB TR 89-19	
	Dispersivity and delay test, inject/pumping			
HYDROCHEMISTRY	Chemical sample, pore fluids*		SKB TR 86-05, 87-15	

Figure A4. Activities in borehole HFI01. Data from borehole sections stored in GEOTAB have thick lines.

APPENDIX B

ACTIVITIES IN CORED BOREHOLES

This appendix presents all activities that have been performed in the cored boreholes, in separate activity schemes for each borehole. Each scheme contains information on activities/surveys for the particular borehole with reference to depths or intervals. Also borehole coordinates, survey periods, references to reports and information on storage in the SKB database GEOTAB is presented.

Locations of the cored boreholes are presented below in Figure B1. Intersections of fracture zones with boreholes are summarized in Table 3 and in Appendix C, Figures C1-C4. Location of interpreted fracture zones are presented in Appendix D, Figure D1.

Data regarding the availability of the cored boreholes for new investigations have obtained from Ekman (1989) and Persson (1985). The obstacles reported by them are described in this Appendix.

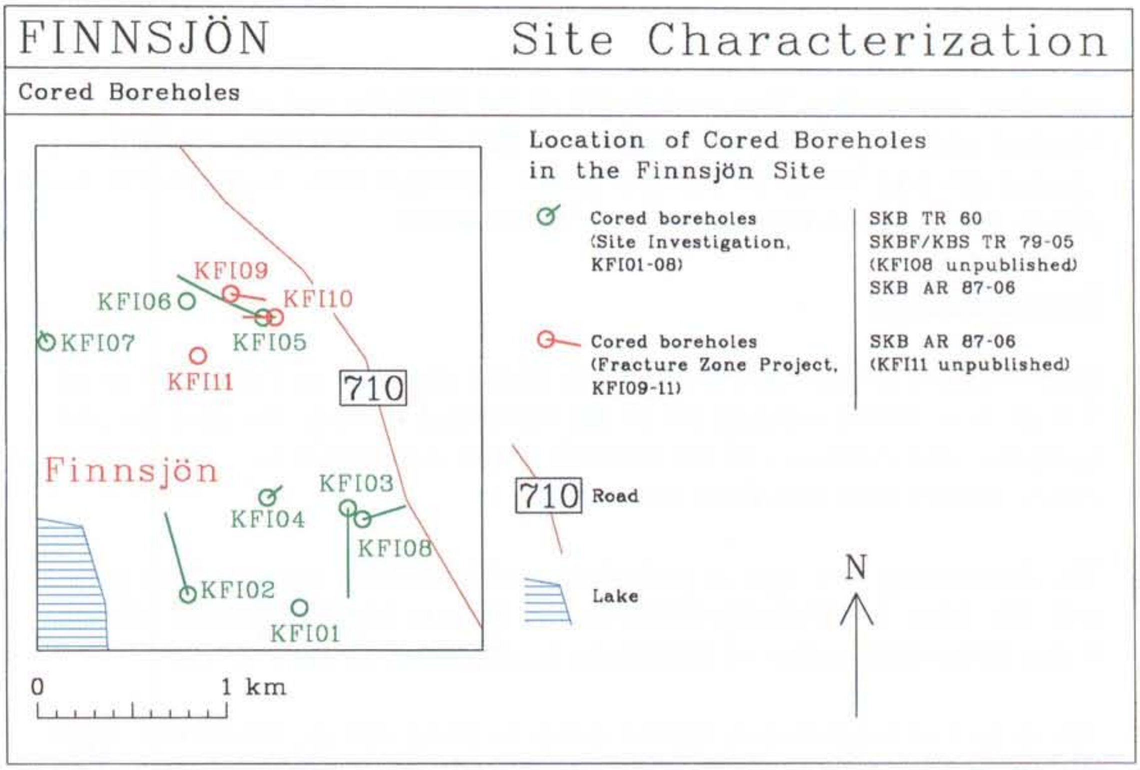


Figure B1. Locations of cored boreholes at Finnsjön study site.

Borehole KFI01

This borehole (Figure B2) is drilled vertical to a depth of 501 m below the ground. The objective was to obtain data regarding rock types, degree of fracturing and hydraulic conductivity in a rock block at the central part of the site. Borehole coordinates and activities performed are presented in Figure B2. Generalized results concerning rock types, fracturing and hydraulically conductive sections are presented in Appendix C, Figure C1.

Granodiorite is the dominating rock type in the borehole. Some metre-wide dykes of pegmatite and aplite are also encountered. The degree of fracturing is low down to 200 m. Below this depth the degree of fracturing increases although there still exists wide sections with low fracture frequencies. Highly fractured sections occurs between 214-217 m, 336-355 m and 360-361 m. In Ahlbom and Tirén (1991) the two latter sections are interpreted to be a part of a c. 100 m wide gentle dipping (35^0) fracture zone, Zone 11, occurring in the borehole between 332-436 m.

The mean fracture frequency of the borehole is 2.3 fr/m. (Assuming 5 cm as a mean fracture spacing in sections only marked in the core logs as fractured or crushed rock).

Borehole availability: The total length of the borehole was at one time blocked with a hydraulic test equipment. Part of the borehole was later cleared down to 340 m or possible longer, although there might still be some plastic debris left in the upper part of the borehole.

Borehole KFI02

This borehole (Figure B3) is 699 m in length and ends at a depth of about 535 m. It is drilled inclined 50° to the horizontal to study the geologic and hydraulic characteristics of the bedrock and of northwesterly oriented fracture zones, mainly indicated from lineaments.

The dominating rock type is granodiorite which colour changes from grey to red. The latter is commonly found in and close to highly fractured sections. Some metre-wide dykes of metabasite is also noted in the core logs.

The degree of fracturing is highest down to about 110 m. Below this depth the fracturing decreases somewhat until the lowermost part of the borehole where a strongly fracture section occurs (677-690 m). It is possible that this sections might represent Zone 1. Mean fracture frequency for the total borehole length is 3.2 fr/m. Generalized results are presented in Appendix C, Figure C1.

Borehole availability: The borehole is blocked with a hydraulic test equipment from 100 m and downwards.

Borehole KFI03

Borehole KFI03 (Figure B4) is 731 in length and drilled inclined 50°, reaching a depth of about 560 m. The borehole is drilled in the eastern part of the site close to, and more or less parallel with Zone 3, the Gåvastbo fracture zone.

With the exception of one 1.5 m wide metabasitic dyke all cores from this borehole consists of grey or red granodiorite. The fracture frequency is high over the total length of the borehole. Mean fracture frequency is 5.8 fr/m. The most fractured sections occurs at 150-190, 220-270, 340-360, 590-640, 670-730 m. In Ahlbom and Tirén (1986) a gentle dipping and 100 m wide fracture zone (Zone 11) is interpreted to occur in the borehole between 107-275 m. Another zone, Zone 10, is interpreted by the same authors to intersect the borehole at 57-62 m.

The strongly fractured sections in the borehole from 340 m and downwards have not been correlated with any fracture zone at the surface, although the most plausible one appears to be the Gåvastbo fracture zone (Zone 3). Generalized results are presented in Appendix C, Figure C1.

Borehole availability: A hydraulic test equipment blocks the total length of the borehole.

Borehole KFI04

This borehole (Figure B5) has a length of 603 m and drilled inclined 80°, reaching a depth of 596 m. The borehole is located in the central part of the site in a tectonically affected rock block (in what way is not reported). The objective was to study the continuation of this tectonics towards depth and to study its influence on the hydraulic conductivity.

The borehole consists mainly of grey or red granodiorite down to 527 m where the main rock type is changed to a reddish granite, which continues to the end of the borehole. Granite also occurs as dykes at 388-391 m and 397-428 m borehole length. The granodiorite is also cut by several pegmatite and metabasitic dykes.

The cores are, compared to other boreholes in Finnsjön, relatively low fractured, although several sections with increased fracturing do occur. The most prominent fractured section occurs between 370-440 m. Ahlbom and Tirén (1991) interpret this section to represent the gentle dipping Zone 11. Mean fracture frequency of the borehole is 3.6 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C2.

Borehole availability: During borehole logging 1985 a blockage at 75 m depth was detected, indicating a borehole collapse at this depth.

Borehole KFI05

This borehole (Figure B6) is inclined, 50°, with a length of 752 m and a depth of 558 m. It is drilled to investigate a topographically and geophysically mell marked lineament (Zone 1).

The borehole is dominated by grey and red granodiorite. Granite dykes, pegmatite dykes and to some extent metabasic dykes occurs frequently throughout the borehole.

The degree of fracturing is high down to c. 240 m depth. Below this depth the fracturing decreases somewhat but several highly fractured sections also occurs below this depth. The first interpretation of the borehole results indicated that the borehole was more or less parallel to Zone 1, which would explain the long fractured section. During the Fracture Zone Project the borehole results was reinterpretated. The present interpretation is that Zone 1 is located in the uppermost 50 m of the borehole (which is cased in this part). From 166-305 m the borehole penetrate the gently dipping Zone 2. Ahlbom and Tirén (1991) further interprets a 2-6 m wide and 60^0 dipping fracture zone (Zone 5) to intersect the borehole at 493 m.

The mean fracture frequency for the borehole is 4.7 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C2.

Borehole availability: No known problems with borehole blockage (the borehole is cased down to 56 m).

Borehole KFI06

This borehole (Figure B7) is located in the northern part of the site and is drilled vertically to 691 m depth. The objective was to obtain rock characteristics in this part of the site.

The borehole is dominated by grey and red granodiorite. Granite dykes, pegmatite dykes and to some extent metabasic dykes occurs frequently throughout the borehole. The frequency of pegmatites increases with depth.

Borehole KFI06 is, together with other boreholes in the northern part of the site, relatively low fractured compared to boreholes in the central and southern part of the site. Fractured rock occurs mainly between 193-284 m, although other fractured sections occurs both above and below this section. Ahlbom and Tirén (1991) interprets the gently dipping Zone 2 to be located between 201-305 m in the borehole and Zone 5 at around 555 m depth.

Mean fracture frequency is 3.0 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C2.

Borehole availability: No known problems with borehole blockage.

Borehole KFI07

Borehole KFI07 (Figure B8) is drilled 85^0 to a borehole length of 553 m, corresponding to a depth of 549 m. It is located in the northwestern part of the site with a general objective to investigate rock characteristics in this part of the site.

The borehole is strongly dominated by grey and red granodiorite. The amount of red granodiorite (tectonically affected rock) is less than in other boreholes at Finnsjön. The borehole only cuts one metabasite dyke and a few pegmatites.

The relatively low amount of fractured rock in this borehole is also seen on the mean fracture frequency, 1.8 fr/m. The main fractured sections occurs between 288-388 m and 513-531 m. These sections were interpreted in Ahlbom and Tirén (1991) to represent Zone 2 and Zone 6, respectively. Based on surface data they also interpreted another fracture zone, Zone 9, to occur between 109-154 m in the borehole. However, this is not conclusively shown in the core logs nor in the geophysical or hydraulical borehole measurements. Main results from borehole investigations are shown in Appendix C, Figure C3.

Borehole availability: No known problems with borehole blockage.

Borehole KFI08

This borehole (Figure B9) is 464 m in length and is drilled inclined 60°, reaching a depth of 399 m. The borehole is located in the eastern boundary to the Finnsjön Rock Block site with the objective to characterize the Gåvastbo fracture zone (Zone 3).

The core mapping of this borehole has not been reported. A compilation of rock type distribution has however been made from available working documents. This compilation is presented in Appendix C, Figure C3, together with other main borehole results.

According to this compilation granodiorite and reddish granite occurs in more or less equal amount, reflecting the closeness to the main granitic body occurring close to the east.

Due to the absence of a fracture core log no study of mean fracture frequency has been made for the borehole. However the resistivity logging, presented in Ahlbom et al., 1986, indicate a major fracture zone from more or less the ground surface and down to 150 m borehole length, which are interpreted to represent Zone 3. Minor fractured sections also occur 200-215 m, 315-335 m and 410-430 m.

Borehole availability: No known problems with borehole blockage.

Borehole KFI09

This borehole (Figure B10) is drilled 60° to the horizontal and has a length of 376 m, corresponding to a depth of about 322 m. The objective was to investigate the character of Zone 1. However, after the discovery of the gently dipping Zone 2 in the borehole, the main efforts were changed to characterize this latter fracture zone.

The borehole is dominated by red and grey granodiorite. In addition, pegmatites occur towards the end of the borehole. The main fractured section in the borehole occurs between 134-217 m. This section contains several tectonized and brecciated sections of granodiorite. It is interpreted to represent the gently dipping Zone 2 down to 212 m. Between 212-216 m a 5 m wide and 60^0 dipping fracture zone (Zone 5) intersects the borehole. Other, fractured sections occur at 65-67 m, 74-77 m and 245-250 m. Mean fracture frequency for the whole borehole is 2.8 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C3.

Borehole availability: No known problems with borehole blockage.

Borehole KFI10

This borehole (Figure B11) is 256 m in length and is drilled inclined 50°, reaching a depth of 193 m. The borehole is positioned to penetrate both Zone 1 and Zone 2.

Pink or red granodiorite dominates in the cores, although there are also some sections with grey granodiorite. Also some small dykes of pegmatite or granite occur in the upper part of the borehole,

High fracture frequency and tectonization occurs within two intervals, 75-105 m and 152-256 m (end of borehole). The upper interval is interpreted to represent Zone 1 and is characterized by a high fracture frequency and the fracture minerals hematite and asphaltite. The lower interval is interpreted to represent Zone 2 and is characterized by several minor sections of tectonized rock including breccias and mylonites.

The position of the borehole in the area where these two zones crosses each other is reflected in a high mean fracture frequency for the borehole, 4.8 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C4.

Borehole availability: No known problems with borehole blockage.

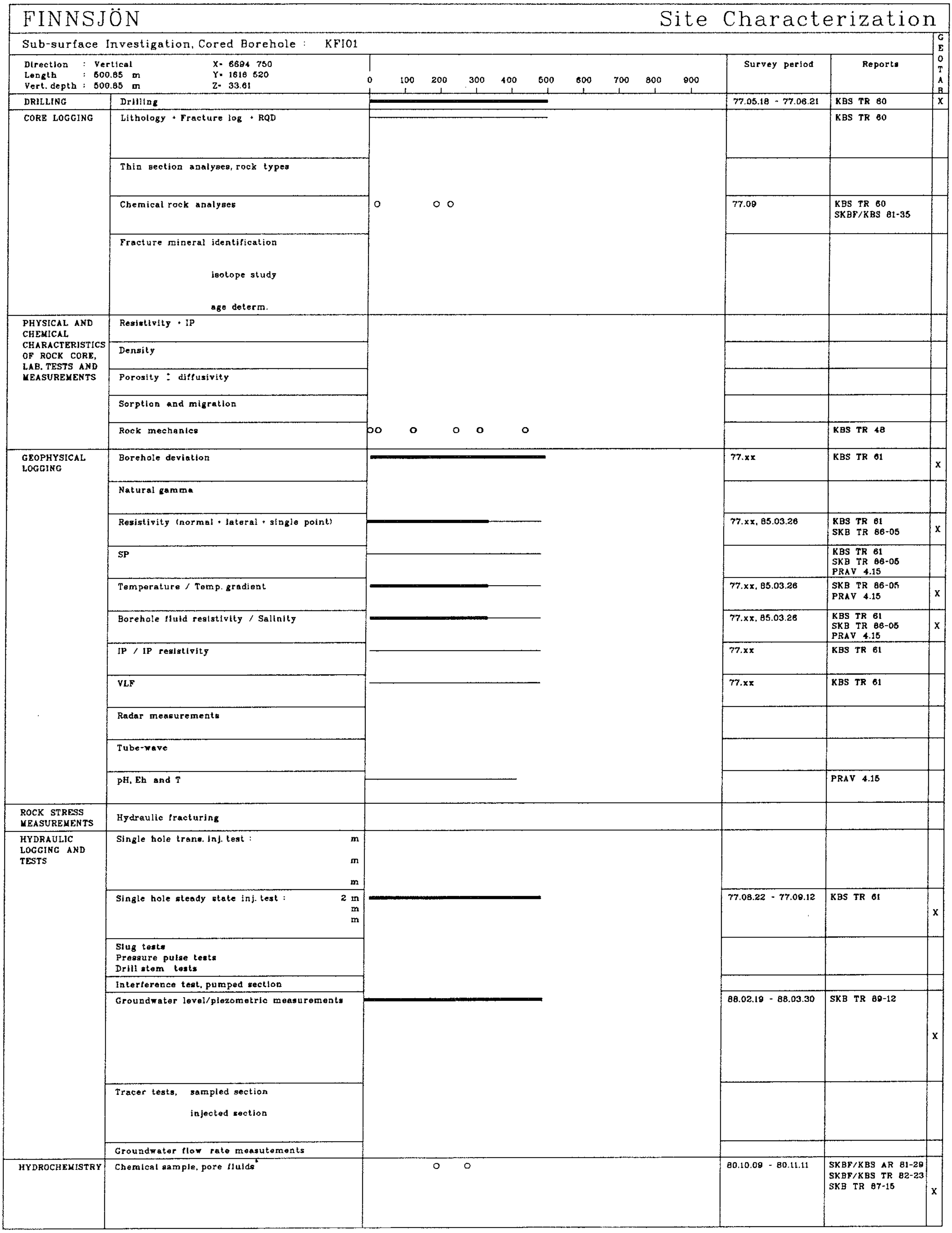
Borehole KFI11

This borehole (Figure B12) is located in the central, northern part of the site and is drilled vertically 390 m below the ground surface. The objective was to investigate Zone 2 in a position where no other fracture zone would interfere with the results.
Grey granodiorite dominates the bedrock down to 220 m. Below this depth red granodiorite dominates. Pegmatites and metabasic and aplitic dykes constitute 8% of the total core length.

The fracture frequency down to 220 m is 0.9 fr/m reflecting the low degree of fracturing in this part. Zone 2 is interpreted to be located between 221-338 m. In this section a c. 10 cm wide open fracture occurs at 224 m causing very high hydraulic conductivity. The fracture is at least partly filled with unconsolidated rock debris. The most intensely deformed section occurs at 290-305 m. Characteristic fracture minerals for the zone are calcite, laumontite and iron oxy-hydroxides.

The lower boundary of Zone 2 is somewhat uncertain due to repeatedly occurring fractured sections at the lowermost part of the borehole. The mean fracture frequency for the whole borehole is 2.0 fr/m. Main results from borehole investigations are shown in Appendix C, Figure C4.

Borehole availability: No known problems with borehole blockage.



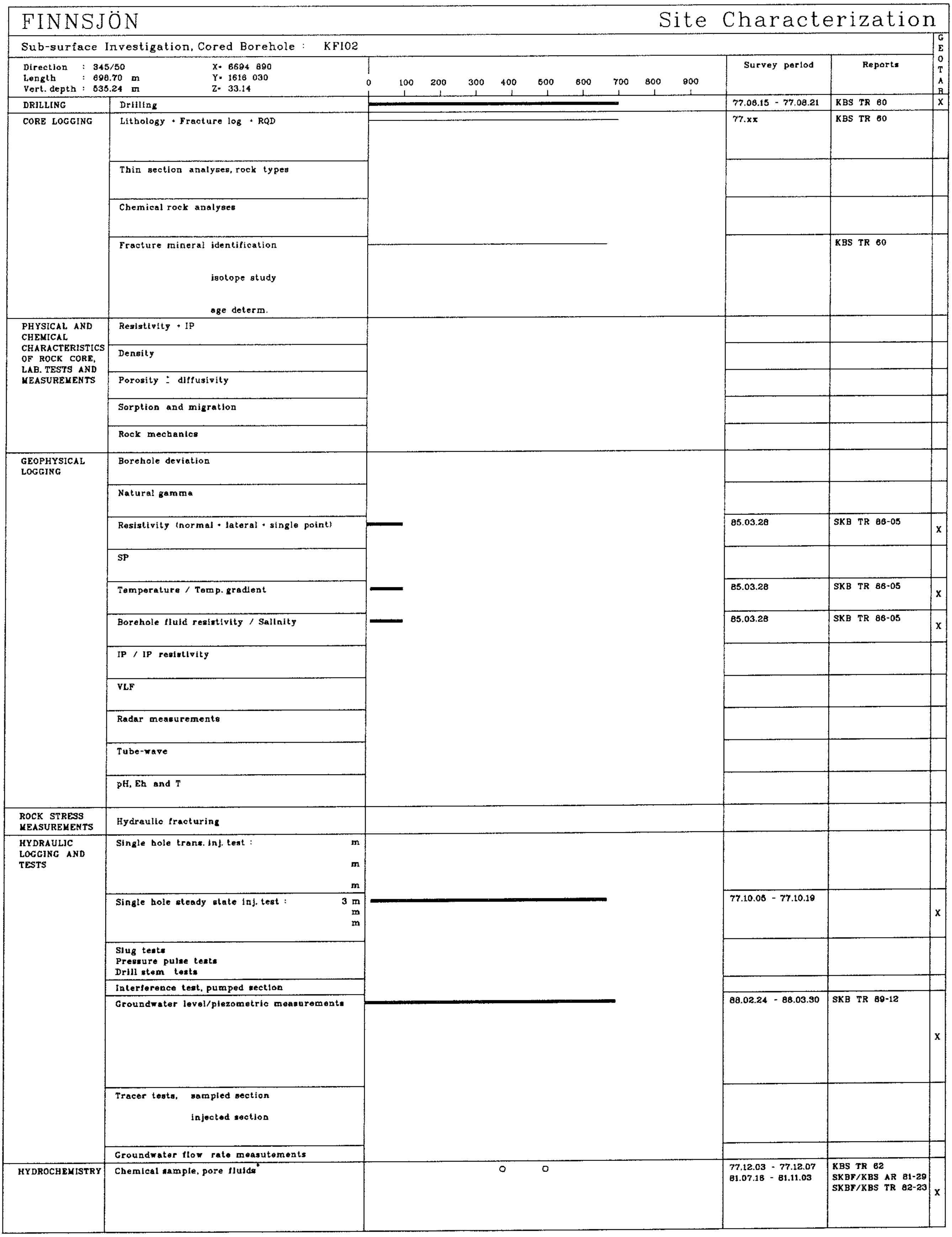
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI01

Direction : Vertical X- 6694 750
Length : 500.85 m Y- 1616 520
Vert. depth : 500.85 m Z- 33.61

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling	━━━━━	77.05.18 - 77.06.21	KBS TR 60	X
CORE LOGGING	Lithology + Fracture log + RQD	─────		KBS TR 60	
	Thin section analyses, rock types				
	Chemical rock analyses	o o o	77.09	KBS TR 60 SKBF/KBS 81-35	
	Fracture mineral identification isotope study age determ.				
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP				
	Density				
	Porosity ; diffusivity				
	Sorption and migration				
	Rock mechanics	oo o o o o		KBS TR 48	
GEOPHYSICAL LOGGING	Borehole deviation	━━━━━	77.xx	KBS TR 61	X
	Natural gamma				
	Resistivity (normal + lateral + single point)	━━━━──	77.xx, 85.03.26	KBS TR 61 SKB TR 86-05	X
	SP	─────		KBS TR 61 SKB TR 86-05 PRAV 4.15	
	Temperature / Temp. gradient	━━━━──	77.xx, 85.03.26	SKB TR 86-05 PRAV 4.15	X
	Borehole fluid resistivity / Salinity	━━━━──	77.xx, 85.03.26	KBS TR 61 SKB TR 86-05 PRAV 4.15	X
	IP / IP resistivity	─────	77.xx	KBS TR 61	
	VLF	─────	77.xx	KBS TR 61	
	Radar measurements				
	Tube-wave				
	pH, Eh and T	────		PRAV 4.15	
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m				
	Single hole steady state inj. test : 2 m m m	━━━━━	77.08.22 - 77.09.12	KBS TR 61	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements	━━━━━	88.02.19 - 88.03.30	SKB TR 89-12	X
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids*	o o	80.10.09 - 80.11.11	SKBF/KBS AR 81-29 SKBF/KBS TR 82-23 SKB TR 87-15	X

Figure B2. Activities in borehole KFI01. Data from borehole sections stored in GEOTAB have thick lines.



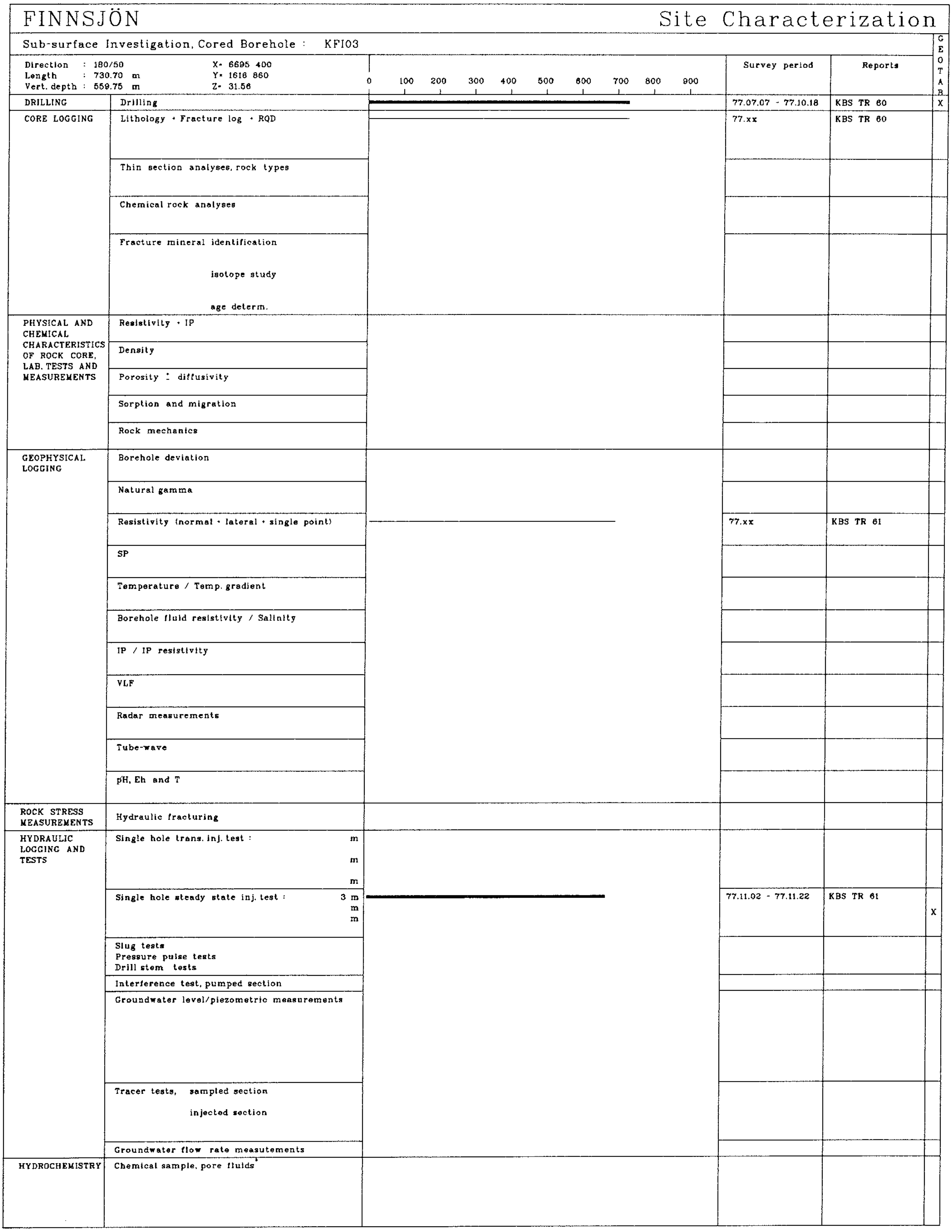
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI02

Direction : 345/50 X= 6694 890
Length : 698.70 m Y= 1616 030
Vert. depth : 535.24 m Z= 33.14

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		77.06.15 - 77.08.21	KBS TR 60	X
CORE LOGGING	Lithology + Fracture log + RQD		77.xx	KBS TR 60	
	Thin section analyses, rock types				
	Chemical rock analyses				
	Fracture mineral identification isotope study age determ.			KBS TR 60	
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP				
	Density				
	Porosity ⁚ diffusivity				
	Sorption and migration				
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation				
	Natural gamma				
	Resistivity (normal + lateral + single point)		85.03.28	SKB TR 86-05	X
	SP				
	Temperature / Temp. gradient		85.03.28	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity		85.03.28	SKB TR 86-05	X
	IP / IP resistivity				
	VLF				
	Radar measurements				
	Tube-wave				
	pH, Eh and T				
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m				
	Single hole steady state inj. test : 3 m m m		77.10.05 - 77.10.19		X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements		88.02.24 - 88.03.30	SKB TR 89-12	X
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids*	○ ○	77.12.03 - 77.12.07 81.07.16 - 81.11.03	KBS TR 62 SKBF/KBS AR 81-29 SKBF/KBS TR 82-23	X

Figure B3. Activities in borehole KFI02. Data from borehole sections stored in GEOTAB have thick lines.



FINNSJÖN Site Characterization

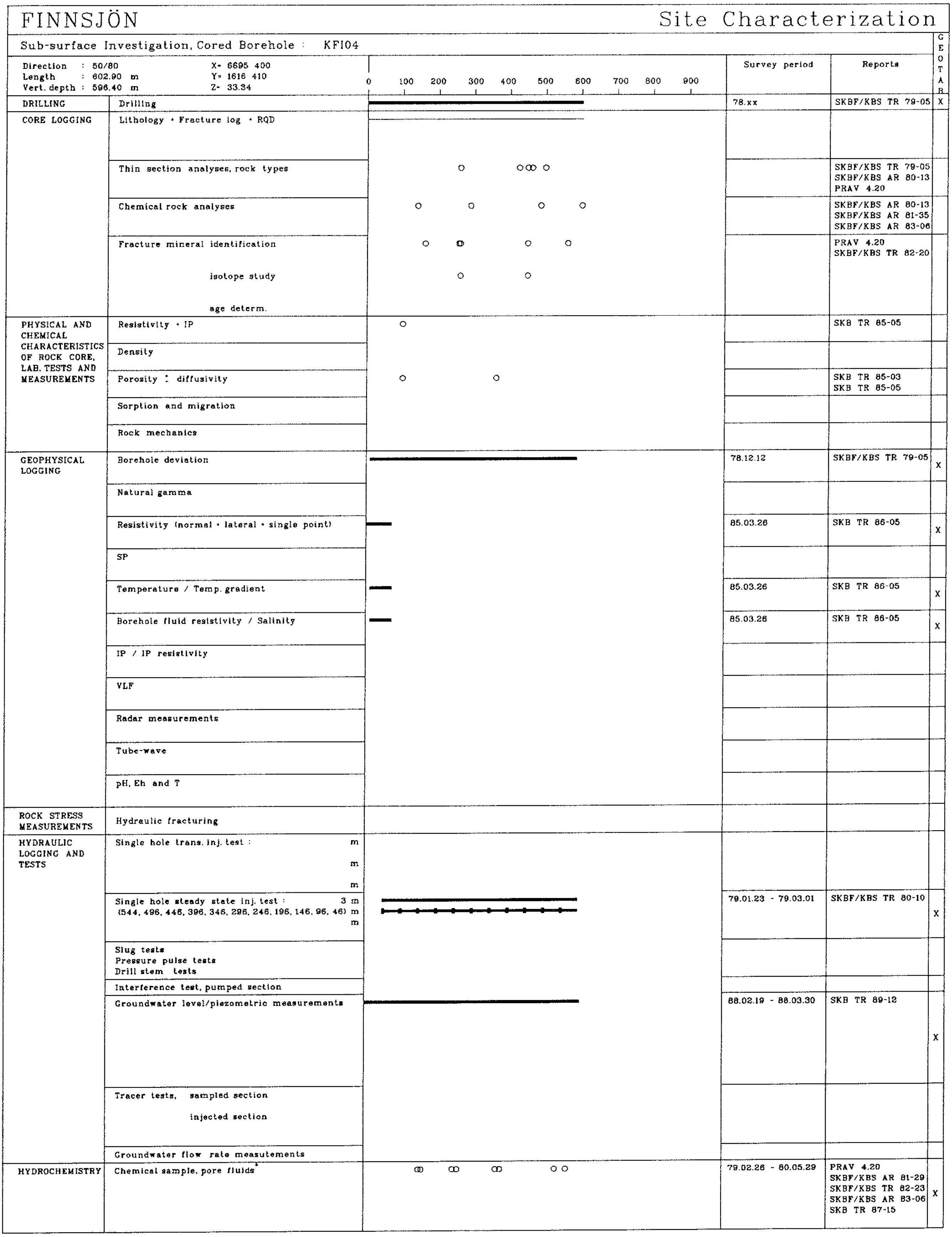
Sub-surface Investigation, Cored Borehole : KFI03

Direction : 180/50
Length : 730.70 m
Vert. depth : 559.75 m

X- 6695 400
Y- 1616 860
Z- 31.56

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		77.07.07 - 77.10.18	KBS TR 60	X
CORE LOGGING	Lithology • Fracture log • RQD		77.xx	KBS TR 60	
	Thin section analyses, rock types				
	Chemical rock analyses				
	Fracture mineral identification isotope study age determ.				
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity • IP				
	Density				
	Porosity ⁚ diffusivity				
	Sorption and migration				
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation				
	Natural gamma				
	Resistivity (normal • lateral • single point)		77.xx	KBS TR 61	
	SP				
	Temperature / Temp. gradient				
	Borehole fluid resistivity / Salinity				
	IP / IP resistivity				
	VLF				
	Radar measurements				
	Tube-wave				
	pH, Eh and T				
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m				
	Single hole steady state inj. test : 3 m m m		77.11.02 - 77.11.22	KBS TR 61	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements				
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids				

Figure B4. Activities in borehole KFI03. Data from borehole sections stored in GEOTAB have thick lines.



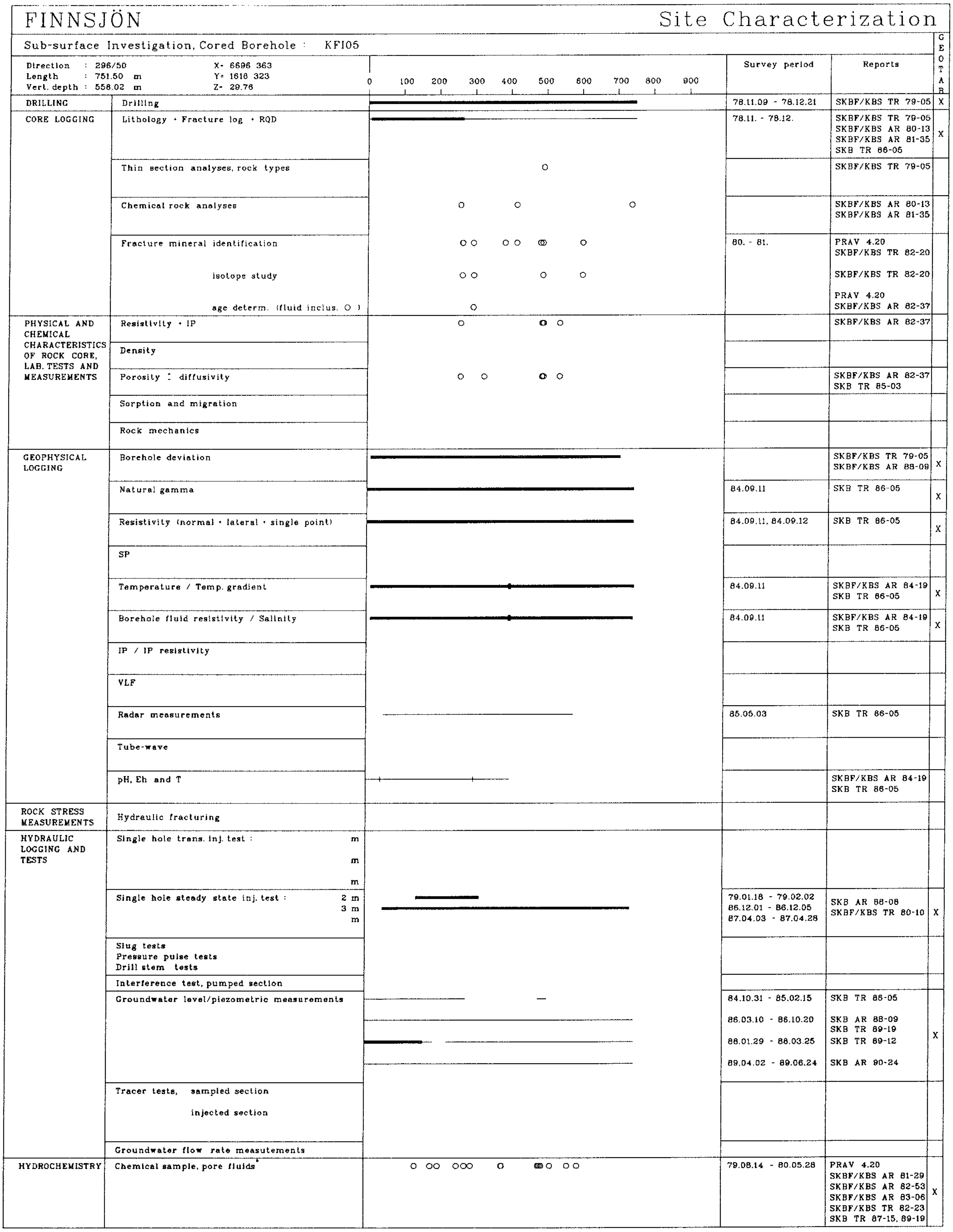
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI04

Direction : 50/80 X= 6695 400
Length : 602.90 m Y= 1616 410
Vert. depth : 596.40 m Z= 33.34

		Survey period	Reports	GEOTAB
DRILLING	Drilling	78.xx	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology + Fracture log + RQD			
	Thin section analyses, rock types		SKBF/KBS TR 79-05 SKBF/KBS AR 80-13 PRAV 4.20	
	Chemical rock analyses		SKBF/KBS AR 80-13 SKBF/KBS AR 81-35 SKBF/KBS AR 83-06	
	Fracture mineral identification isotope study age determ.		PRAV 4.20 SKBF/KBS TR 82-20	
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP		SKB TR 85-05	
	Density			
	Porosity ⁚ diffusivity		SKB TR 85-03 SKB TR 85-05	
	Sorption and migration			
	Rock mechanics			
GEOPHYSICAL LOGGING	Borehole deviation	78.12.12	SKBF/KBS TR 79-05	X
	Natural gamma			
	Resistivity (normal + lateral + single point)	85.03.26	SKB TR 86-05	X
	SP			
	Temperature / Temp. gradient	85.03.26	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity	85.03.26	SKB TR 86-05	X
	IP / IP resistivity			
	VLF			
	Radar measurements			
	Tube-wave			
	pH, Eh and T			
ROCK STRESS MEASUREMENTS	Hydraulic fracturing			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m			
	Single hole steady state inj. test : 3 m (544, 496, 446, 396, 346, 296, 246, 196, 146, 96, 46) m m	79.01.23 - 79.03.01	SKBF/KBS TR 80-10	X
	Slug tests Pressure pulse tests Drill stem tests			
	Interference test, pumped section			
	Groundwater level/piezometric measurements	88.02.19 - 88.03.30	SKB TR 89-12	X
	Tracer tests, sampled section injected section			
	Groundwater flow rate measutements			
HYDROCHEMISTRY	Chemical sample, pore fluids*	79.02.26 - 80.05.29	PRAV 4.20 SKBF/KBS AR 81-29 SKBF/KBS TR 82-23 SKBF/KBS AR 83-06 SKB TR 87-15	X

Figure B5. Activities in borehole KFI04. Data from borehole sections stored in GEOTAB have thick lines.



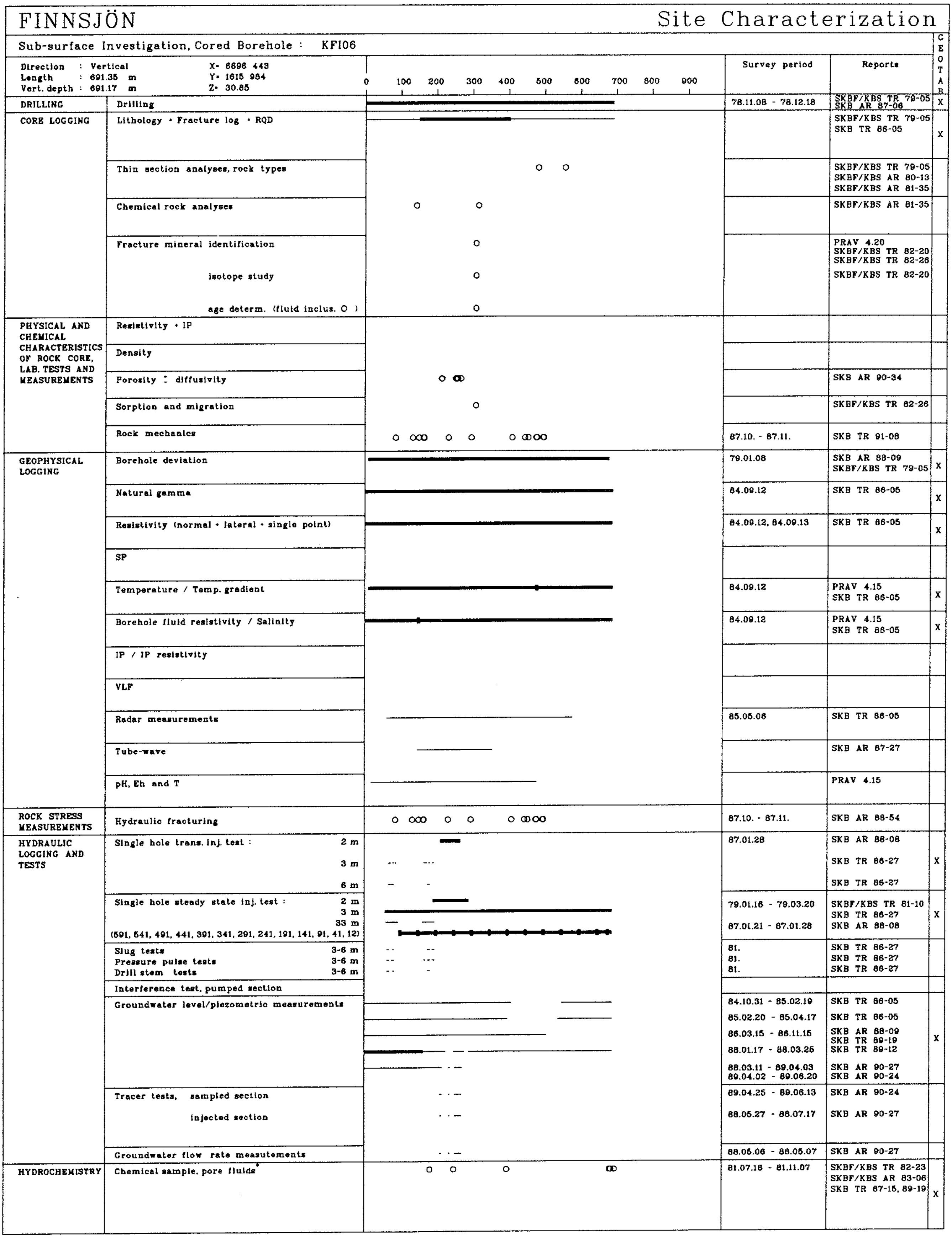
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI05

Direction : 296/50 X- 6696 363
Length : 751.50 m Y= 1618 323
Vert. depth : 558.02 m Z- 29.76

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		78.11.09 - 78.12.21	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology + Fracture log + RQD		78.11. - 78.12.	SKBF/KBS TR 79-05 SKBF/KBS AR 80-13 SKBF/KBS AR 81-35 SKB TR 86-05	X
	Thin section analyses, rock types	○		SKBF/KBS TR 79-05	
	Chemical rock analyses	○ ○ ○		SKBF/KBS AR 80-13 SKBF/KBS AR 81-35	
	Fracture mineral identification	○○ ○○ ○○ ○	80. - 81.	PRAV 4.20 SKBF/KBS TR 82-20	
	isotope study	○○ ○ ○		SKBF/KBS TR 82-20	
	age determ. (fluid inclus. ○)	○		PRAV 4.20 SKBF/KBS AR 82-37	
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP	○ ● ○		SKBF/KBS AR 82-37	
	Density				
	Porosity ⁝ diffusivity	○ ○ ● ○		SKBF/KBS AR 82-37 SKB TR 85-03	
	Sorption and migration				
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation			SKBF/KBS TR 79-05 SKBF/KBS AR 88-09	X
	Natural gamma		84.09.11	SKB TR 86-05	X
	Resistivity (normal + lateral + single point)		84.09.11, 84.09.12	SKB TR 86-05	X
	SP				
	Temperature / Temp. gradient		84.09.11	SKBF/KBS AR 84-19 SKB TR 86-05	X
	Borehole fluid resistivity / Salinity		84.09.11	SKBF/KBS AR 84-19 SKB TR 86-05	X
	IP / IP resistivity				
	VLF				
	Radar measurements		85.05.03	SKB TR 86-05	
	Tube-wave				
	pH, Eh and T			SKBF/KBS AR 84-19 SKB TR 86-05	
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : m m m				
	Single hole steady state inj. test : 2 m 3 m m		79.01.18 - 79.02.02 86.12.01 - 86.12.05 87.04.03 - 87.04.28	SKB AR 88-08 SKBF/KBS TR 80-10	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements		84.10.31 - 85.02.15 86.03.10 - 86.10.20 88.01.29 - 88.03.25 89.04.02 - 89.06.24	SKB TR 86-05 SKB AR 88-09 SKB TR 89-19 SKB TR 89-12 SKB AR 90-24	X
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids*	○ ○○ ○○○ ○ ●○ ○○	79.08.14 - 80.05.28	PRAV 4.20 SKBF/KBS AR 81-29 SKBF/KBS AR 82-53 SKBF/KBS AR 83-06 SKBF/KBS TR 82-23 SKB TR 87-15, 89-19	X

Figure B6. Activities in borehole KFI05. Data from borehole sections stored in GEOTAB have thick lines.



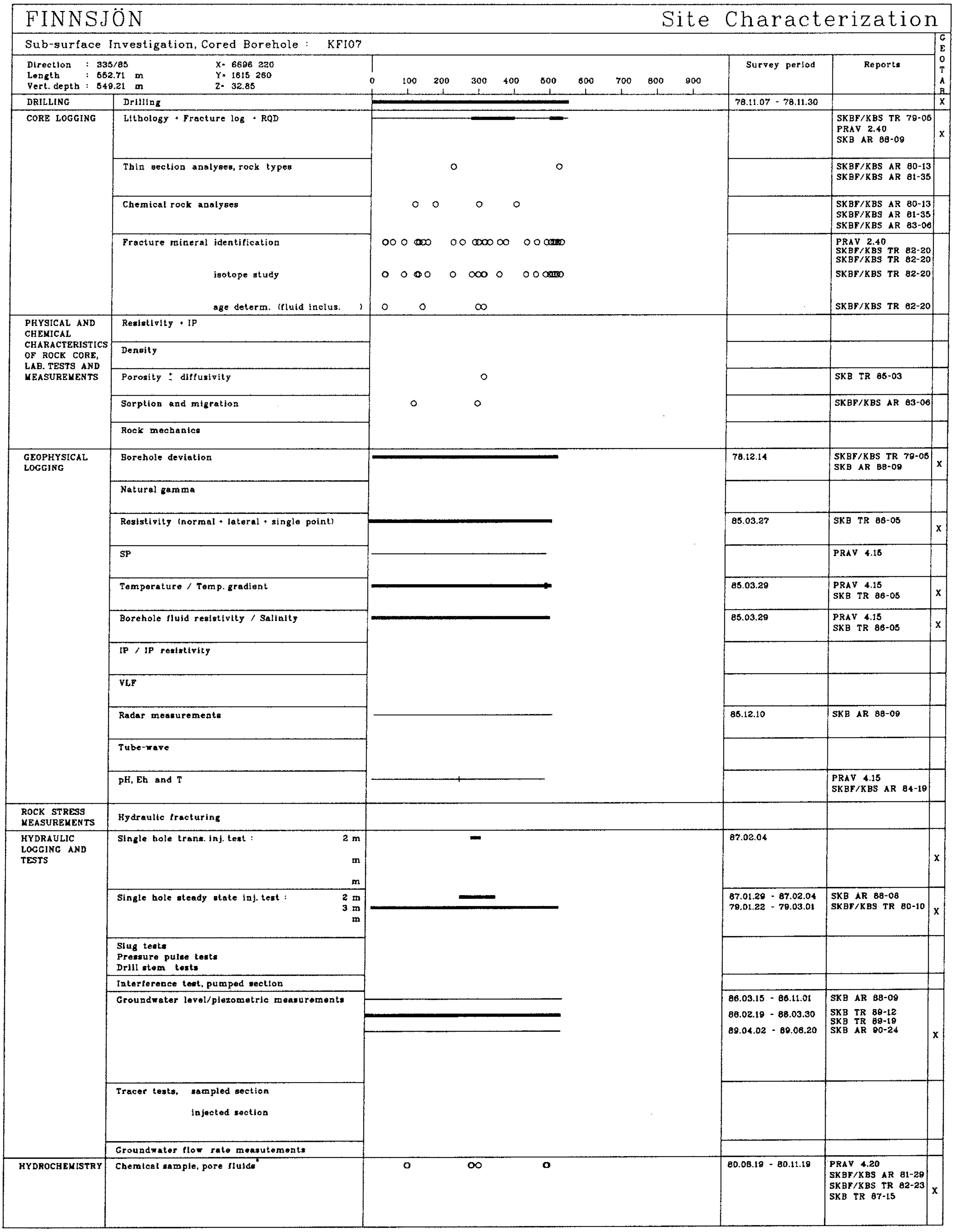
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI06

Direction : Vertical X- 6696 443
Length : 691.35 m Y- 1615 984
Vert. depth : 691.17 m Z- 30.85

		Survey period	Reports	GEOTAB
DRILLING	Drilling	78.11.08 - 78.12.18	SKBF/KBS TR 79-05 SKB AR 87-06	X
CORE LOGGING	Lithology + Fracture log + RQD		SKBF/KBS TR 79-05 SKB TR 86-05	X
	Thin section analyses, rock types		SKBF/KBS TR 79-05 SKBF/KBS AR 80-13 SKBF/KBS AR 81-35	
	Chemical rock analyses		SKBF/KBS AR 81-35	
	Fracture mineral identification		PRAV 4.20 SKBF/KBS TR 82-20 SKBF/KBS TR 82-26	
	isotope study		SKBF/KBS TR 82-20	
	age determ. (fluid inclus. O)			
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP			
	Density			
	Porosity : diffusivity		SKB AR 90-34	
	Sorption and migration		SKBF/KBS TR 82-26	
	Rock mechanics	87.10. - 87.11.	SKB TR 91-08	
GEOPHYSICAL LOGGING	Borehole deviation	79.01.08	SKB AR 88-09 SKBF/KBS TR 79-05	X
	Natural gamma	84.09.12	SKB TR 86-05	X
	Resistivity (normal + lateral + single point)	84.09.12, 84.09.13	SKB TR 86-05	X
	SP			
	Temperature / Temp. gradient	84.09.12	PRAV 4.15 SKB TR 86-05	X
	Borehole fluid resistivity / Salinity	84.09.12	PRAV 4.15 SKB TR 86-05	X
	IP / IP resistivity			
	VLF			
	Radar measurements	85.05.06	SKB TR 86-05	
	Tube-wave		SKB AR 87-27	
	pH, Eh and T		PRAV 4.15	
ROCK STRESS MEASUREMENTS	Hydraulic fracturing	87.10. - 87.11.	SKB AR 88-54	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 2 m	87.01.28	SKB AR 88-08	
	3 m		SKB TR 86-27	X
	6 m		SKB TR 86-27	
	Single hole steady state inj. test : 2 m 3 m	79.01.16 - 79.03.20	SKBF/KBS TR 81-10 SKB TR 86-27	X
	33 m (591, 541, 491, 441, 391, 341, 291, 241, 191, 141, 91, 41, 12)	87.01.21 - 87.01.28	SKB AR 88-08	
	Slug tests 3-6 m	81.	SKB TR 86-27	
	Pressure pulse tests 3-6 m	81.	SKB TR 86-27	
	Drill stem tests 3-6 m	81.	SKB TR 86-27	
	Interference test, pumped section			
	Groundwater level/piezometric measurements	84.10.31 - 85.02.19	SKB TR 86-05	
		85.02.20 - 85.04.17	SKB TR 86-05	
		86.03.15 - 86.11.15	SKB AR 88-09 SKB TR 89-19	X
		88.01.17 - 88.03.25	SKB TR 89-12	
		88.03.11 - 89.04.03 89.04.02 - 89.06.20	SKB AR 90-27 SKB AR 90-24	
	Tracer tests, sampled section	89.04.25 - 89.06.13	SKB AR 90-24	
	injected section	88.05.27 - 88.07.17	SKB AR 90-27	
	Groundwater flow rate measutements	88.05.06 - 88.05.07	SKB AR 90-27	
HYDROCHEMISTRY	Chemical sample, pore fluids*	81.07.16 - 81.11.07	SKBF/KBS TR 82-23 SKBF/KBS AR 83-06 SKB TR 87-15, 89-19	X

Figure B7. Activities in borehole KFI06. Data from borehole sections stored in GEOTAB have thick lines.



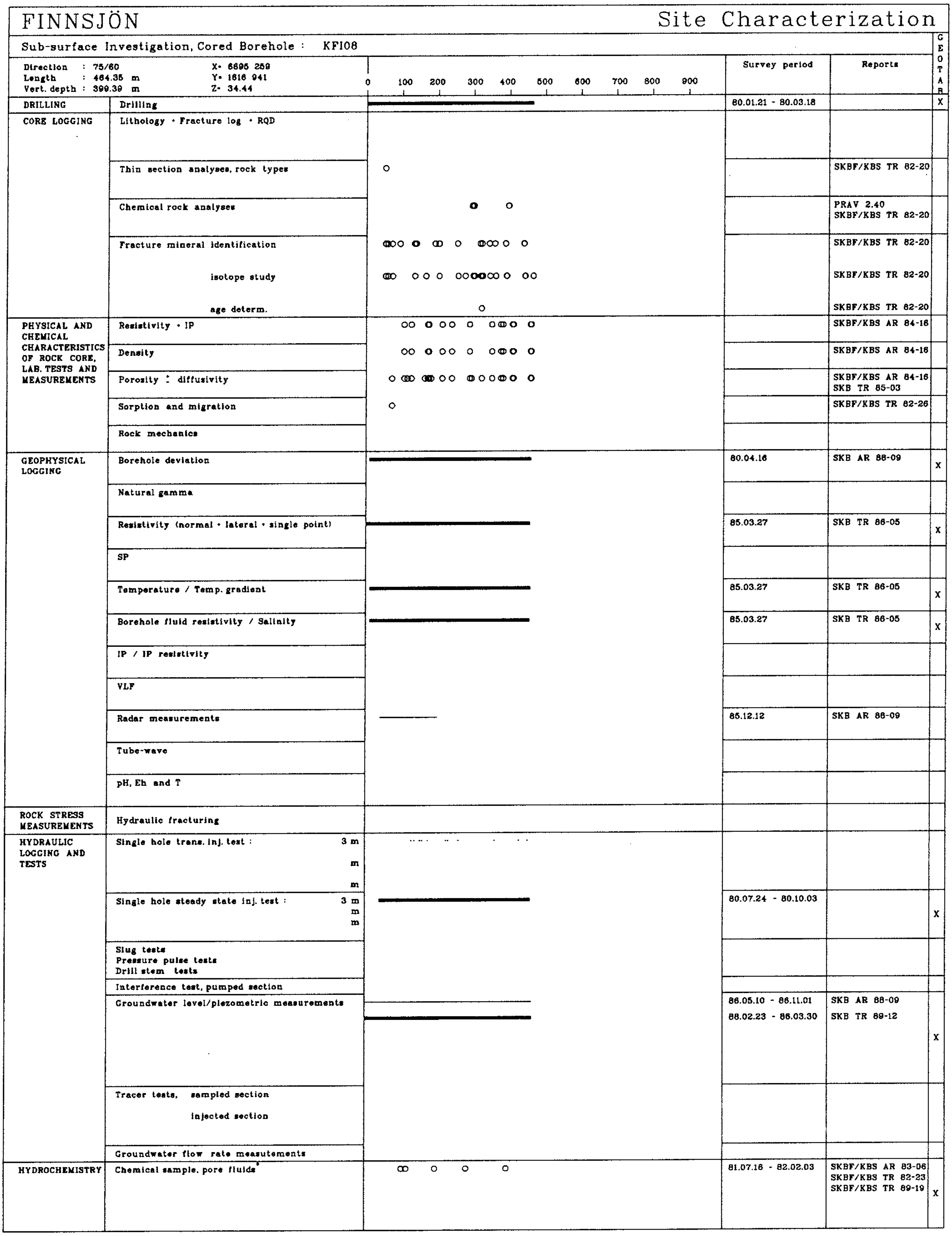
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI07

Direction : 335/85 X- 6696 220
Length : 552.71 m Y- 1615 260
Vert. depth : 549.21 m Z- 32.85

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		78.11.07 - 78.11.30		X
CORE LOGGING	Lithology + Fracture log + RQD			SKBF/KBS TR 79-05 PRAV 2.40 SKB AR 88-09	X
	Thin section analyses, rock types			SKBF/KBS AR 80-13 SKBF/KBS AR 81-35	
	Chemical rock analyses			SKBF/KBS AR 80-13 SKBF/KBS AR 81-35 SKBF/KBS AR 83-06	
	Fracture mineral identification			PRAV 2.40 SKBF/KBS TR 82-20 SKBF/KBS TR 82-20	
	isotope study			SKBF/KBS TR 82-20	
	age determ. (fluid inclus.)			SKBF/KBS TR 82-20	
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP				
	Density				
	Porosity : diffusivity			SKB TR 85-03	
	Sorption and migration			SKBF/KBS AR 83-06	
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation		78.12.14	SKBF/KBS TR 79-05 SKB AR 88-09	X
	Natural gamma				
	Resistivity (normal + lateral + single point)		85.03.27	SKB TR 86-05	X
	SP			PRAV 4.15	
	Temperature / Temp. gradient		85.03.29	PRAV 4.15 SKB TR 86-05	X
	Borehole fluid resistivity / Salinity		85.03.29	PRAV 4.15 SKB TR 86-05	X
	IP / IP resistivity				
	VLF				
	Radar measurements		85.12.10	SKB AR 88-09	
	Tube-wave				
	pH, Eh and T			PRAV 4.15 SKBF/KBS AR 84-19	
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 2 m m m		87.02.04		X
	Single hole steady state inj. test : 2 m 3 m m		87.01.29 - 87.02.04 79.01.22 - 79.03.01	SKB AR 88-08 SKBF/KBS TR 80-10	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements		86.03.15 - 86.11.01 88.02.19 - 88.03.30 89.04.02 - 89.06.20	SKB AR 88-09 SKB TR 89-12 SKB TR 89-19 SKB AR 90-24	X
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids*		80.08.19 - 80.11.19	PRAV 4.20 SKBF/KBS AR 81-29 SKBF/KBS TR 82-23 SKB TR 87-15	X

Figure B8. Activities in borehole KFI07. Data from borehole sections stored in GEOTAB have thick lines.



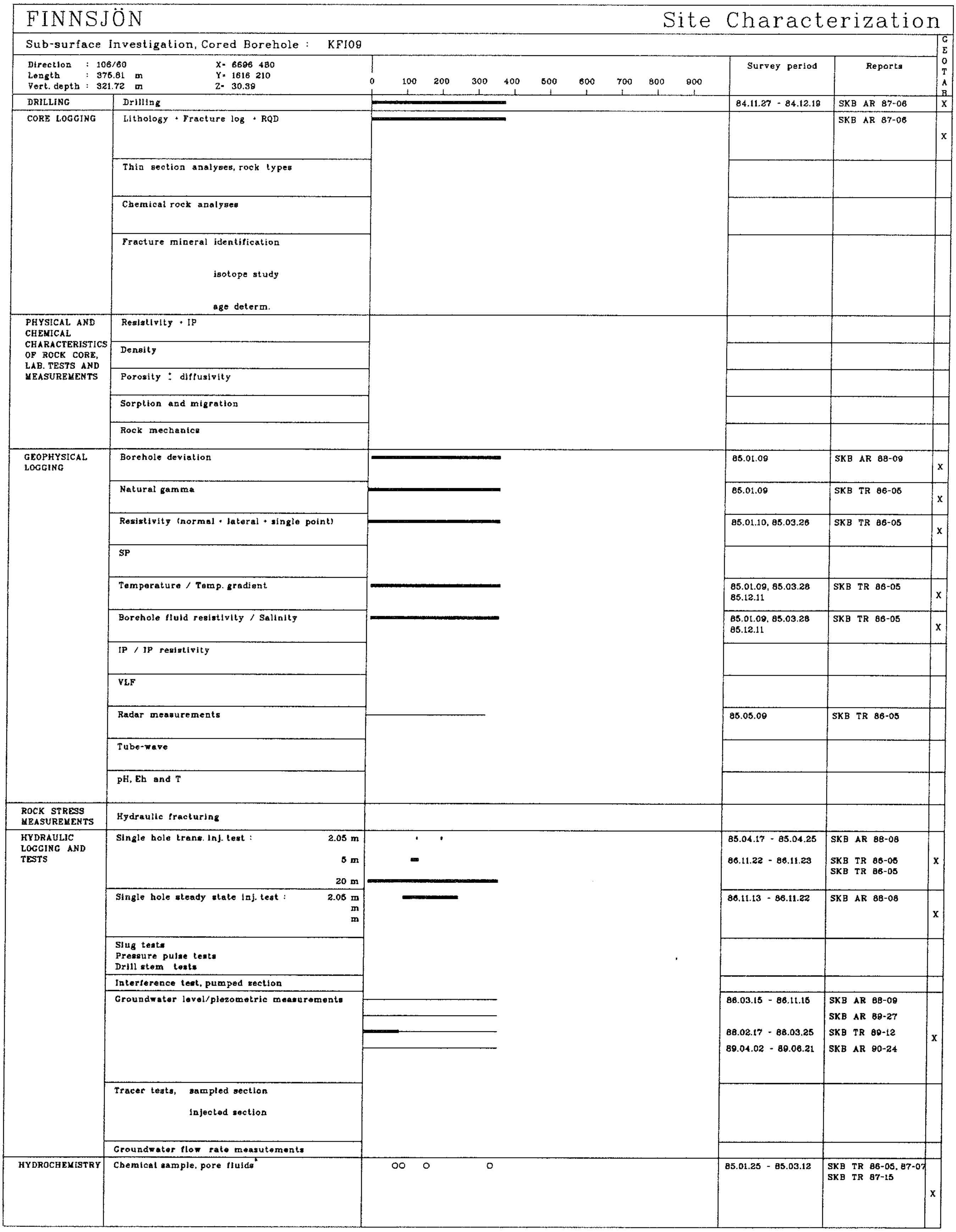
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI08

Direction : 75/60
Length : 464.35 m
Vert. depth : 399.39 m
X- 6695 259
Y- 1616 941
Z- 34.44

		Survey period	Reports	GEOTAB
DRILLING	Drilling	80.01.21 - 80.03.18		X
CORE LOGGING	Lithology • Fracture log • RQD			
	Thin section analyses, rock types		SKBF/KBS TR 82-20	
	Chemical rock analyses		PRAV 2.40 SKBF/KBS TR 82-20	
	Fracture mineral identification		SKBF/KBS TR 82-20	
	isotope study		SKBF/KBS TR 82-20	
	age determ.		SKBF/KBS TR 82-20	
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity • IP		SKBF/KBS AR 84-16	
	Density		SKBF/KBS AR 84-16	
	Porosity ⁚ diffusivity		SKBF/KBS AR 84-16 SKB TR 85-03	
	Sorption and migration		SKBF/KBS TR 82-26	
	Rock mechanics			
GEOPHYSICAL LOGGING	Borehole deviation	80.04.16	SKB AR 88-09	X
	Natural gamma			
	Resistivity (normal • lateral • single point)	85.03.27	SKB TR 86-05	X
	SP			
	Temperature / Temp. gradient	85.03.27	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity	85.03.27	SKB TR 86-05	X
	IP / IP resistivity			
	VLF			
	Radar measurements	86.12.12	SKB AR 88-09	
	Tube-wave			
	pH, Eh and T			
ROCK STRESS MEASUREMENTS	Hydraulic fracturing			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 3 m m m			
	Single hole steady state inj. test : 3 m m m	80.07.24 - 80.10.03		X
	Slug tests Pressure pulse tests Drill stem tests			
	Interference test, pumped section			
	Groundwater level/piezometric measurements	86.05.10 - 86.11.01 88.02.23 - 86.03.30	SKB AR 88-09 SKB TR 89-12	X
	Tracer tests, sampled section injected section			
	Groundwater flow rate measutements			
HYDROCHEMISTRY	Chemical sample, pore fluids*	81.07.16 - 82.02.03	SKBF/KBS AR 83-06 SKBF/KBS TR 82-23 SKBF/KBS TR 89-19	X

Figure B9. Activities in borehole KFI08. Data from borehole sections stored in GEOTAB have thick lines.



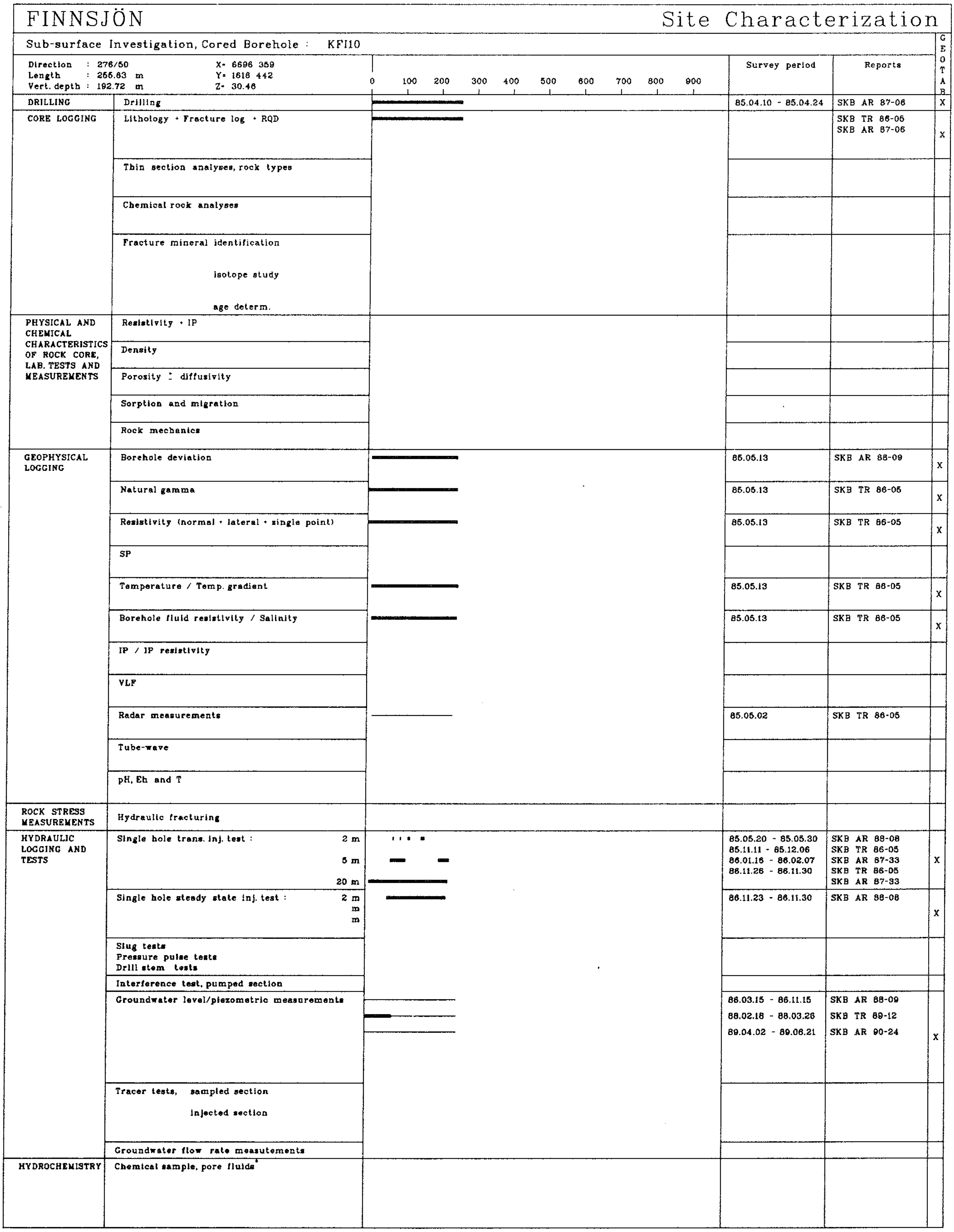
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI09

Direction : 106/60 X= 6696 480
Length : 375.81 m Y= 1616 210
Vert. depth : 321.72 m Z= 30.39

		Survey period	Reports	GEOTAB
DRILLING	Drilling	84.11.27 - 84.12.19	SKB AR 87-06	X
CORE LOGGING	Lithology + Fracture log + RQD		SKB AR 87-06	X
	Thin section analyses, rock types			
	Chemical rock analyses			
	Fracture mineral identification isotope study age determ.			
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP			
	Density			
	Porosity : diffusivity			
	Sorption and migration			
	Rock mechanics			
GEOPHYSICAL LOGGING	Borehole deviation	85.01.09	SKB AR 88-09	X
	Natural gamma	85.01.09	SKB TR 86-05	X
	Resistivity (normal + lateral + single point)	85.01.10, 85.03.26	SKB TR 86-05	X
	SP			
	Temperature / Temp. gradient	85.01.09, 85.03.28 85.12.11	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity	85.01.09, 85.03.28 85.12.11	SKB TR 86-05	X
	IP / IP resistivity			
	VLF			
	Radar measurements	85.05.09	SKB TR 86-05	
	Tube-wave			
	pH, Eh and T			
ROCK STRESS MEASUREMENTS	Hydraulic fracturing			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 2.05 m 5 m 20 m	85.04.17 - 85.04.25 86.11.22 - 86.11.23	SKB AR 88-08 SKB TR 86-05 SKB TR 86-05	X
	Single hole steady state inj. test : 2.05 m m m	86.11.13 - 86.11.22	SKB AR 88-08	X
	Slug tests Pressure pulse tests Drill stem tests			
	Interference test, pumped section			
	Groundwater level/piezometric measurements	86.03.15 - 86.11.15 88.02.17 - 88.03.25 89.04.02 - 89.06.21	SKB AR 88-09 SKB AR 89-27 SKB TR 89-12 SKB AR 90-24	X
	Tracer tests, sampled section injected section			
	Groundwater flow rate measutements			
HYDROCHEMISTRY	Chemical sample, pore fluids*	85.01.25 - 85.03.12	SKB TR 86-05, 87-07 SKB TR 87-15	X

Figure B10. Activities in borehole KFI09. Data from borehole sections stored in GEOTAB have thick lines.



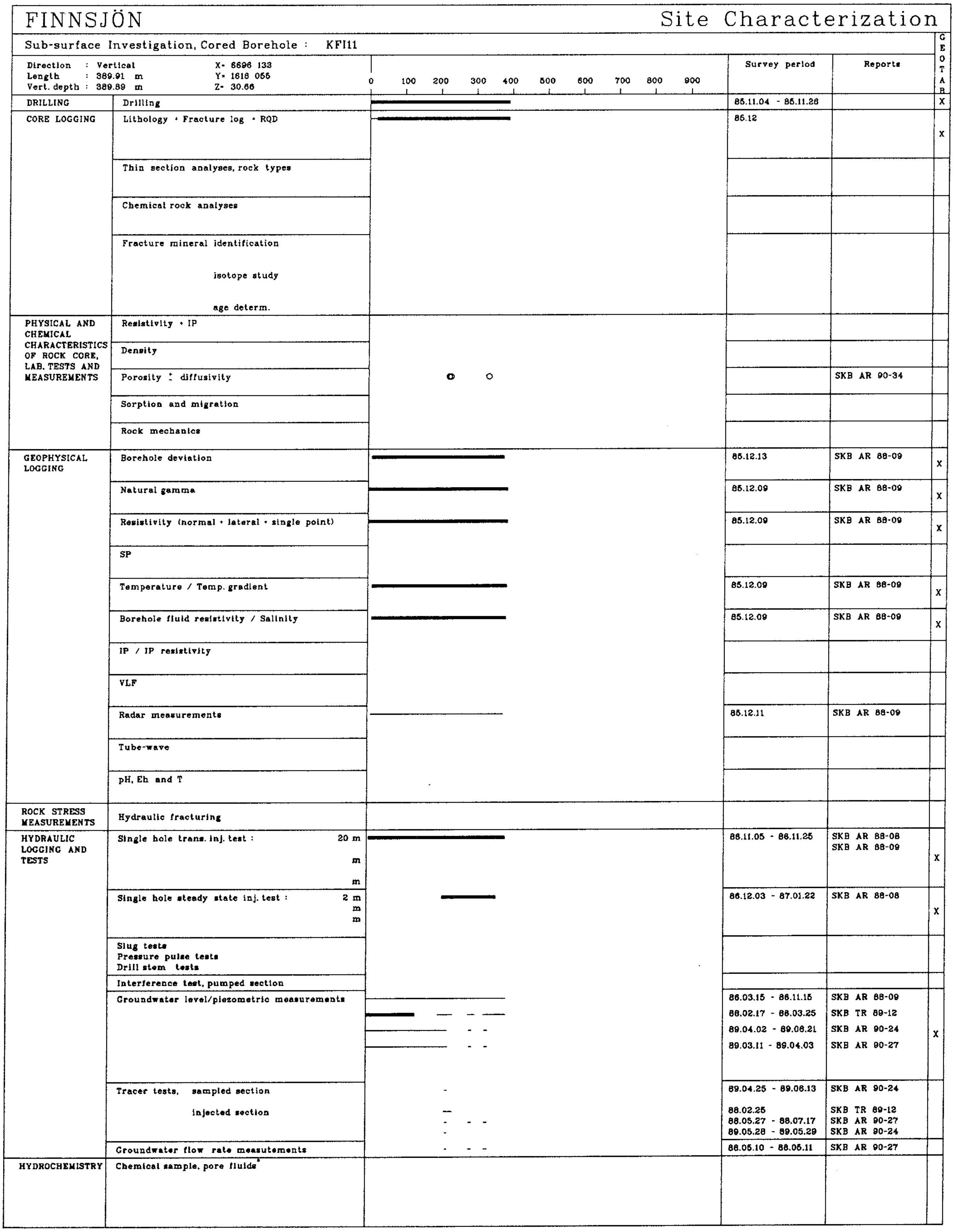
FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI10

Direction : 276/50 X- 6696 359
Length : 266.63 m Y- 1618 442
Vert. depth : 192.72 m Z- 30.46

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		85.04.10 - 85.04.24	SKB AR 87-06	X
CORE LOGGING	Lithology + Fracture log + RQD			SKB TR 86-05 SKB AR 87-06	X
	Thin section analyses, rock types				
	Chemical rock analyses				
	Fracture mineral identification isotope study age determ.				
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP				
	Density				
	Porosity : diffusivity				
	Sorption and migration				
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation		85.05.13	SKB AR 88-09	X
	Natural gamma		85.05.13	SKB TR 86-05	X
	Resistivity (normal + lateral + single point)		85.05.13	SKB TR 86-05	X
	SP				
	Temperature / Temp. gradient		85.05.13	SKB TR 86-05	X
	Borehole fluid resistivity / Salinity		85.05.13	SKB TR 86-05	X
	IP / IP resistivity				
	VLF				
	Radar measurements		85.05.02	SKB TR 86-05	
	Tube-wave				
	pH, Eh and T				
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 2 m 5 m 20 m		85.05.20 - 85.05.30 85.11.11 - 85.12.06 86.01.16 - 86.02.07 86.11.26 - 86.11.30	SKB AR 88-08 SKB TR 86-05 SKB AR 87-33 SKB TR 86-05 SKB AR 87-33	X
	Single hole steady state inj. test : 2 m m m		86.11.23 - 86.11.30	SKB AR 88-08	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements		86.03.15 - 86.11.15 88.02.18 - 88.03.26 89.04.02 - 89.06.21	SKB AR 88-09 SKB TR 89-12 SKB AR 90-24	X
	Tracer tests, sampled section injected section				
	Groundwater flow rate measutements				
HYDROCHEMISTRY	Chemical sample, pore fluids				

Figure B11. Activities in borehole KFI10. Data from borehole sections stored in GEOTAB have thick lines.



FINNSJÖN Site Characterization

Sub-surface Investigation, Cored Borehole : KFI11

Direction : Vertical X= 6696 133
Length : 389.91 m Y= 1618 065
Vert. depth : 389.89 m Z= 30.66

		0 100 200 300 400 500 600 700 800 900	Survey period	Reports	GEOTAB
DRILLING	Drilling		85.11.04 - 85.11.26		X
CORE LOGGING	Lithology + Fracture log + RQD		85.12		X
	Thin section analyses, rock types				
	Chemical rock analyses				
	Fracture mineral identification isotope study age determ.				
PHYSICAL AND CHEMICAL CHARACTERISTICS OF ROCK CORE, LAB. TESTS AND MEASUREMENTS	Resistivity + IP				
	Density				
	Porosity ± diffusivity	○ ○		SKB AR 90-34	
	Sorption and migration				
	Rock mechanics				
GEOPHYSICAL LOGGING	Borehole deviation		85.12.13	SKB AR 88-09	X
	Natural gamma		85.12.09	SKB AR 88-09	X
	Resistivity (normal + lateral + single point)		85.12.09	SKB AR 88-09	X
	SP				
	Temperature / Temp. gradient		85.12.09	SKB AR 88-09	X
	Borehole fluid resistivity / Salinity		85.12.09	SKB AR 88-09	X
	IP / IP resistivity				
	VLF				
	Radar measurements		85.12.11	SKB AR 88-09	
	Tube-wave				
	pH, Eh and T				
ROCK STRESS MEASUREMENTS	Hydraulic fracturing				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test : 20 m m m		86.11.05 - 86.11.25	SKB AR 88-08 SKB AR 88-09	X
	Single hole steady state inj. test : 2 m m m		86.12.03 - 87.01.22	SKB AR 88-08	X
	Slug tests Pressure pulse tests Drill stem tests				
	Interference test, pumped section				
	Groundwater level/piezometric measurements		86.03.15 - 86.11.15 88.02.17 - 88.03.25 89.04.02 - 89.06.21 89.03.11 - 89.04.03	SKB AR 88-09 SKB TR 89-12 SKB AR 90-24 SKB AR 90-27	X
	Tracer tests, sampled section injected section		89.04.25 - 89.06.13 88.02.25 88.05.27 - 88.07.17 89.05.28 - 89.05.29	SKB AR 90-24 SKB TR 89-12 SKB AR 90-27 SKB AR 90-24	
	Groundwater flow rate measutements		88.05.10 - 88.05.11	SKB AR 90-27	
HYDROCHEMISTRY	Chemical sample, pore fluids*				

Figure B12. Activities in borehole KFI11. Data from borehole sections stored in GEOTAB have thick lines.

APPENDIX C

GENERALIZED RESULTS FROM BOREHOLE MEASUREMENTS

Generalized results from core mapping and borehole measurements/tests in the cored boreholes KFI01-KFI11 are presented in Figures C1-C4. For each borehole the following information is presented; rock types, location of fractured sections (including interpreted fracture zones) and locations of sections with increased hydraulic conductivity. For comparison, also intersections with interpreted fracture zones are shown in the figures. The generalizations have been made in the following way:

Rock types

Main rock types are shown, i.e. rocks with a width/extension along the core greater than 1 m. Amphibolitic and doleritic bodies or dykes are collectively termed greenstone.

Fracturing

Increased fracturing is noted where the fracture frequency exceeds 10 fr/m over a 10 m section of the core.

Increased hydraulic conductivity

Increased hydraulic conductivity is noted for borehole sections where the conductivity is more than 10 times higher than the average hydraulic conductivity for the rock mass at the depth in question (see Figure 19 in Chapter 6). Highly increased hydraulic conductivity is noted where the conductivity in the borehole section is more than 100 times higher.

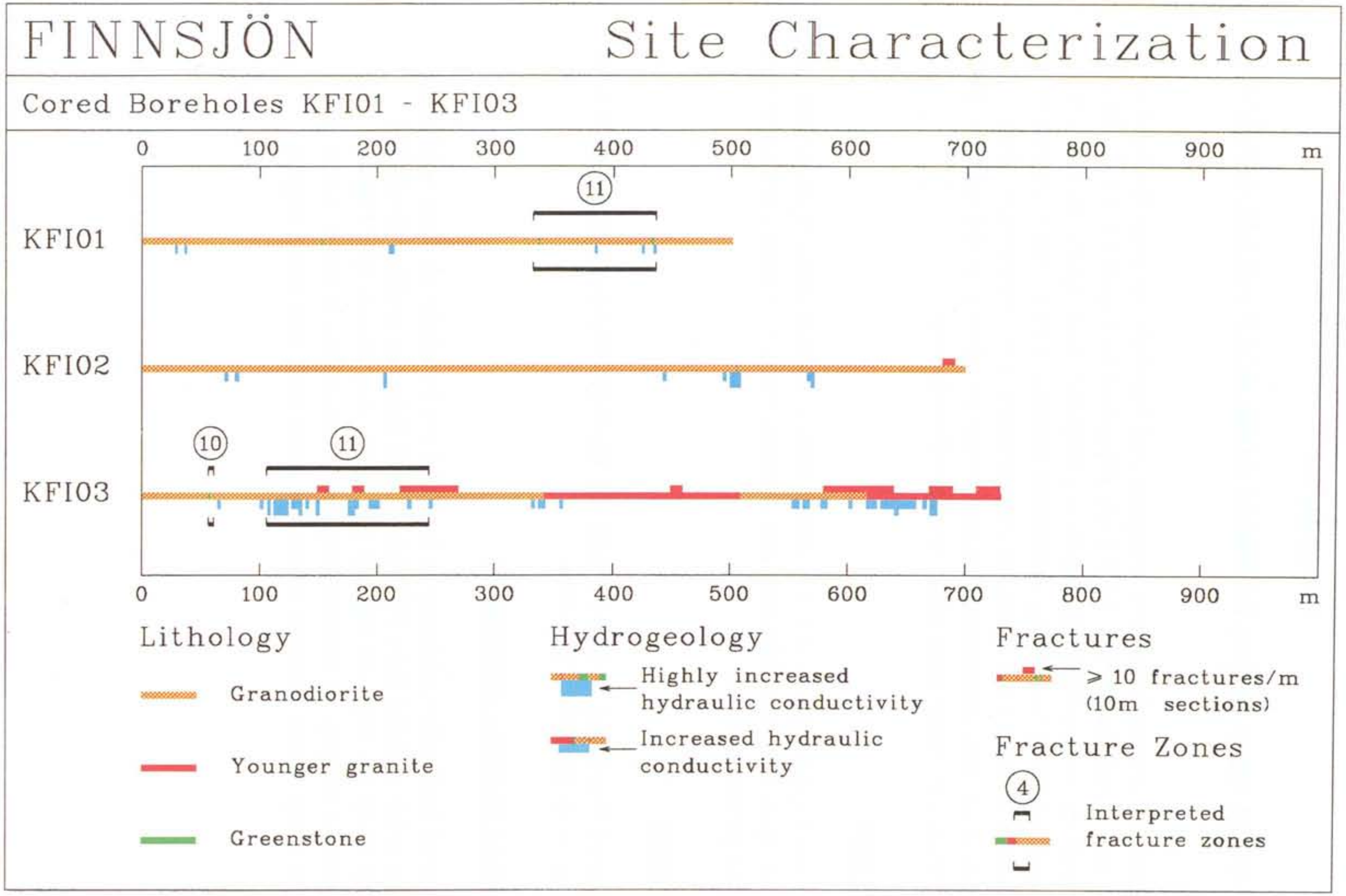


Figure C1. Results from borehole surveys in KFI01-KFI03. The horizontal axis represent borehole length.

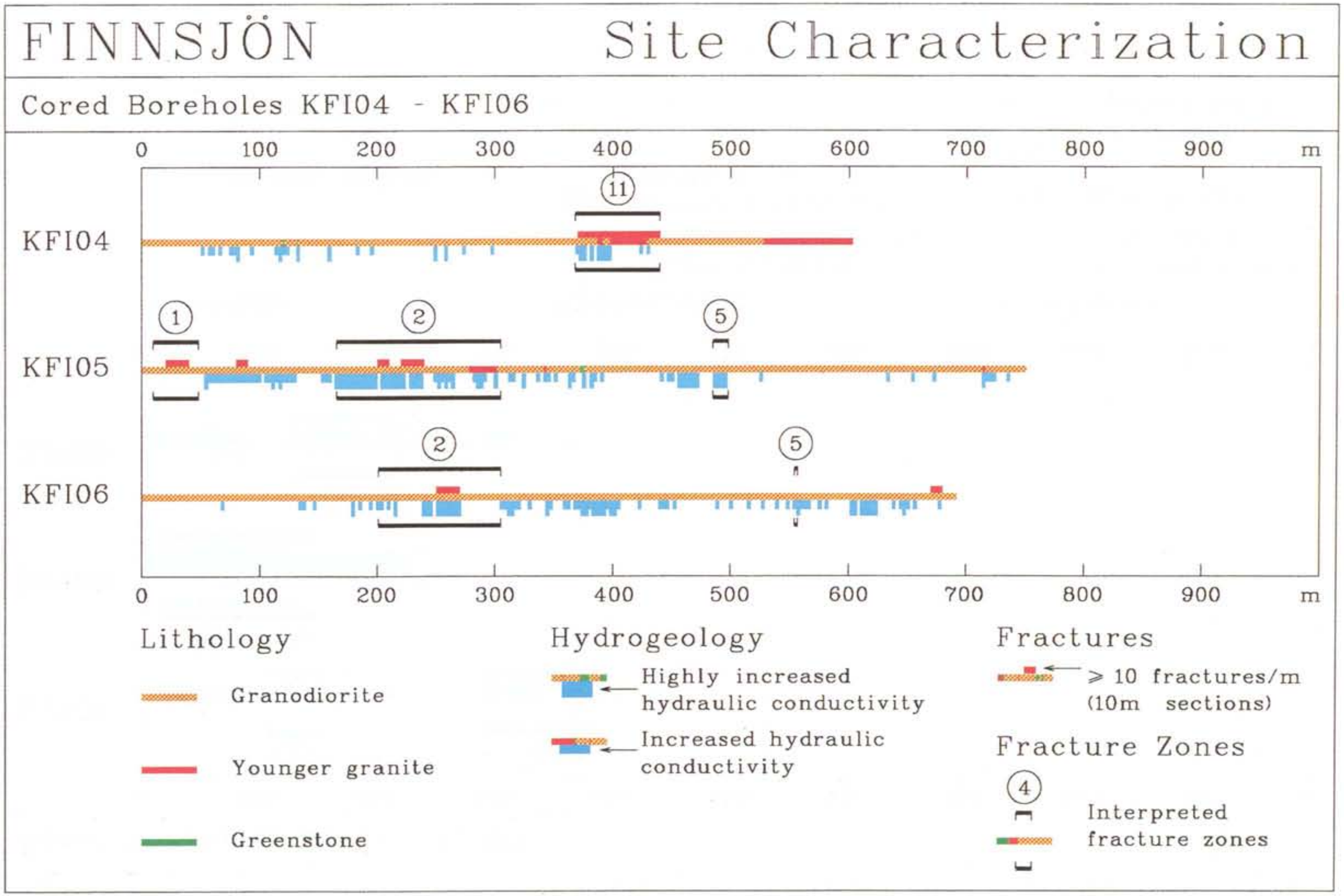


Figure C2. Results from borehole surveys in KFI04-KFI06. The horizontal axis represent borehole length.

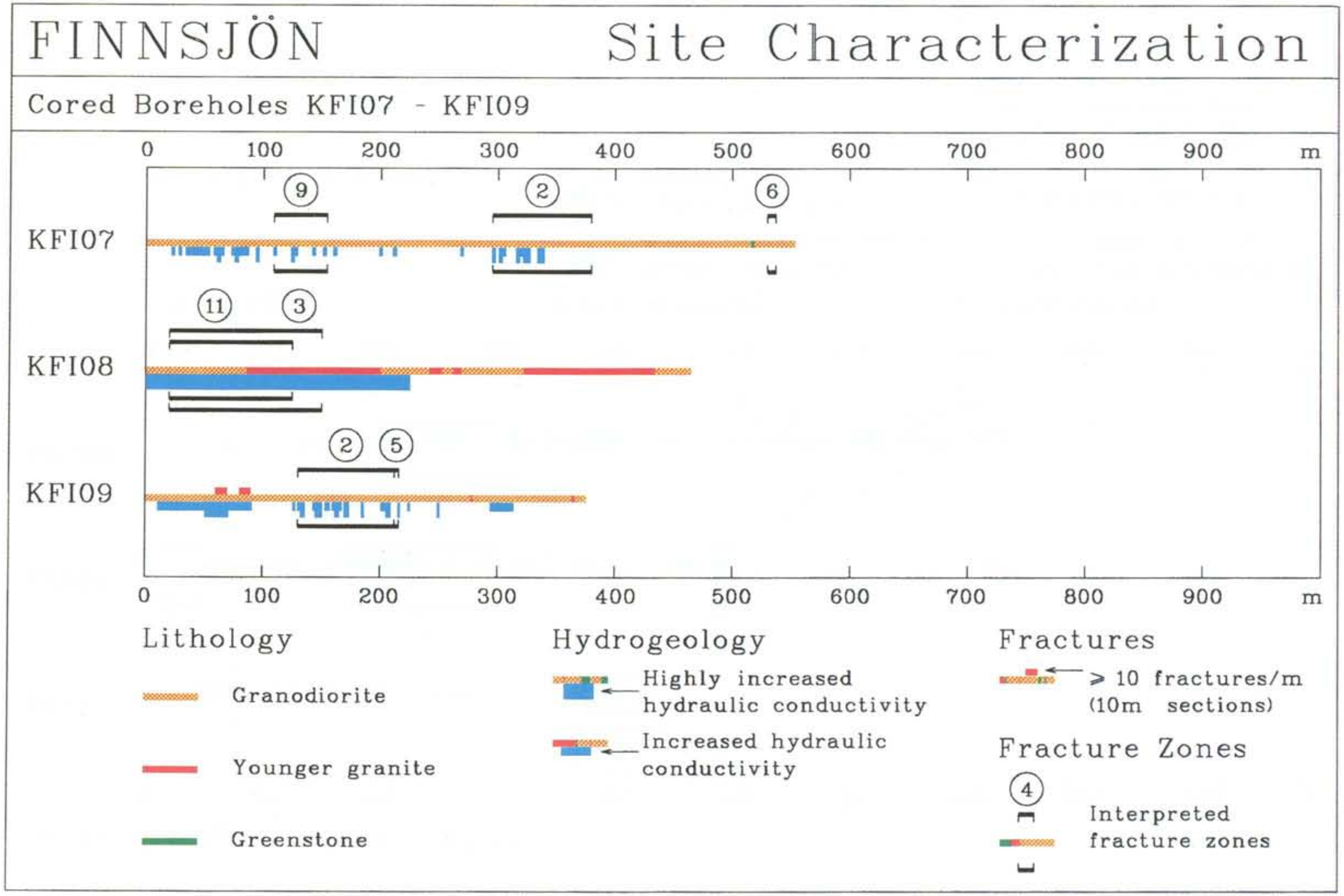


Figure C3. Results from borehole surveys in KFI07-KFI09. The horizontal axis represent borehole length.

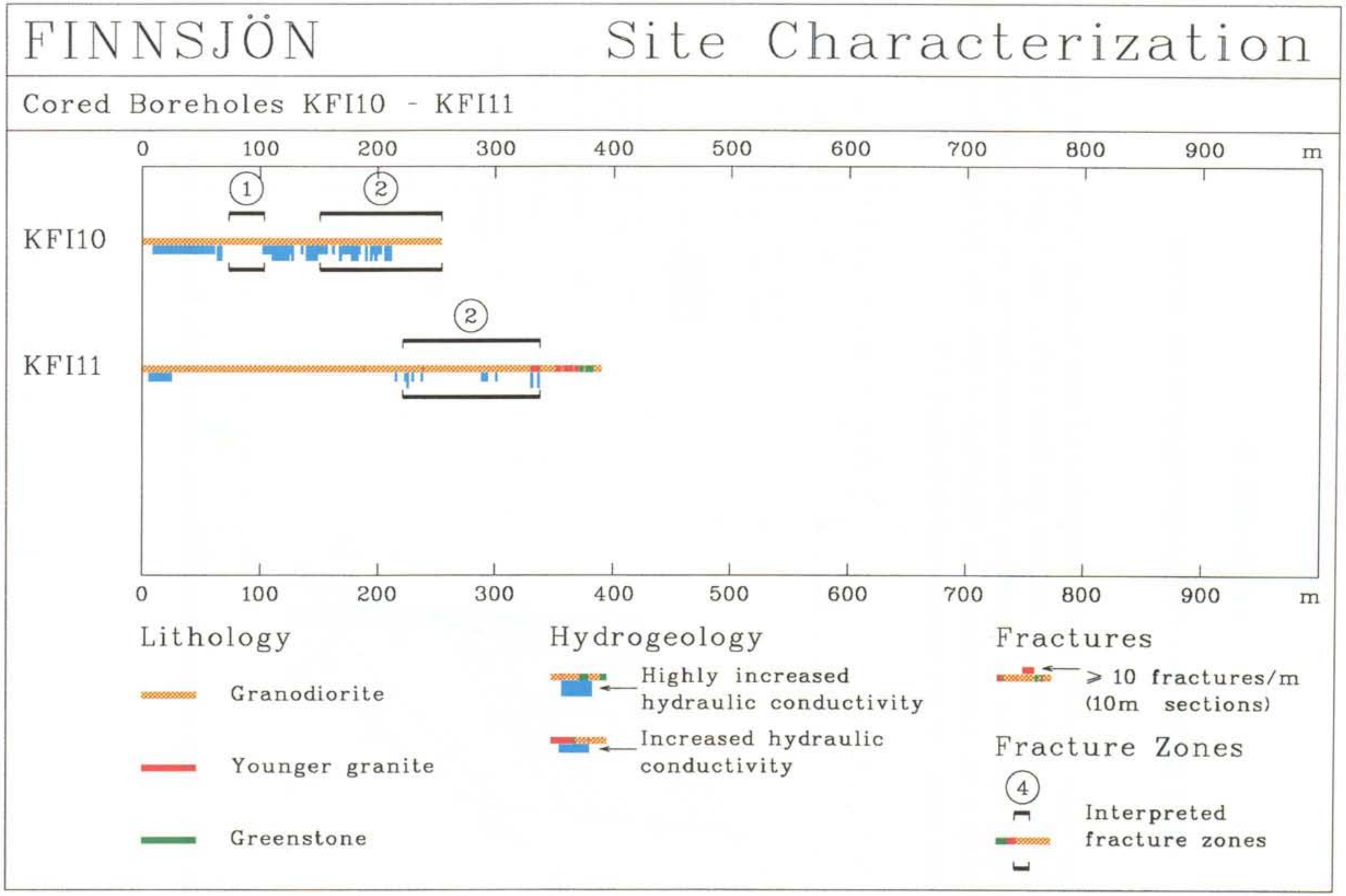


Figure C4. Results from borehole surveys in KFI10-KFI11. The horizontal axis represent borehole length.

APPENDIX D

DESCRIPTIONS OF EACH FRACTURE ZONE

This appendix presents brief descriptions of each fracture zone, based on the interpretation presented in Ahlbom and Tirén (1991), see Figure D1. General comments regarding the reliability of the interpretation are also presented, according to the nomenclature by Bäckblom (1989). The fracture zones in the Finnsjön study site are summarized in Section 5.3.

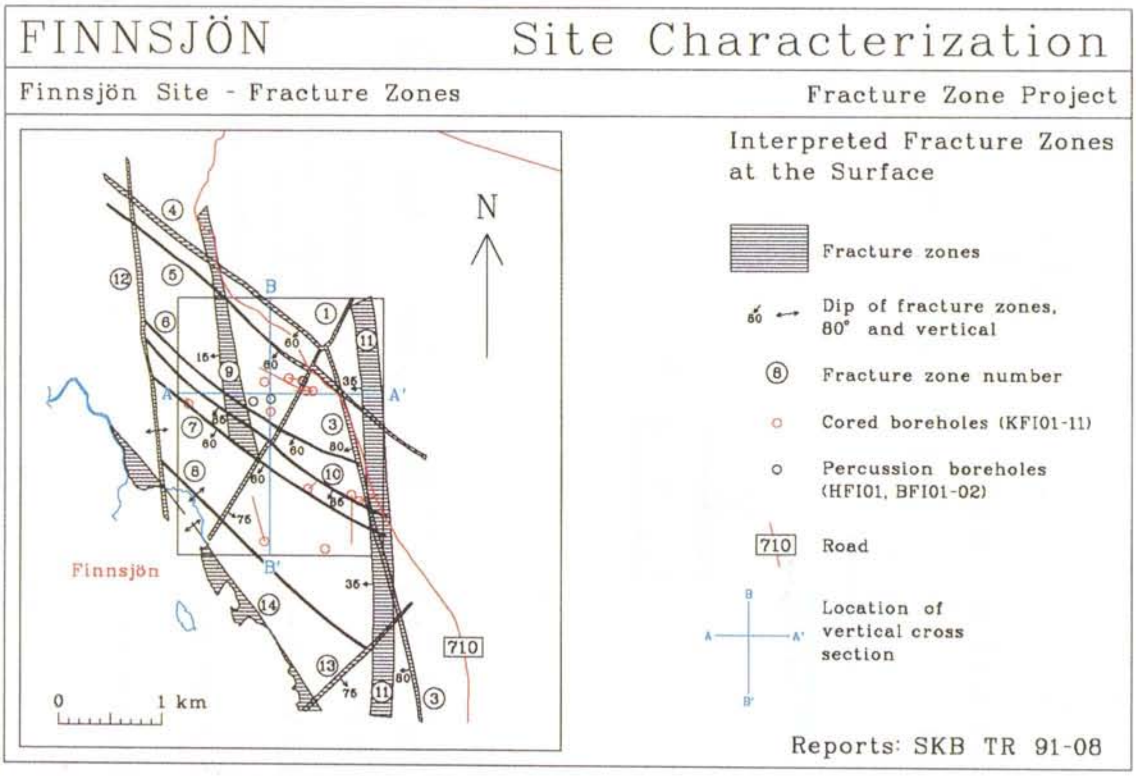


Figure D1. Map of interpreted fracture zones in the Finnsjön site.

ZONE 1 (Brändan fracture zone)

The most prominent lineament transecting the Finnsjön Rock Block is caused by Zone 1. The zone is oriented N30E/75SE and with a length of c. 5 km. The width is estimated to 20 m. In addition to its lineament expression, the zone is also indicated on geophysical maps and identified in the cores from borehole KFI05 and KFI10.

The surface expression of Zone 1 is an open, about 5-50 m wide, peat covered gully. Fracture surveys in the eastern part of the Finnsjön site indicate that Zone 1 constitute a border between rock blocks of different tectonic character. The rock block south of Zone 1 is characterized by northeast trending fractures with pink coatings of laumontite and hematite. Fractures of this type is rare in the northern rock block. The different tectonic character between the blocks indicate that faulting has occurred on Zone 1. The degree of fracturing in the surrounding outcrops does not increase significantly when approaching the zone.

The difference in tectonic character is also indicated by a ground resistivity survey (Ahlbom et al., 1986) in which Zone 1 constitute a boundary between a fractured part of the southern rock block (in the area where boreholes KFI05 and KFI10 are located) and a low-fractured northern rock block.

Two cored boreholes, KFI05 and KFI10, intersects the Brändan zone. The cores from the Brändan zone are altered and red coloured. The fracture frequency in the zone is high, ranging between 8-20 fr/m, with the highest values along the western side of the zone. Characteristic fracture infillings are hematite and asphaltite.

Water injection tests in Zone 1 have been carried out in borehole KFI10. This borehole penetrates, within a close distance, both the Brändan zone and the upper part of Zone 2. This is reflected in a high hydraulic conductivity for all 20 m sections for the total length of the borehole (256 m). However, an increase of the conductivity is measured at the intersection with Zone 1. Here, the conductivity values ranges between $1 \cdot 10^{-6}$ m/s and $5 \cdot 10^{-5}$ m/s at vertical depths between 57 and 76 m. The hydraulic conductivity of the country rock is 5-10 times lower.

Reliability: The strong surface expression of the zone, both as a lineament and as a geophysical anomaly, together with the identification of the zone in two boreholes implies a reliability level of "certain", according to the Bäckblom nomenclature.

ZONE 2 (the subhorizontal - gently dipping fracture zone)

Zone 2 has been thoroughly investigated during the Fracture Zone Project (Ahlbom & Smellie, eds., 1989). A great amount of data is therefore available and is summarized below. Zone 2 is oriented N28W/16SW, c. 100 m wide and with a estimated length of c. 1.5 km. Zone 2 has not been found to outcrop within the Finnsjön Rock Block.

Zone 2, is defined in eight boreholes located within an area of c. 500 m x 500 m in the eastern part of the northern block (north of Zone 1).
In the eastern part of the northern block the upper boundary of Zone 2 is almost planar, oriented in N28W/16W, and located in boreholes between 100 to 240 m below the ground surface. The location of the lower boundary is less distinct. In general, Zone 2 is interpreted to have a width of about 100 m. In the western part of the northern block the upper boundary of Zone 2 is interpreted to occur in borehole KFI07 at a depth of 295 m. Since this is somewhat shallower than expected, Zone 2 can not be planar between the eastern and western parts of the northern block (cf. Figure 38). There is no indication in the boreholes in the southern block that Zone 2 extends across Zone 1, into the southern block.

Although Zone 2 is expressed as an c. 100 m wide more or less altered zone, the fracture frequency is generally low within Zone 2, except for two or three fractured sections in each borehole. These sections are narrow, 2-30 m wide (often 2-5 m wide) and are mainly located at the upper and lower boundaries of the zone. The hydraulically conductive parts of these sections are even more narrow, in some boreholes the widths of these parts are in the order of 0.5-1 m. Narrow fractured parts in the central part of the zone also occur in some boreholes. The average fracture frequency for Zone 2 is 5 fr/m.

The water injection tests show for most boreholes a general decrease in hydraulic conductivity towards depth for the bedrock above Zone 2. This decrease is interrupted by the zone, where the hydraulic conductivity increases by one to four orders of magnitude to values between 10^{-6} - 10^{-5} m/s (measured in 20 m sections). Using much smaller packer intervals, 2.0 m and 0.11 m respectively, the latter only in borehole BFI02, indicate that the most conductive parts of Zone 2 merely consist of a few very narrow subzones with a width of only about 0.5 m. The uppermost of these subzones, which coincides with the upper boundary of Zone 2, is highly water conductive (10^{-4} m/s). This subzone can be correlated between all boreholes in the northern block.

Towards the bottom of Zone 2 there are several "narrow subzones" with very high hydraulic conductivity (more than 10^{-4} m/s measured in 20 m packed-off sections). These conductive subzones are separated by bedrock with low hydraulic conductivity. Below the zone the conductivity is in general low (10^{-10}-10^{-8} m/s) with several minor sections with high hydraulic conductivity (10^{-7}-10^{-6} m/s). Given the narrow widths of the subzones, the hydraulic properties of Zone 2 should preferably be expressed in terms of transmissivity rather than average hydraulic conductivity of longer test sections. The transmissivity of each subzone has been estimated to $1\text{-}4{\cdot}10^{-3}$ m^2/s.

Reliability: The observation of Zone 2 in a large number of boreholes implies a "certain" reliability level for the zone.

ZONE 3 (the Gåvastbo fracture zone)

The N15W/80W trending Zone 3 delimits the Finnsjön Rock Block to the east. The zone is at least 5 km long and c. 50 m wide. Zone 3 is penetrated by one cored borehole, KFI08.

Zone 3 is morphologically expressed as a depression floored by moraine, then clay and on top a thin layer of peat. Soundings indicate a depth of the sedimentary cover in the order of 5 m.

The core mapping of KFI08 has not been reported. However, a brief look a the worksheets from the core logs show the following characteristics for the Gåvastbo fracture zone. Zone 3 is highly fractured with mylonized and brecciated sections. Common fracture minerals are epidote and chlorite. The amount of aplite and pegmatite dykes increases towards the end of borehole, indicating that the contact between the granodiorite and the young granite, east of Gåvastbo fracture zone, is close.

The core mapping, geophysical logging and radar measurements suggest that this fracture zone is subvertical, dipping 80-85 degrees towards the west. However, as discussed under Zone 11 (see below) the dip can also be more gently c. 30-40° to the west.

The geophysical logs indicate a strongly fractured bedrock down c. 120 m borehole length corresponding to a width of the zone of about 60 m. However, since it is possible that this fractured section also includes Zone 11 (see below), the width estimate is uncertain.

Water injection tests in 3 m sections have been performed in borehole KFI08 from 43 m to the end of the borehole (458 m). The results have not been evaluated and reported but available data suggest values of hydraulic conductivity between 10^{-6} m/s to 10^{-7} m/s down to 225 m borehole length, corresponding to c. 200 m depth. Below this depth the hydraulic conductivity is commonly between 10^{-9} m/s to 10^{-10} m/s.

Reliability: Zone 3 is strongly expressed topographically as a wide and extensive lineament. Borehole KFI08 confirms the existence of a fracture zone. There are however uncertainties regarding its dip. The present interpretation should therefore be regarded as "probable".

ZONE 4

This northwesterly trending fracture zone is located outside the Finnsjön Rock Block to the northeast. Zone 4 is defined by a c. 1 km long N50W trending lineament indicated on topographical maps and aerial-photos. No borehole information exist regarding this zone. However, as this zone is situated close to and is related to Zone 5 and has the same orientation, the same dip as Zone 5 (60 degrees towards SW) is suggested. Assumed width of Zone 4 is 10 m. Reliability: "possible".

ZONE 5

This zone (Norrskogen lineament, Figure 27) is traceable for c. 5 km and has a northwesterly orientation (N50W). Zone 5 delimits the Finnsjön Rock Block to the northeast. It is well expressed as a lineament on both aerial-photos and on topographical maps. A dip of 60 degrees towards the southwest is suggested for this zone. If so, the Zone 5 coincides with weathered and fractured sections in the boreholes KFI05, KFI06 and KFI09 at 493 m, 555 m and 214 m, respectively (borehole length). This interpretation will result in a width of the zone of, at least, 2-6 m. The hydraulic conductivity of Zone 5 decreases with depth from $2 \cdot 10^{-5}$ m/s to $9 \cdot 10^{-8}$ m/s, at depths of 185 m to 555 m.

Reliability: The combination of a lineament and three fractured sections in three boreholes all lying in the same plane is a strong argument for the existence of the interpreted zone. However, the frequent occurrence of fractured sections in boreholes and the lack of a comparison of core characteristics between the sections makes "probable" a relevant reliability level for Zone 5.

ZONE 6

This smoothly curved northwesterly (N55-65W) trending fracture zone, c. 2 km long, is only poorly expressed on aerial-photos and on topographical maps. However, ground geophysical measurements indicates that the southeastern part of the zone constitutes a boundary between a fractured rock, to the north, and low fractured rock to the south of the zone. As this zone has the same trend as Zone 5, a dip of 60° towards SW is suggested. With the assumed dip Zone 6 will intersect borehole KFI07 at c. 500 m. At this depth the core of KFI07 is strongly fractured, thus supporting the suggested dip. Estimated width is 5 m. Reliability: "possible".

ZONE 7

Zone 7 trends N55W and is traceable for more than 2 km. It is well expressed on aerial-photos and topographical maps. No borehole information exist regarding this lineament. In accordance with earlier presented northwest trending fracture zones, a dip of 60 degrees towards SW is suggested for Zone 7. Assumed width is 5 m. Reliability: "possible".

ZONE 8

Zone 8 trends N50W and is more than 3 km long. It is apparent as a distinct lineament in the southwestern part of the Finnsjön Rock Block. No borehole information is available. A vertical dip is assumed for this zone due to the closeness and probable affiliation to the vertical, wide and extensive Zone 14 (see below). A width of 5 m is assumed for Zone 8. Reliability: "possible".

ZONE 9

Zone 9 represent a 200-300 m wide N10W trending lineament of low topographical relief in a c. 2 km long stripe of peat and moraine. No conclusive data exist regarding the dip, width and character of Zone 9.

There are two alternative interpretations regarding the orientation of Zone 9. In Ahlbom et al. (1986), two steeply dipping fracture zones of lower order was interpreted to be located at the east and west margin of Zone 9. In Andersson et al. (1989), Zone 9 is interpreted as a gently inclined zone, dipping 15 degrees, which comprises gently dipping fractures, less than 5 fractures/m. The interpretation was based on fracture studies on outcrops and in borehole KFI07. The latter interpretation, with a gently dipping fracture zone, is in this report regarded as the most probable. In this case Zone 9 will intersect borehole KFI07 at c. 100-150 m. Since no significant increase in hydraulic conductivity have been measured in this section, Zone 9 has probably no or only limited influence on the groundwater flow conditions. Reliability: "possible".

ZONE 10

Zone 10 have northwesterly trend. It is traceable for more than 2.5 km and poor to well expressed in the detailed topographical map. It is observed in the field, north of its intersection with Zone 1, as increased fracture frequency in the surrounding outcrops to a 10 wide gully. Zone 10 is curved in the southern block. Field observations and indications in borehole KFI03 (57-62 m) indicate a vertical to steep westerly dip (85°). Estimated width is 5 m. Reliability: "possible".

ZONE 11

The existence of a N5W, gently and westerly dipping (35°) fracture zone in the southern block is indicated by geological and geophysical data from boreholes KFI01, KFI03 and KFI08. Combining data from these boreholes with core mapping of KFI04, it is possible to define a c. 100 m wide fracture zone. The available information does not allow an accurate determination of strike and dip, but generally the zone is interpreted to strike north-south and dip 30-40° west.

The existence of a gently dipping fracture zone in boreholes KFI01 and KFI04 is supported by gentle-subhorizontal dipping fractures in the drill cores (similar as for Zone 2) and borehole geophysical characteristics similar as those registered across Zone 2. Borehole KFI08 intersects Zone 11 at the same location as Zone 3. This could possibly imply that the earlier interpretation of a subvertical Zone 3 could be wrong and instead Zone 3 is the same as Zone 11, or that both alternatives exist. The limited data available does not allow any further elaboration on this possibility.

Reliability: In spite of the location of Zone 11 in four boreholes, the existence of this zone is uncertain due to the frequent occurrence of fractured borehole sections. Thus the reliability level of Zone 11 is "probable".

ZONE 12

There are no borehole data available for this c. 6 km long and north-south trending fracture zone, delimiting the Finnsjön Rock Block to the west. However, due to the similarities in strike and morphology, Zone 12 is given a vertical dip. Assumed width is 25 m. Reliability: "possible".

ZONE 13

There are no borehole data available for this c. 7 km long and northeast (N30E) trending fracture zone, delimiting the Finnsjön Rock Block to the south. As a first attempt this zone are given the same characteristics as Zone 1 (a dip of 75° to SE and a width of 20 m). Reliability: "possible".

ZONE 14

Ground surface and borehole data are lacking for the wide and regionally extensive (>50 km, c.f. Figures 26 and 27) northwest trending zone delimiting the Finnsjön Rock Block in the southwestern part. Changes in rock types can be observed while crossing the zone, implying that faulting have occurred. As this zone have the same strike as the Singö fault, and are interpreted to be related genetically, data from this fault are used as a first assumption. In this case, a width of 100 m and a vertical dip should be denoted for this zone. Using values from the Singö fault, an hydraulic conductivity of about 10^{-7} m/s to 10^{-6} m/s is expected for the upper 100 m of the zone. Reliability: according to Bäckblom classification "possible". However, it could as well be argued that Zone 14 is "certain". This is because of the well expressed and regional extension of the lineament, together with the faulting associated with the zone.

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[1]MBT, Barcelona Spain
[2]SKB, Stockholm, Sweden
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[1]Golder Associates Inc., Seattle, Washington, USA
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[1]Geological and Environmental Assessments (GEA), Zürich, Switzerland
[2]Geologiska Institutionen, Lund, Sweden
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[1]Conterra AB
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L Romero, L Moreno, I Neretnieks
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John Smellie[1], Marcus Laaksoharju[2]
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