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Fjällveden study site. Scope of activities and main results

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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 the ones 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 Fjällveden 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), Rune Nordqvist (groundwater chemistry), Clifford Voss (assessment of solute transport) and Christer Ljungren (rock mechanics).

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1. ASSESSMENT OF THE FJÄLLVEDEN STUDY SITE

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

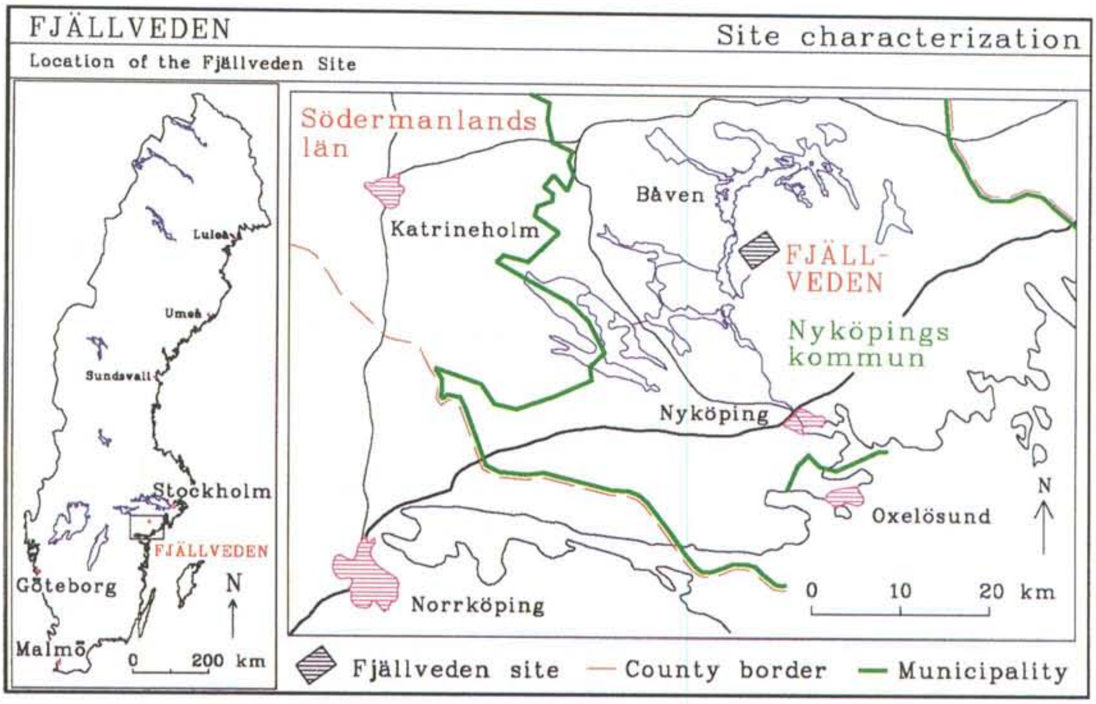

Figure 1. Location of the Fjällveden study site.

1.1 Main characteristics and uncertainties

Rock type distribution

The Fjällveden study site is situated in a region dominated by grey sedimentary gneiss with subordinate intercalated layers of weakly foliated dark grey granodioritic rocks (here denoted as granite gneiss), greenstones and local bodies of granite and associated pegmatites. All these rocks are older than 1700 milj. years. The youngest rocks are 1 500 milj. year old dolerite dykes.

The regional foliation is subvertical and trends northeast and it is tightly folded along subhorizontal northeast trending fold axis and refolded along east–west trending fold axis. The bedrock is later distorted by regional northwest trending and regular spaced (separation 2–3 km) shear zones.

On regional scale surface maps the bedrock is composed of 80 % sedimentary gneiss, the corresponding number on the local scale (study site) is 75 %, and in the boreholes 93 %.

The sedimentary gneiss is banded, so-called veined gneiss, and is composed of 0.1–0.2 m wide alternating medium grained quartzo-feldspatic layers and fine grained biotite rich layers. The banding is parallel to the regional foliation and the mineral (mica) fabric in the rock. The bulk mineralogy of the gneiss is quartz (50 %), potash feldspar (25 %), biotite (15 %) and plagioclase (10%). Accessory minerals are cordierite, sillimanite, chlorite (after biotite), zircon and apatite. Local dissemination of sulfide minerals occur, usually in the form of pyrite and pyrrhotite.

Granite gneiss is the dominating rock type in the northern part of the site, while it represent less than 3 % of the drilled rock volume in the central part. In the central part the granite gneiss occurs as relative thin and very extensive layers (0.2–14 m wide, locally more than 1 km long), often situated within zones of intense mylonitic and cataclastic deformation. In spite of this, the granite gneiss is only weakly foliated (parallel to the regional foliation) and have a mineral liniation. Its granodioritic composition resembles that of the biotite rich layers in the sedimentary gneiss.

Borehole data indicate that the strata of granite gneiss are more continuous in a horizontal direction as compared with the vertical. This can be explained by the fact that the granite gneiss and the sedimentary gneiss have been folded isoclinically along horizontal fold axes causing the layers of granite gneiss to stretch and become thinner and be pulled apart at the fold limbs. The granite gneiss layers today probably remain as horizontal elongated bodies.

Small lenses of dark amphibolite frequently occur in the sedimentary gneiss parallel to the foliation. The lenses are between 0.1 m to several meters in cross-section. The relative occurrence of amphibolites in the bedrock is 3.5 %. The mineral assemblage is amphibole, feldspar and biotite.

The youngest rock in the area are northwest trending vertical doleritic dykes (1 500 milj. year old). They are oriented perpendicular to the regional foliation and sub-parallel with the regional shear zones. These dykes are 0.4–4 m wide and grey to black in color. They are most common in the northern part of the study site.

The overall fracture frequency is low for the Fjällveden site. This is specially pronounced in the bedrock below 200 m depth. Judging from the mean fracture frequency for all drill cores, the frequency decreases from about

4 fr/m close to the ground surface to about 2 fr/m from 200 m and down to 700 m depth.

Uncertainties: The granite gneiss is the most important rock component in the Fjällveden study site, since this rock type is highly water conductive (see below) and may act as pathways for groundwater from a repository in the central part of the site to the surrounding regional fracture zones. A detailed and correct geometric and hydraulic information about these layers are therefore of necessary for a reliable assessment of the performance of a repository at this site. However, the locations of these layers have only been interpreted by correlation between boreholes. Considering this, and also the limiting length of each layer, especially in the vertical direction, there are substantial uncertainties involved in the present interpretation.

Fracture zones

Interpretation of fracture zones in the upper part of the bedrock was primarily based on lineament analyses and subsequently tested by shallow percussion boreholes. The results from the electrical ground geophysical surveys could only be used to a minor degree due to strong disturbances caused by electrical conductive postglacial clays in the overburden. The seismic refraction survey was used when possible. The interpreted fracture zones at the ground surface have been correlated with fractured sections in the deep boreholes.

A total of 11 (local) fracture zones have been interpreted in the central part of the site. These zones are mainly trending NW and NNE, and with widths varying from 0.2 to 14 m. The rock within the fracture zones are commonly strongly clay altered. This may explain the generally low hydraulic conductivity measured in these zones (see below).

Well expressed NW–trending lineament of regional extent bounds the site to the east and the west. A borehole through the eastern lineament showed strongly fractured and altered bedrock indicating a major shear zone with a width of 90 m and a dip a 75° W.

Uncertainties: Most interpreted fracture zones within the Fjällveden site are uncertain. Only six out of eleven local fracture zones are classified as "certain" or "probable" zones (c.f. SKB–nomenclature of fracture zones, Bäckblom, 1989). Others zones should be regarded as "possible", at the most. This is mainly because of uncertainties in the location of fracture zones at the ground surface due to problems interpreting the ground geophysical measurements and a low topographical relief. The uncertainties also include the correlations made between interpreted fracture zones at the ground surface with minor, and sometimes insignificant, fractured sections in the cores.

It should be noted that during the KBS–3 studies a conservative approach was taken when interpreting fracture zones. To avoid discussions of possible additional fracture zones, all suspected fracture zones were included in the model, even if the indications were weak. A renewed interpretation will probable identify two or three additional fracture zones, while many of the earlier interpreted zones will be regarded as non–existent. The outcome of a renewed interpretation of fracture zones at Fjällveden will therefore probable results in an overall decrease in the number of fracture zones.

Regarding the existence of subhorizontal fracture zones there are borehole hydraulic observations that might indicate the existence of such zones close to the ground surface. Although no such indication has been reported for deeper levels of the bedrock the existence of subhorizontal fracture zones at depth could not be ruled out.

Hydrology

The topography of the groundwater table within the Fjällveden site is very flat with elevations ranging between 40–65 m.a.s.l. The site mainly constitutes a recharge area for groundwater. Major discharge areas are located to the west and south of the site in connection to large lakes. The groundwater flow in the upper part of the bedrock is primarily directed towards northeast and southwest towards the bounding regional fracture zones. In the southern part of the site the shallow groundwater flow is directed towards south.

Uncertainties: No study of the regional groundwater flow pattern has been performed in the Fjällveden area. Consequently, it is not known whether the waters at repository depth belong to a shallow local groundwater system or a regional flow system.

Hydraulic units

The main hydraulic units included in the conceptual model of the Fjällveden site are the rock mass and regional and local fracture zones. The rock mass was subdivided into sedimentary gneiss and granite gneiss in the modelling. The latter strata was assumed to be continuous, striking northeast and vertical, thus implying anisotropic conditions in the rock mass.

Uncertainties: The geometry (orientation, extension and dip) and the hydraulic properties of the layers of granite gneiss are not known in detail.

The highly water conductive properties of these layers, as indicated from the existing data, makes detailed information very important in the modelling. The division in rock mass and fracture zones is preliminary since most interpreted fracture zones are uncertain. In addition to the interpreted fracture zones there is still a possibility for the existence of unidentified strong hydraulic conductors, e.g. subhorizontal fracture zones.

Hydraulic conductivity

The estimated hydraulic conductivity of the sedimentary gneiss is low, about 10^{-11} m/s at 500 m depth, while the hydraulic conductivity of the granite gneiss is more than two orders of magnitude higher. The number of measurements in the fracture zones are very limited but, with one or two exceptions, the measured conductivities are generally low, in the same order as the sedimentary gneiss. The conductive fracture frequency in the rock mass at the Fjällveden site is estimated to about 0.06–0.09 fr/m, based on all tested 25 m sections in the rock mass in cored boreholes.

In the hydraulic modelling the fracture zones have no or only minor influence on the groundwater flow. Uniform anisotropic hydraulic properties were assumed for the rock mass parallel and perpendicular to the granite gneiss strata in the modelling. At 500 m depth the anisotrophy ratio applied in the rock mass in these directions was about 7.7:1.

Uncertainties: The derived hydraulic conductivity functions versus depth for the different hydraulic units are uncertain, partly due to uncertainties in the division of data in hydraulic units from the geological interpretation, and partly due to the analysis technique based on regression analysis. An alternative interpretation of the hydraulic conductivity data 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. Also uncertain are the applied anisotropic hydraulic conductivity functions in the rock mass.

Groundwater flow rates at repository depth

Nine cases were modelled in the Fjällveden site. In the first case both the rock mass and the fracture zones were modelled as separate isotropic continua. In the second case the rock mass was assumed to have uniform anisotropic hydraulic properties parallel and perpendicular to the granite gneiss strata, whereas the hydraulic conductivity of the fracture zones was the same as in the first case. In the third case the hydraulic conductivity of the fracture zones was assigned the same value as the conductivity of the rock mass. The second case was considered as the most realistic. In cases 4–9 the hydraulic conductivity functions of the rock mass and the fracture zones were altered to assess the sensitivity on the groundwater flow of these functions.

The calculated groundwater flow rates at a potential repository depth of 500 m varied between 3–15 ml/m^2/year in the first three cases and between 5–50 ml/m^2/year in cases 4–9. The cases with anisotropic hydraulic conductivity in the rock mass all resulted in higher (representative) flow rates than the isotropic first case with factors ranging from about 1.2 in the second case to maximum about 2.5.

Uncertainties: The modelling was made using the assumption of a porous media composed of one single continuum or two overlapping continua (rock mass and fracture zones). This generalization implies a large uncertainty in the flow calculations. Another uncertainty is the assumption of no regional flow.

Groundwater chemistry

A total of three boreholes and twelve borehole sections have been sampled at Fjällveden. The samples indicate groundwaters of varying ages, but no particular depth dependence can be noted. The general groundwater chemistry indicate an environment common to Swedish crystalline bedrock. The groundwaters are generally of a reducing character. Samples from only one of the sections was considered representative for the depth sampled. This section represented relatively deep, old groundwater (506 m depth) showing high chloride contents and low bicarbonate contents.

Uncertainties: As only one of the sampled sections were considered representative for the depth sampled, the groundwater chemistry conditions in general at the site remains as a main uncertainty. In fact, the spatial variation of the groundwater chemistry is essentially unknown. The redox measurements are especially uncertain, except for the additional sampling reported by Wikberg et al. (1987).

Rock mechanics

The rock mechanical investigations at Fjällveden only includes measurements of thermal parameters on core samples. These measurements showed normal thermal properties for the bedrock.

1.2 Suggestions for complementary studies

Conceptual geologic models

As discussed earlier the layers of granite gneiss constitutes the main pathways for groundwater at the Fjällveden site. A detail knowledge of the location and extent of these layers, as well as the geological, tectonical, geochemical and geohydrological characteristics is therefore needed. The schematic conceptual model of the layers of granite gneiss that exist today should therefore be validated and extended to cover a three-dimensional model including the whole site (to the regional fracture zones that bounds the site to the west and east). The extended model will require remapping of outcrops and drill cores and reinterpretation of geophysical logs. Some new boreholes will probable also be required.

Although most fracture zones at Fjällveden does not appear to be hydraulical conductive a detailed geometrical knowledge is needed for identification of potential planes of future bedrock movements. This is also needed for assessments regarding the "constructability" of the site. As discussed in Chapter 7 the fracture zones, in spite of their generally low hydraulic conductivity, could also be important when considering radionuclide transport. To improve the existing model it is suggested to; 1) utilize the large number of existing percussion boreholes (evaluation of drilling rates and existing and new geophysical logs), 2) remapping of all drill cores with emphasis of fractured borehole sections and 3) reinterpretation of geophysical logs and hydraulic tests. Also trenches should be considered to expose the bedrock and thus to test the reliability of interpreted steeply dipping fracture zones and the occurrence of layers of granite gneiss.

Conceptual geohydrological models and data sampling

A first step to improve the conceptual hydraulic model at Fjällveden is to identify the types of numerical models which might be utilized in the modelling, e.g. continuum models, fracture network models or stochastic continuum (parametric and non-parametric) models. This process should be based on experiences from the SKB-91 study and the Äspö Hard Rock Laboratory. Depending on the selected model(s) additional data sampling might be necessary.

The regional groundwater flow, within a larger area around the Fjällveden site, should be investigated qualitatively to determine the overall groundwater flow circulation on a regional scale. The primary goal of this investigation is to establish a general conceptual model of the regional groundwater flow, including possible flow paths from a repository to the biosphere. The outer boundary conditions of the local model should be defined after analyzing the regional flow field.

The above study will require drilling of at least one deep borehole in the regional area. In this borehole combined logging of temperature and salinity, together with a spinner survey, should be performed both during natural and pumping conditions to measure the vertical flow under open borehole conditions and to identify conductive structures in the borehole. Subsequently, tracer dilution measurements could be carried out to measure the natural flow through the borehole. In addition, head measurements and water sampling should be carried out in isolated borehole sections.

The boundary conditions of the local model should be further investigated. Improved definition of the location and type of the outer boundary conditions of the local model is required. This task implies renewed geological and geohydrological characterization of fracture zones, together with the investigations and conceptualization of the regional groundwater flow pattern outlined above.

The hydraulic properties of different rock types, mainly layers of granite gneiss, should be further investigated. This could probably be made using existing data from hydraulic tests together with a new geological model, as suggested above. The study should also include new analyses of depth dependence of the hydraulic conductivity of different rock types and fracture zones, together with alternative analyses (models) of the hydraulic conductivity data, taking account of the variance of the measured data.

In some of the boreholes high hydraulic conductivities have been measured at great depths. In spite of this, no strong hydraulic conductor have so far been identified/located at Fjällveden. Since the occurrence of such conductors is of importance for the performance of a repository, it should be considered to further study the possible occurrence of such conductors.

As a final test of the validity of the (revised) conceptual model of the Fjällveden site, a long-term pumping test should be carried out in one of the deep boreholes, centrally located within the site. Observations of drawdown should be made in isolated sections in all available observation boreholes within the site. The observed drawdowns should be compared with predicted ones. The pumping test should be combined with tracer and dilution tests by injecting tracers in some of the nearest observation sections before the test. Observations of changes of the water chemistry during pumping should also be made.

Groundwater chemical conditions

Since the available hydrochemical data is not sufficient for a proper characterization of chemical conditions at the Fjällveden site, there is a need for additional sampling. This should primarily be made in new boreholes. 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 Fjällveden has been evaluated thoroughly, there might be possible to gain some further hints about hydrological conditions by complementary evaluation of existing data. Firstly, one may attempt to compare the general chemistry characteristics of the different sections for all the boreholes. This 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. Secondly, it may be worthwhile to do a careful examination of the time series of the chemistry data from some of the different sampled sections. The changes in the chemical composition in a particular section during the sampling period, may in some cases reflect changes in mixing conditions. For example, the chemical composition in the deepermost level in KFJ04 changes in character during the sampling period from and old, relatively saline type, to a mixed groundwater. It is possible that such additional analysis would help in the interpretation of where local or regional flow conditions prevails.

Solute transport

To improve knowledge of transport at the Fjällveden 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?) and, 2) investigation of geometry and connectivity of conductive structures if such exist (what are the major flow paths that need be considered in a model?). Once these facts are established, the point of next greatest importance would be determination of hydraulic conductivity distribution including possible depth dependence. The major practical steps to achieve such improvement are listed under the heading "Conceptual geohydrological models" in this chapter.

Sorption coefficients including estimates of sorptive surface, 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 effective 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

It is suggested to perform rock stress measurements in at least one borehole down to 500 m or preferable down to 700 m. The rock mechanical programme should also include tests on cores to investigate the mechanical properties of the various rock types at Fjällveden.

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 the 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.

One of the investigated sites is Fjällveden. This study site was investigated during the years 1981 –1983 with the main objective to provide site–specific data for the performance assessments for the KBS–3 report (SKBF, 1983). The purpose of this report was to demonstrate that a safe repository for spent nuclear fuel can be located in Sweden.

When the scope of site investigations at Fjällveden was established it was considered most important to address those factors that have appreciable potential for rendering the site relatively unfavorable. Key factors in this respect are the groundwater flow system and the chemical conditions of the deep groundwaters. In addition, data was required on available area of "sound rock" at 500 m depth that is potentially suitable for a repository.

To obtain the data needed to evaluate the importance of these key factors at Fjällveden, the site investigations had the following main objectives:

- Identify and characterize major and minor fracture zones, dykes and other lithological inhomogeneities.
- Identify and characterize "homogeneous" rock blocks.
- Determine groundwater heads, groundwater recharge and discharge areas and groundwater divides.
- Determine the chemical constituents and redox conditions of groundwater.

2.2 Selection of the Fjällveden study site

The Fjällveden site is located in the southeastern part of Södermanland county, Nyköping municipality, about 20 km NNW of Nyköping and 80 km SW of Stockholm, Figure 2. The total areal extent of the site is 2.7 x 3.7 km. However, most surveys have been made within an area of 2 x 2 km, located in the central part of the site (Figure 5).

Fjällveden was one of several alternative areas located in a vast region consisting mainly of the Stockholm and Södermanland counties. The areas were defined during the reconnaissance studies of 1980–1981 (not reported). Detailed geological reconnaissance studies and geophysical profile measurements were made in two areas, Björksund and Fjällveden, which were selected for drilling. At Björksund several percussion boreholes were used to obtain data regarding the geological and hydrological characteristics of a frequent and morphological well expressed set of lineaments striking NW–SE. These lineaments were found to be strongly water conductive fracture zones and as a consequence the area was closed.

At Fjällveden only a few minor lineaments were identified within the central part of the area. Other favourable factors were low fracture frequency in outcrops and a flat topography. To confirm favourable conditions, a 700 m deep borehole was drilled during the summer of 1981 in the central part of the Fjällveden site. The core indicated sound rock (sedimentary gneiss of low fracture frequency) to the end of the borehole, with the exception of some minor fractured sections. The result of this borehole investigation was regarded favourable and a decision to initiate complete site investigations was taken in Aug. 1981.

At the time of the site selection no major geologic or non–geologic factor was judged unfavourable for the Fjällveden site. The only concern was the existence of postglacial clays in the overburden. To a great extent these clays prevents the use of electrical geophysical measurements since the clays contain saline pore water and thus are highly electrical conductive.

In summary, the Fjällveden site was selected due to the following conditions:

* The site consists of migmatitic sedimentary gneiss. Well surveys show low water capacities for this rock type (Knutsson & Fagerlind, 1977).
* Experience from excavating rock caverns and tunnels in this type of gneiss has been favorable (e.g. Stockholm subway).
* The region within and surrounding the Fjällveden site has a flat topography, inferring small hydraulic gradients.
* Regional fracture zones delimit a large (>30 km^2) rock block (plinth) in which the Fjällveden site is situated.
* A low frequency of fracture zones, interpreted from aerial photographs.
* Well exposed bedrock facilitates geological studies.
* Low frequency of fractures in outcrops.
* Easy accessible and favorable land ownership (Domänverket).

2.3 Investigation periods

The time schedule for the main activities are shown in Figure 2. The main period of site characterization took place between 1981–1983. With the exception of some groundwater sampling and some minor tests of methods and instruments, there has been no further activities in the site.

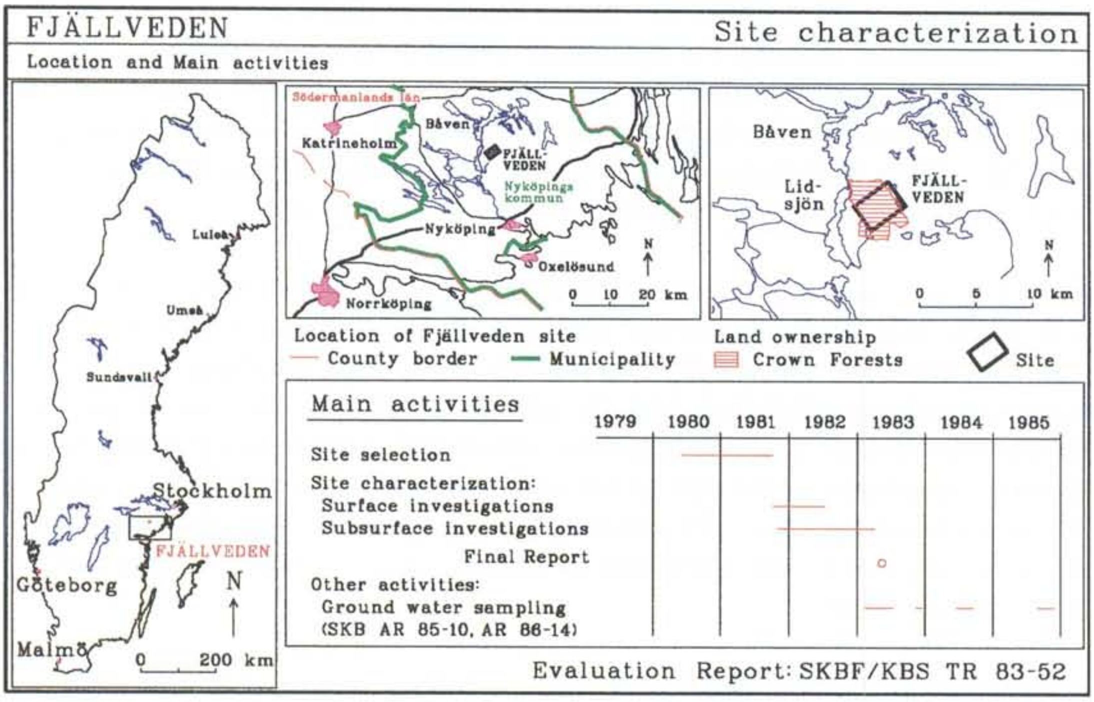

Figure 2. Location of the Fjällveden study site. Administrative borders and land ownership are shown. Main activities refer to the KBS–3 studies. Other activities refer to activities after the KBS–3 report.

3. SCOPE OF ACTIVITIES

3.1 Reconnaissance

The Fjällveden site was selected in 1981 as a result of reconnaissance studies in the counties of Södermanland and Stockholm (unpublished).

The reconnaissance phase included studies of geological maps and literature, lineament interpretation based on aerial photos and topographical maps and brief field checks. These checks included observation/estimates regarding rock types and degree of rock exposure, as well as degree of fracturing and other general tectonic characteristics. Interpreted lineaments were inspected.

No modern detailed geological maps were available for the Fjällveden region. Only small scale overview maps was available for the reconnaissance work. Furthermore, there were neither airborne nor ground geophysical measurements available for the region. An important part of the field checks was therefore to ensure that sedimentary gneiss dominated the bedrock.

Data regarding general hydraulic characteristics of the bedrock in a regional scale was obtained by a compilation of water capacities in rock drilled wells in southern Sweden by SGU "brunnsarkivet" (Knutsson and Fagerlind, 1977). For the reconnaissance work detailed "print-outs" of the locations of wells and water capacities were used (unpublished).

3.2 Surface investigations - regional area

Geology

There are no modern geological bedrock maps for the Fjällveden site and its surroundings. The only available maps are map sheet "Tärna" (Erdmann, 1867) and "Mellersta Sveriges Bergslag" (Törnebohm, 1882). However, modern geological maps in the scale of 1:50 000 exist for the neighboring map sheets Nyköping NO, SV and SO (Stålhös, 1975, Lundström, 1974 and 1976), as well as Katrineholm SO (Wikström, 1979).

During the summer of 1981 a map of the bedrock for the region including the Fjällveden site was therefore made (Carlsten et al., 1983). The map is in the scale of 1:50 000 and covers an area of about 150 km^2, Figure 3 and 10.

Lineaments were interpreted from aerial photos and topographical maps of an 300 km^2 area including the Fjällveden site, Figure 3 (Ahlbom et al., 1983).

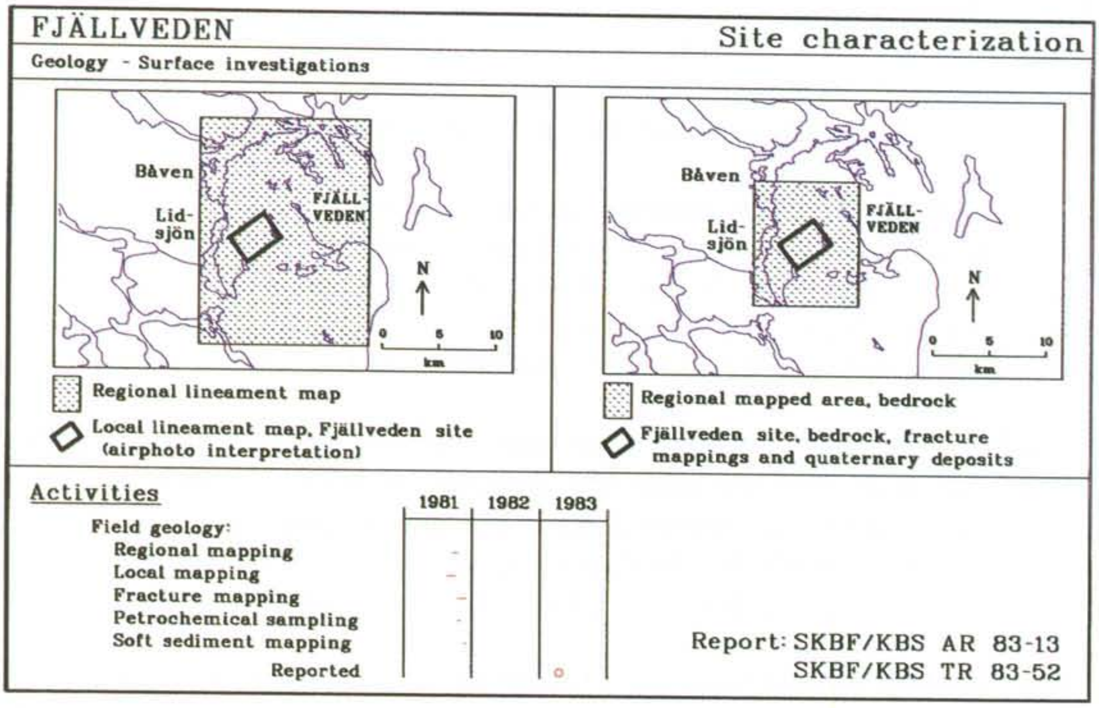

Figure 3. Regional geologic and tectonic studies. Left – area investigated for lineament analysis. Right – extent of the regional geologic map together with the areal extent of the Fjällveden site.

Hydrology

Based on data from SMHI:s stations the hydrometerological conditions of the Fjällveden region was compiled (Larsson, 1983). This compilation included temperature, precipitation, evapotranspiration, water run–off, and gross water budget. The report by Larsson (1983) also includes maps of regional and local drainage systems, as well as regional (90 km^2) and local (18 km^2) maps of groundwater levels. The areal extent of these maps is shown in Figure 4.

Geophysical profiles

Ground geophysical magnetic, VLF and slingram measurements were made in 3 profiles (Figure 5) covering both the Fjällveden site and its surroundings (Carlsten et al., 1983). The objective was to identify regional fracture zones and lithological boundaries and to provide some estimates regarding their character (mainly dip estimates). The total length of these profiles is 12.5 km.

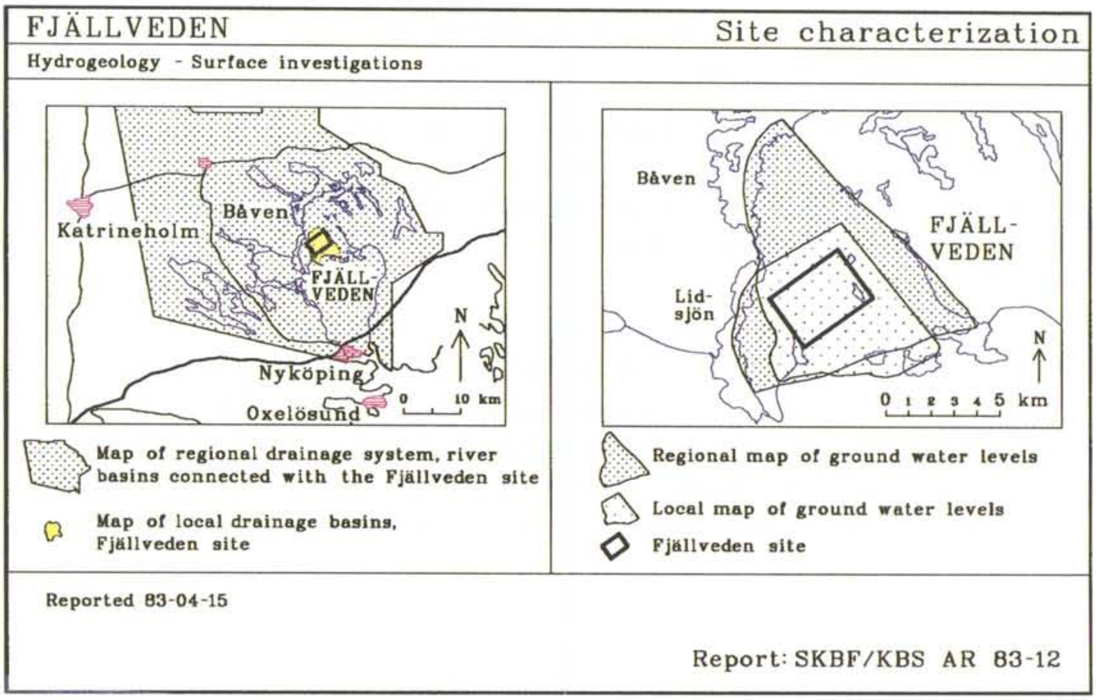

Figure 4. Left – regional and local maps of groundwater table. Right – extent of maps showing the regional and local drainage systems.

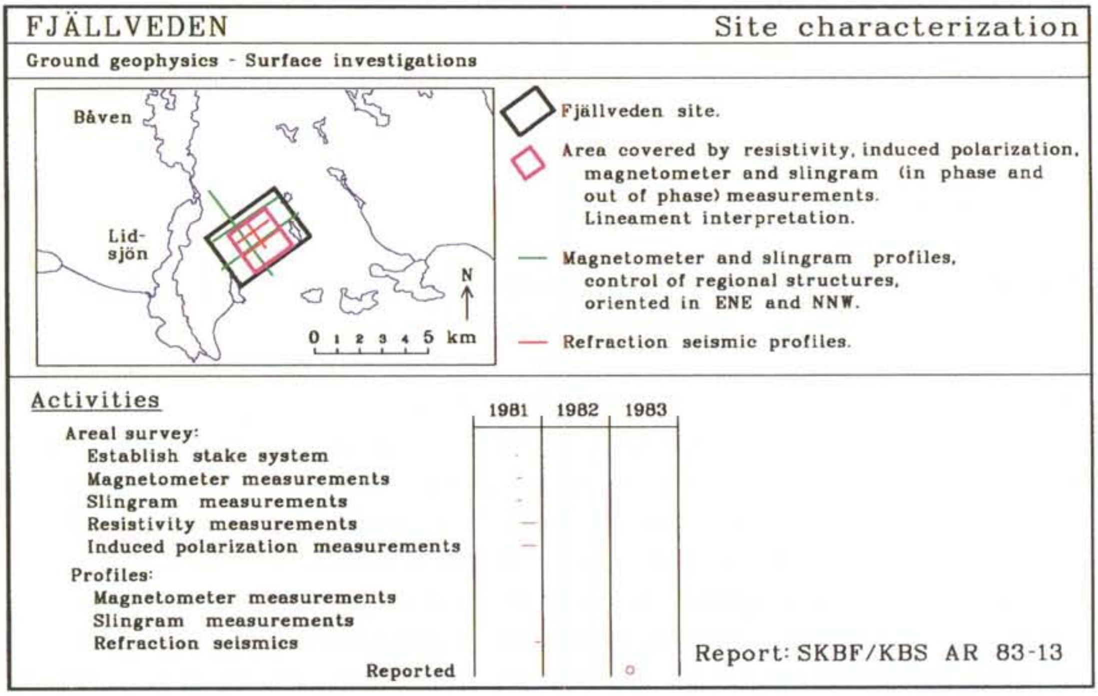

Figure 5. Extent of ground geophysical measurements.

3.3 Surface investigations - Fjällveden site

Geology

The geological survey at the Fjällveden site included outcrop mapping, mapping of rock types and scan-line fracture studies at 51 localities within the site. Petrographical studies and chemical whole-rock analyses were made on 8 samples (Carlsten et al., 1983).

Manual coring using an auger was made at 50 locations were the ground resistivity survey showed anomalies. The objective was to investigate the possible presence of postglacial clays, since these clays contain salt and therefore will strongly influence the resistivity measurements. The corings showed that indeed postglacial clays were present at all locations and that the thickness of the clays varied between 0.5-9.1 m (Carlsten et al., 1983).

Geophysical surface surveys

Detailed geophysical surveys were made within a 4 km^2 square, Figure 5, located in the central part of the site (Carlsten et al., 1983). The objective was to map lithological boundaries and to identify fracture zones. The surveys were made in a grid system with a separation of 40 m between survey lines and 20 m between measurement points. The orientation of the measurement lines was N 35 W. The methods included the following (see also Figure 5):

- protonmagnetometer
- slingram 18 kHz
- resistivity (gradient method)
- induced polarization

In addition, 3 profiles of seismic refraction measurements were made, Figure 5. These profiles have a total length of 6 km.

The magnetic and seismic data was judged good and consequently the results was used with confidence to identify magnetic rock types and fracture zones. However, this was not the case for the electrical measurements (slingram, VLF, resistivity and induced polarization). The reason is the presence of electrical conductive postglacial clays in the overburden and possible also electrical conductive graphite and sulphide minerals in the bedrock. The clay deposits caused strong electrical anomalies in most parts of the site and as a result the anomalies caused by the fracture zones were greatly disturbed. The results from the electrical surveys could therefore only to a minor extent be used to identify and characterize fracture zones.

3.4 Percussion boreholes

Percussion drilling were used to investigate possible fracture zones interpreted from geophysical measurements and from lineament studies. In total 49 percussion boreholes were drilled with borehole lengths varying between 30–175 m, Table 1. A map showing the locations of the percussion boreholes is presented in Figure 6, while Figure 7 presents activities, including time–tables, in these boreholes.

Inflow and groundwater capacity

Identification of fracture zones intersected by the percussion boreholes were made from anomalies in drilling rates and from locations of major groundwater inflows (Carlsten et al., 1983).

Borehole geophysical logging

The percussion boreholes in the Fjällveden site was logged with the following methods; borehole deviation, natural gamma radiation, and single point resistance. An brief interpretation of the locations of granitic/pegmatitic and mafic sections in these boreholes is reported by Duran (1983). Apart from this, no report has been made describing the results and the interpretations from the geophysical logging of the percussion boreholes. (There is no storage of these data in the SKB database, see Chapter 4).

Hydraulic tests/measurements

The percussion boreholes were used to monitor the variations in the groundwater table for the period jan–nov 1983 (Larsson, 1983). For most boreholes this was made in open holes. However, in 11 percussion boreholes a packer was installed about 10 m below the groundwater level. This made it possible to monitor variations both in the groundwater table in the upper part of the bedrock and the groundwater head in the deeper groundwater.

An interference test was also performed using some percussion boreholes in the central part of the site. The objective was to evaluate the hydraulic characteristics of the fracture zones 3, 5 and 6. The interference test involved pumping of borehole HFJ18 for 20 days. The resulting draw–down (20 days) and recovery (19 days) was monitored in 8 percussion boreholes. The result of the test is reported by Andersson and Hansson (1986).

Table 1. Percussion boreholes at the Fjällveden site. Water capacity refers to total capacity for the borehole. Zero water capacity refer to a "dry borehole" or only insignificant inflow. Major inflow refer to location of individual strong inflows (borehole lengths).

No (HFJ)	Direction/Dip	Length/Depth (m)	Water capacity l/h	Major inflow (m)
01	N25E /65	100 /91	900	70,85
02	S25W /65	100 /83	175	76
03	N30W /60	170 /147	150	29
04	N85W /60	120 /97	100	30
05	S42W /55	60 /45	300	?
06	N35E /50	55 /–	500	5,48
07	N45W /50	100 /76	30	–
08	S19E /59	160 /143	100	5
09	N55W /64	160 /140	1300	40–55,95
10	N38W /62	160 /142	500	62,78
11	S50E /60	120 /108	100	58,89
12	N30E /50	105 /64	5000	6,49,90,100–105
13	N40W /60	150 /123	1100	75,113–120
14	S35W /60	120 /98	800	11,14,48
15	S70W /60	100 /91	90	–
16	N70E /60	100 /89	500	84–89
17	N30E /50	140 /109	700	20,67,87
18	S40E /60	141 /114	3000	60
19	N30E /60	150 /113	1100	36
20	N9OE /60	150 /	1200	38,59
21	S75E /60	150 /136	300	65–70
22	S70E /60	120 /112	14000	46,88,92
23	N70E /60	140 /131	550	29,136
24	S70E /60	100 /82	250	–
25	N70W /60	100 /87	1000	90
26	S55E /60	100 /83	0	–
27	N55W /60	100 /72	200	71
28	S7OE /45	100 /78	75	–
29	N25E /60	100 /80	1200	37–40,53,65
30	N30E /60	100 /86	1000	24,74–80
31	S30W /60	100 /85	2000	30
32	N50E /60	100 /89	200	17,28–32
33	N35W /60	100 /86	800	20–25
34	S40W /60	100 /84	0	–

Table 1 cont. Percussion boreholes at the Fjällveden site.

No (HFJ)	Direction/Dip		Length/Depth (m)		Water capacity l/h	Major inflow (m)
35	S35E	/60	100	/78	400	35,80
36	Vert.	/90	50	/49	<100	30
37	N50E	/60	150	/129	1500	33,125–145?
38	N50E	/60	120	/103	1000	26,?
39	N40W	/60	120	/105	30	–
40	S75W	/80	58	/57	700	9
41	S75W	/50	175	/133	2000	33,49,48,134
42	N70W	/62	150	/126	100	–
43	S60W	/58	150	/125	600	?
44	N52E	/45	150	/105	100	–
45	Vert.	/90	50	/50	0	–
46	Vert.	/90	50	/50	900	36
47	Vert.	/90	30	/30	1000	6,10,13
48	S10E	/35	150	/88	0	–
49	S14E	/40	150	/96	0	–

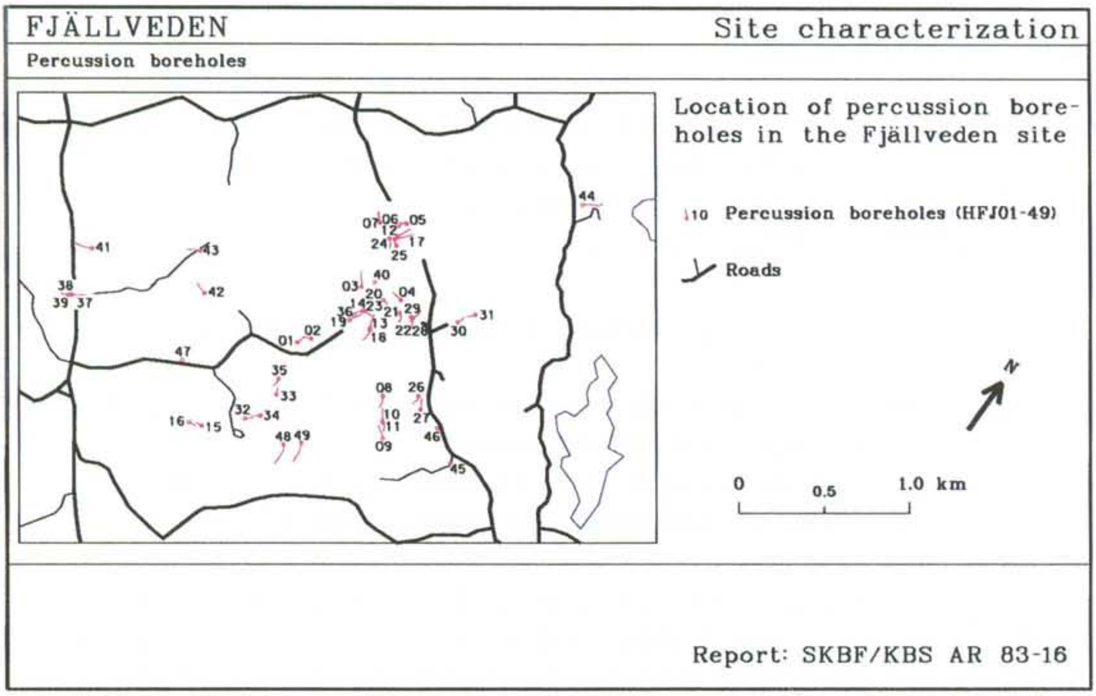

Figure 6. Location of percussion boreholes.

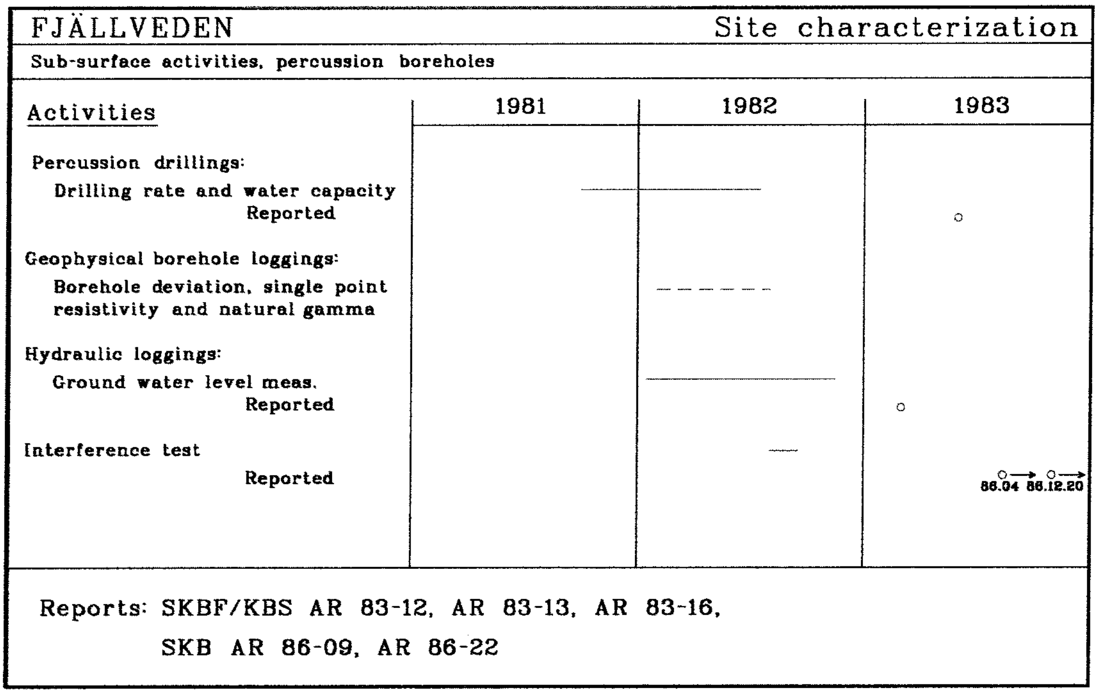

Figure 7. Activity periods – percussion boreholes.

3.5 Cored boreholes

A total number of 15 cored boreholes have been drilled at the Fjällveden site (Figure 8) down to a maximum vertical depth of 695 m. Most boreholes are drilled inclined, 60 degrees from the horizontal, with a borehole length of 700 m (Table 2). The main objectives was:

- to test and improve the preliminary geological model obtained from the surface investigations.
- to obtain data of the hydraulic characteristics of different hydraulic units (rock mass, rock types and fracture zones).
- to obtain groundwater samples from different depths and in different hydraulic environments (discharge and recharge areas).

To fulfil these objectives most of the boreholes were directed to intersect interpreted fracture zones or dykes at depth (Carlsten et al., 1983, Ahlbom et al., 1983). A map showing the locations of cored boreholes is presented in Figure 8. The drilling periods is shown in Figure 9. Detailed break–downs of activities in each borehole are presented in Appendix A.

Table 2. Cored boreholes at the Fjällveden site.

No (KFJ)	Direction/Dip		Length (m)	Depth (m)
01	S35E	/85	711,4	695
02	NIOE	/60	700,7	575
03	S50E	/60	426,1	370
04	S42E	/60	700,5	585
05	N35W	/60	700,4	570
06	S70W	/60	702,6	590
07	N20E	/60	760,4	647
08	N76W	/60	731,8	615
09	S18E	/50	700,4	520
10	N50E	/45	199,0	140
11	S45E	/60	250,6	211
12	S54E	/60	150,4	130
13	S74W	/80	151,3	146
14	S20W	/60	350,1	298
15	N35E	/50	355,4	275

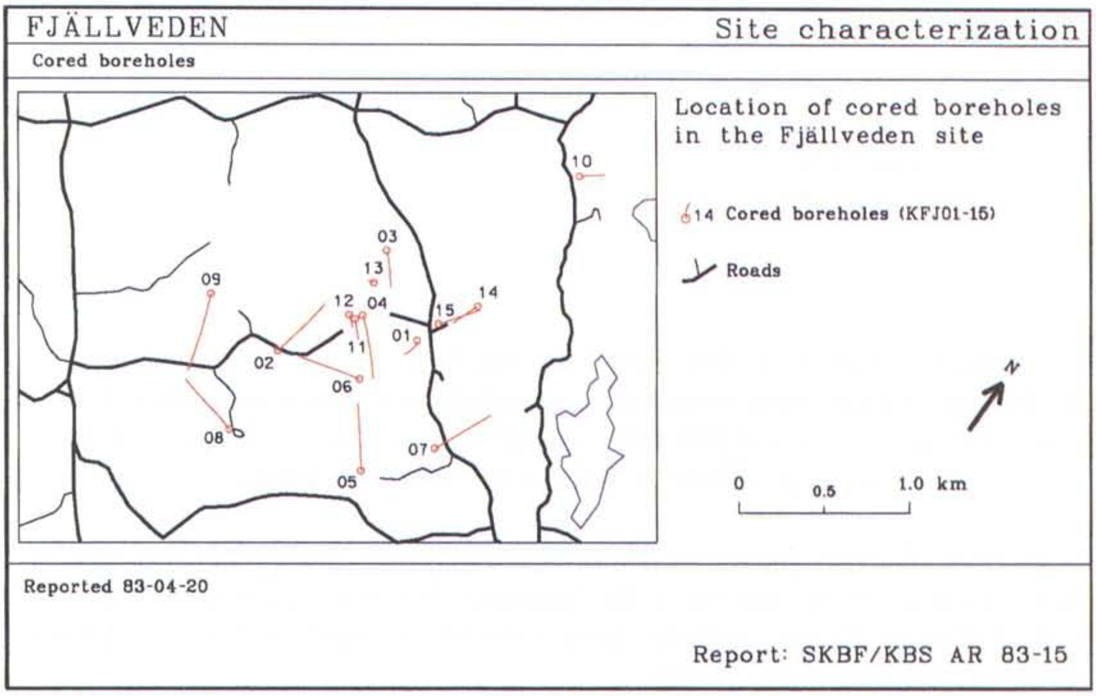

Figure 8. Location of cored boreholes at the Fjällveden site.

3.6 Core logging and petrophysical measurements

The drill cores were mapped with respect to rock types, fractures and fracture minerals. In total, the drill cores from Fjällveden amounts to 7 334 m. The core mapping data, except for descriptions of rock types, was stored on discs using a computerized system (Almén et al., 1983). Detailed print–outs in a scale of roughly 1:30 is available in borehole reports (Carlsten, 1983). Generalized results concerning fracture frequency and rock types are presented in scales of 1:5 000 and 1:2 000 (Carlsten et al., 1983). The computerized storage (now transferred to the SKB database GEOTAB) 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

Core samples for petrophysical measurements (in total 234 samples) were taken at regular intervals from all cores (Duran, 1983). The samples were measured with respect to:

- density
- porosity
- magnetic susceptibility
- remanent magnetization
- resistivity
- induced polarization

The density values were determined by weighing the sample in water and in air. Porosity values were obtained by weighing fully saturated samples and then re–weighing the samples after drying in an hot oven. A description of the methods used is presented by Öqvist and Jämtlid (1984).

In addition, thermal properties (thermal conductivity, diffusivity and heat capacity) was determined using the "transient hot strip" method (Gustavsson et al., 1979) on 15 core samples from 300–700 m depth in borehole KFJ01 (Ahlbom and Karawacki, 1983).

3.7 Geophysical logging

The following "standard" set of geophysical logs were used in the cored boreholes at Fjällveden (see Figure 9 and Appendix A):

- borehole deviation
- natural gamma radiation
- point resistance
- resistivity, normal 1.6 m
- resistivity, lateral 1.65 m
- spontaneous potential
- temperature
- resistivity of borehole water
- induced polarization

The results from the geophysical logging are reported in the scale 1:5 000 (Duran, 1983). In addition to the "standard" methods above, boreholes KFJ02 and KFJ03 was measured with an electrochemical log (pH, Eh and pS^{2-}) (Duran, 1984). The geophysical loggings made in each of the cored borehole are presented in Appendix A.

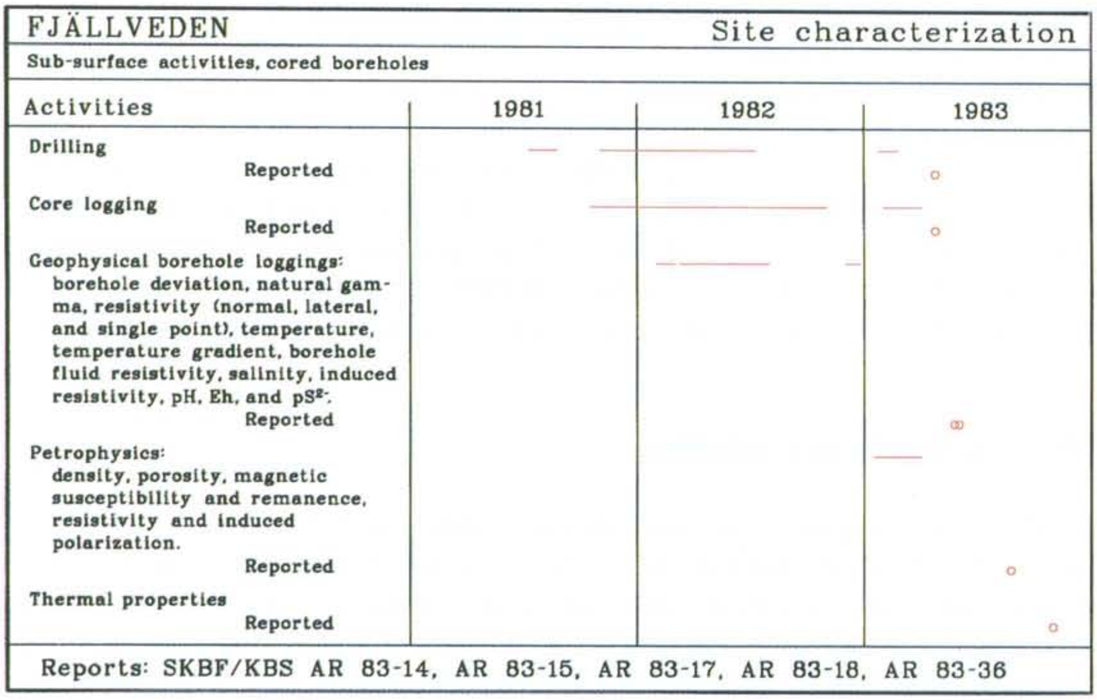

Figure 9. Activity periods – drilling, core logging, geophysical logging and petrophysical measurements on samples from the cored boreholes.

3.8 Hydraulic tests and monitoring

Water injection tests

The hydraulic conductivity of the bedrock has been determined by single hole water injection tests in packed–off sections in the cored boreholes. The majority of these measurements were made in 25 m sections throughout the boreholes from 10–30 m below the ground surface down to c. 10 m from the bottom of the boreholes. In total, 219 sections with a length of 25 m were tested, c.f. section 6.1. To obtain detailed information in crushed and fractured parts of the bedrock totally 61 measurements in 10 and 5 m section length were made. Furthermore, 2 m sections were tested in a part of borehole KFJ02 to obtain data on the conductive fracture frequency. Ten single packer tests were also made to measure the average hydraulic conductivity from the packer to the bottom of the borehole.

Most tests were transient injection tests at constant head. An exception is the steady state injection tests in 2 m sections performed in borehole KFJ02 (Appendix A) for calculating the conductive fracture frequency. With the exception of these 2 m sections, the hydraulic testing methods and results are presented in Larsson (1983) and in Ahlbom et al. (1983). The activity periods for the hydraulic tests are presented in Figure 10. Scope of water injection tests in the different boreholes is presented in Appendix A.

Groundwater head measurements

The location of the groundwater table was measured during most part of 1982 in the cored boreholes. The groundwater head in sections in the deeper parts of the bedrock was estimated from the pressure recovery phase of the water injection tests. In two boreholes, KFJ07 and KFJ08, piezometric measurements were also made in five isolated sections for about one month.

3.9 Groundwater sampling

Groundwater sampling was made in four isolated sections in each of the boreholes KFJ02 and KFJ04, and in two sections in KFJ08. The chemical characteristics of the groundwaters sampled in these sections are presented by Laurent (1983) and in Wikberg et al. (1983) and Smellie et al. (1985). Locations of sampled sections and chemical characteristics are discussed in Chapter 7.

3.10 Studies in the Fjällveden Site since KBS–3

After the main investigations for the KBS–3 report, which were terminated in 1983, the boreholes at the Fjällveden site have been used for testing new equipment for groundwater sampling and for in situ groundwater Eh and pH determinations (Wikberg, 1987). Also, to a minor extent the Fjällveden site has been used for testing the geophysical mise–á–la masse method for orientation of fracture zones (Magnusson, 1985).

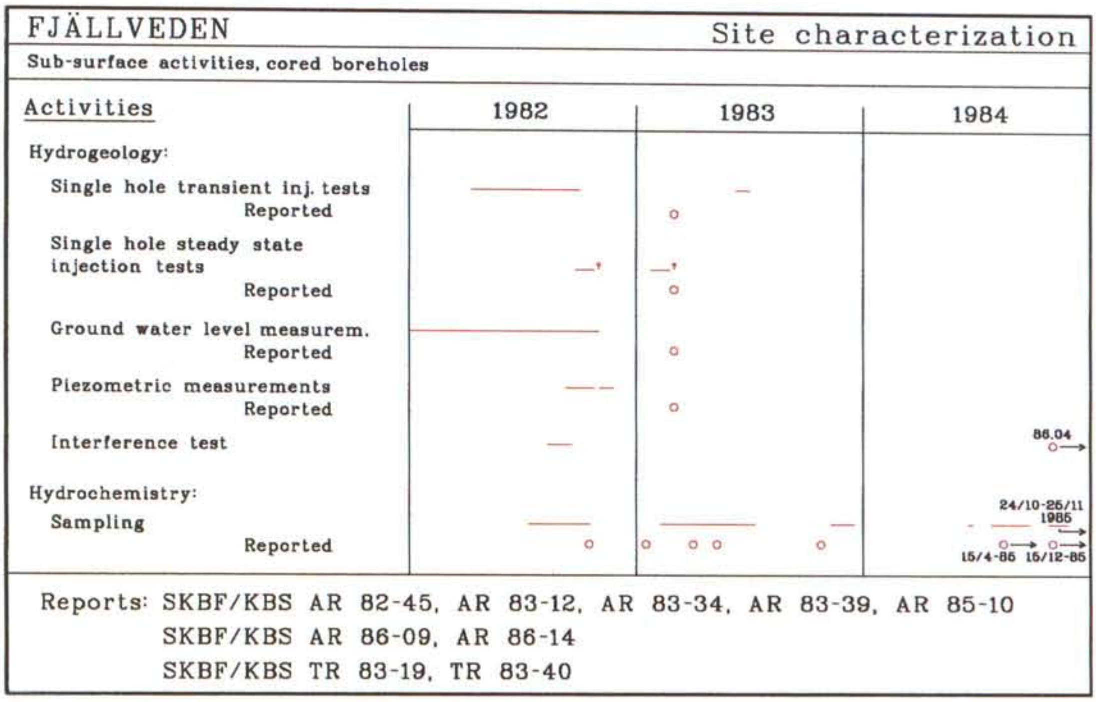

Figure 10. Activity periods – hydraulic measurements and groundwater sampling in the cored boreholes.

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. The database also includes data from the fracture survey. Other "surface data", such as geological maps, lineament interpretations, depth of overburden, hydro–meterological 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. Apart from borehole geometrical data (coordinates, length, dip, deviation etc), this also includes results from core logging, "standard" geophysical logs, petrophysical measurements and single hole hydraulic packer tests. Also stored are chemical analyses of sampled groundwater from the cored boreholes. For the percussion boreholes the database also includes groundwater level monitoring and interference tests. A description of stored data from surveys in each borehole are presented in Appendix A (under the heading GEOTAB in Figures A2–A14).

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

Percussion boreholes. No drilling rates or data regarding drilling debris are stored. This also applies for the borehole deviation data and the geophysical loggings. 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 measurements. The database does not include thermal parameters measured on core samples. This is also the case for the mise–á–la–masse measurements. As noted above none of the geophysical logs in the percussion boreholes are stored in the GEOTAB.

5. GEOLOGIC MODELS

5.1 Regional geologic models

Geology

The bedrock surrounding the Fjällveden site consists mainly of migmatitic sedimentary gneiss and late orogenic granodioritic intrusions, here denoted as granite gneiss, Figure 11. These rocks have been part of the Svecokarelian orogeny (c. 1 800 milj. years). Postdating the orogeny, granites penetrated into the old bedrock. These granites are comparatively undeformed and are generally referred to as younger granites. Two minor bodies of young granite occurs north of the Fjällveden study site, Figure 11. The youngest rock types are dolerite dykes of a probable age of 1200 milj. years. Descriptions of rock types and geologic evolution of the area are to be found in the descriptions to surrounding geological map-sheets, e.g. Wikström (1979), Lundström (1976), and Stålhös (1975). The geologic surface data has not been compiled into profiles showing the vertical distribution of different rock bodies for the Fjällveden region.

Lineaments

The Fjällveden region is characterized by extensive and well marked lineaments with northwesterly orientation, Figure 12. This set of lineaments occur with a regular spacing of 2.5 - 3.0 km. The Fjällveden site is located between two such lineaments. As described below, observations both by geological mapping and by drilling confirm that these lineaments represent wide and extensive fracture zones. During geological mapping of the neighboring map Nyköping SO (Lundström, 1976) mylonites and breccias, as well as Jotnian dolerite dykes, was found in these lineaments, i.e they represent fracture zones with an age of jotnium (1 250 milj. year) or older.

The regional lineament bounding the eastern part of Fjällveden was examined with the cored borehole KFJ10. The results from this borehole indicates a 80-90 m wide shear zone which dips 75 degrees in southwesterly direction, i.e. towards the Fjällveden site. In the fracture zone there are crushed sections, mylonites and breccias and an abundance of clay-filled fractures and slickensides (indications of shear-movements). Displacements of rock bodies across this fracture zones, as seen in Figure 13, is an result of these movements. The regional lineament bounding the Fjällveden site to the west is assumed to be a fracture zone of the same orientation and magnitude as the eastern one. Although the available data should permit tectonic 3D models of brittle and plastic deformation, no such model has been made for the region surrounding the Fjällveden site.

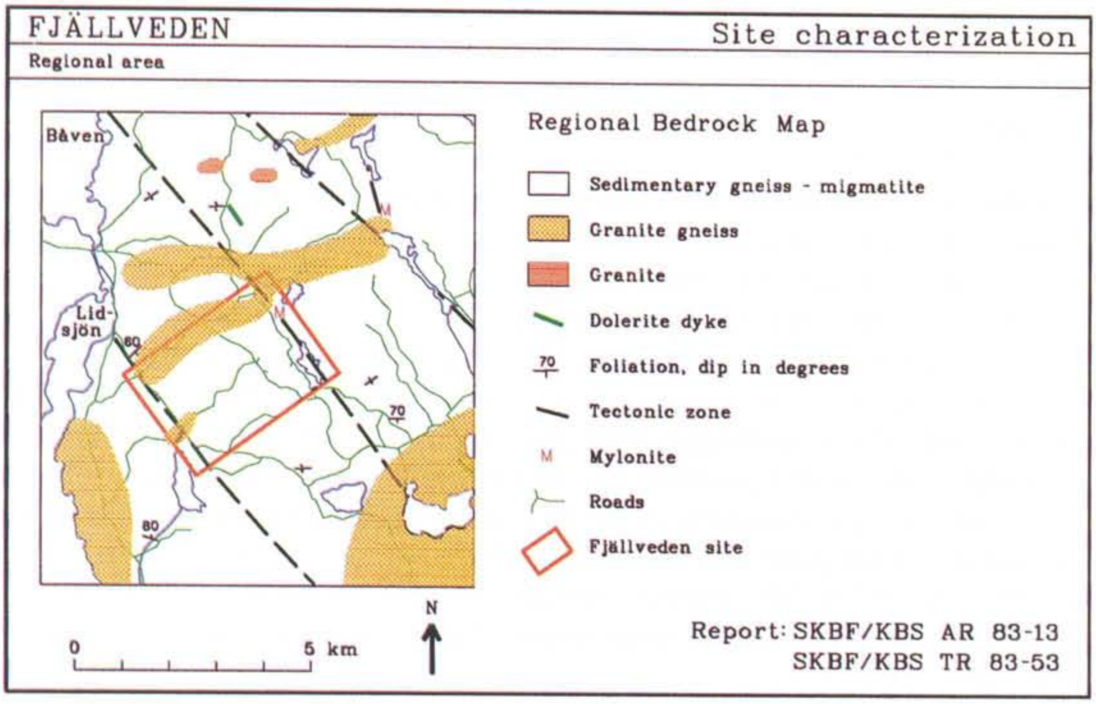

Figure 11. Distribution of rock types in the Fjällveden region (from Carlsten al., 1983).

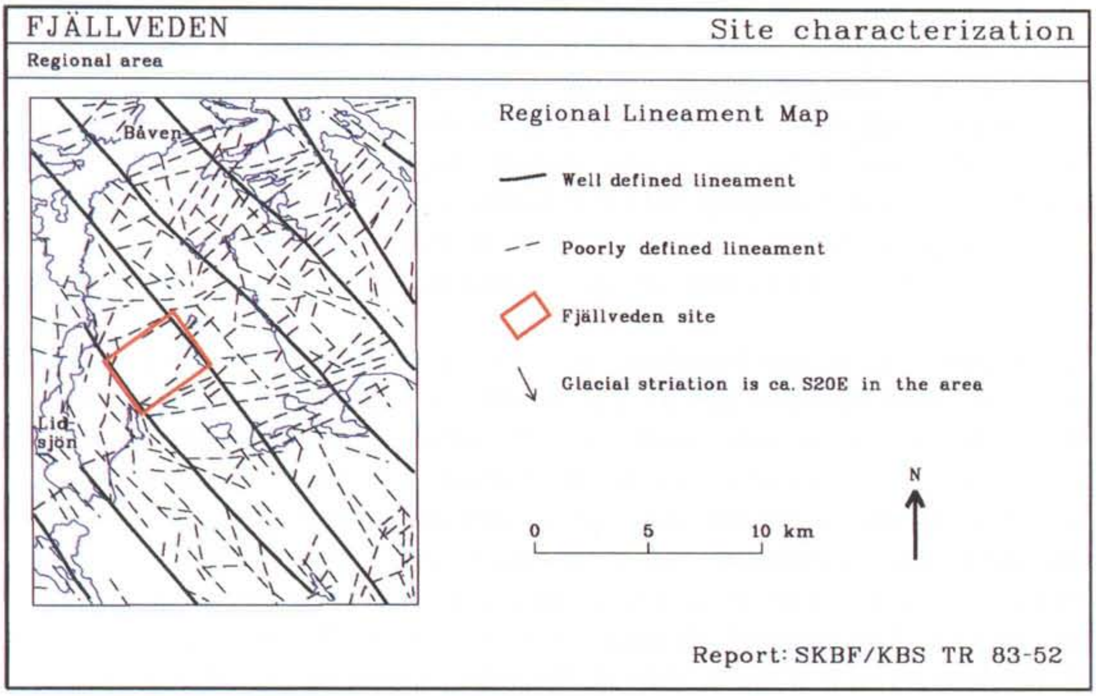

Figure 12. Lineaments in the Fjällveden region interpreted from topographical maps in scale 1:50 000.

5.2 Geological characteristics of the Fjällveden site

Rock types

The Fjällveden area is dominated by migmatitic sedimentary gneiss, Figure 13. The gneiss varies in structure and composition due to the composition of the original sediments. The sedimentary gneiss is usually grey and fine– to medium–grained. The main minerals are quartz (50%), potash feldspar (25%), biotite (15%), and plagioclase (10%). Accessory minerals are cordierite, sillimanite, chlorite (after biotite), zircon and apatite. There are also sulphide minerals, usually in the form of pyrite and pyrrhotite.

The gneiss is veined with coarse grained quartzo–feltspatic layers, alternating with biotite dominated medium grained layers. Individual layers generally have a thickness of about 0.1 m. The veins are parallel with the biotite fabric in the rock and the regional foliation.

The foliation generally trends northeast with a vertical dip. The foliation is tightly folded along subhorizontal northeast trending fold axis and refolded along east–west trending fold axis.

The veined gneiss usually contains small elongated bodies of amphibolite parallel to the foliation. They mainly consist of amphibole, feldspar and biotite. They are also garnet bearing. The thickness of the amphibolite layers are between 0.1 m to several meters wide.

A large body of granite gneiss has been found in the northern (northwesterly) part of the site. The granite gneiss is grey and fine– to medium–grained and have a NE–trending foliation, i.e. the same direction as for the sedimentary gneiss. Its mineralogical composition resembles that of the sedimentary gneiss although with a more granodioritic character.

Granite gneiss has also been found at 27 locations in the drill cores. They constitute in total, 179 m of a total borehole length of 7 334 m. By interpolating between boreholes it was found that granite gneiss appears as layers parallel to the foliation of the gneiss, which means that the layers are oriented in a northeasterly direction and with vertical dip. The width of the layers varies between 0.08 to 14.2 m, with a mean width of 3.1 m. The contact between granite gneiss and sedimentary gneiss in the drill cores is well defined. In the percussion–drilled holes the granite gneiss has been detected due to their slightly higher natural radiation level and higher resistivity (Tirén, 1986). Detailed descriptions of the distribution of rock types in each of the cored boreholes are presented Appendix B.

In the geologic map, Figure 13, the layers of granite gneiss found in core-drilled and percussion-drilled holes have been projected to ground-level. The projection is based on the borehole information and assuming that the inlayers of granite gneiss are oriented parallel to the foliation. Judging from this map the distance between the layers of granite gneiss varies from 20 up to 260 m, estimated in a profile through the central part of Fjällveden site. The mean distance between the layers is estimated to about 100 m.

Borehole data indicate that the granite gneiss strata are more continuous in a horizontal direction as compared with the vertical. This can be explained by the fact that the granite gneiss and the sedimentary gneiss have been folded isoclinically along horizontal fold axes causing the layers of granite gneiss to stretch and become thinner and be pulled apart at the fold limbs. The granite gneiss layers today remain as horizontal elongated bodies.

The projected locations of the granite layers to the ground surface, Figure 13, have not been confirmed by the geologic outcrop mapping. This is due to three reasons. Firstly, the mapping of outcrops were made early in the site investigation, where the existence and importance of the layers was not known. As the layers are thin and resemble the sedimentary gneiss they might have been omitted in the mapping. Secondly, the projections from the borehole locations indicate that most of the granite gneiss outcrop in topographical depressions where there are few outcrops, and thirdly, as discussed above the layers might not continue to the ground surface.

Other subordinate rock types at the Fjällveden site are pegmatite and dolorite. Pegmatite occurs as dykes or minor bodies more or less evenly distributed over the hole site. Dolorite, which is the youngest rock type, is present as vertical dykes oriented in a northwesterly direction, i.e. perpendicular to the gneissic structure and subparallel to the regional fracture zones. These dykes are most common in the northern part of the site. The dolerites are grey to black and fine- to medium-grained. The widths of the dolorite dykes varies between 0.5 and 4 m.

Sulphide mineralizations

As mentioned earlier, there are sulphide minerals present at the site primarily in the form of pyrite and pyrrhotite. The geophysical maps indicate that increased concentrations of sulphide minerals primarily exist within the sedimentary gneiss. The sulphide minerals are dispersed in the bedrock (disseminated) and occur as fracture minerals and as thin streaks parallel with the gneiss structure.

The geophysical maps indicate that pyrrhotite dominates the sulphide minerals in the north and pyrite in the south. The pyrrhotite in the north appears as an approx 300 m wide magnetic anomaly. The cored borehole KFJ13 is drilled through this area. The drill cores contains disseminations of pyrrhotite, chalcopyrite and bornite, mainly between 60–117 m levels. In this section every 10th m has been sampled for analysis. No high concentrations of sulfides was found which implies that the area is not of interest for mineral prospecting, e.g. the highest copper concentrations in the analyses were 0.01%.

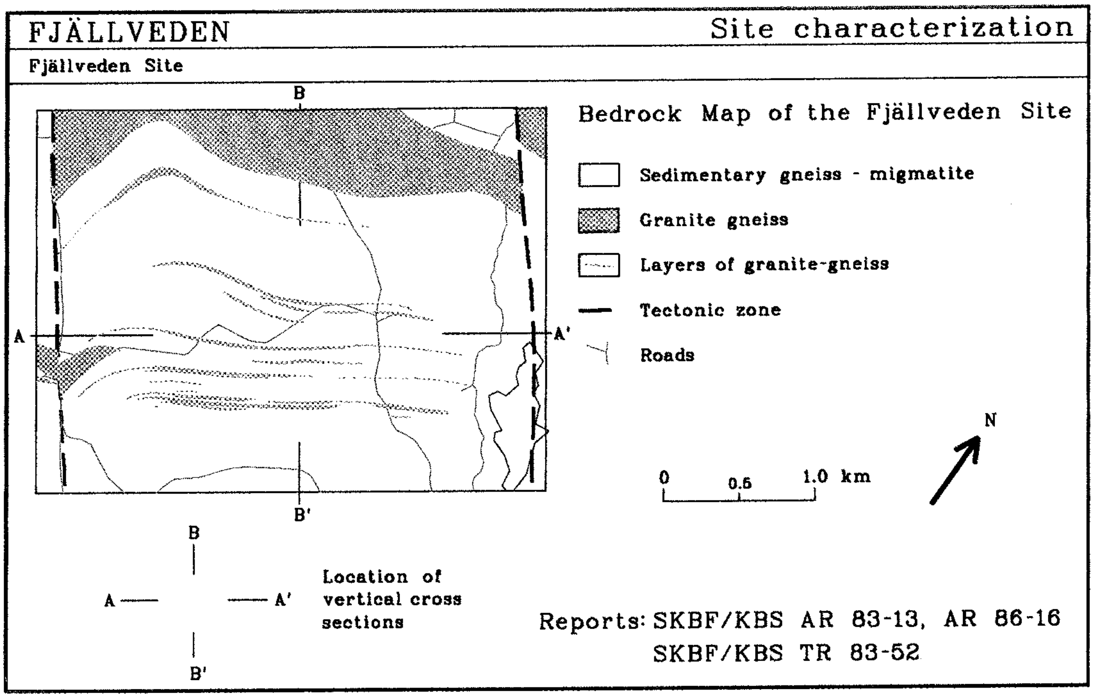

Figure 13. Bedrock map of the Fjällveden site.

Fractures

Fractures have been mapped on outcrops along scan–lines. This survey showed two main fracture orientations, viz. northeast and northwest, i.e. parallel with and perpendicular to the gneissosity. The fracture frequency is 0.9 fr/m (for fractures longer than 0.5 m).

The results from the core mapping show that the average fracture frequency, in the upper 100 m of all drill cores, is about 4 fr/m. The fracture frequency decreases with depth until 200 m. From 200 m and down to 700 m the average fracture frequency is more or less constant, about 2 fr/m.

The location of sections with high fracture frequency in each of the cored boreholes are presented in Appendix B.

The average fracture frequency for various rock types, irrespective of depth in the drill cores, is lowest for sedimentary gneiss, 2.8 fr/m, followed by granite gneiss with 4.3 fr/m and amphibolite with 5.9 fr/m.

Common fracture filling minerals in the cores are calcite, chlorite, kaolinite, and pyrite. In addition, the clay minerals smectite, montmorillonite and illite have been identified. These clay minerals are frequently in–mixed with one another and difficult to separate. Some of the analyzed clay samples indicate swelling ability. The presence of kaolinite down to 600 m depth indicates that the groundwater at Fjällveden has, or had, chemical properties promoting deep alteration (weathering) of feltspar into kaolinite. An alternative possibility is alteration by hydrothermal fluids.

5.3 Fracture zones

Possible locations of fracture zones was interpreted from aerial photographs (scale 1:20 000), geological mapping and geophysical ground measurements. This first attempt to identify fracture zones was regarded as preliminary and highly uncertain because of the flat topography in general, and because of the uncertainties involved in the interpretation the electrical ground geophysical surveys. A large percussion drilling programme was therefor made to compensate this lack of knowledge. Almost 50 percussion boreholes were drilled, which means that almost all lineaments/geophysical anomalies in the central part of the site were tested to determine the existence and characteristics of fracture zones.

Since only a minor part of the tested anomalies were verified as fracture zones in the boreholes, the electrical anomalies were reinterpreted as being caused by clay deposits in the overburden and/or by sulphide minerals. Boreholes were also drilled to test the character of lineaments. Many of these lineaments could not be verified as fracture zones. Instead, as most of the lineaments were oriented parallel to the gneissosity, they were reinterpreted as a result of differential weathering rather than fracture zones. Lineaments of other orientations were in most cases verified as fracture zones.

Percussion drill holes in general yield small water capacities. The median capacity of the percussion drill holes in the Fjällveden area is 350 l/h and the mean capacity 650 l/h. After the geometrical characteristics of the fracture zones in the upper part of the bedrock were determined, cored boreholes were directed to intersect the zones at deeper levels. In this way information regarding the continuation of the fracture zones was obtained, as well as quantitative data regarding geologic characteristics and hydraulic properties of fracture zones at deeper levels.

Within the study site, 11 local fracture zones have been identified. These zones have been examined by means of cored boreholes in a total of 21 different locations. A summary of all interpreted fracture zones, together with some of their properties, are presented in Table 3. Descriptions of each interpreted fracture zone are presented in Appendix C. This includes general geological characteristics for each zone, as well as basis for interpretation and reliability (c.f. Bäckblom, 1989).

The locations of interpreted fracture zones at the ground surface are shown in Figure 14, while the locations at 600 m depth is shown in Figure 15. The fracture zones are usually steep, the dip varying between 70 and vertical. North–south and east–west cross–sections are shown in Figure 16. The interpreted locations of each fracture zone in individual boreholes are presented in Appendix B.

No horizontal fracture zone has been interpreted. The common occurrence of sections with high fracture frequency down to 100–150 m depth, as well as hydraulic responses between boreholes down to these depths are interpreted as a result of extensive horizontal release joints (Carlsten et al., 1983).

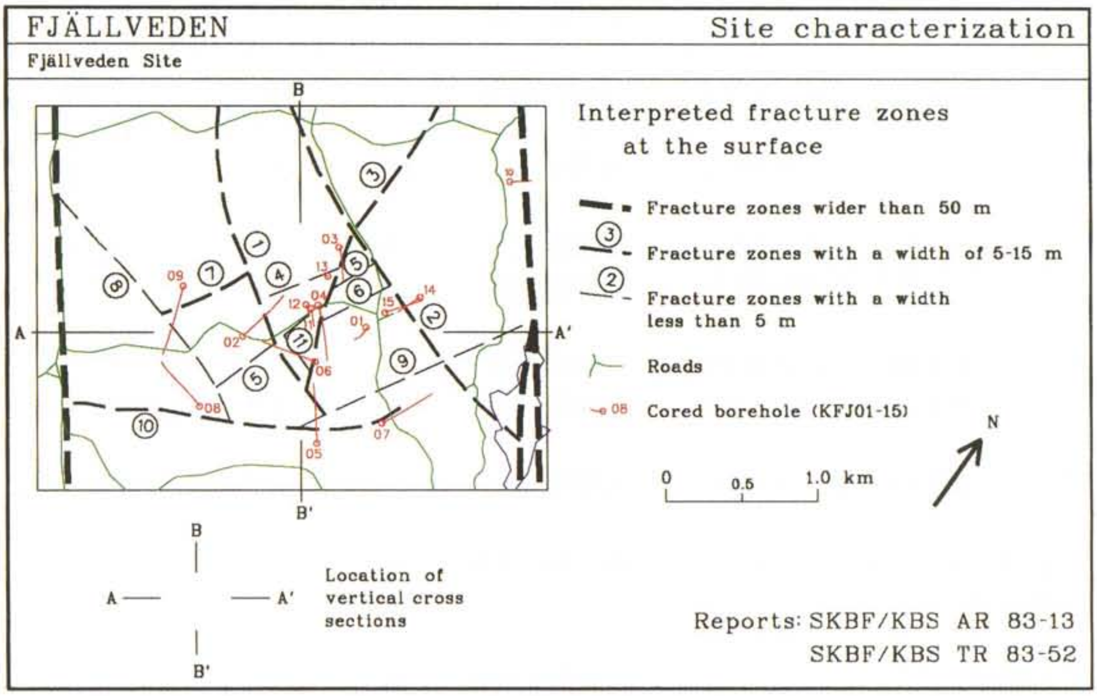

Figure 14. Interpreted fracture zones at the ground surface.

Table 3. Geometrical data, hydraulic conductivities and fracture frequencies for interpreted fracture zones, Fjällveden study site.

Fracture zone	Position in borehole (m)	Strike/Dip (degrees)	Width (m)	Fracture freq.(fr/m)	K–value (m/s)
1	KFJ02 (340–354)	N55W/90	7	12	$3 \cdot 10^{-9}$
	KFJ05 (469–473)	N55W/90	1	7	$2 \cdot 10^{-9}$
	KFJ06 (479–486)	N55W/90	3	6	$8 \cdot 10^{-10}$
2	KFJ14 (115–134)	N65W/80N	12	11	not meas.
	KFJ15 (304–321)	N65W/80N	9	13	not meas.
3	KFJ03 (150–175)	N20W/90	5	8	$3 \cdot 10^{-7}$
	KFJ04 (140–192)	N20W/90	10	12	$1 \cdot 10^{-7}$
	KFJ06 (37–59)	N20W/90	11	5	not meas.
4	KFJ02 (596–600)	N35E/80E	1	16	$7 \cdot 10^{-9}$
5	KFJ04 (61– 63)	N25E/80W	1	15	$1 \cdot 10^{-6}$
	KFJ06 (610–611)	N25E/80W	0.5	30	$1 \cdot 10^{-11}$
	KFJ11 (64– 66)	N25E/80W	1	30	not meas.
	KFJ12 (99–101)	N25E/80W	1	25	not meas.
6	KFJ01 (674–676)	N30E/75E	0.2	15	$1 \cdot 10^{-10}$
7	KFJ09 (110–130)	N30E/60W	14	10	$2 \cdot 10^{-8}$
8	KFJ09 (424–433)	N70W/90	4.5	12	$5 \cdot 10^{-9}$
9	KFJ05 (173–185)	N30E/75E	5	8	$5 \cdot 10^{-7}$
	KFJ07 (685–731)	N30E/75E	5	7	$1 \cdot 10^{-10}$
10	KFJ05 (96–102)	N60E/70S	5	12	$2 \cdot 10^{-9}$
	KFJ07 (53– 89)	N60E/70S	6	10	not meas.
11	KFJ06 (245–256)	N70W/90	3	8	not meas.
Regional eastern zone	KFJ10 (70–165)	N35W/75W	90	24	$1 \cdot 10^{-6}$
Regional western zone		N35W/75W*	90		

*Calculated from geophysical information

The width of the fracture zones varies from 0.2 to 14 m with a mean width of 5 m. The width of the fracture zones has been determined in the drill holes from the point where the fracture frequency increases markedly to the point where it returns back to its normal value. In order to calculate the actual width of the fracture zone, a correction has been made for the intersection angle between the drill hole and the fracture zone.

Within the fracture zones there are, as a rule, one or more sections of crushed bedrock, generally one or a few dm wide, which often are clay altered and sealed. Commonly occurring fracture infilling minerals in the fracture zones are calcite, kaolinite, chlorite and illite.

5.4 Validity of models

Rock type distribution

Two 2D models of rock type distribution have been presented for the Fjällveden site. The first constitute the geological map based on geological mapping of outcrops (Carlsten et al., 1983). This map was made at the early stage of the site investigations before any borehole results were available. The map shows the main distributions of rock types, i.e. migmatitic sedimentary gneiss except for a large body of granite gneiss in the northwest,

The second model was based on information from the cored and percussion boreholes (Ahlbom et al., 1983), Figure 13. The model shows a projection of granite gneiss inlayers found in the boreholes extrapolated to the ground surface. The projected locations of the inlayers at the ground surface has not been checked by geological remapping of outcrops.

The hydraulic tests and the hydraulic modelling strongly suggest that the inlayers of granite gneiss largely governs the groundwater flux, as well as groundwater path-ways and travel-times (see Chapters 6 and 8). However, only a preliminary interpretation of the location of these inlayers exist. To complement the existing data with new surface and borehole data, in order to develop a detailed and comprehensive 3D-model, is therefore important. Such complementary investigations should include both geological and structural remapping of outcrops, with emphasis on the occurrence of granite gneiss, and new boreholes specifically located to resolve questions regarding the locations and continuation of the inlyers of granite gneiss.

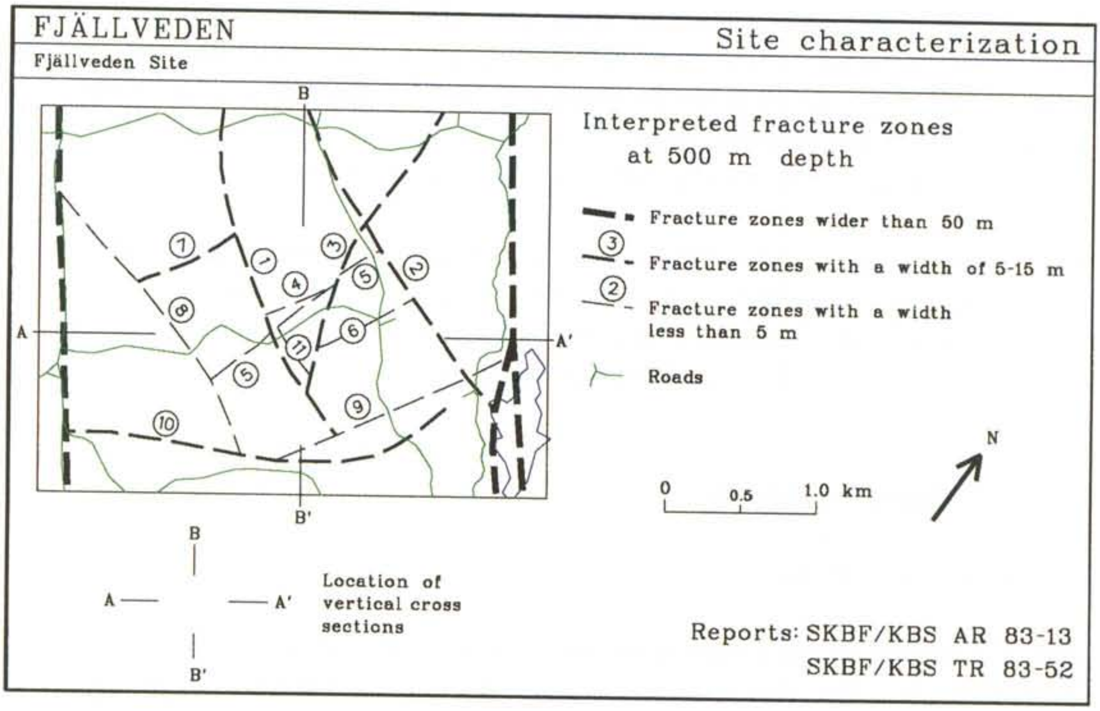

Figure 15. Interpreted fracture zones at 500 m depth.

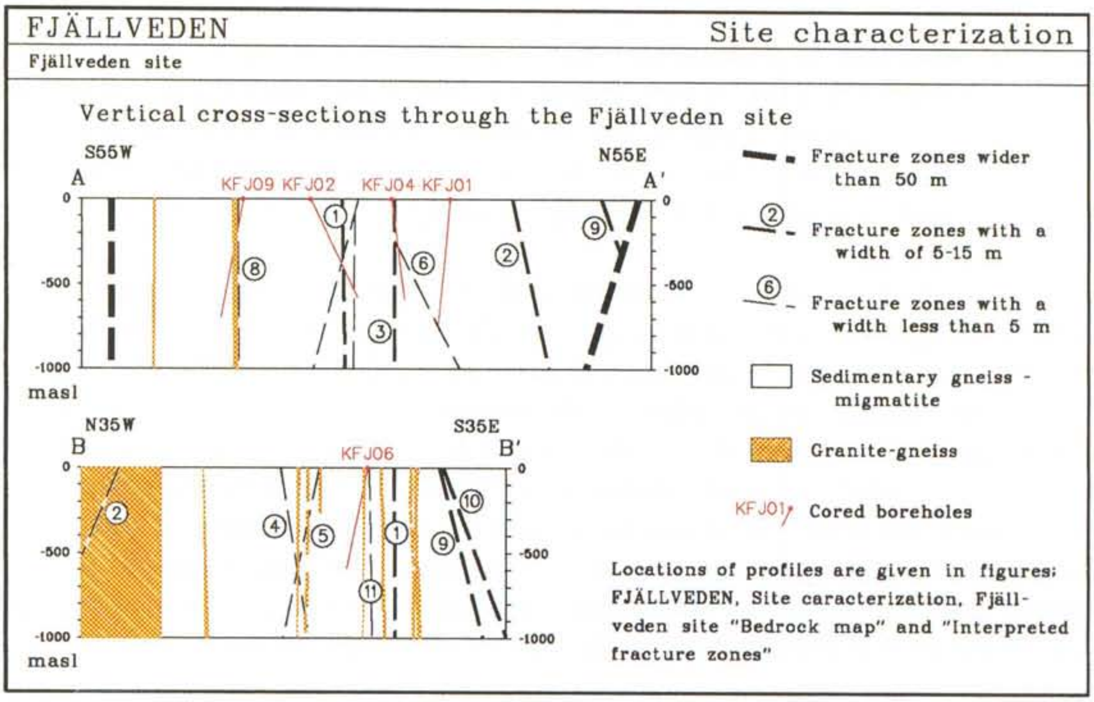

Figure 16. Vertical cross–sections through the Fjällveden site. Locations of sections is indicated in Figures 13, 14 and 15.

Interpreted fracture zones

A description of each fracture zone is presented in Appendix C. This includes on what grounds the 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 given, including main geologic/tectonic characteristics in the cores or, for the percussion boreholes, amount of groundwater inflows. 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 4 most interpreted fracture zones at the Fjällveden site should only be regarded as "possible" or "probable" fracture zone, thus implying large uncertainty in the interpretation.

Table 4. Reliability of interpreted fracture zones mainly according to the nomenclature of Bäckblom (1989).

Fracture zone	Reliability
Zone 1	Probable
Zone 2	Probable
Zone 3	Probable
Zone 4	Possible
Zone 5	Certain
Zone 6	Possible
Zone 7	Possible
Zone 8	Possible
Zone 9	Probable
Zone 10	Certain
Zone 11	Possible
Eastern regional	Certain
Western regional	Probable

There are two main reasons for the low reliability for the interpreted fracture zones. Firstly, the flat topography of Fjällveden in general with large areas covered by peat bogs is not well suited for lineament interpretation, and secondly the electrical conductive clays in the overburden and the sulphide minerals in the bedrock cause large anomalies in the electrical measurements, preventing the identification of the small anomalies caused by the fracture zones.

As discussed in Appendix C, it is questionable if several of the suggested fracture zones really exist. However, it should also be noted that during the KBS–3 studies a conservative approach were taken when interpreting fracture zones. To avoid discussions of possible additional fracture zones, all suspected fracture zones were included in the model, even if the indications were weak.

Regarding the possible occurrence of subhorizontal fracture zones it was considered conservative to not include such zones in the model, since generic modelling showed that a conductive subhorizontal fracture zone in the bedrock above a repository would substantially reduce the groundwater flow at repository level. Because of this reason, and also because of the general lack of time for detailed analysis during KBS–3, it was decided not to strongly investigate the existence of subhorizontal fracture zones at Fjällveden.

In conclusion, most interpreted fracture zones at the Fjällveden site are uncertain. Although a renewed interpretation probable will identify two or three additional fracture zones, many of the earlier interpreted zones will probably be regarded as non–existent. It is therefore probable that the final outcome of a renewed interpretation will be an overall decrease in the number of fracture zones.

6. GEOHYDROLOGICAL MODELS

6.1 Available data and numerical model

The available background data at Fjällveden for potential use in hydraulic modelling consist of the conceptual model of fracture zones, distribution of rock types in outcrops and in drill cores, hydrological and meteorological data, contour maps of the groundwater table, hydraulic conductivity data (both from single hole tests and one interference test in the upper part of the bedrock) and estimated piezometric head values in sections along some of the boreholes. All background data are presented in Ahlbom et al. (1983). The results from the interference test in the upper part of the bedrock are presented by Andersson and Hansson (1986).

Table 5 presents the number of single hole water injection tests. To provide an estimate on "investigation density" also the number of tests per km^2 is presented in the table. The size of the investigated area for this purpose is defined as the area included in the groundwater flow modelling (4.3 km^2). Double packer tests were performed in totally 10 cored boreholes. In addition, 10 single packer tests were carried out (c.f. Appendix A).

Table 5. Number of borehole sections tested with different length together with number of tests per km^2 in the Fjällveden site.

Number of sections	Section length (m)	No of tests/km^2	Test type
219	25	51	double-packer
48	10	11	double-packer
13	5	3	double-packer
188	2	44	double-packer
10	111-510	2	single-packer
478		111	all sections

The geohydrological modelling of the Fjällveden site is presented by Carlsson et al. (1983). Steady-state groundwater flow calculations were performed using a three-dimensional model code based on the Finite Element Method described by Thunvik and Braester (1980) and Grundfelt (1983). Model geometry and boundary conditions were obtained using geological and geophysical interpretations of fracture zones, hydrological data and a map of the groundwater table. The core mapping was used for the division in different rock types. The material properties, i.e. hydraulic conductivity, were derived from the single hole water injection tests and from the interference test. The hydrometeorological data and piezometric head data were used in assessing the relevance of the model results.

The total number of elements in the mesh of the model was 1932, distributed in six horizontal layers. The element mesh contained 8538 nodal points. The fracture zones was modelled with one row of elements. The basic assumption in the type of model code used 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.

6.2 Regional model

No regional hydraulic modelling of the Fjällveden area has been performed.

6.3 Local model

Modelled domain and boundary conditions

The topography of the groundwater table within the Fjällveden site is very flat with elevations ranging from about 65 to 40 m.a.s.l. The site mainly constitutes a recharge area for groundwater. Major discharge areas are located to the west and south of the site in large lakes. The groundwater flow in the upper part of the bedrock is primarily directed northeast and southwest towards the regional shear zones, and in the southern part, towards the south.

The upper boundary condition on the top of the modelled domain corresponds to the elevation of the groundwater table, i.e. zero prescribed pressure. The applied upper boundary condition within the modelled domain in digitized form is shown in Figure 17 as a contour map and as a vertical cross–section. Outside the modelled domain the contours are extracted from the local groundwater table map presented by Ahlbom et al. (1983).

The modelled domain (4.3 km^2) is bounded by the regional fracture zones in the northeast and southwest, towards south by Zone 8 and towards southeast by Zones 9 and 10, Figure 18. In the northwest the domain is bounded by a topographical groundwater divide, Figure 17.

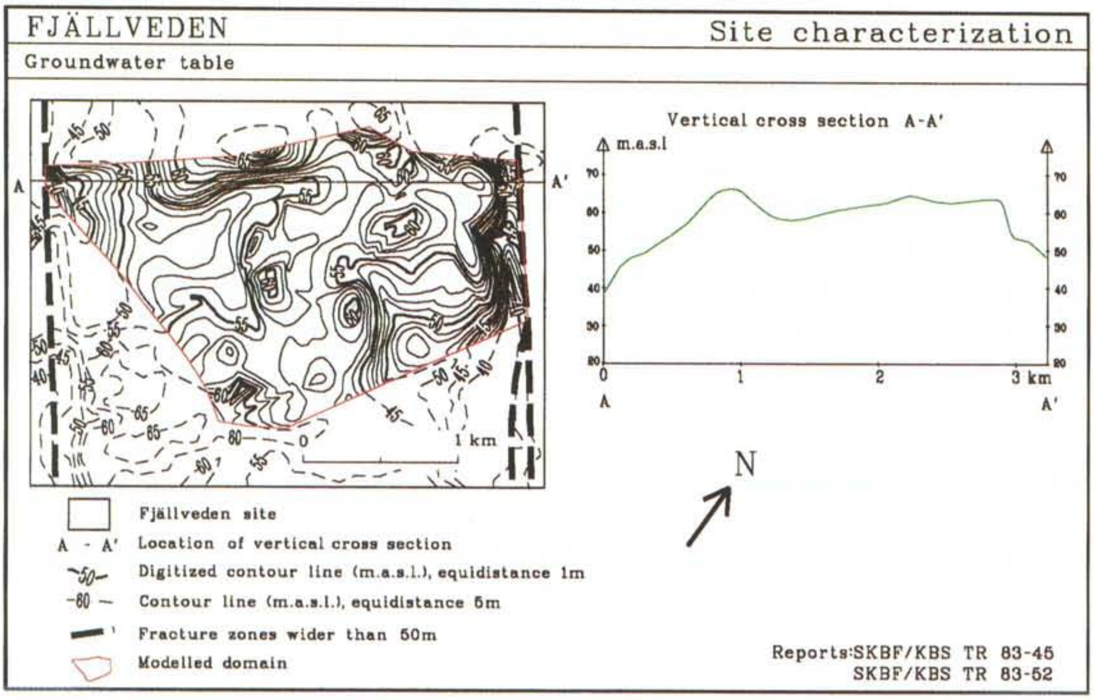

Figure 17. Digitized map of the groundwater table at the Fjällveden site used in the numerical modelling. Modelled domain is outlined.

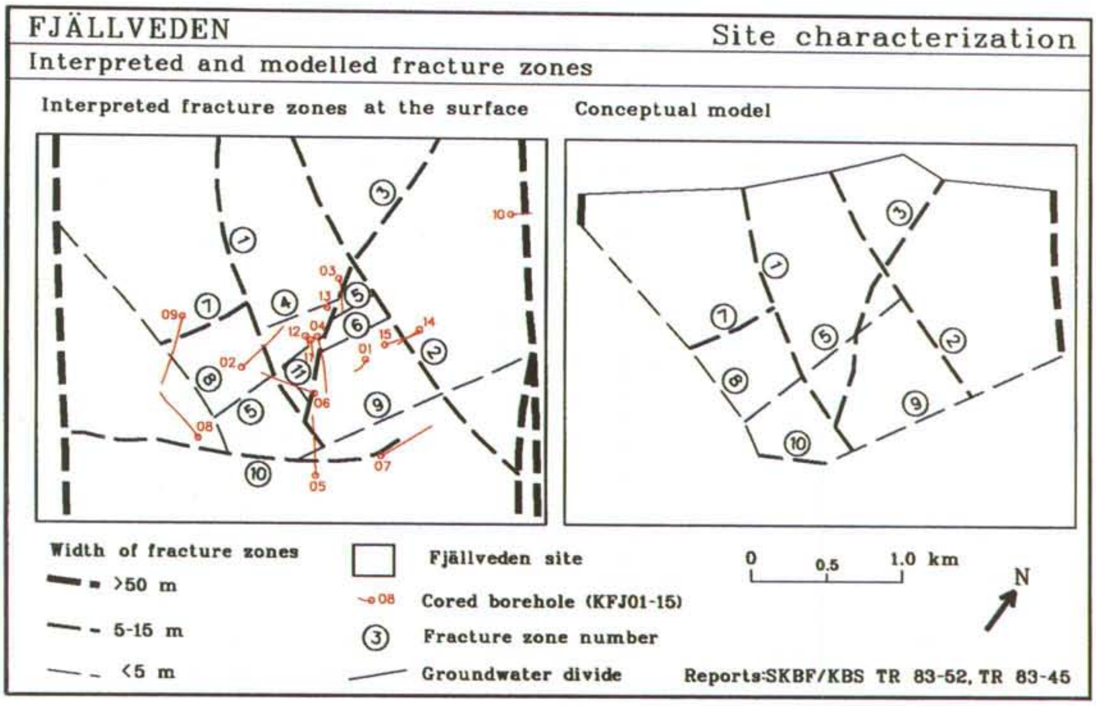

Figure 18. Interpreted and modelled fracture zones at the surface in the Fjällveden site.

The steeply dipping fracture zones, which constitute the boundaries of the modelled domain (except in the northwest) are treated as non–flow boundaries at the outer surfaces of the zone elements. The northwestern boundary constitute a vertical non–flow boundary, coinciding with a topographical groundwater divide. At the lower boundary of the modelled domain a non–flow boundary condition is applied at 1500 m depth.

Hydraulic units

The main hydraulic structures included in the model are 1) the rock mass (excluding interpreted fracture zones), and 2) regional and local fracture zones. The surface locations and the width and strike of the interpreted and modelled fracture zones are presented in Figure 18 and Table 6, respectively. The thin local fracture zones 4, 6 and 11 were omitted in the model since they were assumed to exert a minor influence on the main groundwater flow conditions within the site (as discussed in Appendix C, the existence of these zones are questionable). The intersections between boreholes and fracture zones are described in Table 3. As seen in Table 6 the deviations between the interpreted and modelled fracture zones are small.

Table 6. Interpreted and modelled fracture zone properties in the Fjällveden site (Carlsson et al., 1983).

Fracture zone	Interpreted width (m)	dip(°)	Modelled width (m)	dip(°)
1	1–7	90	5	90
2	9–12	80NE	20	80NE
3	5–11	90	10	90
4	1	80NE	not included	
5	0.5–1	80NW	5	80NW
6	0.2	75SE	not included	
7	14	60NW	14	60NW
8	4.5	90	5	90
9	5	75SE	5	75SE
10	5–6	70SE	5	70SE
11	3	90	not included	
Regional eastern	90	75SE	100	90
Regional western	–	–	100	90

At the Fjällveden site the rock mass is composed of sedimentary gneiss with granite gneiss layers conform with (parallel to) the foliation, i.e. vertical with a northeasterly strike. Since these layers exhibit a significantly higher hydraulic conductivity than the sedimentary gneiss, c.f. Figure 19, it was decided to divide the rock mass into two hydraulic subunits, i.e. sedimentary gneiss and granite gneiss.

Hydraulic conductivity

Hydraulic conductivity functions versus depth were assigned to the hydraulic units defined in the model. Figure 19 shows all measured hydraulic conductivity data from the 25 m test sections versus depth at the Fjällveden site, both for the rock mass and the fracture zones. For these tests sections the lower measurement limit for the water injection tests corresponds to a hydraulic conductivity of 10^{-11} m/s.

The hydraulic conductivity data from the rock mass were subdivided into sections with only sedimentary gneiss and sections with both sedimentary gneiss and granite gneiss (almost no section consisted of only granite gneiss). This subdivision in rock types was made from the core mapping. Regression curves of effective hydraulic conductivity versus depth (curves I–III in Figure 19) were determined for these two rock types and for all measured sections.

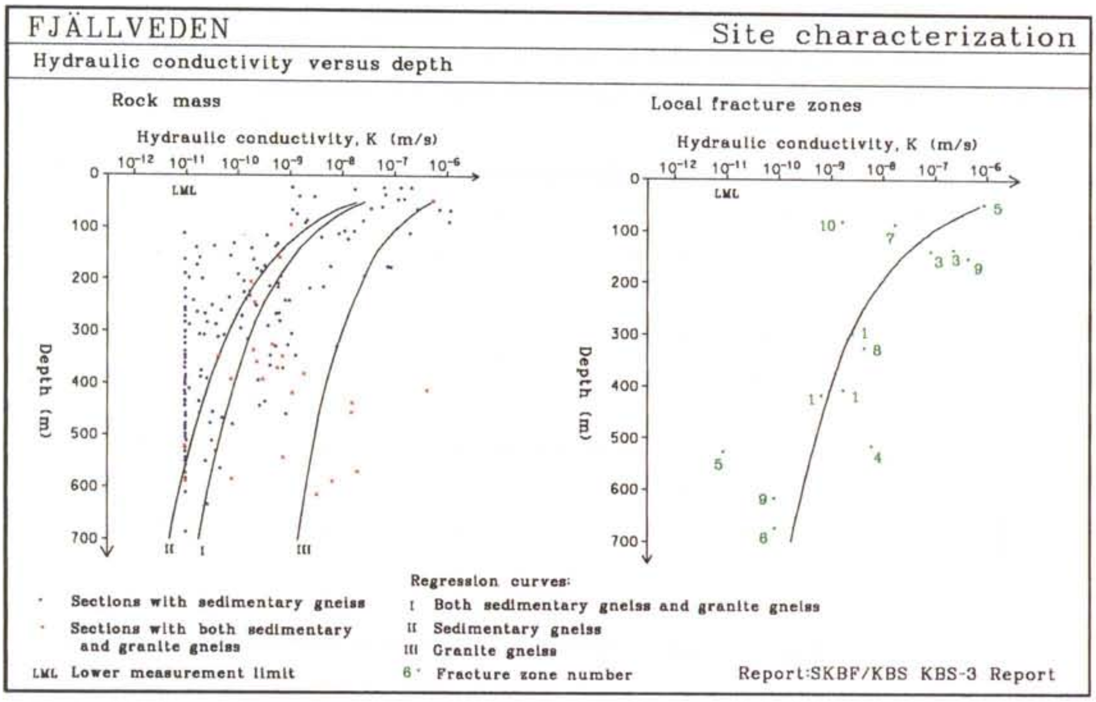

Figure 19. Hydraulic conductivity versus depth for rock mass (left) and for fracture zones (right).

The regression curve for the granite gneiss (curve III) was calculated as the difference between the total section transmissivity and the estimated transmissivity of the portion consisting of sedimentary gneiss (from regression Curve II) divided by the assumed length of granite gneiss in the section (Carlsson et al., 1983). The regression curves are based on a power function of the following form:

$$K_e = A \cdot z^{-b} \quad (z > 0) \qquad (6.1)$$

where K_e is effective hydraulic conductivity, z is vertical depth below ground surface and A and b are constants. The effective hydraulic conductivity of the different hydraulic units was calculated from geometric means of all measured data in 25 m sections, assuming a 3D flow geometry for the rock mass and a 2D flow geometry for the fracture zones. Measured data below the lower measurement limit were assigned the actual value of this limit.

Table 7 shows the derived constants A and b in Eqn. (6.1) from the regression analysis, expressing the hydraulic conductivity versus depth functions for the different hydraulic structures and rock types together with the number of data used (n) and the regression coefficients (r^2). In the table also the calculated anisotropic hydraulic conductivities are presented.

Table 7. Calculated constants A and b in Eqn. (6.1), number of data (n) and regression coefficients (r^2) for the different hydraulic structures and rock types together with calculated anisotropic hydraulic conductivities in the Fjällveden site (Carlsson et al., 1983).

Hydraulic structure	A	b	n	r^2
Rock mass	0.00154	2.78	200	0.44
Sedimentary gneiss	0.00338	3.11	175	0.58
Granite gneiss	0.00332	2.24	22	0.15
K_e parallel to structure (NE and vert)	0.00028	2.38		
K_e perpendicular to structure (NW)	0.00338	3.11		
Local fracture zones	0.17	3.15	14	0.58

Figure 19 shows that the estimated hydraulic conductivity of the granite gneiss is significantly higher than that of the sedimentary gneiss and in the same order as the conductivity of the local fracture zones, at depth even higher. This fact justifies the treatment of the granite gneiss as a separate hydraulic unit. The hydraulic conductivity of the fracture zones is in general relatively low, probable due to fracture sealing by clay alteration.

The assumed occurrence of alternating strata of sedimentary gneiss and granite gneiss implies that anisotropic hydraulic conditions prevails in the rock mass. Consequently, in directions parallel to the orientation of the granite gneiss strata (NE–SW) the hydraulic conductivity of the rock mass was represented by the arithmetic mean of the two rock types in the modelling. Perpendicular to the orientation of the strata the hydraulic conductivity was represented by the harmonic mean. The hydraulic conductivities in different directions are presented in Figure 20. The effective hydraulic conductivities in the two directions were in the modelling weighted in proportion to the occurrence of the two rock types, as described by Carlsson et al. (1983). In the Fjällveden site the granite gneiss was assumed to constitute about 3 % of the rock mass.

The interference test in a fracture zone in the upper 100 m of the bedrock (Anderson and Hansson, 1986) resulted in an average hydraulic conductivity of $2 \cdot 10^{-7}$ m/s, which is in good agreement with the mean value of the hydraulic conductivity of the local fracture zones in this depth interval.

The conductive fracture frequency (CFF) in the rock mass at Fjällveden was estimated by Osnes et al. (1988) by a probabilistic method using hydraulic conductivity data from all 25 m sections in the rock mass. The estimated range of CFF was 0.06–0.09 fr/m.

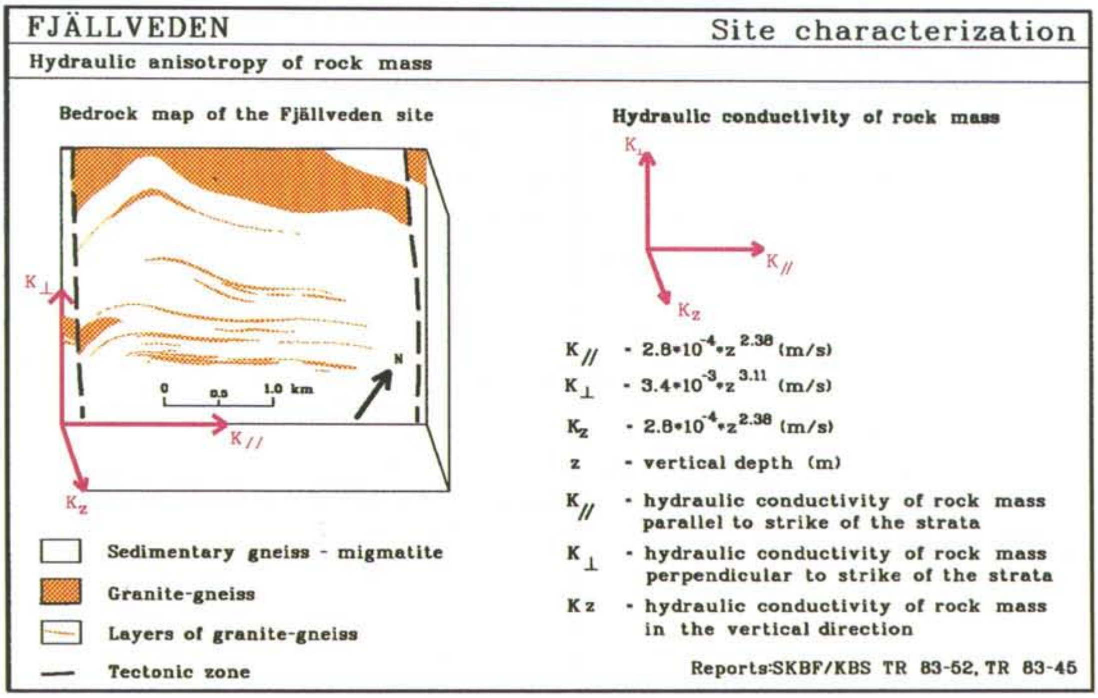

Figure 20. Assumed hydraulic anisotropy of the rock mass due to the presence of hydraulically conductive layers of granite gneiss.

Model cases

Three cases were initially modelled of the Fjällveden site in the KBS–3 study (Carlsson et al., 1983). In Case 1 both the rock mass and local fracture zones were modelled as separate isotropic continua with hydraulic conductivity versus depth functions according to Table 8. In Case 2 the rock mass was assumed to have uniform anisotropic hydraulic properties parallel and perpendicular to the granite gneiss layers, whereas the hydraulic conductivity function for the local fracture zones was the same as in Case 1. In Case 3 the conductivity of the local fracture zones was equal to that of the rock mass.

Case 2 was considered as the most realistic case since the anisotropic conditions of the rock mass are included in the model. The hydraulic conductivity functions used in the different model cases are summarized in Table 8 and illustrated in Figure 21. In Table 8 the actual type of mean value used in the calculation of the effective hydraulic conductivity (K_e) for the different cases is also shown.

Subsequently, a parameter variation study involving six additional cases (Cases 4–9) was performed in the Fjällveden site (Larsson and Markström, 1988). The same conceptual model was used as in Cases 1–3. Cases 4–6 are variations of Case 2 with increased hydraulic conductivities applied for the local fracture zones but the same anisotropic rock mass functions as in Case 2. In Case 4 the local fracture zones were assigned a step function based on arithmetic means of hydraulic conductivity data above and below 260 m depth. In Case 5 a power function based on arithmetic means of all hydraulic conductivity data from the local fracture zones was used. This case was considered to be a "worst case" of the main Case 2. In Case 6 a constant hydraulic conductivity with depth, based on the geometric mean, was assigned to the local fracture zones, Figure 21.

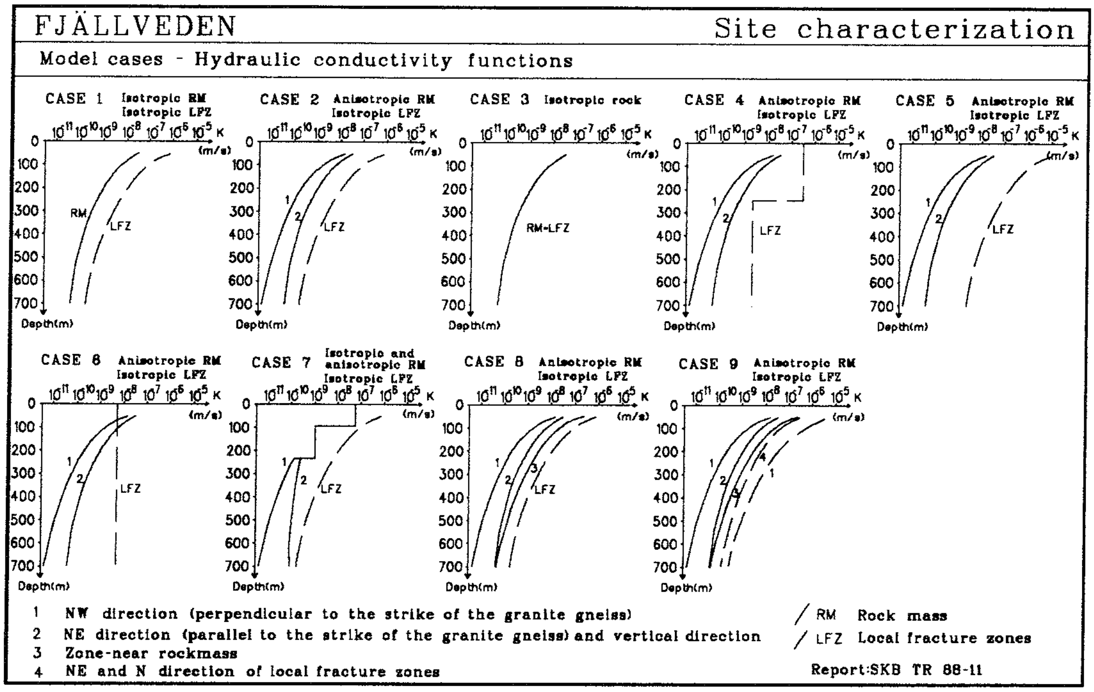

Figure 21. Hydraulic conductivity functions for different hydraulic units and for different model cases (see text).

Also Cases 7–8 are variations of Case 2 but in these the hydraulic conductivity functions for the rock mass were altered whereas the hydraulic properties of the local fracture zones were the same as in Case 2. In Case 7 the rock mass was assumed to be homogeneous (regarding rock types) down to about 220 m and heterogeneous below that depth, reflecting the observed hydraulic properties of the granite gneiss. The upper, homogeneous part was further subdivided in two separate blocks at 100 m depth. The hydraulic conductivity of the rock mass was represented by a step function based on geometric means down to 220 m depth and by the anisotropic conductivity functions in Case 2 below that depth. In Case 8 a "zone–near" rock mass structure with increased hydraulic conductivity adjacent to the local fracture zones is introduced.

In Case 9, which is an extension of Case 8, consideration was taken to the effect of the orientation of fracture zones on hydraulic conductivity. The northeast and northwest striking local fracture zones were assumed to have different hydraulic conductivities, whereas the hydraulic properties of the rock mass were the same as in Case 8, see Table 8.

Table 8. Parameters describing the hydraulic conductivity functions according to Eqn.(6.1) used in the different model cases of the Fjällveden site. Also shown are type of mean value used (MV), assumed flow geometry (m) and number of data used (N). K_a , K_g and K_h represent the arithmetic, geometric and harmonic mean, respectively (Larsson and Markström, 1988).

Case	Rock mass					Fracture zones			
	A	b	MV	m	N	A	b	MV	N
1	$1.5 \cdot 10^{-3}$	2.78	K_g	3D	200	0.17	3.15	K_g	14
2 NE & Vert.	$2.8 \cdot 10^{-4}$	2.38	K_a	2D	200	= Case 1			
NW	$3.4 \cdot 10^{-3}$	3.11	K_h	2D	200	= Case 1			
3	= Case 1				–	–	–	–	
4 0–260 m	= Case 2					$3.12 \cdot 10^{-7}$	–	K_a	6
> 260 m	= Case 2					$2.26 \cdot 10^{-9}$	–	K_a	8
5	= Case 2					2.29	3.15	K_a	14
6	= Case 2					$5.12 \cdot 10^{-9}$	–	K_g	14
7 0–100 m	$6.3 \cdot 10^{-8}$	–	K_g	3D	23	= Case 1			
100–220 m	$1.1 \cdot 10^{-9}$	–	K_g	3D	40	= Case 1			
>220 m									
NE&Vert	$2.9 \cdot 10^{-9}$	0.49	K_a	2D	137	= Case 1			
NW	$3.0 \cdot 10^{-5}$	2.32	K_h	2D	137	= Case 1			
8 Zone near	$3.9 \cdot 10^{-2}$	3.13	K_g	3D	27	= Case 1			
NE & Vert.	$6.8 \cdot 10^{-4}$	2.53	K_a	2D	173	= Case 1			
NW	$1.2 \cdot 10^{-3}$	2.93	K_h	2D	173	= Case 1			
9 NE & Vert.	= Case 8					$4.5 \cdot 10^{-2}$	3.02	K_g	8
NW	= Case 8					7.6	3.73	K_g	4

Results

The distribution of groundwater potential and groundwater flow rate were calculated in a number of horizontal planes at different depths of the modelled domain. The calculated ranges of flow rates in the rock mass at 400 m, 500 m and 600 m below the ground level for Cases 1–9 are listed in Table 9. At the 500 m level also the representative flow rates are indicated within brackets. The groundwater flow rate distribution in the rock mass at 500 m depth below the ground level for the main case (Case 2) is illustrated in Figure 22. The general groundwater flow pattern calculated at the 500 m level is characterized by a flow from the north and the south to a saddle point in the center of the modelled domain. From the saddle point the groundwater is drained towards the regional fracture zones in NE and SW.

Table 9. Calculated range of groundwater flow rates and (representative value) in the rock mass at 400 m, 500 m and 600 m depth for different model cases in the Fjällveden site. From Larsson and Markström (1988).

Case	Groundwater flow rate (ml/m^2/year) at a depth of 400 m	500 m	600 m
1	5–25	3–10 (9)	3–10
2	5–50	3–15 (11)	2–15
3	3–25	3–10 (6)	2–4
4	7–50	7–50 (24)	3–15
5	7–50	7–50 (24)	3–15
6	5–50	7–30 (21)	3–15
7	7–50	7–30 (23)	5–30
8	5–50	5–50 (22)	3–15
9	5–50	5–50 (22)	3–15

According to the representative values of groundwater flow rate in Table 9 the cases with anisotropic hydraulic conductivity functions in the rock mass (Case 2, 7 and 8) all exhibit higher flow rates than the isotropic Case 1. This is a consequence of the general hydraulic gradient being parallel with the main direction of anisotropy. The introduction of a "zone–near" rock mass with increased hydraulic conductivity (Case 8) enhances the flow rate with a factor of about 2, compared to Case 2 despite that the rock mass included in the "zone–near" bedrock is only a small volume of the total rock mass. The combined isotropic/anisotropic rock mass hydraulic conductivity functions

(Case 7) result in almost the same average flow rate, but the range is smaller compared to Case 8.

A lack of hydraulic contrast between the rock mass and local fracture zones (Case 3) results in a low flow rate due to small hydraulic gradients. The cases with increased hydraulic conductivity of the local fracture zones (Case 4, 5, 6 and 9) all result in higher groundwater flow rates compared to Case 2. As expected, the highest average flow rates in the rock mass were obtained in Case 5 and 4, which both are based on arithmetic mean values for the hydraulic conductivity of the fracture zones. The effect of anisotropic hydraulic properties of the fracture zones (Case 8 versus 9) is insignificant.

To conclude, the large number of model cases performed for the Fjällveden site resulted in only insignificant variation in the groundwater potential distribution and thus in the groundwater flow rates. However, it should be remembered that all cases were based on the assumption of porous media and no regional groundwater flow.

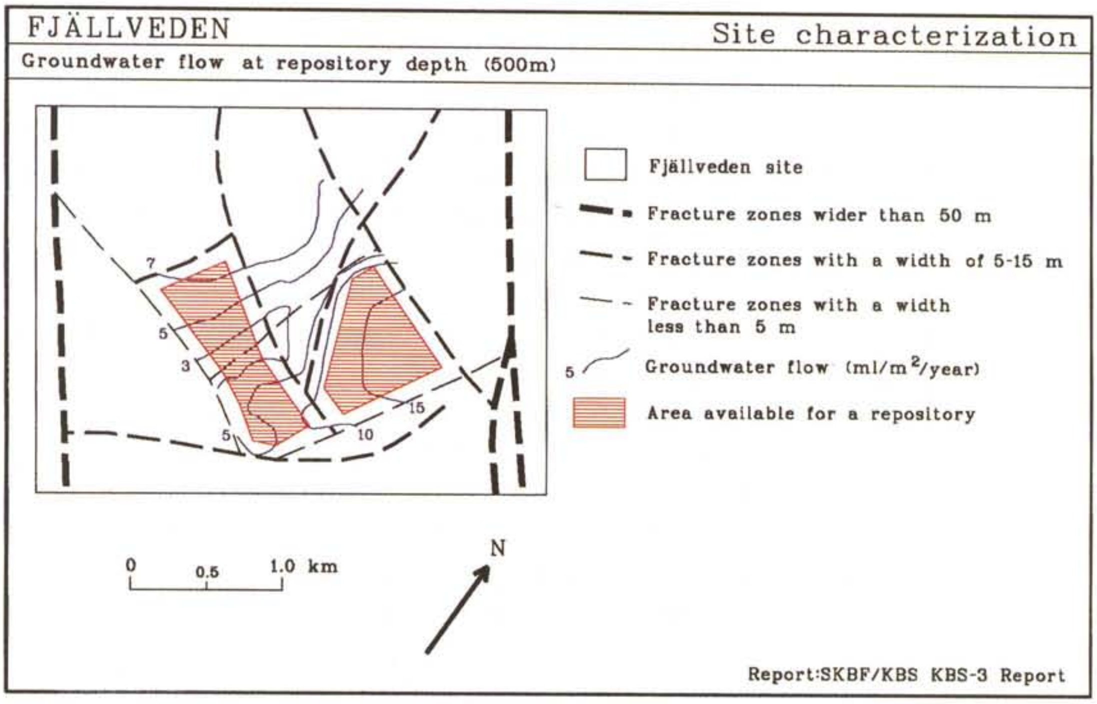

Figure 22. Groundwater flow at 500 m depth for anisotropic hydraulic conductivity of the rock mass (Case 2) (see text).

Relevance of results

The relevance of the numerical model was assessed from calculations of groundwater recharge and mass balance for the individual finite elements. Furthermore, calculated groundwater potentials along boreholes were compared with measured piezometric heads in the tested sections.

The groundwater recharge in the Fjällveden site has been estimated by Carlsson et al. (1983) for Cases 1–3 and by Larsson and Markström (1988) for Cases 1–9. Only the estimates from the second study are presented here. The recharge rate was calculated as the total recharge across the top surface of the modelled domain divided by the area of the top surface. The recharge was also calculated for each hydraulic unit (rock mass and fracture zones) separately. The total recharge rate varies between 1.7 mm/year (Case 6) to 39.1 mm/year (Case 5). The recharge rate in the rock mass varies from 1.8 mm/year (Case 3 and 6) to 14.7 mm/year (Case 7) and in the fracture zones from −0.1 mm/year (Case 6) to 36.4 mm/year (Case 5). The calculated recharge rates are within the interval expected from current understanding of groundwater recharge in crystalline rock.

As pointed out by Larsson and Markström (1988) the calculated recharge rates mainly reflect the groundwater conditions and the hydraulic properties of the uppermost part of the bedrock including fracture zones and have little influence on the groundwater flow conditions at repository depths, c.f. Case 5 and 6. Thus, groundwater recharge calculations may be of limited use as a factor to assess the relevance of the model.

The mass balance was calculated for each element in the mesh to check the numerical quality of the solution. According to Larsson and Markström (1988) the proportion of elements deviating from mass conservation by less than 1% range from 16% (Case 6) to 33% (Case 3). In conclusion, anisotropic hydraulic properties of the rock mass were found to have an insignificant influence on the mass conservation of the solution. High hydraulic contrasts, particularly in areas where high hydraulic gradients prevail, decrease the mass conservation and therefore the quality of the solution.

The groundwater potentials were calculated along lines coinciding with the boreholes KFJ02, KFJ04 and KFJ05 for Case 1 by Carlsson et al. (1983), Figure 23. In the figure also the estimated piezometric heads in conjunction with the injection tests in the 25 m long test sections are shown together with the potential at the top of the boreholes. The upper part of borehole KFJ05 falls outside the modelled domain. It should be observed that the measured data represent "short–time" measurements of piezometric head and may thus be somewhat uncertain, particularly in low–conductive sections. Although the general trends of the measured and modelled potentials are similar, the correlation in detail is not perfect.

6.4 Validity of models

The model results from the Fjällveden site can be assessed by examining some of the specific assumptions made by the conceptualization of the model in relation to existing geological and geohydrological conditions at the site.

Boundary conditions

Since no modelling on a regional scale was performed of the Fjällveden site, the groundwater flow and head conditions at the outer boundaries of the local model were assumed. It is however difficult to assess the uncertainties in these assumptions without making sensitivity studies.

There also exist some uncertainties in the geological interpretation of some of the fracture zones bounding the modelled domain (Zone 8, 9 and 10) since they are penetrated by only one or two boreholes, see Chapter 5. Thus, the no–flow boundary conditions applied for these zones in the model may be critical. On the other hand, the regional fracture zones bounding the modelled domain in NW and SE are well defined. The non–flow boundary conditions applied along the topographical groundwater divide in NW is also considered as uncertain since this reflects near–surface conditions which may not be applicable at depth.

Hydraulic units

Since most of the interpreted fracture zones at Fjällveden are uncertain (c.f. Chapter 5) also the division of the bedrock into rock mass, regional and local fracture zones should be considered as preliminary and uncertain. However, for the modelling of groundwater flow rates this uncertainty is probably not critical due to the low hydraulic conductivity contrast between fractured bedrock in general (of which most are interpreted as local fracture zones) and the surrounding rock mass.

The further division of the rock mass with respect to rock types in sedimentary gneiss and granite gneiss seems justified geologically due to the distinct granite gneiss layers and their significantly higher hydraulic conductivity compared to the sedimentary gneiss. The occurrence of granite gneiss in the test sections can readily be identified from the core logging, thus facilitating the division of the hydraulic conductivity data into these two hydraulic subunits.

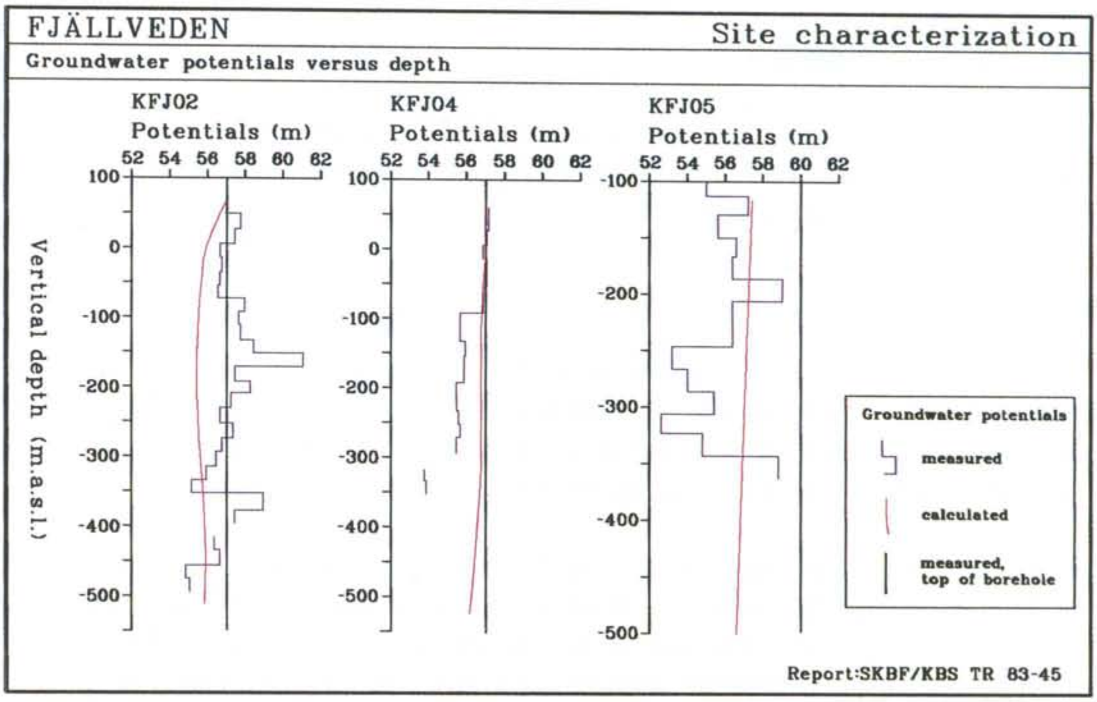

Figure 23. Groundwater potentials in 25 m sections versus depth for boreholes KFJ02, KFJ04 and KFJ05.

There are several observations described that indicate extensive subhorizontal fractures in the upper 100 m of the bedrock (Carlsten et al., 1983). In spite of this, the existence of subhorizontal zones in the Fjällveden study site has not been studied. The effect of a subhorizontal high–conductivity zone would be to hydraulically short–circuit the steep fracture zones, as well as the steeply dipping and hydraulically conductive inlayers of granite gneiss. This would result in a decrease in the groundwater flow below such a zone.

Hydraulic conductivity

The derived hydraulic conductivity versus depth functions are uncertain due to the large scatter of the data, Figure 19. The averaging process also subdues extreme (high) values. For the Fjällveden site several mathematical functions were tested by the regression analysis of the hydraulic conductivity data, i.e. linear, power, logarithmic and exponential functions. The power function, which was found to give the best correlation, was selected for the regression analysis. As can be seen from Table 7, the correlation coefficients are generally rather low for the derived conductivity functions. Other uncertainties are assumed flow geometries in the calculation of the effective hydraulic conductivity, and how to treat data which are below the lower measurement limit.

The calculated anisotropic hydraulic conductivity functions of the rock mass parallel and perpendicular to the granite gneiss strata are regarded as uncertain. The derivation of both functions involves an averaging and weighing process of the hydraulic conductivities of sedimentary and granite gneisses in proportion to their estimated occurrence within the site. Furthermore, by the calculation of the hydraulic conductivity of the granite gneiss, the derived conductivity function of the sedimentary gneiss was utilized (subtracted) since both rock types are present in the tested sections. Although, theoretically correct, both calculations are uncertain in practice. Also, the derived hydraulic conductivity function for the local fracture zones is uncertain for reasons described above.

Nevertheless, the parameter variation study (Cases 4–9) shows that the model results are rather insensitive to the magnitude of the hydraulic conductivity functions applied for the different hydraulic units. This fact is considered to be an inherent feature of the representation of the hydraulic structures as extensive continua (porous media) in the modelling.

Results

The calculated head and groundwater flow distributions at a potential repository depth in the crystalline rock should be regarded as average values in an equivalent single continuum within the bounded modelled domain (when only one hydraulic unit is considered, e.g. Case 3) or in overlapping continua when several hydraulic structures are considered. The results are rather insensitive to the hydraulic conductivity functions applied to the hydraulic units (Larsson and Markström, 1988).

7. GROUNDWATER CHEMISTRY

7.1 Scope and reliability of samples

Most of groundwater chemistry data available form this site was obtained during the KBS–3 investigations 1981–1983. These results, including sampling methods, are presented by Laurent (1983). Three boreholes were investigated, KFJ02, KFJ04 and KFJ08. For KFJ02, four sections at depths 106, 293, 409 and 506 m were sampled. KFJ04 was also sampled in four sections at depths 131, 272, 349 and 420 m. Finally, two sections at depths 402 and 562 m were sampled in KFJ08.

The results of the KBS-3 investigations are discussed and interpreted in detail for each sampled horizon by Smellie et al. (1985) by considering chemistry, geology and hydrology. Measurements of hydraulic conductivity and piezometric pressures in each borehole were used along with results from site specific groundwater flow modelling in an attempt to put each sampled section in relation to local groundwater flow conditions. By considering the various sources of contamination it was concluded that only one of the ten sampled horizons was truly representative for the depth sampled.

Additional groundwater sampling and interpretation of chemistry data at Fjällveden is reported by Wikberg et al. (1987), where new and improved sampling techniques were developed and tested. An additional two sections were sampled, one in KFJ02 and one in KFJ07. These new sampling and analysis methods are also described by Almén et al. (1986).

In the following sections some of the most important results of the chemical analyses from the KBS-3 investigations will be presented and commented on briefly. 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 Smellie et al. (1985).

7.2 Results

General chemistry

The chemical composition of the samples from the different boreholes in Fjällveden is shown in Table 11. The compositions indicates the presence of several main water types: 1) near-surface and shallow groundwaters, 2) intermediate to deep old groundwater (non-saline), and 3) deep to very old groundwater (saline). The major-ion chemistry generally show calcium and sodium as the dominating cations, while the anions are dominated to varying degrees by bicarbonate and sulphate/chloride, respectively. One section very distinctly deviates from this general pattern, showing a major-ion composition characteristic for an old, saline water (but not marine). This section, at 506 m depth in KFJ02, is also the only sample which is considered representative for the sampled depth. The dominating ions in this case are sodium and chloride and the electrolytical conductivity values are approximately three times as high as for all other sampled horizons.

Table 11. General chemistry parameters at Fjällveden.

Sampled borehole	Depth m	pH	Conductivity mS/m	Na^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	K^+ mg/l	HCO_3^- mg/l	Cl^- mg/l	SO_4^{2-} mg/l
KFJ02	106	8.0	27	37	18	3.0	2.4	160	5	6.1
KFJ02	293	7.3	27	26	19	2.3	2.3	144	8	10.0
KFJ02	409	7.4	30	33	21	2.6	2.6	170	8	0.2
KFJ02	506	8.9	78	130	12	1.0	1.0	83	170	0.2
KFJ04	131	8.2	35	65	15	3.0	3.0	218	6	8.0
KFJ04	272	7.5	34	38	28	2.7	2.7	196	9	7.0
KFJ04	349	8.2	32	54	17	2.5	2.5	195	5	3.4
KFJ04	420	8.4	18	62	14	2.0	2.0	198	8	3.5
KFJ08	402	8.6	24	13	25	3.1	3.1	130	4	6.0
KFJ08	562	8.9	24	14	26	3.0	3.0	130	4	5.0

Except for the deep, old saline-type water sampled in the deepermost level in KFJ02, there are no general trends with depth considering pH, electrolytical conductivity or the major-ion chemistry at the Fjällveden site. All other sampled sections indicate groundwaters with varying degrees of mixing between water of different ages. However, as been indicated earlier, most of these sections are not being considered representative for the sampled depth, meaning that the sampled waters originate from sources other than the section of the borehole sampled. In fact, the deepermost level in KFJ04 (at 420 m) initially exhibit major-ion chemistry typical for a old, saline water, which fades as the sampling continues over several days.

Additional results from this site is presented by Wikberg et al. (1987). Measurements in boreholes KFJ02 at depth 468 m, and KFJ07 at depth 722 m, were performed with new and improved sampling equipment. The results from these investigations does not contradict the results from the previous, with a groundwaters of varying ages. The sampled section in KFJ07 is the deepest one sampled at this site, and has similar general chemistry characteristics as the deepermost section in KFJ02, which means a deep, old, relatively saline groundwater. This section shows relatively high chloride contents and low bicarbonate contents. The section at 468 m in KFJ02, on the other hand, shows the opposite for these constituents. This, and other general chemistry parameters, agrees well with the measurements from the KBS-3 investigations in the same borehole.

Redox-sensitive parameters

A summary of some of the redox-sensitive parameters is presented in Table 12. Generally, all samples taken at this site are more or less reducing as indicated by negative Eh-values. There is also a general trend of decreasing Eh-values with depth. An exception is the deepermost section in KFJ0 2 at 506 m, which also is the only section which is considered truly representative for the depth sampled. One can also note that the highest Eh-values in Table 12 are accompanied by high O_2-values, thus indicating contamination from the atmosphere. In general, there is a large variation with time in Eh-values for all sampled sections, as given by results presented by Laurent (1983). There are no apparent trends with depth for any of the other redox parameters.

Redox parameters are especially sensitive to contamination by oxygen during sampling, by high pumping rates and drilling fluid residue. The samples in Table 12 were not filtered immediately after sampling, and this is likely to have yielded erroneously high Fe(III)-values (Nordstrom and Puigdomenech, 1986). Thus, iron can not be expected to fully reflect redox conditions in this case, although the mere presence of Fe(II) indicate reducing conditions. Wikberg et al. (1983) also show that Eh calculations based on the iron system does not explained the measured ones in this case.

Table 12. Redox parameters at Fjällveden, sampled in cored boreholes.

Sampled borehole	Depth m	Eh mV	Fe(II) mg/l	Fe-tot mg/l	S(-II) mg/l	O_2 mg/l	NO_3^--N mg/l	NH_4^+-N mg/l
KFJ02	106	-85	1.0	1.1	0.06	0.05	0.007	0.070
KFJ02	293	-40	5.7	12	0.08	0.20	0.005	0.043
KFJ02	409	-110	6.5	7.0	0.02	0.05	0.008	0.050
KFJ02	506	-20	0.22	0.34	0.01	0.30	0.010	0.039
KFJ04	131	-70	1.1	1.3	0.05	0.04	0.006	0.202
KFJ04	272	-85	8.1	10	0.01	0.04	0.014	0.089
KFJ04	349	-100	1.37	1.4	0.04	0.02	0.008	0.050
KFJ04	420	-160	1.2	1.4	0.13	0.03	0.010	0.039
KFJ08	402	-110	2.2	2.9	0.01	0.02	0.005	0.012
KFJ08	562	-140	2.7	3.2	0.01	0.03	0.007	0.025

Nordstrom and Puigdomenech (1986) also concluded that dissolved sulfide is the dominant redox–determining species in groundwaters from Fjällveden, as well as at several other sites in Sweden, rather than iron. They also point to the possibility of organic carbon contents being important for redox conditions in Swedish groundwaters. Further, they state that measurements of dissolved sulfide by ion–sensitive electrode at Fjällveden are not reliable.

As discussed earlier, to improve sampling and analysis techniques renewed groundwater sampling in Fjällveden were conducted from 1983 to 1985. The new techniques included the mobile field laboratory, described Almén et al. (1986). One of the aims with the new technique was to minimize contamination from the atmosphere. As reported by Wikberg et al. (1987), much more consistent results regarding redox determining parameters was obtained. For example, almost all dissolved iron is Fe(II), being consistent with the low Eh–values measured.

Uranium geochemistry

The measurements of uranium content and the activity ratio $^{234}U/^{238}U$ were performed in two different ways. Some samples were measured by high–resolution alpha spectrometry, while other measurements were performed by delayed neutron activation (DNA). The former method eventually became part of the hydrochemical program.

As can be seen from Table 13, and which also is concluded by Smellie et al. (1985), there is a tendency to find relatively high uranium contents closer to the surface and relatively low concentrations in the deeper sections. This is consistent with more reducing conditions at greater depths.

Environmental isotopes

A summary of some of the analyses of the environmental isotopes from the KBS–3 investigations of the Fjällveden site are presented in Table 14.

The isotope data generally indicate a predominately meteoric origin to the groundwaters. there are no particular trends with depth. However, for the only section which are considered representative in this case, at depth 506 m in KFJ02, all the isotope data is characteristic for a deep, old groundwater. The ^{14}C–data for this section indicates an age of 13 920 years.

Table 13. Uranium geochemistry at Fjällveden.

Sampled borehole	Depth m	U ppb*	U ppb**	$^{234}U/^{238}U$ act. ratio
KFJ02	106	–	0.55	–
KFJ02	293	–	0.24	–
KFJ02	409	0.12	<0.1	2.1
KFJ02	506	–	<0.2	–
KFJ04	131	3.5	3.66	4.1
KFJ04	272	3.0	3.03	2.0
KFJ04	349	–	0.63	–
KFJ04	420	–	<0.2	–
KFJ08	402	0.90	1.10	3.5
KFJ08	562	0.60	0.43	3.6

*Analysis by high resolution alpha spectrometry.
**Analysis by delayed neutron activation (DNA).

Table 14. Environmental isotopes at Fjällveden.

Sampled borehole	Depth m	Tritium TU	^{14}C years	$\delta^{18}O$ ‰ vs SMOW	$\delta^{2}H$ ‰ vs SMOW
KFJ02	106	–	4725	–11.24	–80.5
KFJ02	293	19	10960	–11.31	–
KFJ02	409	19	4235	–11.35	–
KFJ02	506	<3	13920	–14.11	–
KFJ04	131	9	3950	–11.50	–
KFJ04	272	21	3475	–11.57	–82.6
KFJ04	349	12	5535	–11.73	–81.6
KFJ04	420	6	6850	–11.88	–84.7
KFJ08	402	8	3980	–11.21	–79.3
KFJ08	562	10	3975	–11.16	–77.8

7.3 Summary and relevance of results

A total of 4 boreholes and 12 different sections have been sampled, including both the KBS–3 study and later groundwater sampling. Smellie et al. (1985), presented a careful and thorough examination of the 10 sections sampled during the KBS–3 study by considering geological, hydrological and chemical information in combination. Measurements of piezometric pressure along each borehole were used together with hydraulic modeling of the site in order to consider the effect of groundwater flow patterns on the groundwater chemistry. However, the results from the hydrological modelling generally did not agree well with measured piezometric pressures. As discussed in Chapters 5 and 7, this could partly be explained by the lack of consideration of any regional hydrological components. Consequently, results from the hydraulic modelling might not provide significant help in interpreting the hydrochemistry results.

In spite of limited knowledge regarding flow conditions at depth the actual measurements of the piezometric pressures along each borehole can be utilized as an indication of whether water was flowing to or out from the sampled section of the borehole. Using this information, along with consideration of other disturbing factors Smellie et al. (1985) concluded that only one out of ten sampled sections were representative for the depth sampled. Thus, it is difficult to make comments about the groundwater chemistry that are site–specific. To some extent the cause of this is related to the boreholes generally being located in recharge areas, thus with downward gradients along the boreholes.

Drilling and sampling methods used for the main part of the investigations at Fjällveden were relatively "old". New techniques were developed and tested during the later part of the investigations (Wikberg et al., 1985), resulting in additional sampling from two other sections. However, it is not possible to direct compare the different sampling techniques as the latter two sampled section were not identical with any of the sampled sections during the main part of the investigation.

Thus, there is a very limited amount of hydrochemical results that can be considered truly representative for the depth sampled. At least one sample, but at most three, of a total of 12 sampled sections can be considered truly representative for the depth sampled. Measurements of redox potentials are especially uncertain, except for the samples collected with the new equipment. However, all the redox measurements show that the groundwaters are of a reducing character.

Although most samples are not representative for the depth sampled, some general observations regarding chemical composition can be made. The sampled groundwaters indicate a variety of waters with different ages. As so few of the samples can be considered representative for the depth sampled, no significant depth dependence can be noted. However, two samples show that old, relatively saline groundwaters exist at greater depths.

8. ASSESSMENT OF SOLUTE TRANSPORT

8.1 General considerations

No specific models of solute transport at the Fjällveden site exist. The report by Carlsson et al. (1983), however, describes a model of the groundwater system in which both a three-dimensional flow field and groundwater travel times from a repository at the -500 m level are shown. This model of the groundwater system at the site has been discussed in Chapter 6. A groundwater flow field is the essential basis of a groundwater solute transport model, and thus the implications of the existing work for solute transport at the sites may be evaluated. All of the uncertainties that are relevant to the model of the groundwater system, described in Chapter 6, are relevant to the transport as well. These and additional considerations are reviewed here with emphasis on their impact on solute migration. Of greatest interest for transport are typical flow paths through a hypothetical repository located in a bedrock block at the -500 m level which eventually reach either the surface or a conductive fracture zone which quickly leads flow to the surface. The discussion focuses on flow and transport along such paths through the repository as predicted by the existing model of the groundwater system.

Boundary conditions

The external boundaries of the Fjällveden model are placed so as to approximately enclose a three-dimensional block having sides of 2 km with depth of about 1.5 km, which includes the region of the site. A groundwater table with maximum relief of about 25 m is specified as the surface condition, whereas the four near-vertical sides and bottom are closed to flow. Of the four sides, three are positioned along inferred conductive fracture zones, whereas the northwest side is placed below a groundwater table divide. The depth to the bottom of the block was arbitrarily chosen. In model analyses for Fjällveden, no variations were carried out to examine the implications for flow and transport of the location and type of boundary conditions.

The combination of boundary specifications used may cause unnatural conditions of modelled solute transport through the repository level of these sites in two ways, both of which may strongly affect magnitude and direction of flow. First, because all vertical sides are closed, all water moving through the modelled region must enter and exit through the top surface. Second, some of the water entering through the top surface in the model region must reach the bottom of the model region no matter how deep the bottom is, and no matter what the hydraulic conductivity distribution is.

Under natural conditions at Fjällveden, however, different flow fields would occur if water actually flowed across some of the vertical sides. In one situation, waters in the bottom portion of the modelled cube have their recharge area located at considerable distance outside of the field site in the direction of the regional topographic gradient. In this case, waters actually recharging within the model area are limited to fill only the upper portion of the section. In another situation, waters recharging through the upper surface of the model region flow out of the model region through a near-vertical side and discharge to the surface at some considerable distance from the modelled region in a direction down the regional topographic gradient. Furthermore, all combinations of these two flow regimes are possible in reality with waters at various depths having different recharge and discharge areas that may or may not be within the site area.

Finally, the choice of a groundwater divide as a "no-flow" boundary extending to considerable depth in the model is questionable. As the flow field is three-dimensional rather than two-dimensional, the divide may be applied with certainty only to the uppermost groundwater flow cell and not necessarily to a deep regional flow system.

Hydraulic structures

Any uncertainty in location and connectivity of hydraulically conductive structures such as fracture zones leads to mild uncertainty in the calculation of hydraulic potentials in the groundwater model, as discussed in previous sections. Such uncertainty, however, often can lead to extreme differences in details of predicted transport of solutes through the same model. Modelled groundwater heads may be of similar value whether or not fracture zones are distinctly included in a model, or whether their contribution to the local transmissivity is spread homogeneously through the model. This is shown by the parameter variations in Cases 1, 2 and 3 for the Fjällveden site. In contrast, the location and direction of transport paths and fluid velocities along paths are exceptionally sensitive to the particular location and connectivity of conductive structures. This is demonstrated by the Case 3 simulation, which eliminates discrete fracture zones. Thus predicted transport at the site is subject to uncertainty stemming from wrong or missing connections of known structures, and from missing structures such as sub-horizontal conductive zones not discovered at the time of transport modelling.

When conductivity contrasts of two or more orders of magnitude exist between conductive zones/layers and less-conductive bedrock blocks, then the spatial distribution and connectivity of the conductive zones, whether at model boundaries or within model bounds, have a major influence on groundwater flow and solute transport. However, in the model analyses, no variations were carried out to evaluate the implications for flow and transport of uncertainty in existence, location, and connectivity of conductive structures.

Hydraulic and transport parameter values

Knowledge of the spatial distribution of hydraulic conductivity is of direct importance to calculation of volumetric fluid flux (volume of fluid per cross-sectional area of rock per year) which is required to determine possible radionuclide source rates exiting the repository, as well as to determine the longevity of engineered barriers. Two variations of hydraulic conductivity distributions were tested in the Fjällveden model. These consisted of mildly different depth-dependencies of hydraulic conductivity as well as mild anisotropy (ten times or less differences among principal values). Model results for transport through the site (flow direction and travel times), show that such parameter variations have limited effect on flow behavior. Rather, geometry and connectivity of conductive structures, as discussed above, may be the most important control on groundwater flow and transport to be studied by variations.

Knowledge of both hydraulic conductivity and effective porosity for flow ("kinematic porosity") is important to determination of actual fluid velocity through a repository region. The effective 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. In the model analysis, the effective porosity was held fixed at a value of 10^{-4}. While this parameter was not varied in the simulations, it is merely a scaling value on fluid velocities and travel time, and the effect of ten-times-higher effective porosity on transport is simply a ten-times longer travel time.

Dispersivities and sorption coefficients were not treated in the site model as these are parameters only of true solute transport models and not of groundwater flow models. Neither of these parameters have been measured at the site. Measurements in laboratory of porosity and diffusivities on rock samples are reported by Skagius (1986).

8.2 Transport Calculations

Groundwater flow fields showing fluid velocity vectors are presented for various cross–sections through the Fjällveden model block for each of three variations. All three have decreasing conductivity with depth. Two have isotropic conductivity, one of these without fracture zones (Case 3) and one with zones (Case 1). The third variation has both fracture zones and anisotropic conductivity in the bedrock blocks between fractures (Case 2). The transport velocities at the –500 m level are quite similar in all three cases as are volumetric fluid fluxes. Patterns are similar and actual values differ by less than one order of magnitude at most points.

Travel times for various paths to the surface, beginning at the –500 m level, are reported for cases Case 1 and Case 3 (ie. with and without fracture zones). The travel times for Case 1 are from a few hundred years to a few ten–thousands of years. Travel times for the variation without fracture zones are longer ranging from a few thousand years to a few hundred–thousands of years. This demonstrates the importance of conductive structures to transport paths from a hypothetical repository at the Fjällveden site.

8.3 Implications of existing information for solute transport

The groundwater system model analyses of the Fjällveden site 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 –500 m. Under the conditions studied, travel times are predicted within large ranges, from as little as few hundred to as much as a few ten thousands of years. Travel times and paths are found to be most dependent on the existence of conductive fracture zones, but tests varying structure and connectivity were not carried out. Rather variations concerned relatively minor changes to assumed hydraulic conductivities, resulting in relatively unimportant differences in predicted flow fields and groundwater behavior.

Boundary conditions are equally important to the transport predicted by the model analysis, but these were not varied either to test their impact. In fact, it is entirely possible and even likely that the –500 m level 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, a possibility that is excluded by the choice of closed vertical boundaries in all the variations carried out.

Considerations towards improving the transport predictions of the Fjällveden 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 sub–horizontal zones that do no outcrop.

9. ROCK MECHANICAL CONDITIONS

None of the boreholes at the Fjällveden study site have been tested to determine the stress field in the area. Neither has the rock in the area been tested for its mechanical properties. The rock mechanical investigations conducted at the Fjällveden study site are limited to laboratory determination of the thermal properties on core samples.

9.1 Thermal properties of the bedrock

The properties thermal conductivity, diffusivity, heat capacity per unit volume and density were determined on core samples from borehole KFJ01 using the transient hot strip method (Gustafsson et al., 1979). The density of the samples were determined with the standard method of weighing the samples in air and in water. The results are presented in Table 14 below.

The thermal conductivity varies between 3.13 – 4.55 W/(m·K) (Ahlbom and Karawacki, 1983) reflecting the inhomogeneity of the sedimentary gneiss at the site. The thermal properties for Fjällveden rock are normal to high as judged by the compilation on crystalline rocks by Sundberg (1988).

Table 14. Thermal properties measured on core samples from borehole KFJ01, Fjällveden. (Ahlbom and Karawacki, 1983).

Depth m	Thermal conductivity W/(m·K)	Thermal diffusivity m^2/s	Heat capacity J/kg·K	Density kg/m^3
300	3.58	$1.60x10^{-6}$	830	2700
400	3.48	$1.43x10^{-6}$	890	2720
450	3.42	$1.55x10^{-6}$	900	2610
460	3.33	$1.33x10^{-6}$	930	2690
470	3.13	$1.16x10^{-6}$	920	2940
480	3.41	$1.62x10^{-6}$	810	2610
490	4.55	$1.85x10^{-6}$	930	2640
500	4.06	$1.65x10^{-6}$	900	2750
510	4.24	$2.05x10^{-6}$	780	2660
520	4.23	$1.68x10^{-6}$	930	2710
530	3.72	$1.61x10^{-6}$	860	2700
540	3.66	$1.79x10^{-6}$	760	2700
550	3.85	$1.66x10^{-6}$	880	2650
600	3.94	$1.52x10^{-6}$	960	2720
700	4.05	$1.63x10^{-6}$	920	2720
Mean:	3.78	$1.62x10^{-6}$	880	2700

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APPENDIX A

ACTIVITIES IN THE 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 A1. Intersections of fracture zones with boreholes are summarized in Table 3 and in Appendix B, Figures B1–B3. Location of interpreted fracture zones are presented in Appendix C, Figure C1.

The present (Oct–91) availability of the cored boreholes have been studied by brief visits to each borehole. These inspections showed that all boreholes at Fjällveden are severely damaged by human action. The borehole locks are broken and the boreholes are filled with debris of different kinds. Problems with borehole stability or instrument blockage during the KBS–3 investigations are described in a report by Persson (1985). The obstacles reported by him are described in this Appendix.

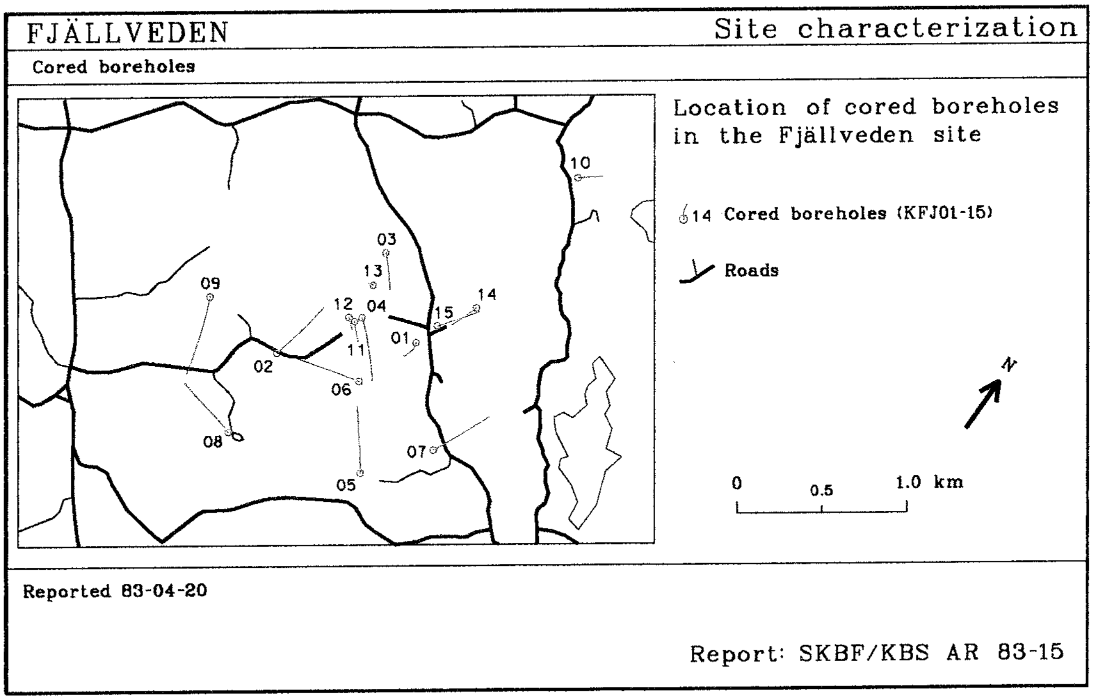


Figure A1. Locations of cored boreholes at Fjällveden study site.

Borehole KFJ01

Borehole KFJ01 (Figure A2) is vertical and 711 m in length. The borehole was drilled at an early stage of the site investigation programme to confirm favorable conditions at depth as indicated by the reconnaissance surveys. Borehole coordinates and activities performed in the borehole are presented in Figure A2. Generalized results concerning rock types, fracturing and hydraulically conductive sections are presented in Appendix B, Figure B1. Although, the borehole in general display a low fracture frequency the borehole is interpreted to penetrate Zone 6 between 674–676 m borehole length. The estimated thickness of the zone is 0.2 m. Mean fracture frequency of the borehole is 2.5 fr/m.

Borehole availability: A multi-hose umbilical cable blocks the borehole over its entire length.

Borehole KFJ02

Borehole KFJ02 (Figure A3) is 701 m in length and ends at a depth of 575 m. It is drilled inclined 60° to the horizontal. It is directed to intersect Zone 1, which is one of the most topographically well expressed fracture zones. Zone 1 is interpreted to be penetrated by the borehole between 340–360 m borehole length. The borehole is also interpreted to intersect Zone 4 at borehole length 596–600 m. In spite of the two fracture zones the mean fracture frequency is generally low, 2.6 fr/m. Generalized results are presented in Appendix B, Figure B1.

Borehole availability: During the preparations in 1984 for groundwater sampling a blockage in the borehole was found at 595 m. The borehole was later filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ03

Borehole KFJ03 (Figure A4) has a length of 426 m in length and drilled inclined 60°, reaching a depth of 370 m. The borehole is located in the central part of the site with the objective to investigate the cause of strong magnetic and electrical anomalies in this area. Another objective was to investigate Zone 3. The cores contains several small sections with pyrite, graphite and pyrrhotite which are believed to cause the geophysical anomalies. The borehole is interpreted to intersect Zones 3 at 150–175 m borehole length and Zone 5 at 336–340 m. Also in the surrounding bedrock the degree of fracturing is higher than normal for Fjällveden. Mean fracture frequency for the borehole is 3.7 fr/m. Generalized results are presented in Appendix B, Figure B1.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ04

Borehole KFJ04 (Figure A5) has a length of 701 m and drilled inclined 60°, reaching a depth of 585 m. The borehole was positioned to investigate an area with peat bogs where fracture zones were suspected. The fracture frequency is high in the cores down to 200 m borehole length. This section contains two fracture zones, Zone 5 (intersected around 62 m) and Zone 3 (140–192 m). The fracture frequency is low below 200 m. Mean fracture frequency for the whole borehole is 3.1 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B1.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ05

Borehole KFJ05 (Figure A6) is inclined, 60°, with a length of 700 m and a depth of 570 m. The borehole is positioned to penetrate and characterize fracture zones interpreted as lineaments on aerial photos and from ground geophysical measurements. The borehole is interpreted to penetrate Zone 10 at 96–102 m and Zone 9 at 173–185 m borehole length. Apart from these zones, the degree of fracturing is in general low for the borehole with a mean fracture frequency of 2.1 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B1.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ06

Borehole KFJ06 (Figure A7) has a length of 703 m. It is drilled inclined 60°, reaching a depth of 590 m. The objective was to investigate a peat covered area in the central part of the site and also to correlate the results from the borehole investigation with results from the seismic survey. The borehole is interpreted to intersect Zone 3 between 37–59 m and Zone 11 at 245–256 m. Due to borehole collapse in this section the borehole was cased down to 260 m depth, before the drilling could be continued. The borehole also intersects Zone 1 and 5 at borehole lengths of 479–486 m and 610–611 m, respectively. Mean fracture frequency for the whole borehole is 2.7 fr/m. Generalized results are presented in Appendix B, Figure B2.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ07

Borehole KFJ07 (Figure A8) has a length of 760 m. It is drilled inclined 60°, reaching a depth of 647 m. The objective was to increase the investigated area to the east and to study a possible fracture zone (lineament). The borehole intersects a strongly fractured zone at 53–63 m borehole length. Also at 87 m and 102 m borehole length occurs fractured sections. These sections are collectively interpreted as parts of Zone 10. These fractured sections made it necessary to case the borehole down to 105 m borehole length. Another fracture zone is encountered towards the lower end of the borehole. This is Zone 9 which intersects the borehole at 685–697 m and 725–731 m. Mean fracture frequency for the borehole is 2.5 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B2.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ08

Borehole KFJ08 (Figure A9) is 732 m in length and is drilled inclined 62°, reaching a depth of 615 m. The borehole is located in the southwestern part of the site with the objective to increase the investigated area. The borehole is generally low fractured and no fracture zone was found. Mean fracture frequency of the cores from this borehole is 1.9 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B2.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ09

Borehole KFJ09 (Figure A10) is drilled 50° to the horizontal and has a length of 700 m, corresponding to 520 m depth. The objective was to increase the investigated rock volume and to study the character of a NE oriented lineament. This borehole penetrates several fractured sections of which one at 90–130 is interpreted to belong to Zone 15. Another fractured section between 424–433 m borehole length is assumed to be a part of Zone 8. Mean fracture frequency is 3.3 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B2.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ10

Borehole KFJ10 (Figure A11) is 199 m in length and is drilled inclined 45°, reaching a depth of 139 m. The borehole is positioned in the northern part of the site to intersect and characterize the eastern regional fracture zone. The first strongly fractured rock is encountered after 70 m. From that borehole length and down to 163 m the bedrock is strongly tectonized, fractured and clay altered. Mean fracture frequency in the cores from this borehole is 15.5 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B2.

Borehole availability: The borehole is filled by debris. Also the upper casing has been removed from the borehole. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ11

Borehole KFJ11 (Figure A12) is inclined 60° and has a length of 251 m and a depth of 211 m. This borehole was drilled to investigate the continuation and dip of fracture zone 5. Between 64–66 m Zone 5 was encountered. In this section there are three 0.1 m wide core losses. Towards the end of the borehole, between 225–250 m, another fractured section was found. This section is interpreted to be a part of Zone 3. Mean fracture frequency is 3.1 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B3.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ12

Borehole KFJ12 (Figure A13) is drilled inclined 60° and is 150 m in length, corresponding to a depth of 130 m. Similar to borehole KFJ11 the objective was characterize Zone 5, including its dip. The borehole was interpreted to intersect Zone 5 between 99–101 m. Mean fracture frequency of the cores from this borehole is 6.5 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B3.

Borehole availability: The borehole is filled by debris to the borehole head. Until it is cleared the borehole is not available for complementary studies.

Borehole KFJ13

This borehole (Figure A14) is 151 in length and drilled inclined 80°, reaching a depth of 146 m. The borehole is located in the central part of the site to investigate the cause of a geophysical anomaly. Between 0–58 m percussion drilling was used. However, technical difficulties at this depth made it necessary to change drilling method to cored drilling. The sedimentary gneiss in this borehole contains pyrite, pyrrohtite, chalcopyrit and bornite, all sulphide minerals which very well could explain the geophysical anomaly. Although these minerals occur frequently in the cores from this borehole, the total amounts are small. No fracture zone was encountered. Mean fracture frequency of the cores from this borehole is 3.1 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B3.

Borehole availability: The borehole could not be located during the inspection of Oct–91. The casing has probably been removed.

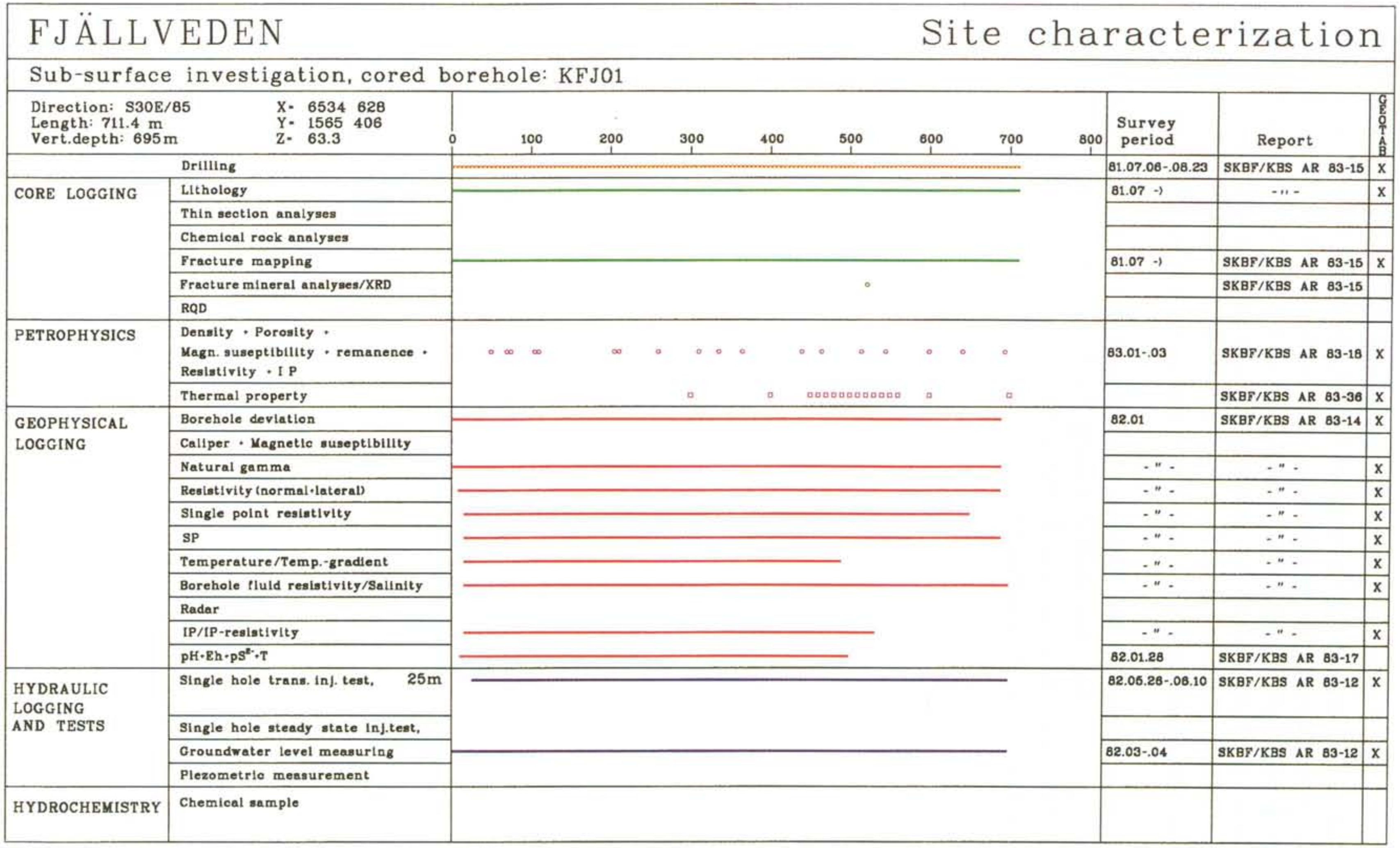
Borehole KFJ14

This borehole (Figure A15) is 350 in length and drilled inclined 60°, reaching a depth of 298 m. This borehole was drilled to investigate the character and dip of fracture zone 2. Although the cores are relatively highly fractured from the surface and down to 160 m, the Zone 2 is interpreted to occur between 115–134 m. Mean fracture frequency of the cores from this borehole is 4.3 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B3. Borehole availability: unknown.

Borehole KFJ15

This borehole (Figure A16) is 355 in length and drilled inclined 50°, reaching a depth of 275 m. Similar to borehole KFJ14 this borehole was drilled to characterize Zone 2. The borehole is rather highly fractured with several small sections with crushed bedrock. Zone 2 is interpreted to occur at 304–321 m borehole length. In this section there also occur a core loss of 0.2 m. Mean fracture frequency of the cores from this borehole is 4.3 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B3.

Borehole availability: The borehole was blocked due to borehole collapse shortly after the hole was drilled. During the inspection of Oct–91 the borehole could not be located. Probably the casing has been removed during construction work for a turnaround.



FJÄLLVEDEN

Site characterization

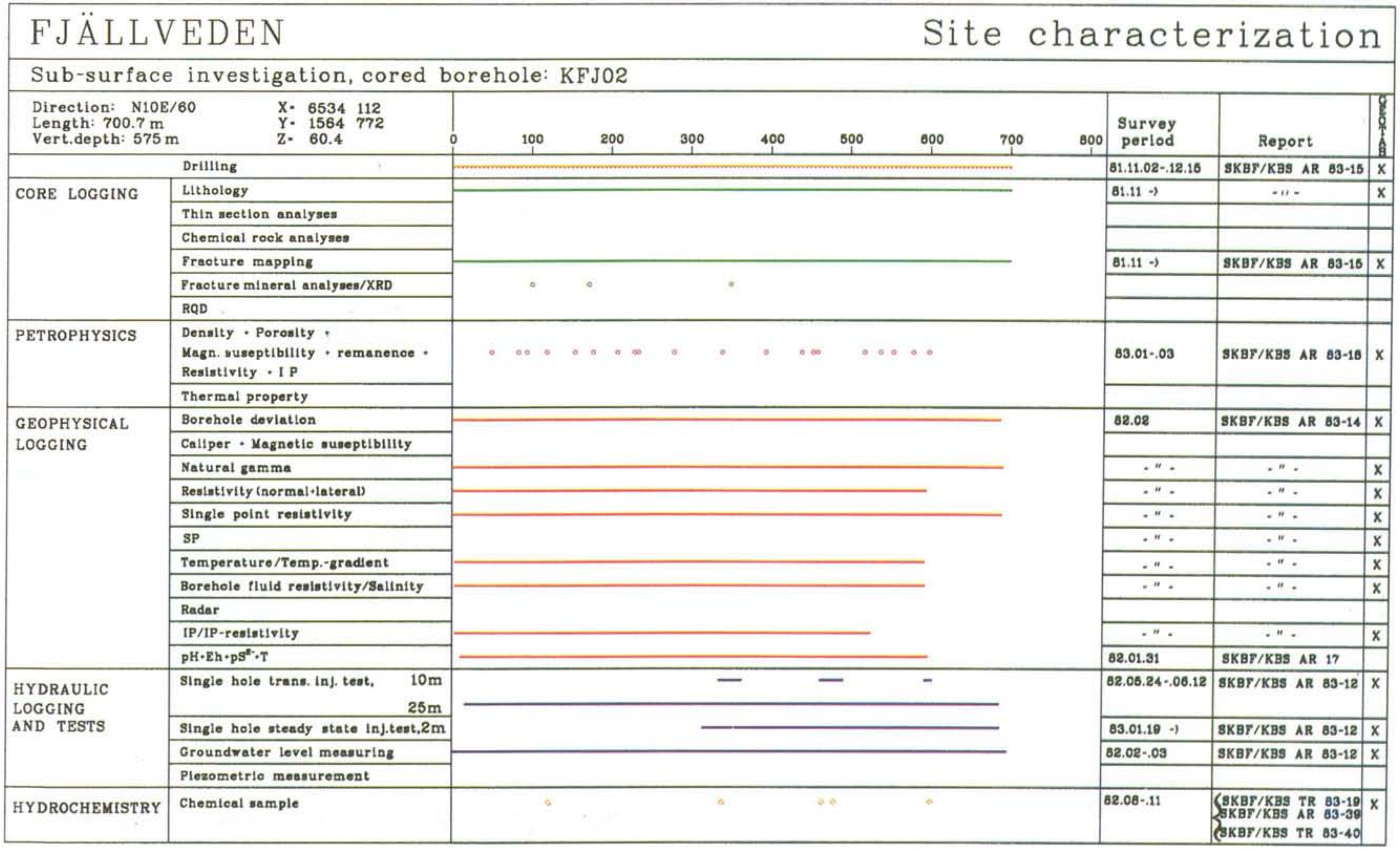
Sub-surface investigation, cored borehole: KFJ01

Direction: S30E/85
Length: 711.4 m
Vert.depth: 695 m

X- 6534 628
Y- 1565 406
Z- 63.3

		Survey period	Report	GEOTAB
	Drilling	81.07.06-.08.23	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	81.07 -)	- " -	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping	81.07 -)	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD		SKBF/KBS AR 83-15	
	RQD			
PETROPHYSICS	Density · Porosity · Magn. susceptibility · remanence · Resistivity · I P	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property		SKBF/KBS AR 83-36	X
GEOPHYSICAL LOGGING	Borehole deviation	82.01	SKBF/KBS AR 83-14	X
	Caliper · Magnetic susceptibility			
	Natural gamma	- " -	- " -	X
	Resistivity (normal·lateral)	- " -	- " -	X
	Single point resistivity	- " -	- " -	X
	SP	- " -	- " -	X
	Temperature/Temp.-gradient	- " -	- " -	X
	Borehole fluid resistivity/Salinity	- " -	- " -	X
	Radar			
	IP/IP-resistivity	- " -	- " -	X
	pH·Eh·pS^{2-}·T	82.01.28	SKBF/KBS AR 83-17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 25m	82.05.26-.06.10	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.03-.04	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A2. Activities in borehole KFJ01.



FJÄLLVEDEN — Site characterization

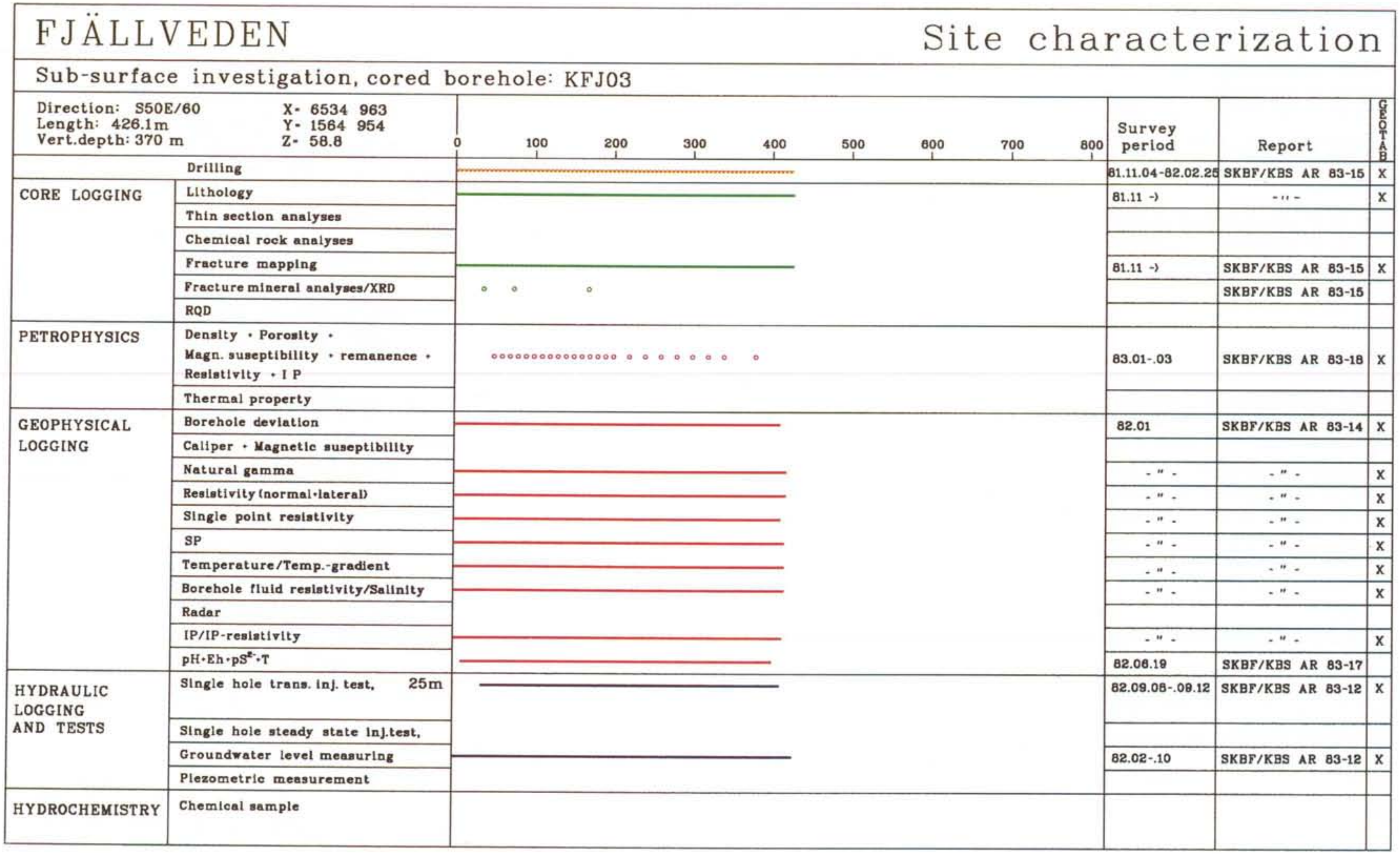
Sub-surface investigation, cored borehole: KFJ02

Direction: N10E/60
Length: 700.7 m
Vert.depth: 575 m

X- 6534 112
Y- 1564 772
Z- 60.4

		Survey period	Report	GEOTAB
	Drilling	81.11.02-.12.15	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	81.11 -)	-〃-	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping	81.11 -)	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			
	RQD			
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P	83.01-.03	SKBF/KBS AR 83-16	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.02	SKBF/KBS AR 83-14	X
	Caliper · Magnetic suseptibility			
	Natural gamma	-〃-	-〃-	X
	Resistivity (normal·lateral)	-〃-	-〃-	X
	Single point resistivity	-〃-	-〃-	X
	SP	-〃-	-〃-	X
	Temperature/Temp.-gradient	-〃-	-〃-	X
	Borehole fluid resistivity/Salinity	-〃-	-〃-	X
	Radar			
	IP/IP-resistivity	-〃-	-〃-	X
	pH·Eh·pS^{2-}·T	82.01.31	SKBF/KBS AR 17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m	82.05.24-.06.12	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,2m	83.01.19 -)	SKBF/KBS AR 83-12	X
	Groundwater level measuring	82.02-.03	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample	82.08-.11	SKBF/KBS TR 83-19 SKBF/KBS AR 83-39 SKBF/KBS TR 83-40	X

Figure A3. Activities in borehole KFJ02.



FJÄLLVEDEN

Site characterization

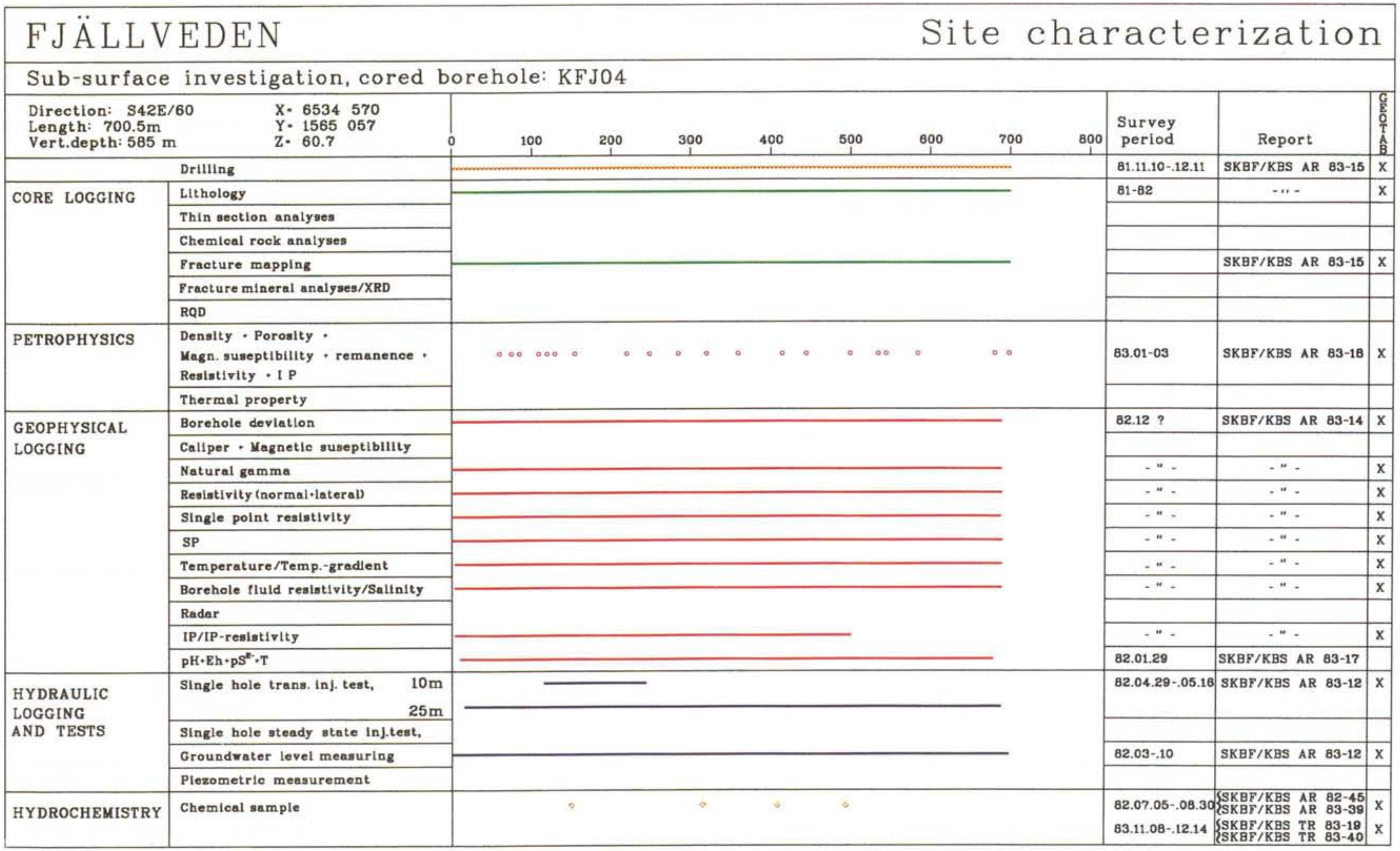
Sub-surface investigation, cored borehole: KFJ03

Direction: S50E/60
Length: 426.1m
Vert.depth: 370 m

X- 6534 963
Y- 1564 954
Z- 58.8

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		81.11.04-82.02.25	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology		81.11 -)	- " -	X
	Thin section analyses				
	Chemical rock analyses				
	Fracture mapping		81.11 -)	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			SKBF/KBS AR 83-15	
	RQD				
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P		83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property				
GEOPHYSICAL LOGGING	Borehole deviation		82.01	SKBF/KBS AR 83-14	X
	Caliper · Magnetic suseptibility				
	Natural gamma		- " -	- " -	X
	Resistivity (normal-lateral)		- " -	- " -	X
	Single point resistivity		- " -	- " -	X
	SP		- " -	- " -	X
	Temperature/Temp.-gradient		- " -	- " -	X
	Borehole fluid resistivity/Salinity		- " -	- " -	X
	Radar				
	IP/IP-resistivity		- " -	- " -	X
	pH-Eh-pS^{2-}-T		82.06.19	SKBF/KBS AR 83-17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 25m		82.09.06-.09.12	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,				
	Groundwater level measuring		82.02-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement				
HYDROCHEMISTRY	Chemical sample				

Figure A4. Activities in borehole KFJ03.



FJÄLLVEDEN

Site characterization

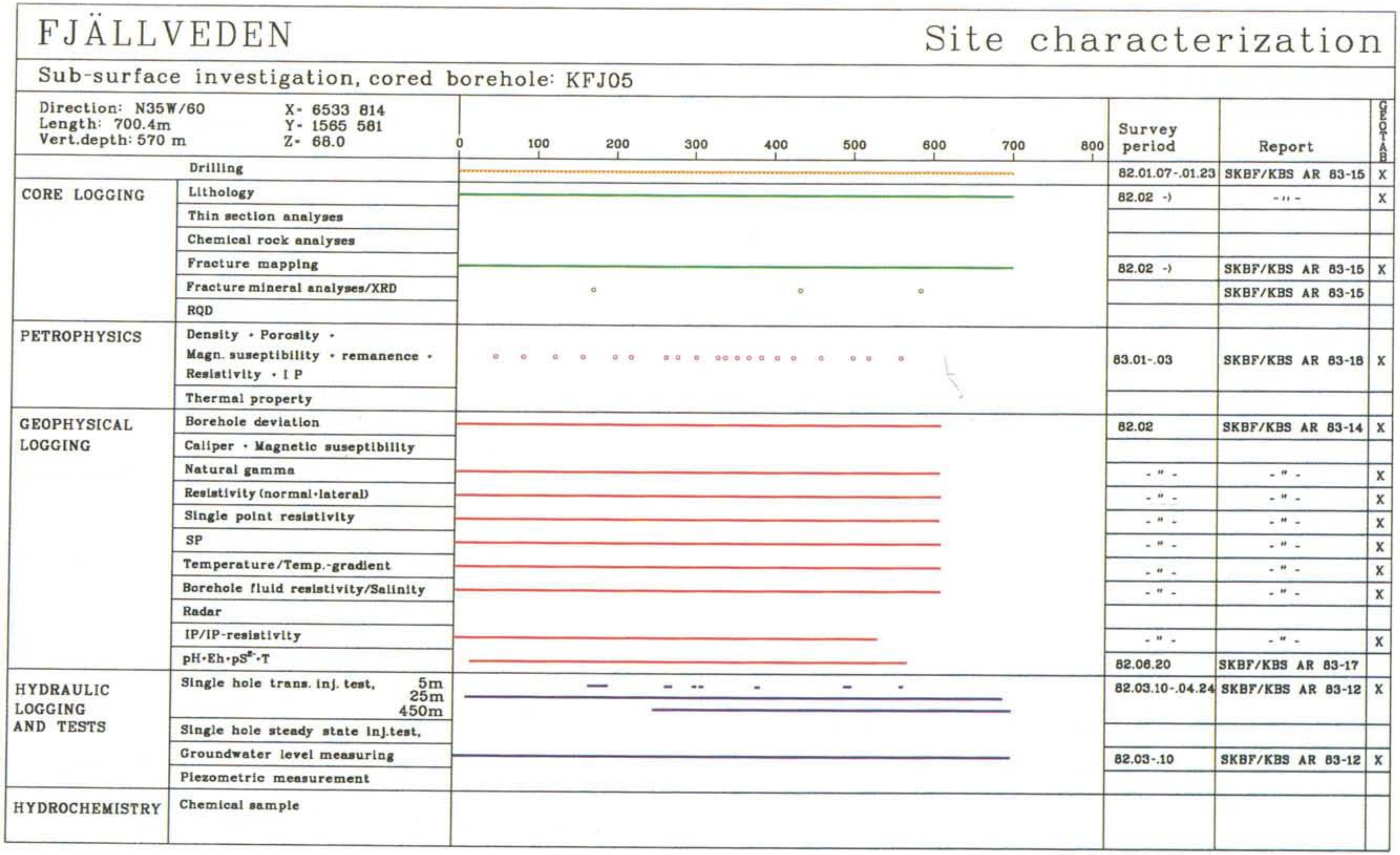
Sub-surface investigation, cored borehole: KFJ04

Direction: S42E/60
Length: 700.5m
Vert.depth: 585 m

X- 6534 570
Y- 1565 057
Z- 60.7

		Survey period	Report	GEOTAB
	Drilling	81.11.10-.12.11	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	81-82	-"-	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			
	RQD			
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P	83.01-03	SKBF/KBS AR 83-18	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.12 ?	SKBF/KBS AR 83-14	X
	Caliper · Magnetic suseptibility			
	Natural gamma	-"-	-"-	X
	Resistivity (normal·lateral)	-"-	-"-	X
	Single point resistivity	-"-	-"-	X
	SP	-"-	-"-	X
	Temperature/Temp.-gradient	-"-	-"-	X
	Borehole fluid resistivity/Salinity	-"-	-"-	X
	Radar			
	IP/IP-resistivity	-"-	-"-	X
	pH·Eh·pS^{2-}·T	82.01.29	SKBF/KBS AR 83-17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m	82.04.29-.05.16	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.03-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample	82.07.05-.08.30 83.11.08-.12.14	{SKBF/KBS AR 82-45 SKBF/KBS AR 83-39 {SKBF/KBS TR 83-19 SKBF/KBS TR 83-40	X X

Figure A5. Activities in borehole KFJ04.



FJÄLLVEDEN

Site characterization

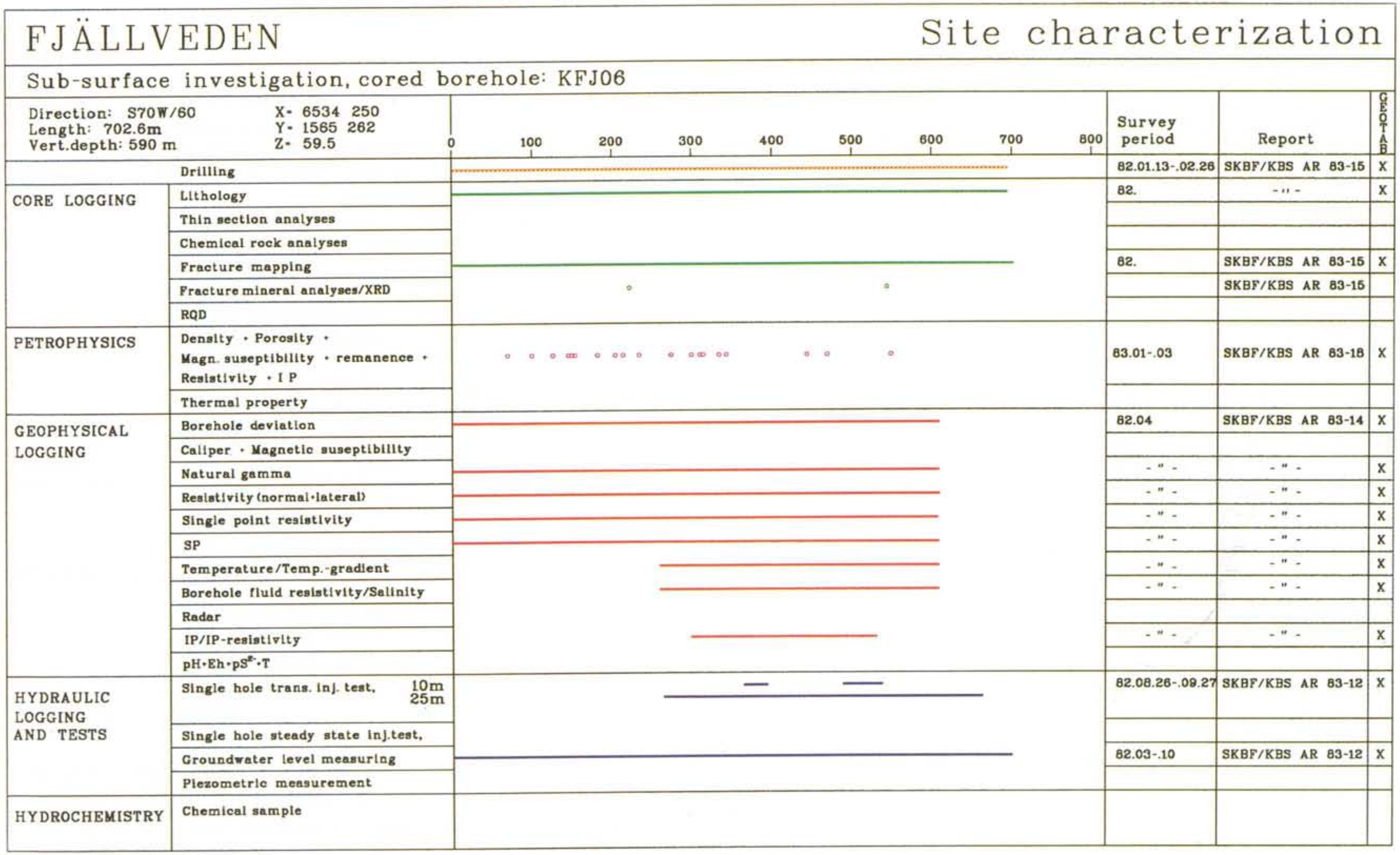
Sub-surface investigation, cored borehole: KFJ05

Direction: N35W/60
Length: 700.4m
Vert.depth: 570 m

X- 6533 814
Y- 1565 581
Z- 68.0

		Survey period	Report	GEOTAB
	Drilling	82.01.07-.01.23	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	82.02 -)	-"-	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping	82.02 -)	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD		SKBF/KBS AR 83-15	
	RQD			
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.02	SKBF/KBS AR 83-14	X
	Caliper · Magnetic suseptibility			
	Natural gamma	-"-	-"-	X
	Resistivity (normal·lateral)	-"-	-"-	X
	Single point resistivity	-"-	-"-	X
	SP	-"-	-"-	X
	Temperature/Temp.-gradient	-"-	-"-	X
	Borehole fluid resistivity/Salinity	-"-	-"-	X
	Radar			
	IP/IP-resistivity	-"-	-"-	X
	pH·Eh·pS^{2-}·T	82.06.20	SKBF/KBS AR 83-17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 5m 25m 450m	82.03.10-.04.24	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.03-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A6. Activities in borehole KFJ05.



FJÄLLVEDEN Site characterization

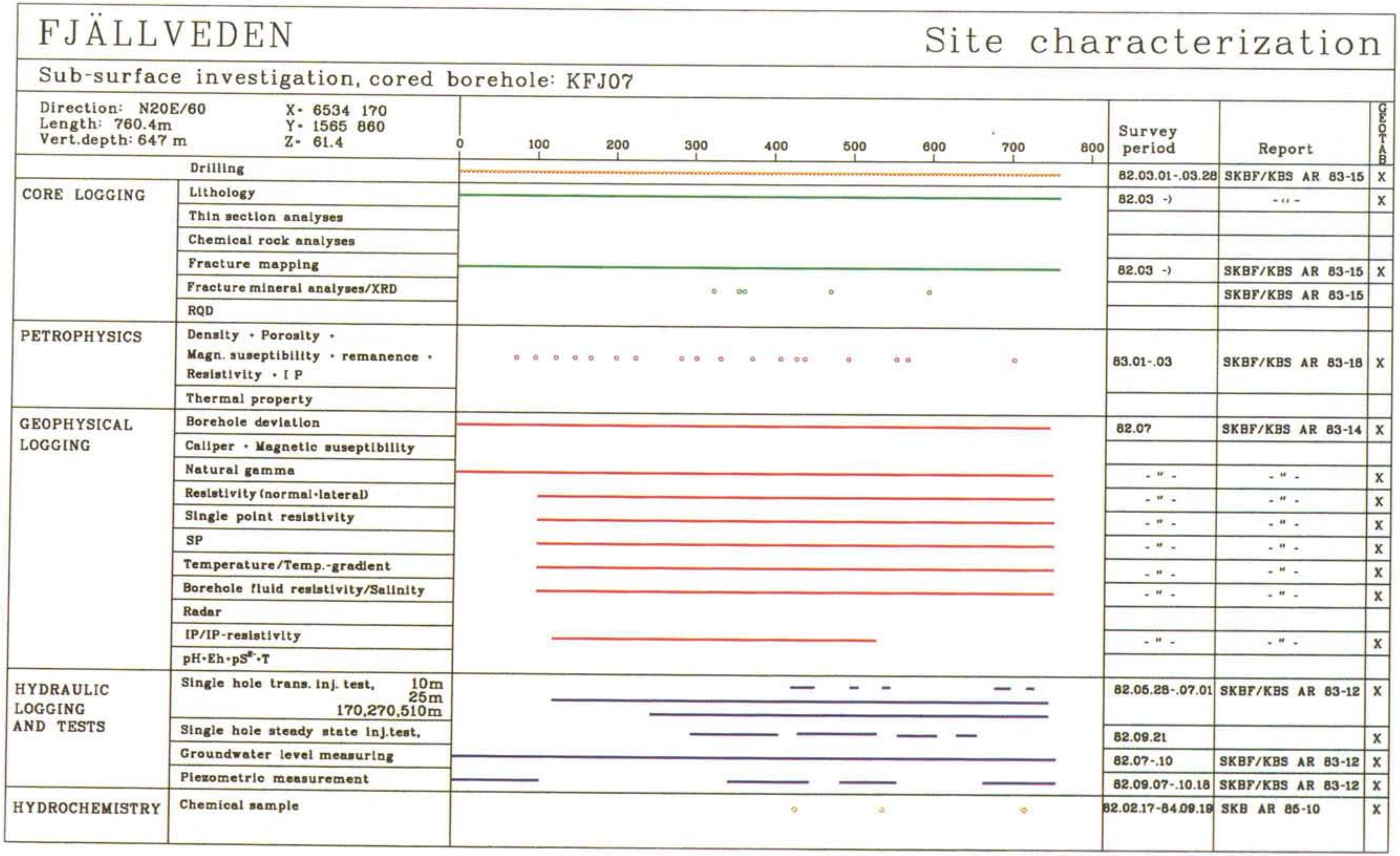
Sub-surface investigation, cored borehole: KFJ06

Direction: S70W/60
Length: 702.6m
Vert.depth: 590 m

X- 6534 250
Y- 1565 262
Z- 59.5

		Survey period	Report	GEOTAB
	Drilling	82.01.13-.02.26	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	82.	- " -	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping	82.	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD		SKBF/KBS AR 83-15	
	RQD			
PETROPHYSICS	Density • Porosity • Magn. suseptibility • remanence • Resistivity • I P	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.04	SKBF/KBS AR 83-14	X
	Caliper • Magnetic suseptibility			
	Natural gamma	- " -	- " -	X
	Resistivity (normal•lateral)	- " -	- " -	X
	Single point resistivity	- " -	- " -	X
	SP	- " -	- " -	X
	Temperature/Temp.-gradient	- " -	- " -	X
	Borehole fluid resistivity/Salinity	- " -	- " -	X
	Radar			
	IP/IP-resistivity	- " -	- " -	X
	pH•Eh•pS^{2-}•T			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m	82.08.26-.09.27	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.03-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A7. Activities in borehole KFJ06.



FJÄLLVEDEN

Site characterization

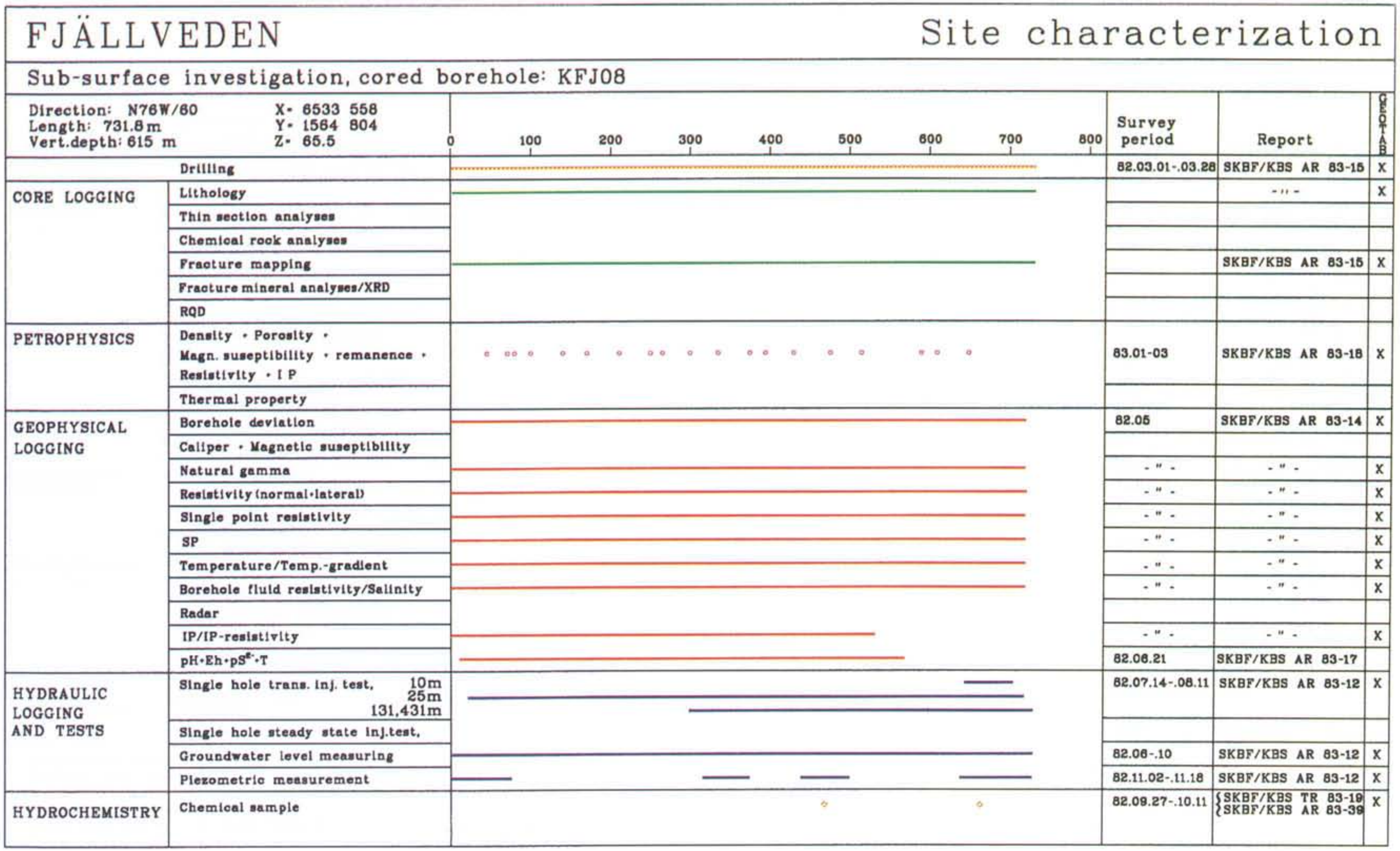
Sub-surface investigation, cored borehole: KFJ07

Direction: N20E/60
Length: 760.4m
Vert.depth: 647 m

X- 6534 170
Y- 1565 860
Z- 61.4

		Survey period	Report	GEOTAB
	Drilling	82.03.01-.03.28	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	82.03 -)	- " -	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping	82.03 -)	SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD		SKBF/KBS AR 83-15	
	RQD			
PETROPHYSICS	Density • Porosity • Magn. suseptibility • remanence • Resistivity • I P	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.07	SKBF/KBS AR 83-14	X
	Caliper • Magnetic suseptibility			
	Natural gamma	- " -	- " -	X
	Resistivity (normal-lateral)	- " -	- " -	X
	Single point resistivity	- " -	- " -	X
	SP	- " -	- " -	X
	Temperature/Temp.-gradient	- " -	- " -	X
	Borehole fluid resistivity/Salinity	- " -	- " -	X
	Radar			
	IP/IP-resistivity	- " -	- " -	X
	pH•Eh•pS^{2-}•T			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m 170,270,510m	82.05.28-.07.01	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,	82.09.21		X
	Groundwater level measuring	82.07-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement	82.09.07-.10.18	SKBF/KBS AR 83-12	X
HYDROCHEMISTRY	Chemical sample	82.02.17-84.09.19	SKB AR 85-10	X

Figure A8. Activities in borehole KFJ07.



FJÄLLVEDEN Site characterization

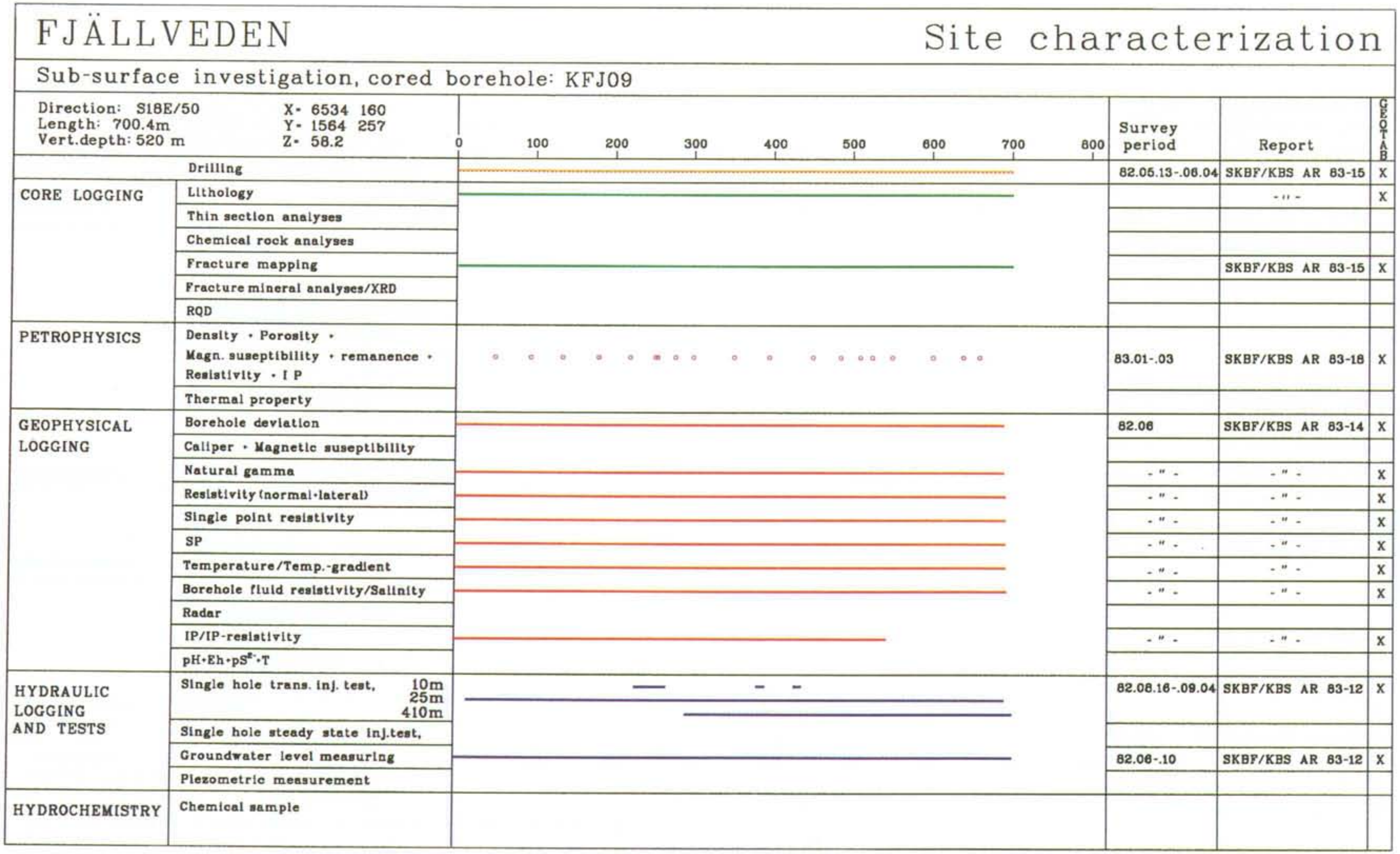
Sub-surface investigation, cored borehole: KFJ08

Direction: N76W/60
Length: 731.8 m
Vert.depth: 615 m

X- 6533 558
Y- 1564 804
Z- 65.5

		Survey period	Report	GEOTAB
	Drilling	82.03.01-.03.28	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology		- " -	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			
	RQD			
PETROPHYSICS	Density · Porosity · Magn. susceptibility · remanence · Resistivity · I P	83.01-03	SKBF/KBS AR 83-16	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.05	SKBF/KBS AR 83-14	X
	Caliper · Magnetic susceptibility			
	Natural gamma	- " -	- " -	X
	Resistivity (normal·lateral)	- " -	- " -	X
	Single point resistivity	- " -	- " -	X
	SP	- " -	- " -	X
	Temperature/Temp.-gradient	- " -	- " -	X
	Borehole fluid resistivity/Salinity	- " -	- " -	X
	Radar			
	IP/IP-resistivity	- " -	- " -	X
	pH·Eh·pS^{2-}·T	82.06.21	SKBF/KBS AR 83-17	
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m 131,431m	82.07.14-.08.11	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.06-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement	82.11.02-.11.18	SKBF/KBS AR 83-12	X
HYDROCHEMISTRY	Chemical sample	82.09.27-.10.11	SKBF/KBS TR 83-19 SKBF/KBS AR 83-39	X

Figure A9. Activities in borehole KFJ08.



FJÄLLVEDEN

Site characterization

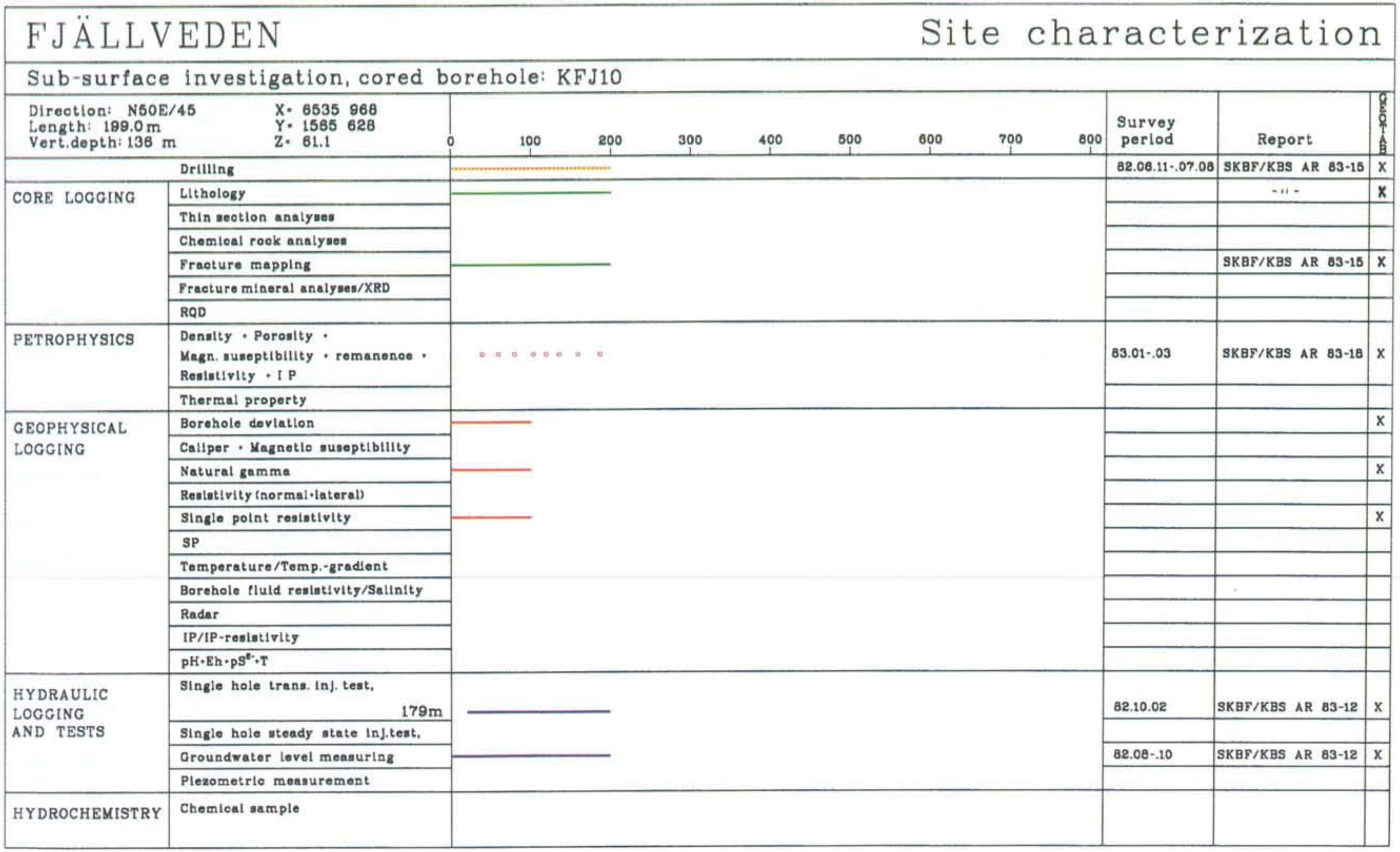
Sub-surface investigation, cored borehole: KFJ09

Direction: S18E/50
Length: 700.4m
Vert.depth: 520 m

X- 6534 160
Y- 1564 257
Z- 58.2

		Survey period	Report	GEOTAB
	Drilling	82.05.13-.06.04	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology		- " -	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			
	RQD			
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.06	SKBF/KBS AR 83-14	X
	Caliper · Magnetic suseptibility			
	Natural gamma	- " -	- " -	X
	Resistivity (normal-lateral)	- " -	- " -	X
	Single point resistivity	- " -	- " -	X
	SP	- " -	- " -	X
	Temperature/Temp.-gradient	- " -	- " -	X
	Borehole fluid resistivity/Salinity	- " -	- " -	X
	Radar			
	IP/IP-resistivity	- " -	- " -	X
	pH·Eh·pS^{2-}·T			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 10m 25m 410m	82.08.16-.09.04	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.06-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A10. Activities in borehole KFJ09.



FJÄLLVEDEN Site characterization

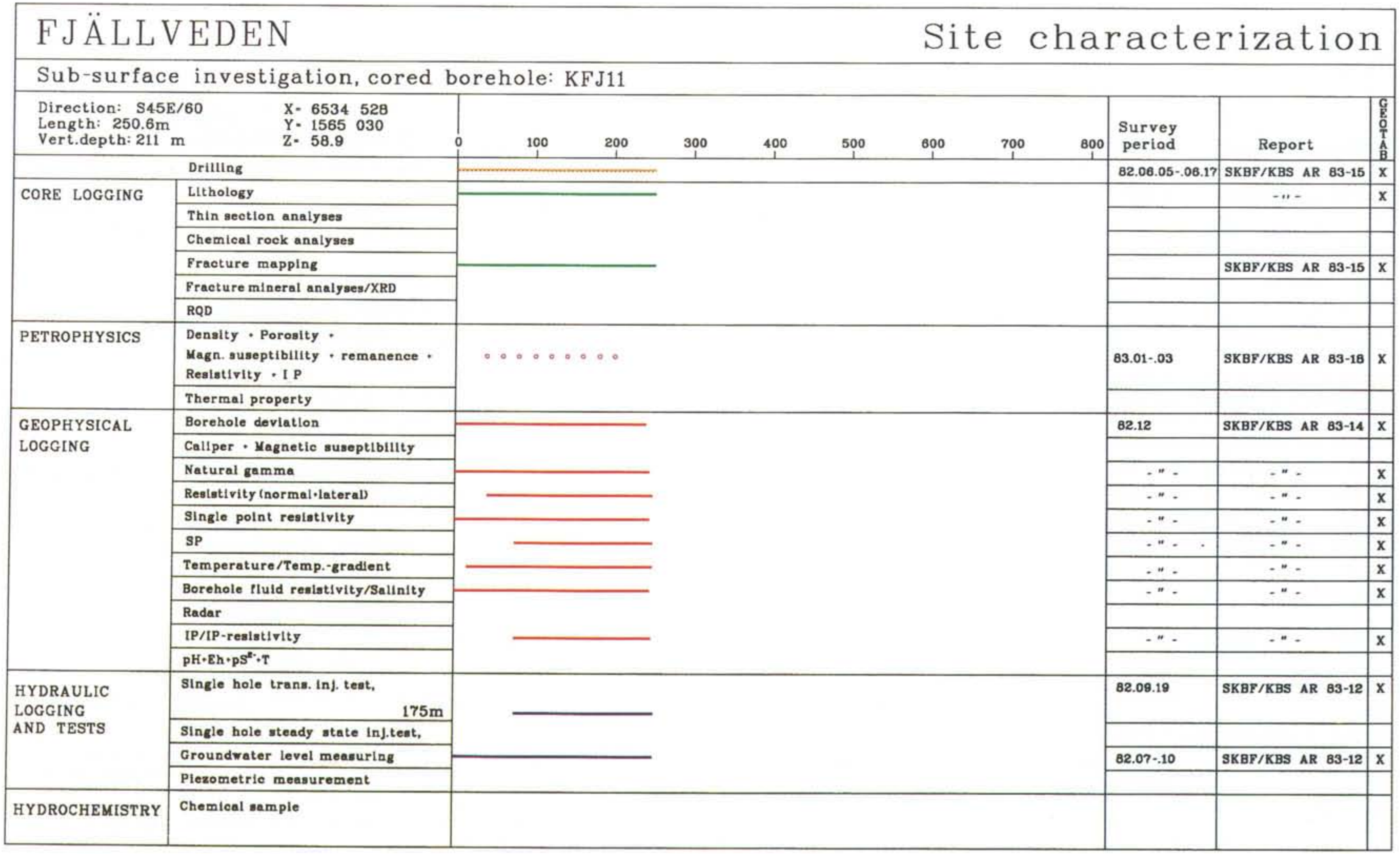
Sub-surface investigation, cored borehole: KFJ10

Direction: N50E/45
Length: 199.0 m
Vert.depth: 136 m

X= 6535 968
Y= 1565 628
Z= 61.1

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling	—	82.06.11-.07.08	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology	—		-"-	X
	Thin section analyses				
	Chemical rock analyses				
	Fracture mapping	—		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD				
	RQD				
PETROPHYSICS	Density • Porosity • Magn. suseptibility • remanence • Resistivity • I P	○ ○ ○ ○ ○ ○ ○ ○	83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property				
GEOPHYSICAL LOGGING	Borehole deviation	—			X
	Caliper • Magnetic suseptibility				
	Natural gamma	—			X
	Resistivity (normal-lateral)				
	Single point resistivity	—			X
	SP				
	Temperature/Temp.-gradient				
	Borehole fluid resistivity/Salinity				
	Radar				
	IP/IP-resistivity				
	pH-Eh-pS^{2-}-T				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 179m	—	82.10.02	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,				
	Groundwater level measuring	—	82.08-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement				
HYDROCHEMISTRY	Chemical sample				

Figure A11. Activities in borehole KFJ10.



FJÄLLVEDEN

Site characterization

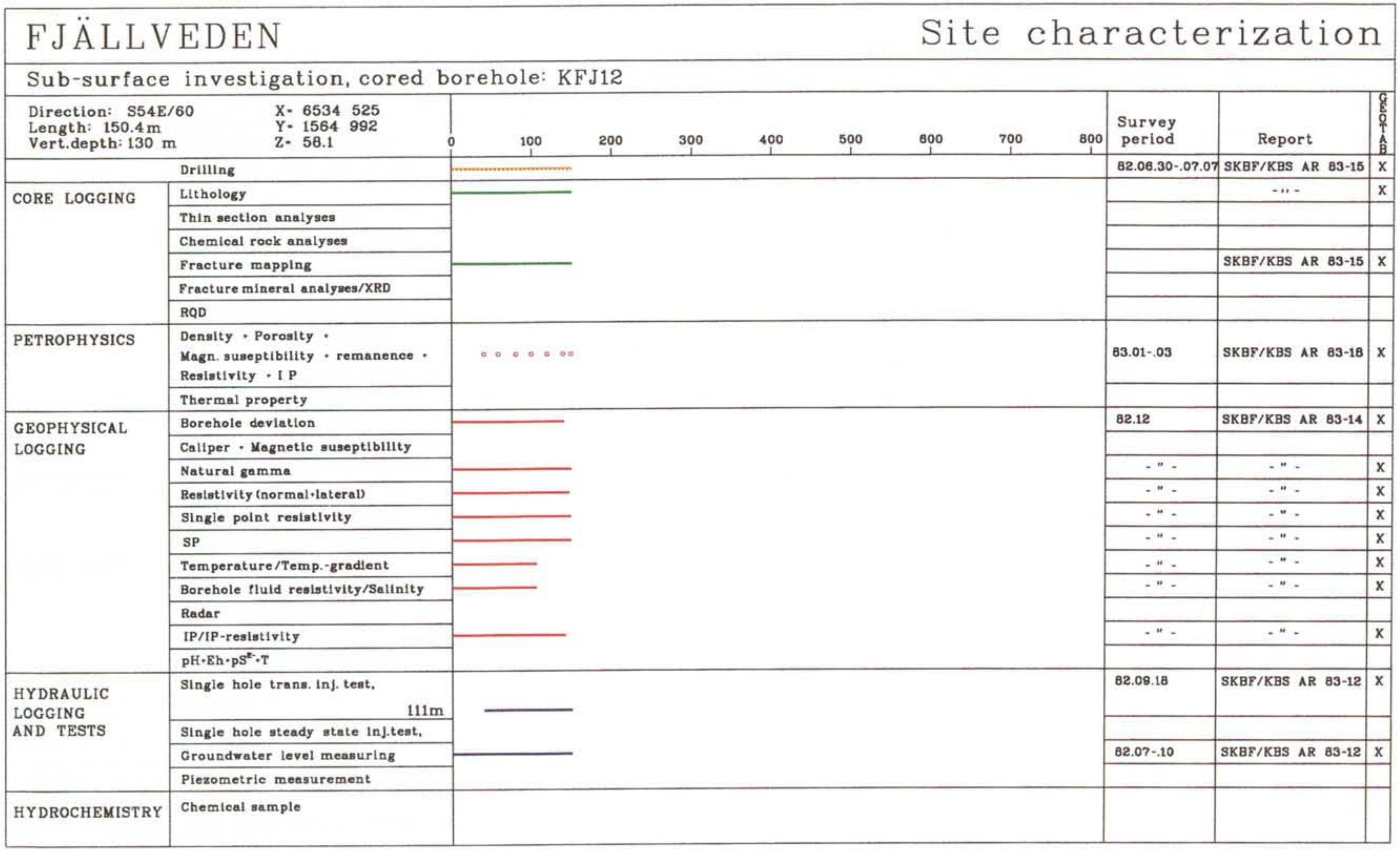
Sub-surface investigation, cored borehole: KFJ11

Direction: S45E/60
Length: 250.6m
Vert.depth: 211 m

X- 6534 528
Y- 1565 030
Z- 58.9

		Survey period	Report	GEOTAB
	Drilling	82.06.05-.06.17	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology		-"-	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			
	RQD			
PETROPHYSICS	Density · Porosity · Magn. susceptibility · remanence · Resistivity · I P	83.01-.03	SKBF/KBS AR 83-16	X
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation	82.12	SKBF/KBS AR 83-14	X
	Caliper · Magnetic susceptibility			
	Natural gamma	-"-	-"-	X
	Resistivity (normal·lateral)	-"-	-"-	X
	Single point resistivity	-"-	-"-	X
	SP	-"-	-"-	X
	Temperature/Temp.-gradient	-"-	-"-	X
	Borehole fluid resistivity/Salinity	-"-	-"-	X
	Radar			
	IP/IP-resistivity	-"-	-"-	X
	pH·Eh·pS^{2-}·T			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 175m	82.09.19	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,			
	Groundwater level measuring	82.07-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A12. Activities in borehole KFJ11.



FJÄLLVEDEN Site characterization

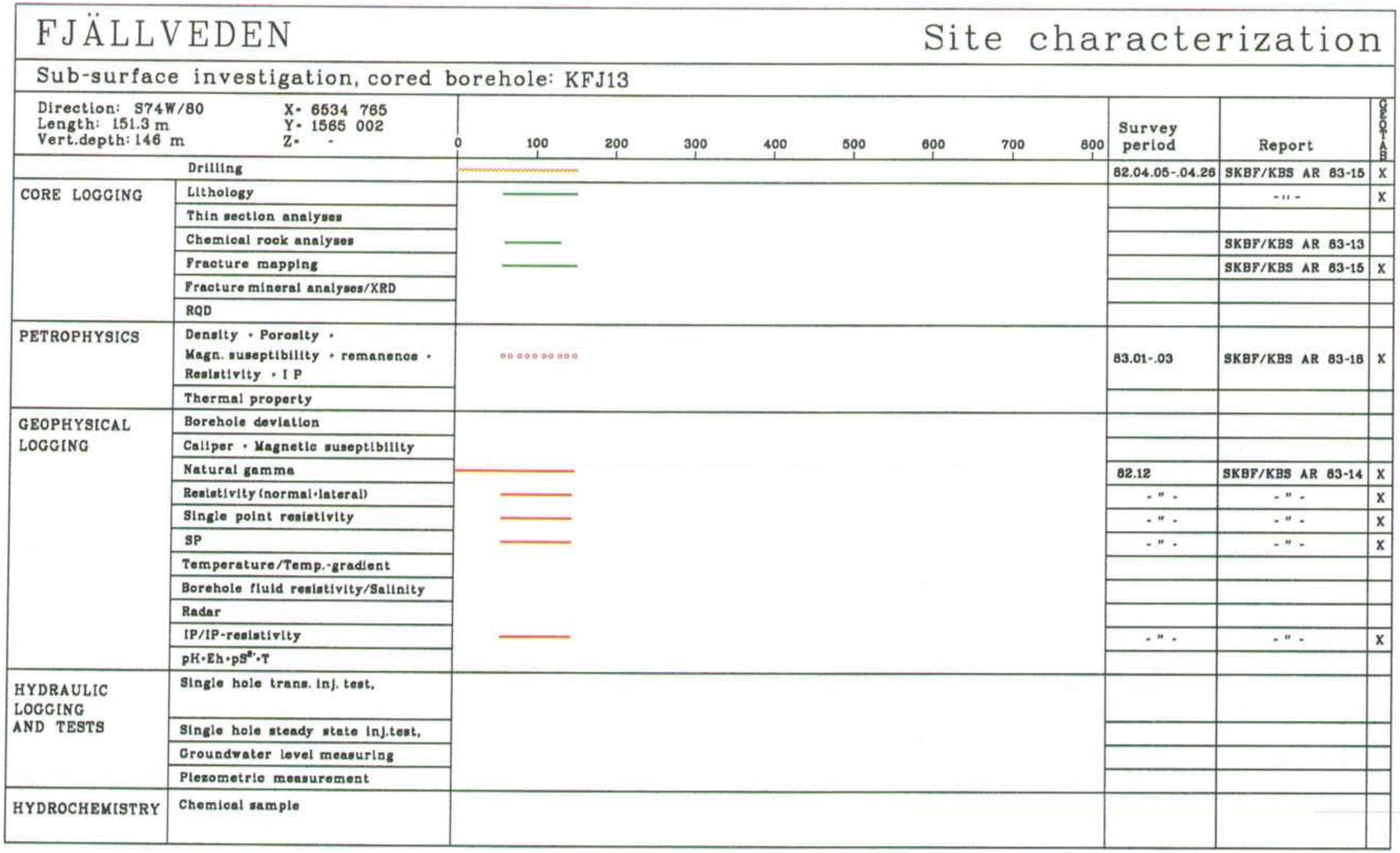
Sub-surface investigation, cored borehole: KFJ12

Direction: S54E/60
Length: 150.4 m
Vert.depth: 130 m

X- 6534 525
Y- 1564 992
Z- 58.1

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		82.06.30-.07.07	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology			-"-	X
	Thin section analyses				
	Chemical rock analyses				
	Fracture mapping			SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD				
	RQD				
PETROPHYSICS	Density • Porosity • Magn. suseptibility • remanence • Resistivity • I P		83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property				
GEOPHYSICAL LOGGING	Borehole deviation		82.12	SKBF/KBS AR 83-14	X
	Caliper • Magnetic suseptibility				
	Natural gamma		-"-	-"-	X
	Resistivity (normal•lateral)		-"-	-"-	X
	Single point resistivity		-"-	-"-	X
	SP		-"-	-"-	X
	Temperature/Temp.-gradient		-"-	-"-	X
	Borehole fluid resistivity/Salinity		-"-	-"-	X
	Radar				
	IP/IP-resistivity		-"-	-"-	X
	pH•Eh•pS^{2-}•T				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 111m		82.09.18	SKBF/KBS AR 83-12	X
	Single hole steady state inj.test,				
	Groundwater level measuring		82.07-.10	SKBF/KBS AR 83-12	X
	Piezometric measurement				
HYDROCHEMISTRY	Chemical sample				

Figure A13. Activities in borehole KFJ12.



FJÄLLVEDEN

Site characterization

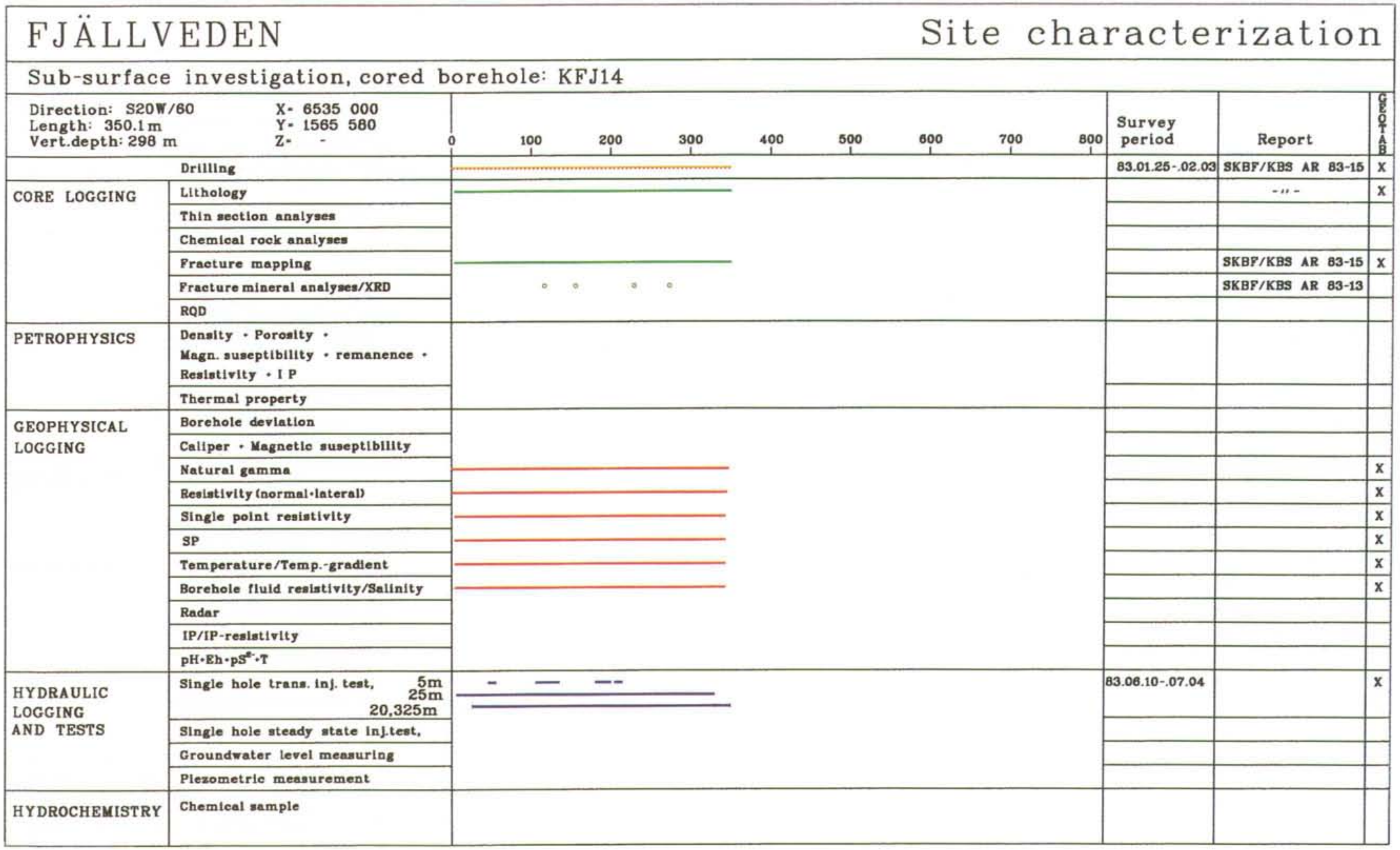
Sub-surface investigation, cored borehole: KFJ13

Direction: S74W/80
Length: 151.3 m
Vert.depth: 146 m

X- 6534 765
Y- 1565 002
Z- -

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		82.04.05-.04.26	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology			-"-	X
	Thin section analyses				
	Chemical rock analyses			SKBF/KBS AR 83-13	
	Fracture mapping			SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD				
	RQD				
PETROPHYSICS	Density • Porosity • Magn. suseptibility • remanence • Resistivity • I P		83.01-.03	SKBF/KBS AR 83-18	X
	Thermal property				
GEOPHYSICAL LOGGING	Borehole deviation				
	Caliper • Magnetic suseptibility				
	Natural gamma		82.12	SKBF/KBS AR 83-14	X
	Resistivity (normal-lateral)		-"-	-"-	X
	Single point resistivity		-"-	-"-	X
	SP		-"-	-"-	X
	Temperature/Temp.-gradient				
	Borehole fluid resistivity/Salinity				
	Radar				
	IP/IP-resistivity		-"-	-"-	X
	pH-Eh-pS^{2-}-T				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test,				
	Single hole steady state inj.test,				
	Groundwater level measuring				
	Piezometric measurement				
HYDROCHEMISTRY	Chemical sample				

Figure A14. Activities in borehole KFJ13.



FJÄLLVEDEN

Site characterization

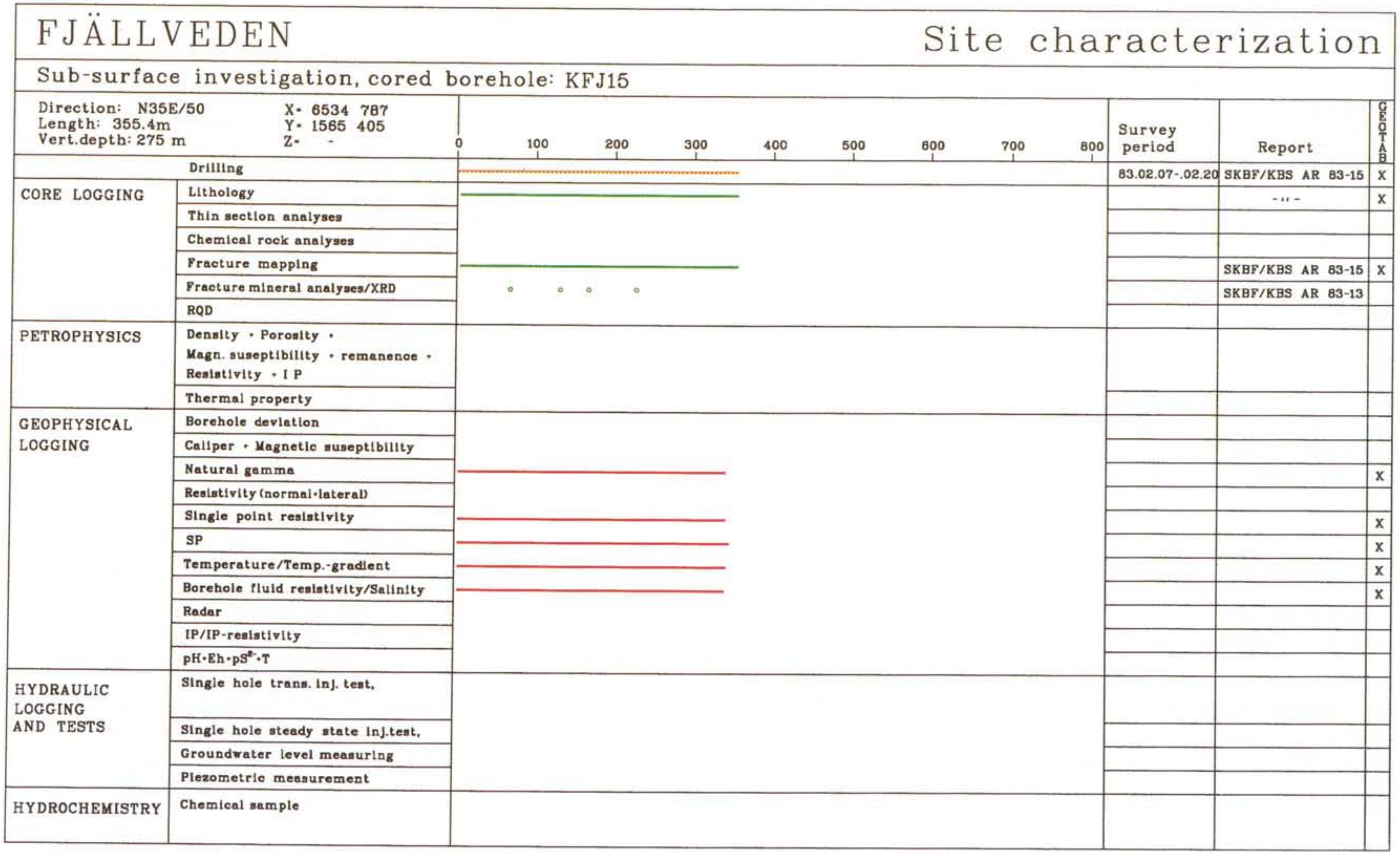
Sub-surface investigation, cored borehole: KFJ14

Direction: S20W/60
Length: 350.1 m
Vert.depth: 298 m

X- 6535 000
Y- 1565 580
Z- -

		Survey period	Report	GEOTAB
	Drilling	83.01.25-.02.03	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology		-"-	X
	Thin section analyses			
	Chemical rock analyses			
	Fracture mapping		SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD		SKBF/KBS AR 83-13	
	RQD			
PETROPHYSICS	Density · Porosity · Magn. susceptibility · remanence · Resistivity · I P			
	Thermal property			
GEOPHYSICAL LOGGING	Borehole deviation			
	Caliper · Magnetic susceptibility			
	Natural gamma			X
	Resistivity (normal·lateral)			X
	Single point resistivity			X
	SP			X
	Temperature/Temp.-gradient			X
	Borehole fluid resistivity/Salinity			X
	Radar			
	IP/IP-resistivity			
	pH·Eh·pS^{2-}·T			
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test, 5m 25m 20,325m	83.06.10-.07.04		X
	Single hole steady state inj.test,			
	Groundwater level measuring			
	Piezometric measurement			
HYDROCHEMISTRY	Chemical sample			

Figure A15. Activities in borehole KFJ14.



FJÄLLVEDEN

Site characterization

Sub-surface investigation, cored borehole: KFJ15

Direction: N35E/50
Length: 355.4m
Vert.depth: 275 m

X- 6534 787
Y- 1565 405
Z- -

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		83.02.07-.02.20	SKBF/KBS AR 83-15	X
CORE LOGGING	Lithology			- " -	X
	Thin section analyses				
	Chemical rock analyses				
	Fracture mapping			SKBF/KBS AR 83-15	X
	Fracture mineral analyses/XRD			SKBF/KBS AR 83-13	
	RQD				
PETROPHYSICS	Density · Porosity · Magn. suseptibility · remanence · Resistivity · I P				
	Thermal property				
GEOPHYSICAL LOGGING	Borehole deviation				
	Caliper · Magnetic susceptibility				
	Natural gamma				X
	Resistivity (normal·lateral)				
	Single point resistivity				X
	SP				X
	Temperature/Temp.-gradient				X
	Borehole fluid resistivity/Salinity				X
	Radar				
	IP/IP-resistivity				
	pH·Eh·pS^{2-}·T				
HYDRAULIC LOGGING AND TESTS	Single hole trans. inj. test,				
	Single hole steady state inj.test,				
	Groundwater level measuring				
	Piezometric measurement				
HYDROCHEMISTRY	Chemical sample				

Figure A16. Activities in borehole KFJ15.

APPENDIX B

GENERALIZED RESULTS FROM BOREHOLE MEASUREMENTS

Generalized results from core mapping and borehole measurements/tests in the cored boreholes KFJ01–KFJ15 are presented in Figures B1–B4. For each borehole the following information is presented; variation in rock types, location of fractured sections 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. Amfibolitic bodies and other basic rock types are collectively described as "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.

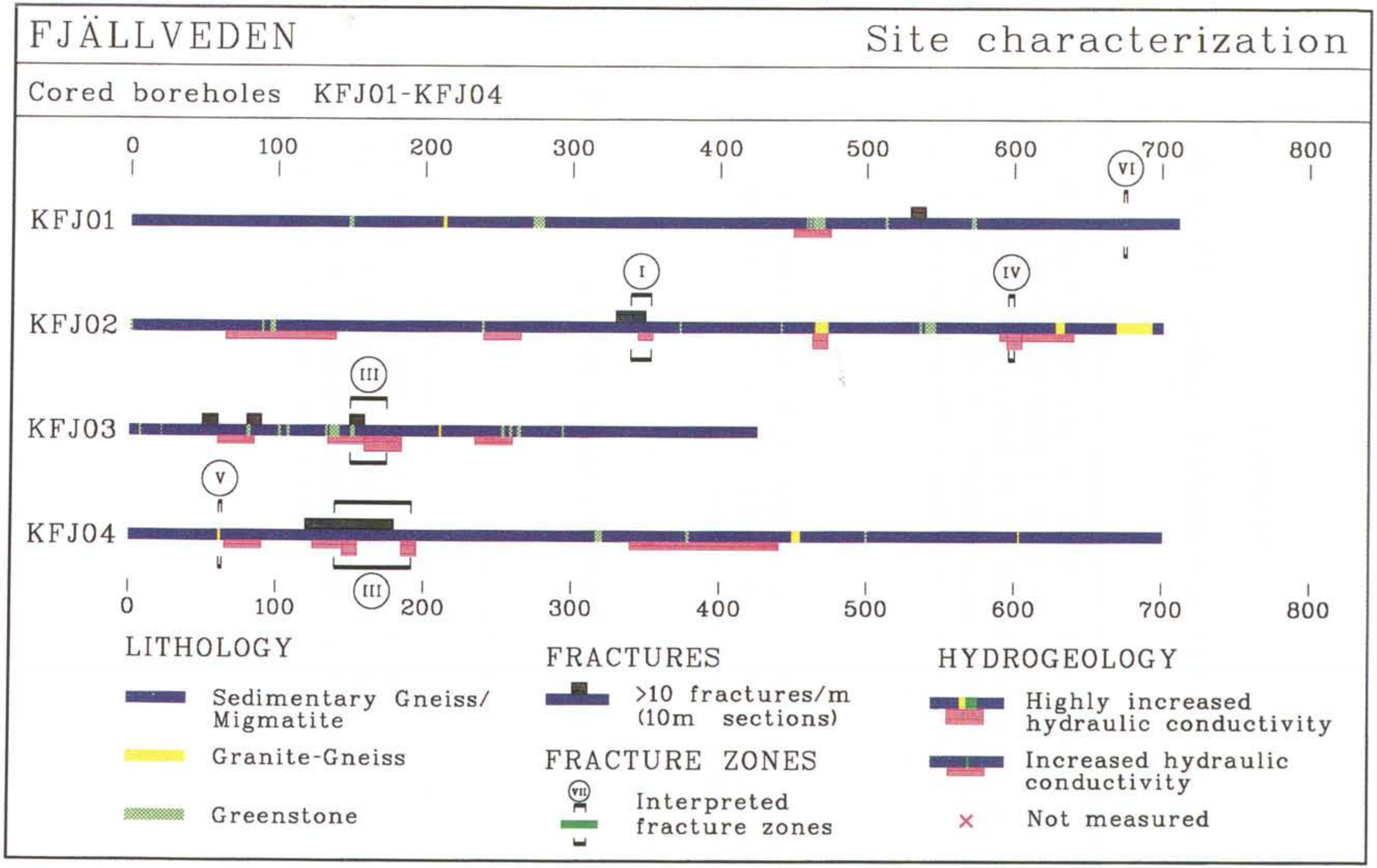


Figure B1. Results from borehole surveys in KFJ01-KFJ04. The horizontal axis represent borehole length.

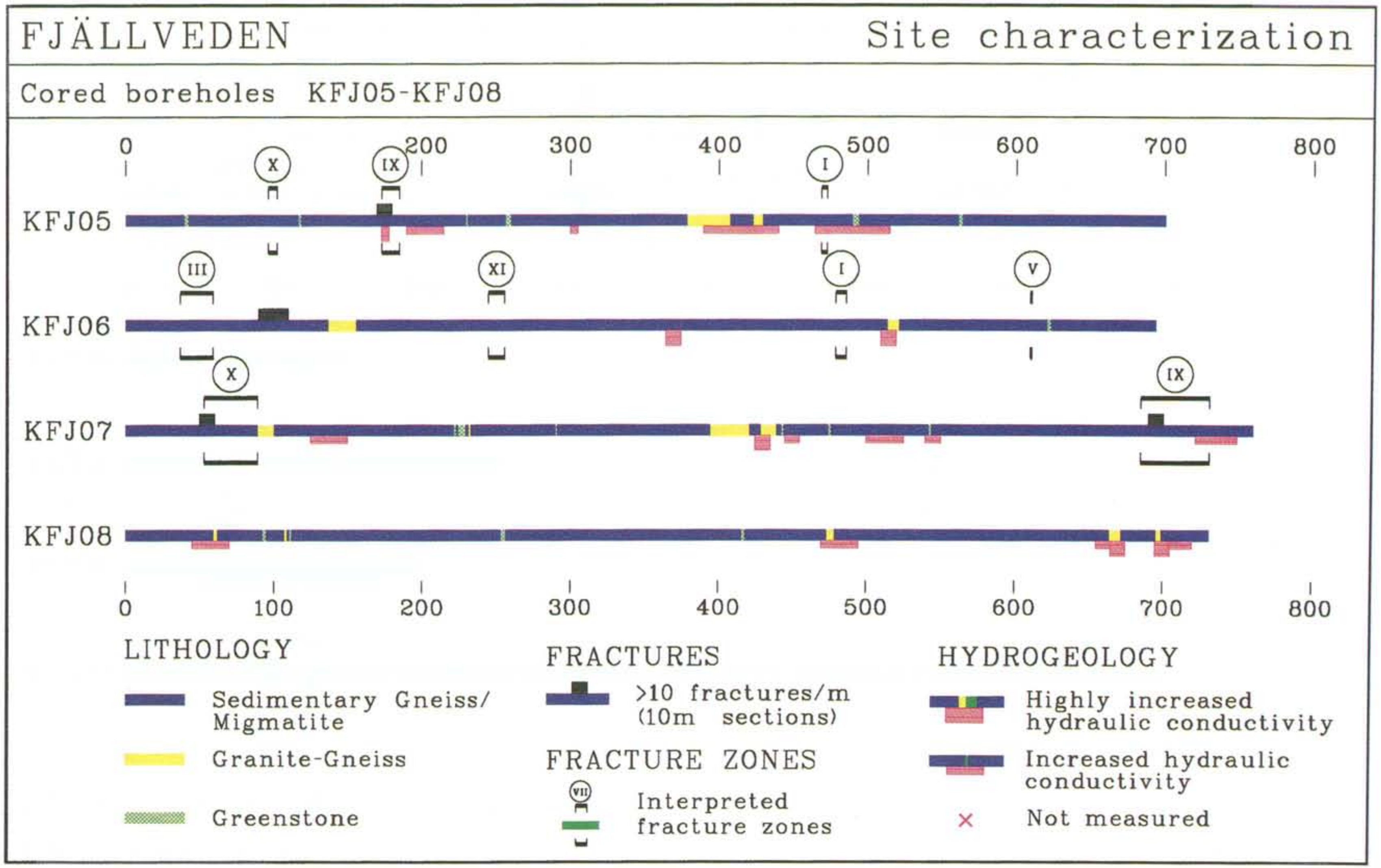


Figure B2. Results from borehole surveys in KFJ05–KFJ08. The horizontal axis represent borehole length.

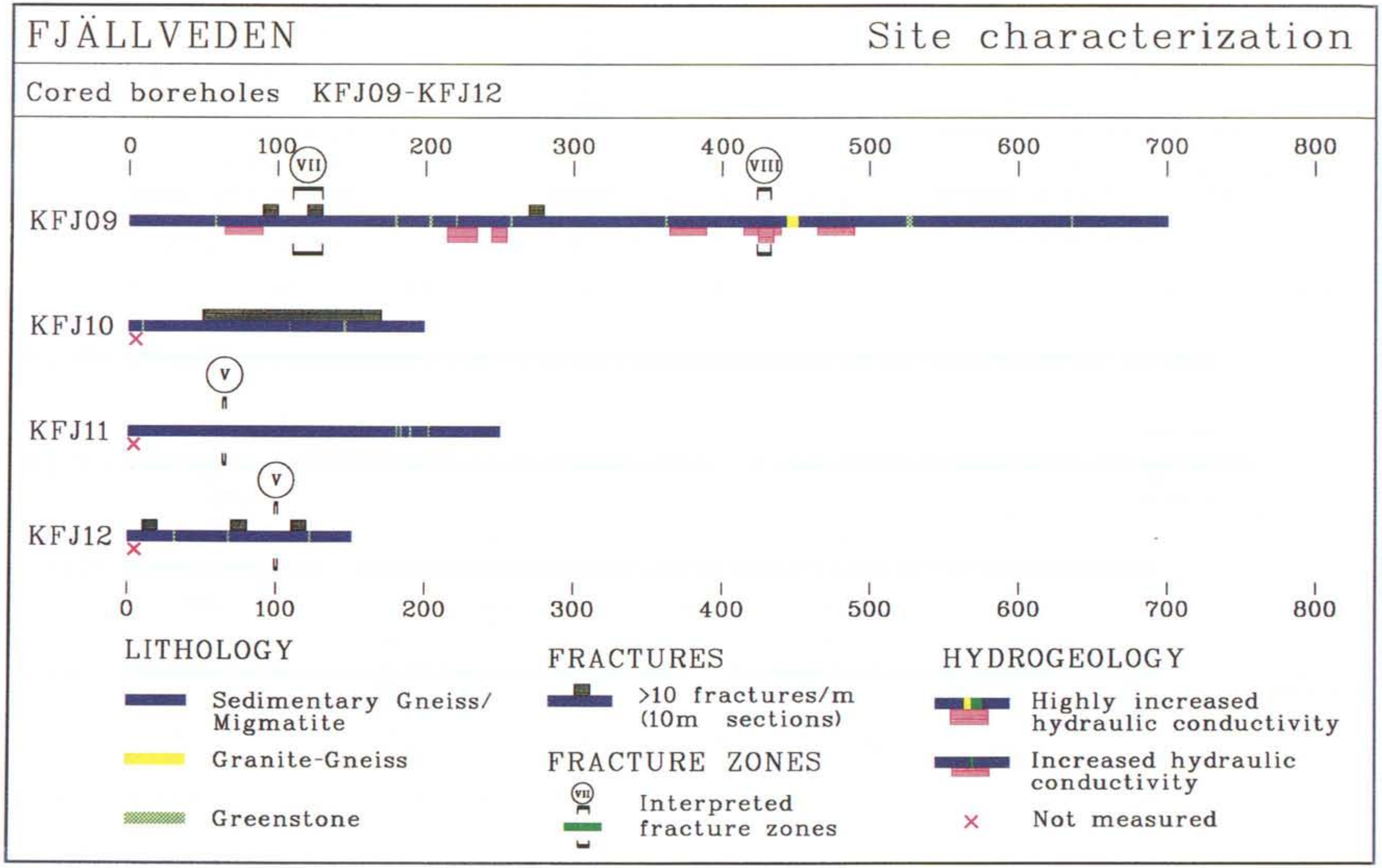


Figure B3. Results from borehole surveys in KFJ09–KFJ12. The horizontal axis represent borehole length.

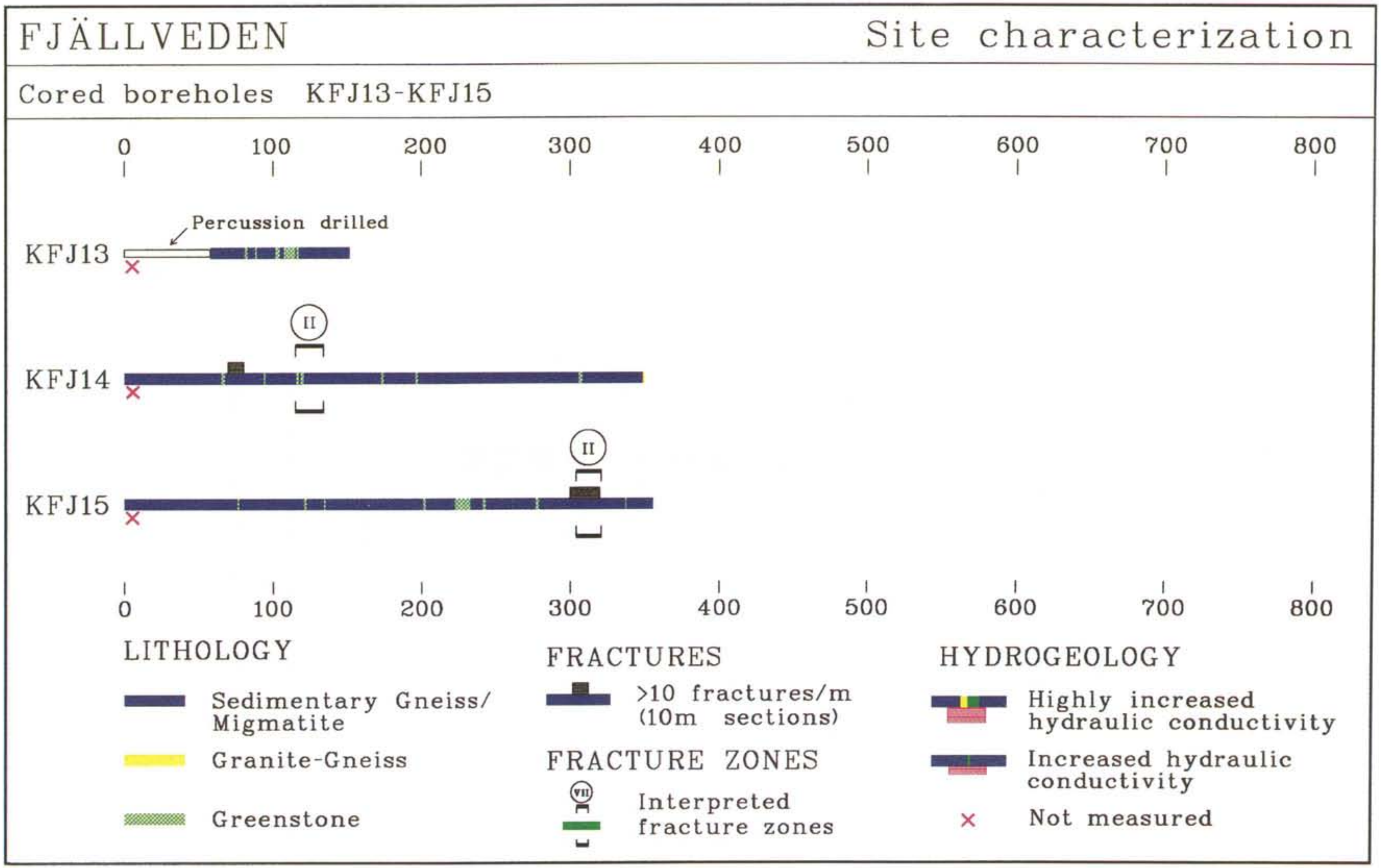


Figure B4. Results from borehole surveys in KFJ13–KFJ15. The horizontal axis represent borehole length.

APPENDIX C

DESCRIPTIONS OF EACH FRACTURE ZONE

This appendix presents brief descriptions of each interpreted fracture zone, Figure C1, together with general comments regarding the reliability of the interpretation, according to the nomenclature by Bäckblom (1989). The fracture zones at Fjällveden are summarized in Section 5.4.

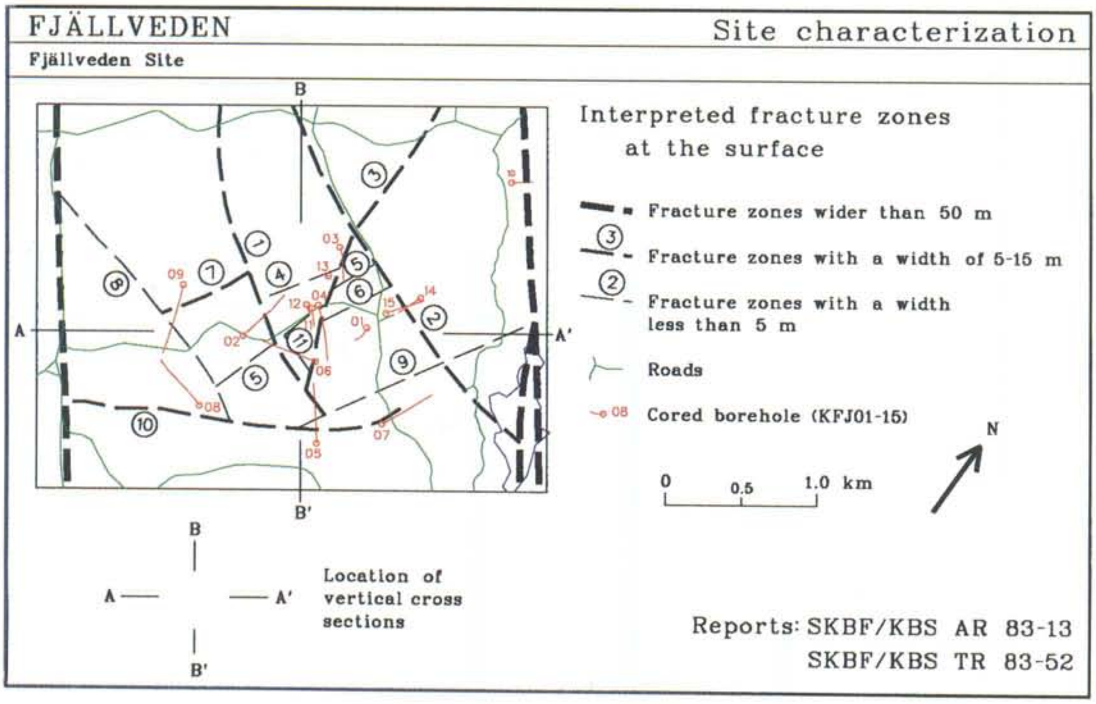


Figure C1. Map of interpreted fracture zones in the Fjällveden site.

ZONE 1

Zone 1 is located in the central part of the site. The strike varies from N70W in the southern part of the site to N30W in the northern part. The mean strike is N55W. The zone is partly expressed on the slingram measurements and on two out of the three refraction seismic profiles. The zone is partly well expressed as a lineament (at boreholes HFJ01 and 02 and KFJ02), outside this area the zone is only weakly topographically indicated.

Two percussion boreholes (HFJ01 and HFJ02) were drilled in the area where the Zone 1 is well defined by topography and geophysics. The results from the boreholes indicated that Zone 1 is about 1 m wide and vertical. The total water capacity of the boreholes were 900 and 175 l/h, respectively, indicating a low hydraulic conductivity for the zone. Below the percussion boreholes the cored borehole KFJ02 intersects Zone 1 at 340–354 m borehole length (corresponding to a depth of about 295–307 m). The cores display brecciated parts as well as parts with crushed rock.

Also boreholes KFJ05 and KFJ06 are interpreted to intersect Zone 1 at 469–473 m and 479–486 m borehole length, respectively. However, the cores from these sections only display a modest increase in fracturing and with no other sign of tectonization.

Reliability; although there probably exist a minor fracture zone at borehole KFJ02, the orientation and continuation of this zone is uncertain. The interpretation of Zone 2 intersecting boreholes KFJ05 and KFJ06 at the borehole sections suggested above is questionable. According to the Bäckblom nomenclature the reliability level therefore is "probable" at the location of borehole KFJ02, but "possible" regarding its continuation.

ZONE 2

Zone 2 is oriented N70W and located in the eastern part of the site. The zone is apparent as a lineament, but is only partially indicated on the slingram measurements. There are two refraction seismic profiles crossing the zone. Although there are low velocity sections close to the interpreted location of the zone, no such section is actually located at the zone.

The zone has been investigated at two locations. At its northern part three percussion boreholes (HFJ05, 06 and 12) were drilled. Two of these boreholes (HFJ05 and HFJ06) indicated several impermeable fractured sections. There are also fractured sections in the third borehole (HFJ12), but in this borehole they are highly permeable as indicated by strong inflows (5000 l/h).

The overall interpretation from these boreholes is a 20 m wide fracture zone that dips vertically or 80° toward NE.

At its southern part, 600 m towards the southeast from its norther part, Zone 2 has been investigated by two percussion boreholes (HFJ30 and 31) and two cored boreholes (KFJ14 and 15). The borehole results are also at this location somewhat contradictional to each other. Borehole HFJ30, which is interpreted to intersect Zone 2, shows a total inflow of 1000 l/h. Borehole HFJ31, which is interpreted not to intersect Zone 2, show a total inflow of 2000 l/h.

The cored borehole KFJ14 showed a general high fracture frequency the first 160 m of its length, although only the interval 115–134 m was interpreted to represent Zone 2. In this interval there are strongly fractured and clay altered parts. Zone 2 is furthermore interpreted to intersect borehole KFJ15 between 304–321 m borehole length, where the core is partly crushed. The width of Zone 2 in these two boreholes are 12 and 9 m, respectively.

Reliability; although there are five percussion and two cored boreholes interpreted to intersect the zone the geometric and hydraulic characteristics are still somewhat uncertain. The reliability should therefore be "probable".

ZONE 3

The northerly oriented and vertical Zone 3 is located in the central and northern part of the site. The zone is weakly expressed as a topographical lineament and weakly indicated by three seismic profiles. The other ground geophysical measurements do not indicate any fracture zone with the proposed extent as Zone 3.

Zone 3 is interpreted to be intersected by the percussion boreholes HFJ05 and HFJ12 in the northern part of the zone and HFJ13, HFJ17 and HFJ18 in its southern part. Zone 3 is only weakly indicated in the northern boreholes. In these boreholes there are some fractured rock and also some minor inflows at the interpreted locations of Zone 3, but several other alternative explanations are possible. Similar uncertainties applies more or less to the southern boreholes.

Three cored boreholes are interpreted to intersect Zone 3. Borehole KFJ03 intersects Zone 3 in the interval 150–175 m (increased fracture frequency), in borehole KFJ04 between 140–192 m (several crushed and fractured sections), and in borehole KFJ06 between 37–59 m (weathered, clay altered, Kaolinite). The width of Zone 3 in the cored boreholes is estimated to be between 10–15 m.

Reliability; Zone 3 is interpreted to be intersected by five percussion boreholes and three cored boreholes the location and continuation is still uncertain. This is because the fracture zone is only weakly topographical and geophysical expressed. This in turn open the possibility of alternative interpretation of borehole results. The reliability level should therefore be "probable".

ZONE 4

The interpreted location of Zone 4 in the central part of the site have been investigated by one percussion and one cored borehole. Although there is a slingram anomaly and also a seismic low-velocity section in the vicinity of the interpreted outcropping of the zone, the percussion borehole HFJ03 did not confirm the fracture zone. In spite of this, the geophysical anomaly at the ground surface was correlated with a fractured section in the lower part of borehole KFJ02 at the interval 596–600 m, where the bedrock is strongly weathered and contains clay altered rock. The interpreted orientation of the Zone 4 is N30E/80SE and its width is 1 m.

Reliability: "possible" (at the most).

ZONE 5

This zone is oriented N15E and is located in the central part of Fjällveden. Geophysically, the zone is indicated on the slingram map only in the central part of its interpreted extension. Outside this area, there is no geophysical anomaly that correlate with Zone 5. Topographically the zone is partly expressed a boundary between a slightly elevated area to the NW and an area dominated by peat bogs to the SE.

The zone is interpreted to be intersected by three percussion boreholes and four cored boreholes. The percussion boreholes are HFJ19, in the central part of the site, and HFJ33 and HFJ35 in the southern part. The results from these boreholes indicate a thin and steeply dipping fracture zone of low permeability as judged from the low groundwater inflows.

In the central part of the site three cored boreholes were drilled, with a separation of 100 m, to intersect the zone at relative shallow levels. The boreholes and their intersections with Zone 5 are; KFJ04 (62 m), KFJ11 (64–66 m) and KFJ12 (99–101 m and/or 109–119 m). The combined data from all boreholes results in a dip of 80° towards NW. A fractured section at 610–611 m borehole length in borehole KFI06 and a fractured section at

336–340 m in borehole KFJ03 fits well with Zone 5. In all boreholes Zone 5 is characterized by high fracture frequency, clay altered bedrock and core losses. The width of the zone is 0.5 - 1 m.

Reliability; in the central part of the site the zone is indicated both as a lineament and as a geophysical anomaly. In this area the zone is also penetrated by five cored boreholes and one percussion borehole. The zone should therefore be regarded "certain" in the central part of the site. However, there is much less information regarding the southern and northern interpreted extension of the zone. Here the reliability is "possible".

ZONE 6

A interval with slightly increased fracture frequency in borehole KFJ01 at 674–676 m was interpreted to be related to a weak N25E trending lineament located about 200 m NW of the borehole. This interpretation gives a dip of 75° towards SE and a width of 0.2 m of Zone 6. There are no other indication, geophysical or in other boreholes, that indicates the presence of Zone 6.

Reliability; the existence of this zone is questionable. The reliability should therefore be "possible" (at the most).

ZONE 7

Also for this zone, an interval between 110–130 m with somewhat increased fracture frequency in borehole KFJ09, was regarded to be related to a weak N25E trending lineament about 100 m SE of the borehole. This interpretation gives a dip of 60° towards NW and a width of 14 m of Zone 7. For the SW part of Zone 7 the slingram measurements weakly indicate a fracture zone at the interpreted location of Zone 7.

Reliability; "possible".

ZONE 8

This zone is located in the western part of the site. The zone is slightly curved with a mean trend of N75W. The zone is not indicated by slingram nor by the resistivity measurements. Possibly, a seismic low velocity section could be correlated with the zone. The interpreted location and extent of the zone is thus only based on a weak topographical expression. A fractured section in borehole KFJ09 (424–433 m) is associated with the zone. This gives a vertical dip and a width of 4.5 m of Zone 8.

Reliability; "possible", (at the most).

ZONE 9

This zone is oriented N30E and is located in the eastern part of the site. The zone is indicated as a weakly expressed topographical lineament and partly also as a anomaly on the slingram map. The zone is interpreted to be located in boreholes KFJ05 and KFJ07 at 173–188 and 685–731 m borehole length respectively. This interpretation gives a dip of 75° towards SE and a width of 5 m of Zone 9. In both boreholes the zone is represented by a somewhat higher fracture frequency. Zone 9 is also indicated in the percussion borehole HFJ09 at 35–55 m, where a groundwater inflow of about 1000 l/h is registered.

Reliability; the zone is only weakly expressed on the surface. However, the interpretation is strengthen by the occurrence of the zone in several boreholes. The Zone 9 should therefore be considered as "probable".

ZONE 10

This zone is slightly curved with a mean trend of N60E. It is located at the southernmost part of the site. The zone is well expressed both as a lineament on the topographical map and as an anomaly on the slingram and resistivity maps. The character and dip of the zone has been studied by means of two cored and two percussion boreholes.

Zone 10 is interpreted to be located in borehole KFJ05 and borehole KFJ07 at 96–102 m and 53–89 m borehole length, respectively. The zone is characterized by high fracture frequency and clay altered bedrock in both boreholes. This interpretation results in a dip for Zone 10 of 70° towards SE and a width of 5–6 m. The interpreted orientation of the zone is strengthen by the two percussion boreholes, HFJ48 and HFJ49. These boreholes were located in the northern surrounding bedrock to the zone and drilled southwards. Since no zone were identified in these boreholes the Zone 10 must (if it exist) dip to the south.

Reliability; the zone is interpreted from topographical and geophysical indications and from the results from four boreholes. The reliability level should therefore be "certain".

ZONE 11

An interval with brecciated rock and a slight increase in fracture frequency in borehole KFJ06 at 245–256 m was interpreted to be related to a weak N70W trending lineament about 100 m SW of the borehole. This interpretation gives a vertical dip and a width of 3 m of Zone 6. Apart from a possible seismic low velocity section in the vicinity of Zone 11, there are no other data, geophysically or other boreholes that indicates the presence of this zone.

Reliability; the existence of this zone is questionable. The reliability should therefore be "possible" (at the most).

EASTERN REGIONAL ZONE

The N35W regional fracture zone that bounds the site to the east is strongly indicated topographically and geophysically. This zone has been investigated by the cored borehole KFJ10. The core is highly fractured between 70–163 m. The bedrock is generally clay altered and slickenside striations are common, indicating extensive shear. Interpolating between the borehole and the surface gives a width of 80–90 m and a dip of 75^0 towards SE for this zone, i.e. the zone is dipping towards the Fjällveden site.

Reliability; "certain".

WESTERN REGIONAL ZONE

The western regional zone has been investigated by four percussion boreholes HFJ37, HFJ38, HFJ39 and HFJ41. Although the zone is as strongly indicated on the surface as the Eastern Regional Zone, only weak indications of the presence of a fracture zone is found in the boreholes. For example, the total groundwater inflows to each of the boreholes varies between 30–1 500 l/h. The reason for this is probably due to clay alteration of the bedrock resulting in a low hydraulic permeability.

Reliability; although the surface expression of the zone is convincing no borehole have confirmed the existence of the zone. The reliability should therefore be "probable".

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R S Forsyth
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I Puigdomènech[1], J Bruno[2]
[1]Enviromental Services, Studsvik Nuclear, Nyköping, Sweden
[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
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Kaj Ahlbom[1], Sven Tirén[2]
[1]Conterra AB
[2]Sveriges Geologiska AB
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Eva Hakami[1], Anders Ekstav[2], Ulf Qvarfort[2]
[1]Vattenfall HydroPower AB
[2]Golder Geosystem AB
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[1]KEMAKTA Konsult AB
[2]Chalmers Institute of Technology
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[1]Starprog AB
[2]SKB AB
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[1]KEMAKTA Consultants Co
[2]Chalmers Institute of Technology

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[1]Conterra AB
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K Ollila[3]
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Roland Pusch[1], Ivars Neretnieks[2], Patrik Sellin[3]
[1] Clay Technology AB. Lund
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October 1991