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Sternö study site. Scope of activities and main results

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Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40) and 1990 (TR 90-46) is available through SKB.

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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 previously investigated 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 Sternö study site. This site was one of the first sites to be investigated by SKB. The studies at Sternö were made under severe time–constraints and with prototype borehole instrumentations. These limitations should be kept in mind when reading the report.

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 Ljunggren (rock mechanics).

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1. ASSESSMENT OF THE STERNÖ STUDY SITE

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

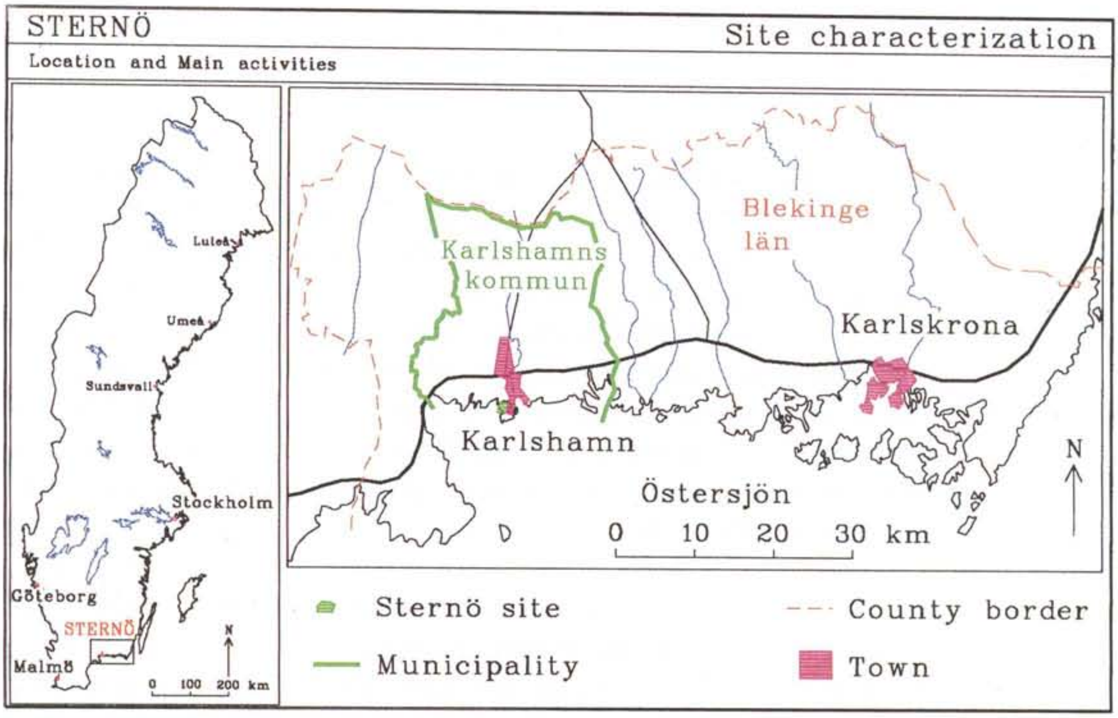


Figure 1. Location of the Sternö study site.

1.1 Main characteristics and uncertainties

Rock type distribution

The Sternö region is dominated by metavolcanic gneiss (the Blekinge Coastal Gneiss), foliated granodiorite and Karlshamn granite. These rock types are 1400 million years old or older. The youngest rock type, 900 million years old, is extensive dykes of dolerite trending NNE and are steeply dipping.

The Sternö study site is located on a peninsula south of Karlshamn. The dominating rock type is the Coastal Gneiss. At depth the bedrock is dominated by foliated granodiorite and Karlshamn granite. In the borehole cores, no significant difference in degree of fracturing between these rock types has been observed.

The eastern part of the Sternö peninsula is transected by a ca 200 m wide and highly fractured dolerite dyke. Geophysical modelling of the dyke indicate a 80° dip towards SE, i.e. away from the site.

Uncertainties: Only a generalized model of rock distribution within the Sternö study site has been presented. This model mainly gives tendencies in rock distribution with depth.

Fracture zones

Seven fracture zones have been interpreted in the Sternö study site, mainly from lineament analyses. The zones are all assumed to be vertical. Borehole data are available from two fracture zones, Zone 2 and Zone 4. Zone 2 is highly fractured including several sections with crushed rock. The zone is apparent in the cores of KKA04 between 200–500 m. A tentative width of 30 m is assumed for this fracture zone. In contrast, Zone 4 is apparent in the core logs only as a 2 m section of increased fracturing. The "hydraulic width" of the zone is however considerable larger, ca 50 m, as interpreted from the water injection tests. In the reports the estimated width of the zone varies between 10 to 80 m.

Uncertainties: The lack of a detailed 3D tectonic model and the fact that only two fracture zones have been drilling implies a large uncertainty regarding interpreted zones. However, the generally low or very low fracture frequency in all boreholes (with the exception of borehole KKA04) makes it unlikely that other large fracture zones exists at the site. It is however likely that new drillings or even a renewed tectonic model would change assumed geometrical characteristics of interpreted fracture zones. This could also include the exclusion of some of the presently interpreted zones.

No subhorizontal fracture zones has been interpreted at Sternö. (Although several such zones were suggested by the "SKI geology group", see section 2.1). Judging from the core logs there is no reason to suspect any extensive subhorizontal or gently dipping zones. Another indication that strengthen this interpretation is the absence of saline water in the boreholes, even down to such large depths as 800 m. Experiences from e.g. the Finnsjön study site indicate that such a zone, located in a small peninsula as Sternö, surrounded by sea, would most likely have preserved a saline water beneath the zone.

Hydrology

The central part of the Sternö peninsula constitutes an elevated area with the highest point located c. 50 m above the sea level. From this part, which is a presumed recharge area for groundwater, the ground level generally slopes continuously towards the surrounding Baltic Sea. The mean altitude of the site is c. 25 m above the surrounding sea.

Uncertainties: Although systematic monitoring of the groundwater table has been performed in connection with the construction and operation of oil rock caverns in the central part of Sternö and in some of the SKB boreholes, these data has not been utilized in the hydraulic modelling. Thus, the assumed distribution of the groundwater table, used as the upper boundary condition, along the modelled sections is uncertain. In addition, no study of the regional groundwater flow pattern in deeper parts of the bedrock has been performed in the Sternö 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

Three hydraulic units were defined in the conceptual model of sections within the Sternö study site. These are the rock mass, the fracture zones and the intersections of fracture zones. The hydraulic units were modelled as separate isotropic continua. All fracture zones were assumed to be vertical in the modelling. The Sternö study site is assumed to be divided into two rock blocks by the steeply dipping Zone 4. These blocks have apparently uniform fracture frequency and water conducting properties.

Uncertainties: No comprehensive structural model exists for the Sternö study site. This, together with the fact that only two fracture zones were tested hydraulically, implies a high degree of uncertainty for the interpreted or the assumed hydraulic properties of these zones and their intersections. Regarding the "rock mass", no subdivision of hydraulic data with respect to rock types has been made.

Hydraulic conductivity

No geostatistical analysis of measured hydraulic conductivity data from single-hole hydraulic tests in different hydraulic units has been made. Thus, the effective hydraulic properties of the hydraulic units have not been evaluated. In the modelling, certain hydraulic conductivity versus depth functions were assigned to the hydraulic units. For the rock mass a step function was assumed with hydraulic conductivities of $1 \cdot 10^{-8}$ m/s in the interval 0–300 m and $1 \cdot 10^{-11}$ m/s in the interval 300–5000 m. For the fracture zones and fracture zone intersections a constant hydraulic conductivity versus depth was assumed, i.e. $1 \cdot 10^{-6}$ m/s and $5 \cdot 10^{-6}$ m/s, respectively.

Uncertainties: Effective hydraulic properties of assumed hydraulic units should be regarded as uncertain. This is due to the lack of a detailed structural model for Sternö and also due to lack of evaluation regarding hydraulic properties for different rock types.

Groundwater flow rates at repository depth

The groundwater flow rate at repository depth was not explicitly calculated but, from the calculated groundwater head distributions and the assumed hydraulic conductivity, the flow rate in the rock mass at a depth of 500 m can be estimated to 2–16 ml/m^2/year along three sections.

Uncertainties: Apart from the conceptual geological and hydrogeological shortcomings described above, the assumptions of isotropic porous continua (rock mass, fracture zones and fracture zone intersections) made in the modelling imply a large uncertainty in the estimated flow rate. In addition, the lack of a regional flow model makes the results uncertain. The presented flow rates are however in the same order as for the KBS–3 sites.

The model analysis of the groundwater system is one of the most insightful of the study sites modelled in the SKB program. Because of the limitation of the two–dimensional model employed to describe a three–dimensional flow field, the analysis had to carefully consider conceptual models of the mechanism of the groundwater system rather than entering all existing data into a numerical code.

Groundwater chemistry

Groundwater sampling were made in two boreholes at relative shallow depths, the sampled sections are located between 226–397 m. The general chemistry data suggest that the groundwaters at the site have high major ion contents, are moderately saline (but not marine), and have relatively high sulfate contents. There is no direct information about redox conditions, however, the presence of Fe^{2+} indicate that the samples come from a reducing environment.

Uncertainties: Sternö was one of the first study sites in which attempts were made to collect groundwaters from the deep bedrock. Instruments used were prototypes and no measures were taken to minimize contamination from the drilling and the hydraulic tests. Consequently, the general reliability of the groundwater samples is low. Furthermore, a proper understanding of groundwater characteristics with depth needs a thoroughly analysis of the geological, hydrological and chemical information in combination. No such analysis has been done for the samples from the groundwaters in Sternö.

Rock mechanics

The rock mechanical investigations in the Sternö study site only includes measurements of some mechanical parameters on core samples. These measurements showed a high quality designation for the bedrock at Sternö.

1.2 Suggestions for complementary studies

Conceptual geologic models

For the Sternö study site and its surroundings a considerable amount of new geoscientific information has been made available since the SKB investigations of 1979. These new information should be utilized in combination with the borehole investigations at Sternö to construct 3D geological and tectonical conceptual models, as well as for assigning hydraulical, mechanical and to some extent hydrochemical properties and conditions. The available information today consists of:

- borehole and surface information from the SKB studies
- modern bedrock maps in the scale of 1:50 000
- airborne magnetic and radiometric maps, scale 1:50 000
- tectonic models made by the "SKI geology group"
- experiences during construction of oil caverns, with a total volume of c. 1 million m^3, 30–60 m below the ground in the central part of the site
- detailed mapping and tectonical analyses of fracture configuration in the three quarries in the Sternö peninsula
- good general knowledge of the geologic and hydraulic conditions in the surrounding region, including several other underground constructions.
- regional structural/rock block map based on the Relief Map of Blekinge in the scale 1:250 000
- analyses of possible late–glacial rock movements in the region surrounding Sternö

The existence of interpreted fracture zones on land could be checked with trenches (which should be rather easy due to the thin soil cover, providing landowner permission is obtained). New boreholes will probably be needed to test the geological model and to assess the geological and hydraulic characteristics at depth.

Conceptual geohydrological models and data sampling

It is suggested to make a 3D conceptual hydraulic model of the Sternö area based on the above discussed renewed geologic/tectonic model. As a first step, the types of numerical models which might be utilized in the subsequent modelling should be identified, e.g. continuum models, fracture network models or stochastic continuum (parametric and non-parametric) models. The selection 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 Sternö study 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. Additional two-dimensional modelling may be necessary to study items of particular importance, e.g. the effect of salt groundwater on flow and transport of nuclides and the regional flow system.

The above study will require drilling of at least one deep borehole specifically designed to investigate the occurrence and, if so, the magnitude of regional groundwater flow. 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.

Sternö constitute a peninsula surrounded by saline water. This implies well defined boundary conditions, at least when local groundwater flow is considered. If regional groundwater flow is important then relevant boundary conditions must be evaluated. Improved definition of the upper boundary condition, groundwater table or groundwater recharge, is however needed.

The effective hydraulic properties of the defined hydraulic units, including different rock types and hydraulic anisotropy, should be investigated. This involves hydraulic testing, flow meter surveying and groundwater head measurements in new boreholes in accordance with the new geological model suggested above. The new hydraulic conductivity data should be analyzed together with the old data. The study should also include analyses of the 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. Also, hydrological data from the construction and operation of the large oil caverns at Sternö should be utilized as much as possible. These might include borehole tests before and during construction, location and magnitudes of inflows to the oil caverns and drawdown of the groundwater table above the caverns.

Since the existing hydraulic tests were performed with prototypes, which has significantly been improved since then, it should be considered to re-test the existing boreholes. The hydraulic tests should also include groundwater head measurements between packers.

As a final test of the validity of the (revised) conceptual model of the Sternö study 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 in the water chemistry during pumping should be made.

Groundwater chemical conditions

Further use of existing groundwater chemical data from the borehole sampling at Sternö may be, of course, to carry out a proper analysis considering geology, hydrology and chemistry in combination. However, it is doubtful whether such an exercise would be meaningful, given the present amount and quality of chemistry data available for the Sternö study site. However, the general chemistry data may be used as a general signature of the groundwater (or at least some of it), to be compared to other sites. It is likely that such a comparison will show a significant difference regarding general chemistry between Sternö and other sites.

Since the available hydrochemical information is not sufficient for a proper characterization of chemical conditions 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.

Solute transport

To improve knowledge of transport at the Sternö study 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 (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. Sorption coefficients including estimates of sorptive surface, and reaction coefficients are of next greatest importance in both the conductive fractures and in bedrock blocks. Of least importance is knowledge of pure parameters of transport, the effective porosity and the dispersivity. Uncertainty in these parameters would likely be overshadowed by uncertainties in the boundary conditions, tectonic 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 thermal properties of various rock types at Sternö, as well as an extended programme for mechanical tests on core samples.

2. BACKGROUND

2.1 Objectives

Geological investigations of study sites in the Swedish programme for disposal of spent nuclear fuel has until 1991 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, denoted study sites.

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.

Sternö is one of the early investigated sites. The site investigations took place between 1977 and 1979. The results are summarized in the KBS-1 and KBS-2 reports (SKBF, 1977 and 1978). The investigations were a result of the "Stipulation Act" which, among else, demanded the reactor owners to demonstrate how and where an "absolutely safe" final storage of high level waste and/or spent nuclear fuel can be effected.

In 1977 a vertical borehole (KKA01) was drilled to 500 m depth. The results of the core logging and the subsequent hydraulic tests were regarded favourable and was used in the KBS-1 report in order to demonstrate that a safe repository for high level waste can be located in Sweden. The government resolution, concerning the application to fuel two nuclear reactors, required that supplementary geological studies should be carried out to ensure that all provisions of the "Nuclear Power Stipulation Act" were fulfilled.

SKB responded to this demand by drilling four additional boreholes at the Sternö study site down to depths of about c. 500 m and deepening the existing borehole KKA01 to 800 m depth. Hydraulic tests, geophysical logging and groundwater sampling were made in all boreholes.

During 1979 the outcome of the supplementary investigations were reviewed by many domestic and international organizations. There was in particular one group of geologists "the SKI geology group", working on contract from the Swedish Nuclear Power Inspectorate (SKI), who strongly objected against the conclusions made by SKB concerning the Sternö study site (SKBF, 1979). Among other things, they interpreted several additional fracture zones at the Sternö study site. SKB accepted one of the fracture zones, the Kölö zone, as possible (Zone 7 in Figure 11). Other suggested fracture zones were not accepted by SKB and its consultants, mainly because of no indications of such zones in the borehole cores.

This report does not discuss nor evaluate the geologic models presented by the SKI geology group. As discussed in Section 1.2 this is something that should be included if SKB decides to make a renewed evaluation of the site.

2.2 Selection of the Sternö study site

The Sternö study site was selected in 1976 to provide input to the KBS-1 performance assessment. The time-constraint of this assessment made it necessary to select easy assessable sites. One of the main reasons to select Sternö was therefore its location on land own by a power company. Another reason was a recommendation to select a site in the region of "the Blekinge Coastal Gneiss". This recommendation was based on experiences from rock caverns in this rock type, which showed favourable characteristics, including low degree of fracturing and low groundwater inflows.

2.3 Investigation periods

The time schedule for the main activities is shown in Figure 2. The main period of site characterization took place between 1977–1979. With the exception of two minor studies (testing of techniques for fracture mapping and a geophysical study of the dolerite dyke) there has been no further activities in the site.

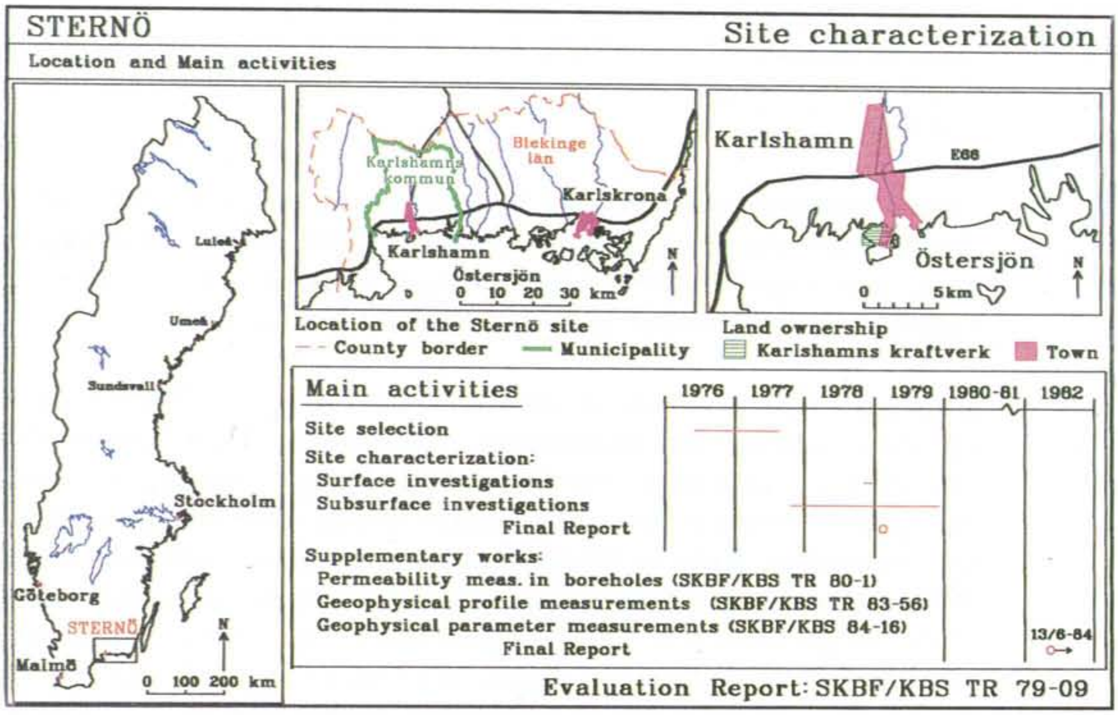


Figure 2. Location of the Sternö study site. Administrative borders and land ownership are shown. Main activities refer to the KBS–1 and KBS–2 studies.

3. SCOPE OF ACTIVITIES

3.1 Reconnaissance

As mentioned earlier the main reasons for selecting Sternö were favourable geologic and hydrologic characteristics in nearby underground constructions in combination with a favourable landownership.

The only reconnaissance studies made consisted of brief visits to the site to confirm favourable conditions. No report exist of the reconnaissance activities for selection of the Sternö study site.

3.2 Surface investigations – regional area

Geology

The geologic and tectonic conditions in the region surrounding Sternö were investigated by Larsson et al. (1977). This study included compilations of existing geologic maps as well as structural analyses and classification of rock units into structural types. Results from inflow measurements to rock caverns in different structural types are presented. The areal extent of the study is shown in Figure 3.

After the site investigations at Sternö were closed several geoscientific maps of the region have been published. Bedrock maps are now available for the Sternö study site and its surroundings in the scale of 1:50 000 (Kornfält and Bergström, 1990a).

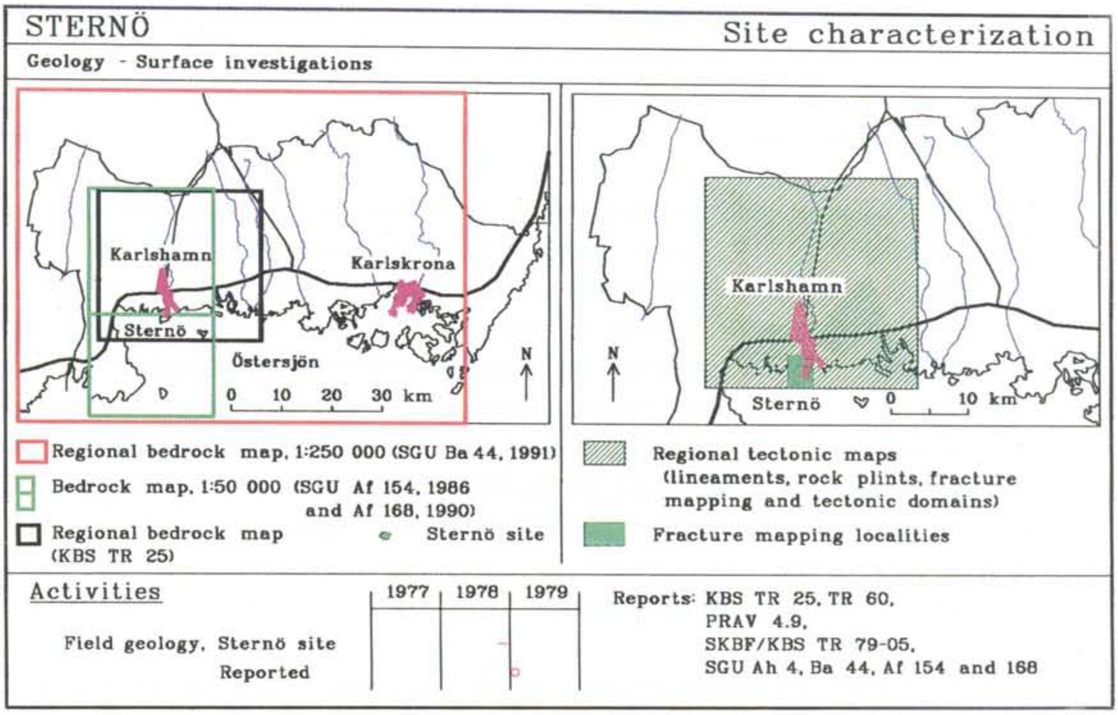


Figure 3. Regional geologic and tectonic maps available for the Sternö study site. Left – areas covered by geological maps. Right – areas covered by lineament and fracture analyses.

Hydrology

With the exception of the studies regarding inflows to the rock caverns mentioned above (Larsson et al., 1977), no hydrological nor hydro-meterological regional studies were made in connection with the Sternö investigations.

A compilation of hydrogeological data for the region (made after the Sternö investigations) is presented in the SGU's hydrogeological map of the Blekinge county (Poussette et al., 1983).

3.3 Surface investigations - Sternö study site

Geology

The geologic surface investigations at Sternö included a map of the bedrock geology (Olkiewicz et al., 1979). The map was made in the scale of 1:10 000 (Figure 10). No other geologic field surveys were made in connection with the investigations of the Sternö study site.

A minor study was made after the main site characterization of Sternö was closed in 1979. The study concerned tests of techniques for scan-line fracture surveys in outcrops (Ahlbom, 1980).

Geophysical surveys

There was no geophysical survey made during the period of site investigations. However, during 1983 one ground and one aeromagnetic profile, Figure 4, were made to determine the dip of the Sternö dolerite dyke (Hesselström, 1983). Also in-situ measurements of susceptibility and remanence determinations on outcrop samples were included in the study. The study utilized an airborne magnetic survey made after the studies of the Sternö study site were finished, Figure 4. The airborne magnetic map is presented in Kornfält and Bergström (1990a). There also exists an unpublished radiometric map for the same region.

3.4 Percussion boreholes

No percussion boreholes were drilled in connection with the site characterization of the Sternö study site.

3.5 Cored boreholes

A total number of 5 cored boreholes have been drilled in the Sternö study site down to a maximum vertical depth of ca 790 m. Geometrical borehole data is presented in Table 1, locations are shown in Figure 5 and drilling periods in Figure 6. Detailed break-downs of activities in each borehole are presented in Appendix A.

3.6 Core loggings

The drill cores were mapped with respect to rock types, fractures and fracture minerals. In total, the drill cores from Sternö amounts to 3 339 m. The results from the core mapping are presented in Scherman (1978) and Olkiewicz et al. (1979).

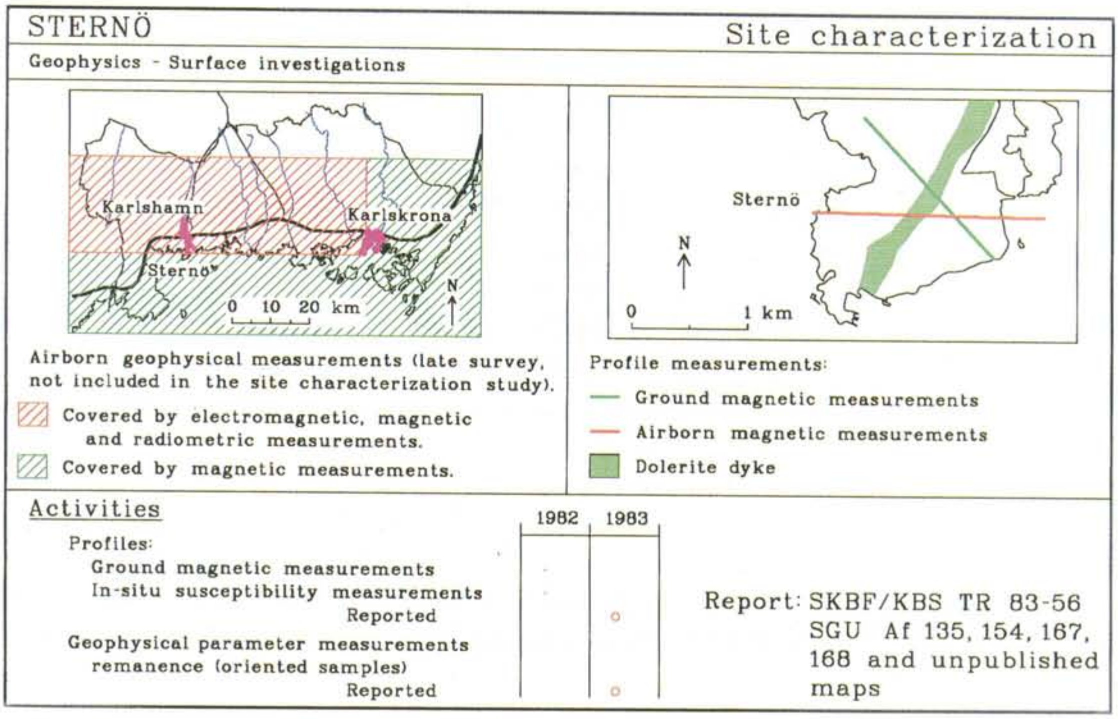


Figure 4. Geophysical surveys made after closure of site investigations. Right – extent of airborne surveys. Left – magnetic profiles.

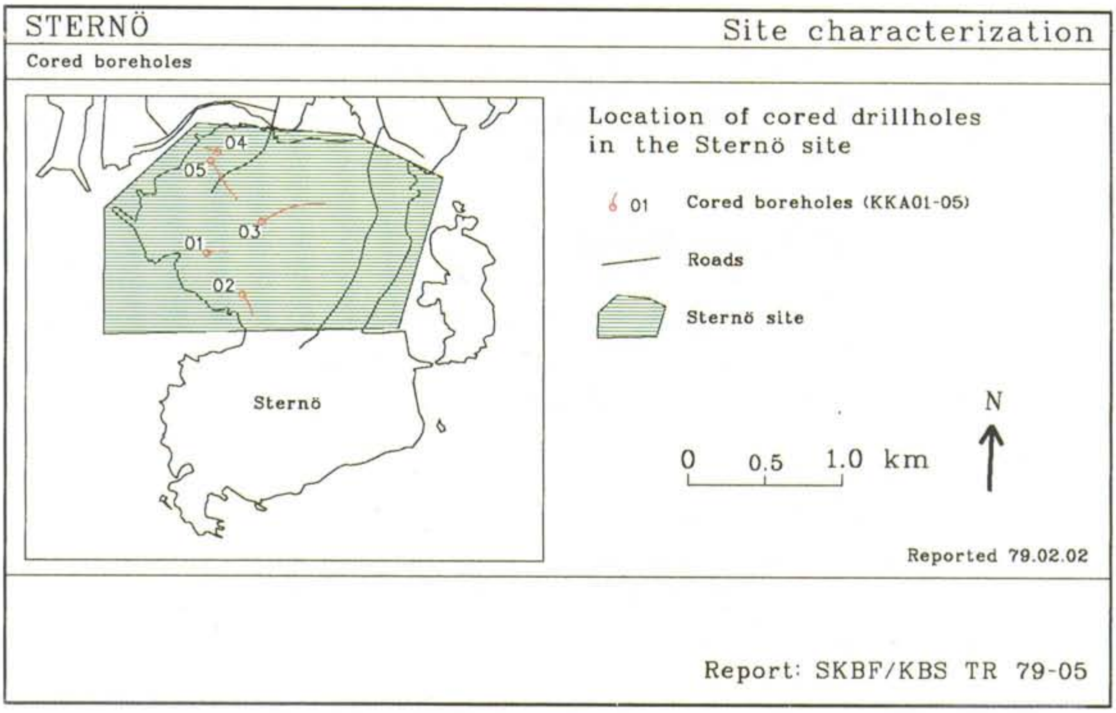


Figure 5. Location of cored boreholes at the Sternö study site.

Table 1. Cored boreholes at the Sternö study site.

No (KKA)	Direction/Dip (start)	Direction/Dip (end)*	Length (m)	Depth* (m)
01	N60E /81	S75E /80	802.6	785
02	S35E /75	S29E /71	578,8	540
03	N62E /52	N86E /54	777,3	575
04	N68W /77	N86W /80	577,3	540
05	S30E /60	S33E /56	602,7	500

*estimated from borehole deviation measurements

Some (7) core samples were taken from borehole KKA01 for rock mechanical analyses (Swan, 1977). Core samples for petrophysical measurements (in total 72 samples) were also taken from borehole KKA01, KKA04 and KKA05. These samples were measured with respect to:

- density
- porosity
- resistivity
- induced polarization

The results are presented in Öqvist and Jämtlid (1984), which also includes a description of the methods used. 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 a hot oven.

3.7 Geophysical logging

Geophysical logging and to some extent TV-logging has been made in three boreholes. The geophysical logs common for all three boreholes are the following (see Figure 6 and Appendix A):

- borehole deviation
- natural gamma radiation
- differential point resistance
- resistivity, normal 5 m, lateral 1.05 and 5.15 m
- resistivity of borehole water

In addition, borehole KKA01 were logged with the following methods:

- induced polarization
- borehole slingram and VLF
- TV-logging

The borehole KKA01 was also logged with a spontaneous polarization (SP) log. However, because of false anomalies due to leak currents from the power plant these measurements are not reported. The geophysical loggings made in each of the cored borehole are presented in Appendix A.

3.8 Hydraulic tests and monitoring

Water injection tests

The hydraulic conductivity of the bedrock has mainly been determined by single hole water injection tests in packed-off 2 or 3 m sections. During the KBS-1 and KBS-2 studies this was made from a depth of 250 m to the borehole bottom for four of the boreholes at Sternö. The exception was borehole KKA04, where no hydraulic tests were made due to lack of time. Complementary measurements were made during the autumn of 1979. These measurements included 3 m packer tests in the entire borehole KKA04 and 3 m packer tests in the surficial parts of the other boreholes (0-250 m). Also single-packer tests were made for all boreholes.

The results from the hydraulic tests are presented by Hult et al. (1978), Gidlund et al. (1979) and Ahlbom et al. (1979). The complementary tests, as well as main results from earlier borehole tests at Sternö, are presented by Ekman and Gentzschein (1980). Activity periods for the hydraulic tests are presented in Figure 7, while the scope is presented in Appendix A.

Groundwater head measurements

The level of the groundwater table was measured during most part of 1979 in the SKB cored boreholes and also in some other boreholes aimed for monitoring groundwater levels in connection to oil caverns in Sternö. The results are presented by Ekman and Gentzschein (1980).

3.9 Groundwater sampling

Groundwater sampling was made from one isolated section in borehole KKA03 and from three sections in borehole KKA04. The chemical characteristics of the groundwaters sampled in these sections are presented by Laurent (1982).

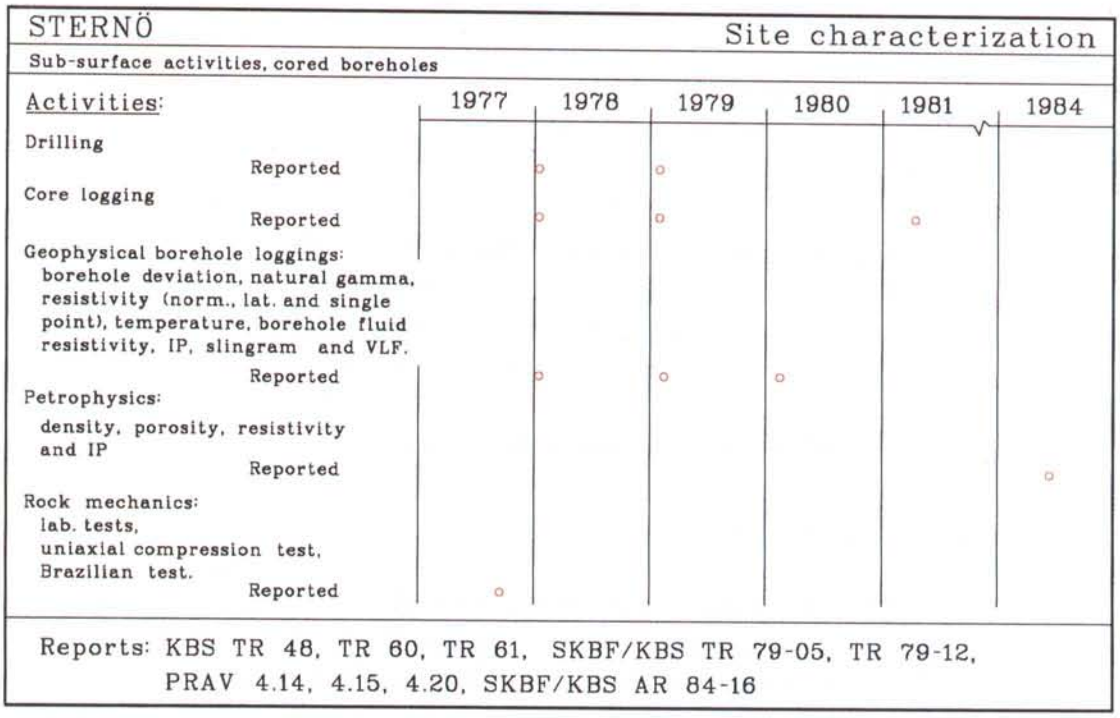


Figure 6. Activity periods – drilling, core logging, geophysical logging and petrophysical measurements on samples from the cored boreholes.

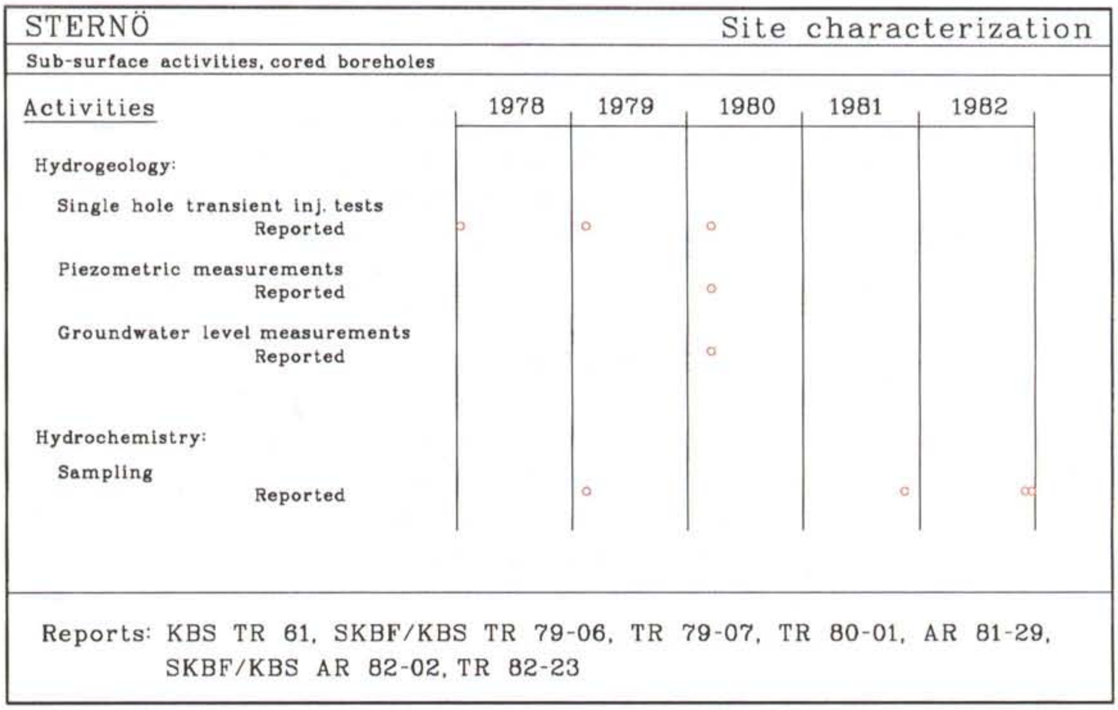


Figure 7. Activity periods – hydraulic measurements and groundwater sampling in the cored boreholes.

4. STORAGE OF INFORMATION IN THE SKB DATABASE

Data from surface surveys

For the Sternö study site the SKB database GEOTAB does not contain any data from geological nor geophysical surface surveys. Nor is any data regarding hydrometerological conditions or groundwater levels stored in the data base.

Data from borehole surveys/tests

GEOTAB contain results from the hydraulic tests at Sternö (both 2 or 3 m sections and single–packer tests). Also some the geophysical logs are stored as well as information regarding borehole geometrical data (coordinates, length, dip, deviation etc). The database does not contain results from core logging, petrophysical and rock mechanical test on core samples nor results from groundwater sampling.

A description of stored data from surveys in each borehole are presented in Appendix A (under the heading GEOTAB in Figures A2–A5).

5. GEOLOGIC MODELS

5.1 Regional geologic models

Geology

The region including the Sternö study site has recently been remapped by the Geological Survey of Sweden (SGU). As a result there are now bedrock maps in the scale of 1:50 000 (Kornfält and Bergström, 1990a) available for this area (3E Karlshamn NO and SO). Also available in these publications are lineament maps as well as airborne magnetic and gravity (Bouguer anomaly) maps in the same scale. In addition, there is a recently published simplified map in the scale of 1:250 000 covering most of the Blekinge county (Kornfält and Bergström, 1991b).

The bedrock surrounding the Sternö study site consists mainly of a Precambrian, medium to fine grained, metavolcanic gneiss denoted the "Blekinge Coastal Gneiss" (Kornfält and Bergström, 1990a). This rock type, together with the more fine–grained metavolcanics of the Västanå complex, constitute the oldest rocks in Blekinge county with an age of about 1 700 million years old (Johansson and Larsen, 1989).

The Coastal Gneiss is reddish grey to grey, quartz–feldspar gneiss with a varying content of mica minerals. Transitions to migmatite or veined gneiss are often observed close to contacts with younger granites. The foliation of the coastal gneiss is commonly oriented between NNE–NNV. In the Karlshamn area also E–W trending foliation is common with gently dips towards north.

Other rock types in Blekinge are (from older to younger); older granitoids (mainly foliated granodiorites), younger granitoids (Karlshamn and Spinkamåla granites) and doleritic dykes. A regional bedrock map is presented in Figure 8. The Karlshamn granite is greyish–red and medium to coarse grained. Characteristic for the granite is its porphyritic appearance with 1–2 cm large augen of microcline. The age of the Karlshamn granite is approximately 1 300 – 1 400 million years old (Kornfält and Bergström, 1990a). The granite is often accompanied by numerous pegmatite dykes and local migmatization of the country rock.

The youngest rocks in Blekinge are the steeply dipping, extensive and wide doleritic dykes. They are 930 million years old (Johansson and Johansson, 1990). These dykes strikes NNE and are up to 200 m wide.

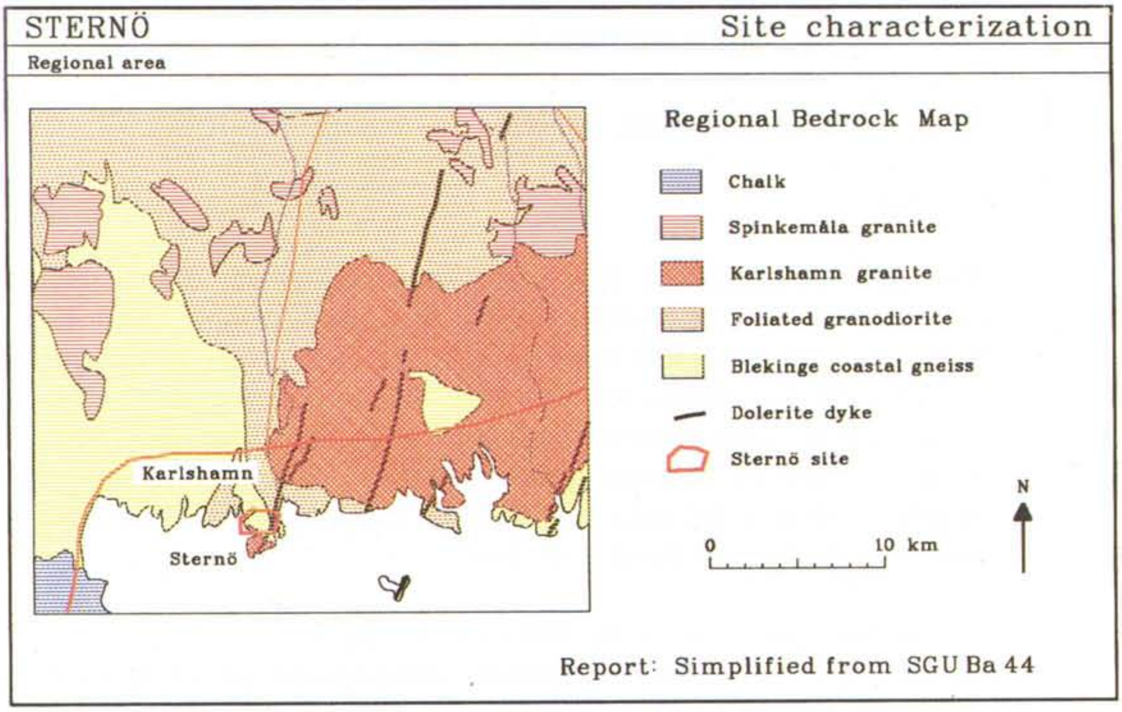


Figure 8. Distribution of rock types in the region surrounding the Sternö study site. (Simplified from Kornfält and Bergström, 1990b).

Lineaments

A map of main lineaments in the western part of the Blekinge county and a model describing their origin is presented by Larsson et al. (1977). Also hydraulic characteristics of different types of fracture zones are postulated based on their mode of origin. The regional lineaments and their interpreted mode of origin is shown in Figure 9.

Two phases of compression are in this model distinguished for the Blekinge county, orientated N–S and NNE–SSW, respectively. Based on these compressional directions, N–S lineaments are interpreted as tension structures, while NW–SE and NE–SW lineaments are interpreted as shear structures.

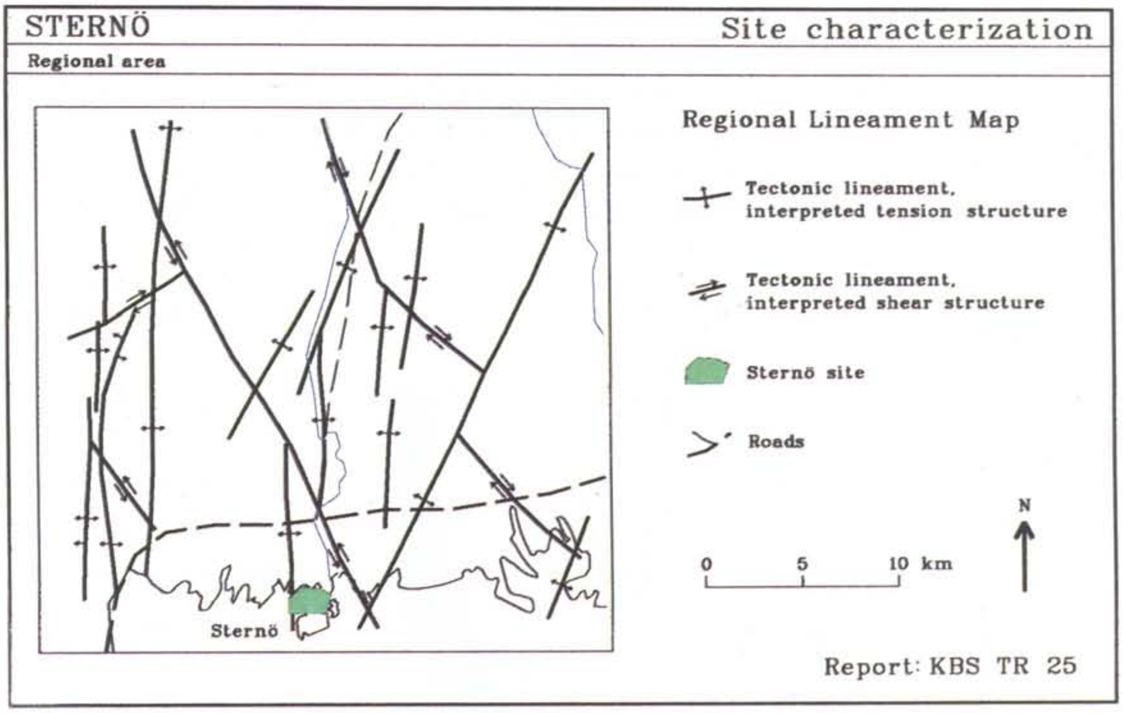


Figure 9. Lineaments in the region surrounding the Sternö study site and their interpreted mode of origin (after Larsson et al., 1977).

5.2 Geological characteristics of the Sternö study site

Rock types

The Sternö study site is dominated by the Costal Gneiss, Figure 10. The gneiss is at the site generally fine grained. Varying orientation of the foliation is characteristic in localities where Coastal Gneiss occurs close to large intrusions of younger granite. Pegmatite and fine grained aplite dykes occurs frequently in the northern part of the site (Olkiewicz et al., 1979).

In the southern part of the site numerous dykes of Karlshamn granite penetrates the coastal gneiss. Characteristic for these dykes are the mega-crysts of microcline described earlier. Hybridic rocks formed by assimilation of the Costal Gneiss by the Karlshamn granite are also found within this area, as well as bodies of medium grained foliated granodiorite.

South of the site, in the southernmost part of the Sternö peninsula, there is a large area with Karlshamn granite. This occurrence, in combination with frequent occurrence of dykes and pegmatites within the site, indicates that Karlshamn granite occurs beneath the Coastal Gneiss. This was also confirmed by the core drillings.

Four different rock types have been mapped in the drill cores. These rock types are: the Costal Gneiss (36 %), foliated granodiorite (often denoted gneissic granite in the core logs) (36 %), Karlshamn granite (12 %) and pegmatite and various types of hybridic rock types (14 %).

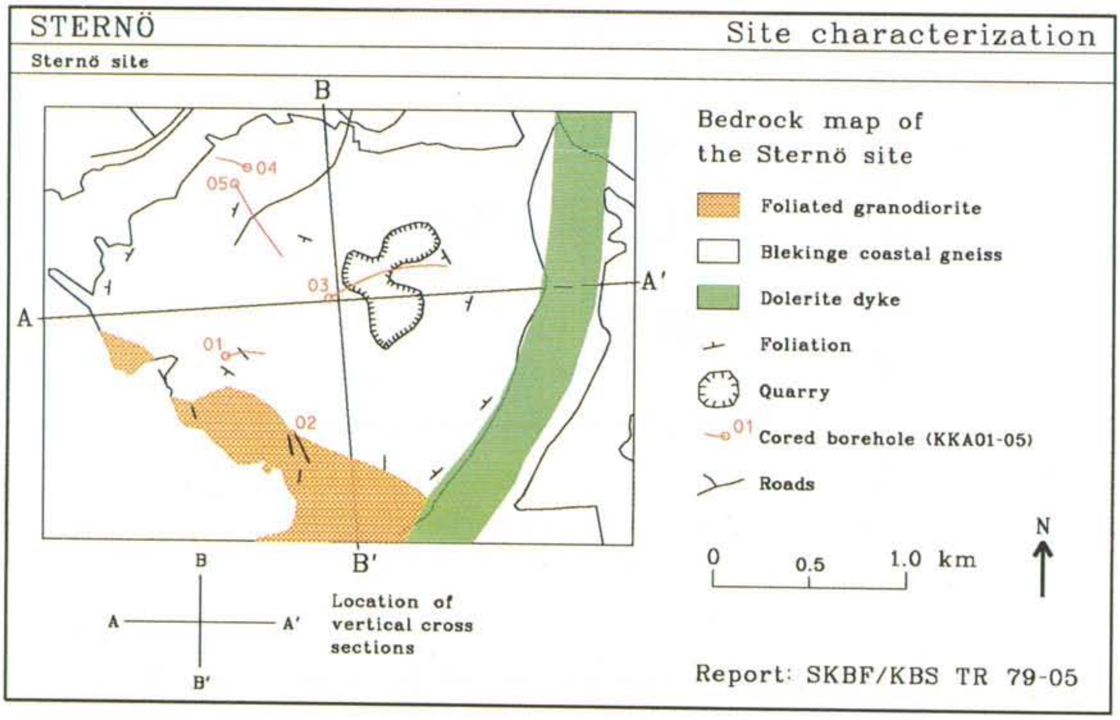


Figure 10. Bedrock map of the Sternö study site.

Fractures

The investigations at Sternö did not include fracture mapping. However, a later scan–line survey, performed along a profile in the southern part of the Sternö (Ahlbom, 1980) showed that the degree of fracturing is low for most rock types at Sternö. An exception is the dolerite dyke which displays a high fracture frequency, although this is based on one locality only. The reporting do not include any compilation on fracture orientations. The fracture frequency for different rock types is shown in Table 2.

Also in most of the cores the degree of fracturing is low. A compilation of fracture frequency for the boreholes is shown in Table 3. In this compilation it is assumed that the sections in the core logs which are denoted as "fracture zone" and "crushed zone" consist of fractures with a spacing of 5 cm or less.

Table 2. Fracture frequency of different rock types in the Sternö study site.

Rock type	Fracture frequency (fr/m)	Standard deviation	Number of localities
Coastal gneiss	1.1	0.4	7
Foliated granodiorite	0.8	0.4	13
Granite	0.9	0.2	5
Dolerite	3.7	–	1
All measurements (not including dolerite)	0.9	0.4	25

A comparison between Table 2 and Table 3 (below) shows that the fracture frequency is 50 % higher in the cores at the upper 100 m, compared to fracture frequencies measured in outcrops. There are several possible reasons for this discrepancy. One possible reason is the influence on the records by a dominance of horizontal or gently dipping fractures. Another is the influence of short fractures (less than 0.5 m) which are mapped on the cores but not by the fracture mapping on outcrops.

The main observation, when studying Table 3, is the general very low fracture frequency at depth for all boreholes except KKA04. The latter borehole is interpreted to penetrate Zone 2. Common fracture filling minerals are calcite, chlorite, pyrite and gypsum.

Table 3. Mean fracture frequency (fr/m) versus depth for boreholes at the Sternö site. Interval represent distance along the core. For boreholes KKA01, 02 and 04 this is almost similar to depth intervals.

Interval (m)	Boreholes KKA01	KKA02	KKA03	KKA04	KKA05
0–100	0.36	1.65	1.27	1.29	1.62
100–200	0.35	1.39	0.89	1.31	1.13
200–300	0.04	0.26	0.38	2.12	0.72
300–400	0.31	0.47	0.75	4.70	0.27
400–500	0.10	0.78	0.24	6.50	0.18
500–600	0.13	0.19	0.39	0.73	0.10
600–700	0.00		0.15		
700–800	0.01		0.02		
Mean fracture frequency	0.16	0.82	0.53	2.87	0.67

5.3 Fracture zones

Fracture zones were interpreted from aerial photographs (scale 1:20 000), topographical maps (1:50 000) and from geological surface mapping. All together six possible fracture zones were interpreted within and surrounding the Sternö study site. As discussed in Section 2.1 "the SKI geology group" suggested several additional fracture zones, of which one were accepted as possible. This zone is here denoted Zone 7. The zone is interpreted from topographical data only (see Appendix C).

Two fracture zones, Zone 2 and 4, have been examined by means of the cored boreholes KKA04 and KKA03, respectively. Zone 2 is characterized by a generally high fracture frequency, including crushed zones, in the cores of borehole KKA04 between 200–500 m. In contrast, Zone 4 is only apparent in the core logs as a 2 m section of increased fracture frequency, including a minor crushed section. In spite of this, the width of Zone 4 has been estimated to 10–80 m, mainly because of results from borehole hydraulic tests (Chapter 6). Both zones, as well as all other fracture zones at Sternö, are assumed vertical. Descriptions of each 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 11. Since all fracture zones are assumed vertical, the locations at 500 m depth will not change. Approximately north–south and east–west cross–

sections are shown in Figure 12. The interpreted locations of each fracture zone in the boreholes KKA03 and 04 are presented in Appendix B.

5.4 Validity of models

Rock type distribution

The site investigations at Sternö has resulted in a geological map and in detailed core logs. These data has not been compiled into a 3D model. Only some generalized statements concerning the distribution of rock types with depth are presented in the reports. The validity of the geologic map can be tested by comparison with the recent SGU bedrock map (Karlshamn NO and SO, Kornfält and Bergström, 1990a). There is good agreement between the two maps. Since no 3D model of rock type distribution exists for the site no assessment regarding its suitability can be made.

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 a judgment regarding the reliability in the interpretation, mainly based on the nomenclature suggested by Bäckblom (1989). 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 should only be regarded as "possible" or "probable", thus implying large uncertainty in the interpretation.

The reason for the low reliability of the interpreted fracture zones at Sternö is simply because only two of them are tested by boreholes. All others are only interpreted from topographical indications.

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

Fracture zone	Reliability
Zone 1	Possible
Zone 2	Probable
Zone 3	Possible
Zone 4	Probable
Zone 5	Possible
Zone 6	Possible
Zone 7	Possible

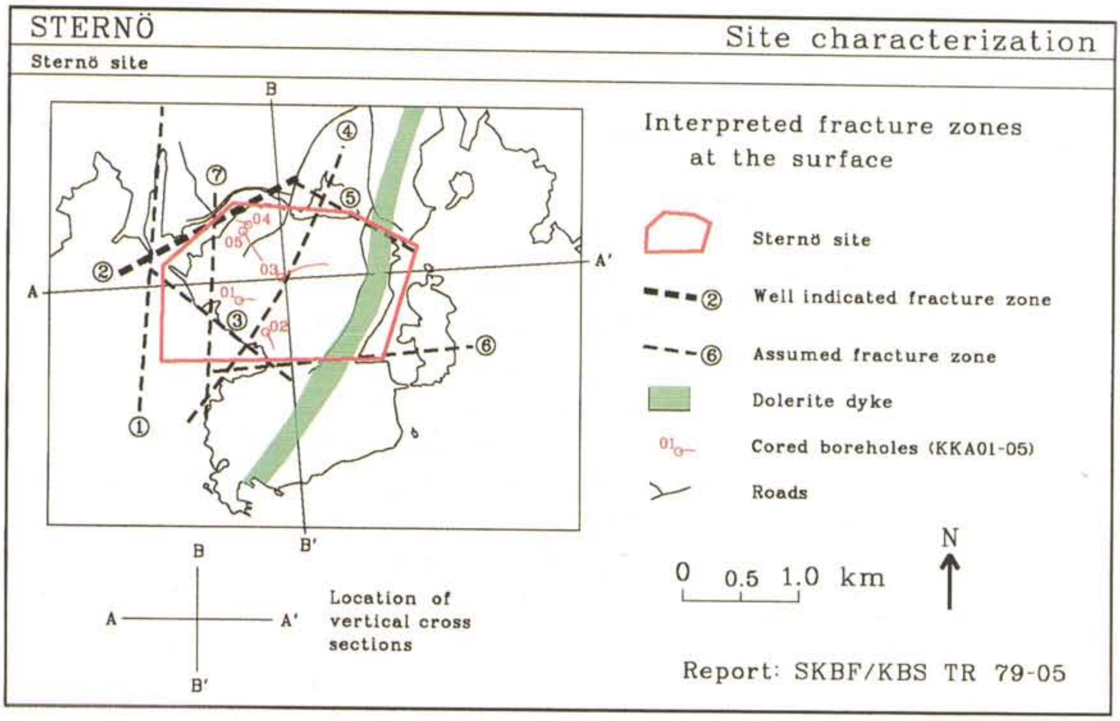


Figure 11. Interpreted fracture zones at the ground surface.

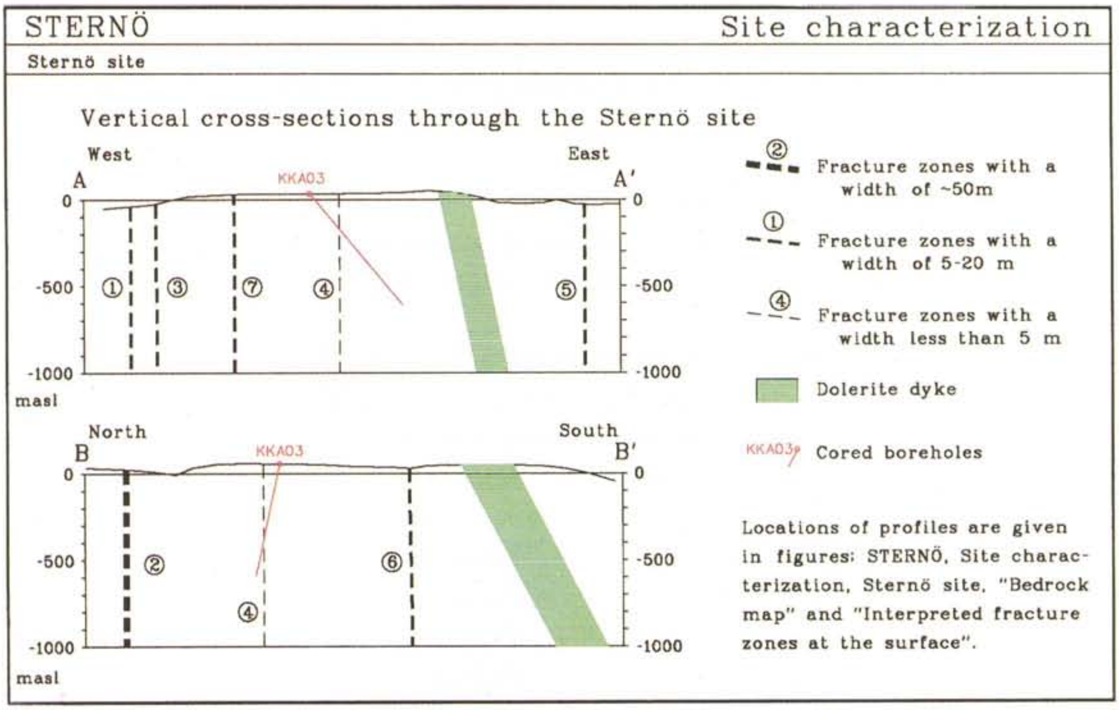


Figure 12. Vertical cross–sections through the Sternö study site. The locations of the sections are shown in Figure 11.

6. GEOHYDROLOGICAL MODELS

6.1 Available data and numerical model

The geoinformation used for hydraulic modelling of the Sternö study site consist of a preliminary conceptual model of fracture zones, distribution of rock types in outcrops and in drill cores and hydraulic conductivity data, both from single packer- and double packer tests. The background data are presented in Ahlbom et al. (1979) and Ekman and Gentzschein (1980).

Table 5 presents the number of single hole water injection tests carried out. To provide an estimate on "investigation density" also the number of tests per square kilometer of the site is presented in the table. The size of the Sternö study site is approximately 2.5 km^2. Five deep core boreholes were tested hydraulically (c.f. Appendix A).

The number of tests/km^2 carried out in the Sternö study site is apparently high compared to e.g. Fjällveden and Gideå sites. This is because all double-packer tests at Sternö were performed in short sections (2 and 3 m), while at Fjällveden and Gideå the double-packer tests were performed in longer sections (25 m). The accumulated borehole length covered by continuous double-packer tests is about 3.2 km at Sternö which should be compared with 5.5 and 7.7 km respectively for the Fjällveden and Gideå sites.

Table 5. Number of borehole sections tested with different length together with the number of tests per km^2 in the Sternö study site. After Ekman and Gentzschein (1980).

Number of sections	Section length (m)	No of tests per km^2	Test type
379	2	152	double-packer
798	3	319	double-packer
40	65-749	16	single-packer
1217		487	all sections

Geohydrological modelling in sections in the Sternö study site has been performed by Stokes (1979) and Axelsson and Carlsson (1979). In the former modelling isotropic conditions were assumed with a constant hydraulic conductivity throughout the rock within the entire area. No division in fracture zones and rock mass was performed. In the latter modelling tectonic zones with increased hydraulic conductivity and rock mass with a decreasing conductivity with depth were considered.

The modelled sections were selected on the basis of topographical, geological and tectonic information. The material properties, i.e. the hydraulic conductivity of the structures assumed in the modelling, were based on the hydraulic borehole tests. The numerical code used in both cases (GEOFEM-G) presumes two-dimensional plane-parallel or axi-symmetrical flow in a confined aquifer (Runesson et al., 1978). Axi-symmetrical flow refers to flow directed radially around a symmetrical axis. The basic assumption in the model code used is that the bedrock can be represented by either one single continuum (porous medium) or by several overlapping continua, e.g. rock mass and fracture zones.

The model calculations do not take into account possible effects of temperature and viscosity on the hydraulic conductivity. Nor do they account for pressure dependence of the hydraulic conductivity.

6.2 Regional model

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

6.3 Local model

Modelled sections and boundary conditions

The groundwater head conditions in the deep bedrock of the Sternö peninsula were modelled along five vertical cross sections (A–E) shown in Figure 13. The central part of Sternö constitutes an elevated area with the highest point located about 50 m above the Baltic sea level. This point is roughly located at the intersection between the sections C, D and E in Figure 13. From the elevated area the ground level generally slopes continuously towards the Baltic sea. The mean groundwater table in the site is 25 m above the sea level.

The assumed groundwater table along sections A and B, used in the modelling of these sections as the upper boundary condition (zero prescribed pressure), is shown in Figure 13. These two sections run along interpreted fracture zones (Zones 2 and 4, Figure 11). In the modelling of sections C, D and E the groundwater table was assumed to coincide with the ground level (and sea level) together with the interpreted groundwater table in the points of intersections with sections A and B. All sections were modelled to a vertical depth of 5 000 m, where a non-flow boundary condition was applied. The lateral boundaries also constitute non-flow boundaries.

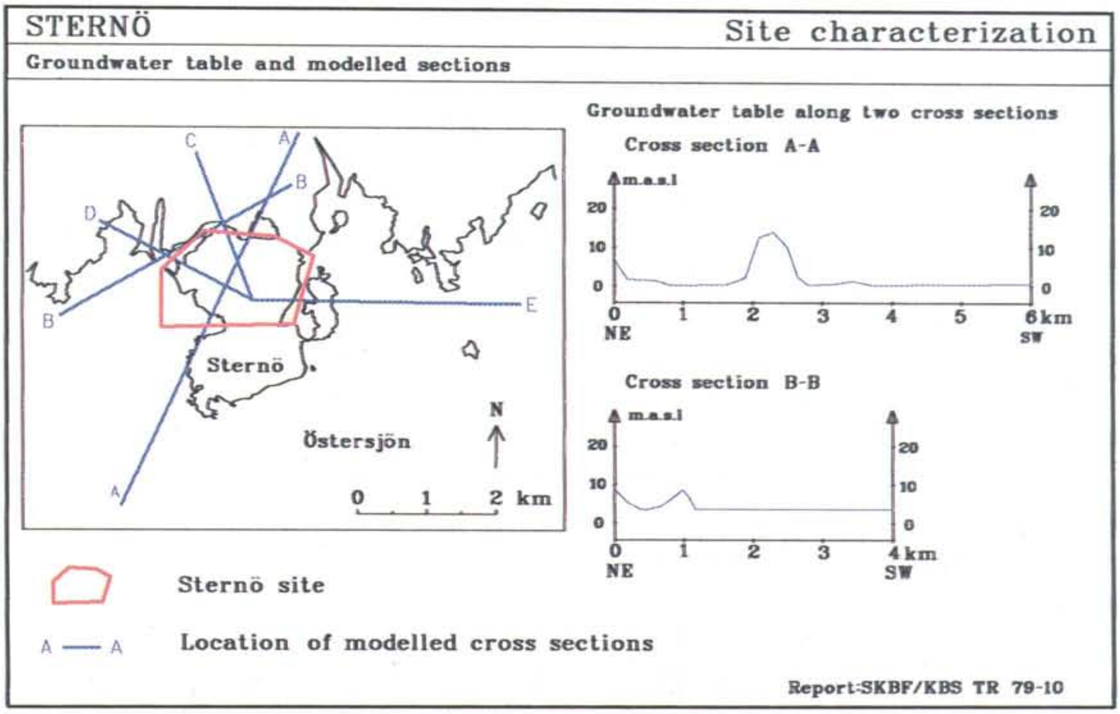


Figure 13. Modelled sections and assumed groundwater table along sections A–A' and B–B'.

Hydraulic units

Three hydraulic units were assumed in the modelling of the Sternö study site; 1) homogeneous rock mass, 2) fracture zones and 3) intersections between fracture zones. The surface locations of the fracture zones are shown in Figure 11, while the assumed widths are presented in Table 6. The intersections between boreholes and fracture zones are described in Appendix B.

All fracture zones were assumed to be vertical in the modelling. This also included the dolerite dyke, Figures 11 and 12, however, since no hydraulic data from this dyke are available it was omitted in the modelling. No subdivision of the rock mass with respect to rock types was made in the modelling.

Table 6. Assumed width of modelled fracture zones in the Sternö study site. (From Axelsson and Carlsson, 1979).

Fracture zone	Modelled width (m)	dip(°)
1	30	90
2	30	90
3	5	90
4	10	90
5	5	90
6	10	90

Hydraulic conductivity

Hydraulic conductivity functions versus depth were assigned to the hydraulic units defined in the model. Figure 14 shows all measured hydraulic conductivity data from double packer tests in 2 m and 3 m test sections versus depth together with results from single packer tests in the deeper part of the boreholes in the Sternö study site (Ekman and Gentzschein 1980). Both hydraulic conductivity data from the rock mass and fracture zones are included in Figure 14. Data from the double packer tests in the interval 367.8–577.8 m in borehole KKA05 have been excluded due to a presumed equipment failure. The lower measurement limits of hydraulic conductivity used by the testing in the different boreholes are clearly seen.

No division of the measured data into different hydraulic units was made. However, in the hydraulic modelling certain functions between hydraulic conductivity versus depth were assumed for the different hydraulic units described above. The conductivity–depth functions are described in Table 7.

Table 7. Assumed hydraulic conductivity versus depth for the hydraulic units used in the modelling. (From Axelsson and Carlsson 1979).

Hydraulic unit	Depth interval (m)	K (m/s)
Rock mass	0–300	$1 \cdot 10^{-8}$
	300–5000	$1 \cdot 10^{-11}$
Fracture zones	0–5000	$1 \cdot 10^{-6}$
Intersections between zones	0–5000	$5 \cdot 10^{-6}$

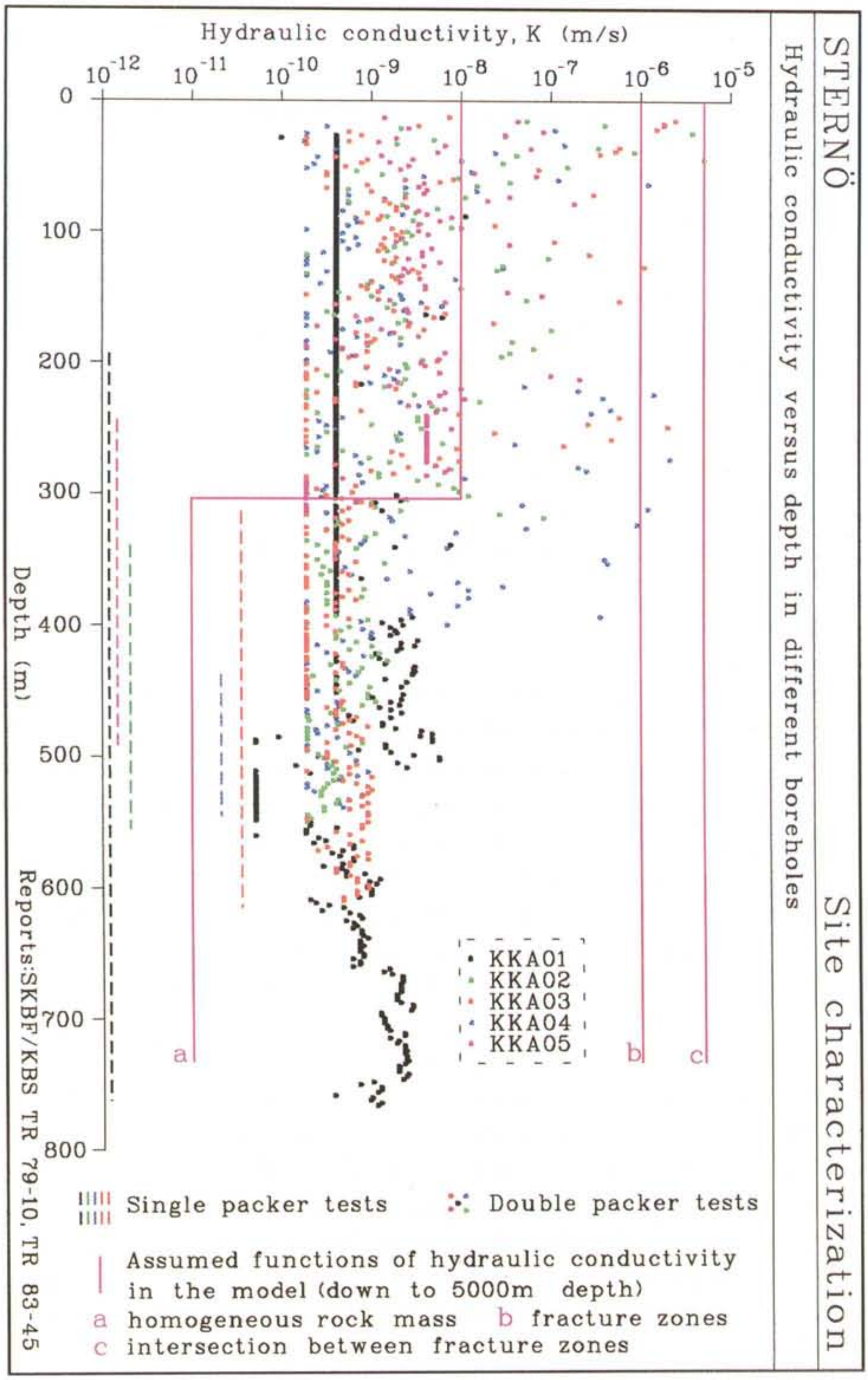


Figure 14. Measured hydraulic conductivity versus depth in the Sternö study site. The conductivity–depth functions assumed in the hydraulic modelling for hydraulic units are also shown.

Model cases

Five sections (A–E in Figure 13) were modelled. The groundwater head and flow conditions were calculated assuming natural conditions and a groundwater discharge of 4 m^3/day (0.05 l/s) in the upper 100 m of the bedrock at the intersection with Zone 4. In addition, a special case was modelled with no intersecting fracture zones in section C. The distribution of groundwater heads were calculated along each section. Based on these head distributions, groundwater travel times was calculated from a depth of 500 m to a nearby fracture zone or to the uppermost 300 m of the bedrock. These calculations assumed a hydraulic conductivity of $1 \cdot 10^{-11}$ m/s and a kinematic (flow) porosity of $1 \cdot 10^{-4}$.

The calculated groundwater travel times in sections C and D are shown in Figure 15 and 16, respectively. The distance is calculated from the top of the central elevated area, i.e. at the intersection between the sections, Figure 13.

Results

The model calculations (Axelsson and Carlsson, 1979) show that the groundwater flow within the centrally located area is largely directed downward, i.e. the area constitutes an inflow area. The groundwater flow in the rock mass between Zones 4 and 2 is directed slightly downward but largely parallel to the ground surface. The main groundwater flow takes place in the upper parts of the bedrock. The groundwater flow at repository depth, i.e. 500 m, is estimated to 2–16 ml/m^2/year in the rock mass along sections C–E. The highest flow rates occurs in the central part of Sternö. A flow divide cause a discontinuity in the curve between Zones 4 and 2.

The groundwater travel times from the central elevated area to Zone 4, are considerably shorter in the case when the fracture zone is present due to its pressure–equalizing effect. Also the groundwater travel times in the bedrock between the locations of Zones 4 and 2 are longer if fracture zones are included in the model. This is because the groundwater flow is directed slightly downwards when the fracture zones are present and upward when not. The latter is a shorter flow path. In combination with higher hydraulic gradients this results in shorter groundwater travel times in the case when no fracture zones are present.

A groundwater discharge at Zone 4 results in shorter travel times between the central elevated area and Zone 4 and in longer travel times between Zones 4 and 2 (Figure 15). These changes is due to an increased hydraulic gradient in the central area and a reduced gradient between Zones 4 and 2.

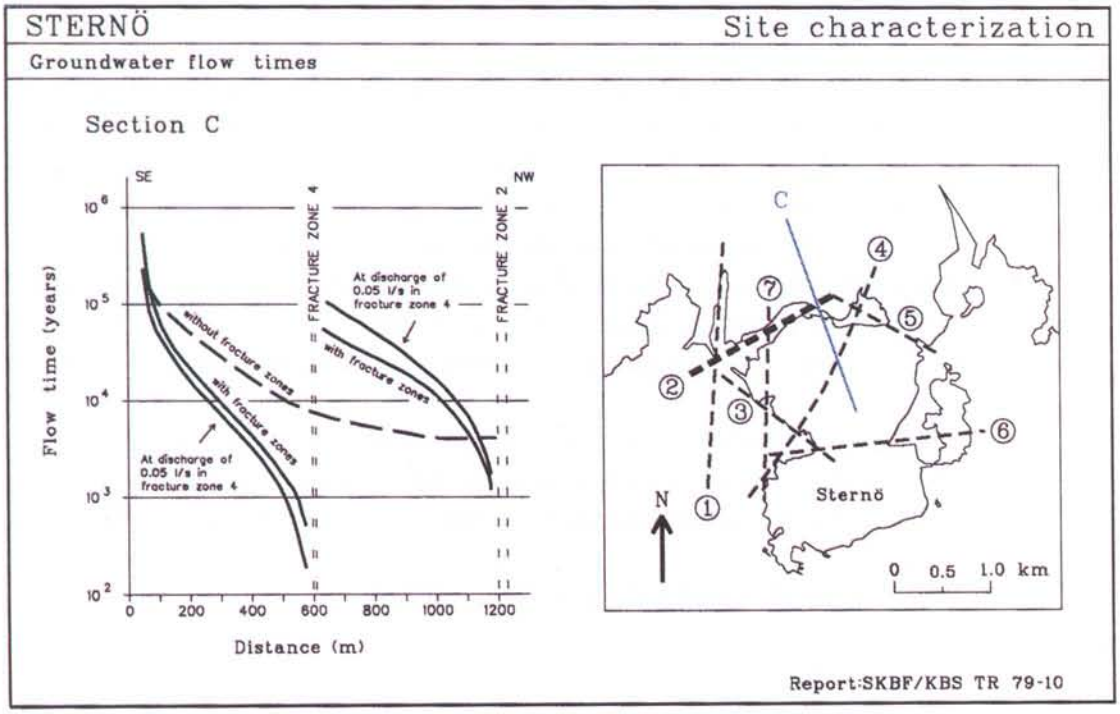


Figure 15. Groundwater travel times along Section C. From Axelsson and Carlsson (1979).

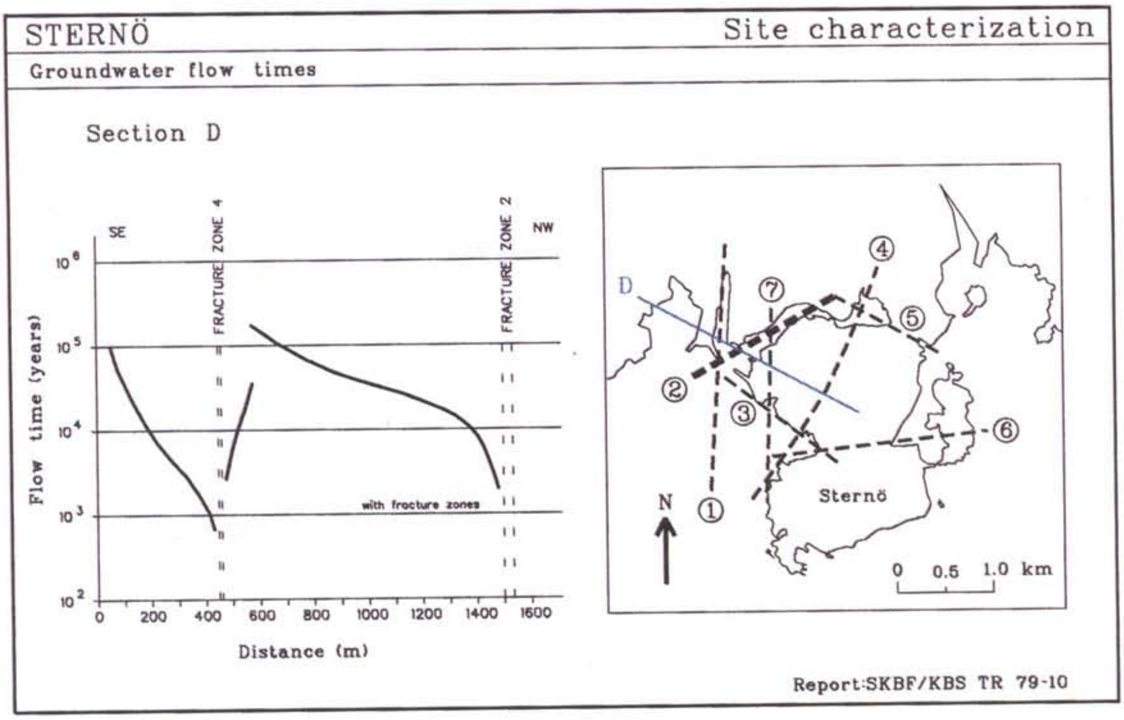


Figure 16. Groundwater travel times along Section D.

6.4 Validity of model results

No calculations of groundwater recharge or mass balance studies nor comparisons of calculated and measured groundwater potentials along boreholes were carried out in the Sternö study site to assess the relevance of the results. The model results must be therefore regarded as preliminary. This is also because of the relatively simple assumptions made concerning boundary conditions, fracture zone geometry and hydraulic conductivity distributions. Particularly the knowledge of the geometry and hydraulic properties of fracture zones is considered insufficient for comprehensive modelling.

In spite of the uncertainties discussed above, it is interesting to note that the calculated groundwater flow rates at 500 m depth in Sternö are in the same order as for the other and more comprehensively modelled SKB study sites.

7. GROUNDWATER CHEMISTRY

7.1 Scope

The groundwater chemistry data available from this site was obtained during 1979–80. Two boreholes were sampled, KKA03 and KKA04. One section at a depths of 232 m in KKA03 was sampled, while three section at depths of 226, 312 and 397 m were sampled in KKA04. The results, including sampling methods, are presented by Laurent (1982).

In the following sections some of the results of the chemical analyses from the Sternö borehole sampling 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.

The results from the chemistry measurements have to some extent been commented on by Bergman and Laurent (1982), regarding analytical procedures, and by Hultberg et al. (1981). However, no proper interpretation or discussion of the reliability of the groundwater samples is available, similar to what was carried by Smellie et al. (1985) for the KBS–3 sites, where geology, hydrology, and chemistry were considered in combination.

7.2 Results

General chemistry

The chemical composition of the samples from the different boreholes at Sternö is shown in Table 8. There are no general trends with depth considering pH, electrolytical conductivity or the major–ion chemistry in the Sternö study site. All samples show relatively high contents of the major ions, with remarkable high sulfate contents. None of the samples show any significant marine influence.

Table 8. General chemistry parameters for groundwaters at Sternö.

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
KKA03	232	6.3	67	17	127	9.5	2.7	265	20	160
KKA04	226	7.5	69	54	75	18.0	3.1	293	36	118
KKA04	312	7.2	66	53	85	16.0	3.2	293	36	110
KKA04	397	7.3	71	58	80	17.0	3.2	295	41	112

As no further interpretation of this data has been made, there is no information about to what extent these samples are representative for the depth sampled. All samples in KKA04 show almost identical chemical composition, while the sampled section in KKA03 differ slightly but distinctly from those in KKA04.

Redox–sensitive parameters

A summary of obtained data regarding the redox–sensitive parameters is presented in Table 9. The table shows that essentially no relevant information is available on redox conditions at this site. The analyses of iron contents are likely to be very sensitive to oxygen contamination during the sampling procedure, and are probably of very little value.

Table 9. Redox parameters of the groundwaters at Sternö.

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
KKA03	232	–	26	27	–	–	*	*
KKA04	226	–	2.3	10	–	–	*	*
KKA04	312	–	9.5	9.7	–	–	*	*
KKA04	397	–	1.1	14	–	–	*	*

* reported values not expressed as nitrogen

Uranium geochemistry

Measurements of uranium content and activity ratio $^{234}U/^{238}U$ was performed for only one section, KKA04 at 397 m depth. The groundwaters from this sampling had a uranium content of 0.56 ppb and an activity ratio of 1.5.

Environmental isotopes

A summary of some of the analyses of the environmental isotopes are presented in Table 10. The results are briefly discussed in Tullborg and Larson (1982). Again, there are no particular trend with depth, and the isotope composition is almost identical for all sections in borehole KKA04. On the other hand, the sample from KKA03 differs from those in KKA04, which also could be seen from the general chemistry data. All data display isotopic values typical for meteoric water.

Table 10. Environmental isotopes in groundwaters from Sternö.

Sampled borehole	Depth m	Tritium TU	^{14}C years	$\delta^{18}O$ ‰ vs SMOW	$\delta^{2}H$ ‰ vs SMOW
KKA03	232	77	1440	−8.8	−59
KKA04	226	58	2025	−10.0	−69
KKA04	312	61	2040	−10.0	−71
KKA04	397	60	2065	−9.9	−71

7.3 Summary and relevance of results

A total of 2 boreholes and 4 different sections have been sampled. The sampled sections are all relatively shallow. The general chemistry data suggest that the groundwaters at the site have high major ion contents, are moderately saline (but not marine), and have relatively high sulfate contents. There are no apparent trends with depth, although the two boreholes show a difference in character. However, such a comparison is very dubious, since it is likely that only one type of water from each borehole has been sampled. There is no direct information about redox conditions however, the presence of Fe^{2+} indicate that the samples come from a reducing environment.

Sternö was one of the first study sites were attempts were made to collect groundwaters from the deep bedrock. Instruments used were prototypes and no measures were taken to minimize the effects of contaminations from the drilling and the hydraulic tests on the chemical samples. Consequently, the general reliability of the groundwater samples is low. Furthermore, a proper understanding of groundwater characteristics with depth needs a thoroughly analysis of the geological, hydrological and chemical information in combination. No such analysis has been done for the Sternö groundwaters. Thus, nothing can be said about the representativity of the samples for the depth sampled.

8. ASSESSMENT OF SOLUTE TRANSPORT

8.1 General considerations

No specific model of solute transport at the Sternö study site exists. However, a model of the groundwater system at the site does exist (Axelsson and Carlsson, 1979), and 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 Sternö study site may be evaluated. All of the uncertainties that are relevant to the model of the groundwater systems, 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 Sternö model considers two–dimensional vertical sections through a block 5–6 km across and 5 km deep, wherein external and bottom boundaries are closed to flow, and the upper boundary is the groundwater table with maximum relief of about 40 m. The depth to the bottom of the block was arbitrarily chosen. In model analyses of the site, no variations were carried out to examine the implications for flow and transport of the location and type of boundary conditions.

Model sections A (Zone 4) and B (Zone 2) represent groundwater flow within fracture zones. Sections C, D, and E represent various vertical sections through bedrock blocks. Sections C and D intersect the above fracture zones. One end of sections C, D and E is located at the center of Sternö (a groundwater table divide) and the other end is located at an apparently arbitrary distance from this point.

Steady–state hydraulic heads are first obtained separately in fracture zone sections A and B, with no–flow boundary conditions at all sides but the top at which a water table elevation is specified. Then heads are modelled for Sections C and D in three sub–portions of each section. In the first sub–portion, cylindrical symmetry is assumed in the flow field between Sternö center and the intersection with section A.

Boundary conditions on Sections C and D for the first sub–portion are no–flow at bottom and Sternö center, a top groundwater table, and heads determined from the model of section A where it intersects with either C or D. The next sub–portions of C and D extend from their intersection with A to their intersection with B. Planar flow is assumed for this portion, with no–flow at the bottom, a top groundwater table, and vertical boundary heads specified according to the independent calculations for sections A and B. The third sub–portions of C and D extend from their intersection with B to an arbitrary end. Boundary conditions on planar flow in these sub–portions are a top groundwater table, heads along the intersection with B taken from the B model, and no–flow at the bottom and the outside vertical side. Thus, the head distributions presented for Sections C and D (Figures 7–12 of Axelsson and Carlsson, 1979) are either composites of model runs on each of three sub–portions, or the mathematical equivalent of separate model runs. Section E is calculated in a single model with no–flow along bottom and vertical sides, and a top groundwater table.

Two possible problems exist with the boundary conditions. First, the heads at the intersection of Zones 4 and 2 do not agree where model sections A and B intersect as they probably should (compare Figures 7 and 8 in Axelsson and Carlsson, 1979). Second, the physical reason for, or interpretation of, cylindrical symmetry in sub–portions of sections C and D is not clear. The assumption implies that the head calculated in Zone 4 (Section A) at the intersection with C or D applies in any direction from Sternö's center. This is not justified in the model analysis.

The combination of boundary specifications used may cause unnatural conditions of modelled solute transport through the repository level of the site in three ways, all of which may strongly affect magnitude and direction of flow. First, because all external 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. Third, because heads do not agree in Zones 2 and 4 where they intersect, discrepancies may occur in the resultant flow fields.

Under natural conditions, however, different flow fields would occur if water flowed across some of the vertical sides. In one situation, waters in the bottom portion of the modelled sections have their recharge area located at considerable distance outside of the study 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.

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. 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 variation at the Sternö study site which eliminates discrete fracture zones. Thus predicted transport 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 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 analysis for the site, 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. While no variations of hydraulic conductivity distributions were tested in the Sternö model, such parameter variations may indeed have limited effect on flow behavior and transport through the site (flow direction and travel times). 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 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.

8.2 Transport Calculations

The report by Axelsson and Carlsson (1979) describes a model analysis of the groundwater system at the Sternö study site. This is one of the most insightful of the study sites modelled in the SKB program. Because of the limitation of the two-dimensional model employed to describe a three-dimensional flow field, the authors had to carefully consider conceptual models of how the groundwater system worked rather than simply entering all existing data into a numerical code. This is a vital step in a model analysis, and in the Sternö case, helped to represent some of the important hydrogeological features of the site that were known at the time of modelling in a strong manner. The conceptual model assumed that the controlling structures in the area were the fracture zones. Groundwater flow in each of these was simulated in a two-dimensional section. Then, having obtained steady hydraulic heads in the fracture zones, various sections through Sternö in directions generally perpendicular to the fractures were modelled using the fracture zone head (and local groundwater table topography) as top and internal boundary conditions to the low conductivity blocks. This separation of the Sternö system into hydrogeologic components could have allowed for more direct manipulation of important features such as boundary conditions and connectivity than a three-dimensional model of the same system. However, only one variation of connectivity was evaluated in the study.

Groundwater travel times from a repository at the −500 m level are shown for cases with and without high conductivity fracture zones (Figures 15–16). Travel times for various paths to the surface, beginning at the −500 m level, are reported for both cases. The travel times for the case with conductive fractures are from a few hundred years to a few hundred thousand years. Without fracture zones, predicted travel times are between ten thousand and a few ten thousands of years longer for most paths.

8.3 Implications of existing information for solute transport

The groundwater system model analysis of the Sternö study 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 at the site. Under the conditions studied, travel times are predicted within large ranges, from as little as few hundred to as much as a few hundred thousand years. Travel times and paths are found to be most dependent on the existence of conductive fracture zones, but tests where these structures and their assumed connectivities were varied were not carried out. Rather the only variation concerned the existence or non-existence of conductive zones. This, however, resulted in a significant difference in transport times.

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 possibly and even likely that the −500 m level at each site 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 groundwater table topography within the site area. Flows at depth may be driven by a more regional gradient in the groundwater table, a possibility that is excluded by the choice of closed vertical boundaries in the model.

Considerations towards improving the transport predictions of the 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 wherein a repository would be situated. Closed vertical boundaries at arbitrary locations may not simply be applied to deep flow systems. Such an assumption, even when inappropriate, is decisive for the groundwater flow and transport that occurs at depth in a model, and essentially overrides other considerations such as conductivity distribution. Further, information on conductive structures which control flow and transport that depends on structures which intersect the ground surface is not likely sufficient to describe the connectivity at depth which may also depend on sub-horizontal zones that do no outcrop.

9. ROCK MECHANICAL CONDITIONS

None of the boreholes at the Sternö study site have been tested to determine the stress field in the area. The rock mechanical investigations is limited to laboratory determinations of some mechanical properties on core samples from borehole KKA01.

9.1 Mechanical properties of the bedrock

At the Sternö study site the following laboratory tests were conducted to determine mechanical properties of the rock (Swan, 1977):

- Uniaxial compression tests
- Brazilian disc tests

Samples for testing were taken from borehole KKA01 at three depth intervals; 0–100 m, 200–300 m and 400–500 m. Two specimens from each depth interval were tested by uniaxial compression. For the Brazilian disc tests 3–5 specimens from each depth interval were tested.

The results from the uniaxial compressive tests are presented in Table 11 below. Included in the Table 11 are also the average value for each parameter. Table 12 reports the results from the Brazilian disc tests.

9.2 Evaluation

Considering the mechanical properties from Sternö on the basis of either the strength classification or the modulus ratio classification of Deere and Miller (1966), it is clear that the rock have a high quality designation. If the properties are compared to the compilation of rock properties on crystalline by Tammemagi and Chieslar (1985) the Sternö rock has to be considered as having medium strength- and modulus properties.

Table 11. Results from uniaxial compression tests on rock from borehole KKA01, Sternö study site.

Depth (m)	Uniaxial compressive strength (MPa)	Young's modulus (GPa)	Poisson's ratio	Failure type*
106.4	133.0	51.2	0.19	1, 2
107.0	165.5	52.6	0.19	1, 2
278.3	153.9	56.8	0.20	2
279.1	160.5	55.0	0.18	1, 2
412.4	192.0	67.4	0.26	1
414.2	208.5	67.4	0.24	1, 2
mean:	168.9	58.4	0.21	

* Failure type 1 refers to axial splitting and 2 refers to failure on inclined plane.

Table 12. Results from Brazilian disc tests, borehole KKA01, Sternö study site.

Depth (m)	Tensile strength (MPa)
106.5	7.0
106.9	11.5
106.5	7.9
107.1	10.6
107.1	10.7
278.4	11.5
278.4	11.1
279.1	9.7
412.4	13.1
412.4	13.1
414.2	11.7
414.2	11.1
mean:	10.8

REFERENCES

In the figures and tables of this report most references are only noted by the SKB report series number (e.g. TR 79–09 or AR 84–16), while reference is made to the authors in the text. Also, some of the figures refers to reports published by PRAV (National Council for Radioactive Waste). Because of this, the reference list catalogues references both according to their SKB or PRAV report number and according to the authors.

Technical Reports (TR)

TR 25 Larsson I., Lundgren T. och Wiklander U., 1977: Blekinge kustgnejs, geologi och hydrogeologi.

TR 48 Swan G., 1977: The mechanical properties of the rocks in Stripa, Kråkemåla, Finnsjön, and Blekinge.

TR 60 Scherman S., 1978: Förarbeten för platsval, berggrunds-undersökningar.

TR 61 Hult A., Gidlund G. och Thoregren U., 1978: Permeabilitetsbestämningar.

TR 61 Magnusson K–Å. och Duran O., 1978: Geofysisk borrhålsmätning.

TR 79–05 Olkiewicz A., Scherman S. och Kornfält K–A., 1979: Kompletterande berggrundsundersökningar inom Finnsjö- och Karlshamnsområdena.

TR 79–06 Gidlund G., Hansson K. och Thoregren U., 1979: Kompletterande permeabilitetsmätningar i Karlshamnsområdet.

TR 79–07 Jacks G., 1979: Kemi hos berggrundsvatten i Blekinge.

TR 79–08 Stokes J., 1979: Beräkningar av grundvattenrörelser inom Sternöområdet i Blekinge.

TR 79–09 Ahlbom K., Carlsson L., Gidlund G., Klockars C–E., Scherman S. och Thoregren U., 1979: Utvärdering av de hydrogeologiska och berggrundsgeologiska förhållandena på Sternö.

TR 79–10 Axelsson C–L. and Carlsson L., 1979: Model calculations of groundwater conditions on Sternö peninsula.

TR 79–12 Magnusson K–Å. och Duran O., 1979: Geofysisk borrhålsmätning.

TR 80–01 Ekman L. och Gentzschein B., 1980: Komplettering och sammanfattning av geohydrologiska undersökningar inom Sternöområdet, Karlshamn.

TR 82–23 Laurent S., 1982: Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön.

TR 83–44 Almén et al., 1983: Final disposal of spent fuel. Equipment for site characterization.

TR 83–56 Hesselström B., 1983: Supplementary geophysical investigations of the Sternö peninsula.

TR 85–11 Smellie J., Larsson N–Å., Wikberg P. and Carlsson L., 1985: Hydrochemical investigations in crystalline bedrock in relation to existing hydraulic conditions: Experience from the SKB test-sites in Sweden.

Progress Reports (AR – arbetsrapporter)

AR 81–29 Hultberg B., Larson S–Å. och Tullborg E–L., 1981: Grundvatten i kristallin berggrund. Kemisk sammansättning och isotopförhållande i grundvatten från Finnsjön, Kråkemåla och Sternö.

AR 82–02 Bergman G. och Laurent S., 1982: Synpunkter på SGUs grundvattenkemiska undersökningar i Finnsjön, Kråkemåla och Sternö 1977–1980.

AR 84–16 Öqvist U. och Jämtlid A., 1984: Geofysiska parametermätningar på borrkärneprov från Finnsjön, Sternö och Stripa.

AR 85–03 Persson K–L., 1985: Borrhålsdata från Svartboberget, Gideå, Fjällveden, Kamlunge, Taavinunannen, Kråkemåla, Karlshamn, Finnsjön, Forsmark och Ävrö.

PRAV reports (National Council for Radioactive Waste)

PRAV 4.14 Duran O. and Magnussion K–Å., 1980b: Evaluation of geophysical borehole studies. Stockholm.

PRAV 4.15 Duran O. och Magnusson K–Å., 1980a: Borrhålsmätningar av temperatur, SP, pH, Eh och borrhålsvätskans resistivitet. Delrapport. Stockholm.

PRAV 4.20 Larson S–Å., Tullborg E–L. och Lindblom S., 1981: Sprickmineralogiska undersökningar. Stockholm.

References by the author (Complete reference list)

Ahlbom K., Carlsson L., Gidlund G., Klockars C–E., Scherman S. och Thoregren U., 1979: Utvärdering av de hydrogeologiska och berggrundsgeologiska förhållandena på Sternö. SKBF/KBS TR 79–09.

Ahlbom K., 1980: Rekognoscerade sprickmätningar utförda under hösten 1979 på områdena: Finnsjön, Sternö, Kråkemåla, Kynnefjäll. Sveriges Geologiska Undersökning. Internrapport. (Unpublished).

Almén et al., 1983: Final disposal of spent fuel. Equipment for site characterization. SKBF/KBS TR 83–44.

Axelsson C–L. and Carlsson L., 1979: Model calculations of groundwater conditions on Sternö peninsula. SKB/KBS TR 79–10.

Bergman G. och Laurent S., 1982: Synpunkter på SGUs grundvattenkemiska undersökningar i Finnsjön, Kråkemåla och Sternö 1977–1980. SKBF/KBS AR 82–02.

Björkman H. and Trägårdh J., 1982: Diferential uplift in Blekinge indicating late–glacial neotectonics. Geologiska Föreningens Förh. Vol. 102.

Bäckblom G., 1989: Guide–lines for use of nomenclature on fractures, fracture zones and other topics. SKB Tekniskt PM Nr 25–89–007.

Deere D. and Miller R., 1966: Engineering classification and index properties for intact rock. Report No. AFWL–TR–65–116, Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, NM.

Duran O. and Magnussion K–Å., 1980a: Evaluation of geophysical borehole studies. PRAV 4.14. Stockholm.

Duran O. och Magnusson K–Å., 1980b: Borrhålsmätningar av temperatur, SP, pH, Eh och borrhålsvätskans resistivitet. Delrapport. PRAV 4.15. Stockholm.

Ekman L. och Gentzschein B., 1980: Komplettering och sammanfattning av geohydrologiska undersökningar inom Sternöområdet, Karlshamn. SKBF/KBS TR 80–01.

Gidlund G., Hansson K. och Thoregren U., 1979: Kompletterande permeabilitetsmätningar i Karlshamnsområdet. SKBF/KBS TR 79–06.

Hult A., Gidlund G. och Thoregren U., 1978: Permeabilitetsbestämningar. KBS TR 61.

Hultberg B., Larson S–Å. och Tullborg E–L., 1981: Grundvatten i kristallin berggrund. Kemisk sammansättning och isotopförhållande i grundvatten från Finnsjön, Kråkemåla och Sternö. SKBF/KBS AR 81–29.

Hesselström B., 1983: Supplementary geophysical investigations of the Sternö peninsula. SKBF/KBS TR 83–56.

Jacks G., 1979: Kemi hos berggrundsvatten i Blekinge. SKBF/KBS TR 79–07.

Johansson L. och Johansson Å., 1990: In Kornfält and Bergström (1990a). Beskrivning till berggrundskartorna Karlshamn SV och SO. Sveriges Geologiska Undersökning. Af 167 och Af 168.

Johansson Å. and Larsen O., 1989: Radiometric age determinations and Precambrian geochronology of Blekinge, southern Sweden. Geologiska Föreningens Förh. Vol. 111.

Kornfält K–A. och Bergström J., 1986: Beskrivning till berggrundskartan Karlshamn NO. Sveriges Geologiska Undersökning. Af 154.

Kornfält K–A. och Bergström J., 1990a: Beskrivning till berggrundskartorna Karlshamn SV och SO. Sveriges Geologiska Undersökning. Af 167 och Af 168.

Kornfält K–A. och Bergström J., 1990b: Beskrivning till provisoriska översiktliga berggrundskartan Karlskrona. Sveriges Geologiska Undersökning. Ba 44.

Larsson I., Lundgren T. och Wiklander U., 1977: Blekinge kustgnejs, geologi och hydrogeologi. KBS TR 25.

Larson S-Å., Tullborg E-L. och Lindblom S., 1981: Sprickmineralogiska undersökningar. Prav 4.20. Stockholm.

Laurent S., 1982: Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön. SKBF/KBS TR 82-23.

Magnusson K-Å. och Duran O., 1978: Geofysisk borrhålsmätning. KBS TR 61.

Magnusson K-Å. och Duran O., 1979: Geofysisk borrhålsmätning. SKBF/KBS TR 79-12.

Olkiewicz A., Scherman S. och Kornfält K-A., 1979: Kompletterande berggrundsundersökningar inom Finnsjö- och Karlshamnsområdena. SKBF/KBS TR 79-05.

Persson K-L., 1985: Borrhålsdata från Svartboberget, Gideå, Fjällveden, Kamlunge, Taavinunannen, Kråkemåla, Karlshamn, Finnsjön, Forsmark och Ävrö. SKBF/KBS AR 85-03.

Pousette J., Fogdestam B., Gustafsson O. and Engqvist P., 1983: Hydrogeologisk översiktskarta i 1:250 000. Beskrivning och bilagor till hydrogeologiska kartan över Blekinge län. Sveriges Geologiska Undersökning. Ah 4.

Runesson K., Tägnfors H. and Wiberg N-E., 1978: GEOFEM-G. Computer programme for groundwater seepage including confined aquifer analysis. User's manual. Chalmers University of Technology.

Scherman S., 1978: Förarbeten för platsval, berggrundsundersökningar. KBS TR 60.

SKBF, 1977: Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste (KBS-1). SKB Stockholm.

SKBF, 1978: Handling and Final Storage of Spent Nuclear Fuel (KBS-2). SKBF/KBS Stockholm.

SKBF, 1979: Kärnbränslecykelns slutsteg. Förglasat avfall från upparbetning. Material angående SKI:s beredning av KBS's geologiska kompletteringsrapport. SKBF Stockholm. (Only available in Swedish).

SKBF, 1983: Final Storage of Spent Nuclear Fuel - KBS-3. SKBF/KBS Stockholm.

Smellie J., Larsson N-Å., Wikberg P. and Carlsson L., 1985: Hydrochemical investigations in crystalline bedrock in relation to existing hydraulic conditions: Experience from the SKB test-sites in Sweden. SKB TR 85-11.

Stokes J., 1979: Beräkningar av grundvattenrörelser inom Sternöområdet i Blekinge. SKBF/KBS TR 79-08.

Swan G., 1977: The mechanical properties of the rocks in Stripa, Kråkemåla, Finnsjön, and Blekinge. KBS TR 48.

Tammemagi H. and Chieslar J., 1985: Interim rock mass properties and conditions for analyses of a repository in crystalline rock. Technical eport BMI/OCRD-18, Office of Crystalline Repository Development, Battelle Memorial Institute, Columbus, OH.

Tullborg E-L. and Larson S-Å., 1982: Appendix 2. Stable isotopes of oxygen and hydrogen in analysed groundwaters from Finnsjön, Kråkemåla and Sternö. In Laurent (1982). Analysis of groundwater from deep boreholes in Kråkemåla, Sternö and Finnsjön. SKBF/KBS TR 82-23.

Öqvist U. och Jämtlid A., 1984: Geofysiska parametermätningar på borrkärneprov från Finnsjön, Sternö och Stripa. SKBF/KBS AR 84-16.

APPENDIX A
ACTIVITIES IN THE CORED BOREHOLES

This appendix presents all activities that have been performed in the cored boreholes. For each borehole a separate scheme of activities/surveys with reference to depths or intervals is presented. 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 shown 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 (Nov–91) availability of the cored boreholes have been studied by brief visits to each borehole. These inspections showed that all borehole heads are intact. All boreholes are locked and in each borehole there is a mechanical packer located 0.5 m beneath the ground to prevent any damage by human action. Problems with borehole stability or instrument blockage during the site investigations are described in a report by Persson (1985). The obstacles reported by him are included in this Appendix.

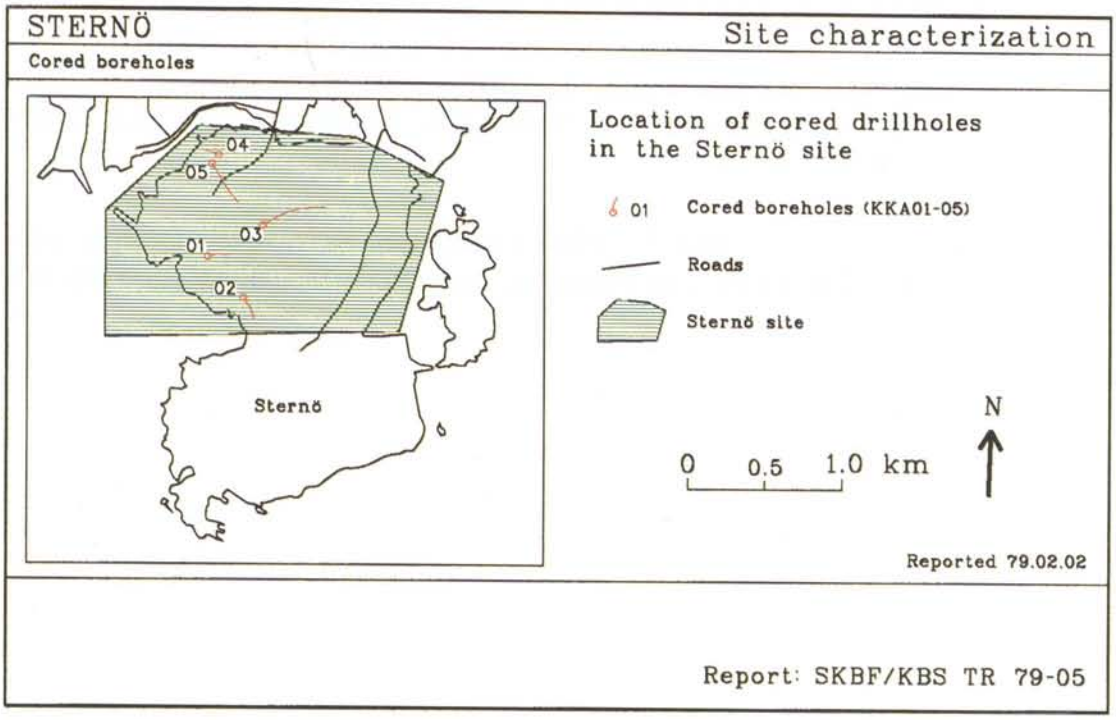


Figure A1. Locations of cored boreholes in the Sternö study site.

Borehole KKA01

Borehole KKA01 (Figure A2) is drilled steeply inclined, 75° to the horizontal, and has a length of 802.6 m and a vertical depth of about 785 m. The borehole was first drilled to 500 m depth during 1977. During the supplementary studies of Sternö the borehole was drilled deeper to 802 m length (about 790 m depth). The objective was to obtain information of the characteristics of the deep bedrock. 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.

The core from this borehole display a very low fracture frequency. (It is probably the least fractured of all boreholes in the SKB study sites). This is especially apparent towards the lower part of the borehole where only one, coated fracture was mapped between 552–802 m. No fracture zone has been identified in the borehole. Mean fracture frequency of the borehole is 0.2 fr/m.

Borehole availability: No reported problems with borehole blockage.

Borehole KKA02

Borehole KKA02 (Figure A3) is 579 m in length and ends at a depth of about 540 m. It is drilled southwards and inclined 75° to the horizontal with the objective to explore a presumed east–west fracture zone (Zone 3) at the southern border of the site.

However, the borehole is not interpreted to intersect any fracture zone. The fracture frequency is somewhat increased, 1.5 fr/m in the uppermost 200 m. Below this depth the degree of fracturing is significant lower (about 0.4 fr/m). The mean fracture frequency for the whole borehole is 0.8 fr/m. Generalized results are presented in Appendix B, Figure B1.

Borehole availability: No reported problems with borehole blockage.

Borehole KKA03

Borehole KKA03 (Figure A4) has a length of 777 m and inclined 50° eastwards, reaching a depth of about 575 m. The objective with the borehole is to investigate the central and eastern part of the site.

A fractured section is found at 300–302 m borehole length, while the hydraulic tests indicate a conductive zone between 300–350 m. This latter interval is interpreted to represent Zone 4. In the reports the zone is trending NNE and is vertical. (Although a steep dip towards SE appears to be more probable). The zone is reported to be formed by tension.

The degree of fracturing is highest in the upper 100 m (1.3 fr/m). Mean fracture frequency for the whole borehole is 0.5 fr/m. Generalized results are presented in Appendix B, Figure B1.

Borehole availability: The borehole is blocked from 320 m and downwards.

Borehole KKA04

Borehole KKA04 (Figure A5) has a length of 577 m and drilled inclined 75° towards NW, reaching a depth of about 540 m. The borehole was positioned to investigate an interpreted NE–trending shear zone (Zone 2) in the bay Munkahusviken.

The degree of fracturing is more or less normal for the Sternö study site down to about 200 m depth. From this depth and down to at least 500 m borehole length there is a significant increase in the degree of fracturing, about 4–5 fr/m, due to Zone 2, compared with other boreholes at Sternö. The mean fracture frequency for the whole borehole is 2.9 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B1.

Borehole availability: No reported problems with borehole blockage.

Borehole KKA05

Borehole KKA05 (Figure A6) is inclined, 60° towards SE, with a length of 603 m and a depth of about 500 m. The borehole is located near KKA04 but directed away from Zone 2. The objective was to characterize the bedrock on the border between Zone 2 and the less disturbed bedrock.

No fracture zone is interpreted to intersect the borehole. This is also indicated by the very low fracture frequency of the cores, at least below 200 m. The mean fracture frequency for the whole borehole is 0.7 fr/m. Main results from borehole investigations are shown in Appendix B, Figure B1.

Borehole availability: No reported problems with borehole blockage.

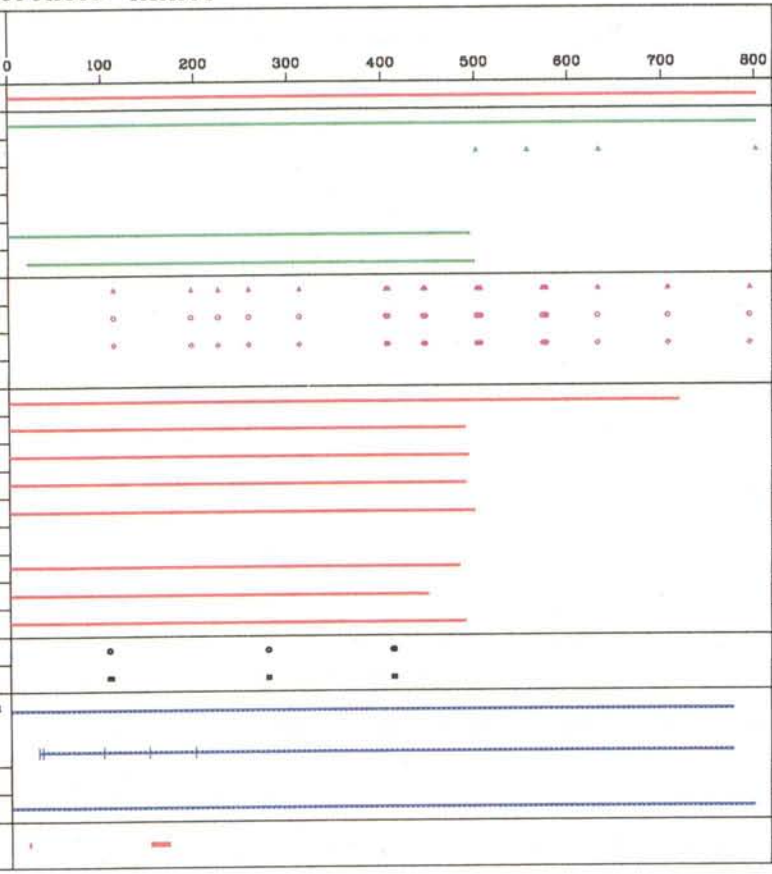
Figure A2. Activities in borehole KKA01.

STERNÖ — Site characterization

Sub-surface investigation, cored borehole: KKA01

Direction: N60E/81 — Length: 802.6 m — Depth: 785 m

X- 6225 106.1 — Y- 1439 673.9 — Z- 12.8



		Survey period	Report	GEOTAB
	Drilling	77-78	KBS TR 60 SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology + Fracture log	- " -	- " -	
	Thin section analyses	79	SKBF/KBS TR 79-05	
	Chemical rock analyses			
	Fracture mineral analyses			
	TV-log	77	KBS TR 61, PRAV 4.14	
	RQD	- " -	KBS TR 60	
PETROPHYSICS	Density		SKB/KBS AR 84-15	
	Porosity		- " -	
	Magn. susceptibility + remanence		- " -	
	Resistivity			
GEOPHYSICAL LOGGING	Borehole deviation	77.10.27-78.02.1	SKBF/KBS TR 79-05	X
	Natural gamma		SKB TR 61	X
	Resistivity (normal+lateral)		- " -	X
	Single point resistivity		- " -	X
	Temperature		PRAV 4.15	
	Borehole fluid resistivity			
	IP		SKB TR 61	X
	Borehole slingram		- " -	X
	VLF		- " -	X
ROCK MECHANICS	Mineral compessive tests		KBS TR 48	
	Brazilian test, tensile strength		- " -	
HYDRAULIC LOGGING AND TESTS	Single hole steady state inj.test, 2m location of singel packer noted: 29.5, 33.5, 99.5, 149.5 and 199.5m		SKB TR 61 SKBF/KBS TR 79-06 SKBF/KBS TR 80-01	X
	Piezometric measurement			
	Ground water level measurements	79.01.01-.11.10		
HYDROCHEMISTRY	Chemical sample	79.02	SKBF/KBS TR 79-07	

STERNÖ — Site characterization

Sub-surface investigation, cored borehole: KKA02

Direction: S35E/75 X- 6224 836.9
Length: 578.8 m Y- 1439 900.2
Depth: 540 m Z- 14.6

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		78	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology - Fracture log		78-79	- " -	
	Thin section analyses			- " -	
	Chemical rock analyses				
	Fracture mineral analyses				
	TV-log				
	RQD				
PETROPHYSICS	Density				
	Porosity				
	Magn. susceptibility - remanence				
	Resistivity				
GEOPHYSICAL LOGGING	Borehole deviation		78.11.30	SKBF/KBS TR 79-05	X
	Natural gamma				
	Resistivity (normal-lateral)				
	Single point resistivity				
	Temperature				
	Borehole fluid resistivity				
	IP				
	Borehole slingram				
	VLF				
ROCK MECHANICS	Mineral compessive tests				
	Brazilian test, tensile strength				
HYDRAULIC LOGGING AND TESTS	Single hole steady state inj.test, 3m location of singel packer noted; 100, 150, 200, 250, 300, and 350m			SKBF/KBS TR 79-06 SKBF/KBS TR 80-01	X
	Piezometric measurement		79	SKBF/KBS TR 80-01	
	Ground water level measurements		79.01.01-.11.10	- " -	
HYDROCHEMISTRY	Chemical sample				

Figure A3. Activities in borehole KKA02.

STERNÖ — Site characterization

Sub-surface investigation, cored borehole: KKA03

Direction: N62E/52 — X- 6225 307.0
Length: 777.3 m — Y- 1440 028.7
Depth: 575 m — Z- 27.2

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		78	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology - Fracture log		78-79	- ,, -	
	Thin section analyses			- ,, -	
	Chemical rock analyses				
	Fracture mineral analyses				
	TV-log				
	RQD				
PETROPHYSICS	Density				
	Porosity				
	Magn. susceptibility - remanence				
	Resistivity				
GEOPHYSICAL LOGGING	Borehole deviation		78.11.30	SKBF/KBS TR 79-05	X
	Natural gamma				
	Resistivity (normal-lateral)				
	Single point resistivity				
	Temperature				
	Borehole fluid resistivity				
	IP				
	Borehole slingram				
	VLF				
ROCK MECHANICS	Mineral compessive tests				
	Brazilian test, tensile strength				
HYDRAULIC LOGGING AND TESTS	Single hole steady state inj.test, location of singel packer noted: 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650 and 700m			SKBF/KBS TR 79-06 SKBF/KBS TR 80-01	X
	Piezometric measurement		79	SKBF/KBS TR 80-01	
	Ground water level measurements		79.01.01-.10.20	- ,, -	
HYDROCHEMISTRY	Chemical sample			SKBF/KBS AR 81-29 SKBF/KBS TR 82-23	

Figure A4. Activities in borehole KKA03.

STERNÖ — Site characterization

Sub-surface investigation, cored borehole: KKA04

Direction: N68W/77 X- 6225 761.8
Length: 577.3 m Y- 1439 748.6
Depth: 540 m Z- 11.6

	0 100 200 300 400 500 600 700 800	Survey period	Report	GEO-TAB
	Drilling	78	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology - Fracture log	78-79	- " -	
	Thin section analyses		- " -	
	Chemical rock analyses			
	Fracture mineral analyses		PRAV 4.20	
	TV-log			
	RQD			
PETROPHYSICS	Density		SKBF/KBS AR 84-16	
	Porosity		- " -	
	Magn. susceptibility - remanence		- " -	
	Resistivity			
GEOPHYSICAL LOGGING	Borehole deviation	78.11.29	SKBF/KBS TR 79-05	X
	Natural gamma		SKBF/KBS TR 79-12	X
	Resistivity (normal-lateral)	79.02.09	- " -	
	Single point resistivity		- " -	
	Temperature			
	Borehole fluid resistivity		- " -	X
	IP			
	Borehole slingram			
	VLF			
ROCK MECHANICS	Mineral compessive tests			
	Brazilian test, tensile strength			
HYDRAULIC LOGGING AND TESTS	Single hole steady state inj.test, 3m location of singel packer noted: 48, 74, 100, 150, 200, 250, 300, 350, 400 and 452 m ?		SKBF/KBS TR 80-01	X
	Piezometric measurement	79	- " -	
	Ground water level measurements	79.01.01-.11.15	- " -	
HYDROCHEMISTRY	Chemical sample		SKBF/KBS AR 81-29 TR 82-23 AR 82-02	

Figure A5. Activities in borehole KKA04.

STERNÖ — Site characterization

Sub-surface investigation, cored borehole: KKA05

Direction: S30E/60 — X- 6225 700
Length: 602.7 m — Y- 1439 700
Depth: 500 m — Z- 12.2

		0 100 200 300 400 500 600 700 800	Survey period	Report	GEOTAB
	Drilling		78	SKBF/KBS TR 79-05	X
CORE LOGGING	Lithology + Fracture log		78-79	- „ -	
	Thin section analyses				
	Chemical rock analyses				
	Fracture mineral analyses				
	TV-log				
	RQD				
PETROPHYSICS	Density			SKBF/KBS AR 84-16	
	Porosity			- „ -	
	Magn. susceptibility + remanence			- „ -	
	Resistivity				
GEOPHYSICAL LOGGING	Borehole deviation		79.01.12	SKBF/KBS TR 79-05	X
	Natural gamma			SKBF/KBS TR 79-12	X
	Resistivity (normal-lateral)		79.02.07	- „ -	
	Single point resistivity			- „ -	
	Temperature				
	Borehole fluid resistivity			- „ -	X
	IP				
	Borehole slingram				
	VLF				
ROCK MECHANICS	Mineral compessive tests				
	Brazilian test, tensile strength				
HYDRAULIC LOGGING AND TESTS	Single hole steady state inj.test, 3m location of singel packer noted: 100, 150, 200, 250 and 300m		79.01-.03	SKBF/KBS TR 79-06 SKBF/KBS TR 80-01	X
	Piezometric measurement		79	SKBF/KBS TR 80-01	
	Ground water level measurements		79.01.01-.11.10	- „ -	
HYDROCHEMISTRY	Chemical sample				

Figure A6. Activities in borehole KKA05.

APPENDIX B

GENERALIZED RESULTS FROM BOREHOLE INVESTIGATIONS

Generalized results from core mapping and borehole measurements/tests in the cored boreholes KKA01–KKA05 are presented in Figures B1–B2. 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 locations of interpreted fracture zones in the borehole are shown. 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.

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 (Figure 14). Highly increased hydraulic conductivity is noted where the conductivity in the borehole section is more than 100 times higher.

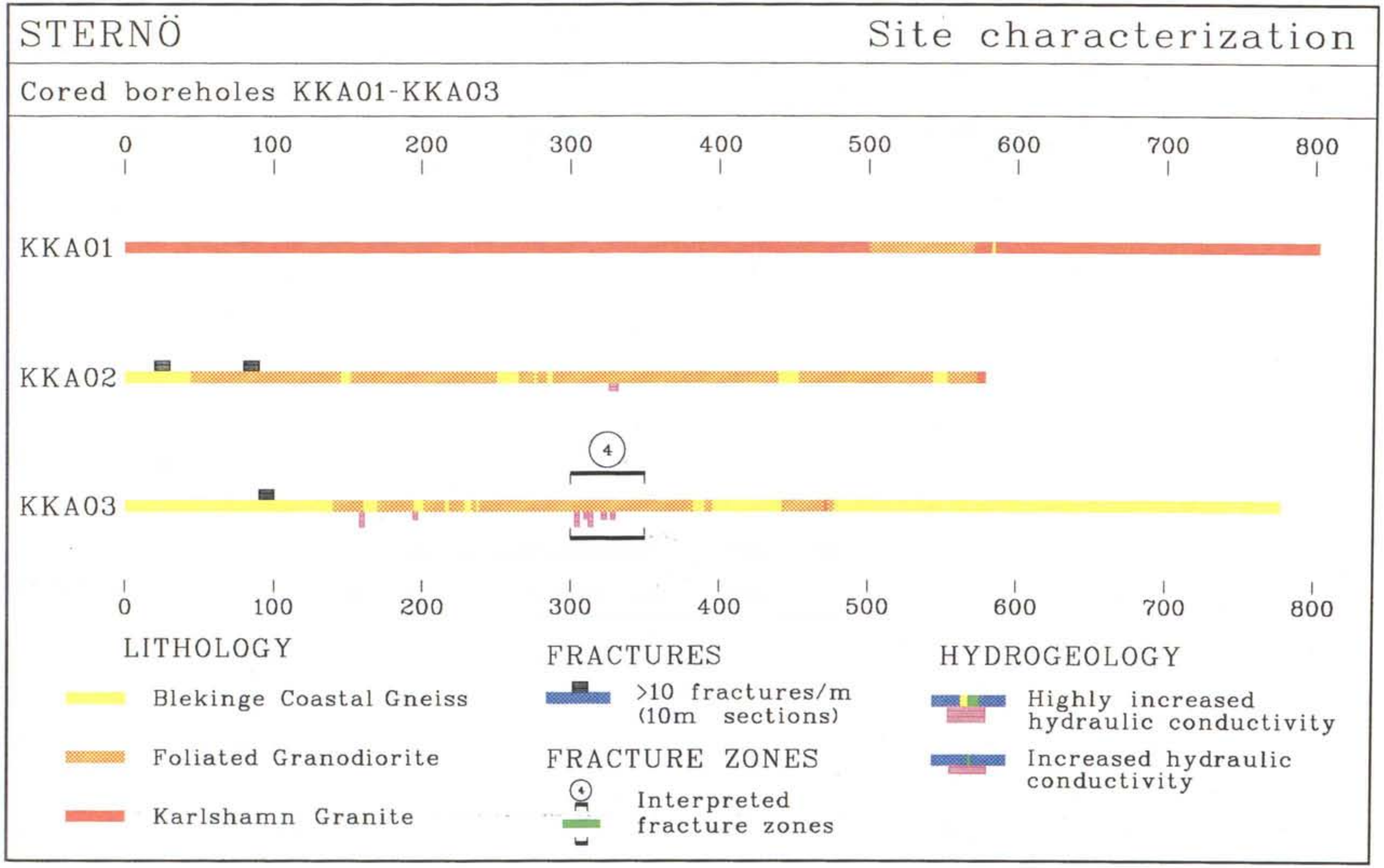


Figure B1. Results from borehole surveys in KKA01–KKA03. The horizontal axis represent borehole length.

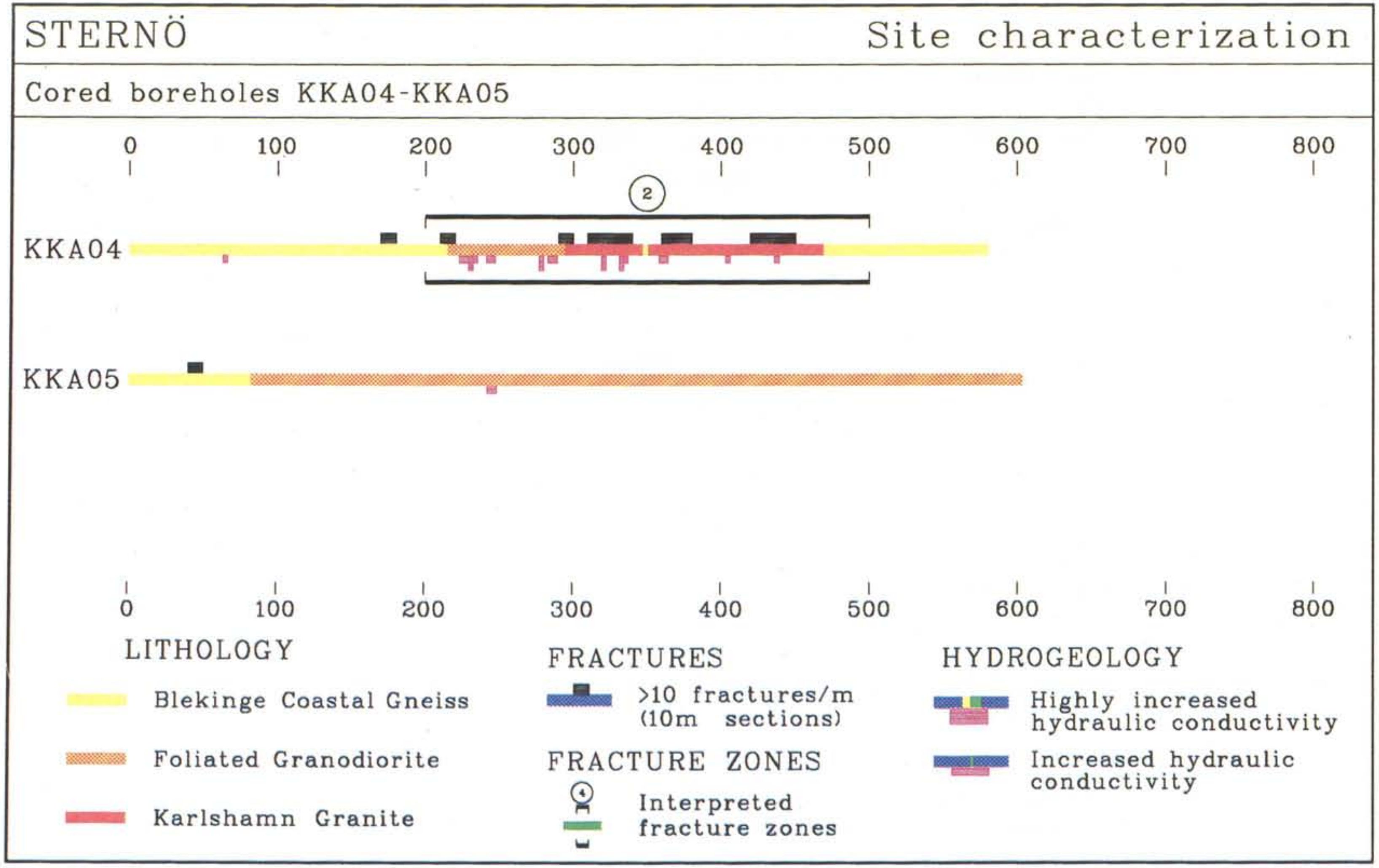


Figure B2. Results from borehole surveys in KKA04–KKA05.

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, mainly according to the nomenclature by Bäckblom (1989). The fracture zones at Sternö are summarized in Sections 5.3 and 5.4.

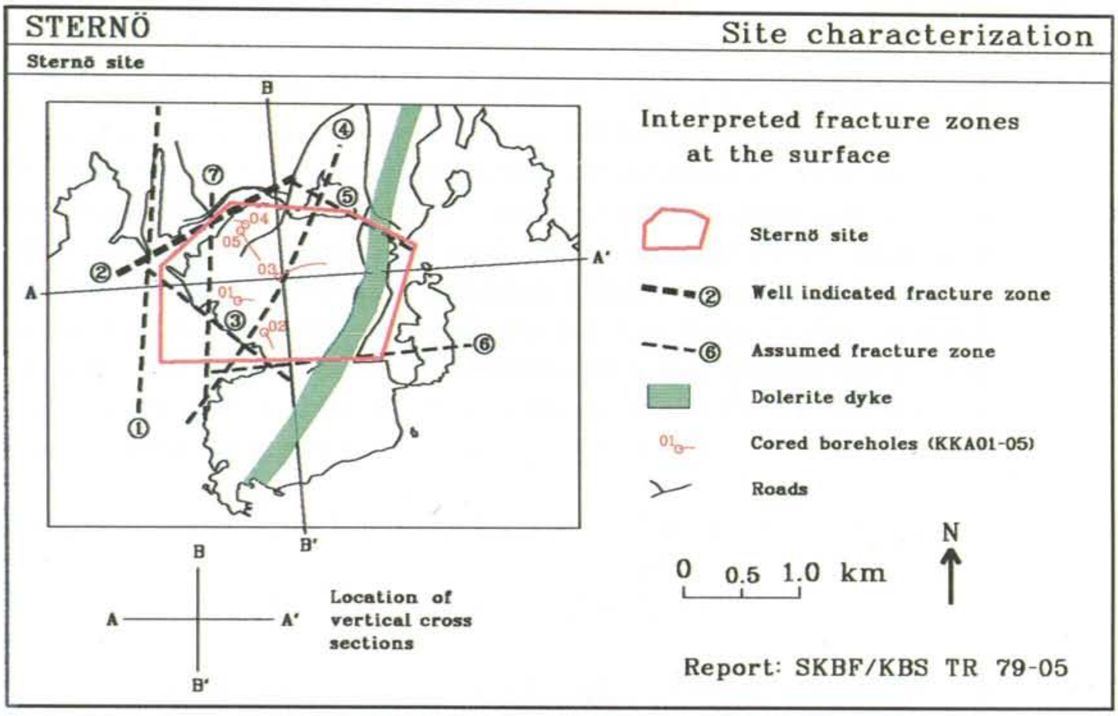


Figure C1. Map of interpreted fracture zones in the Sternö study site.

ZONE 1

The north–south trending Zone 1 is located in the area covered by sea outside the site to the west. At this location the zone represent an extrapolated part of a well expressed lineament of about 8 km in length (see Figure C1). No borehole data exist for the zone. However, as the zone is interpreted as a tension structure a relative high hydraulic conductivity should preliminary be assumed. A vertical dip and a with of 30 m is assumed for this zone (Axelsson and Carlsson, 1979).

Reliability; The morphological well expressed character of the zone should render the zone a "certain" classification. However, due to the extrapolation of the zone to the sea covered area outside Sternö the reliability decreases. According to the Bäckblom nomenclature the reliability level is "possible".

ZONE 2

Zone 2, the Munkahusviken fracture zone, is trending northeast and located in the northwestern part of the site. The zone is apparent as a lineament. The zone has been investigated by borehole KKA04. The degree of fracturing is more or less normal down to about 200 m depth. From this depth and down to at least 500 m borehole length there is a significant increase in the degree of fracturing (about 4–5 fr/m) compared with other boreholes at Sternö. Sections with crushed rock are common. Interpolating the location of the zone at the surface and in the borehole indicates a steep dip towards SW, i.e. towards the site. However, in the reports the zone is assumed vertical. A width of 30 m is assumed for this zone (Axelsson and Carlsson, 1979).

On the north side of the bay Munkahusviken a thrust zone is reported to intersect oil caverns. This zone is dipping 20–30° towards NW. This zone probably also outcrops in Munkahusviken.

Reliability; The combined information from borehole KKA04 and the lineament map makes the existence of Zone 2 more or less "certain", according to the nomenclature of Bäckblom (1989). However, in spite of the existence of the KKA04 borehole information and the information from the oil caverns north of the Munkahusviken, no geological model (except in the review document made by the SKI geology group) has been presented of the fracture zones and their respectively dip, with and other characteristics. Thus, based on the available interpretation a "probable" reliability should be assigned to the Zone 2.

ZONE 3

This northwesterly trending zone, located in the southwestern part of the site, is apparent as a weak lineament (the straight coast line). No borehole information exist. The zone is assumed to have a vertical dip and a width of 5 m (Axelsson and Carlsson, 1979).

Reliability; "possible".

ZONE 4

This zone has been interpreted by combining a fractured section in borehole KKA03 at 300 m depth with a weakly expressed lineament on the surface. This has resulted in a NNE trending fracture zone located in the central part of the site. The Zone 4 is parallel to the dolorite dyke to the east and it is interpreted to be formed under tension. In the reports a vertical dip is assumed for the zone. (Although a steep dip towards east appears to be more likely when reported surface and borehole location of the zone are considered). In the cores from KKA03 the zone is apparent as a fractured section of 2 m (300–302 m). However, the hydraulic tests display increased conductivity between 300–350 m. The estimated width of the zone varies between 80 m (Ahlbom et al., 1979) to 10 m (Axelsson and Carlsson, 1979).

Reliability: "probable".

ZONE 5

This NNW trending zone constitute a part of the northern boundary of the Sternö study site. The zone is apparent as a lineament. No borehole data exist for the zone. A vertical dip and a with of 5 m is assumed (Axelsson and Carlsson, 1979).

Reliability: "possible".

ZONE 6

This east–west trending zone constitute the southern boundary of the Sternö study site. The zone is apparent as a lineament. No borehole data exist for the zone. A vertical dip and a with of 10 m is assumed (Axelsson and Carlsson, 1979).

Reliability: "possible".

ZONE 7

This zone, in some reports denoted "the Kölö fracture zone", was suggested by the SKI geology group (KBS–1 supplement, 1979) after the main part of the site investigation and reporting was finished. The zone was accepted as a possible fracture zone by SKBF/KBS.

Zone 7 is located in the western part of the site and is interpreted from topographical indications only. It is trending north–south and has an assumed vertical dip.

Reliability: "possible".

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

Technical Reports
List of SKB Technical Reports 1992

TR 92-01
GEOTAB. Overview
Ebbe Eriksson[1], Bertil Johansson[2], Margareta Gerlach[3], Stefan Magnusson[2], Ann-Chatrin Nilsson[4], Stefan Sehlstedt[3], Tomas Stark[1]
[1]SGAB, [2]ERGODATA AB, [3]MRM Konsult AB
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