Handling of Spent Nuclear Fuel and Final Storage of Vitrified High Level Reprocessing Waste

I General

II Geology

III Facilities

IV Safety analysis

V Foreign activities

KÄRN -
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II Geology

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1 BACKGROUND

The possibility of disposing of high-level waste in geological formations has been under discussion for many years. It has generally been assumed that the waste is to be disposed of in the country where it was produced, and different types of formations have come under consideration in different countries, depending on their occurrence (salt, clay, shale, crystalline rock). In Sweden, interest has been concentrated on Precambrian bedrock formations (gneiss, granite).

The geological studies conducted for the AKA Committee (The Government Committee on Radioactive Waste) have been supplemented by studies performed by the National Council for Radioactive Waste Management (PRAV). Equipment for water injection testing and geophysical borehole logging as well as a special borehole pump have also been developed by PRAV. Since the KBS project commenced in early 1977, the geological investigations have been concentrated on this project.

In February of 1977, an agreement was reached between KBS and the Geological Survey of Sweden (SGU), which is the central government agency for geological matters, concerning a geological study programme aimed at ascertaining the feasibility of a final storage of high-level waste in the Swedish bedrock. A summary of the contents and principal results of the programme is provided in this chapter. More detailed accounts of the methods and results of the investigations are provided in the reports referred to under section A of the list of references.

2 THE GEOLOGICAL STUDY PROGRAMME

2.1 PURPOSE

The goal of the geological work programme is to carry out studies within several geographical areas in order to obtain basic data on the bedrock and groundwater conditions which determine the long-term safety of a final repository for high-level waste. These studies are complemented by theoretical studies.

The work is aimed at establishing whether the bedrock is composed of a uniform, suitable type of rock of sufficient extent down to depths of several hundred metres. This is important, since inferior conditions may exist at the boundaries between different types of rock. The occurrence of fissures and fracture zones with may influence the design or safety of the repository must also be elucidated.

As regards the groundwater, information is needed on how much water may come into contact with the waste. This requires measurements of the permeability of the rock and theoretical calculations of how the water flow in the rock decreases with depth. Such calculations also provide a basis for determining the final dilution of the water which has been in contact with the waste canisters.

When the waste or the canisters come into contact with the groundwater, some dissolution may occur. The extent of this dissolution depends on the properties of the materials and the chemical composition of the water. The programme therefore includes sampling and analysis of the groundwater at the depths in question.

If the waste substances go into solution, it is important to know their residence time in the rock. If this time is long, certain radioactive elements will decay before they reach the biosphere. Information on the residence time can be derived from the age of the groundwater.

Most waste elements are retarded on their way through the bedrock due to sorption effects and chemical reactions. Such retardation has been investigated by means of laboratory work, theoretical analyses and field tests, of which the latter fall within the framework of the geology programme.

The question of whether and to what extent geological conditions of importance for the safe final storage of high-level radioactive waste may change in the future must be answered. This includes the study of the geographical and chronological distribution of movements in the bedrock.

The geological programme has concentrated primarily on gathering information to serve as a basis for the siting and design of an absolutely safe rock storage facility adapted to the conditions which prevail in Swedish bedrock. Time has not yet permitted a more fundamental analysis of the data.

2.2 SCOPE

SGU has been commissioned by KBS to perform the following main studies:

- Geophysical ground measurements, mapping of outcrops and joints, drilling, evaluation of drill cores, borehole logging and TV examination of boreholes.
- Water injection tests and calculations, water sampling for chemical analysis and age determination.
- Theoretical studies of groundwater movements (carried out through the Department of Land Improvement and Drainage at the Royal Institute of Technology in Stockholm).
- Field tests using tracer elements in fissured rock before and after injection (previously begun by PRAV).

The total cumulative length of drilled core boreholes amounts to slightly more than 5 000 m, distributed among five study areas, three of which have been chosen for further study - namely, Sternö near Karlshamn, Kråkemåla near Oskarshamn and Finnsjö near Forsmark. The bedrock in these areas varies and the choice of study areas was determined partially by the fact that knowledge was desired on the characteristics of the different types of rock.

In addition to the above studies by SGU, KBS has commissioned the following:

- a compilation and supplementation of known data on the Blekinge coastal gneiss,
- a mathematical model study of groundwater movements and rock stresses in and around a final repository,
- a theoretical mathematical study of the expected formation of new fractures when a rock mass is subjected to simple shearing,
- studies of the chemical composition of the groundwater,
- studies of sorption effects which may be encountered when various waste substances are transported with the groundwater in buffer material and rock fissures,
- studies of post-precambrian rock movements and recent earthquakes.

The results of these studies will complement the results of SGU's own studies.

In early February of 1977, KBS and PRAV invited a large number of geologists to a conference for a discussion of questions of importance concerning a final repository for high-level waste in the Swedish bedrock. Among other things, the probability that movements in the bedrock would jeopardize the safety of the repository was discussed. A number of proposals for studies were submitted by the conference participants and many of these proposals led to investigations sponsored by KBS. In early October of 1977, the results were reported and discussed at a second conference arranged by KBS.

A group of specialists called the "Geogroup" has been established within KBS. Its function is to:

- serve as a forum for the discussion of questions concerning geology, hydrogeology and rock engineering,
- participate in the formulation of plans for investigations and experiments,
- assist in the follow-up and evaluation of results of investigations and experiments.

The report submitted in the following chapters 2 through 8 has been prepared by SGU. It is based not only on SGU's own studies, but also on the above-mentioned special investigations carried out on commission from KBS.

2.3 STRIPA EXPERIMENTAL STATION

The experimental programme being conducted by KBS at the Stripa mine is described in chapter 9. Mining operations were recently discontinued at the mine and the opportunity was offered to conduct practical experiments in a granite massif at a depth of about 350 m. These experiments are aimed at studying the properties of granite at this depth, both in the unconditioned state and after heating, and at studying fracturing resulting from the blasting of tunnels. An agreement has been concluded with the US Energy Research and Development Administration (ERDA) concerning cooperation in the execution of a large-scale heating experiment. The results of this experiment will not be available for a couple of years. KBS' own experiments also require such a long time that the most relevant results cannot be reported here. But the experiments are of such a nature that they will not affect the basic conclusions, but will rather primarily serve as a basis for an optimization of the detailed technical design of a final repository.

3 CHOICE OF STUDY AREAS

The preliminary work for the studies has been concentrated on finding areas with suitable bedrock of sufficient extent near the east coast of Sweden between Uppland and Blekinge. On the basis of the selected design capacity - waste from the operation of 13 reactors over a period of 30 years - an area of about 1 km^2 is required. Proximity to the coast is desirable in order to avoid long overland transports. The locations of the nuclear power plants and the desirability of avoiding seismically active areas has restricted the preliminary work to the east coast between Uppland and Blekinge.

In order to be able to complete in-depth drillings and studies in the short time which was available, it was necessary to exclude a number of geologically promising areas where the ownership of the land are complex or where it was not possible to obtain the permission of the proprietor.

Flat areas with much exposed rock have been sought after. The gradient of the water table in such areas is generally low, resulting in a low potential for groundwater movements. Another factor of importance is that the fracture zones in the bedrock in such areas are also normally widely spaced and narrow, with large intervening volumes of good rock. Between the large fracture zones, the bedrock should contain relatively widely spaced, small and irregular fissures, so that the groundwater permeability of the rock is low. This can be studied where the rock is exposed in outcrops. Outcrop mapping also shows whether the bedrock is uniform and consists of some common type of rock - granite or gneiss - which is of little value and therefore unattractive for future mining. The final areas were chosen to provide examples of the conditions in a massive granite which postdates orogenic upthrusting and folding, a gneissic granite and a clearly folded gneiss. Together with the vein gneiss previously studied for the AKA Committee investigation, this makes a total of four different typical types of precambrian bedrock which have been investigated.

In order to find suitable areas, topographical, economical and geological maps - supplemented with satellite and aerial photographs - have been examined. This has made it possible to compare terrain, ownership relation and the distribution of different types of rock in different areas and to chart the major fracture lines in the bedrock. Following this analysis promising areas were inspected in the field. In order to determine the features of the bedrock in unexposed parts and in depth as well, geophysical measurements were carried out, primarily using electromagnetic methods which detect the groundwater-bearing zones in the bedrock on the basis of their increased electrical conductivity.

In certain cases, seismic methods were used to measure the velocity of shock and shear waves in the bedrock in order to gain some insight of its elasticity constant and fissure content.

Three areas were finally chosen for further study and drilling (see fig. 3-1).

- Karlshamn, i.e. the area around the Karlshamn power plant.
- Finnsjön, an area east of the northern part of Finnsjö Lake, some 16 km WSW of the Forsmark nuclear power plant in northeastern Uppland.
- Kråkemåla, an area 1.5 km NW of Kråkemåla and 7.5 km NNW of the Oskarshamn nuclear power plant at Simpevarp in eastern Småland.

In addition, certain studies were conducted at the following places:

- Ävrö, about 1.5 km N of Simpevarp
- Bussvik, about 4.5 km NNW of Simpevarp
- Forsmark, about 3.5 km W of the Forsmark nuclear power plant.

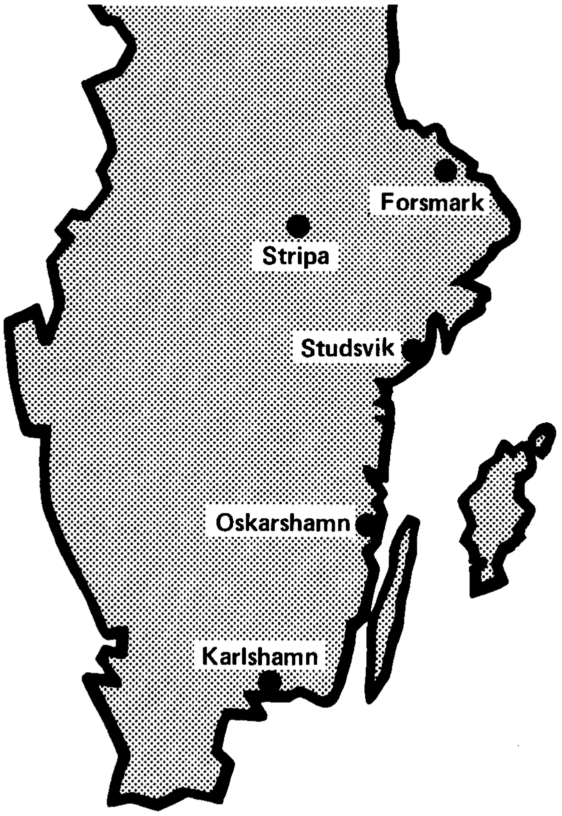

Figure 3-1. Map showing study areas. Test drillings to a depth of about 500 metres were undertaken at Karlshamn (Sternö), north of Oskarshamn (Kråkemåla and Ävrö), and at Forsmark (Finnsjön and Forsmark). The KBS experimental station is located in the Stripa mine. Field studies were carried out at Studsvik.

4 STUDY RESULTS

4.1 GENERAL

Core drillings provide information on conditions in the bedrock hundreds of metres below the surface. The boreholes also provide an opportunity for determining the water permeability of different sections of the rock and to take samples for analysis of the chemical composition and age of the groundwater.

The results have been reported in drilling logs, core maps, RQD and permeability diagrams and geophysical borehole logs. Videotaped TV inspections have also been made.

RQD stands for "Rock Quality Designation" and refers to a method developed by Deere for the approximate indication of rock quality on the basis of drill cores. The RQD factor constitutes the ratio of the total length of unbroken core pieces larger than 10 cm to the length of the corresponding borehole section. The RQD factor was generally calculated for 2-metre intervals in the present study.

The permeability values were determined by measuring the water flow into the rock at given pressures along a defined section of the borehole (normally 2 metres) isolated by packers at both ends.

Various geophysical measurement methods can be used to indicate the quality of the rock - not only in the borehole itself, but also in the surrounding rock. These measurements make use of the electrical conductivity and radioactivity of the rock.

Only the most important results of the borehole studies are reported below - area by area. More detailed data are documented in the reports specified in the list of references.

4.2 KARLSHAMN AREA

Due to previous studies and observations in existing rock caverns, the Karlshamn area can be considered to be the geologically most well-known of the three study areas. A report on the bedrock and groundwater conditions in the district is provided in KBS technical report 25 /4-1/.

The area is composed of Blekinge coastal gneiss, which extends south and west of Karlshamn. This rock is characterized by low permeability and low water content. It is a grey, small- to fine-grained, indistinctly banded gneiss, which consists of plagioclase, microcline, quartz and biotite. This gneiss is often intimately associated with grey and gneissic granitoid rocks. Narrow veins of pegmatite are frequently encountered in this gneiss. Many outcrops exhibit foliation with large areas of flat-lying layering. In the Karlshamn area, the coastal gneiss is bounded on the east by a large massif of coarsely crystalline Karlshamn granite. Its extent in depth is unknown.

The chemical composition of the rock from western Blekinge is given in table 4-1. Information obtained from a number of rock cavern facilities in the area show low reinforcement costs and low groundwater inflow. On the basis of leakage inflow data, permeability has been calculated to be around 10^{-9} m/s only 50 m below the surface. The chief aim of the core drilling to a depth of 500 metres in Karlshamn (see figure 4-1) was therefore to ascer-

Table 4-1. Chemical analyses of rock from western Blekinge.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	73.0	65.8	72.2	72.2	72.2	71.8	66.4	69.2	67.2	70.5	67.9	68.6	68.2	68.2
TiO_2	0.31	1.18	0.36	0.33	0.21	0.30	0.75	0.49	0.66	0.55	0.66	0.51	0.60	0.43
Al_2O_3	13.5	15.0	14.9	13.7	14.0	14.5	15.3	14.8	15.2	14.1	15.3	14.9	14.6	16.4
Fe_2O_3	1.29	3.43	1.14	1.00	1.00	1.43	3.43	2.00	2.57	2.29	2.15	2.15	2.43	1.43
FeO	1.03	3.35	1.29	1.55	1.16	1.29	3.23	3.10	3.74	1.94	2.97	3.35	2.97	1.68
MnO	0.06	0.12	0.03	0.04	0.04	0.03	0.09	0.07	0.08	0.07	0.10	0.07	0.07	0.05
CaO	1.40	3.1	2.0	1.5	1.4	1.2	2.5	2.5	2.9	1.8	2.4	2.7	2.6	3.1
MgO	0.30	1.1	0.5	0.2	0.2	0.5	1.2	0.7	1.0	0.6	1.0	0.8	0.7	0.6
Na_2O	2.80	3.3	3.3	3.1	3.0	2.7	3.1	3.2	3.3	3.2	2.8	3.1	3.0	3.6
K_2O	5.50	4.9	4.6	5.0	5.4	5.9	4.6	4.7	4.4	5.2	5.6	4.5	4.7	4.2
BaO	0.14	0.17	0.14	0.14	0.09	0.13	0.16	0.12	0.11	0.12	0.16	0.13	0.12	0.16

1-5	Coastal gneiss	9	Karlshamn granite
6-8	Gneissic granite	11-14	"
		10	Spinkamåla granite

Data from I Larsson et al.

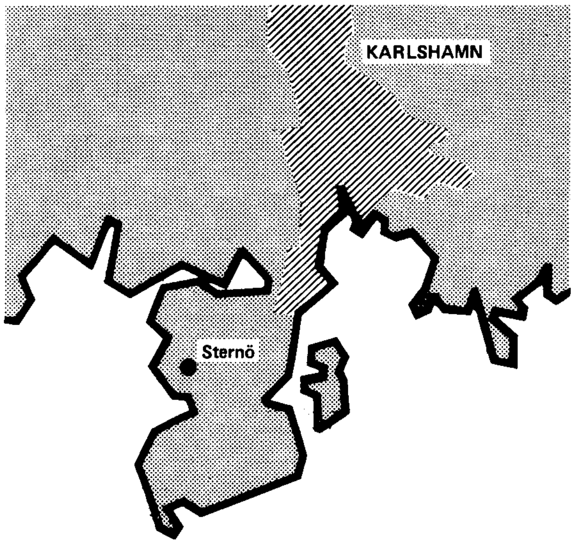

Figure 4-1. Core drillings were performed on Sternö within the municipality of Karlshamn. There are large rock caverns in the vicinity which provide good insight into the characteristics of the rock.

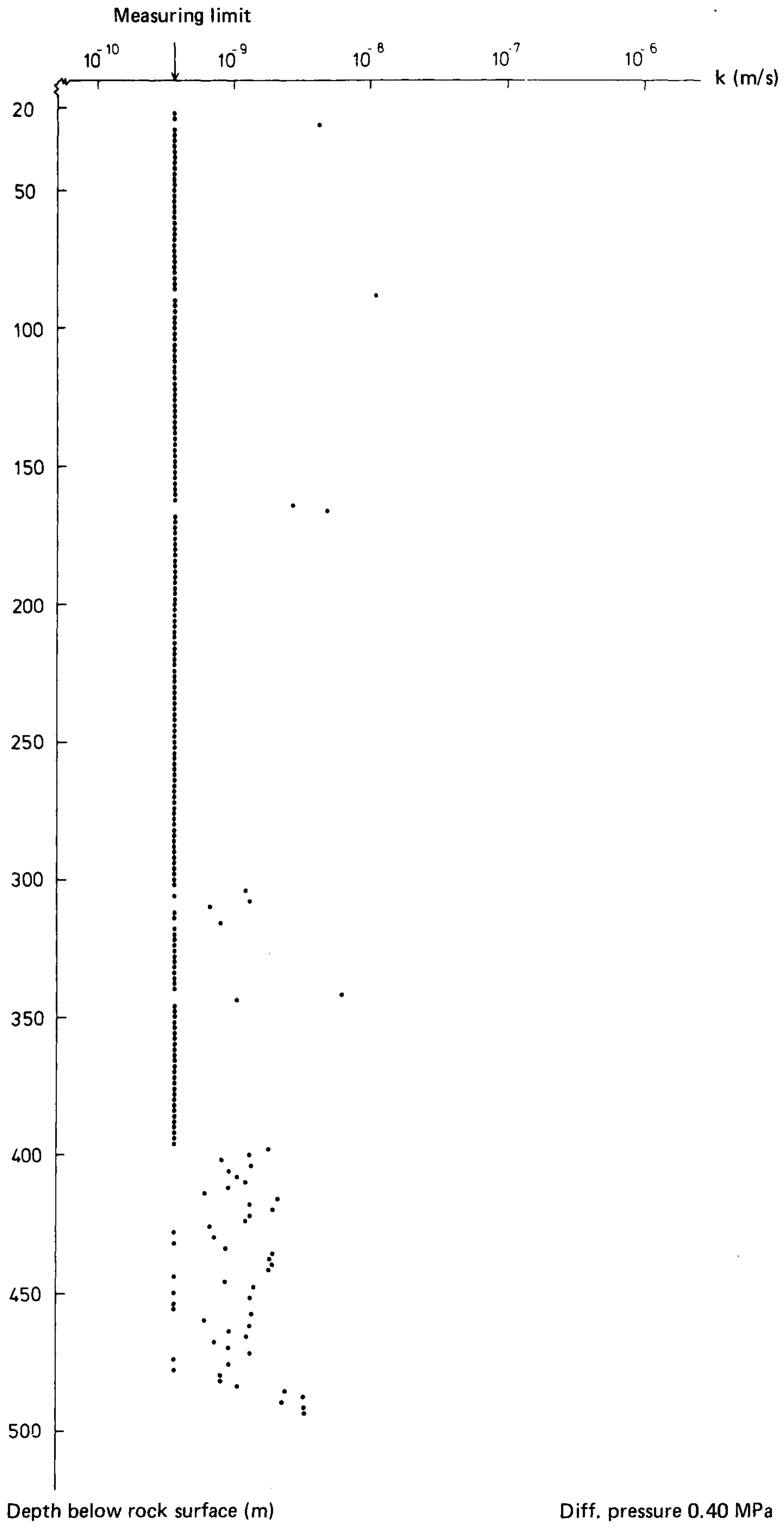

Figure 4-2. Diagram of rock permeability in core borehole 1 at Karlshamn.

tain bedrock conditions at deeper levels. The borehole studies reveal predominantly impervious rock at these depths (see fig. 4-2). No crush zones were found in the study area.

4.3 FINNSJÖ AREA

4.3.1 Location and topography

The Finnsjö area is located about 16 km WSW of the Forsmark nuclear power plant in northeastern Uppland, between route 290 and the northern part of Finnsjö Lake (see fig. 4-3).

The contours of the landscape govern the movements of the surface water and groundwater and reflect the deformation of the bedrock. The landscape in northeastern Uppland gets its very flat character from the subcambrian peneplain - the nearly planar and horizontal land surface which was formed here as the top surface of the bedrock more than 570 million years ago (see atlas of Sweden, Pl 6 /4-2/). This land surface is largely unchanged and undeformed today, but it is frequently broken by fracture lines stretching many kilometres which mark minor dislocations. In general, the difference in elevation at these lines is less than 20 metres.

The study area at Finnsjö Lake consists of a slightly oblique north-south oriented block situated between two such major fracture lines. The west of these, the Finnsjö line, is actually a

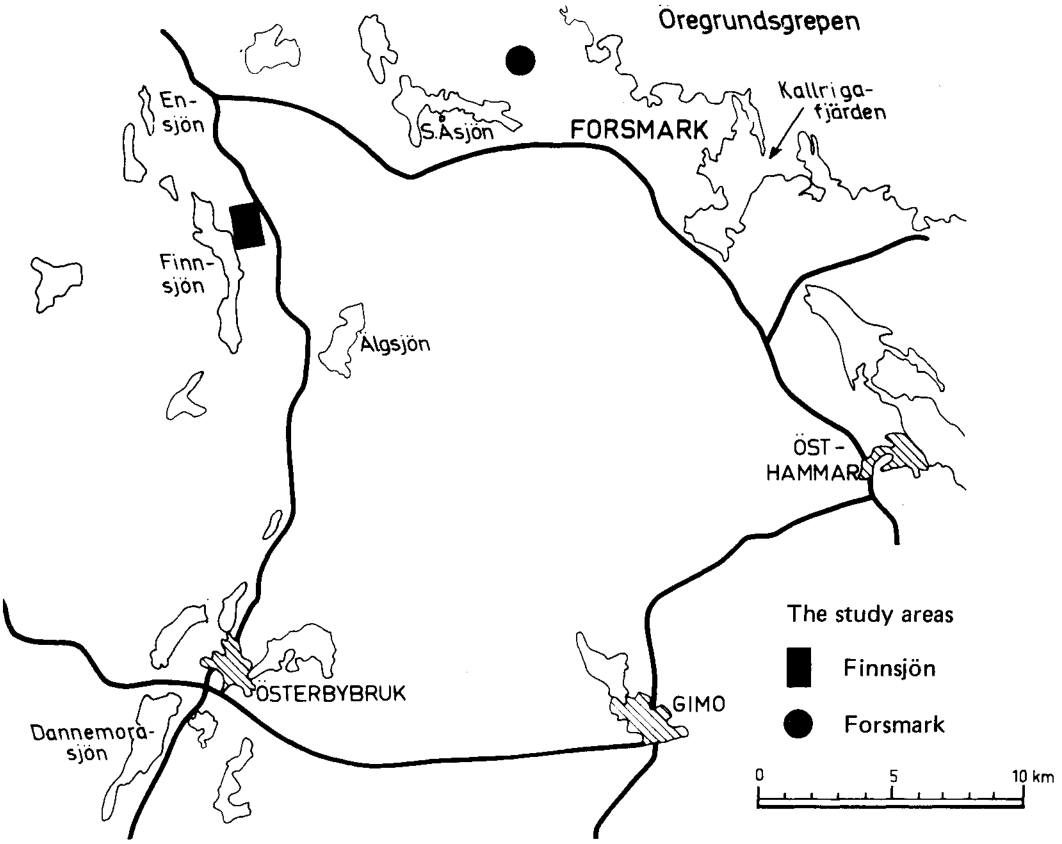

Figure 4-3. Map showing the study areas of Finnsjö Lake and Forsmark.

conglomerate composed of several lines, but runs in a substantially NNW direction through the northern part of Finnsjö Lake and on through Ensjö Lake. From here, it continues in weakened form, ceasing altogether in places, towards Skärplinge, where it joins the Strömmarå River valley and runs out into Lövsta Bay. From Finnsjö Lake to a distance of about 10 km to the NNW, the water table in this line lies very close to 28 metres above sea level. A pass point is reached towards the SSE about 35 metres above sea level between Finnsjö Lake and Älgsjö Lake.

The fracture line on the east runs through Älgsjö Lake towards the north to South and North Åsjö Lake, but cannot be followed out into Gudinge Bay. Instead, the water from Finnsjö Lake and Älgsjö Lake runs through the Forsmark River out into Kallriga Bay.

The Finnsjö line can be said to constitute the western boundary of the bedrock block which contains the actual study area. The eastern boundary of the study area is a small parallel valley along route 290.

The soil layers generally have a levelling effect on the topography determined by the surface of the rock. Local differences in elevation are generally less than 5 m. However, small ridges, such as the one between the southern end of Finnsjö Lake and the town of Film, may give rise to slightly higher hills.

4.3.2 Bedrock conditions

An overall picture of bedrock conditions, over a large area can be obtained from the official geological map sheets on Örbyhus and Öregrund /4-3, 4-4/ from 1869 and 1866. More recent studies have been published by Sund /4-5/. The work on local conditions at Forsmark by A. Carlsson and T. Olsson /4-6/ is also of interest in this context.

The bedrock in the study area east of Finnsjö Lake consists of grey to greyish-red granodiorite - a granite-like type of rock which consists mainly of plagioclase, microcline, quartz, hornblende and biotite. Table 4-2 gives its chemical composition. Its grain size is normally between 3 and 10 mm. The rock is more or less gneissic. To the south and southwest outside of the study area, the granodiorite borders on leptite, i.e. fine-grained, often stratified rock with local strata of limestone and iron ore. They strike around N65°W and stand nearly vertically and are crossed by granodiorite near the border.

The study area is bounded on the east by red, unstratified "Håkansbo" granite. The granodiorite in the study area also contains contiguous veins of pegmatite and aplite.

Field conditions and the character of the rock show that the granodiorite belongs to the Precambrian granites with an age of at least 1 800 million years /Welin, 4-7/.

Metabasite occurs at many places within the study area. Metabasite is a dark, fine-grained metamorphosed rock which runs through the granodiorite in a direction N60-75°W in the form of decimeter-wide, partially non-contiguous veins with a steep dip.

Table 4-2. Chemical analyses of granodiorite from borehole 1 at Finnsjö Lake.

		Depth 23.30 m	Depth 189.50 m	Depth 228.50 m
SiO_2	%	66.6	66.9	68.9
TiO_2	%	0.59	0.54	0.51
Al_2O_3	%	13.1	12.9	13.3
Fe_2O_3	%	1.4	1.7	1.4
FeO	%	3.9	3.7	3.4
MnO	%	0.13	0.11	0.15
CaO	%	4.9	4.8	2.1
MgO	%	2.2	2.0	2.4
Na_2O	%	2.7	2.6	3.1
K_2O	%	3.4	3.6	3.7
BaO	%	0.14	0.14	0.13
S	%	0.02	0.03	< 0.02
U	ppm	< 50	< 50	< 50

Local slate formation and veins of feldspar/epidote in the metabasite indicate that this mineral may be older than the aplites. The metabasites are quantitatively insignificant, but provide important information on the structural development of the bedrock.

Gneissosity, the metabasites and the granite-aplite-pegmatite veins constitute early structural features which hardly affect the permeability of the bedrock in the study area, since they do not give rise to open fractures. The same applies to systematically occurring steep shear zones in east-west and north-south directions, which are mainly signs of a plastic deformation. Mylonite zones, where the granodiorite has been ground down and compacted together again into a fine-grained impervious rock which generally exhibits tight contacts with the surrounding rock, are probably also of little importance to groundwater movements. Fractures in the bedrock, however, especially major fracture lines and crush zones, are of great importance.

The central portions of the area are distinguished by large, low-fissured blocks of bedrock with large, smooth outcrops and areas up to 10^5 m^2. The eastern and western border zones are characterized by less continuous outcrop areas of higher fracture frequency.

Otherwise, the fracture pattern is highly irregular, as can be seen directly from the exposed rock contours on the aerial photographs. Flat cracks of varying direction and dips up to 30° generally comprise the top surfaces of the rock slab. The varying direction of the steep cracks is shown in the fracture diagram (see fig. 4-4), which shows broad and low peaks in the NW and NE. The peak at N30°W corresponds to the direction of the Finnsjö line and the fault valley which borders the study area on the east. The peaks around N60°W and N45°E correspond to more regular, straight and intersecting fractures. N60°W characterizes the metabasites in the study area, but also an important group of partially open, wide and very long fracture zones which are spread over this entire part of the country from Singö and Forsmark to the Storvik region /see Svedmark 4-8, Lundegårdh 4-9/. They are characterized by the fact that the openings are often lined with beautiful crystals of quartz and calcite. Small quantities of bitumenous substances, known as "rock pitch", are also found. The fractures which run in this direction in the outcrops in the Finnsjö area are filled with the same material. A horizontal longitudinal displacement of 0.3 m has been found for one of these faults. But the faults here are few and insignificant and are generally less than 1 cm wide. It must instead be assumed that whatever major fracture zones may exist are not visible in the outcrops, but are rather located in the soil-covered zones between them. The aerial photographs have therefore been examined carefully to determine the location of any fracture lines (see fig. 4-5). Ground examination has shown that these lines for the most part correspond to the edges of outcrops, bog lines and zones of heavy plant growth. Their direction coincides with the direction of the aforementioned shear zones. The only really clear line from the study area runs in a north-south direction

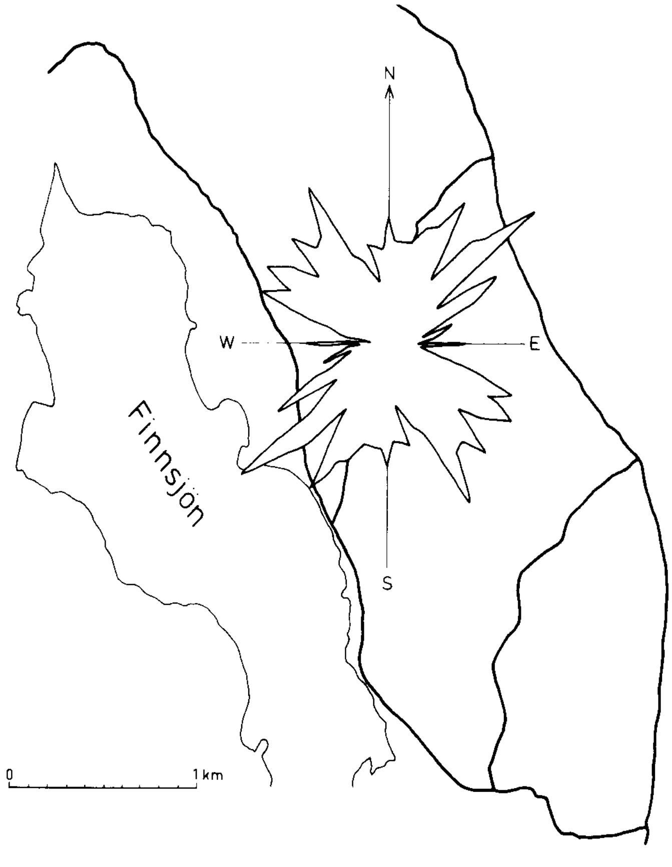

Figure 4-4. Diagram showing the direction of 448 steep fractures within the study area at Finnsjö Lake. The fractures are irregularly oriented in widely varying directions. (Bedrock Bureau, Geological Survey of Sweden).

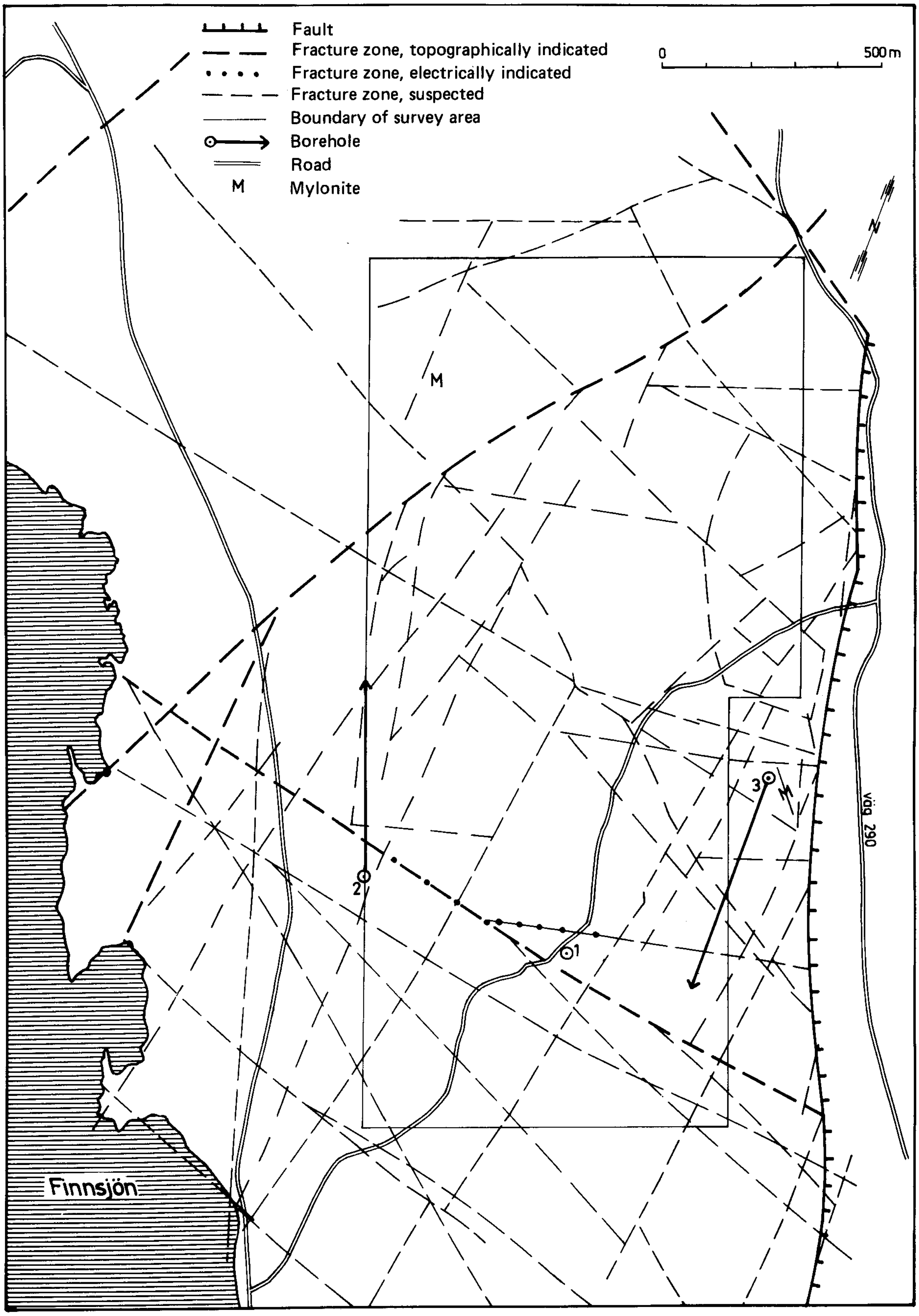

Figure 4-5. Map of the Finnsjö Lake area showing the distribution of fracture lines and the location of boreholes. The indicated survey area was examined by means of magnetic and electrical methods. (Bedrock Bureau, Geological Survey of Sweden).

and exhibits a "horsetail" towards the south. In order to gain further knowledge of the structure of the rock, the area has been covered by geophysical measurements and examined by means of drilling.

4.3.3 Geophysical ground measurements

An area nearly 2 km^2 in size has been surveyed with a magnetometer and an electromagnetic method (slingram). These magnetic measurements do not indicate any distinctive structures. The slingram measurement shows that there is one distinct zone of higher electrical conductivity. It is located in the southern half of the area and runs with some interruptions from near its western edge for approximately 500 metres in an easterly direction and seems to coincide with the photogeologically most clearly indicated east-west line within the area. Other lines have not given any magnetic loop indications.

4.3.4 Drillings

Finnsjö 1 Core Borehole - length 500 m, diameter 56 mm - sunk vertically in good rock, approx. 50 m from the interpolated core line for the electrically conductive zone indicated by slingram measurement.

In brief, the borehole shows that the bedrock is uniform and consists of granodiorite with insignificant variations down to a depth of 500 m. It contains insignificant pockets of isolated, thin pegmatites and metabasites. Below 85 m, the fissure content of the rock is low. More high-fissured zones are found in the sections 214-228 m, 336-362 m and more generally between 432 and 500 m. To a great extent, the fissures are filled with chlorite, quartz (SiO_2) and calcite ($CaCO_3$). The zones of disturbance exhibit a general transformation with reddish coloration of the feldspars.

The permeability of the rock is low, around 10^{-9} m/s or lower. Higher values are found in the surface layer and below 432 m, where a slight increase is noted in connection with a rising fissure content and chlorite content. This is probably connected with the fact that the borehole at this point approaches an electrically conductive zone, as indicated by slingram measurement from the surface. Permeability and RQD diagrams are shown in fig. 4-6.

Finnsjö 2 Core Borehole - diameter 56 mm, length 698 m, depth approx. 525 m - sunk at a 50° angle towards N20°W. It is situated at the western edge of the survey area and crosses the eastwest fracture zones, including the extention of the electrical disturbance zone towards the west. In this way, information is obtained on the boundary of the low-fissured central bedrock blocks towards Finnsjö Lake. At the far north, the hole was also expected to contact the southern branches of the major zone of disturbance which runs through the measuring area in a northeasterly direction without giving rise to any electrical indications.

Bedrock conditions in this borehole are very similar to those in borehole 1. Between 36 and 110 m, however, there is a general

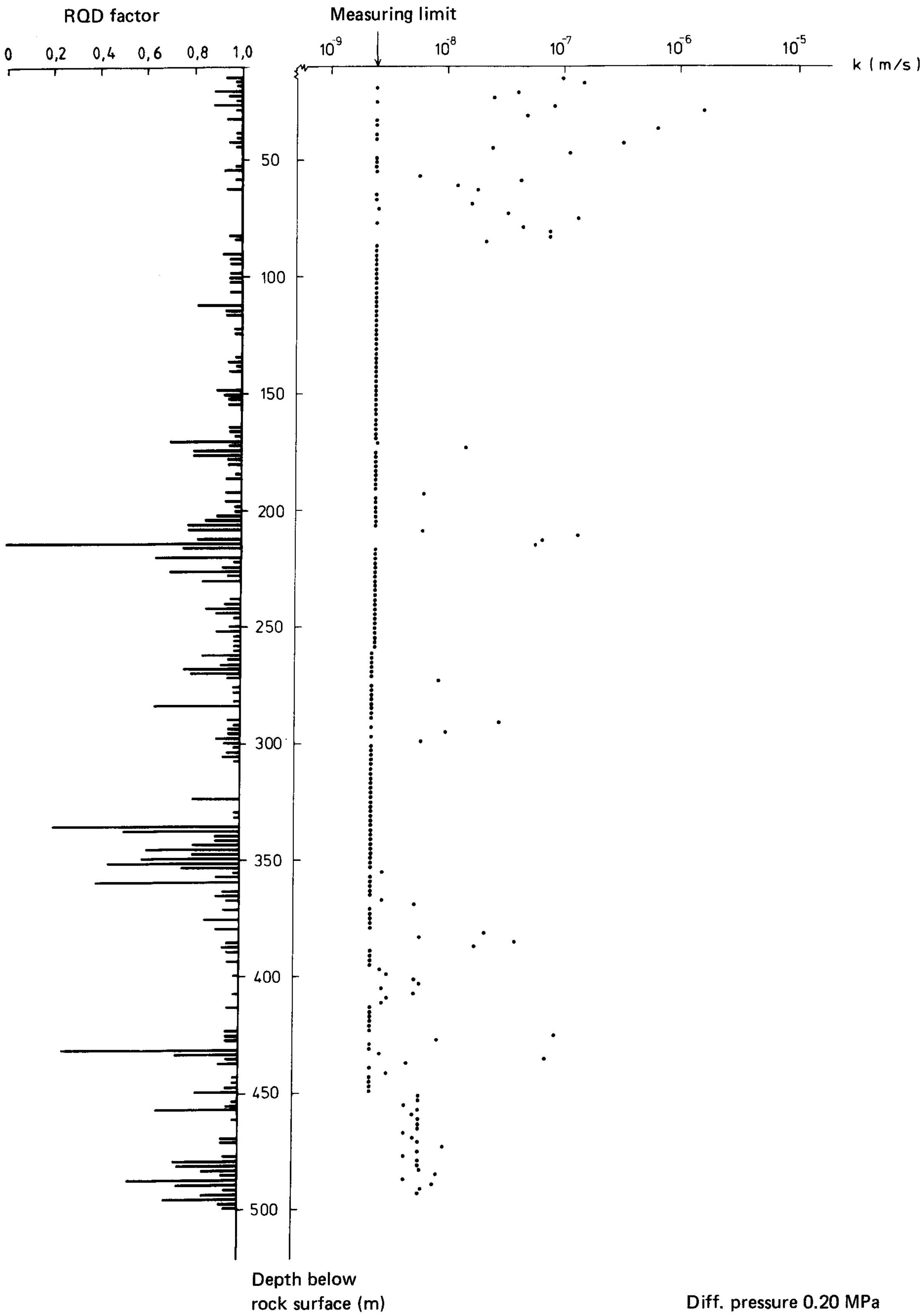

Figure 4-6. Diagram of rock permeability (right) and fissure content expressed as RQD factor (left) in core borehole 1 at Finnsjö Lake (Bedrock Bureau, Geological Survey of Sweden).

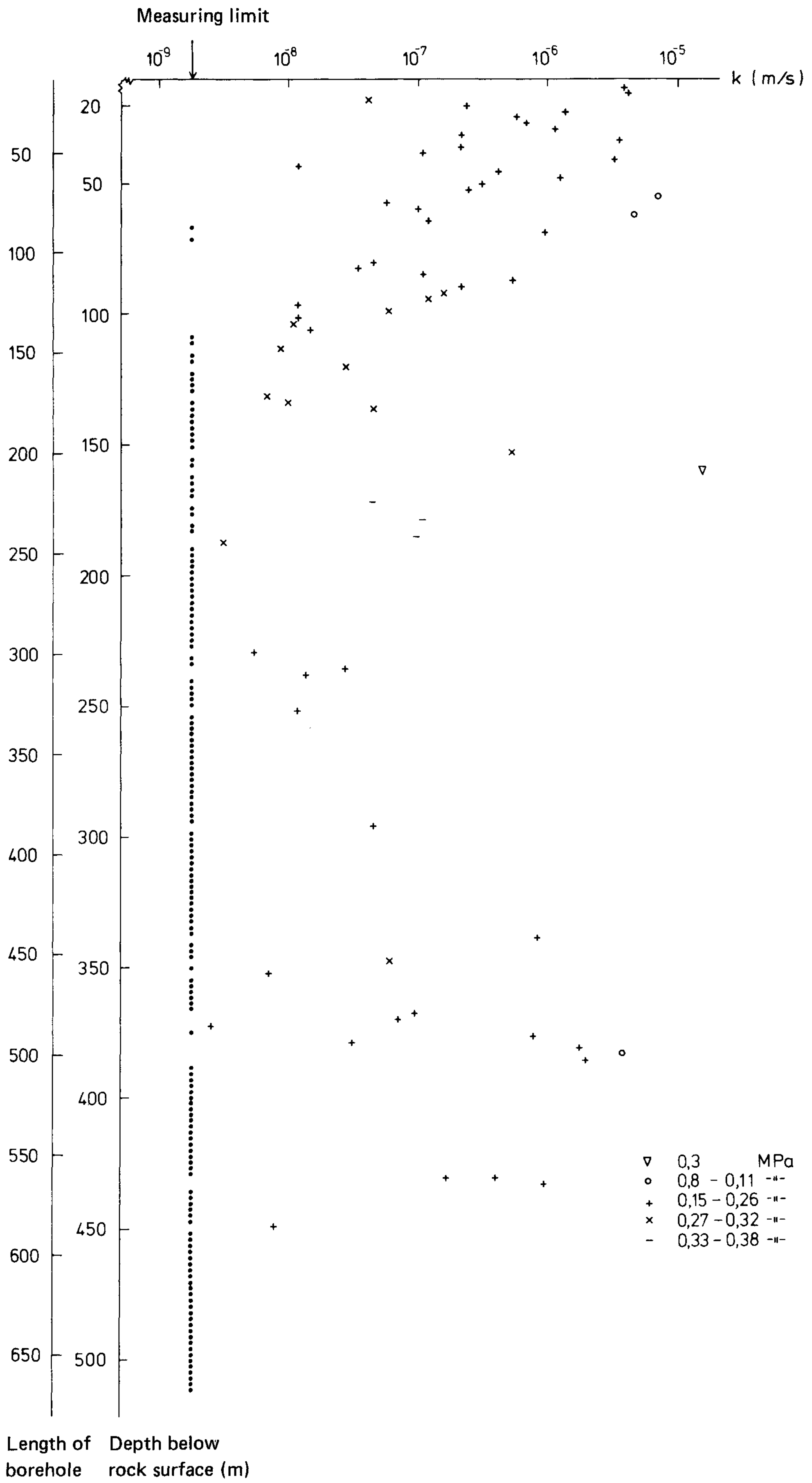

Figure 4-7. Diagram of rock permeability in core borehole 2 at Finnsjö Lake. The borehole was sunk at an angle of 50^0 to the horizontal. (Bedrock Bureau, Geological Survey of Sweden).

fissuring which is accompanied by reddish colouration and the formation of chlorite, calcite and quartz - both in the rock and as crack filler. Between 102.6 and 103.6 m, a lamellar chlorite dyke containing some smectite was found, which caused both core and water losses. The dyke was followed by a zone of intensive crushing. This location coincides well with a vertical projection of the extension of the electrical disturbance zone and the corresponding photogeologically indicated fracture zone.

At 688 m, a crush zone which was filled with a finegrained crush product between 688.4 and 688.9 m was drilled into at an acute angle (approx. 20°). The material from this 50 cm-wide zone filled 4.5 m of the core tube. This remarkable increase in volume indicates the presence of swelling clay minerals which have a low water content to start with and begin to swell when they come into contact with the flush water and the groundwater which collects in the borehole. A corresponding "dry" filler, also in the north-easterly main zone, would explain why no electrical indication of this zone was obtained. Alternatively, this zone may be composed of mylonite.

The borehole was stopped at 698 m (approx. 525 m vertical depth), still in broken rock. Between 110 and 680 m the bore core consists of predominantly good rock. Those cracks which do occur are largely filled with chlorite, calcite, quartz and prehnite, which, like the conditions in the Finnsjö 1 borehole, provide good imperviousness (see fig. 4-7).

Samples of granodiorite and the chlorite dyke at a depth of 103 m and the crushed material from 688.4 m have been examined by means of X-ray diffraction in order to determine what minerals the groundwater is in contact with. The results show that the rock has some illite, that the chlorite dyke contains smectite and perhaps some mixed strata mineral and that the crushed material contains swelling minerals of the mixed strata type. This means that both the rock and the disturbance zones contain ion-exchanging minerals and that the disturbance zones contain swelling minerals which can have some self-sealing effect.

Finnsjö 3 Core Borehole - diameter 56 mm, length 700 m, depth 550 m - sunk at a 50° angle towards the south at the eastern edge of the survey area in order to obtain information on its relatively highly fissured border zone towards the fault valley in the east. The rock here is also uniformly granodioritic, but is more intensively fractured and therefore exhibits reddish coloration and an elevated quartz content. Here as well, the fissures are filled to a large extent with minerals. Despite many small fracture and crush zones, no large dyke zones have been encountered here.

Due to the angle of the borehole towards the fault valley, its distance to the valley increases with increasing depth. The results obtained so far indicate that the zone of impaired rock quality extends some 300 m in from the valley side. It is worth nothing that all boreholes in the Finnsjö area have shown that the zones of disturbance are surrounded by reddish-colour rock with mineral-filled cracks. This means that when a rock repository is being planned and built, warning will be obtained in plenty of time that one is approaching such zones. Virtually no core losses were recorded in connection with drilling through these zones. Nor are they expected to give rise to any special petrological problems.

4.4 KRÅKEMÅLA AREA

4.4.1 Location and topography

The study area in Kråkemåla is located approximately 7.5 km NNW of the Oskarshamn nuclear power plant at Simpevarp and approx. 1.5 km NW of the village of Kråkemåla between the Baltic Sea and Lake Götemaren (see fig. 4-8).

The Kråkemåla area is located near the transition between the subcambrian peneplain along the Baltic coast in the south and the fractured countryside which characterizes the coastal regions of northern Småland and Östergötland. The countryside is characterized by flat landscape broken by pronounced fracture valleys running primarily in north-south, east-west and northwest directions (see fig. 4-9).

The study area comprises the eastern portion of a local watershed between the Baltic Sea and Lake Götemaren, whose average water level is only 1 metre above sea level. The nearly horizontal surface of the area falls from 20 m above sea level in the west to 15 m in the east, where it is bounded by a north-west fracture valley with a pass point about 10 m above sea level between Bussviken Bay (in the Baltic) and the outlet of Lake Götemaren.

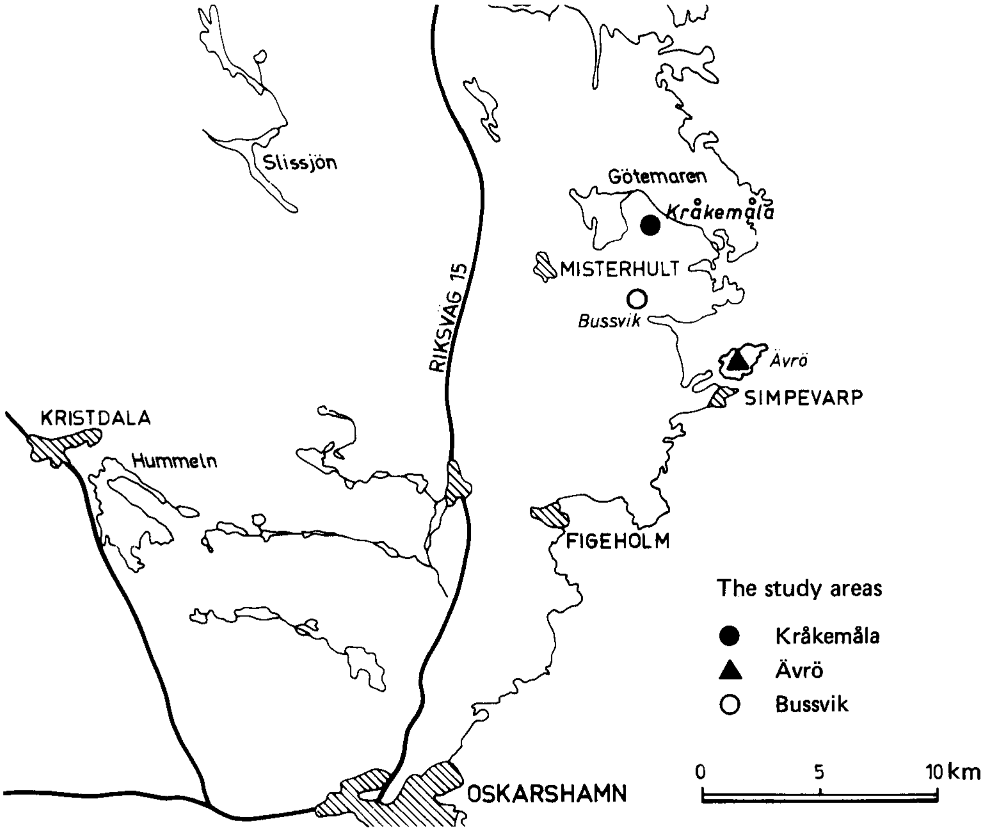

Figure 4-8. Map showing the study areas of Kråkemåla, Ävrö, and Bussvik

The fracture valley is partially filled with sand and gravel deposits. The bottoms of some very small gravel pits reach the local watertable. The soil cover is generally thin and large areas consist of exposed rock.

4.4.2 Bedrock conditions

For an overall picture of bedrock conditions in the area, see the geological map-sheet for Oskarshamn /4-10/. The region is composed of Småland granites while the actual study area is located within the Götemar massif - a body of young granite, the Götemar granite, with a circular outcropping about 9 km in diameter. Its age has been determined at about 1 380 million years /Åberg 4-11/. The massif was recently described by Kresten and Chyssler /4-12/.

The Götemar granite is composed of four subtypes which occur in different parts of the massif and which differ primarily with respect to grain size.

A coarse-grained red granite with a grain size of around 15 mm dominates in the study area. This granite consists primarily of microcline (60-75%), quartz (20-35%), biotite and accessory minerals. In the western part of the area, it borders on medium-grained granite with a grain size of less than 10 mm, often somewhat lighter and muscovitebearing but otherwise of nearly identical composition. Chemical analyses of the rocks in the Kråkemåla area are reported in table 4-3.

Flat, horizontal bodies of pegmatite in which the grain size can reach around 10 cm are encountered frequently in both types of granite. They are seldom more than 0.5 cm thick and a metre or so long.

The general pattern of fractures in the region has been analyzed by Asklund /413/ and Nordenskjöld /4-14/.

The Götemar massif is very uniform with respect to rock structure. It exhibits four pronounced fracture directions. Steep vertical cracks parallel to the circumference of the massif make up a concentric pattern which is complemented by a radial system which, together with the concentric set, produce a very regular, nearly perpendicular pattern of fractures in each local section (see fig. 4-10 and 4-11). In addition to these, there are diagonal fractures and widely dispersed, nearly horizontal fractures areas which are also responsible for the flat rock surface within the study area. The various types of granite in the massif are characterized by varying fissure density (see fig. 4-12). The coarse granite especially is of unusually low fissure content at the surface, which was one of the reasons for choosing this study area.

The same fracture pattern recurs in the surrounding Småland granite, where it is filled with granite and pegmatite veins which are associated with the Götemar granite. This, along with the deposits of primary minerals such as muscovite on the fracture surfaces, show that these cracks belong to a late phase in the formation of the Götemar granite and are therefore just as old, while more recent deformation is of much less importance.

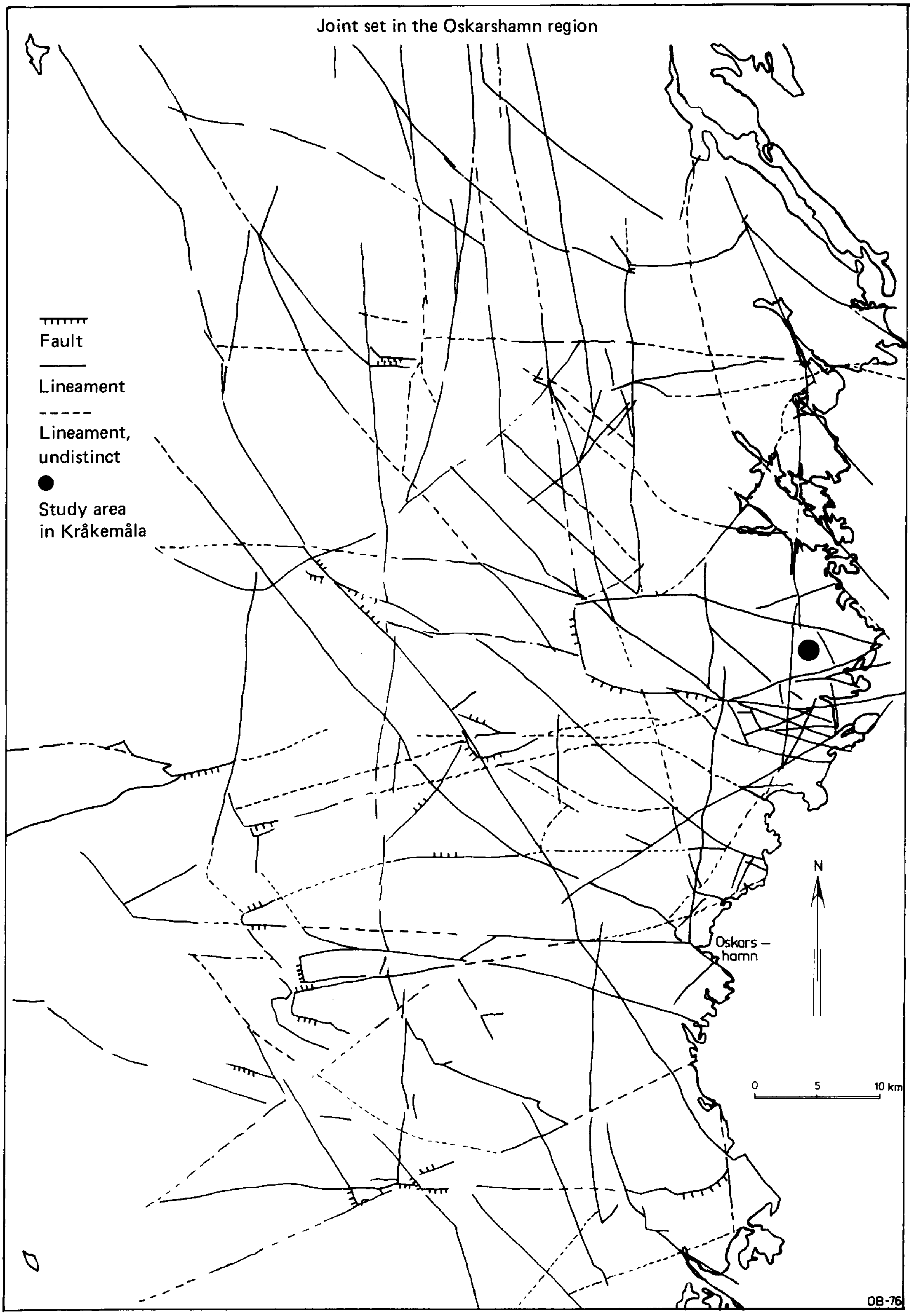

Figure 4-9. Map of the joint set in the Oskarshamn region. (Bedrock Bureau, Geological Survey of Sweden).

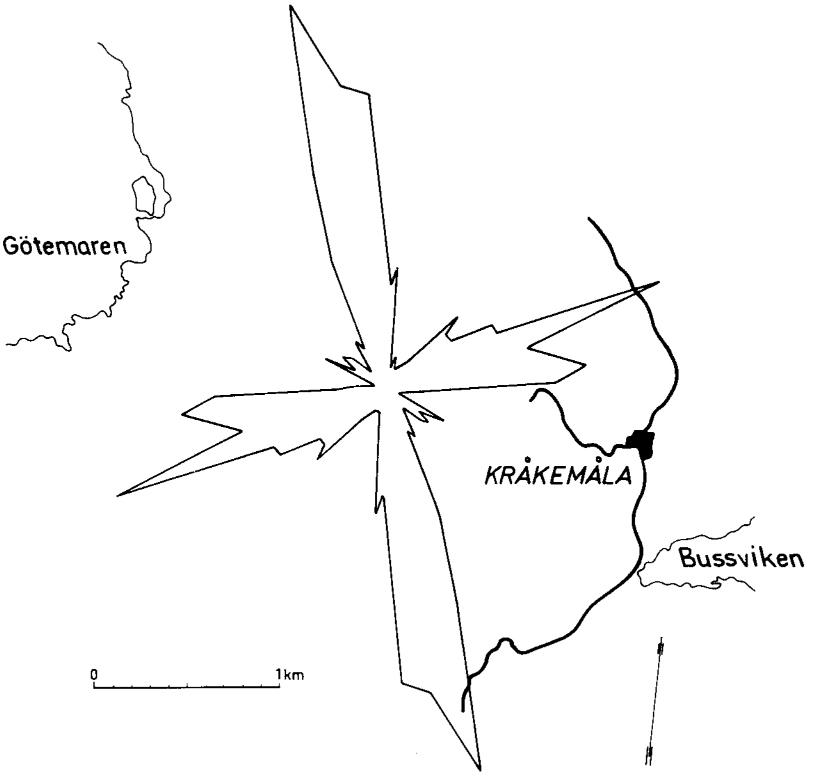

Figure 4-10. Diagram showing the direction of 327 steep fractures within the study area at Kråkemåla. The cracks are regularly oriented and deviate little in terms direction. (Bedrock Bureau, Geological Survey of Sweden).

An early tensional event with a probable age of around 1 200 million years is represented by a diabase vein which cuts through the granite in a NNW direction. East-west fractures, which are undeformed and filled with sandstone of precambrian age, indicate the proximity of the subcambrian peneplain.

More recent post-Cambrian movements can be discerned locally. These include the north-south fault which runs through the massif approximately 5 km west of the study area. The east-west fault at Mönsterås, which constitutes the northern limit of the precambrian sandstone there, can be seen at a greater distance.

4.4.3 Geophysical ground measurements

Two square kilometers within the Kråkemåla area were previously surveyed magnetically, electrically and seismically by Eriksson /4-15/ on commission from PRAV. The measurements showed, in agreement with the fracture pattern, that the coarse Götemar granite possesses very low electrical conductivity, but is subdivided into blocks bounded by zones of higher conductivity. The elastic properties of the rock were determined seismically. The following values were obtained: modules of elasticity 45-55 GPa, modules of shear 22.18 GPa, Poisson's ratio 0.25.

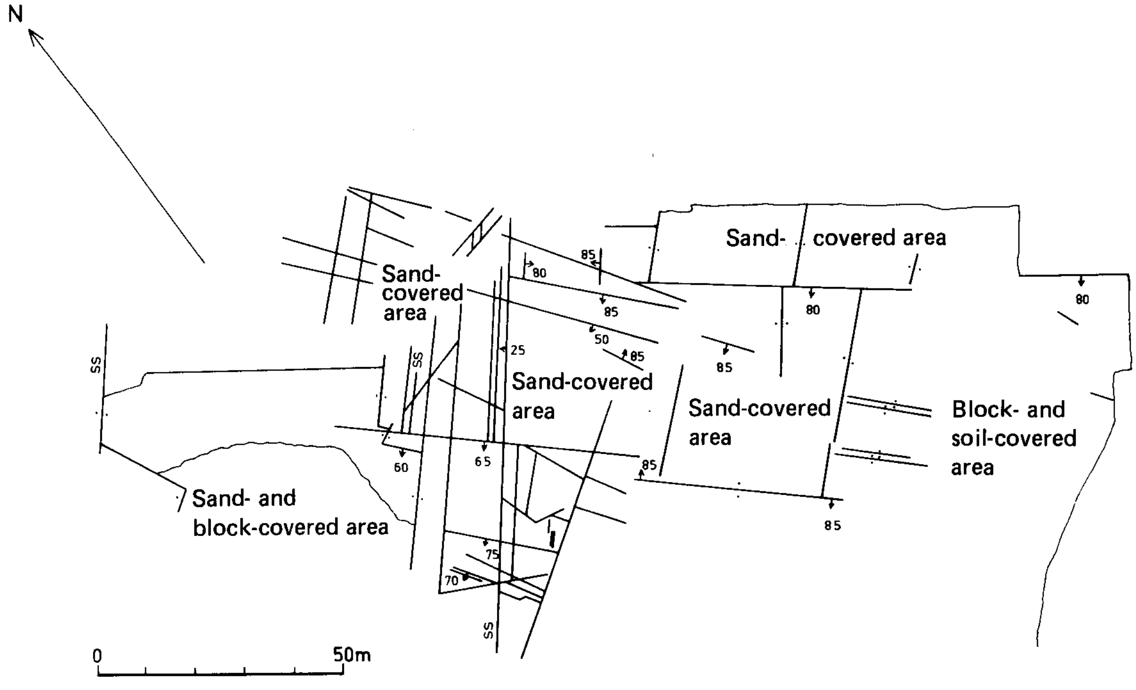

Figure 4-11. Joint map of stone quarry north of Kråkemåla (location, see figure 4-12). It illustrates the regular pattern of cracks. SS marks cracks filled with 550 million-year-old Cambrian sandstone. (Bedrock Bureau, Geological Survey of Sweden).

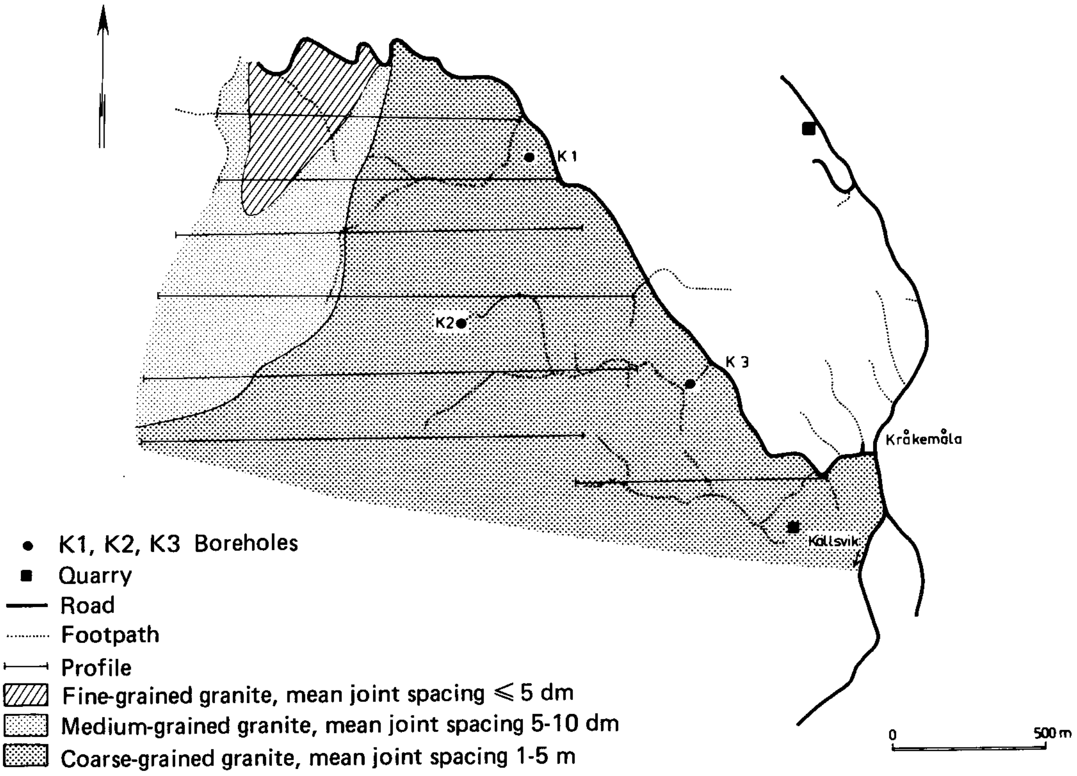

Figure 4-12. Map of study area at Kråkemåla showing the variations in the grain size of the granite. The 3 core boreholes are marked. The mean joint spacing in the different types of granite varies between 0.5 and 5 m. (Bedrock Bureau, Geological Survey of Sweden).

Table 4-3. Chemical composition of the rock in the Kråkemåla area, after Kresten and Chyssler, 1976.

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	73.2	71.9	75.9	72.2	72.4	76.1	74.4	71.7	74.9	73.8	73.3	76.1	67.1
TiO_2	0.41	0.42	0.15	0.36	0.36	0.08	0.13	0.05	0.13	0.07	0.26	0.14	0.80
Al_2O_3	13.7	13.8	12.6	13.2	13.2	12.6	14.8	15.9	12.7	14.3	13.0	12.5	14.5
Fe_2O_3	0.8	0.9	0.1	0.8	0.7	<0.1	<0.1	<0.1	0.2	0.1	0.5	0.1	1.5
FeO	0.6	0.9	0.5	0.8	1.1	0.3	0.1	0.3	0.6	0.3	0.8	0.4	2.3
MnO	0.04	0.06	0.03	0.03	0.05	0.02	0.01	0.18	0.07	0.06	0.04	0.04	0.07
MgO	1.2	1.2	0.8	1.3	1.2	0.5	0.3	0.10	0.6	0.10	1.1	0.5	1.1
CaO	0.6	0.6	0.08	0.33	0.36	0.02	0.2	0.02	0.08	0.4	0.25	0.06	1.9
Na_2O	3.1	3.7	3.6	3.7	3.6	4.2	2.9	6.1	3.9	4.0	3.5	4.0	3.1
K_2O	4.3	5.3	5.0	5.1	5.1	4.4	4.1	4.0	4.6	5.2	5.1	4.5	5.1
H_2O+	-	-	0.4	0.4	0.3	0.3	-	0.3	0.5	0.5	0.3	0.2	0.6
H_2O-	-	-	<0.1	0.1	0.1	<0.1	-	<0.1	0.1	0.1	0.1	<0.1	0.1
P_2O_5	-	-	0.01	0.08	0.07	<0.01	-	<0.01	0.02	<0.01	0.05	0.01	0.22
CO_2	-	-	0.03	0.01	0.11	0.04	-	0.03	0.03	0.02	0.19	0.01	0.12
F	0.49	0.56	0.56	0.59	0.51	0.31	0.06	0.41	0.55	0.24	0.51	0.32	0.18
S	-	-	<0.02	<0.02	<0.02	<0.02	-	<0.02	<0.02	<0.02	<0.02	<0.02	0.04
BaO	0.08	0.08	0.02	0.08	0.08	0.01	0.02	<0.01	0.01	0.01	0.05	0.01	0.13
Sum	98.32	99.32	99.78	99.11	99.26	98.88	97.02	99.09	98.99	99.20	99.05	98.99	98.86
-0 for F, S	0.21	0.24	0.24	0.25	0.21	0.13	0.03	0.17	0.23	0.10	0.21	0.13	0.09
Total	98.11	99.08	99.54	98.86	99.05	98.75	96.99	98.92	98.76	99.10	98.84	98.86	98.77
Norm:													
Q	35.7	27.2	33.7	29.1	29.8	32.9	40.0	19.4	32.9	28.1	31.7	33.7	26.9
Ab	28.7	33.7	32.9	34.0	33.0	38.4	27.1	54.8	35.9	36.5	32.1	36.6	26.6
Or	23.3	29.0	27.3	27.6	27.3	25.0	24.5	22.8	25.9	30.7	27.7	25.6	26.8
An	3.0	3.0	0.2	1.2	1.3	0.1	1.0	0.1	0.2	2.0	0.9	0.2	6.8
Bi	4.6	4.5	3.7	5.2	5.6	2.4	1.1	1.3	3.2	0.9	4.9	2.4	6.0

1. GÖT 11 Coarse-grained granite. 2. GÖT 24 Coarse-grained granite. 3. SL31A Coarse-grained granite. 4. GG 14 Coarse-grained granite. 5. GG 3 Coarse-grained granite. 6. GG 8 Medium-grained granite. 7. GÖT 26 Medium-grained granite, pale pinkish. 8. SL36B Fine- to medium-grained granite, white, with garnet and topaz. 9. SL1A Fine-grained granite, porphyritic. 10. G4a Medium-grained granite. 11. GG 2 Granite porphyry, dyke north of the massif. 12. GG 7 Porphyritic granite, eastern margin of the massif. 13. GG 1 Småland granite, reddish grey, porphyritic variety. Wall-rock to the north.

4.4.4 Drilling

The first hole was drilled in order to determine whether the fundamental characteristics of the rock as regards vertical extent and uniformity were suitable. When this was found to be the case, further holes were drilled. Borehole 2 illuminates the western boundary of the low-fissued, coarse-grained granite, where the medium-grained granite begins. Borehole 3 runs through the border zone of the study area towards the fracture valley which constitutes its boundary towards the east.

Kråkemåla 1 Core Borehole - diameter 56 mm, length 504.65 m - was sunk vertically in good rock and runs throughout nearly its entire length through uniform, coarse-grained, red massive granite. There are, however, five bands of fine-grained aplitic granite with a combined thickness of 12.2 m. Coarse-grained granite thus comprises 97.6% of the core. At a depth of between 60 and 76 m, the granite exhibits scattered grains of pyrite and molybdenite.

The distribution of fractures is depicted by the RQD diagrams - see fig. 4-13. The majority consist of fresh fractures straight through the bore core, and many were created during drilling.

The water injection tests show that the permeability of the rock down to 50 m is distributed around 10^{-7} m/s (see fig. 4-13), while a clear division into high and low values is found at the deeper levels. The high values here are also around 10^{-7} m/s, while the low values are at or below the measuring limit, i.e. no water loss could be measured by means of the equipment which was used. This means that the permeability of the rock is less than 1.9×10^{-9} m/s at a pressure of 0.2 MPa and less than 8×10^{-10} m/s at a pressure of 0.6 MPa. Only four 2-metre sections along the entire section between 320 and 496 m exhibited measurable water loss. These sections contain smooth, deposit-filled fractures while the sections containing the more common fresh cracks do not give rise to any measurable water loss.

The fractures in the Götemar granite exhibit varying mineral content. Sample scrapings from the walls of the cracks in the bore core from Kråkemåla 1 were therefore subjected to closer study. Aside from the usual minerals in the granite and general crack minerals such as chlorite and calcite, the cracks also contained sulphur pyrite and lead glance as well as fluorspar, kaolinite and smectite. Kaolinite was found with certainty in only a single sample near the surface, while smectite was found in four samples down to 326 m, although in little quantity.

Kråkemåla 2 Core Borehole - diameter 56 mm, length 604.8 m - was sunk vertically in good rock near the western boundary of the coarse-grained red granite. This is reflected in the core by many (25) bands of fine-grained granite, which together constitute 14% of the entire length of the core, and a generally higher fissure content - see fig. 4-14. This borehole also exhibits good imperviousness between 330 and 495 m, with values for water loss which lie below the measuring limit. At greater depths, fissure content increases again. It is therefore realistic to assume that this borehole marks the western boundary of the volume of rock which is suitable for housing a rock repository.

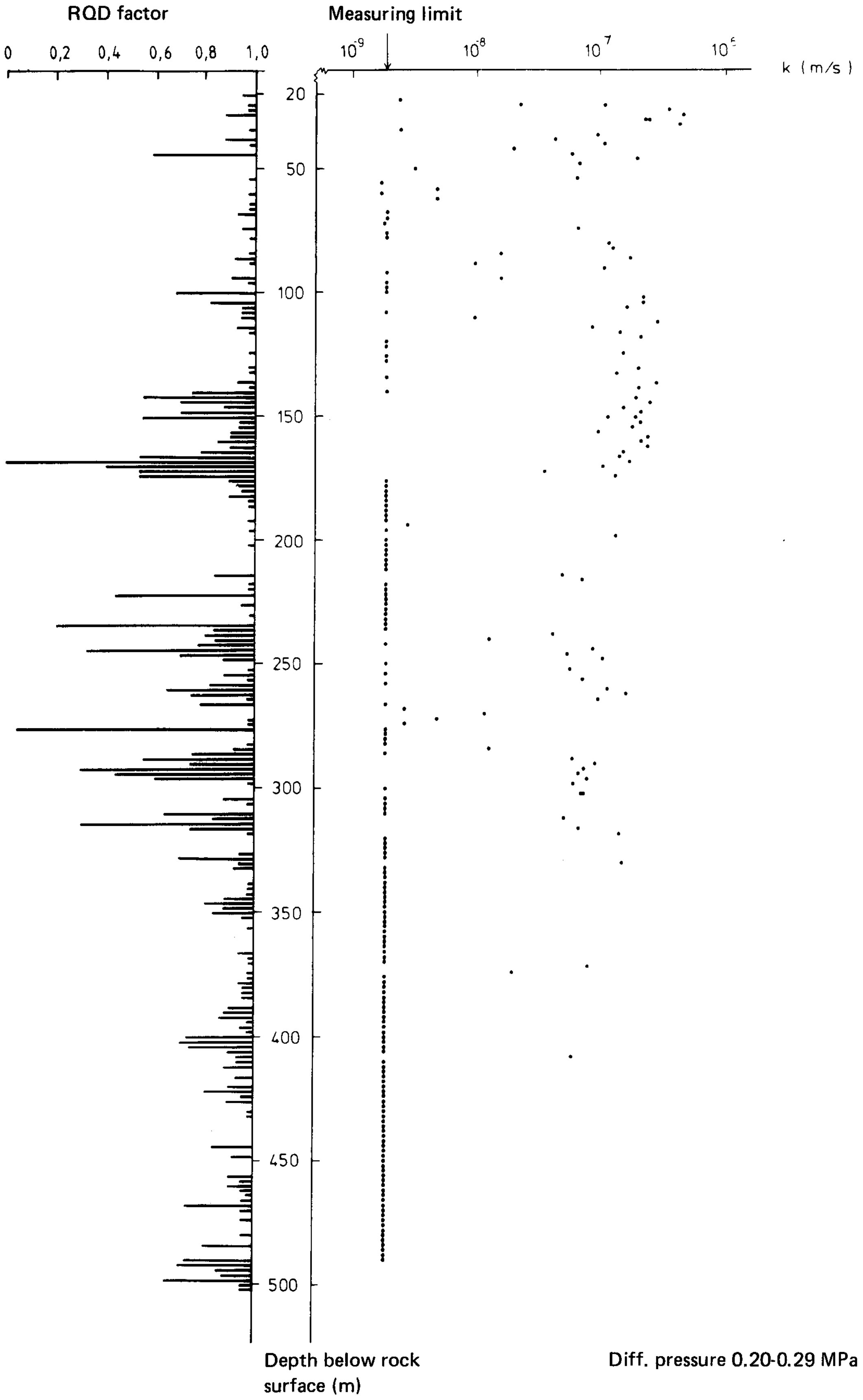

Figure 4-13. Diagram of rock permeability (right) and fissure content expressed as RQD factor (left) in core borehole 1 at Kråkemåla. (Bedrock Bureau, Geological Survey of Sweden).

Kråkemåla 3 Core Borehole - diameter 56 mm, length 760 m, depth approx. 560 m - was sunk with a 50° angle towards the WNW in good rock on Solberget, which is a low-fissured rib between two northwesterly fracture valleys east of the geophysically studied area. Bedrock conditions in this borehole are very similar to those in Kråkemåla 1. Despite the frequency of fissures and narrow crush zones in the upper parts, the fissure content of the rock decreases with depth. This indicates that fissuring of the rock around the topographically prominent valleys in the Kråkemåla area is limited.

4.5 OTHER AREAS

4.5.1 Ävrö

Ävrö is located 1.5 km north of Simpevarp, and most of the land belongs to Oskarshamns Kraftgrupps AB (see fig. 4-8). Topographically, it is an island with many small fracture valleys. The bedrock consists of red to grey, medium-grained and unstratified to weakly gneissic Småland granite. An eastwest steep diabase was observed in one exposed rock slab. Geophysical measurements indicate that the entire area is divided into blocks with intervening, slightly electrically conductive zones. A seismic study revealed the following data: modulus of elasticity 25-43 GPa, modulus of shear 10-17 GPa, Poisson's ratio 0.25.

Ävrö 1 Core Borehole - diameter 56 mm, length 502.2 m - was sunk vertically in good rock in an area of high resistivity. The core shows red granite, which, despite considerable fissure content, has permeabilities below 10^{-7} m/s. Diabase was encountered in four sections, but the lengths of the sections are probably much greater than the thicknesses of the diabases, due to their steep angles. Below 400 m, the granite in this borehole is heavily crushed and highly permeable. The studies were therefore not carried to completion.

4.5.2 Bussvik

Bussvik Bay is located 4.5 km northwest of Simpevarp (see fig. 4-8) and was only studied geologically and seismically from the surface. The area is characterized by large, relatively low-fissured surface slabs of Småland granite. Good seismic values were measured: modulus of elasticity 50-60 GPa, modulus of shear 20-24 GPa, Poisson's ratio 0.25. No drillings have yet been carried out in Bussvik.

4.5.3 Forsmark

Forsmark is located about 3.5 km west of the Forsmark nuclear power plant (see fig. 4-3) and within an area around the power plant which has been surveyed by means of geophysical aerial measurements. Surface geology and geophysical measurements indicate that the area comprises a single coherent bedrock block with high resistivity and a low fracture frequency. The bedrock is composed of medium-grained, weakly gneissic grey quartz diorite, which borders on leptitic gneiss on the south with a northwesterly

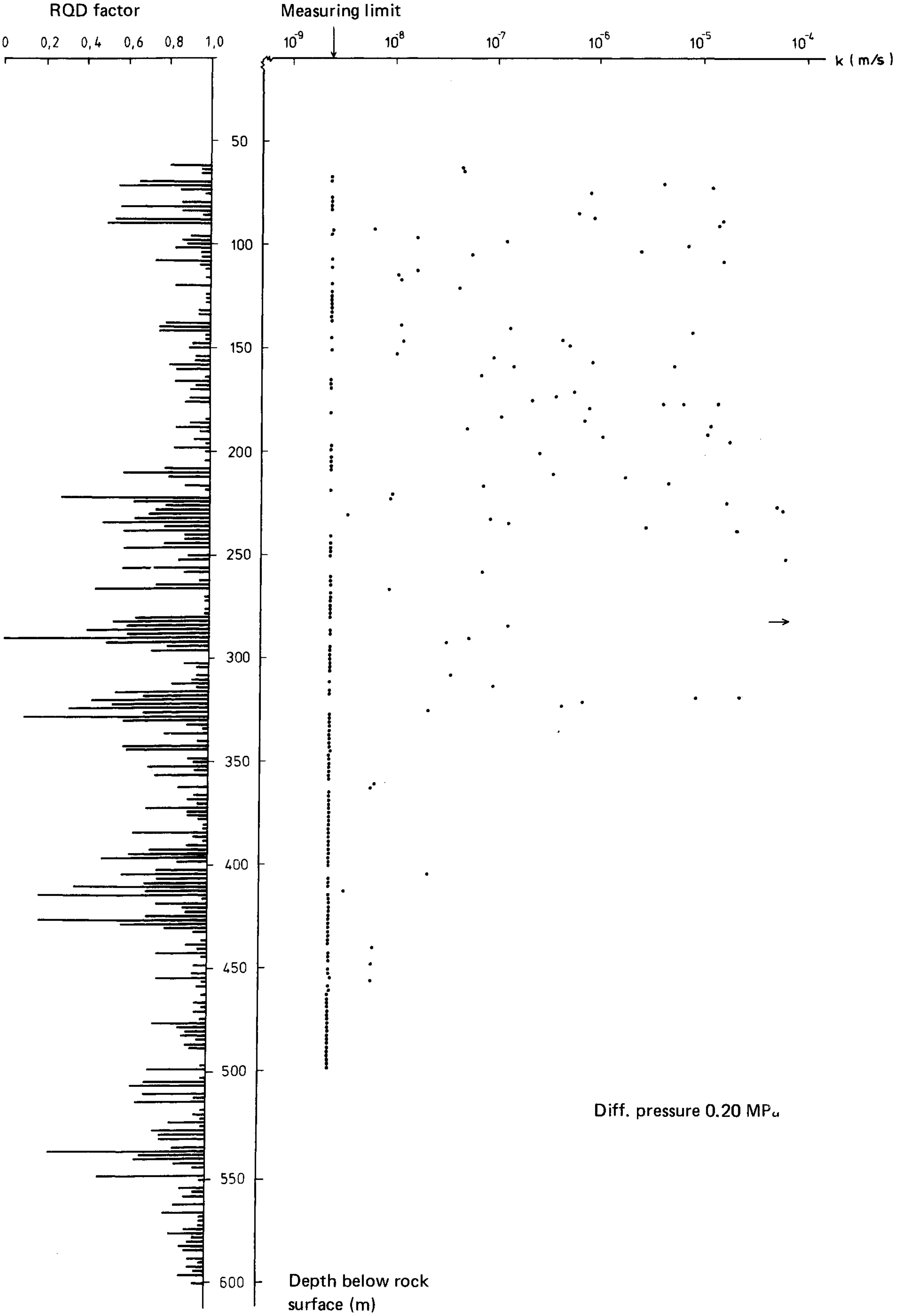

Figure 4-14. Diagram of rock permeability (right) and fissure content expressed as RQD factor (left) in core borehole 2 at Kråkemåla. (Bedrock Bureau, Geological Survey of Sweden).

strike. The leptite is partially folded and has a predominantly northeasterly dip.

Forsmark 1 Core Borehole - diameter 56 mm, length 478.3 m - was sunk vertically in good rock. Down to 219 m, the hole runs through a rather low-fissured diorite with a varying content of hornblende and biotite, and occasional layers (2 m thick) of pegmatite and aplite. At increasing depth, a nearly horizontal banding becomes increasingly pronounced, and below 375 m, banded, light, partially leptitic gneisses predominate. At the same time, the quality of the rock deteriorates considerably. Drilling was therefore terminated at 478.3 m. The drilling results indicate that the study area describes a U-shaped convolution and that the diorite is not sufficiently deep. The area must therefore be regarded as less suitable for a deep rock repository.

5 GROUNDWATER CONDITIONS

5.1 GROUNDWATER HYDROLOGY

Radioactive waste which is stored deep down in the bedrock can be dispersed only via the groundwater. The magnitude of the groundwater flow in the areas under consideration, as well as its velocity, retention time and pattern of movement, are therefore of great interest.

The metallic or ceramic material which is used to encapsulate the waste can be subjected to corrosion attack when it comes into contact with the groundwater. The nature and rate of the corrosion attack depend upon the chemical composition of the groundwater, which is therefore another crucial factor.

5.1.1 Permeability of the bedrock

As was related in chapter 4, the permeability of the bedrock was measured in a number of boreholes in 2 m (in some cases 3 m) long sections from the surface of the rock to the bottom of the borehole. The results can be summarized as follows.

The upper part of the bedrock, which may extend down to a depth of anywhere between 20-30 and a few hundred metres, is often characterized by relatively high permeability, owing to an extensive and coherent network of fissures. The upper sections of the bedrock correspond most closely to the model for fissured rock developed by Snow /5-1/ on the basis of a large number of drillings and permeability determinations down to a depth of 100 m. With increasing depth, the abundance of sections of very low permeability increases, and there is a transition to conditions characterized by large formations of predominantly impervious rock, interrupted by narrower water-bearing fracture zones. The lower sections therefore exhibit the conditions for crystalline rocks at great depth described by Webster et al. /5-2/.

Most of the groundwater flow in the bedrock takes place in the upper part of the rock, where permeability is often between 10^{-5} and 10^{-7} m/s. Hydraulic coherence in this section is generally good, which gives rise to a continuous and level water table /see Larsson et al. 5-3/.

A smaller portion of the groundwater flows through the deeper part of the bedrock, where its movement is for the most part restricted to certain water-bearing zones. Water-bearing zones of high saturation have been found in Swedish mines down to a depth of 900 m. Intervening sections of rock have a permeability of less than 10^{-9} m/s. 5×10^{-11} m/s has been measured in the granite at Stripa /5-4/. Hydraulic coherence between the individual fissures at great depth appears to be severely restricted, as is evidenced by the fact that no measurable water flow was found in sections where both the drill core and TV examination indicate the existence of fissures. Considerable differences in the chemical composition and age of the water also indicate that hydraulic coherence between the waterbearing zones in the same boreholes can be limited at these depths. But there is always some hydraulic coherence via the more permeable upper part of the bedrock.

5.1.2 Groundwater flow

The rate of groundwater flow is determined by the profile of the water table, the permeability of the bedrock and depth below the water table. The water table follows the contours of the landscape, with some smoothing-out.

In order to calculate the groundwater flow, a large number of two-dimensional models with different water table profiles and permeability conditions have been simulated by means of special computer programs /5-4, 5-5/. Figure 5-1 shows the groundwater flow underneath an island, from its centre outwards. The calculation is based on the fact that permeability is known near the surface and decreases with depth in a regular manner. This diagram has been used as a model for the Karlshamn area, which is situated on a peninsula. At a depth of 500 m, a subsurface permeability of 10^{-9} m/s and a water table slope of 0.05, a flow of about 0.2 litres per m^2 and year is obtained.

Figure 5-2 shows the groundwater flow underneath a kilometre-long slope. In the calculation, it is assumed that permeability does not vary with depth, which leads to groundwater flows down to great depths. This model has been applied to the areas at Finnsjö Lake and Kråkemåla. For the Finnsjö area, a flow of 0.1 litres per m^2 and year is obtained at a depth of 500 m, with a permeability of 10^{-9} m/s and a water table slope of 0.008. For the Kråkemåla area, a flow of 0.15 litres per m^2 and year is obtained at the same depth and permeability with a water table slope of 0.012.

The flow values calculated above are probably much higher than the actual values, since the average permeability of the rock is lower than the value of 10^{-9}, which was the measurability limit.

5.1.3 The pattern of groundwater flow

The path of the groundwater through the bedrock can be illustrated by means of the same type of diagram as is shown in figures 5-1 and 5-2, provided the calculations are adjusted to the actual elevations within a given area. For two-dimensional calculations, it is assumed that slopes and other landscape contours are oriented perpendicular to the plane of the figure and extend far in this direction. In order to be realistic, the calculations must be made with regard to a plane which is perpendicular to the direction of the dominant valley. Furthermore, the permeability of

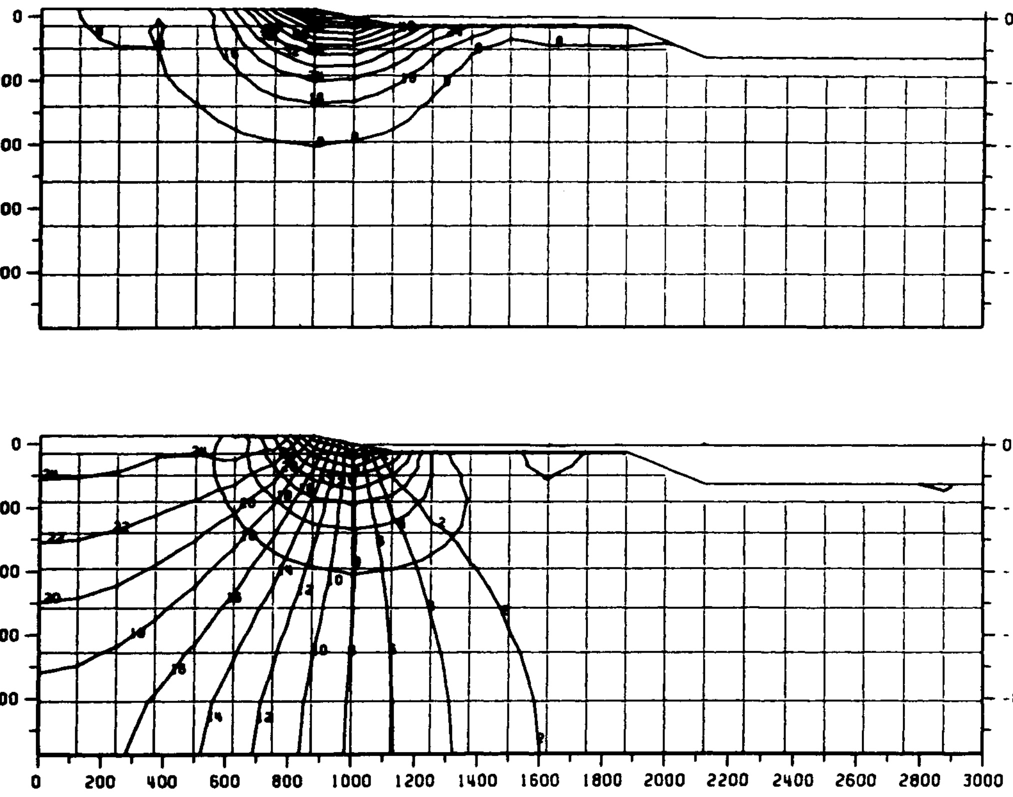

Figure 5-1. Diagram of the calculated groundwater flow under an island from the centre outwards. The height and length scales are in metres. The top chart shows lines for equal flow expressed in 10^{-9} m^3/s and a cross-sectional area of 1 m^2. The lower chart which shows flow lines and equipotential lines, assumes an impenetrable bottom surface at a depth of 1000 metres and a superficial permeability of 10^{-6} m/s. Permeability then decreases exponentially to $5 \cdot 10^{-8}$ m/s at a depth of 1000 metres /5-5/.

the rock within the area must be assumed to be constant or change with depth in a regular manner. The influence of individual zones of higher permeability, which are responsible for much of the flow in the deeper parts of the bedrock, can therefore not be simulated by the model. By varying the assumptions for the calculations and thereby distributing the effects of the individual zones over greater volumes, it is nevertheless possible to shed light upon the general flow conditions. This has been done for the Finnsjö area (see fig. 5-3 and 5-4).

The diagrams show, as was already known, that the groundwater flows downward into the bedrock in elevated areas, after which it turns and flows upward again towards large adjoining valley floors, where it can reach the surface at points of groundwater inflow into waterways. The influence of terrain features often extends down to depths of several thousand metres. The longer the slopes are, the deeper their influence reaches. The surface areas

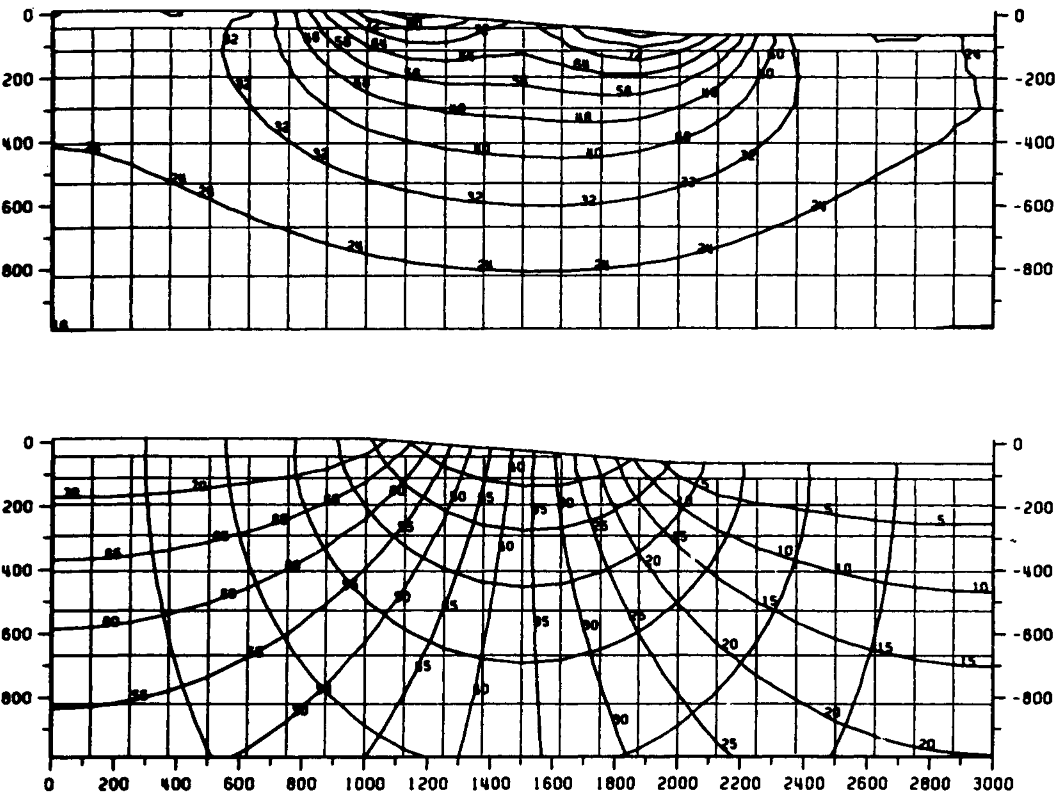

Figure 5-2. Diagram of calculated groundwater flow under a slope. The height and length scales are in metres. The top chart shows lines for equal flow expressed in 10^{-9} m^3/s *and a cross-sectional area of 1* m^2*. The lower chart shows flow lines and equipotential lines. No bottom surface at a finite depth is assumed in this case. Permeability is constant at* 10^{-6} *m/s. /5-5/.*

where groundwater from great depth issues are small, and the upflow is accompanied by a very heavy dilution of the groundwater.

One consequence of these general conditions is that the groundwater movements in an area lacking extensive, flat aquifers are divided into smaller flow cells and that groundwater transport is predominantly of a local character. This pattern becomes more pronounced if the valleys follow fracture zones in the bedrock where permeability is high.

The diagrams for the Finnsjö area show that the flow there is directed towards Finnsjö Lake and towards a valley approximately 2.5 km northeast of the lake. There is probably also some upward flow in the fault valley which borders on the study area towards the northeast. No cold springs have been found here or in other parts of the area, which indicates that none of the deep groundwater reaches up to the surface. The groundwater should therefore follow roughly the pattern illustrated by the diagram.

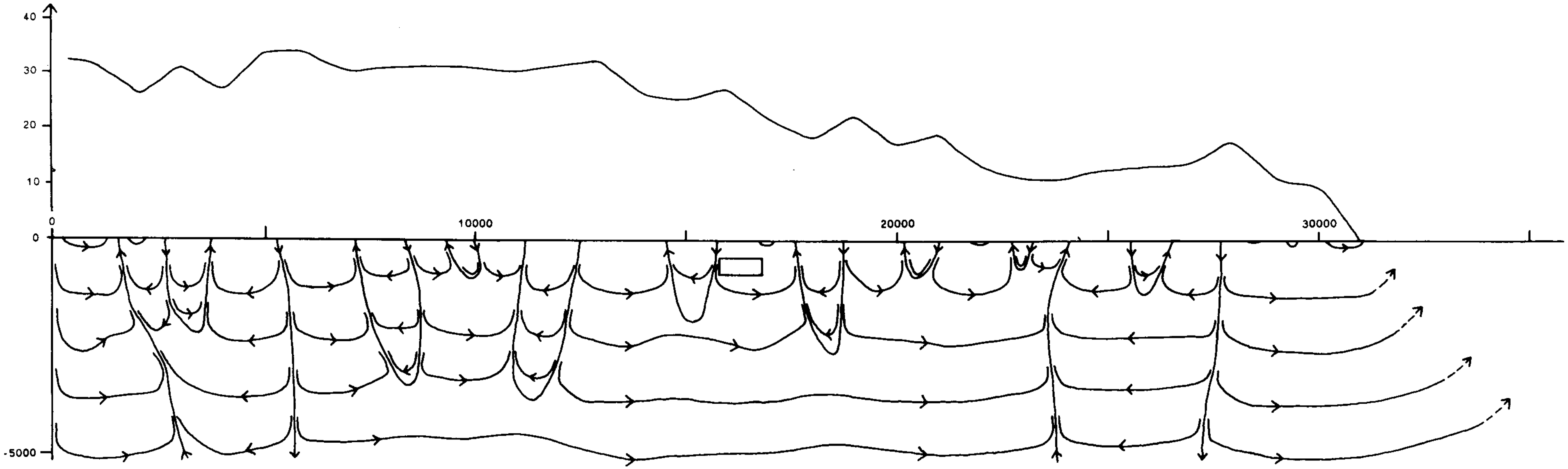

Figure 5-3. Diagram of groundwater flow pattern in a northeasterly section through the area at Finnsjö. An impenetrable bottom surface at finite depth is not assumed in this case. Permeability is assumed to decline by 50% for every 100 metres. The flow lines are chosen so that the flow decreases with depth by a factor of 10 000 between two flow lines. /5-5/.

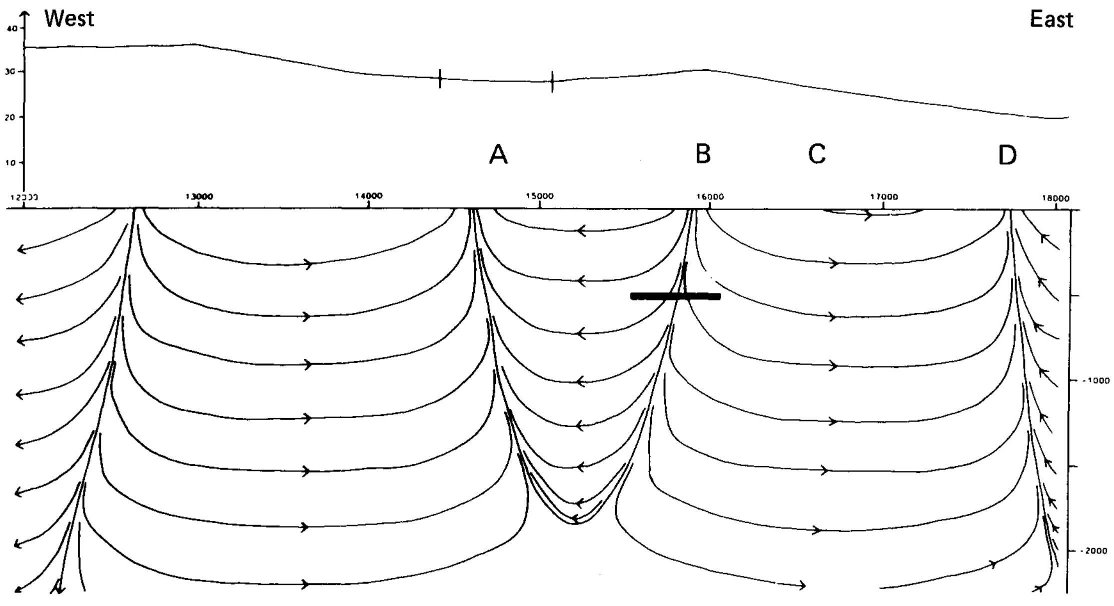

Figure 5-4. Detail from figure 5-3. The flow lines are chosen so that the groundwater flow decreases with depth by a factor of 10 between two flow lines. A marks Finnsjö Lake, B marks the groundwater divide, C marks a fault valley, and D marks the outflow area. The repository is marked with a heavy line under B. Note that the groundwater flows through the repository in a downward direction and does not reach above a depth of 500 metres until it reaches the outflow areas. (The figure was taken from /5-5/, but the repository is shown in another position).

5.1.4 Dilution effects

The diagram in figure 5-4 can serve as a basis for an assessment of the dilution of the groundwater which could come into contact with the waste canisters in a rock repository in the Finnsjö area. Assume that the repository is located at a depth of 500 metres in the middle of the downward groundwater flow at point B in the figure. The repository contains 9 000 canisters with a length of 1.8 m and a diameter of 0.4 m. The cross-sectional area of a canister is thus 0.7 m^2. The flows to Finnsjö Lake and towards the northeast each come into contact with half of the number of canisters, with an area of about 3 000 m^2, and amount to 3 000 x 0.1 = 300 litres per year.

As is evident from the diagram, the flow at the repository is in a downward direction and then remains for the most part at a depth greater than 500 m, until it swings upward underneath Finnsjö Lake (A in figure 5-4) and under the valley in the northeast (D in figure 5-4). It is thus out of reach of normal rock wells along its path.

In Finnsjö Lake, the groundwater is diluted by surface runoff and groundwater from the Finnsjö catchment area, which is about 100 km^2. With an annual precipitation of 550 mm and an evaporation of 300 mm, a total water volume of 2.5 x 10^7 m^3 is obtained. As was mentioned above, a groundwater flow of max. 300 litres per year is expected to come into contact with the waste canisters and then flow into Finnsjö Lake. Its dilution there will then be approximately 1 part in 8 x 10^7.

A similar dilution of the water from a catchment area of 10 km^2 takes place under the valley at D. The dilution is then 1 part in 8 x 10^6.

As regards the fault which borders the Finnsjö area towards the northeast at C in figure 5-4, it is conservatively assumed that an upward flow takes place. It is even more conservatively assumed that this upward flow is so heavy that it leads to a complete and thorough mixing of the groundwater down to the level of the final repository. Dilution takes place by the groundwater from an infiltration area of 2 km^2, whose volume is calculated to be 0.5 x 10^6 m^3. Runoff within the area is regarded as negligible. The dilution ratio is then about 1 part in 1.7 x 10^6, which applies to the water which may be taken out from a rock well. If the upward flow does not reach the surface and mixing of the groundwater in the fault zone is incomplete, the well will tend to be filled by groundwater closer to the surface which has not been in contact with the waste. The dilution ratio will then be considerably greater.

5.1.5 Effects of waste heat generation

Calculations have also been carried out in order to elucidate the effect of the upward flow over a rock repository which may be caused by the heat generated by the waste during the early phase of the storage period. In agreement with previous American estimates by the National Academy of Science /5-6/, this factor has been shown to give rise to an insignificant perturbation of the prevailing pattern of flow in the vicinity of the rock repository.

5.1.6 Lowering and recharging of the aquifer

The effects of the drainage pumping of a rock repository during the construction and deposition phases have also been investigated /5-4, 5-7/. These calculations are of importance for future planning and engineering design work. The recharge time for the aquifer around the final repository, after it has been sealed, can be expected to be lengthy on the basis of experience from abandoned mines. During this period, there can be no outflow from the area.

5.1.7 Short-term variations in the groundwater level

A review of the literature and Swedish studies of short-term variations in the groundwater level has been carried out /5-8/. It shows that the groundwater level in the Swedish bedrock exhibits certain short-term variations which occur without the water content of the rock changing. The level is affected by such factors as tidal movements in the bedrock due to the influence of the sun and the moon and changes in air pressure. Severe earthquakes at distant points on the globe, for example off Portugal and in Japan, also affect the groundwater level. All of these variations are small in comparison with seasonal and precipitational variations and no effects with any appreciable bearing on the conditions in and around a rock repository have been found.

5.1.8 Groundwater age

The time during which the groundwater resides in the bedrock is of importance in view of the natural decay of the radioactive elements and their retardation and retention by the rock. In the same rock volume, the residence time for the water is least in the larger, water-bearing fracture zones. In the intervening bedrock blocks of low permeability, the residence time is many times greater. Residence time in the fracture zone was ascertained by means of age determinations carried out on water samples from the boreholes.

Age determinations on water samples were carried out using the carbon 14 method, which tells how much time has passed since the water became isolated from the atmosphere. Four water samples from the borehole in Kråkemåla have been studied thus far. 70 litres of water are required for each determination, as a result of which samples could only be obtained from zones with high water flow.

Two samples from depths of 291 and 510 m in borehole No. 2 gave ages of 4 400 and 4 275 years respectively. Two samples from 407 and 493 m in borehole No. 1 gave 11 055 and 8 205 years, respectively. The determinations were carried out by the laboratory for radioactive dating. Correction for exchange with carbonate mineral was made on the basis of carbon-13 content.

The analytic uncertainty inherent in these determinations is about ±100 years. However, larger errors in the age determinations may result from various measures undertaken in the boreholes prior to sampling. During drilling, large quantities of "younger" surface water were pumped down into the holes for flushing purposes, and heavy draiage pumping was carried out prior to sampling. These disturbing influences resulted in water of different ages being mixed, presumably resulting in age underestimations. Judging from the chemical composition of the water samples, the sample of the highest age is the one which is least disturbed by surface water.

The difference between the results 4 275 and 4 400 years is within the analytical error limits. The differences between the age results of 4 000 years on the one hand and 8 000 and 11 000 years on the other can probably be explanined by the different positions and permeability conditions of the boreholes, insofar as they are not the result of the aforementioned disturbances. Borehole No. 1 is located on a nearly horizontal plateau-like part of the study area - not far from the fracture valley which comprises the boundary of the area on the northeast. The water table is therefore nearly level. And since the core from this borehole shows a large portion of impervious rock, the rate of groundwater flow is low, the residence time of the water long and its age high. The differences between the ages and compositions of the water samples from the fissures in this hole clearly show that the fissures have little hydraulic coherence.

Borehole No. 2 in Kråkemåla is located closer to the local water divide between Lake Götemaren and the Baltic Sea, and the water table here is located about 10 m below the surface of the ground. This would indicate that the groundwater here is flowing downward, which, together with the predominantly higher permeability of the rock, could explain the lower age of the water.

The Kråkemåla area is certainly not an exceptional case with respect to groundwater age. The general groundwater turnover rate here is, in fact, probably higher than in the other two study areas. Only a few age determinations on groundwater from great depths in the bedrock from other locations are known. One age determination of 4 010 years on mixed water from a depth of 136 m from a well in the bedrock in Finland /Donner and Jungner, 5-9/, and another determination of 9 785 years on a mixed water from a depth of about 300 m at Storjuktan carried out by the Geological Survey of Sweden on behalf of the National Council for Radioactive Waste Management, show that the age determinations from Kråkemåla are not exceptional. The sampling conditions in both of these cases were slightly different, but mixture with younger water should have led to underestimations of age.

The age determinations show that it takes at least 11 000 years for the water to travel from the inflow area to one of the sampling points in the Kråkemåla 1 borehole. Since the dated sample was taken from a water-bearing fissure at a depth of about 400 m, it may be concluded that groundwater which passes through a deep rock repository located in the inflow area in a rock formation of low permeability should require even more time to return to the surface.

The residence time of the groundwater in the rock has been calculated for a number of typical cases with the aid of the flow models mentioned previously. The results vary widely, however, depending on the choice of conditions. As a rule, the calculated residence times are lower than the ages determined by means of the carbon 14 method. This is due, among other things, to the fact that the measured permeability values which were used in the calculations are higher than the actual values, and that their directional dependence, as well as the hydraulic factors which prevail at great depth, are not yet sufficiently well understood.

5.2 GROUNDWATER COMPOSITION

The chemical composition of the groundwater plays a decisive role in determining the durability of the waste and encapsulation materials and in determining the ability of the bedrock to retard and retain the waste substances. The decisive factor which determines the composition of the groundwater is the fact that it is in long-term contact with the minerals in the bedrock, which are solid phases of relatively constant composition. The fissure-filling minerals are especially important in this connection. This contact results in chemical equilibriums which give rise to a given groundwater composition, regardless of local or random disturbances /Garrels 5-10, Eriksson and Khunakasem 5-11, Jacks 5-12, Eriksson and Holtan 5-13/. An example of such equilibrium reactions is that groundwater which can locally become acidic will rapidly return to a pH of around 8 as a result of reactions with the bedrock. If the water should locally become oxidizing due to oxygen infusion, this oxygen will quickly be consumed by reactions with the bivalent iron present in the rock mineral. This has been illustrated by several introductory experiments performed in the presence of atmospheric oxygen:

Samples from the Finnsjö area consisting of granodiorite and chlorite plus crushed material from a crush zone were finely ground in air and mixed with distilled water with a pH of 5.6 and a redox potential of Eh + 610 m V. Following centrifugation in sealed tubes, the Eh of the water dropped to +0.315, +0.267 and +0.084 m V, respectively, while the pH rose to 8.9, 9.2 and 9.4 respectively.

Groundwater analyses from rock wells in Sweden have not been systematically compared. But an extensive body of data is available from Finland, which has the same type of bedrock and groundwater as Sweden. Laakso /5-14/ reviews these data, which specify mean concentrations and ranges of variation for most of the principal substances in water from some 1 100 analyses of samples taken all over Finland, and Lahermo /5-15/ presents a selection from the coastal region of southeastern Finland. However, these data generally apply to shallow wells. The only analyses of water samples from depths of around 500 m which are available apply to mine water, which for many reasons cannot be regarded as being representative in this context.

Water samples from the boreholes in Kråkemåla and Forsmark were analyzed. In Forsmark, samples were taken from a depth of 450 m by means of an apparatus designed to prevent contact with atmospheric oxygen /5-16/. These analyses show that the oxygen content of the groundwater is less than 0.01 mg/l (which is the measurability limit) and that all dissolved iron is bivalent, plus that the water has a sulphide content (in the form of hydrogen sulphide) of 5 mg/m.

Table 5-1, which is taken from /5-16/, gives the results of analyses of water from a number of wells and boreholes in northern Uppland. The table also indicates the estimated range of variation of the analysis values.

Table 5-1. Analyses of natural water from northern Uppland and probable analysis values of groundwater.

Analysis	Unit	Forsmark area (KBS-TR 36 ref 5)	Norrskedika mine 78 m	Hallstavik		Forsmark I 450 m 77-09-26 x)	Forsmark I 450 m 77-10-05	Surface water Forsmark		Groundwater, bedrock, probable analysis		Brackish well in Uppsala area, 100 m	Leach water bentonite sand 95°C 8 days
				70 m 1963	175 m 1977					range	max xx)		
Conductivity	μS/cm		580	504		440	460	121	154	400-600	1100	1920	
pH		7.1 - 7.5	7.1			8.1	7.2	7.0	6.9	7.2 - 8.5	9.0 min 6.5	8.0	
Colour	Pt mg/l		50	10				95	85				
$KMnO_4$ consum.	mg/l	16-32	32	11		32	33	73	68	5-35	50	-	140
COD_{Mn}	O_2 mg/l		8							1.2-9	12.5	-	35
Ca^{2+}	mg/l		} 97 as Ca	} 35 as Ca				9	16	20-60	100	-	
Mg^{2+}	"							16	19	15-30	150	-	
Na^+	"									(~20-40)	200	-	
K^+	"												
Fe - total	"	0.4 - 0.7	7.9	0.12	2.0	29	15	0.26	0.22	1-20	30	0.13	
Fe^{2+}	"				0.5	11	15			0.5 - 15	30		
Mn^{2+}	"	0.1 - 0.4	1.1	0.08		0.30	0.37	0.05	0.06	0.1 - 0.5	3	0.05	
HCO_3^-	"	>90	381	246		390	390	53	55	150-400	500	92	
CO_2	"	0-14	(9 aggr)	(1 aggr)		27	21	7 (aggr)	10 (aggr)	0-25	50	0	
Cl^-	"	30-60	18	27		40	45	9	11	20-100	400	558	
SO_4^{2-}	"		<1	22		10	9	8.8	7.4	20-40	100	40	
NO_3^-	"		0.38	2		0.24	0.23	0.72	0.78	0.1 - 2	10	0.01	
PO_4^{3-}	"		0.11	0.1				<0.01	0.13	0.1 - 0.6	1	0.19	
F^-	"					1.0	1.0	-	-	0.5 - 3	8	-	
SiO_2	"		19			20	22	2.8?	17	15-40	60	14	
HS^- (total)					<0.1	5	5	-	-	<0.2 - 5	10	-	
NH_4	"		0.02	<0.1		0.04	0.14	0.10	0.04	0.1 - 0.4	5	0.02	
NO_2	"		<0.001	0.01		0.075	0.11	0.00	0.0	0.01 - 0.1	0.5	0.00	
°dH	°dH	7-14	13.6	4.9		7.3	7.3	5.0	6.6	6-15	50	12.8	
O_2	mg/l				(<0.6)	<0.01	<0.01			<0.01	1		
TU	-												
Age	Years												

x) The groundwater may be contaminated with surface water.

xx) Estimated probability that the max. value will not be exceeded is 95%.

6 RETARDATION AND RETENTION OF WASTE SUBSTANCES

Various sorption effects and other chemical processes generally lead to a retardation of the substances dissolved in the groundwater in relation to the movements of the groundwater. Laboratory studies and field tests have been conducted in order to shed light on these factors by Allard /6-1/, Landström et al. /6-2/ and Neretnieks /6-3/. The results are generally in agreement with what is reported in the literature /Burkholder et al. 6-4/.

On the basis of the experimental data, retardation factors can be calculated for the different substances /Grundfelt 6-5/.

These and related matters are dealt with in greater detail in volume IV, chapter 6.5.

Field tests concerning such retardation effects were conducted at Studsvik for the National Council on Radioactive Waste Management (PRAV). In these tests, tracers were injected into boreholes at a depth of 70 m in fissured rock with heavy water flow and permeabilities around 10^{-5} m/s. The groundwater flow was accelerated by means of pumping in another hole and samples were taken from a hole between the injection hole and the pump hole as well as from the discharge water. The transmit time of the water was determined with the aid of a water tracer. The test confirmed the retardation effect on strontium and cesium.

In a later study, which was commissioned by KBS, the tests were repeated after the same rock sections had been sealed by means of bentonite grouting. Bentonite is a commonly occurring natural mineral many millions of years old consisting primarily of smectite minerals. Smectite occurs frequently as a natural crack filler in the Swedish bedrock and has also been found at Kråkemåla and Karlshamn. It is in chemical equilibrium with the groundwater and the other minerals in the bedrock /Garrels, 5-10/. The tests are still in progress, but it can be noted that strontium added to the water has not yet (after 4 months) arrived at the metering point located 50 metres from the borehole where it was injected /Landström and Klockars, 6-6/. The transit time of the groundwater over this distance was about 10 hours prior to sealing.

Certain elements take part in chemical reactions so that they are retained in the rock. Such a fixation of cesium has been demonstrated by laboratory experiments /Levi and Miekely, 6-7/. Other experimental studies have shown that hydrogen sulphide or minerals containing bivalent iron can precipitate insoluble uranium dioxide from solutions of carbonate complexes of hexavalent uranium by means of reduction at room temperature /Rafalsky, Miller, 6-8, 6-9/. Theoretically, the same should occur with plutonium and other transuranium elements.

Many examples of such reactions are found in nature. Thus, extensive uranium ore deposits have been formed by precipitation in this manner /Adler, 6-10, Dahl and Hagmaier, 6-11/. In Sweden, uranium dioxide occurs as fissure filler in the crystalline basement rock in such areas as northern Uppland and at Pleutajokk in Norrbotten county /Adamek and Wilson, 6-13/. In both of these cases, the mineral has been retained in the bedrock for more than 1 500 million years. It has also been shown that naturally formed transuranium nuclides in the Oklo uranium field at Gabon have not been dissolved or carried away by the groundwater /6-14/.

7 FUTURE BEDROCK MOVEMENTS

Special studies have been devoted to the question of whether current rock conditions may significantly deteriorate during the long period of waste storage in a rock repository due to new fracturing and future movements in the bedrock. The formation of new fissures could then lead to higher permeability in the rock. Future displacements could also cause damage to the vitrified waste bodies and their canisters. These questions are further explored below.

7.1 ROCK MOVEMENTS AT KARLSHAMN

The exposed rock at the Karlshamn power station provide a good opportunity for examining the extent of the displacements and dislocations which have occurred due to fracturing in a selected area of bedrock. There are recently blasted vertical road cuts as well as large, smooth and clean sections of rock outcrops along the shore with a combined area of many thousands of square metres. The bedrock contains numerous slices of light pegmatite. At points where these slices of light pegmatite are crossed by fractures, the magnitude of the vertical (in the road cuts) or horizontal (in the shore outcrops) displacement in each individual fracture since the formation of the pegmatite can be measured. The pegmatites were formed $1.45 \cdot 10^9$ years ago /Welin and Blomqvist, 7-1/.

Two independent observers have studied the area. There is no significant difference between their reports. The results are summarized in the following table:

Displacement (mm)	1	1-2	2-5	5-10	10-20
Number, observer I	(44)[a]	25	11	5	1
Number, observer II	37	16	15	4	
Percent	51	26	16	6	1

a) Calculated in proportion to the number of cracks exhibiting major displacement.

The studied areas of rock have been exposed to glacial action frost bursting and other disintegration processes (blasting in the road cuts) which have acted on the exposed top surface of the rock. Rock elements at greater depths would have been subjected to uniform constraint from all sides by the surrounding rock. It can therefore be concluded that the total vertical and horizontal movements caused by similar fractures at greater depths are less than 20 mm. The resulting average displacement has thus been less than 0.02 mm per million years. Similar observations at Finnsjö Lake indicate a value 15 times greater. The time dependence of the movements will be discussed later on.

7.2 FAULT MOVEMENTS IN THE VICINITY OF THE STUDY AREAS

Besides internal fissuring, the bedrock also exhibits continuous fracture lines, sometimes many miles in length. These fracture lines divide the bedrock into blocks of varying size which have been displaced more or less in relation to each other. Such fracture zones are called faults. The magnitude of the vertical displacements (throws) in the subcambrian peneplain (see 4.3.1) can be established both in the region around Finnsjö Lake and around Kråkemåla. In northern Uppland, such displacements are generally less than 15 m, while the total movement in the Oskarshamn district is around 30 m. This gives an average vertical displacement in these zones of movement of approximately 6 cm per million years or less during the 570 million years which have passed since the peneplain was formed.

Of special interest is the north-south fault which runs through the Götemar granite west of the study area at Kråkemåla. The subcambrian peneplain here has been displaced some 25 m, while the total movement is estimated on the basis of crystalline bedrock geology to be around 500 m /Kresten and Chyssler, 4-12/. This shows that about 95% of the movement took place more than 570 million years ago, and that the average speed at that time was about 10 times higher than afterwards.

7.3 FAULTS IN SKÅNE

One of Europe's major zones of movement runs through Skåne and can be followed towards the southest all the way to the Carpathians /Yanshin et al., 7-2/. In Skåne, this zone marks the boundary of the Scandinavian Precambrian shield towards the younger bedrock to the south. The boundary zone is characterized by faults which have exhibited major movements during the past 570 million years as well.

Röshoff and Lagerlund /7-3/ have studied two of these faults in relation to the sedimentary rocks of Skåne and their ages, and were thereby able to establish the vertical displacements which have taken place during four different geological periods: over 180, 200, 130 and 65 million years, respectively. The result obtained for the larger fault was a total vertical throw of nearly 2 000 m and an average vertical throw of 3.4 m per million years. Average displacements of similar magnitude were noted for the different periods - the variation is between 4.9 m per million years and 2.6 m per million years. The smaller fault exhibits a total vertical throw of around 240 m and its average rates vary in a similar manner between 0.59 m and 0.23 m per million years. Röshoff and Lagerlund emphasize that these data are mean values taken over long periods of time and that it is assumed that the movements took place in rapid steps separated by long periods of little or no movement.

It is also of interest that the younger rock formations in Skåne exhibit fewer faults than the older underlying Precambrian bedrock. The number of faults in chalk deposits is only about 20% of the number in the bedrock. Approximately one-third of the faults in the Silurian strata and half of the faults in the Triassic strata do not extend down into the Precambrian bedrock. Conditions are similar in many other areas with sedimentary bedrock, and have also been simulated in instructive model studies /7-4/.

7.4 RECENT ROCK MOVEMENTS OF THE FAULT TYPE

Rock movements which occurred in Sweden during or since the ice age and are still in progress have been known for a long time, but have often been regarded with some doubt. The AKA Committee's report made special mention of the occurrence of such movements in south-eastern Sweden. Since that time, new and more definitive observations have been made. A review of these observations and a general regional inventory of recent fracture zones in southern Sweden has been carried out by Röshoff and Lagerlund /7-3/. A similar study for central and northern Sweden is reported by Lagerbäck and Henkel /7-5/.

According to these reviews, the most important examples of recent faults are to be found at Kullaberg in Skåne and in certain recently geologically surveyed parts of Norrbotten and Västerbotten counties. An area exhibiting indices of recent fissuring of another character has also been noted on the Fulu massif in Dalarna. The irregularities in the land elevation process noted by Mörner /7-6/ should also be mentioned here.

The inventory of fracture zones has included studies of satellite pictures and a review of topographical maps and aerial photographs. No certain, previously unknown, recent faults have been found, with the possible exception of a fracture zone at Ekorva on the Åsheda topographical map-sheet.

This is no guarantee that recent faults have not occurred in other areas, but it does indicate that large parts of Sweden lack clear examples of such zones of movement. In particular, it should have been possible to discover recent faults, if such existed, in the very flat areas where KBS bedrock studies were conducted.

Further studies are required to obtain a complete picture of the formation and importance of reported recent rock movements. But an important factor which recurs in the cited reports is that these recent movements are associated with older zones of movement in the Precambrian bedrock. It is said that the faults at Kullen in Skåne were initiated more than 570 million years ago, and that subsequent movements have taken place during several geological periods, including since the ice age. It is also noted that the recent faults in Norrbotten and Västerbotten counties conform largely to older faults. Mörner also shows that the irregularities which he reports in shorelines and in the land elevation rate are caused by the fact that movements are still taken place in the contacts between different types of rock and in the fault lines in the bedrock. This agrees with the basic geological observation that large cracks and fissure zones are very old and have been reactivated in recent periods of deformation /Cloos, 7-7/. This has also been confirmed by a large-scale study of the entire structure of Eurasia by Yanshin et al. /7-2/ and in Scandinavia by Tuominen et al. /7-8/ as well as Strömberg /7-9/. Knowledge of existing zones of fracture is of great importance in planning a rock repository. By locating the repository in an area without major fault lines, and in a block of bedrock which is bounded by joint planes where any existing stresses can be released, it is possible to isolate the repository from the effects of recent fault movements.

7.5 ROCK MECHANICS STUDIES

One reason why recent fracture and fault movements follow older fracture lines is that such fracture lines represent already existing joint planes where stresses can be released more easily. This has been elucidated by means of rock mechanics calculations by Stephansson /7-10/. The results show that the risk of fissuring decreases as the number of existing fissures increases and the distance between them decreases. A sample calculation shows that a displacement of 10 m/km in rock with a fissure interval of 2 metres does not give rise to new fissures. Instead, the movement is distributed over existing fissures, and the change in fissure width, and thereby in permeability, is negligible.

In this context, it should also be noted that certain rock mechanics parameters have been determined in the laboratory for drill core samples from the areas at Finnsjö Lake and Kråkemåla. Tests on materials from Karlshamn are still in progress. The results obtained thus far are presented in table 7-1.

No measurements of the internal stresses in the bedrock have been undertaken within the study areas. However, a relatively large number of stress measurements have been carried out in Scandinavian bedrock at varying depths down to about 900 m over the years 1951-1976. The results show a very wide spread both geographically and locally. Some of this spread seems to be a result of the fact that earlier measurements /7-11/ indicated considerably greater stresses than recent measurements /7-12, 7-13/ using improved and more well-defined measuring methods. There are, nevertheless, undoubtedly genuine wide regional and local variations in the internal stresses in the rock due to various geological factors, topography etc. /7-13/.

In general, it can be concluded that the measurements indicate the existence of larger horizontal stresses than could be expected on the basis of purely theoretical elasticity considerations. The same applies for the maximum shear stress, which determines the risk of fracture in the rock mass. However, the shear strength of the rock increases almost linearly with increasing depth due to the pressure of overlying rock masses /7-14/. Judging from the rock stress measurements which have been made, it can therefore be concluded that, apart from isolated cases, adequate safety margins against rock fracture exist at the depths in question due to the internal stresses of the rock. The same conclusion can be drawn on the basis of the results of the earlier

Table 7-1. Rock mechanics parameters from drill cores, determined at the Division of Rock Mechanics at the Luleå Institute of Technology.

	Compressive strength	Tensile strength	Modulus of elasticity, 50% breaking load	Poisson's ratio
Kråkemåla 1 (6 samples)	MPa	MPa	GPa	
M (Mean value)	188.2	8.92	61.4	0.20
d (Standard deviation)	17.8	0.94	4.3	0.03
Kråkemåla 2 (6 samples)				
M	152.7	6.77	57.1	0.21
d	18.7	1.59	6.7	0.05
Finnsjön 1 (6 samples)				
M	252.5	13.47	81.5	0.18
d	7.7	2.30	3.6	0.01
Finnsjön 2 (6 samples)				
M	228.8	13.50	83.6	0.21
d	11.2	1.50	2.4	0.02

measurements. This conclusion is also in full agreement with practical experience from mining operations at various depths.

Naturally, measurements of rock stresses will be included in the arsenal of preliminary study methods which will be used to determine a suitable location for a final repository.

7.6 FRACTURING FORECAST

It is possible to forecast the formation of new fractures and fracture movements during the storage period on the basis of average values and their expected deviation. Such considerations can be based on the age of the bedrock and the local frequency of fractures in each area. The existing fractures in the bedrock constitute a natural record of all previous occasions on which permanent cracks were formed.

As an example, consider a 1 000 m long section of a rock formation which is 1 000 million years old and where the number of cracks is also 1 000 (in other words, the average distance between the cracks is 1 metre). This means that an average of one new fissure was formed every million years. Assume that this section is representative for the rock surrounding a rock repository. A storage period of one million years with an average amount of rock movement would then lead to an increase in the fissure content of the rock, and thereby its permeability, by a factor of 0.001 of the present value. A more qualified forecast of this type of future has been worked out by Ringdahl et al. /7-15/. Such a forecast is dependent upon whether the rock movements during the forecast period are greater or less than average. Another factor which must be taken into consideration is that the risk that a deformation will generate a new fracture diminishes as the distance between existing fissures decreases.

The question of whether the rock movements which will occur during the storage period will correspond to an average frequency for a very long period of time can be clarified by considering the rock movements in their chronogeological context. It is important to begin by noting that the most of the fracturing of the Precambrian bedrock outside of Skåne took place more than 570 million years ago, i.e. prior to the formation of the subcambrian peneplain. In the Karlshamn area, the fracturing took place primarily about 900 million years or more ago. The fracture pattern at Kråkemåla is for the most part 1 300 million years old. The general mineralization of the fractures in the Finnsjö area and their proximity to the Jotnian rock formations at Gävle indicate a similar or greater age /see Wiman 7-16, Welin 6-12, Gorbatschev 7-17 and Welin and Lundqvist 7-18/.

The generally small amount of movement in the Precambrian bedrock over the past 570 million years is evident in the large extent and limited deformation of the subcambrian peneplain and in the largely undisturbed stratification of the overlying aluminous slates and limestones. Disturbances in the peneplain consist of an elevation of the land surface of up to several hundred metres which can be followed from the west coast to Skellefteå and which comprises the western boundary of the peneplain. Then there are also the previously mentioned faults, which divide the bedrock into blocks. The faults are normally steep and the displacement is predominantly vertical.

All of this shows that fracturing and movements in the precambrian bedrock over the past 570 million years have been small and below the average for a longer period of time. The above-cited data from the Götemar fault show that the aggregate deformation there was about 20 times less, and the deformation rate between 5 and 10 times lower, during this period than previously. Similar conditions have also been reported for other parts of the country by Röshoff and Lagerlund /7-3/. This abating tendency in rock movements indicates that the previous forecast is based on excessively high average values. Thus, change in the rock during the storage period will be considerably less than calculated.

However, movements in the bedrock have not been constant during the past 570 million years either. Peaks in the fissuring process can be established on the basis of the general connection which exists between the fissuring of the earth's crust and volcanic activity. The following age determinations have been reported for volcanic formations in Sweden which are younger than the Precambrian bedrock /see Klingspor 7-19, Byström et al. 7-20, Kresten et al. 7-21/:

- 540 million years, alkaline rocks from Alnön and Åvike near Sundsvall.
- 450 million years, bentonite from Kinnekulle in Västergötland.
- 295-280 million years, basaltic rocks in northern Skåne and Västgötaberg, alkaline rocks in Särna.
- 167 million years, basalts, northern Skåne.
- 108 million years, basalts, northern Skåne.

No more recent basaltic volcanism has occurred in Sweden, but faults in the chalk deposits in Skåne indicate movements which have taken place during the past 65 million years.

These data show that the past 570 million years, with their lower average fracture movement data, have also had periods of higher activity. The concentration of these events in Skåne is clear.

Age determinations make it possible to consider movements in the Precambrian bedrock in a larger context. Three major and extensive deformation periods during the past 570 million years have led to extensive orogeny, granitization, fracture movements and volcanism in the areas between the Mediterranean Sea and the North Atlantic. During all of this period, the Nordic bedrock has remained an extremely stable area, whose low level of deformation is proved by the subcambrian peneplain and superimposed rock strata. It may be added that many other precambrian rock areas in the world exhibit a similar appearance, while areas with more active rock movements and volcanism are also characterized by different conditions with respect to age, rock types and geological structural features. Probing deeper, it can be noted that basalt volcanism in Sweden and associated break-up of the subcambrian peneplain approximately 290 million years ago coincides with similar activities in Greenland, Europe, East Africa, Madagascar and Western Australia /see Kent 7-22, Turner and Verhoogen 7-23/. Similarly, more recent basaltic volcanism and fault movements in Skåne can be chronologically associated with other areas, of which the North Atlantic and the continental part of Europe north of the Alps are of the greatest interest as far as our forecast is concerned.

A survey of bedrock movements and their age relationships in the North Atlantic was recently submitted by Bott /7-24/. Volcanic activity in the area is summarized by Turner and Verhoogen. The geological development which is described began some 180 million years ago and culminated about 40 million years ago. At that time, volcanic activity extended from Greenland, Jan Mayen and Spitzbergen all the way to Ireland, at the same time as northern Europe separated from North America. The rock movements in Skåne can be regarded as a marginal part of this progression, where volcanism comprised an introductory phase. The same progression also affected other parts of northwestern Europe, although with much less intensity. This probably explains the weak upwarping which constitutes the western boundary of the subcambrian peneplain in Sweden, the much greater upfaulting which gave rise to the steep Atlantic coast of Norway and the subsidence of the previously forested parts of the Baltic Sea, which are the source of Baltic amber. The studies in the North Atlantic make it possible to follow developments over the past 100 million years as well, although observations in Sweden concerning this period of time are very incomplete. The decrease in rock movements over

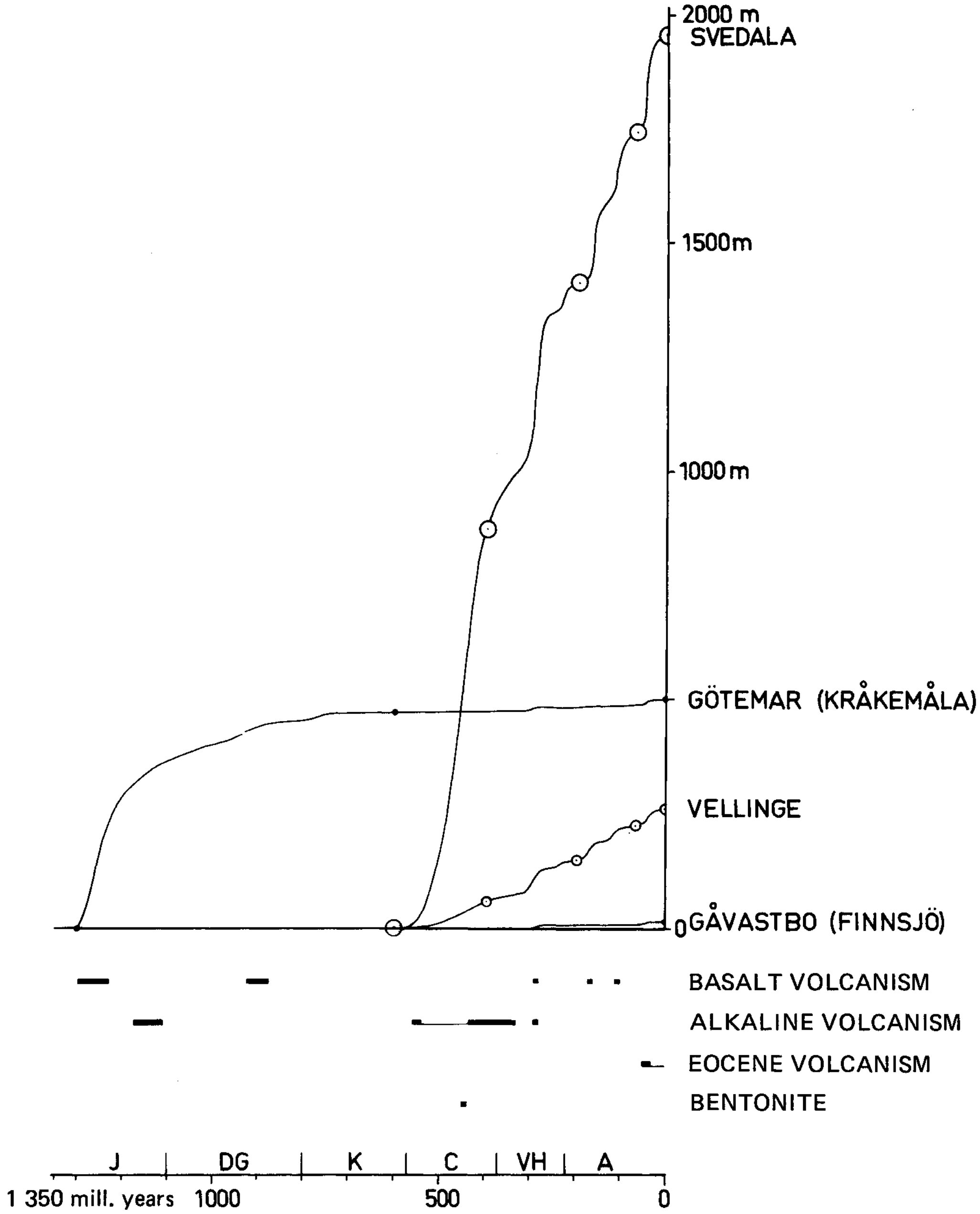

Figure 7-1. Diagram of fault movements, deformation periods and volcanism over the past 1 350 million years. The diagram shows the elevation in metres of the upthrown rock block in relation to the subsided block at four studied faults. The curves connecting the points were drawn on the basis of the peneplain formation of the Precambrian rock (flat portions), volcanism (deep portions) and the character and thickness of the sedimentary bedrock. The values on the flatter portions of the curves for the elevations of the faults in Svedala and Vellinge are approximate between the measured points. The large movements between 400 and 600 million years ago in Skåne (Svedala and Vellinge) have only insignificant counterparts within the Precambrian rock area. Only the Götemar fault can be followed back farther than 600 million years. Bentonite indicates extensive volcanism in the area of the Scandinavian mountain chain (the Caledonians). Eocene volcanism took place outside of Scandinavia. The thickness of the vertical axis corresponds to the next 4 million years.

The following deformation periods are marked on the time axis:

J = Jotnian
DG = Dalsland–Grenville
K = Katanga
C = Caledonian
VH = Variscan–Hercynian
A = Alpine

the past 40 million years, as well as the fact that volcanism is currently restricted for the most part to Iceland, show that the entire region is now in a period of insignificant and abating rock movement.

A similar picture is obtained of the continental part of Europe north of the Alps /Rutten 7-25/. This region once contained a somewhat fragmented volcanic province which extended from France to Poland. This volcanic activity has been connected with later phases in the formation of the Alps. As in the North Atlantic, volcanism in this province reached a maximum during the Tertiary period and has diminished steadily since that time. The most recent volcanic eruption occurred 11 000 years ago in southern Germany. The rock movements in Scandinavia can also be regarded as a part of this phase.

The movements which took place in connection with certain faults in Sweden during various periods and which can be derived from geological observations are presented in figure 7-1 in order to depict schematically the progression of movement and the difference between the Precambrian shield and adjacent areas.

Thus, extensive regional observations support the conclusion that movements in the Swedish bedrock constitute part of an extensive and long-range process which is clearly in slow decline. Realistic estimates of how soon new fractures can be expected to occur must therefore be well below the mean values obtained from forecasts based on the age of the bedrock and the local fracture frequency alone. From this it is evident that changes in the fissure content and permeability of the rock due to rock movements during the storage period will be so small that they cannot have an adverse effect on the function of a rock repository which is suitably situated in relation to existing fracture and crush zones.

7.7 LAND ELEVATION AND GLACIATION

The current land elevation in Sweden has been studied on the basis of field observations /Mörner 6-7/ and on the basis of gravitational considerations /Bjerhammar 7-26/. Despite the differences in basic data and analysis techniques, quite similar results were obtained. But there are certain discrepancies which should be the object of further study.

In summary, it can be said that the land elevation following the ice age reached a maximum of nearly 1 000 m on the coast of Ångermanland. For the most part, the land elevation represents a rebound of the land following its depression by the weight of the inland ice. According to Mörner, this rebound ceased 2 000 - 3 000 years ago, and the current land elevation has other causes. A rebound from the elevation of western Scandinavia and subsidence of the Baltic Sea, which was dealt with in the previous section, could possibly explain this process. According to Bjerhammar's analysis, the land is still rebounding from the depression caused by the inland ice.

Fracturing and movements in the bedrock in connection with the land elevation and in connection with a future ice age can be assessed on the basis of the present distribution of fractures in the bedrock. Permeability values from the study boreholes show that fissuring is limited for the most part to the uppermost 100 or 200 m of the bedrock. Deeper portions which have undergone the same movements still possess good imperviousness. This shows that the land elevation and the preceding depression did not affect the permeability of the bedrock. Furthermore, there have been a total of 10 to 20 Quarternary glaciations /Kukla 7-27/ and the present state of the bedrock reflects the cumulative effect of all of these. This leads to the conclusion that one more glaciation would not disturb a deep rock repository.

7.8 EARTHQUAKES IN SWEDEN

The effects of earthquakes on a rock repository are discussed in recent studies by Dowding /7-28/ and Yamahara et al. /7-29/. The latter concentrated primarily on Japanese conditions. He notes in his introduction that no serious earthquake damage has been reported from Japan's many mines and tunnels. He also shows by means of rock mechanics calculations that earthquake movements in rock abate rapidly with increasing depth. At a depth of about 100 m, rock movements are only about 1/4 to 1/3 of what they are at the surface. The greatest induced rock stress at a depth of 100 metres when the surface acceleration is 2.24 m/s^2 is only 1.2 MPa. Even the severest conceivable earthquake in Japan would give rise to a maximum stress which is estimated to be only 3.0 MPa. These stresses are negligible in relation to the strength of the types of rock in question in Sweden. Dowding uses practical cases to show that no damage was caused to rock caverns by earthquakes where acceleration on the surface was 1.9 m/s^2 or less. This corresponds to an intensity of VII - VIII on the Modified-Mercalli Intensity scale (MM), which is a measure of the effects of earthquakes on the surface. Minor damage, falling stones and cracking were observed at accelerations up to 5 m/s^2, corresponding to an intensity of VIII-IX. The severest known earthquake in Fennoscandia, at Oslo in 1904, had an intensity of VII-VIII. The tunnels and storage holes in the repository are filled with compacted soil material, rendering minor damage to superficial rock insignificant.

Earthquakes are rare and weak in Sweden. The earliest known earthquake occurred in the year 1497. Since 1891, systematic statistics have been kept on earthquakes /Båth 7-30, 7-31/. Since 1951, earthquakes have been registered by means of sensitive instruments which can detect quakes at sea and in uninhabited regions as well. A review of known observations up to 1972 was published in a study by Kulhanek and Wahlström /7-32/. A map of Swedish earthquakes during the period 1951 - 1976 with comments and other material was obtained from Båth /7-33/.

The frequency of earthquakes exhibits wide variations during the observation period. The geographical distribution of earthquakes in Sweden and adjoining areas has, however, remained relatively unchanged.

Southeastern Sweden exhibits extremely few earthquakes. On the preliminary map in figure 7-2 provided by Båth /7-33/, only 3 quakes near the Roxen-Motala fault zone are shown for the period 1951 - 1976. Most of the quakes are instead located in a belt extending from the west coast, across the Lake Väner district - where they are relatively numerous - towards Gävle and then along the coast of the Gulf of Bothnia. From the northernmost part of the Gulf of Bothnia, the belt turns towards the northwest and then again towards the southwest in the North Sea and runs along the coast of Norway, thereby forming a circle around central Scandinavia /7-34/. The distribution of the quakes is thus related to bedrock movements on and off the Norwegian coast, and in Sweden a connection can be seen with the fault lines in the Vänern-Vättern region, the western boundary of the subcambrian peneplain and the areas of recent rock movement in Skåne, Västerbotten and Norrbotten. This would indicate - as is maintained by Kvale /7-35/ - that the Scandinavian earthquakes are related to bedrock movements which are independent of the ice age.

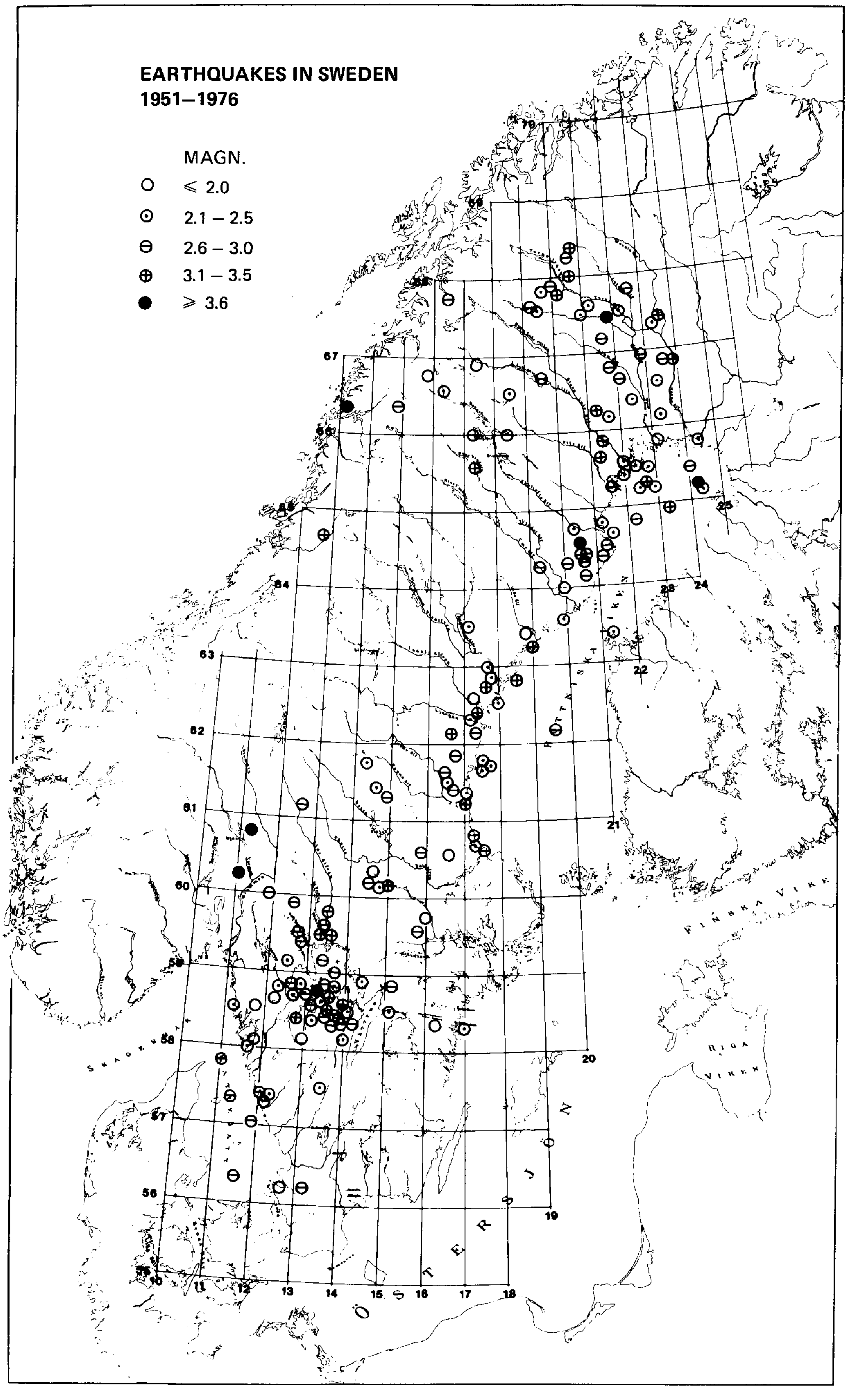

Figure 7-2. Map of earthquakes in Sweden registered by instruments during the years 1951–1976. Note the low number of quakes in southeastern Sweden. (Professor Markus Båth, Department of Seismology at the University of Uppsala).

8 SUMMARY AND EVALUATION

Bedrock and groundwater conditions have been studied in five areas: at Karlshamn, Finnsjö Lake, Kråkemåla, Ävrö and Forsmark.

In the first three areas, large volumes of uniform and sound rock with a permeability of around 10^{-9} m/s or less have been found.

The Karlshamn area exhibits the least occurrence of crush and fracture zones.

The groundwater flow in sound rock at depths of around 500 m within the areas has been calculated at 0.2 litres per square metre and year or less.

Determinations of groundwater age show that the transit time of the groundwater up to the surface of the earth from a rock repository in an area of inflow can amount to several thousand years.

Deep groundwater samples have been found to be oxygenfree and weakly alkaline with a pH of between 7 and 9. They contain bivalent iron in solution. Sulphide, determined as hydrogen sulphide, has been found in the groundwater at Forsmark.

The radioactive waste elements, with the exception of iodine and technetium, are retarded in the bedrock in relation to the movements of the groundwater.

Uranium, plutonium and other transuranium elements can be precipitated in the form of insoluble oxides of bivalent iron and sulphide or in the form of hydrogen sulphide in solution.

The effects of future rock movements in rock formations without major zones of fracturing and movement can be neglected.

The changes around a rock repository which are caused by blasting and the heat generated by the waste are of a highly local nature. The risk that new flow paths for the groundwater will be created in this manner is negligible.

The above conclusions, together with the safety analysis, provide a basis for the judgement that the three closely studied areas of Karlshamn, Finnsjö Lake and Kråkemåla fulfil the basic requirements for a safe rock repository for high-level waste. This assumes that the rock repository is properly situated in relation to the geometry of the existing formations of low permeability. The study areas on Ävrö and at Forsmark have been found to be less suitable and the studies there have not been carried to completion.

On the basis of current knowledge, the Blekinge coastal gneiss area is the most attractive from a geological point of view of all the studied areas for a rock repository.

The slightly gneissic granite at Finnsjö Lake also offers large volumes of good imperviousness. Existing internal fracture and crush zones, however, may present certain technical problems of the type which are normally encountered in tunneling and rock cavern excavation. Compared to the Blekinge coastal gneiss, this type of rock permits greater freedom of choice in the location of a future rock repository, since similar rock conditions are found throughout large parts of southeastern Sweden.

The Götemar granite at Kråkemåla exhibits, despite sections of very low permeability, a number of features which may require more extensive reinforcement and grouting during the construction phase. These features include lower strength, a regular fracture system with extensive horizontal fracture surfaces and high local groundwater flow, which may also be associated with radon problems.

The three study areas can be clearly arranged in order of priority: the Blekinge gneiss, the gneissic granodiorite in the Finnsjö area and the undeformed stocklike granite in the Kråkemåla area. This confirms previous experiences regarding the structural and water-bearing characteristics of these types of rock. Against this background, other gneiss areas may also be of interest.

9 STRIPA EXPERIMENTAL STATION

9.1 OVERVIEW

9.1.1 Reasons for an experimental station

Only a very limited quantity of basic data on rock at great depths below the ground surface (500 - 1 000 m) are available today. Additional data should be obtained on which to base decisions regarding the siting, design and construction of a final repository for high-level waste. For this purpose, an experimental station at great depths is of great value. It also provides an opportunity for the demonstration of working methods and the design of the various sections of the final repository.

When KBS was organized in late 1976, it was decided that an experimental station should be established in the Stripa Mine, 15 kilometres north of Lindesberg. The ore in the mine was nearly played out and iron ore mining was scheduled to be discontinued in early 1977. Immediately adjacent to the mine is a granite massif which is directly accessible at a level 350 m below the surface. Since the personnel and equipment required for immediate commencement of the rock work was available, considerable savings in time and costs could be made in comparison with the alternative of constructing a new experimental station somewhere else.

An experimental station in rock permits the following studies and tests to be conducted:

- testing and demonstration of working methods for a final waste repository,
- detailed characterization and surveying of a rock massif a great depth,
- analyses and comparisons between the results of various measuring methods and actual conditions in order to evaluate the accuracy of the methods to be used in future rock studies,
- studies of how blasting, heating and grouting affect the rock and its characteristics,
- analysis of groundwater movement and groundwater composition at great depth,
- studies of the properties of the materials which may be used in a final repository.

A number of researchers and institutions with special experties in the field of petrology were contacted for assistance in planning appropriate studies. An advisory group of experts, the "Geogroup", was formed and instructed to propose suitable studies at Stripa. The group also participates in the evaluation of the test results.

Studies within the following subject areas have been initiated at Stripa:

- The effect of blasting on surrounding rock
- Rock characterization
- Rock stress measurements
- Material properties of the Stripa granite
- Permeability of the rock at different pressures and temperatures
- Thermal stresses
- Injection studies
- Water analyses

Most of the results obtained from KBS experiments at Stripa will be reported during the first quarter of 1978.

9.1.2 Construction work

Blasting work for the test station started in December of 1976. The final appearance of the excavated rock caverns is illustrated in figure 9-1. The tunnels were blasted using a technique known as smooth blasting and with nearly circular or oval sections in order to minimize stresses on the rock. Cross-sectional tunnel

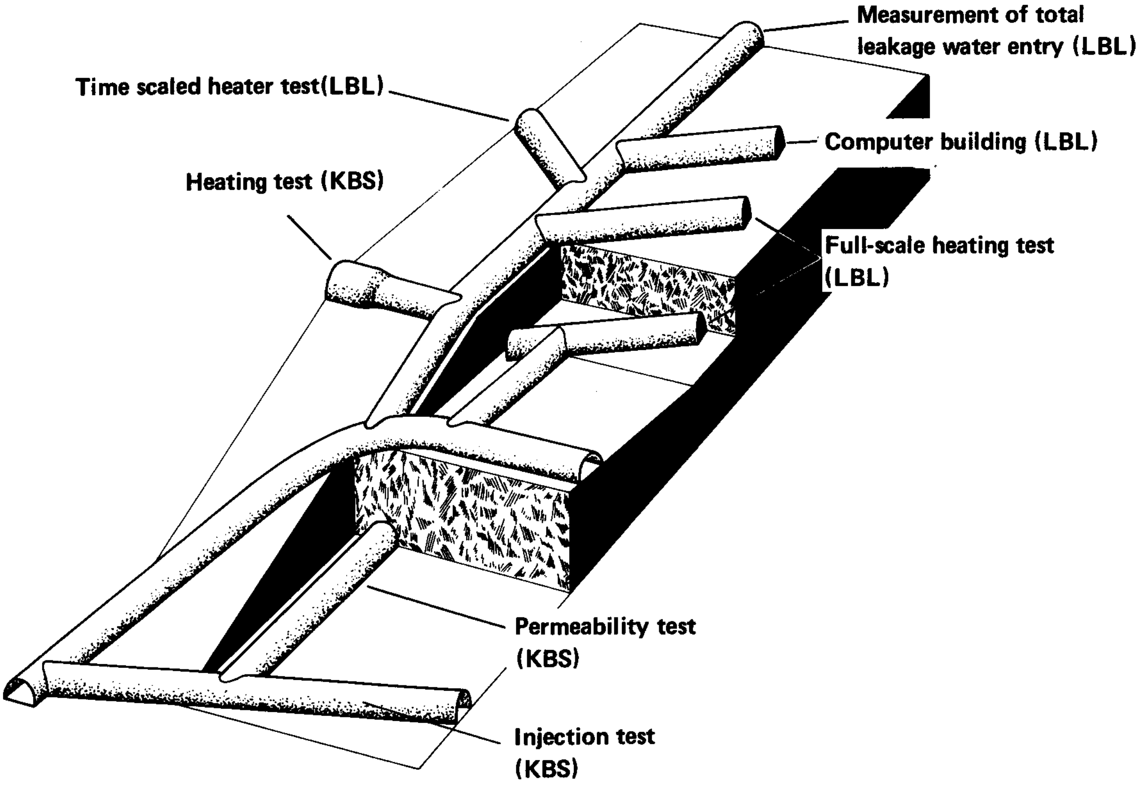

Figure 9-1. KBS experimental station at Stripa. The layout of the excavated rock caverns and the sites of the various tests are illustrated in the figure.

area varies from 12 m^2 to 26 m^2, depending on the space required for construction machines or testing activities.

The quality and strength of the Stripa granite is very good. Reinforcement bolting has not been considered necessary and no rock fall has been observed.

In order to permit the execution of planned experiments and tests, a large number of holes of varying length and diameter have been drilled from the tunnels. A total of approximately 1 500 metres of holes have been drilled for KBS's own tests, beyond those required for the blasting work. Most of the holes have been diamond drilled to a diameter of 56 mm.

Blasting and drilling work has been in progress for about 10 months and has employed around 20 men.

9.1.3 Cooperation with the US ERDA

KBS's experimental programme in Stripa has attracted international interest, and in the spring of 1977, KBS was contacted by a group from the USA in order to discuss the possibilities of a joint research project concerning waste storage in crystalline rock. The conditions for such a joint project at Stripa were clarified during the early summer, and an agreement was signed between SKBF (Swedish Nuclear Fuel Supplies Inc.) and the US ERDA (United States Energy Research and Development Administration). According to this agreement, SKBF shall be responsible for holding the mine open through October of 1979 and for all rock blasting work, rock drilling (approx. 3 800 m) and certain services on the worksite. The US ERDA will be responsible for and defray the costs of the actual study work. KBS is responsible for Swedish commitments during its period of activity.

The US ERDA has contracted Union Carbide to administer and execute an extensive development project concerning the final deposition of high-level waste. A special unit has been organized for this purpose within Union Carbide - OWI, Office of Waste Isolation. The execution of the Stripa programme has in turn been entrusted to a group of researchers at the Lawrence Berkely Laboratory, LBL, at the University of California.

The research programme was drawn up by LBL, but SKBF/KBS are kept continuously informed concerning the planning and execution of the tests and experiments and also have a voice in planning the experimental programme. The results of the tests will be the common property of the parties.

9.2 STUDIES CONDUCTED UNDER THE AUSPICES OF KBS

9.2.1 Rock characterization

In order to be able to evaluate the alternative sites for a repository for high-level waste, reliable and economically feasible methods are required to establish the properties of the rock. The experimental station at Stripa provides an opportunity for the testing and evaluation of such testing methods. For this purpose, the properties of the Stripa granite must be well-known. For this reason, a rock characterization must be carried out. This includes:

- assembling all available geological information on the area in question,
- mapping of the network of fractures on the rock surfaces which have been exposed for the tests,
- core surveys and TV examinations of diamond boreholes near the tunnels before and after blasting,
- studies in a vertical deep borehole from the bottom of the mine (from the 410 m level to the 900 m level),
- water injection tests in all boreholes. In cases where blasting has been carried out near the hole, this test is performed both before and after blasting.

The dominant type of rock in the experimental area in the Stripa mine is a red to grey, medium-grained, unstratified granite. The granite contains a few narrow, steep veins of pegmatite and younger diabase.

The grain size of the essential materials in the granite varies between 1 and 5 mm. A typical sample exhibits the following mineral composition:

quartz	44%
plagioclase (partially altered)	39%
microline	12%
chlorite	3%
muscovite	2%

The granite at Stripa can be said to be representative of a large group of younger granites in central Sweden.

Despite its relatively high fracture frequency, the granite is highly impervious, with permeability values around 10^{-10} m/s. This can be explained by the high degree of crack filling.

9.2.2 Rock stress measurements

The purpose of the tests is to establish the primary stress state in the Stripa granite. This information is required for certain other tests and as a basis for theoretical calculations of stress and flow conditions.

Three-dimensional stress conditions were measured at 19 points along a 20 m long borehole from a side drift. Measurement cells based on Leeman's method were used in the procedure. The measurements showed that the maximum main stress is 10 MPa and is oriented parallel to the strike of the granite. The intermediate main stress, 5.7 MPa, is nearly horizontal and is oriented perpendicular to the contact. The minimum main stress is 2.7 MPa. The measured vertical stress, 9.8 MPa, is of the same order of magnitude as the theoretically calculated stress of 9.2 MPa. A detailed report of obtained results is provided in KBS technical report No. 49 /9-1/.

9.2.3 Properties of the Stripa granite

In order to interpret the obtained data and carry out theoretical calculations, information is required on the mechanical and physical properties of the rock. Theoretical calculations and practical test results can then be compared in order to provide a more reliable basis for the evaluation of planned areas for waste disposal.

The following data have been obtained:

- Modulus of elasticity, Poisson's ratio and uniaxial compressive fracture stress at 25°C, 50°C, 100°C and 200°C.
- Compressive fracture stress and elasticity properties as a function of normal stress.
- Coefficient of linear expansion as a function of radial load.
- Brazilian tensile fracture stress.
- Residual shear strength as a function of normal stress.
- Anisotropy ratios in strength and elasticity properties.
- Coefficient of thermal conductivity.

The following data have been calculated for the Stripa granite and do not exhibit any significant deviations from normal data for central Swedish granite.

Poisson's ratio	0.21
Young's modulus	69.4 GPa
Uniaxial compressive strength	207.6 MPa
Tensile strength	15.0 MPa
Thermal conductivity	3.0-3.6 W/C°m

A detailed account of obtained results is provided in KBS technical report No. 48 /9-2/.

9.2.4 Permeability of the rock at various pressures and temperatures

This test is intended to provide information on variations in the permeability of the rock at different temperatures.

The test equipment is shown in fig. 9-2. The leakage water flow into a 300 mm diameter and 10 m long vertical borehole was measured in the test. In a circle at a distance of approx. 1 m from the 300 mm hole, 16 3" holes were drilled. Water was pumped into these holes at a given pressure and temperature. The rock mass was heated to the desired temperature by circulating hot water in the boreholes. By changing the water pressure at different temperatures and measuring the quantity of water leaking out of the centre hole, permeability can be determined as a function of pressure and temperature. The results of the tests are then compared with theoretical calculations.

Measurements of the permeability of the rock carried out thus far have given values which are approximately 10 times lower than results from conventional "packer test" measurements. The test used here probably gives more correct values of the actural permeability of a large rock formation. This indicates that the permeability values obtained from boreholes in the field studies may be too high. Preliminary test results have also shown that permeabi-

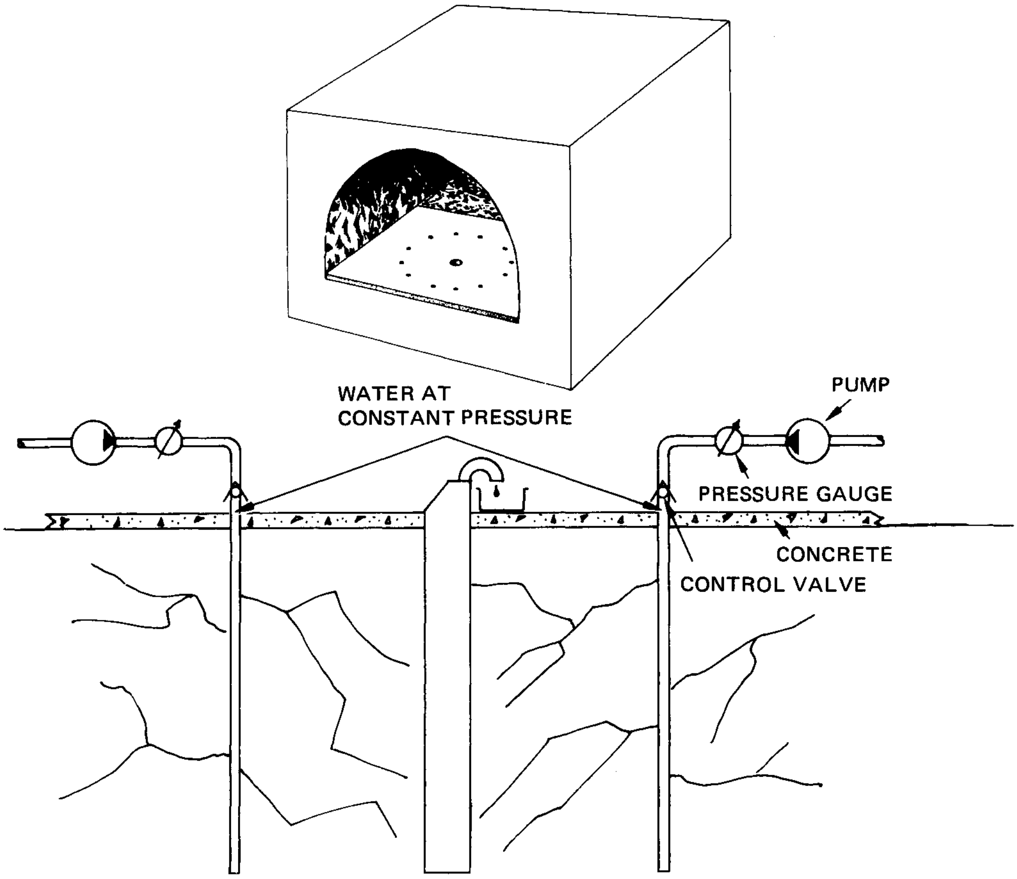

Figure 9-2. Permeability measurements. By varying the water pressure and the temperature, the manner in wich the permeability of the rock varies with pressure and temperature is measured.

lity decreases to about half when the rock is heated from 10° to 40°C.

9.2.5 Thermal stresses

This test is aimed at elucidating changes in existing rock stresses and fracture conditions which occur in a rock formation in connection with local heating. Owing to the low thermal conductivity of the rock, a relatively long test period is required for such a test.

The test set-up is illustrated in figure 9-3. The primary 3-dimensional rock stresses in the rock adjacent to the test drift are measured. The heaters and measuring holes are oriented so that their direction coincides with the direction of one of the main stresses.

The heat source consists of a specially designed 5 kW electric heater which is lowered into a 300 mm borehole. Three 1 kW auxiliary heaters are lowered around this centre hole at a distance of about 1.25 m. Temperature and rock stresses are then measured continuously in ten boreholes parallel to the centre hole and located in three directions and at a distance varying between 2 m and 6 m from the centre hole. The instruments also register changes in the width of major fissures within the test area.

The test is also aimed at recording conditions during a cooling-

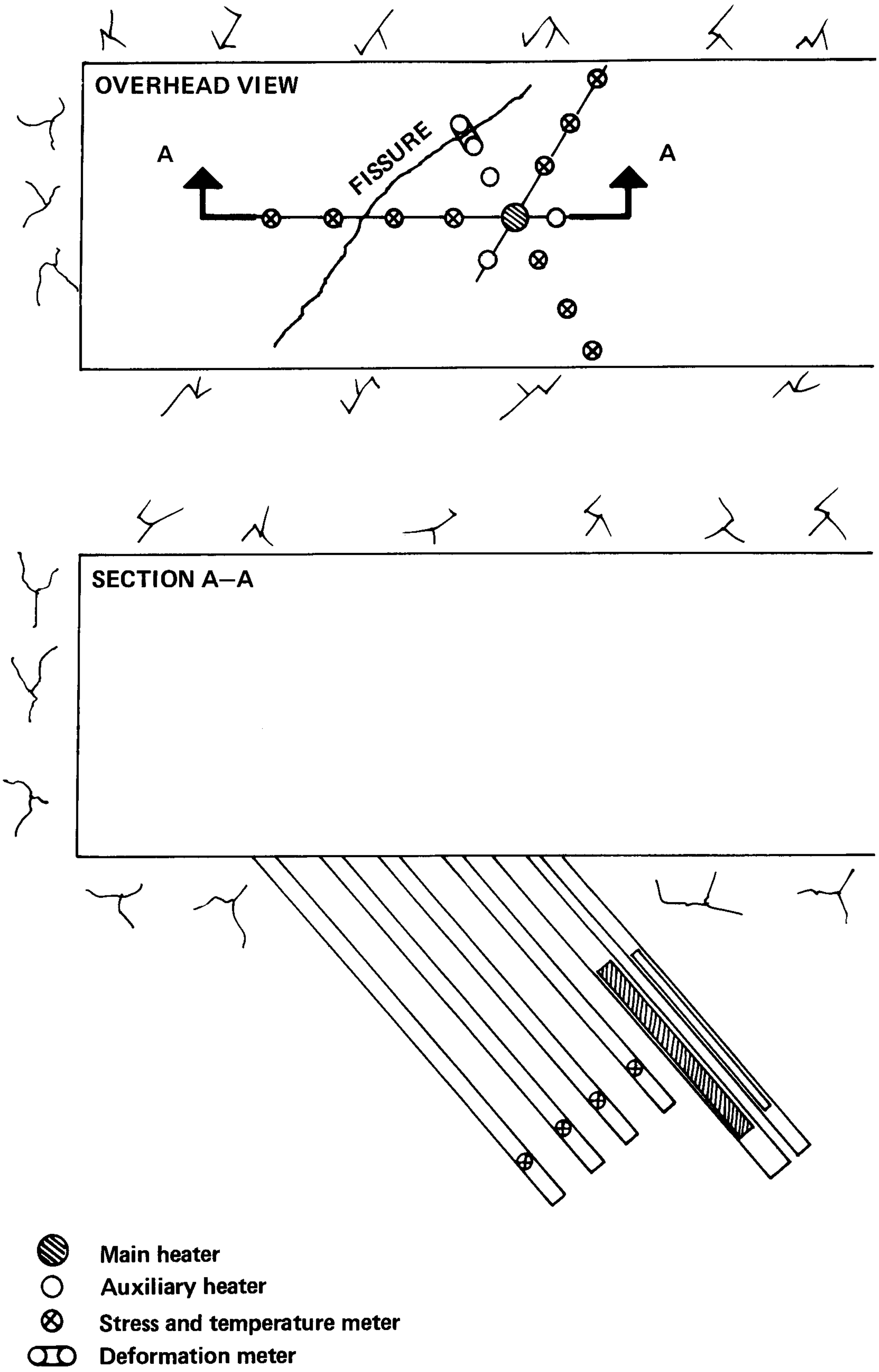

Figure 9-3. Measurement of changes in rock stresses and fissure widths in connection with local heating.

off period after a max. temperature of 60°C has been reached in the central portions of the test area. The obtained results will be compared with theoretical calculations.

9.2.6 Grouting

A final repository for radioactive waste should be located in rock which is as impervious as possible. Nevertheless, allowance must be made for the fact that some local rock volumes will be of higher permeability. It is then possible to inject such formations with material which will remain intact over a very long period of time.

A suitable grouting material seems to be silica (quartz). This is a highly durable material and is also available in very fine-grained form so that it can penetrate into very small fissures. However, during the preparatory work for a planned experiment, the permeability of the rock was found by hydraulic testing to be so low that grouting was not considered necessary.

9.2.7 Water analyses

The chemical composition of the groundwater is of importance for the rate of corrosion of the encapsulation and buffer materials and for the leaching rate of the waste glass.

Relatively few data are available on the composition of groundwater at great depths.

At Stripa, the groundwater is accessible at various levels from 350 m down to about 900 m below the surface. Since the mine has been drained for a long time - the mine was opened about 500 years ago - the groundwater conditions are disturbed, especially down to the level of the lowest point in the mine (-490 m). The samples which have been collected are therefore not representative of groundwater at corresponding levels under undisturbed conditions.

The following available results from analysis of the groundwater are worth mentioning:

- its age 340 m below the surface of the ground is about 15-20 years,
- its chemical composition shows low mineral and salt contents and
- the pH of the water is about 8.5.

9.3 STUDIES UNDER COOPERATION WITH US ERDA

A large-scale programme of tests and studies is planned by LBL at Stripa. The content of this work can be summarized in the following points:

1 Investigation of how the properties of the rock (pressure, expansion, thermal conductivity etc.) are affected by local heating.

2 Mapping of the fissures in the rock (extent, size, direction contents etc.) with the aid of borehole studies and geophysical surveys.

3 Laboratory determination of various material data for the rock (microcracks and permeability as a function of pressure and temperature).

4 Measurement of the total leakage of water into a rock cavern for determination of the permeability of the rock.

5 Measurement of rock pressure by forcing water into boreholes to the point of fracture (hydraulic fracturing).

As previously mentioned, these experiments are planned to be carried out during 1978 and 1979. The first results of the tests will therefore probably not be available until 1978. Consequently, no results can be reported in KBS's main report, and only incomplete results will be available when KBS concludes its activities in the middle of 1978.

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