Final Storage of Spent Nuclear Fuel – KBS-3

I General

II Geology

III Barriers

IV Safety

SKBF/KBS

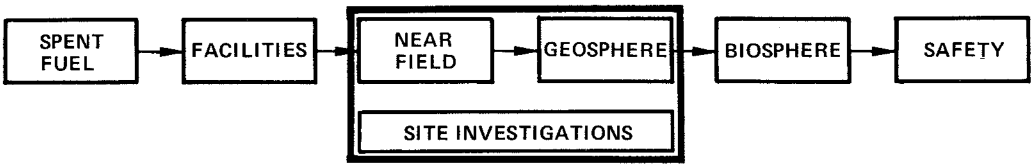
Final Storage of Spent Nuclear Fuel – KBS-3

II Geology

SKBF/KBS
Swedish Nuclear Fuel Supply Co/Division KBS
MAILING ADDRESS: SKBF/KBS, Box 5864, S-102 48 Stockholm, Sweden
Telephone: 08-67 95 40

TABLE OF CONTENTS

5 SITE INVESTIGATIONS



The programme of geological and hydrological investigations that has been carried out within a number of potential repository sites - study sites - is described in this chapter. The investigation methods used and their application are described in brief.

5.1 BACKGROUND AND PURPOSE

A quantitative safety analysis for a final repository on a given site requires the availability of site-specific data considering the bedrock and fracture zones, the hydraulic properties of the rock and chemical conditions in the rock. The development work of recent years, not least in Sweden, has led to considerably improved instruments and methods for mapping of the bedrock and for measurements from the ground surface and in boreholes. This applies especially in the following respects.

- A refined technique for determining the hydraulic conductivity of the bedrock permits a considerably lower measuring limit and better control of measured values.

- Borehole equipment for long-term registration of pressure conditions at different depths.

- Methods for shedding light on the redox conditions in a rock mass are available

- Computer-based programs for storing and processing investigation results facilitate and broaden the possibilities for evaluation.

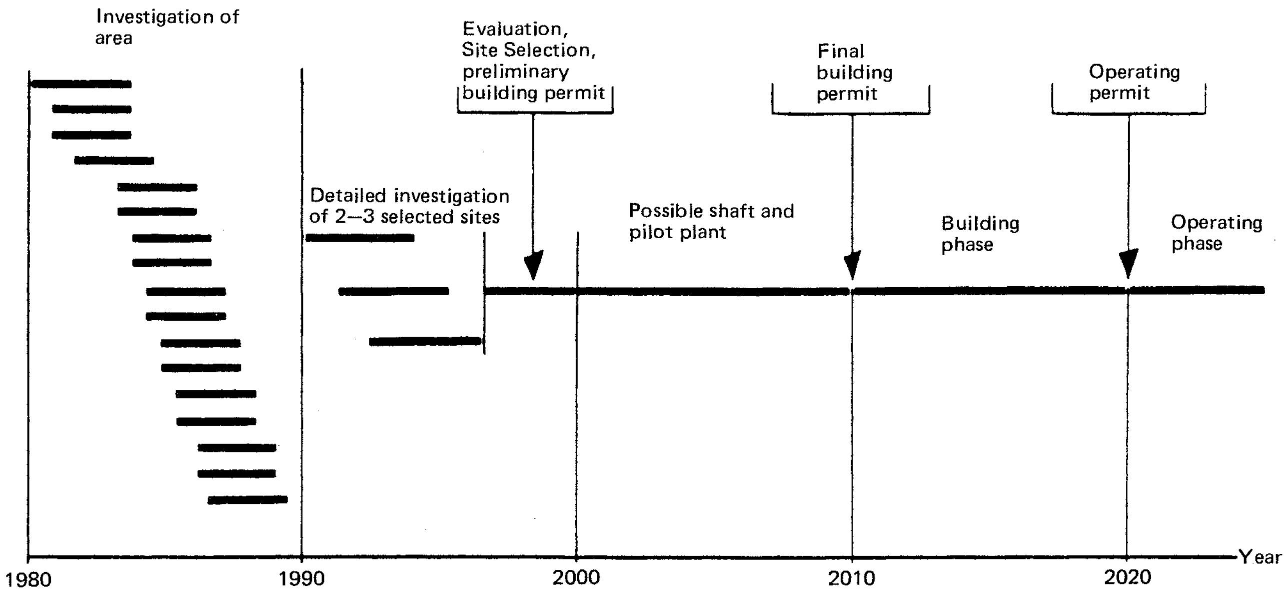


Figure 5-1. General timetable for final repository for spent fuel.

The site investigations have primarily focussed on studies of

- the large-scale fracturing of the bedrock
- the hydraulic properties of the bedrock
- the chemical composition of the groundwater
- the chemical composition of the different rock types and fracture minerals

The fracture studies and the hydrological investigations constitute a basis for numerical calculations of the three-dimensional groundwater flow and related calculations of how different radionuclides migrate in the rock. Chemical data and calculated groundwater flows are included in the background material that is required to determine how and at what rate the canisters containing the spent fuel can corrode and at what rate the spent fuel can dissolve.

The site investigations also provide a basis for a schematic placement of a conceived final repository at the sites. The detailed design of a repository can only be specified after progressively more detailed investigations are completed. The next detailing stage is planned to be carried out during the 1990s when, according to the current plan, two or three sites will be selected for further studies, see fig. 5-1. The final repository design will not be established until a detailed investigation and verification programme has been carried out in connection with the excavation work.

5.2 SCOPE

The investigations reported here have been carried out on the following sites:

- Fjällveden in the municipality of Nyköping	/5-1/
- Gideå in the municipality of Örnsköldsvik	/5-2/
- Kamlunge in the municipality of Kalix	/5-3/
- Svartboberget in the municipality of Ovanåker	/5-4/

Of previously investigated areas, additional investigations are reported from Finnsjön in the municipalities of Tierp and Östhammar and Sternö in the municipality of Karlshamn in chapter 18 /5-5/, /5-6/.

The intention is not to propose a site for the location of the final repository at this time. This account is aimed solely at showing that areas exist in Sweden where a safe final storage of spent nuclear fuel can be effected. Naturally, the data and experiences reported here will also be utilized in the more long-range work, whose goal is a finished final repository ready to receive spent nuclear fuel in the year 2020, see fig. 5-1.

5.3 INVESTIGATION PROGRAMME

5.3.1 Investigation phases

The investigations at the different study sites are based on a standard programme that provides a general overview of the information which the investigation are intended to yield as well as investigation methods used and work sequence /5-7/. The programme is flexible and is adapted to the specific characteristics of the different sites and the information that is continuously received. The programme is divided into the following phases:

1 Recognaissance for selection of study site
2 Investigations from the ground surface
3 Investigations in boreholes
4 Evaluation and model work

The results from completed investigations are presented in evaluation reports summarizing all data obtained from the different study sites.

5.3.2 Recognaissance for selection of study site

The choice of a study site is determined primarily by the following factors:

- Topograpy
- Distance between major fracture zones
- Frequency of minor fracture zones and small fissures
- Rock types, including their extent
- Structure of the rock mass between fracture zones
- Occurrence of ore mineralizations
- Groundwater capacity in wells drilled in the rock

In areas with flat ground and bedrock topography, the variations in groundwater head are small, which means that the driving force for groundwater movements is small.

The distance between major fracture zones should be great and the intervening rock mass should exhibit low fracture frequency. Existing rock types and their extent, as well as the structure of the rock mass, are of importance for the suitability of the site. Homogeneous bedrock is striven for.

The presence of workable mineral deposits within a site makes it unsuitable for a final repository.

The groundwater capacity in rock-drilled wells in the region should be low, indicating low permeability.

Other factors that also influence the choice of study sites are previous experience from geologically similar areas, land ownership, access to roads and population structure.

After a judgment taking all of these factors into consideration and comparison between a large number of study sites, a smaller number are selected for geological and geophysical recognaissance studies. The results of these studies then serve as a basis for a decision on whether to drill reconnaissance boreholes at the most interesting sites in order to obtain information on the bedrock at depth. All gathered information is then evaluated in order to determine whether a given site is sufficiently interesting for the investigation programme to be fulfilled.

5.3.3 Investigations from the ground surface

On a selected study site, detailed surface investigations are carried out within an area of approximately 4-5 km^2. The purpose of the surface investigations within the site is to determine the bedrock composition and the occurrence of fracture zones and fractures in the superficial parts of the bedrock. At the same time, geological and tectonic studies are carried out within a larger region around the site.

The programme begins with a detailed mapping of existing rock types plus aerial and ground surveys of fracture zones and fractures. At the same time, geophysical ground measurements are carried out in order to obtain an idea of the composition of the bedrock at greater depth and to obtain information on fracture zones in soil-covered sections. The geophysical ground measurements include:

- Determination of the electrical resistance of the bedrock by means of geoelectrical and electromagnetic methods. Fracture zones as well as many ore minerals are electrically conductive and can be located by means of electrical methods.

- Determination of the magnetization of the bedrock through measurements of variations in the earth's magnetic field. Different rock types normally have different contents of magnetic minerals, and rock type variations can be deduced from the ground surface by means of magnetic methods.

- Determination of the bedrock's content of metallic minerals by measurement of induced polarization - an electrical method by means of which sections of bedrock containing sulphide minerals and graphite can be located.

- Determination of regions in the bedrock with high fracture content, presence of fracture zones or other zones of weakness by means of seismic measurements. In seismic measurements, the velocity with which a shock wave from a small explosive charge propagates is measured. A low velocity indicates fractured rock, while a high velocity indicates rock with a low fracture frequency.

The surface investigations provide information on of the composition and fracture content of the bedrock in the superficial parts plus the presence and location of fracture zones as well as their character and orientation.

5.3.4 Investigations in boreholes

The results of the surface investigations serve as a basis for a drilling programme with short holes (<250 m) to study changes in rock composition as well as the character and orientation of detected fracture zones. Normally, hammer (percussive) drilling with a diameter of 110 mm is used for these boreholes. The drilling rate and the groundwater inflow rate are measured during drilling. An irregular and rapid drilling rate indicates the presence of fracture zones. Fracture zones are also registered by means of electrical measurements. Different rock types are located by measurement of the natural radioactivity of the bedrock in the boreholes. In general, about 10-30 short holes have been drilled within each study site, see chapter 18.

The depth investigations, which are carried out in core boreholes with a diameter of 56 mm, are aimed at characterizing the deeper parts of the rock from a geological and hydrological point of view. Special emphasis is placed on the character of the fracture zones, fracture minerals and groundwater flow as well as the chemistry of the groundwater at great depth.

The location and direction of the core boreholes is based on the results of the surface investigations and the observations in the short boreholes. The holes are drilled down to a vertical depth of about 600 metres and normally dip about 60° from the horizontal plane, making them about 700 m long. In most cases, the core boreholes have been directed towards fracture zones observed on the surface and in the hammer-drilled boreholes with the purpose of penetrating these zones at a depth of 300-500 metres. In some cases, they have been aimed at presumed rock type boundaries, and in some cases at areas where the surface investigations have yielded results that are difficult to interpret. The number of core boreholes needed to provide the necessary information depends on the geological character of the site. Between 5 and 15 deep holes have been drilled within each site.

The drill cores are mapped with regard to rock type, ore minerals, fracture frequency and fracture minerals. Geophysical measurements are made in the boreholes to supplement the geological-tectonic information on the site. Through different hydraulic measurements in the boreholes, the hydraulic properties of the bedrock and the fracture zones are determined. Groundwater samples are taken from varying depth in the boreholes for water chemistry analyses.

The depth investigations yield information on the composition of the bedrock, the presence of fracture zones and fractures and chemical conditions down to a depth of about 600 m. Data on the hydraulic capacity of the rock and the fracture zones are obtained through hydraulic tests.

5.3.5 Evaluation and model work

The evaluation and model work involves processing the collected material and compiling the results into a descriptive model of the different hydraulic units in the rock. This model then serves as a basis for numerical model calculations of groundwater flow, travel times and transport paths for the groundwater from a conceived repository to the biosphere. Related matters are dealt with more thoroughly in chapter 6.

5.4 INVESTIGATION METHODS

The most important methods used in the site investigations are described in brief below. The areas of application of the methods are also shown in table 5-1. A more detailed description of methods employed is provided in /5-8/.

5.4.1 Methods for determining the properties of fracture zones

Fracture zones are characterized by a higher frequency of fractures than surrounding rock. The rock in and around fracture zones has normally been chemically altered, mainly by the influence of the groundwater, and different fracture minerals have formed.

Core boreholes through fracture zones provide data on the width and degree of fracturing of the zones. Studies of fracture minerals provide an idea of the age of fracture zones and their ability to retard the transport of radioactive substances (sorption). Fracture zones have a higher electrical conductivity than the surrounding rock due to higher porosity and alteration. When electrical measurements are made in boreholes or from the ground surface, these properties are utilized to locate the zones.

Information on the hydraulic properties of fracture zones is obtained through hydraulic and geophysical measurements. The most important measurements are water injection tests in boreholes. The method, which is the same both for fracture zones and for the rest of the rock mass, is described in greater detail in section 5.4.2 and in chapter 6.

Table 5-1. Field investigations according to the standard programme

INVESTIGATION PHASE	INVESTIGATION METHODS	EXPECTED RESULTS
1. RECONNAISSANCE FOR SELECTION OF STUDY SITE		
A GEOLOGY	Map material and literature are collected. Studies of geological, topographical and aerial maps are carried out.	Information on topography, degree of exposure, fracture zones and low-factured rock blocks.
B HYDROGEOLOGY	Well data are studied.	Provides an idea of the water capacity of different areas.
C GEOPHYSICS GEOLOGY	Review of available airborne geophysics, geologic inspection on the site and measurement of geophysical profiles on the ground surface.	Information on the tectonics of the area, location of fracture zones, rock composition and soil cover.
D DRILLING	Drilling of one Ø 56 mm core borehole to 800 m.	Information on nature of rock at depth.
2. INVESTIGATIONS FROM THE GROUND SURFACE		
E GEOLOGY	Tectonic and geologic mapping of the site.	Information on the composition of the bedrock, fractures, fracture frequency and orientation of fracture zones.
F GEOPHYSICS	Geophysical measurements from the ground surface such as magnetometer, horizontal loop EM, IP and seismics.	Gives information on of fracture patterns, geological structure and mineralizations.
3. INVESTIGATIONS IN BOREHOLES		
G DRILLING	Hammer drilling, depth <200 m. Core drilling, depth 500-700 m	Provides information on fracture zones' dip and width at depth. Determines boundaries between different rock types.

H	CORE LOGGING	Geologic, tectonic and fracture mineral mapping of core.	Provides a detailed picture of rock type distribution and fracture frequency as well as distribution of fracture minerals.
I	GAS LIFT PUMPING	Flushing out of the bore-with nitrogen gas.	Done to flush out drill cuttings and drilling water.
J	BOREHOLE GEOPHYSICS	Borehole deviation measurement, gamma radiation point resistance, resistivity, spontaneous potential, temperature, salinity, induced polarization.	Provides information on the nature and composition of the bedrock, presence and character of fractures, groundwater salinity and natural water flow in the boreholes.
K	HYDRAULIC INVESTIGATIONS	Water injection tests between packers, measurement of hydraulic gradients at different levels (piezometric measurements), interference tests.	Provides a measure of the hydraulic conductivity and groundwater head in the bedrock as well as the variation of these properties with depth.
L	WATER SAMPLING	Pumping of groundwater from sealed-off sections in boreholes.	Chemical data on groundwater.

The information from the water injection tests is limited to the immediate environment of the borehole. In order to obtain data on the hydraulic properties of fracture zones over longer distances, interference tests are used. In these tests, water is pumped continuously from one borehole while the change in the groundwater head (pressure) is recorded in a nearby borehole. For practical reasons, these tests have so far been limited to depths of between 100 and 200 m.

Valuable information on groundwater flow is also provided by geophysical borehole measurements. Here, it is primarily temperature measurements that show where the water naturally flows in and out of the boreholes.

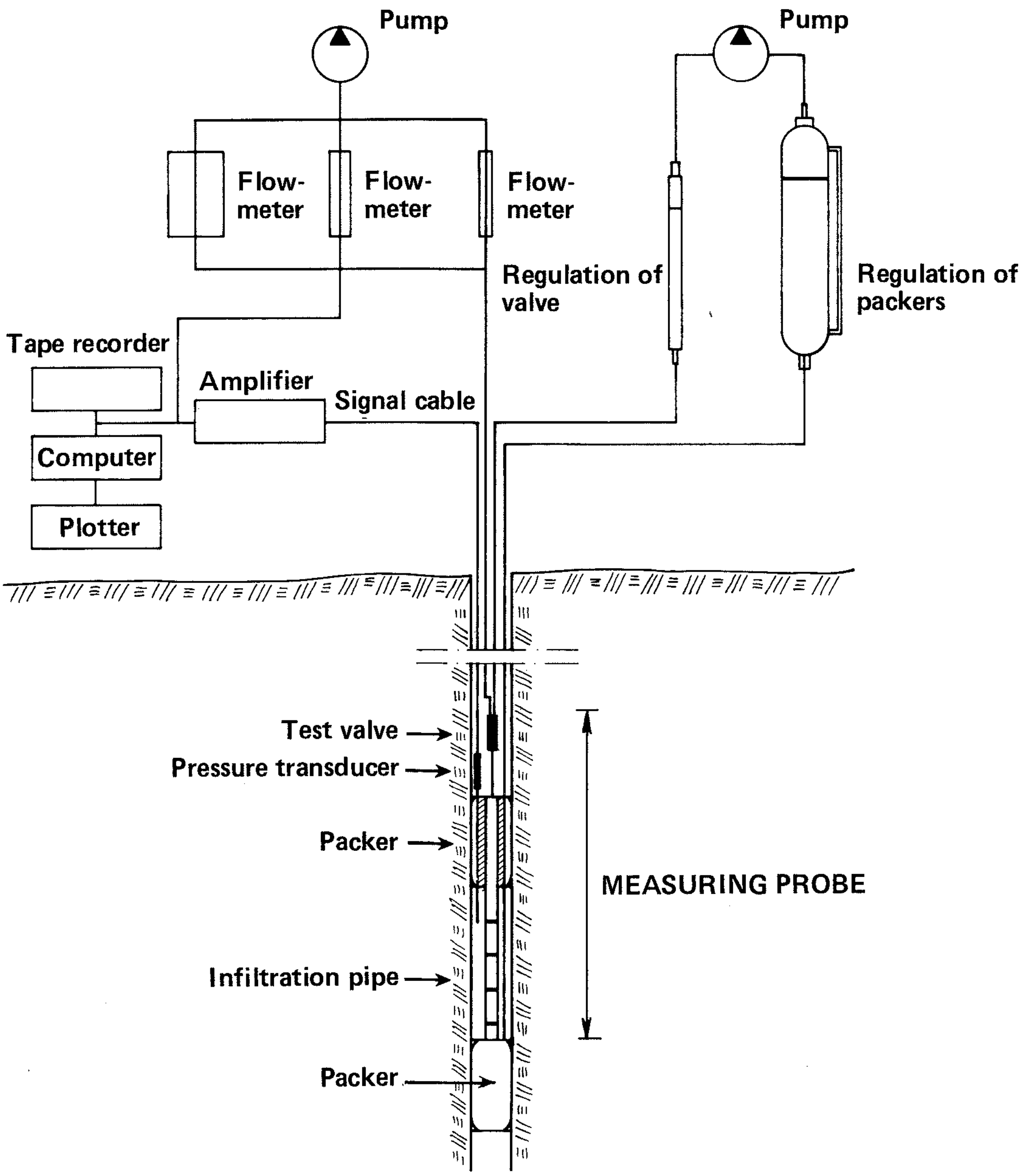


Figure 5-2. Schematic drawing of water injection test with double packers and with a multihose outfit.

5.4.2 Methods for determining the properties of the rock mass

The extent of different rock types and the frequency of fractures within a site are determined from geological mapping on the ground surface and from the drill cores that are recovered from the deep boreholes. Geophysical ground and borehole measurements also shed light on these properties. For example, magnetic measurements from the ground surface indicate the occurrence and orientation of diabase dykes. Radiation measurements in boreholes are used to

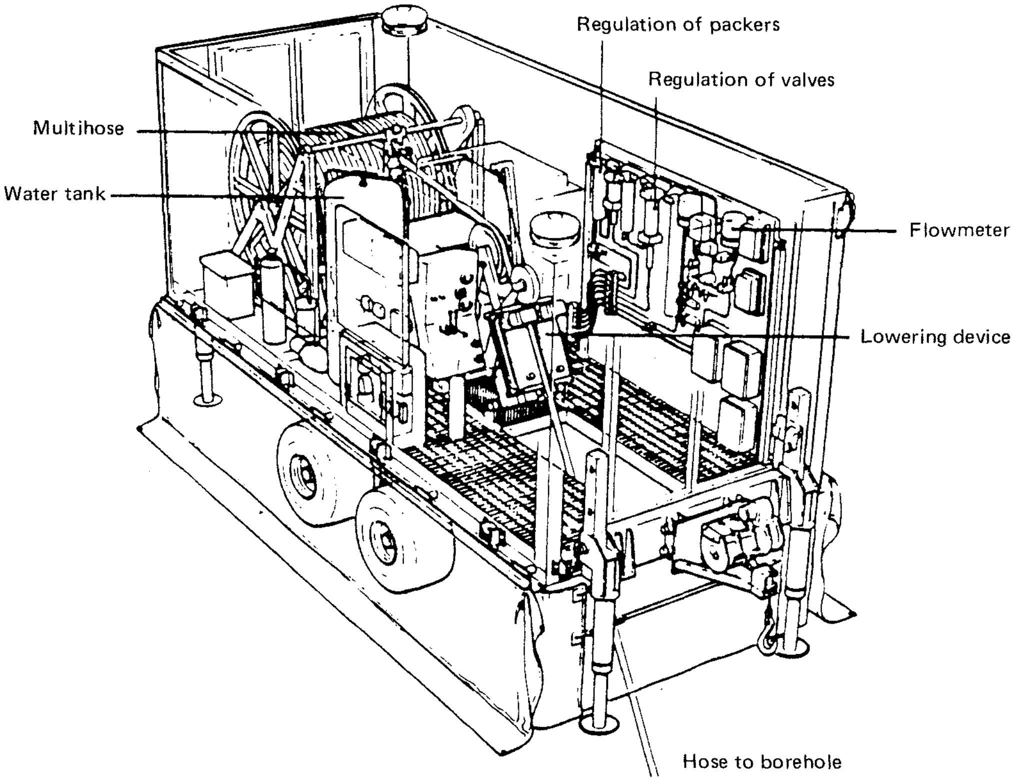


Figure 5-3. Multihose outfit for water injection tests.

distinguish different types of granite. Resistivity measurements from the ground surface and in boreholes distinguish areas with different degrees of fracturing. Analyses and measurements of drill core samples provide information on the chemical composition and physical properties of the rock, such as density, porosity, thermal conductivity etc.

Water injection tests in the rock mass outside the fracture zones are performed in order to obtain information on the hydraulic conductivity of the bedrock and its variation with depth and in different rock types. The water injection tests entail forcing water under pressure into sealed-off sections in the core boreholes. These sections are sealed off by the expansion of rubber packers against the walls of the boreholes, see fig. 5-2. Normally, measurements are performed in 25 m long sections. Measurements in 2-10 metre-long sections have been performed in sections of particular interest or where the results of the 25 metre measurements have warranted checking. In some cases, single-packer measurements have been carried out in short boreholes or as check measurements in long boreholes. The measurement section then consists of the section between the packer and the bottom of the hole.

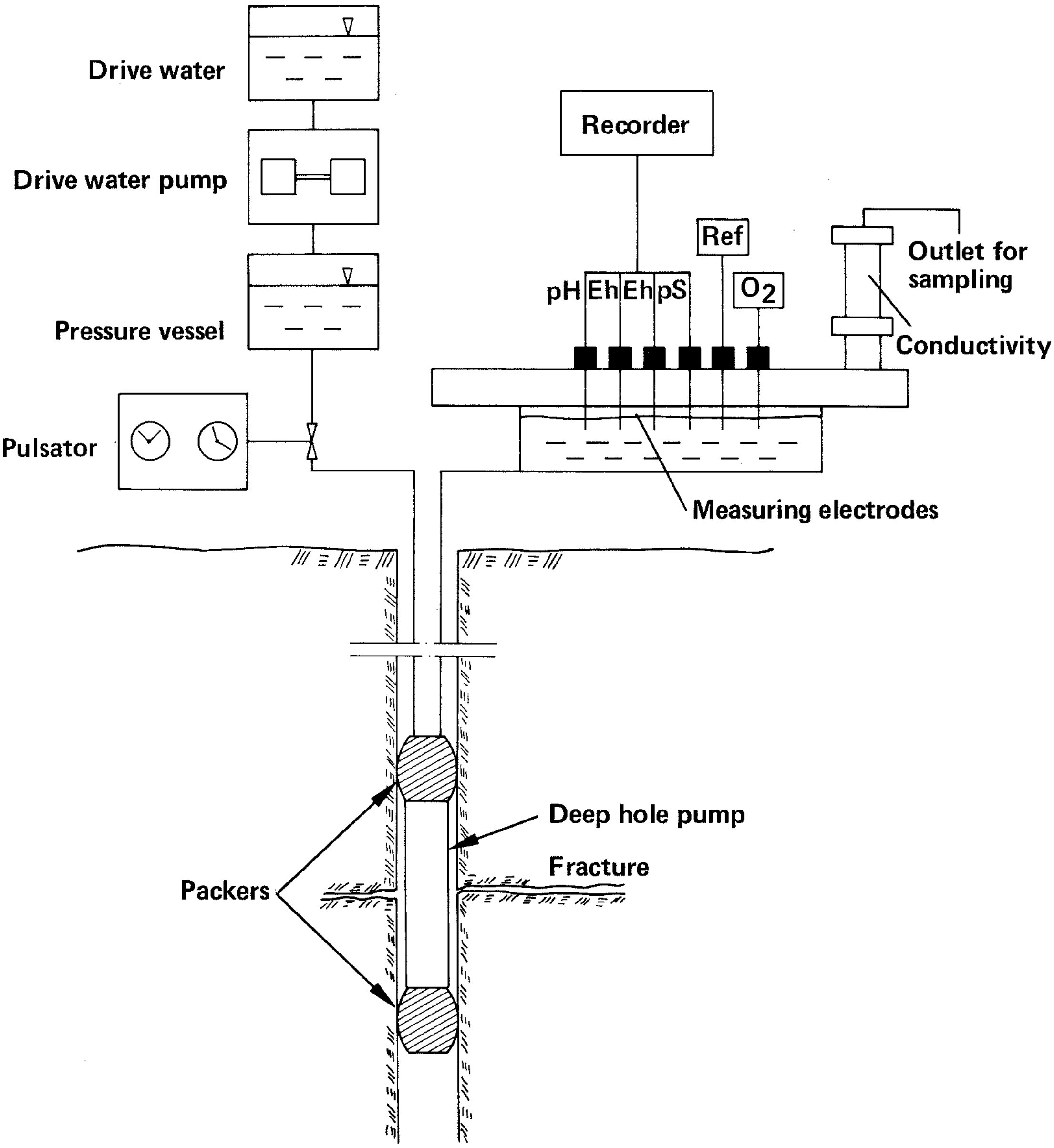


Figure 5-4. Schematic drawing of method used for water sampling in deep boreholes.

Two different types of measuring equipment have been used in the water injection tests: steel mandrel equipment and a newly-developed multihose outfit /5-9/. The steel mandrel equipment is lowered by screwing together 3 m lengths of tube. The multihose outfit is lowered with a hose containing all control and measuring lines, see figure 5-3.

In connection with the water injection tests, measurements of the natural groundwater head (pressure) at different levels in the boreholes are also made (piezometry). In addition, variations in the groundwater head over long periods of time are recorded in certain boreholes. For this purpose, a packer arrangement similar to the one shown in figure 5-2 is used, by means of which up to five sections can be sealed off at different depths in a borehole. With knowledge of the piezometric conditions, sections in the boreholes with inflow and outflow of groundwater can be recorded.

5.4.3 Methods for determining the chemical properties of the groundwater

In order to determine the chemical properties of the groundwater and their variations, water samples have been taken from different sections in the deep core boreholes that have been sealed off with packers, figure 5-4. Certain determinations, such as Eh and pH, have been done in the field, while other samples have been analyzed at different laboratories. The scope of the analyses is shown in table 5-2.

As a rule, water sampling has been done in two deep holes within each site and at four levels between about 100 and 650 m in each borehole. The holes within each area have been chosen so that the one hole can be expected to represent an inflow area for the groundwater and the other an outflow area. Long sampling times shed light on local variations in groundwater chemistry. In certain sections, the water supply has been insufficient for sampling at the intended level, in which case it has been necessary to relocate the sampling section to where water-bearing fractures are present.

In order to prevent the analysis values from being affected by impurities that may have entered the borehole from the surface, the boreholes are flushed out before sampling by means of repeated gas lift pumping, whereby the water in the borehole is blown out with nitrogen gas under high pressure. Moreover, the drilling water has been marked with a tracer (iodide) to indicate any contamination of the water samples. Yet another indication of surface water contamination is provided by tritium analysis.

Special rules govern water sampling and the storage, packing and transport of the samples for the purpose of preventing contamina-

Table 5-2. Sampling and analysis of groundwater from water-bearing levels down to about 600 m.

Field analysis - performed continuously on the pumped-up water

pH
Eh
Conductivity
Sulphide
Oxygen

Laboratory analyses of the composition of the water - 5 samples per level and at different times

Alkalinity (total carbonate content)
Sulphate
Sulphide
Phosphate
Fluoride
Chloride
Iodide (added to the drilling water as a tracer)
Nitrite
Nitrate
Ammonium
Sodium
Potassium
Calcium
Magnesium
Iron(II)
Iron (total content)
Manganese
Silicon (SiO_2)
Turbidity
TOC (total organic carbon)

Special sampling - 1-3 samples per level and at different times

Aluminium
Strontium
Uranium
Thorium
Radium
Radon
Helium
^{3}H, ^{2}H, and ^{18}O in water
^{14}C and ^{13}C in carbonate
Fulvic and humic acids

---

tion or changes during the time that elapses until the analysis is performed.

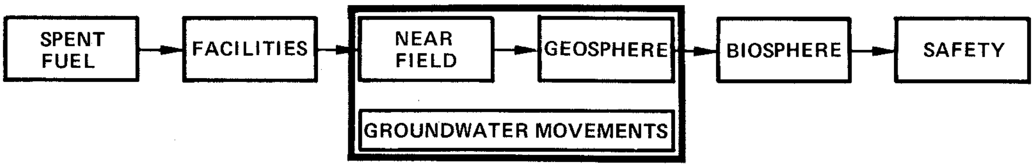
5.5 DATA PROCESSING AND REPORTING

Obtained data are processed preliminarily in the field simultaneously as they are gathered for central storage and final processing. Every other month, a compilation of the data is made and used as a basis for possible modification of the continued programme.

A total geological and hydrological evaluation of a site and a compilation of chemical groundwater data are provided in evaluation reports. These reports also present data that are of importance for a descriptive model of tectonic zones, geology and groundwater conditions /5-1, 5-2, 5-3, 5-4/.

Site-specific data from the different study sites are reported in chapter 18.

6 GROUNDWATER MOVEMENTS IN THE ROCK



This chapter deals with the movements of the groundwater in the bedrock and the bedrock's fracture systems. Fundamental properties for the hydraulic capacity of the bedrock are discussed, as well as the parameters and relationships that describe the groundwater movements. The mathematical calculation model that simulates groundwater flow is presented. The results of hydrogeological model calculations for the different study sites are presented in chapter 18.

6.1 THE BEDROCK AS A WATER-CONDUCTING MEDIUM

6.1.1 Darcy's law

The occurrence and movement of groundwater in bedrock is dependent on existing fracture systems. A highly fractured bedrock can contain a great deal of groundwater, but in order for this water to be mobile as well, the fractures must be interconnected. The velocity with which water moves in the fractures depends on the permeability of the fracture systems and differences in groundwater head.

Fractures in the bedrock have uneven walls and varying apertures. The fracture walls are in contact with each other at a number of points or surfaces. The groundwater flow is thereby limited to the open parts of the fractures, a process known as channelling.

The width of the individual fractures generally decreases with depth, due to increasing load on the fractures. As a result, the water-bearing part of each fracture decreases and that the possibility of hydraulic contact between different fractures decreases.

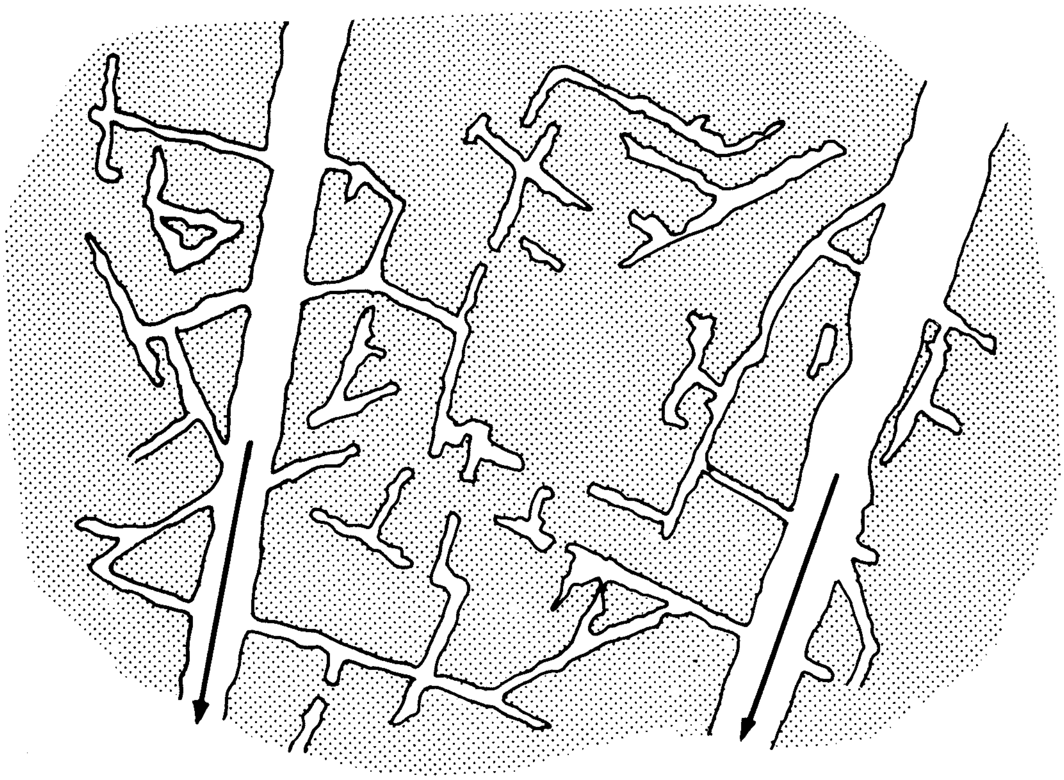


Figure 6-1. Schematic diagram of different fractures and their geometric relationships in a rock mass. Arrows mark the fractures that constitute the kinematic porosity and through wich water flow takes place. Smaller fractures connected to these main fractures constitute the diffusion porosity, while other fractures constitute the residual porosity.

In crystalline bedrock, which can be regarded as a porous medium in a large-scale pattern, the groundwater flow is laminar. This means that its velocity is proportional to the pressure gradient.

The groundwater flow can then be described by Darcy's law /6-1/.

$$q = Ki \tag{6.1}$$

which gives the relationship between the flow (q) through a unit area of material and the existing water pressure gradient (i). The coefficient (K) is called the permeability of the material, or in this case, the hydraulic conductivity of the rock. Darcy's law is the fundamental equation used in the hydrogeological model calculations for each study site.

6.1.2 Water-bearing part of the bedrock

The portion of the rock that is not occupied by mineral grains or other solid matter is called porosity. Of this porosity, only a small fraction is water-conducting. The water-conducting fraction is called the kinematic porosity or the flow porosity and consists of those fractures that sufficiently open for water to flow through them and have an open connection with each other as shown in the schematic drawing in figure 6-1.

According to /6-2/, the bedrock's porosity can be divided into three parts:

$$\varepsilon_t = \varepsilon_f + \varepsilon_p + \varepsilon_r \qquad (6.2)$$

where ε_t = total porosity

ε_f = kinematic porosity
ε_p = diffusion porosity
ε_r = residual porosity

The total porosity can be calculated from density measurements. Realistic values of the kinematic porosity of the bedrock have only been obtained from field experiments where the flow velocity of the groundwater has been investigated under controlled conditions with suitable chosen tracers. The sum of the kinematic and the diffusion porosity is measured by filling the continuous pore volume in specimens with liquid after drying-out under vacuum. It can also be estimated by determining the electric conductivity of the rock after calibration against water saturation tests /6-3/.

With knowledge of the above porosities, the residual porosity can be determined. This is normally the largest portion of the total porosity in the primary rock.

The rock's kinematic porosity is utilized for the transport of dissolved substances with the flowing groundwater. In addition, dissolved substances can be transported through diffusion, which utilizes both the kinematic porosity and the diffusion porosity of the rock. This transport is dependent on concentration differences and is independent of the groundwater flow.

The magnitude of the measured kinematic porosity varies and depends on where in the bedrock the measurement is performed. The kinematic porosity is higher in a fracture zone than in a rock mass of low fracture content. Values of between 0.013 and 0.5% have been measured /6-4/ - /6-9/. The porosity of the bedrock is also dealt with in chapter 14.

6.1.3 Fracture frequency

The total fracture frequency of the bedrock has been determined from drill cores. The number of fractures per m varies widely. In well-defined zones along which movements and major stress reliefs in the bedrock have taken place - tectonic zones - fracturing is sometimes so great that the number of fractures cannot be determined. In some cases, the fracturing may have gone so far that the rock in the zone is crushed to fragments. In such cases, the zone is called a crush zone.

Even in the bedrock between well-defined tectonic zones - the rock mass - the degree of fracturing varies. Ordinarily, the fracture frequency is higher adjacent to the tectonic zones.

Only a certain portion of all fractures in the rock mass are hydraulically conductive and can be included in the kinematic porosity. This fraction, known as the hydraulic fracture frequency, has been determined by water injection tests in boreholes sealed off in 2-3 metre sections /6-10/.

The hydraulic fracture frequency is used in the nuclide transport calculations, chapter 14. Data on fracture frequency within the sites is reported in chapter 18.

6.1.4 Hydraulic units

A descriptive model of the bedrock's hydraulic units has been set up for each study site. In the model, the rock has been divided into the following units:

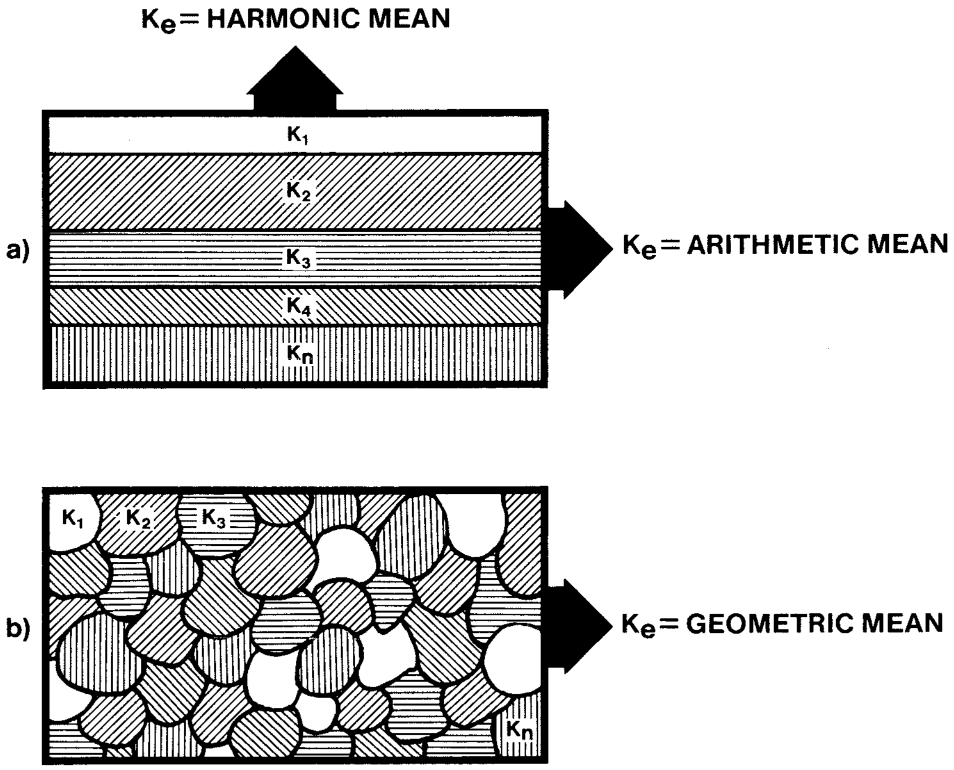


Figure 6-2. Different mean value estimations for calculating the effective hydraulic conductivity (K_e). The arrows indicate the direction of the groundwater flow.

1. Regional fracture zones of great extent and bordering large rock blocks.

2. Local fracture zones of limited extent with a well-defined position and orientation.

3. Rock mass, including normally occurring fracturing and fracture zones that cannot be assigned to categories 1 or 2.

Hydraulic conductivity varies from point to point in the bedrock, and the medium can be considered highly heterogeneous. It is possible to differentiate between large-scale, local-scale and microscale variation of hydraulic conductivity. By large-scale is meant the variation that occurs between the different hydraulic units. The local-scale variation is the variation within each hydraulic unit. Variations on a microscale are, for example, the variation of the hydraulic conductivity along a fracture or between a fracture and the crystalline part of the rock.

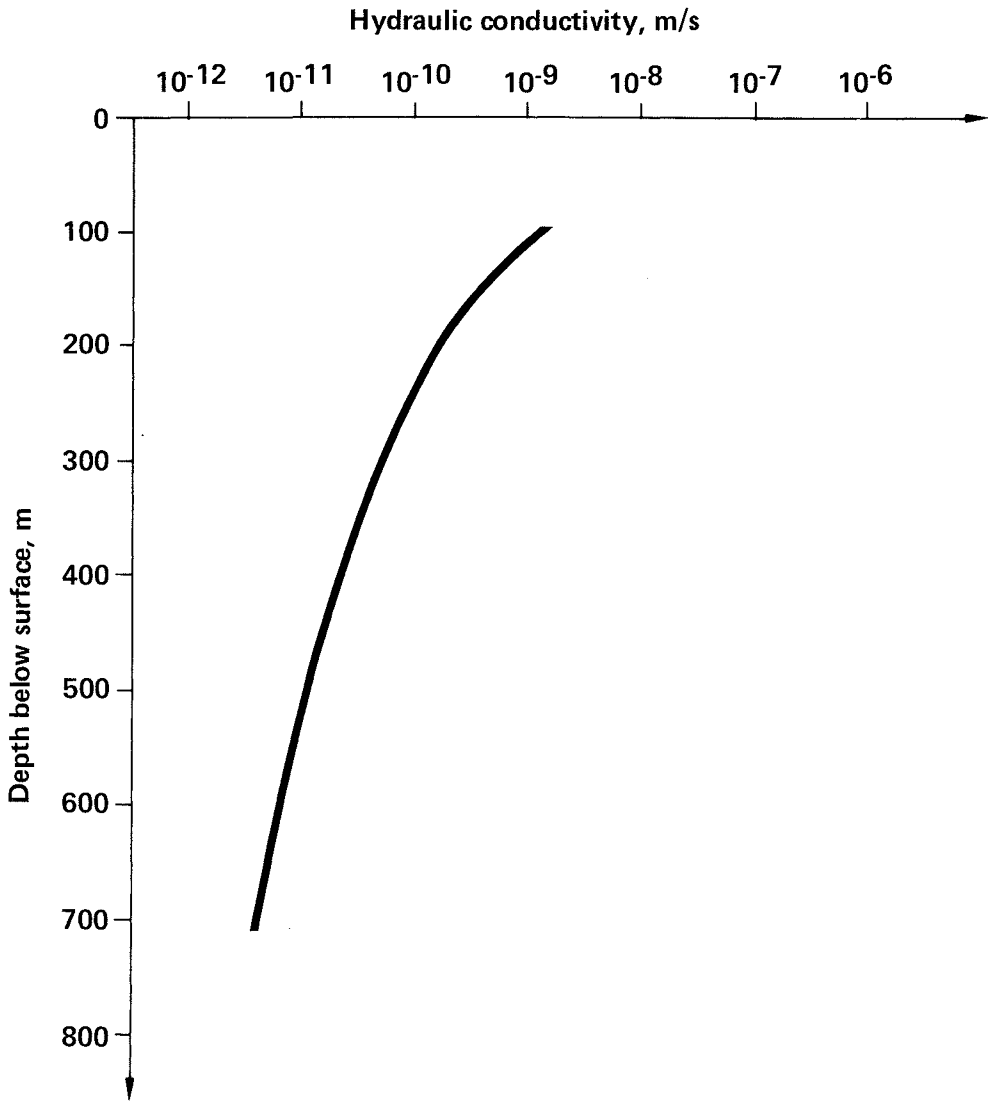


Figure 6-3. Variation of the effective hydraulic conductivity with depth in the rock mass in Kamlunge. The curve is based on geometric mean value formation of measured data /6-18/.

6.1.5 Mean value of the hydraulic conductivity

An effective hydraulic conductivity (K_e) based on all measured values within each unit is used to characterize the hydraulic properties of the different units in connection with model calculations, see section 6.3. This effective conductivity constitutes a mean value of individual measured conductivities. Each individual measured value represents in itself a limited part of a hydraulic unit. The interrelations of these parts are decisive for the choice method of mean value calculation. Figure 6-2 illustrates different relations between conductive parts of the bedrock. In case (a) each measured value represents a stratum in the bedrock of virtually infinite extent. In the case of groundwater flow parallel or perpendicular to the strata, the effective hydraulic conductivity is described by the arithmetic or harmonic mean, respectively.

The hydraulic conductivity values are randomly distributed within the different hydraulic units. The distribution can be regarded as logarithmically normally distributed /6-11, 6-12/. Figure 6-2b illustrates a random scatter of the different hydraulic conductivities. An effective hydraulic conductivity is represented in this case by a geometric mean value, also taking into account whether the flow is two- or three-dimensional /6-13, 6-14/.

In the fracture zones, hydraulic conductivity varies from point to point. Fracture zones as hydraulic units constitute strata of elevated hydraulic conductivity that cut through the rock mass. Within the fracture zones, however, each measured value represents a limited part of the fracture zone with a random scatter. Hence, an effective hydraulic conductivity for the fracture zones is represented by a geometric mean value, where the groundwater is considered to be two-dimensional.

In the remaining part of the bedrock, the small fractures that normally occur have not been found to constitute continuous strata. Here as well, each measured value represents a limited part of the rock mass and with a random scatter. As for the fracture zones, a geometric mean value calculation from measured data therefore provides the most realistic estimation of the effective hydraulic activity of the rock mass.

Hydraulic conductivity in both fracture zones and rock mass decreases with depth below the surface. This decrease is due mainly to the increase in rock stress, which leads to a reduction of the size of the apertures of existing fractures /6-15, 6-16, 6-17/. The relationship between measured K values and depth is given by /6-10/:

$$K_e = a \cdot z^{-b} \qquad (6.3)$$

Where K_e = effective hydraulic conductivity
z = vertical depth below surface ($z>50$ m)
a and b = constants that characterize each hydraulic unit and study site.

Fig. 6-3 shows the relationship between effective hydraulic conductivity and depth for the rock mass in Kamlunge.

The measurement limit in the hydraulic tests, see section 6.2.1, affects the calculation of both effective hydraulic conductivity and depth dependence. Measured values corresponding to the measurement limit have been assigned the value of the measurement limit. The mean value calculations therefore yield higher values of effective hydraulic conductivity than what corresponds to the natural conditions.

6.1.6 Hydraulic gradient

The groundwater flow is determined by both the hydraulic conductivity and the differences in groundwater head (pressure). These differences in groundwater head, the hydraulic gradient, are dependent on the topography and conductivity of the bedrock and on the groundwater recharge. At the groundwater surface (i.e. the water table), the hydraulic gradient is equal to the slope of the water table.

Owing to the humid Swedish climate and the low hydraulic conductivity of the bedrock, the water table largely follows topographical level variations. Extensive formations with high hydraulic conductivity cause a levelling of the topographically determined water table. Examples are gravel eskers and certain permeable sandstones, but large fracture zones in the primary rock can also have this levelling effect. Differences in the level of the water table give rise to hydraulic gradients, which in turn give rise to groundwater flow.

The ground surface is the highest level to which the groundwater can rise. After this, outflow and runoff in the form of surface water takes place. Pressure differences resulting from differences

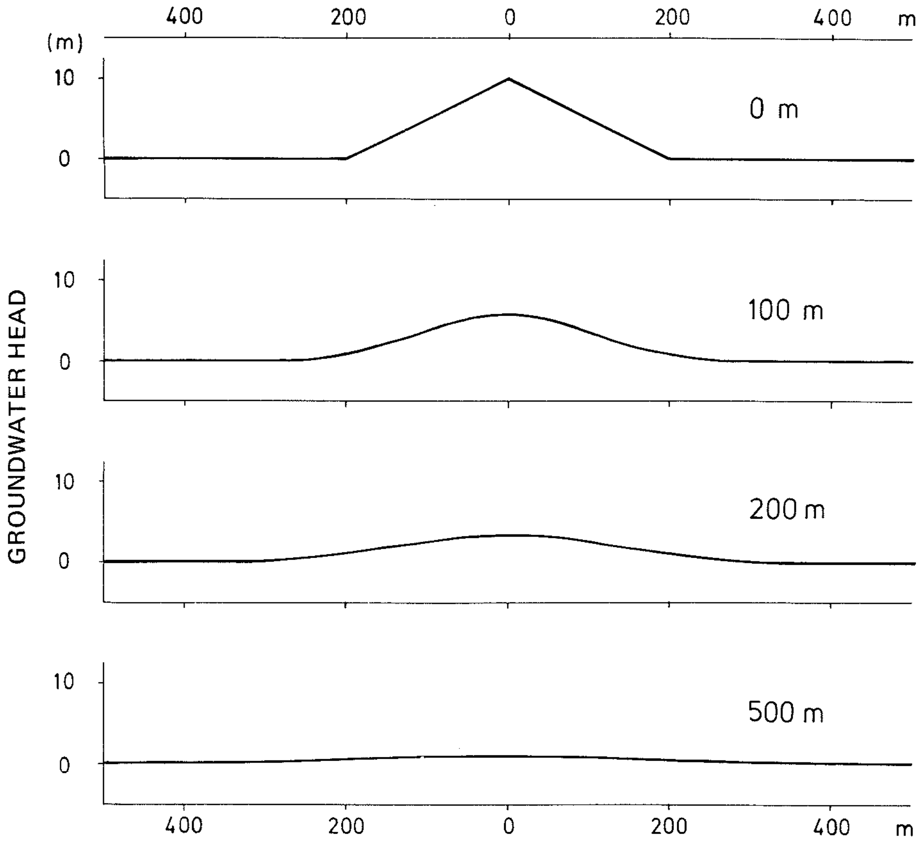


Figure 6-4. Levelling of the groundwater head with depth below a circular hill with a radius of 200 metres. The largest gradient in the horizontal direction at the ground surface is 5 % and at a depth of 500 metres about 0.1 % /6-10/.

in the togographically determined groundwater level (i.e. head differences) are levelled out with increasing depth below the water table, see fig. 6-4.

The level of the water table and the water pressure in the bedrock fluctuate depending on climatological factors and on changes in air pressure and gravitation. These fluctuations are dominated by climatological factors. The difference between the highest and lowest groundwater level is different in different types of water-bearing strata. Climatological conditions determine when these extreme values occur.

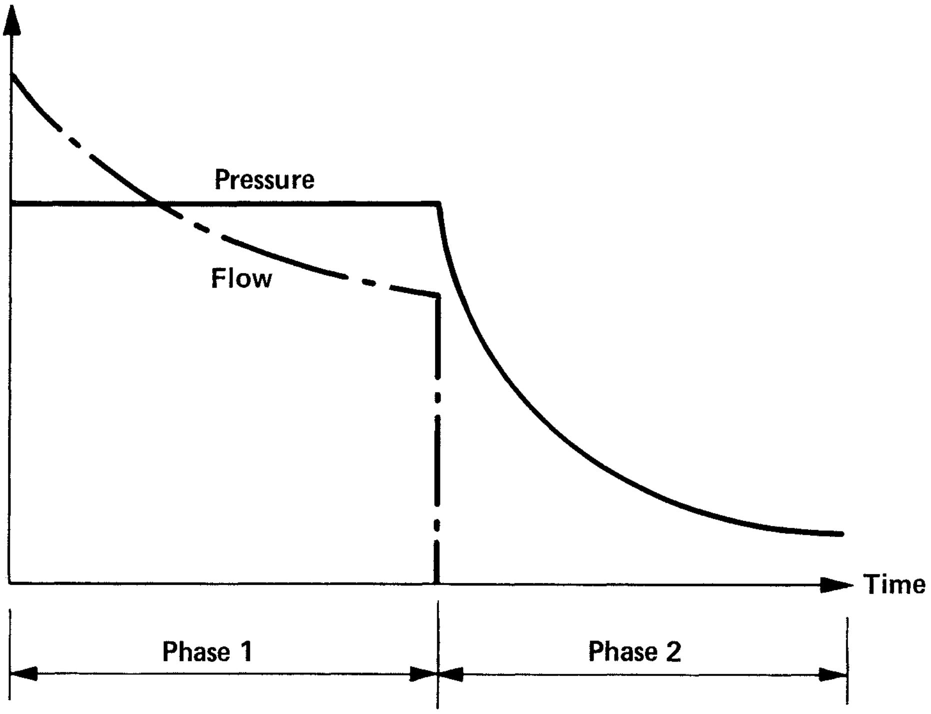


Figure 6-5. Schematic diagram of pressure and flow variations during water injection test.

6.2 METHODS OF MEASUREMENT

6.2.1 Hydraulic conductivity

The hydraulic conductivity of the bedrock is determined by means of measurements in boreholes. Water under pressure is injected in a section of a borehole sealed off by packer sleeves, see fig. 5-2. Hydraulic conductivity is calculated on the basis of how the water flow rate declines with time after application of the water injection pressure and how the water pressure declines with time when the flow is stopped, see fig. 6-5.

The measurements have been carried out with two different sets of equipment /6-19/, see section 5.4.2. The length of the tested sections is normally 25 m. Measurements in shorter sections, 2-10 m, have also been performed in order to provide information on special sections such as water-bearing fracture and crush zones. The flows and variations in pressure that have been possible to record correspond to a minimum measurement limit of 2.5×10^{-12} m/s for the hydraulic conductivity in measurements in 25-metre sections. In shorter sections, the measurement limit increases so that measurements in 2-metre sections give a minimum limit of 1 x 10^{-11} m/s. The measurement limit is determined by the possibilities of obtaining a reliable measurement of very low water flows.

The measured values give a hydraulic conductivity that is representative of the area nearest the borehole. The size of this area varies and depends on, among other things, the permeability of the rock. In test sections where conductivity is high, the determinations represent conditions within a larger area around the borehole than in the case of low conductivities. In the present investigations with conductivities of between 10^{-11} and 10^{-7} m/s, this area extents 0.2-60 metres out from the borehole /6-10/. In general, the water flow that is injected at a given pressure constitutes a direct measure of the hydraulic conductivity. A flow lower than that which corresponds to the permeability of the bedrock can be recorded if the fractures nearest the borehole are affected by the drilling and the drilling mud. Prior to hydraulic testing, the holes are therefore flushed with nitrogen gas, a technique known as gas lift pumping. These factors are also taken into account when evaluating the results of the measurements /6-6/.

In some cases, hydraulic conductivity has been determined by recording a pressure change in boreholes when injection or pumping of water has been carried out in a nearby hole, so-called interference tests. The measurements provide information on the properties of the intervening bedrock as a weighted value. The distance between boreholes varies from 5 to 250 metres. The measurements indicate the existence and scope of hydraulic connections between the boreholes. These measurements have been carried out in the upper parts of the bedrock in order to obtain values of the hydraulic conductivity in large fracture zones and in the upper part of the rock mass.

The hydraulic conductivity of the bedrock varies widely. In large fracture and crush zones and in the upper, more fractured part of the bedrock, values in excess of 10^{-6} m/s can occur, while in the less transmissive rock mass, values below 10^{-11} m/s are common, especially in the deeper parts of the bedrock /6-10/.

6.2.2 Groundwater head

The groundwater head in the bedrock within the study sites has been measured by means of the following methods:

- Continuous measurement of the level of the water table in boreholes by means of water level gauge observations and soundings. In the boreholes, packers have been installed about 5-10 m below the water table in order to avoid disturbances from the deeper parts of the bedrock.

- Recording of the groundwater head at different levels in boreholes sealed off by packers (piezometry). Those sections that have been sealed off have mainly been zones of high hydraulic conductivity, for example large crush or fracture zones.

- Calculations of groundwater head from hydraulic measurements. These measurements have been carried out in two phases, see section 6.2.1. The natural water pressure in the tested section has been calculated on the basis of the results from the two phases in fig. 6-5 /6-20/.

6.2.3 Groundwater level maps

Groundwater level maps have been drawn up for each study site. The maps are based on topographical maps and measurements of the level of the water table in boreholes. The groundwater level maps comprise the basis for the numerical model calculations of the groundwater conditions within each site.

The measurements in the boreholes verify the following general assumptions which have been made in map production.

- The distance between the ground surface and the water table is greater under isolated elevated parts of the terrain than under lower-lying parts.

- At lakes, the water table coincides with the lake surface.

- Lower-lying sections of the terrain with major water courses, large bogs or highly permeable zones constitute outflow areas for groundwater. Here, the water table coincides with the ground surface.

6.3 MODEL CALCULATION

6.3.1 General

The purpose of the model calculations is to provide a description of the natural groundwater conditions in the bedrock within the study sites. Analytical calculations can be used with good results for approximate calculations. It is thereby normally assumed that constant properties exist in the bedrock and the groundwater, and that well defined conditions exist along the boundary lines or surfaces of the calculation area.

In cases with more complicated geometric conditions and where the properties of the rock vary, numerical models are required. The area is then divided into a number of three-dimensional blocks (element generation). These blocks are chosen to conform to existing hydraulic units and the level of the groundwater table within the area. The equations for flow and water balance are solved within each block. The conditions along the common boundary surfaces of the blocks must coincide in order for a representative picture of the groundwater conditions to be obtained. Owing to the large number of equations to be solved, the numerical models require considerable computer capacity.

The groundwater conditions within the sites have been calculated using a numerical model according to the finite element method /6-10, 6-21/. The model is a so-called deterministic model that works with mathematically defined relationships where mean values or effective values are used to represent, among other things, the hydraulic conductivity of the rock mass and the fracture zones.

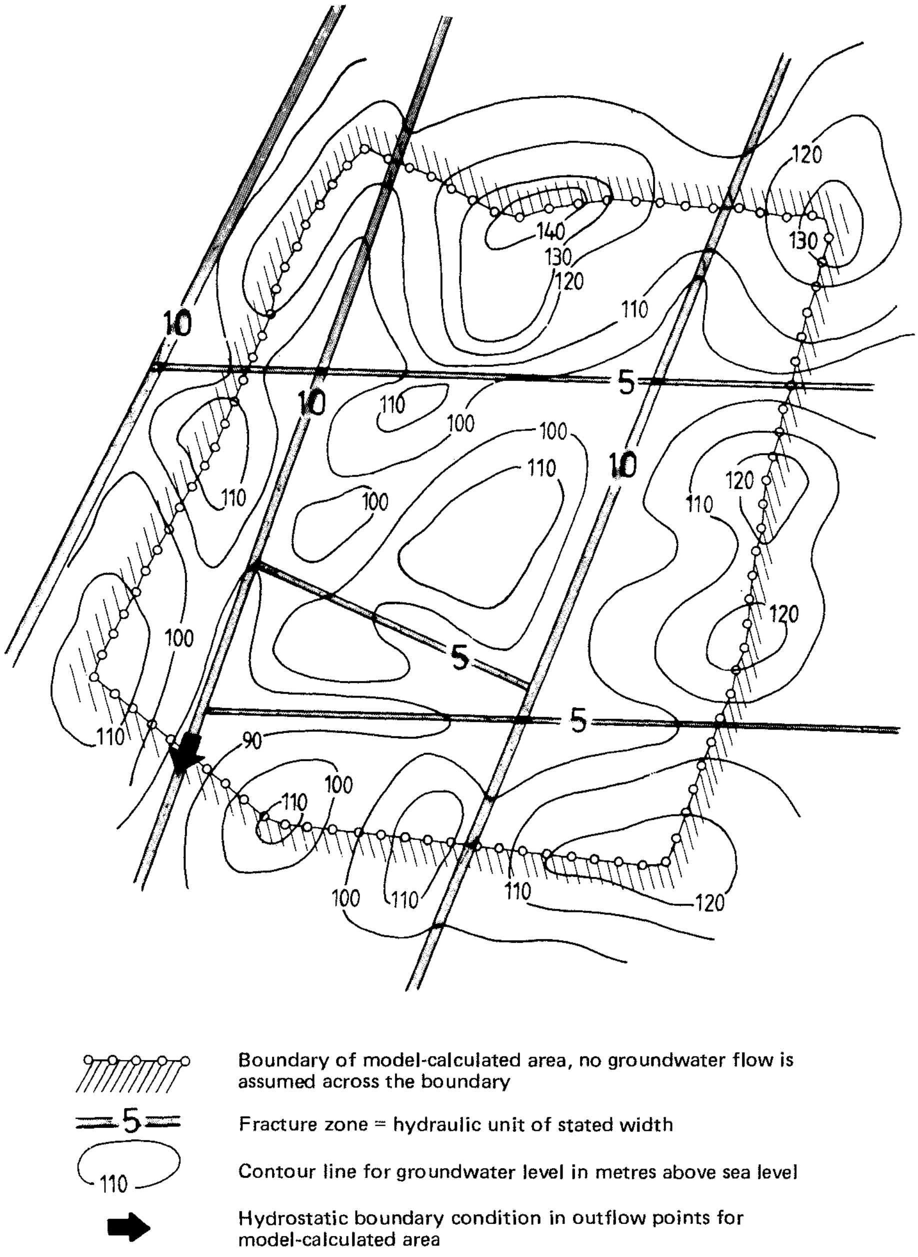


Figure 6-6. Schematic diagram of premises for model calculation of an area.

Another type of calculation model can be gathered under the heading of stochastic models. Stochastic models take into account variations in included parameters, usually standard deviation or variance. The models also provide a calculated variation of the obtained results. At present, these models have only been developed for simplified cases and have not been used here. Instead, several calculations have been carried out with the deterministic model, where the included parameters have been varied.

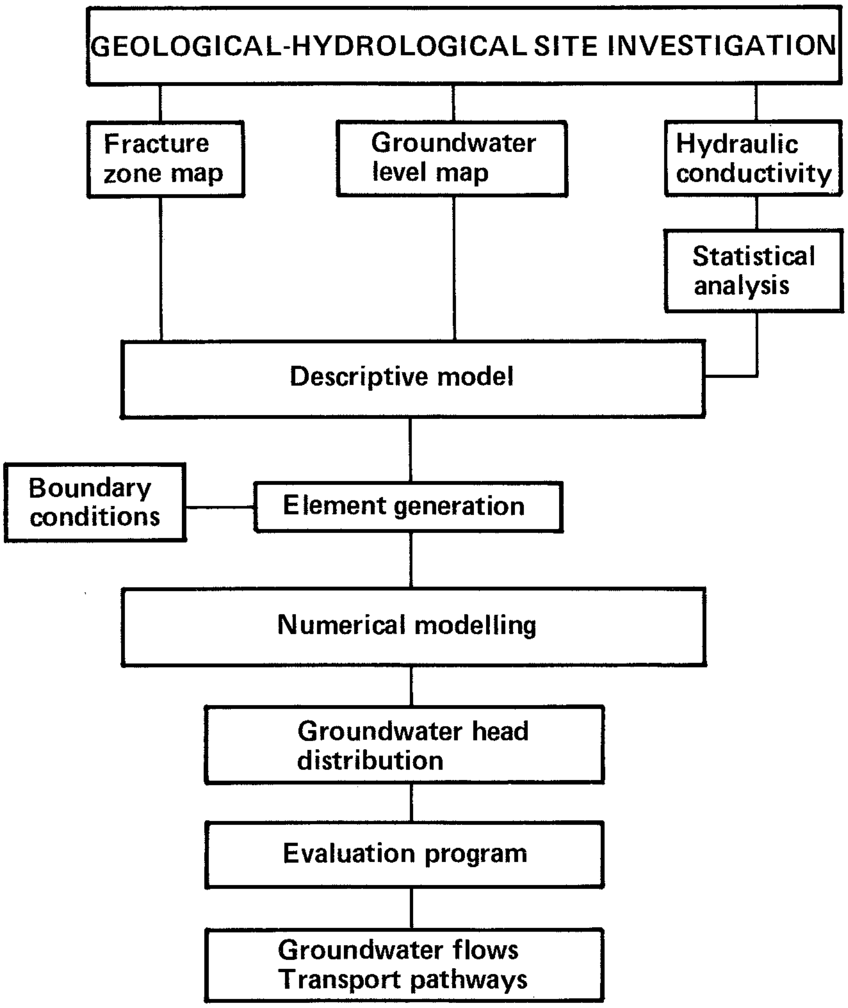


Figure 6-7. Work sequence for model calculations of the groundwater conditions within a site.

6.3.2 Calculation procedure

Each calculation is based on a descriptive model of the bedrock's hydraulic units, based on site-specific data and conditions. The groundwater conditions are regarded on such a scale that the equations for flow in porous media apply.

The descriptive model on which the numerical calculation for a site is based includes:

- Location, width and extent of different hydraulic units.

- Properties (hydraulic conductivity, fracture frequency etc) of different hydraulic units.

- Boundary conditions along the boundaries of the studied site.

Figure 6-6 shows a schematic diagram of a site with different hydraulic units and boundaries.

The geological investigations within each site result in maps of detected fracture zones, their location, extent and width both on the surface of the ground and at repository level.

Figure 6-7 shows a scheme of the work and calculation sequence with the different steps in gathering of data for the model up to the final results of the calculation.

Hydraulic conductivity in each fracture zone has normally been determined by means of detailed measurements. Normally, only one limited part of the fracture zone has elevated conductivity. In the calculation models, however, elevated conductivity over the entire width of the zone has been assumed.

The fracture zones have been assumed to have the same width and dip along their entire extent in the vertical and horizontal directions.

The properties of the different hydraulic units are described with effective values, see section 6.1.5. All measured values within each hydraulic unit have been used for calculating the effective conductivity. This means, for example, that all fracture zones within the area have been given the same hydraulic conductivity regardless of width, direction or length. The decline of conductivity with depth below the ground surface is described by means of the equations presented in section 6.1.5. The equation has been extrapolated down to a depth of 1 500 metres, to which all hydraulic units have been assumed to be continuous.

Anisotropic hydraulic properties in the bedrock can be distinguished and taken into account in the model calculations.

The boundary condition on the upper boundary surface is defined by the location of the groundwater table. The modelled area is chosen so that its vertical boundaries consist of elevated ridges or low-lying sections in the form of valleys. A completely downward groundwater flow is assumed in the ridges, and a completely upward flow in the valleys. This means that no flow can take place straight across an imaginary vertical surface through the ridges or valleys; in other words, an impervious limit has been assumed. This assumption has also been made for the model's lower boundary surface.

In the model calculations, the vertical boundary surfaces have been located at such a great distance from the conceived repository area that they do not affect the groundwater conditions within this area. Normally, the model calculations have been limited to a local area around the repository whose size varies from between 2 to 6 km^2. In one case (Kamlungekölen), the groundwater conditions (heads, flows) have first been calculated in a 34 km^2 regional area in order to establish the boundary conditions for the local area around the repository. The groundwater head has hereby been specified on the vertical boundary surfaces of the local area.

The results of the numerical calculations comprise the groundwater head distribution within the modelled area. From the head distribution, the groundwater flow and direction at different points within the area are calculated. On the basis of these results, transport paths from the conceived site of the final repository to the biosphere are determined.

6.3.3 Relevance

Hydraulic properties and conditions are not determined for every point or volume in a rock mass. Instead, the investigations have been concentrated to parts that are representative or exhibit large anomalies. The equations for hydraulic conductivity that are used in the calculations and that have been derived from measured values can therefore not describe the rock's properties on a microscale. The greatest differences between calculated and actual conditions are obtained in those parts of the bedrock where the scatter of measured values for hydraulic conductivity is greatest, and where boundary conditions affect the calculations. This applies in particular in the upper parts near the surface of the ground, where the detailed topography influences the location of the groundwater table. The magnitude of these differences decreases with increasing depth.

A certain check can be obtained of the model calculations by comparing the calculated groundwater recharge with measured hydrometeorological data. These comparisons are reported in chapter 18.

6.4 LONG TERM CHANGES IN GROUNDWATER CONDITIONS

6.4.1 Influence of changes in natural conditions

The hydraulic conditions that are sought after at a final repository can be summarized in the following points:

- low hydraulic conductivity
- low hydraulic gradient
- long transport path for groundwater from repository to biosphere
- high kinematic porosity

Present-day conditions may very well change over a time span of a million years. The magnitude of the changes in relation to the present-day situation can be estimated on the basis of what is known about past geological history, see chapter 8.

Hydraulic conductivity can be altered by the creation of new fractures, deep weathering or erosion, bringing parts of the bedrock closer to the ground surface. The gradients can change due to changes in hydraulic conductivity, land uplift and depression or through increased or decreased groundwater recharge. The flow paths can be lengthened or shortened by the changes mentioned above or by movements in the bedrock.

Bedrock movements have occurred in Sweden over the past 50 million years, see section 8.4. In conjunction with ice ages three million years ago and up to the present, these movements have primarily comprised repeated long-lasting depressions of the bedrock interrupted by shorter phases of rebound during ice-free periods.

The upper part of the bedrock, about 100 m, is affected by the inland ice sheet and the subsequent removal of the ice load in the form of increased fracturing. This phenomenon has been found in the site investigations where relatively high values of hydraulic conductivity have been measured in the upper parts of the bedrock. The ice sheet also has an eroding effect on the bedrock, which means that the affected upper 100 metres gradually come closer to the repository. The maximum erosion caused by the ice sheet at the investigated sites is on the order of 10 or so metres, probably around 3 m /6-22/. Over a period of one million years, roughly five glaciations can be expected, which means an erosion equivalent to 15-50 m, mainly affecting the elevated parts of the terrain.

In addition to glaciation, other climatological factors can also cause erosion (wind, water etc). With present-day conditions at the study sites, this erosion can be estimated at a maximum of 3-5 cm per 1 000 years /6-22/. Hence, during a million years, the distance between the repository and the ground surface would decrease by 30-50 m.

In connection with erosion, a deep weathering process takes place whose extent is determined by climatological factors, among other things. This type of weathering can be found today along major fracture zones, see section 8.6. Similar conditions are expected to prevail in the future as well. This weathering process leads to alteration of minerals and rock fragments in the fractures by, among other things, the uptake of water. The increase in the volume of the material that hereby takes place causes the fractures to become less transmissive, i.e. their hydraulic conductivity decreases.

Climatological changes may result in a higher or lower rate of water supply to the bedrock. A change in the level and contour of the water table causes changes in hydraulic gradients and thereby changes in groundwater flow within the area.

In the long run (a million years or more), the following relatively pessimistically chosen examples of changes in the hydrogeological situation in an area are conceivable:

- Erosion resulting from glaciation and other climatic influences causes the distance from the repository to the ground surface to decrease by 100 m.

- Topographical conditions remain unchanged despite a levelling erosion.

- The hydraulic conductivity of the fracture zones remains unchanged - i.e. no deep weathering occurs.

- The groundwater table follows the topography of the ground surface.

Such changes would result in increased hydraulic gradients and conductivities at the repository level as well as shorter transport distances for the groundwater. The model calculations carried out for the sites at Fjällveden, Gideå and Kamlungekölen show that such a changed situation increases the groundwater flow through the repository be less than a factor of 2. Geophysical factors that can influence a repository in the future are discussed in chapter 8.

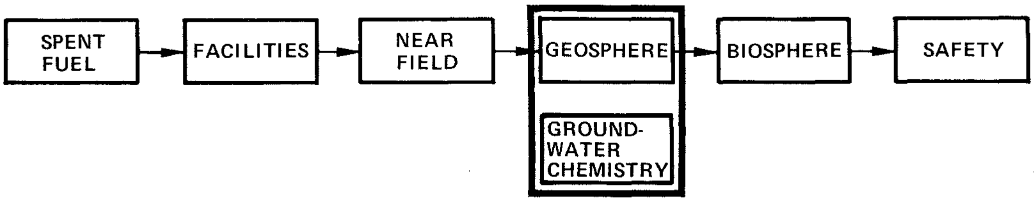
6.4.2 Influence of heat from the waste

The spent nuclear fuel develops a certain amount of residual (decay) heat - see section 4.5.4. As a result of this, the temperature at the repository level rises to max. 80°C, then declines and gradually returns to its original natural temperature.

This temperature increase in the rock mass and the groundwater gives rise to a driving force that wants to make the groundwater flow upwards. The influence of heat generation has been studied in different typical cases /6-21/. In the calculations, a generic repository has been placed in areas with a downward regional hydraulic gradient or downstream of a large regional slope. Hydraulic conductivity has been assumed to decrease with depth below the surface.

The results show that the groundwater flow caused by heat generation only has a marginal influence on the groundwater's travel times from the repository to the ground surface. All investigated sites exhibit a greater decrease of hydraulic conductivity with depth than has been assumed in these calculations. A greater decrease of conductivity with depth means longer travel times.

7 CHEMISTRY OF THE GROUNDWATER AND THE FRACTURE SYSTEMS



This chapter deals with the chemical system constituted by the rock, the groundwater and the fracture-filling materials. The interaction of the radionuclides with this system is treated in chapter 12 and site-specific data are presented in chapter 18.

7.1 CRYSTALLINE ROCK AS A GEOCHEMICAL SYSTEM

The rock repository can be regarded as a system where the rock's different mineral components, fracture-filling products, as well as the buffer and backfill material constitute a solid, stationary phase and the groundwater a liquid, mobile phase.

The principal transport of radionuclides and dissolution products away from the repository as well as of reactants into the repository takes place in the mobile water phase. The groundwater also constitutes a medium that actively participates in many chemical processes between the components in the repository and the rock.

Reactions between the groundwater and rock surfaces lead to weathering processes and mineral alterations, which in turn determine or influence the chemical properties in the system. The solid mineral phases also influence the transport of dissolved substances in the water phase through various sorption and exchange reactions.

Reactions and equilibria in the groundwater-bedrock system are thus very important both for transport processes and for e.g. chemical alteration processes and dissolution reactions. This applies both in the undisturbed rock (the far field) and in the repository's immediate vicinity (the near field).

7.1.1 Importance of groundwater chemistry

The corrosion resistance of the canister material is dependent on the chemical environment in the repository. Chemical parameters of the groundwater that are of particular importance for canister dissolution are pH and redox conditions, as well as the content of corrosive substances in the groundwater (see chapter 10).

Dissolution of uranium oxide fuel and formation of mobile radionuclide complexes are also processes that are heavily influenced by the chemical properties of the water phase, especially pH and redox conditions, as well as the presence of complexing agents (e.g. carbonate) (see chapters 11 and 12).

The chemical form of dissolved radionuclides is determined by the aqueous environment. Once again, aqueous chemistry parameters such as pH, redox conditions, concentrations of potential complexing agents and, for certain radionuclide systems, the water's total salinity are of the greatest importance for radionuclide mobility in the rock. Depending on the properties of dissolved species - such as chemical composition, charge, coordination, molecular structure, oxidation state, properties of the counterion etc. - drastic differences can be obtained in the radionuclides' degree of sorption on water-exposed geological materials and thereby also in transport velocities (see chapter 12).

7.1.2 Importance of fracture minerals

Fractures, both open and sealed and of varying sizes, as well as microfissures and crevices in mineral grain boundaries, are potential water transport pathways in crystalline rock. Water-exposed surfaces are subjected to mineral decomposition processes (weathering), but are also sites for precipitation of products from the water phase. Thus, the mineralogy of the fracture-filling materials is often significantly different from the mineralogy of the bulk rock /7-1/. Decomposition of the bulk rock, as well as precipitation of low-solubility products and mineralization in the water pathways, are dependent on the groundwater composition.

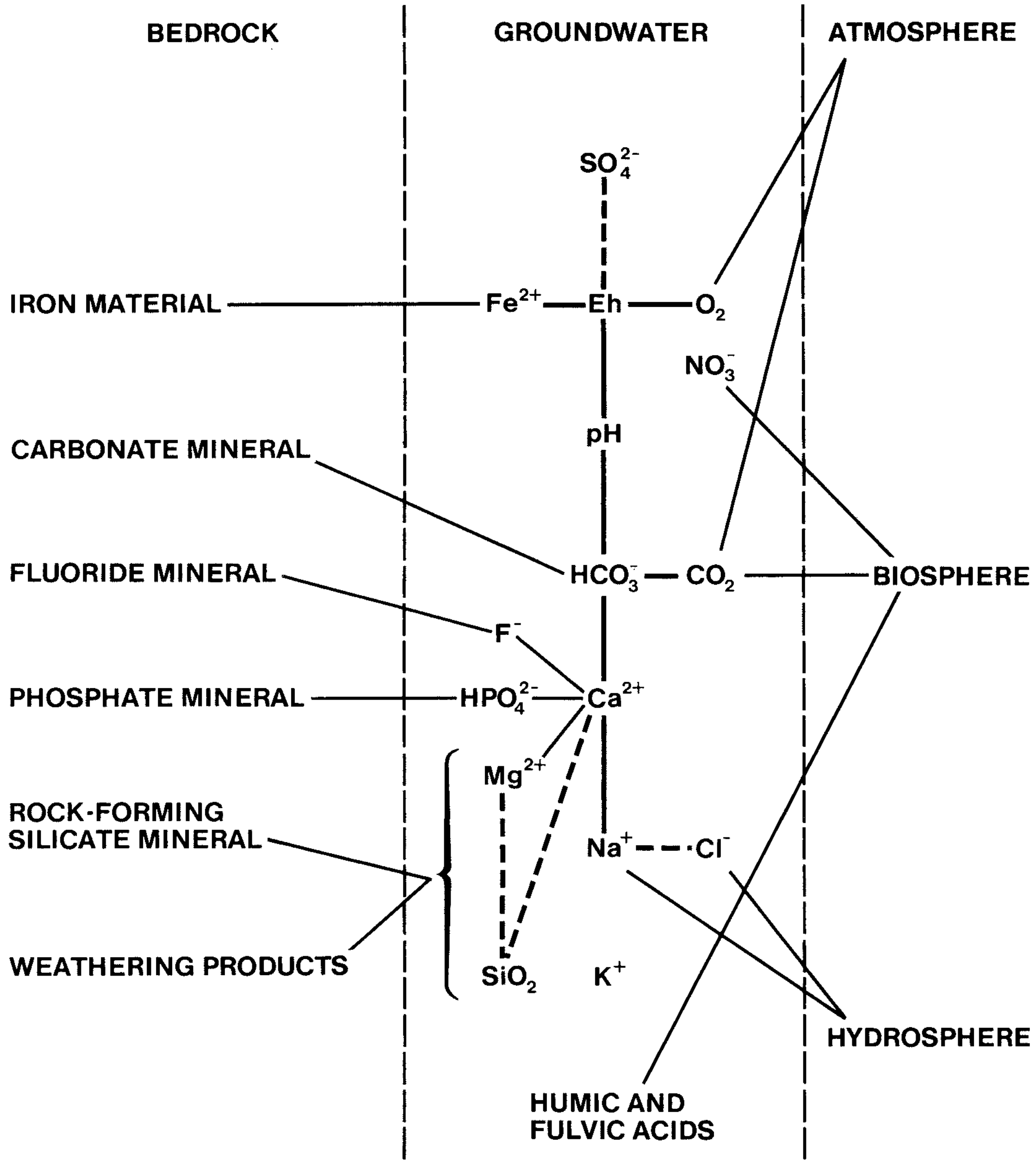


Figure 7-1. Connection between groundwater chemistry, mineral composition of the rock and the atmosphere/biosphere.

As a result of the presence of a repository and the disturbances it causes in the rock even relatively far away from the repository due to temperature increases, the normal weathering and precipitation sequences may be disturbed.

Since radionuclides dissolved in the groundwater primarily come into contact with the weathering or precipitation surface layer on rock surfaces in the water pathways, the exchange between the fracture-filling minerals and species in the water phase is of great importance. If impervious surface coatings are formed, they function as diffusion barriers and reduce the rock volume that is potentially available for sorption reactions. In most cases, however, weathering reactions cause a transformation to poorly crystallized decomposition products with a high frequency of structural defects and often elevated ion exchange capacity in comparison with the original material /7-2/. The effect of this is higher sorption capacity in the solid phase and thereby a reduction of the mobility of e.g. radionuclides dissolved in the groundwater.

7.1.3 Relationship between rock composition, water chemistry and fracture mineralogy

Granitic bedrock consists of a relatively small number of major components, mainly quartz, feldspars (potassium feldspar, plagioclase), micas (biotite, muscovite) and amphiboles (hornblende). In addition, so-called accessory minerals are present in minor amounts. The main features of the reactions between substances in the water and solid minerals and the exchange with the atmosphere (O_2, CO_2), the biosphere (CO_2, organic substances) and saline waters are depicted in figure 7-1.

The bedrock will directly affect the groundwater composition through the release and liberation of ions that takes place in connection with weathering and alteration of various mineral phases. Important parameters that affect these processes are pH, temperature and contact time.

An indirect influence on groundwater composition is exerted by secondary processes such as ion exchange and precipitation in the water phase. These secondary processes are pH- and temperature-dependent, but are also affected by the total content of dissolved salts.

Despite the fact that the accessory minerals generally are present at low concentrations, they are important for the composition of the water phase, especially with regard to complexing anions such as phosphate and fluoride and the redox potential. Some accessory minerals with potential groundwater influence are given in table 7-1 /7-1, 7-2, 7-3, 7-4 and 7-5/.

Table 7-1. Examples of accessory minerals in granitic bedrock of importance for groundwater chemistry.

Mineral	Dependent aqueous chemistry parameter
Pyrite	Fe^{2+}, S^{2-}, Eh^a, SO_4^{2-}
Chlorite, magnetite	Fe^{2+}, Eh
Calcite, dolomite	Ca^{2+}, HCO_3^-, pH
Fluorite	F^-
Apatite	HPO_4^{2-}
Anhydrite	SO_4^{2-}
Clay mineral	Na^+, Ca^{2+}, Mg^{2+}, pH

a Eh = redox potential

7.2 GROUNDWATER CHEMISTRY IN GRANITIC BEDROCK

The most important system in many undisturbed groundwaters from the viewpoint of aqueous chemistry is the CO_2-H_2CO_3 system. This system directly or indirectly affects pH, the levels of HCO_3^- and Ca^{2+} and thereby also Na^+ (in water with low salt content), Mg^{2+}, F^- and HPO_4^{2-} /7-6/. Another important chemical system is Fe^{2+}-O_2, which is of importance for the water's redox properties /7-5/.

In connection with geological site investigations in Swedish crystalline bedrock, the composition of deep groundwaters has been studied in detail at nine different sites, table 7-2 /7-3 to 7-5 and 7-7 to 7-14/. The measurement program for the sites studied during 1982-83 in particular has included a large number of chemical parameters, see chapter 5. These water data, which reflect the influence of different granitic and granodioritic rocks on the groundwater chemistry, constitute the basis for discussions and conclusions concerning the concentration relationship of important dissolved components.

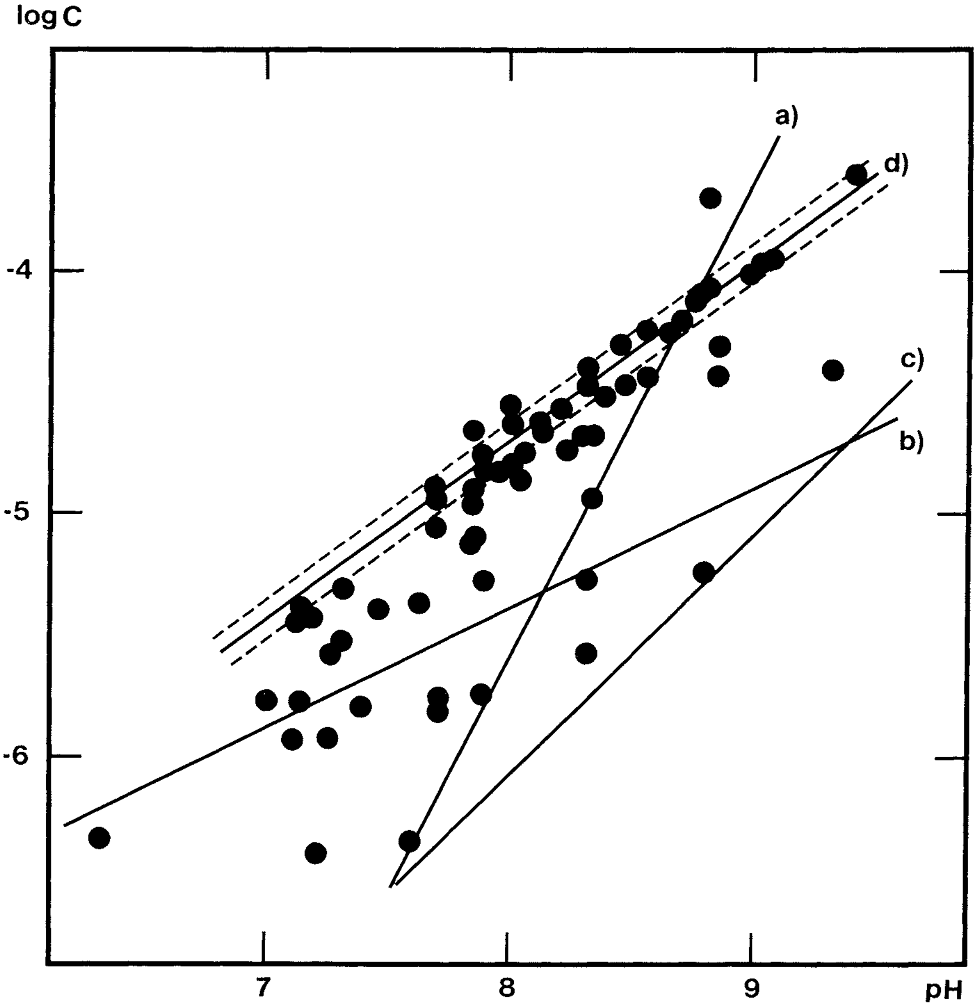


Figure 7-2. Interrelated values of the CO_3^{2-} *content and pH of deep groundwaters. The points indicate measured values; the lines indicate calculated theoretical relationships.*

a. Open system; equilibrium with atmospheric carbon dioxide

b. Closed system; equal concentrations of Ca^{2+} *and* HCO_3^-

c. Closed system; dissolution of $CaCO_3(s)$ *without other calcium or carbonate sources (corresponds to lowest expected carbonate concentrations)*

d. Closed system; saturation with respect to $CaCO_3(s)$*. Empirical relationship:* $\log [CO_3^{2-}] = 0.76\ pH - 10.83 \pm 0.08$

7.2.1 Carbonate content and acidity

Descending surface waters absorb carbon dioxide from the atmosphere and from the biological activity of the root zone. As a result, undisturbed groundwaters will almost always contain considerable amounts of carbonate, even in a bedrock without any carbonate minerals at all. Due to protolysis in the CO_2-H_2O system and due to the coupling to equilibria in the Ca^{2+} -CO_3^{2-} system, the concentrations of both Ca^{2+} and HCO_3, which is the dominant carbonate spe-

Table 7-2. Sampling sites for groundwater studies in rock of granitic and granodioritic composition.

Area	Number of sampled boreholes	Number of sampled sections	Sampling depth (m)
Stripa	> 5		> 1 200
Forsmark	6	12	55 458
Kråkemåla	2	5	103-510
Sternö	2	7	226-397
Finnsjön	7	30	103-688
Svartoberget	2	8	82-718
Gideå	2	10	91-596
Fjällveden	3	10	107-563
Kamlunge	2	3	106-555

cies, as well as pH will be directly related to each other /7-6/. A relatively stable pH in the interval 7-9 is obtained, which is illustrated by figure 7-2.

The total carbonate contents of the granitic groundwaters investigated lie between 30 and 400 mg/l. Most values fall within the range 90-275 mg/l.

7.2.2 Redox properties

The redox properties of the water - which have a significant influence on the dissolution of the uranium oxide matrix, canister corrosion processes and the chemical properties of the actinides in the groundwater system - are generally determined completely by the presence of oxygen in open systems (i.e. systems in contact with air). At equilibrium with atmospheric oxygen, the redox potential can be approximated as follows /7-15/:

$$Eh = 0.8 - 0.06pH \pm 0.1 \text{ (V)}$$

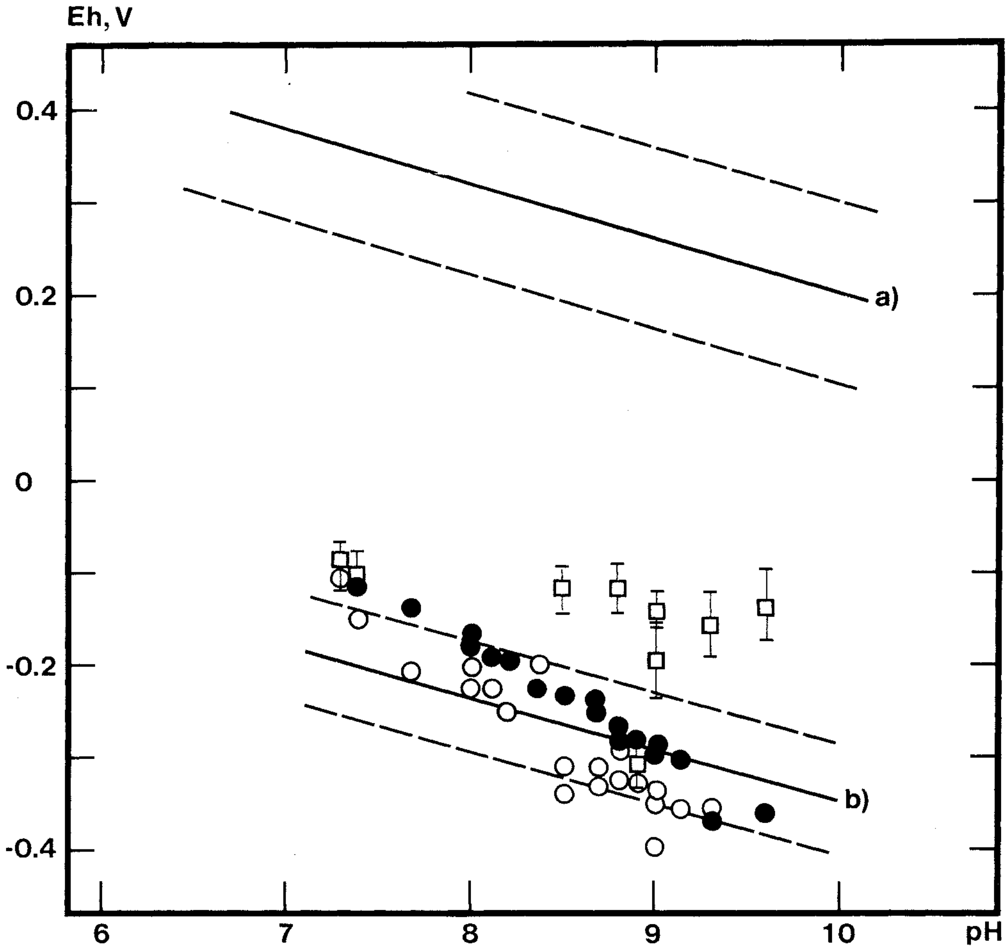


Figure 7-3. Measured and calculated Eh/pH values for deep groundwaters. o Eh(Fe), •Eh(CO_3), Eh (measured).

The following Eh/pH relationships are plotted:

a. Eh = 0.8 – 0.6 pH ±0.1 (contact with air)
b. Eh = 0.24 – 0.06 pH ±0.06 (Fe(II)/Fe(III) system)

In closed systems, the redox properties of the groundwater are determined by the presence of redox components in the rock or in the water phase. In crystalline granitic or granodioritic rock, it is the presense of Fe(II) and Fe(III) minerals that will determine the redox potential. The bedrock at the water sampling sites (see table 7-2) generally contains more than 1% iron, and most of this in bivalent form. A considerable portion of this iron is accessible for oxidation, as shown by redox experiments with oxygen-containing water in contact with rock /7-16/.

In cases where equilibrium exists with magnetite (Fe_3O_4) and hematite (Fe_2O_3), the redox potential of the water can be calculated as Eh = 0.21 - 0.06pH (V). In the KBS-2 report, a redox potential of Eh = 0.26 - 0.06pH ± 0.1 (V) has been used for a water system in contact with solid Fe(III)- and Fe(II)-minerals.

Measured and calculated Eh/pH data in deep groundwaters are given in figure 7-3. The calculated redox potentials are based on measured Fe(II)-concentrations and pH, under the assumption of equilibrium with an insoluble solid phase, namely goethite (FeOOH) or geothite and siderite ($FeCO_3$) /7-4, 7-5/. (Corresponding designations in figure 7-3 are Eh(Fe) and Eh(CO_3). If other solid Fe(III) phases are assumed, e.g. $Fe(OH)_3$, slightly higher calculated potentials are obtained /7-5/.

Equilibrium with siderite appears to be less probable than with goethite, since siderite has not been encountered as a fracture-filling mineral at the investigation sites. Agreement with the estimate Eh = 0.26 - 0.06pH (V) is relatively good. A better estimate may be Eh = 0.24 - 0.06pH ± 0.06 (V). The less probable Eh(CO_3) values have then also been taken into account /7-15/.

Direct measured values in the field do not as a rule agree with the values determined from measured Fe(II) concentrations. This reflect experimental difficulties in the field measurement of redox potentials. Good agreement has been obtained between measured and calculated potentials in laboratory tests, where contamination by air or oxygen-containing water can be avoided /7-5/.

A general conclusion is that reducing conditions exist generally in the undisturbed deep groundwaters, and that the redox potential is determined by the Fe(III)/Fe(II)-system. High or appreciable Fe(II) concentrations and sulphide concentrations reinforce these conclusions. Another confirmation of the fact that reducing conditions exist is provided by the low measured total uranium concentrations, which correspond to expected concentrations in systems in equilibrium with $UO_2(s)$ (see chapter 12).

7.2.3 Other inorganic dissolved components

A large portion of the groundwater's content of fluoride comes from the weathering of fluorite $CaF_2(s)$, which, due to its low solubility, limits the maximum fluoride concentration to levels that are dependent on the calcium concentration. A good correlation has been demonstrated between the presence of fluorite as a fracture mineral and high fluoride concentrations in the groundwater. As a rule, the fluoride concentration is less than 5 mg/l.

Another groundwater component that is also dependent on the calcium concentration is phosphate, with a maximum concentration limited by the solubity of apatite. As a rule, the total phosphate concentration is less than 0.2 mg/l.

Along with calcium, sodium is one of the dominant cationic components in the groundwater. Both sodium and calcium are liberated during the weathering of the relatively easily-weathered feldspars. Both also participate in ion exchange reactions, not seldom in identical positions, due to their similar ionic radii (0.99 Å for Ca^{2+}, 0.95 Å for Na^{+}). As a result, the Na^{+} and Ca^{2+} concentrations are often related to each other, as well as to some extent to pH. As a rule, the sodium and calcium concentrations do not exceed 100 and 40 mg/l, respectively, in non-saltine waters.

Both magnesium and potassium are liberated through weathering processes and participate in ion exchange equilibria, although not in direct exchange with sodium or calcium, due to their different ionic radii (0.65 Å for Mg^{2+} and 1.33 Å for K^{+}). Normally, the magnesium and potassium concentrations do not exceed 10 and 5 mg/l, respectively.

Chloride and sulphate (along with hydrogen carbonate) dominate among anionic species at both low and high total salt contents. Sulphate can be formed in connection with the oxidative weathering of sulphide minerals, dissolution of sulphate minerals, or enter the groundwater via the atmosphere. Normally, the chloride and sulphate concentrations are below 15 mg/l in non-saline waters.

Nitrate, ammonium and silicic acid, SiO_2, which are liberated in connection with the weathering and dissolution of feldspars, micas and quartz, should be mentioned among other inorganic components in granitic groundwaters. As a rule, the concentration of dissolved silicic acid is less than 14 mg/l.

7.2.4 Colloidal particles and organic complexing agents

Significant concentrations of colloidal particles have been found even in deep, undisturbed groundwaters. Iron hydroxide constitutes an insignificant fraction of these particulate components. The chances for certain clay minerals and silicic acid to exist in metastable colloidal form increase at low total salt concentrations /7-4/.

The content of organic matter is considerable, even in old and isolated groundwaters, as a rule in the range 1-5 mg/l, expressed as total organic carbon. Analyses of organic components have been carried out for some 10 or so different deep groundwaters /7-4, 7-17/. The organic fraction is dominated by relatively low-molecular-weight substances (molecular weight 700-1000), equivalent to about half of the organic matter. A comparable or slightly smaller fraction with a molecular weight over 1000 has also been isolated. Both of these fractions can probably be considered as fulvic acids and can be expected to have considerable metal complexing properties in certain pH ranges (see chapter 12). The fraction of low-molecular-weight, and probably non-complexing organic components is 10-20%. Humic acid contents are always low (0-6% of the total quantity of organic matter) in the deep groundwaters studied.

7.2.5 Saline waters

High salt concentrations, dominated by NaCl and sometimes $CaCl_2$, are relatively common in deep groundwaters. Sodium or calcium concentrations greater than 1000 mg/l have occasionally been measured in these saline waters, as compared to normal levels of 100 and 40 mg/l, respectively, in non-saline waters. Corresponding chloride concentrations of up to about 6000 mg/l have been noted, as compared to normal levels of less than 15 mg/l in non-saline waters. High sulphate concentrations have also been encountered in some waters (above 300 mg/l as compared to a normal level of less than 15 mg/l). These waters may originate from relict seawater. They may also come from fluid inclusions, which are microscopic bubbles filled with salt solution in otherwise homogeneous mineral bodies. The presence of high salt concentrations and sharp concentration limits against low-concentration waters indicates that the water exchange between nearby aquifers can be very slow /7-14, 7-18, 7-19/.

7.2.6 Potential complexing agents for radionuclides

The aqueous environment defines the chemical states of dissolved radionuclides and thereby indirectly their transport properties. Size and charge, sorption mechanisms, solubility etc. are affected by redox reactions and complex formation with anions in the groundwater.

Actinides and lanthanides form strong complexes with OH^-, CO_3^{2-}, F^- and PO_4^{3-} as well as with humic acids and high-molecular-weight fulvic acids. Many of these complexing agents can form low-solubility solid phases.

Strontium and radium form weak complexes with CO_3^{2-} and SO_4^{2-}, as well as low-solubility solid phases.

All of these complexing agents, except F^- and SO_4^{2-}, participate in protolysis systems and their concentrations are, like the redox potential, highly pH-dependent. Relevant chemical equilibria are discussed in detail in chapter 12.

7.2.7 Age data

The water's content of the radioactive isotopes tritium (half-life 12.3 years) and ^{14}C (half-life 5 730 years) provides information on how long the water has been isolated from the atmosphere and thereby shows indirectly whether there has been any intrusion of shallow groundwaters.

Tritium and ^{14}C concentrations have been measured at most of the water sampling sites. However, with the present state of knowledge, this information cannot be used to determine absolute ages or the degree of mixing between deep and shallow waters /7-20, 7-21, 7-22/.

7.3 MINERALOGY AND CHEMISTRY OF FRACTURE SYSTEMS IN GRANITIC BEDROCK

7.3.1 Composition of fracture minerals

Three main types of fracture-filling minerals can be distinguished, depending on their conditions of formation /7-1/:

- Weathering products from minerals in the bulk rock. Examples of such products are kaolinite and montmorillonite, which can be obtained from the decomposition of feldspars.

- Hydrothermal and metamorphic mineralizations. Epidote and prehnite are examples of this type of fracture-filling material, which were formed under conditions other than those prevailing now.

- Precipitation products from supersaturated aqueous solutions at normal temperatures. These products represent mineralization processes still in progress, heavily dependent on groundwater composition. Calcite and gypsum are examples of precipitation products.

Some of the fracture-filling products found in drilling cores from the studied sites are presented in table 7-3.

The most commonly occurring fracture mineral is calcite, which can be a fairly recent formation (Quarternary period). In some locations, the calcite is probably of postglacial origin, which makes it probable that mineralization through precipitation is still in progress.

Other dominant fracture-filling products are chlorite, prehnite, quartz and laumontite, which should be regarded as hydrothermal formations. In certain areas, kaolonite and smectite are also common.

Less common fracture minerals are generally pyrite, epidote, dolomite, wairakite, analcime and illite etc, as well as the primary weathering products kaolinite and montmorillonite (smectite).

Table 7-3. Identified fracture minerals in drilling cores from the investigated sites.

Mineral	Note
Chlorite	W, H, M
Kaolinite	W, H
Montmorillonite	W, H
Illite	W, H
Pyrite	M, H
Epidote	M, H
Prehnite	M, H
Laumontite	M, H
Stilbite	M, H
Analcime	M, H
Quartz	P, H
Calcite	P, H
Dolomite	P, H, M
Gypsum	P, (H)

W = weathering product

H = hydrothermal formation

M = in metamorphic formations

P = precipitation product

7.3.2 Isotope data

The distribution of stable isotopes (e.g. oxygen, ^{18}O-^{16}O, and carbon, ^{13}C-^{12}C) in the groundwater and in the fracture filling minerals can provide information concerning the origin of the water and the conditions of formation and relative age of the fracture-filling products /7-1, 7-19/.

The measured distributions of the stable oxygen and carbon isotopes in fracture-filling calcite from Finnsjön shows that three different groups of calcite with different origins can be distinguished.

One calcite type has been precipitated in an aqueous environment that differs significantly from present-day groundwaters.

Most samples from open fractures represent a calcite that has been precipitated under conditions prevailing now. In other words, most of the fracture-filling calcite in water-bearing fractures may have been precipitated in an environment very like the present-day one, which makes it probable that calcite precipitation is still in progress.

Other calcites, especially from closed fractures, probably have a hydrothermal origin and are in that case probably old formations (100 million years or older).

Studies of fluid inclusions in the calcite show that these inclusions were formed under temperature conditions that have varied between present-day conditions and 175°C /7-1/.

7.3.3 Occurrence of chemisorbing components and high-capacity minerals

Of special importance for the transport of the radionuclides along water-exposed fracture paths are the sorption properties of the fracture minerals (cf. chapter 12). Most silicate minerals among the fracture-filling products in table 7-3 have a higher cation exchange capacity than the underlying bulk rock, with the exception of prehnite and epidote, which have ion exchange characteristics similar to those of the feldspars, and quartz, which has a very low ion exchange capacity (less than 1 meq/kg) /7-22/. Generally, an average ion exchange capacity per unit area or weight that is greater than that of the unweathered mother rock is obtained. Pyrite and calcite both have poor ion exchange properties, but do not appear - at least in the case of calcite - to form impervious weathering or precipitation surface coatings that could prevent a water and radionuclide-exposure of underlying mineral fractions /7-23/. Fluorite can be mentioned as one of the potentially chemisorbing minerals (see chapter 12) /7-24/.

7.4 IMPACT OF EXTERNAL FACTORS

7.4.1 Impact of the repository

The transport of products from the repository as well as disturbances in the natural water flow and the creation of local temperature gradients can affect the chemical and mineralogical conditions in the vicinity of the repository. The extent of the propagation of the radiolysis front and associated redox changes, as well as pH effects resulting from the presence of a buffer zone with montmorillonite, are discussed in chapter 13.

The presence of concrete structures in the repository can lead to local pH effects at the contact surface between concrete and bentonite. The pore water in fresh concrete has a pH of 13-14. In an aqueous environment, a relatively rapid transport of water-soluble sodium and potassium hydroxide takes place out of the cement matrix, and the pH of the pore water eventually stabilizes around 12.6, corresponding to the dissolution of calcium hydroxide. As the cement continues to decompose the pH will remain above 10 /7-25/. Radionuclide reactions at a pH above 10 are discussed in chapter 12.

Altered saturation and precipitation conditions can be expected in the groundwater-fracture system, especially with respect to calcite, which exhibit a solubility decrease with rising temperature. Small temperature changes, for example of the order that can be caused by the construction of a repository in the rock, do not, however, lead to any fundamental changes in the chemical reactions behind the precipitation processes.

7.4.2 Climatic effects

The possibility of changes in the composition of surface groundwaters on a local or global scale as a result of climatic changes, acid precipitation, biological activity, seawater intrusion etc cannot be excluded in the time perspective that applies to a waste repository. However, the variations in water composition that can be observed now are already great. It appears improbable that future changes in groundwater chemistry will bring about chemical conditions that fall beyond the conditions associated with the maximum and minimum levels that can be observed at the present time, since the system has considerable inertia and a high buffering capacity.

Table 7-4. Probable composition of deep non-saline granitic groundwaters (concentrations in mg/l).

	Expected intervals[a]	Simulated groundwaters[b]
Conductivity, mS/m	22-30	
pH	7-9	8.2
Eh, V	0-(-0.45) >0.25[c]	
HCO_3^-	90-275	123
SO_4^{2-}	0.5-15	9.6
HPO_4^{2-}	0.01-0.2	
NO_3^-	0.01-0.5	
F^-	0.5-5	
Cl^-	4-15	70
HS^-	0-0.5	
Ca^{2+}	10-40	18
Mg^{2+}	1-10	4.3
Na^+	10-100	65
K^+	1-5	3.9
Fe^{2+}	0.02-5	
Fe(tot)	1-5	
Mn^{2+}	0.01-0.5	
Al^{3+}	0-0.02	
NH_4^+	0.05-0.2	
SiO_2(tot)	3-14	11
TOC[d]	1-8	

[a] Probable interval for the majority of <u>non-saline</u> waters. Values outside the interval can be encountered locally. The composition of saline waters is given in table 7-5.

b Artificial groundwater used as a reference system in sorption and solubility measurements etc.

c Aerated systems.

b Total organic carbon.

Table 7-5. Composition of deep saline groundwaters (concentrations in mg/l).

	Maximum concentrations		
	Finnsjön-Forsmark	Other sites[a]	Seawater
HCO_3^-	400	300	140
SO_4^{2-}	370	38[b]	2 710
F^-	5	7.5	1.4
Cl^-	6 300	330[c]	19 350
Ca^{2+}	2 100	85[d]	410
Mg^{2+}	210	18	1 290
Na^+	1 660	277	10 770
K^+	37	9	400
SiO_2(tot)	22	22	7

a See table 7-2

b 120 mg/l at one site in Karlshamn, 102 mg/l in Stripa

c 630 mg/l in Stripa

d 172 mg/l in Stripa

7.5 BACKGROUND DATA

7.5.1 Groundwater chemistry data

The composition of granitic groundwaters as well as observed variations in the various chemical parameters are presented in table 7-4.

Table 7-6. Mineral composition in granitic rock.

Mineral	Cation exchange capacity meq/kg[a]	Potential chemical importance
Essential minerals		
Quartz	>1	Colloidal[b]
Feldspars	3-10	Easily-weathered
Biotite	20	Easily weathered
Hornblende	3	
Augite	9	
Olivine	<1	
Accessory minerals and fracture-filling products		
Pyrite	2	Eh, pH, SO_4^{2-}
Magnetite	<1	Eh
Fluorite	<1	F^-
Apatite	<1	HPO_4^{2-}
Anhydrite, gypsum	<1	SO_4^{2-}
Calcite, dolomite	<1	HCO_3^-, pH
Other fracture-filling products		
Limonite	7	Colloidal
Gibbsite	3	Colloidal
Epidote	6	
Prehnite	1	
Chlorite	50	Ion exchange, colloidal, Eh
Kaolinite	30	Ion exchange, colloidal
Montmorillonite	900	Ion exchange, colloidal, pH
Laumontite	35	Ion exchange, colloidal
Stilbite	600	Ion exchange, colloidal, pH

a At pH 8.2. Large variations are observed, depending on the degree of weathering, purity etc. The stated values are examples of measured capacities for representative mineral fractions.

b Can form colloidal particle fractions.

A simulated groundwater (see column b) has usually been used for laboratory studies of sorption, diffusion, leaching etc.

Maximum concentrations in saline waters found at the sampling sites are given in table 7-5.

High salt concentrations have been found in Finnsjön and Forsmark, but only occasionally in other areas.

7.5.2 Fracture mineral data

The most important components in crystalline rocks (essential minerals, accessory minerals, fracture-filling products) and the properties of these components that are of interest from the viewpoint of groundwater chemistry are presented in table 7-6.

7.6 REFERENCE DATA

The following values have been assumed for the aqueous chemistry parameters that are of special importance for radionuclide sorption and migration (see also chapter 12):

Redox potential:

$Eh = 0.24 - 0.06pH \pm 0.06$ V (reducing systems)
$Eh = 0.8 - 0.06pH \pm 0.1$ V (oxidizing systems)

pH: 7 - 9

Carbonate content:

$\left[\log CO_3^{2-}\right] = 0.76pH - 10.83 \pm 0.08$ (closed system saturated with respect to calcite)

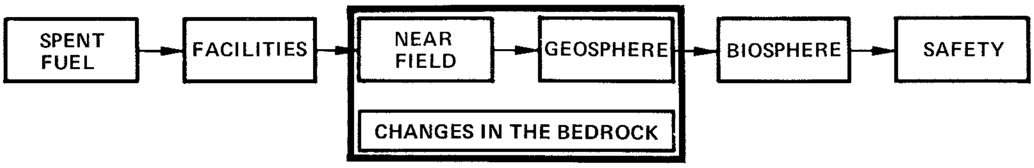
Organic components:

5 mg/l (contains 10% complexing humic and fulvic acids with a capacity of 6 meq/g)

Solid particles:

0.5 mg/l (silicate material, diameter 2 µm).

8 NATURAL CHANGES IN THE BEDROCK



This chapter deals with long-term changes in the bedrock. The impact of different natural processes on the bedrock in the past is analysed to permit an assessment of what changes these processes can bring about in the future over a span of one million years, particularly in view of the bedrock conditions at the investigated sites. The phenomena dealt with are orogenesis (mountain-building), land uplift, block movements and volcanism, earthquakes, displacements within bedrock blocks, mineralization and glaciation.

8.1 BACKGROUND AND OVERVIEW

The investigations at the selected sites provide a picture of present-day conditions in the bedrock. These conditions are the result of a long and complex evolution which is still going on. This chapter deals with different natural processes and phenomena that could conceivably alter the properties of the bedrock and thereby the conditions for the safety of a final repository.

First, a brief overview is given of the evolution of the Swedish bedrock to date and its chronology. This overview shows that the bedrock that has been investigated at the sites underwent the most important part of its evolution more than 650 million years ago. Its evolution since that time is characterized by relatively insignificant changes. However, episodes characterized by severe bedrock deformations and volcanism have also occurred during this latter phase, in sharp contrast to the very placid conditions of today.

Different events in this evolution are then dealt with individually. Their impact on the quality of the bedrock in general and on the investigated sites in particular is considered in relation to their duration, as well as to where, how and in what contexts they have occurred. This information, obtained from the site investigations, is then used as the basis for an evaluation of how similar processes, if they occur in the future, may affect the bedrock over a period of one million years. In comparison, it can be mentioned that the radioactive decay in the spent nuclear fuel will render its content of the most important fission products, strontium-90 and cesium 137, harmless within one thousand years, and its content of plutonium within half a million years, see chapter 3. It is important to understand that the approach used here does not actually define what will happen in the future. Any attempt here to account for the mechanics of the earth's crust and for plate tectonics, and to indicate the lines of evolution that appear probable against this background, would carry us far. This has not been done, although various possibilities suggested by such considerations are mentioned briefly in the presentation. Instead, an endeavour has been made to furnish an empirical basis for an evaluation of how the bedrock may change if different conceivable events should occur within a given time span.

8.2 BEDROCK EVOLUTION AND ITS CHRONOLOGHY

The bedrock generally contains small quantities of radioactive substances which decay at a mathematically defined rate. In many cases, this regular decay can be utilised to measure how much time has passed since a given rock or fracture-filling substance was formed or altered. As a result of extensive international research in this field, a well-established and reproducible time scale is now available for different phases in the evolution of the earth's crust.

Such measurements make it possible to determine the age of rocks and to place various bedrock events in a larger chronological and regional context. It is possible to see what happened at roughly the same time in different places and what occurred before and after a given event. This provides an overall picture of how long it takes for a process in the bedrock to start, reach its peak and decline. It is also found that the evolution of the earth's crust exhibits many similar features in different parts of the world.

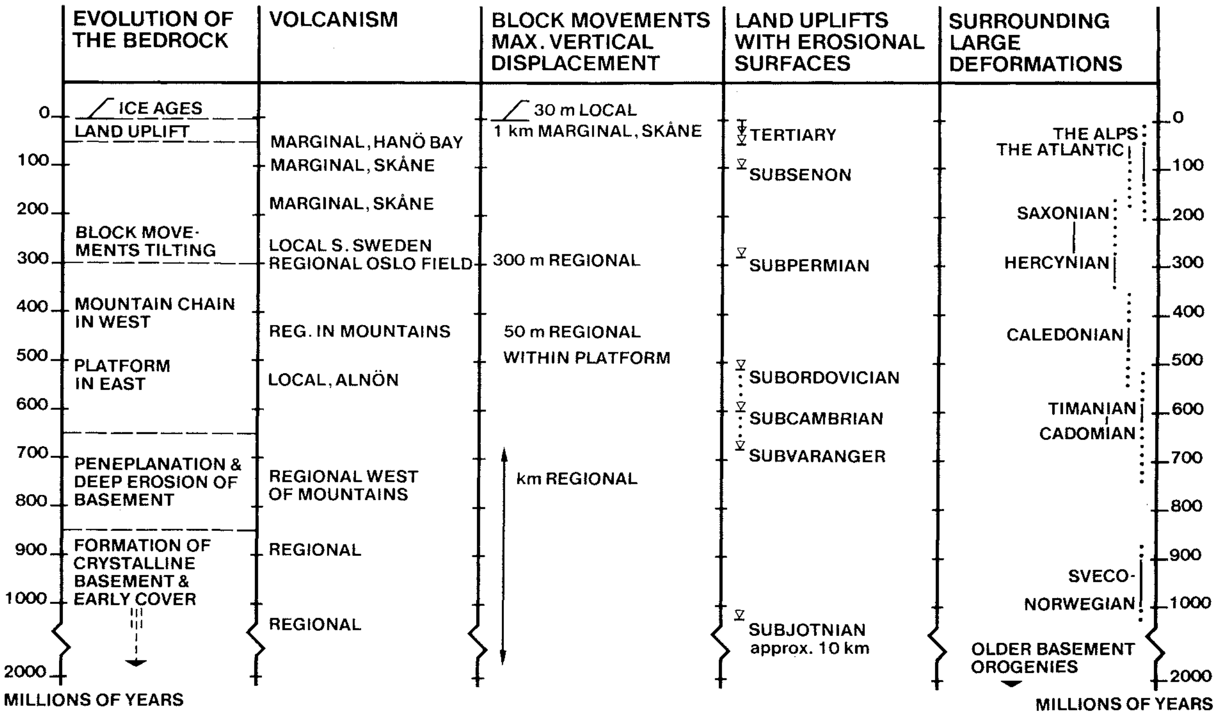


Figure 8-1. Time frames for the evolution of the bedrock as well as for volcanism, block movements, surfaces and surrounding large crustal deformations. The development of the surfaces between the Subvarangian and the Subordovician entailed only moderate changes in the level of the earth's crust. The regional extent of the Subpermian and Subsenonian surfaces is known only in parts of southern Fennoscandia. Of the Tertiary land uplifts, five occurred more than 23 million years ago, four between 23 and 6 million years ago and five between 6 and 3 million years ago /8-13/. The ice ages occurred during the last 3 million years and are marked in the time scale of the diagram only by the line on which "ICE AGES" is written.

Datings of samples from the Swedish bedrock carried out up to 1979 have been compiled /8-1/. These data, with some additions, give the following time frames for some important phases in the evolution of the bedrock, see figure 8-1.

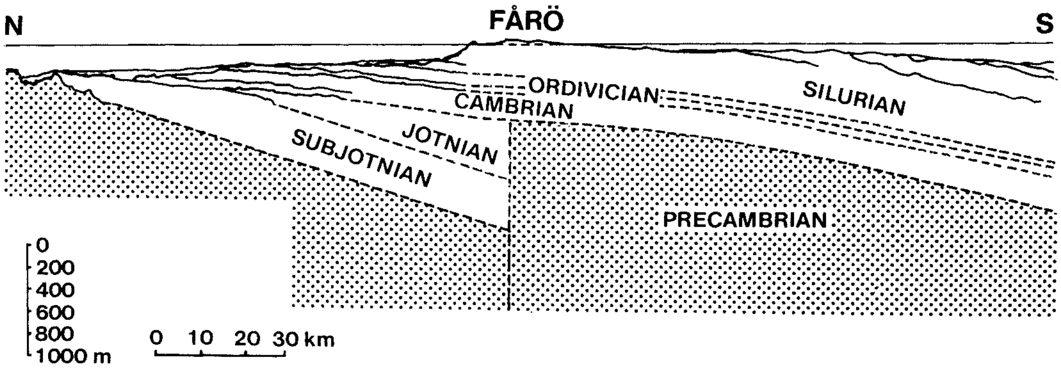


Figure 8-2. Vertical section through the bedrock along a north-south line in the Baltic Sea around the island of Fårö, according to Flodén /8-4/. The figure shows that the Cambrian and younger deposits in the south rest on an even surface of the basement. Subjotnian and Jotnian rocks, which previously covered the basement had already been subjected to tilting and subsidence by large block movements in the northern part of the profile, and been eroded away in the southern part, before deposition of the Cambrian.

8.2.1 Formation of the crystalline basement, approx. 2000 to 850 million years

Most of the Swedish bedrock east of the Scandinavian mountains consists of more or less deformed, fractured and distinctly crystalline rocks. Towards the east - starting in eastern Småland, and continuing over Öland, Gotland, the Baltic and all the way to the Ural Mountains - corresponding crystalline rocks are overlain by a widespread, continuous cover of nearly horizontal stratified rocks. The crystalline bedrock in Sweden thus forms an older basement on which the stratified and for the most part undeformed cover rocks have later been deposited.

Radiometric measurements of the oldest Swedish rocks generally give ages of up to around 2000 million years, although a few even higher ages have been measured. The Bohus granite on the West Coast represents the youngest formations of the crystalline basement and has an age of around 900 million years. During the intervening period of more than 1000 million years, the bedrock was affected in many ways, including mountain-building, block movements, land uplift and volcanic activity. (Block movements occur when adjacent portions of the bedrock are displaced in relation to each other as rigid blocks.) Already at this time, extensive deposition of sand and other decomposition products was taking place in certain regions.

8.2.2 Denudation of the basement,850-650 million years ago

After the formation of the Bohus granite, a new period of general denudation of the bedrock took place. Sand and other decomposition products were carried away from more high-lying parts of the bedrock, and deposited in depressions, partially created in connection with block movements in the bedrock. These sediments are now found in the Vättern depression (the Visingö series, 710 million years old) /8-2/, and in the Scandinavian mountain range and its eastern margin (the sparagmite series). Moraine-like formations from this time have been encountered here at several places.

Volcanic rocks connected with these block movements have only been found in a part of the Scandinavian mountain chain that corresponds to a location far west of the Swedish basement (the Ottfjäll diabases, 740 million years) /8-3/.

8.2.3 Stable bedrock conditions in the east, orogenesis in the west, 650-300 million years ago

In the southern part of the Baltic Sea depression, the basement and the earliest block-displaced sandstone deposits are covered by a kilometre-thick series of nearly horizontal sedimentary rocks, lying on a very level basal surface /8-4/, see figure 8-2. This shows that the elevation differences that were formed in connection with the preceding block movements had been levelled-out before sedimentation took place. On the mainland, remnants of the lower parts of the series are preserved in limited areas and in a more continuous belt along the eastern margin of the Scandinavian mountain range. Here, from southeastern Norway up to the Varanger Fjord, remains of lithified moraine deposits (tillites) are found locally near the bottom of the series, providing evidence of an early, very widespread ice age. It has been dated at 670 million years /8-5/.

Further towards the west, in the Scandinavian mountain chain, much thicker deposits from the same time are found incorporated in a complex of major folds and nappes. It was formed under very strong bedrock movements and deformations, which have been divided into at least nine different phases, dated to between 540 and 410 million years /8-6/. Some of these phases were accompanied by extensive volcanism.

Almost nothing of these movements is seen in the Precambrian shield and the Baltic Sea depression. An isolated occurrence of a volcano's root zone (550 million years) is found at Alnön /8-7/, and small, rare faults have been found in the sedimentary beds from the time of the formation of the mountain chain /8-4/. Otherwise, the stratified rocks that were deposited while the orogeny was occurring in the west are virtually undisturbed. Moreover, they are overlain by later beds without any obvious angular unconformity. This shows that the entire crust, i.e. both the basement and the stratified rock cover on top of it, were not subjected to any significant faulting or even any detectable tilting, despite the fact that intensive bedrock movements took place in what is now the Scandinavian mountain chain. Ever since the consolidation of the mountain chain about 400 million years ago, it forms - together with the basement rocks of Sweden and Finland and the sediment-covered areas up to the Ural mountains, an integrated unit of the earth's crust, called the North European platform.

8.2.4 Tilting, block movements, scattered and marginal volcanism, 300-50 million years

The sedimentary rocks that were deposited around 300 million years ago and that are still preserved in the Baltic Sea depression clearly break with the previous pattern. Their basal beds rest unconformably upon the older deposits, reaching progressively older strata towards the west. On land, in southern Småland, remains of an erosion surface /8-8/, which probably corresponds to the same interface have even been found on the basement itself. These conditions show that the crust of the earth in the entire area was subjected at this time to a tilting so that the western parts were raised and eroded.

At approximately the same time as this tilting was taking place, a swarm of important basaltic dykes were formed in northern Skåne, and a large rift zone formed in the Oslo district with very extensive volcanism. Dykes associated with this volcanic activity are found far south along the Swedish West Coast /8-9/. Volcanic rocks of a similar age (around 280 million years) are also found south of Lake Vänern and at Särna. Smaller block movements probably occurred at many other places in the crystalline basement at the same time. These include, for example, down-faulted blocks overlain by alum shales and limestones, which are found in Östergötland and Närke. Here, vertical displacements of up to 300 m have been observed.

Renewed crustal movements are marked by later discordant erosion surfaces in Skåne and the southern Baltic Sea, and by volcanism in Skåne (170 and 110 million years ago). Signs of even more recent volcanism have been found in the Hanö Bay /8-10/. Large block movements took place in Skåne and Bornholm less than 65 million years ago. In comparison, it can be mentioned that volcanic formations that formed 55 million years ago have been found off the Norwegian coast. In this context, northern Skåne and the Norwegian coast mark the western border of the North European platform. Bedrock movements as well as volcanism during the past 170 million years therefore seem to be primarily associated with this border zone. Volcanic formations from the past 250 million years have not, on the other hand, been identified with certainty within the Swedish part of the Precambrian shield.

8.2.5 Regional land uplift, 50-3 million years ago

An extensive analysis of the landforms in the inland of Västerbotten County shows that a series of at least 13 distinct pulses of land uplift occurred here before the onset of glacial erosion. The total uplift is around 1 250 m /8-11/. Between these uplifts, prolonged intervals of relative stability prevailed, during which extensive and almost level erosional surfaces were formed, which are largely independent of rock boundaries and fracture zones in the bedrock. They form a flight of piedmont surfaces from the high mountains down to the coast. Their insignificant slopes and wide extent show that only small block movements and negligible tilting can have occurred since the origin of these surfaces. A weak tilt is, however, noted in a border zone against the flat lowland of the coast, indicating more local bedrock movements in this particular zone. It can be followed all the way to the area north and west of Lake Vänern /8-8/. However, the movements within this zone appear to be too small to account for the total uplift. This would indicate that areas east and southeast of the border zone have also been uplifted, although to a lesser extent. Comparable but smaller movements have been reported from the southern Swedish highland /8-12/. It is even possible that similar uplifts have affected all of Fennoscandia. In deep boreholes at sea off Trondheim, 14 separate sand layers have been encountered within a more than 1000 m thick series of clayey sediments. They were deposited after the volcanics that formed 55 million years ago, but before the Quaternary glaciations /8-13/. The individual sand layers probably represent coarser clastics from the mainland indicating separate pulses of uplift.

8.2.6 Glaciations, 3 million years to present

Investigations of oceanic sediments show that continental ice sheets began to form in the Antartic 14 million years ago and in the Arctic 3 million years ago. Between 4 and 11 glaciations have been distinguished at different places in the marginal areas of the European ice caps, and isotope studies of climatic variations show an even greater number of cool periods. Warmer intervals occurred between the cold periods, often lasting only 10 000 years or so. Each glaciation lasted much longer, 100 000 years or more.

The thickness of the most recent ice sheet in Sweden is estimated to have been between two and three kilometres. The ice was thinnest at the margins and over the Scandinavian mountains, where the highest peaks appear to have projected through the ice for long periods of time. The weight of the ice sheet depressed the crust of the earth approximately 1 kilometre where the load was greatest. As the ice sheet melted, a gradual unloading occurred. It was interrupted repeatedly during cooler periods, when the ice front advanced several kilometres. In this manner, the front of the ice could pass over the same place several times. Similar oscillations may also have occurred when the ice sheet was built up. The movements of the

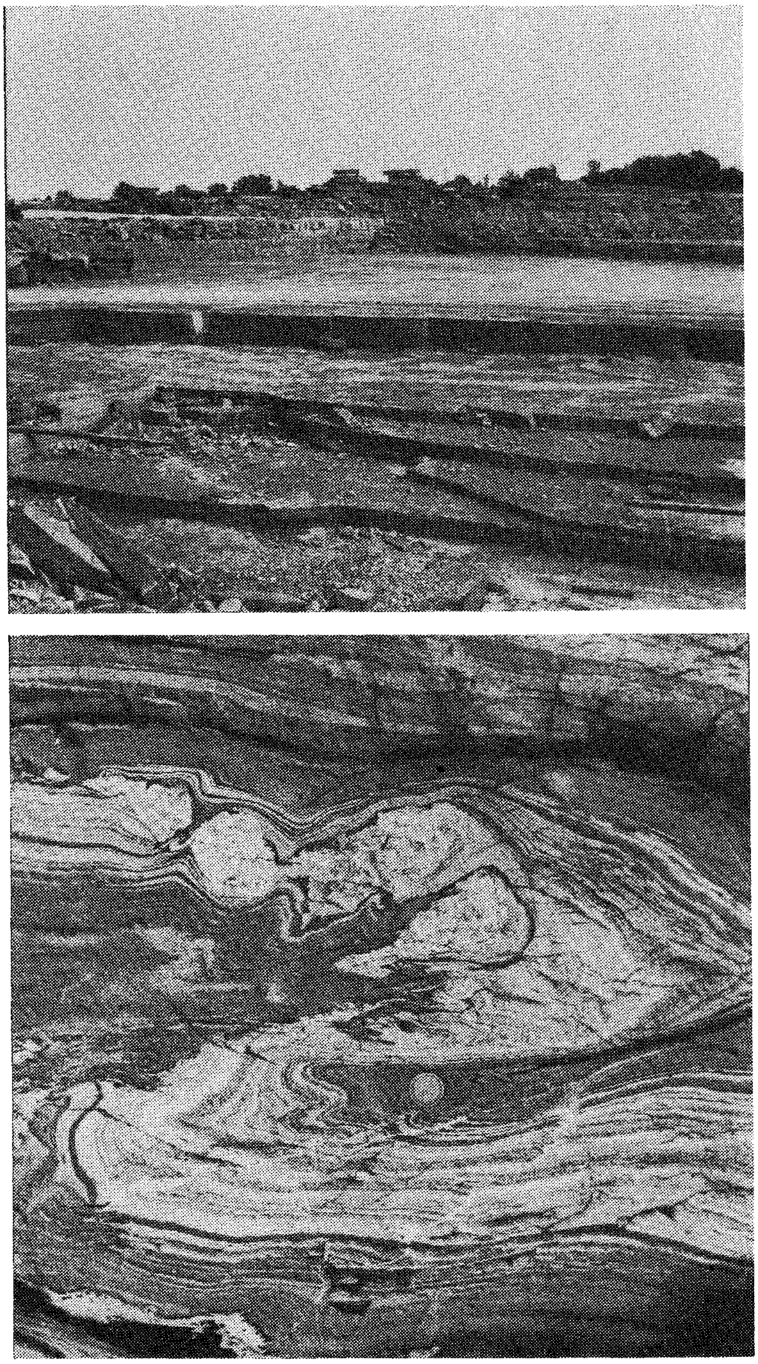


Figure 8-3. The lower picture illustrates the heavy deformation of originally horizontal strata in the crystalline basement, while the upper picture represents the nearly undisturbed plane stratification in the cover rocks (approx. 500 million year old limestone on Öland).
Photo: P H Lundegårdh.

earth's crust during the glaciations have therefore primarily consisted of repeated depressions of long duration, interrupted by shorter periods of rebound when the ice melted. Smaller fluctuations have occurred within these larger undulations.

The glaciations covered large parts of northern Europe. The most recent glaciation seems to have been of considerably smaller extent than the immediately preceding one, however. The ice-cap left the area of Stockholm about 10 000 years ago. The subsequent rebound is still going on. This land uplift affects the entire Nordic region, see figure 8-4.

In addition, local block movements associated with the deglaciation have been detected in certain areas, especially in upper Norbotten County and adjoining parts of Finland. Present-day bedrock movements are marked by earthquakes.

8.2.7 Summary

Altogether, the time span that can be surveyed in this manner with regard to the evolution of the Swedish bedrock encompasses approximately 2000 million years. The crystalline basement acquired its main features and underwent its essential changes during the first three quarters of this time. It was then it acquired its structural features, it was then its rocks, originally formed at great depth, were lifted up to their present near-surface position. It was also then, more than half a billion years ago, that most of the large fracture zones in the bedrock were formed. Comparatively small changes have occurred in the basement rocks during the past 650 million years, which have essentially been a period of platform conditions and of only minor deformation. This is evident from the difference between the highly disturbed structures of the basement rocks and the undeformed attitude of the stratified cover rock, see figures 8-2 and 8-3. The background of this difference, and its importance for assessing the implications that various future events may have for a rock repository, are dealt with in the following sections.

8.3 OROGENESIS

During its evolution, the Swedish bedrock has been subjected to various kinds of change. The most profound changes are associated with long periods of orogenesis - i.e. mountain building. As a rule, the structures in the crystalline basement rocks deviate strongly from the horizontal. Folds, tears and other deformation structures can be seen on different scales, from millimetre to kilometre, see e g /8-14/. Such conditions are typical for the structures of the earth's mountain chains. Mountain building also affects the internal structure of the rock mass, its texture, grain structure and grain contacts, and thereby determines its tendency to fracture in certain directions. In this manner, the rock mass as a whole is affected by orogenesis, even though the degree of influence varies both regionally and locally.

The orogenies of the basement have all affected the bedrock structures in their respective areas and given rise to regionally extensive gneiss and granite terrains. An example is the latest orogeny in the Swedish Precambrian, the Sveconorwegian, which involved the southwestern part of Sweden and adjacent parts of Norway. An early granite in this area, the Hästefjord granite, has been dated at 1 250 million years, and the most recent, the Bohus granite, at 900 million years. Together, they define a time span of 350 million years.

The next orogeny in Scandinavia occurred west of the Sveconorwegian and gave rise to the bedrock structures in the present-day Scandinavian mountain chain. It was, as mentioned above, formed in several phases with ages between 540 and 400 million years. However, it was preceded by extensive deposition of sediments derived from the crystalline basement. This deposition was associated with subsidence of the earth's crust and with fracture volcanism far to the west (the Ottfjäll diabases, 740 million years). In the northeast, on the Fiskar penninsula and in Timan, it is also possible to distinguish orogenic phases around 630 and 520 million years ago that may be independent of, or forerunners to, the Scandinavian orogeny. Altogether, this complex orgenic evolution marks crustal movements with some interruptions during a period of 350 million years.

No further orogenesis has taken place in Fennoscandia or within the North European platform during the past 400 million years. South of this, however, a new orogeny, the Hercynian, began in Europe north of the Alps and on the Iberian penninsula around 350 million years ago. It reached its peak between 330 and 280 million years ago. It corresponds to block movements with regional volcanism taking place at about the same time in the Oslo field and northern Skåne, and even outside these areas on a more local scale.

The latest orogeny in Europe is represented by the Alps and associated mountain chains in the Mediterranean area. Their formation started around 200 million years ago and culminated between 120 and 50 million years ago. Since then, affiliated block movements and volcanism have continued north of the Alps with generally decreasing intensity up to the present time. The most peripheral manifestations of this activity are represented by large fault movements through Bornholm, Skåne and the Hanö Bay. North of this zone of movement, no similar large bedrock movements of the same age have been found in Sweden.

It can thus be shown that each orogeny is a long-lasting process that takes more than 100 million years to reach full development and completion. It is also evident that the Swedish basement has not undergone orogenesis during the past 900 million years and has only been insignificantly affected by more recent orogenies in the surrounding regions. Furthermore, an evolutionary trend may be noted which indicates that new orogenies occur outside the preceding ones and thus farther and farther away from the North European platform. The two most recent orogenies have been accompanied by large block movements, respectively, in the Oslo field and the Rhine rift and its continuation towards the south. Here again, the Rhine rift, which is chronologically associated with the Alps, is found farther away from the platform than the Oslo field, which belongs to the earlier, Hercynian orgeny.

A similar tendency is also noted in other parts of the world. Platform areas with nearly undisturbed overlying cover-rocks resting on a basement of granites and heavily deformed gneisses are a recurrent feature in the structure of the continents. Mountain chains constitute zones of deformation surrounding or between such platform areas, and younger mountain chains are located outside those formed in a preceding period. Moreover, a study of the individual mountain chains shows that all have originated in marine areas outside of or between continental platforms. (Even the peak of Mount Everest consists of former marine deposits!) Many scientists are therefore of the opinion, supported by direct observation, that a new orogeny has already begun in the Mediterranean region. The notion that a new mountain chain may start to form along the west coast of Scandinavia due to a compression in the North Atlantic has also been expressed.

In view of the fact that each previous orogeny has required on the order of 100 million years for their full development, and that their integrated effects over the latest 650 million years on the bedrock at our sites has been rather insignificant, it is clear that new orogenies cannot be expected to alter present-day conditions in the Swedish basement rocks appreciably within a time span of one million years. An orogeny in the Mediteranean region, for example, may be compared to the formation of the Alps, although it would take place at greater distance. The formation of the Alps took a total of about 200 million years and included at least three major culminations. Despite this, its effect on the basement rocks in the interior of Fennoscandia can only be observed locally and on a very limited scale. It can therefore be concluded that the effect on the Swedish basement rocks of a similar development in the Mediteranean area over a period of one million years could not reasonably be of a comparable magnitude.

With regard to an orogeny along the Atlantic coast of Scandinavia, it should first be pointed out that North America and Eurasia are still moving away from each other and that a reversal in the direction of movement of these land masses, which would lead to a compression in the North Atlantic, must take considerable time. It is therefore unlikely that it will happen at all within one million years. If it did, its effect on the crystalline basement of Sweden could be compared with the effect of the formation of the Scandinavian mountain chain. The effect of such a compression during one million years could only be a negligible fraction of this.

The possibility of a new orogeny occurring in the North European platform region during the next one million years can be regarded as non-existent. Hence, the conclusion of this discussion is that ongoing and future orogenies will not, despite the crucial importance of the process during the period of formation of the crystalline basement, affect the safety of a repository in the Swedish bedrock.

8.4 LAND UPLIFT

The rocks and minerals in the crystalline basement show that the greatest rock deformation and the main crystallization of minerals took place at a depth of around 10 km and at a temperature of around 700°C /8-14/. When these rocks are now encountered at the surface, this therefore indicates a total uplift of around 10 km and a cooling of nearly 700°C. The oldest rocks covering the crystalline basement, the Jotnian sandstones, contain volcanic units that are 1 250 million years old. This shows that the uplift to the level of the erosional surface upon which the sandstones were deposited, the Subjotnian surface, had already taken place before this time. Other observations /8-15/ show that the uplift within certain parts of Fennoscandia was almost completed more than 1 600 million years ago.

After this early large uplift, which in itself took place in several different stages, a number of depressions and uplifts of the bedrock have taken place. In connection with the deposition of the Jotnian sandstones, the earth's crust was loaded in proportion to their thickness, which in some areas may amount to some kilometres. A new uplift, which led to decomposition and removal of the Jotnian sediments and the more recent Visingö series from large areas, ended around 650 million years ago. The land surface from this time, which was very flat and level is preserved at many places in today's landscape and has been given a special name, the Subcambrian peneplain.

Subsidences and uplifts have occurred since this time as well, but their amplitude never seems to have exceeded 1.5 km. These movements have not been accompanied by any regional and significant heating or cooling.

The current uplift of Fennoscandia deserves particular mention. Its rate in Sweden has been measured by the National Land Survey Administration of Sweden on the basis of nationwide precision levellings. These data have also been combined with corresponding data from neighbouring countries /8-16/, see figure 8-4. Geological studies show that the uplift rate was greatest shortly after the retreat of the ice and has declined since then. The maximum total cumulative

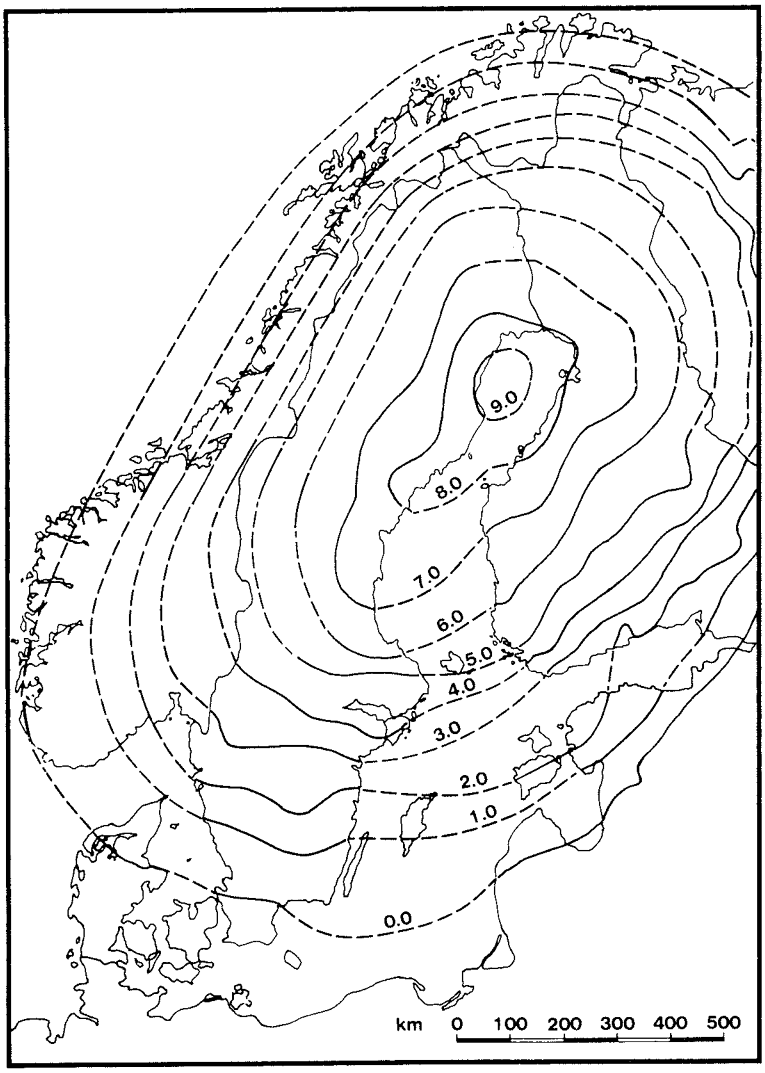


Figure 8-4. Observed rate of land uplift rate in Fennoscandia, millimetres per year, according to the National Land Survey Administration /8-16/.

land uplift since the deglaciation is estimated at about 850 m. It occurred just off the coast of Ångermanland /8-17/. The remaining future uplift can be estimated on the basis of the change of the rate of uplift with time and from the gravitational field over Fennoscandia. Both methods give values of between 20 m and 200 m /8-18, 8-19, 8-20/. This agrees well with the fact that the submarine bed of the Lule River from the time before the most recent glaciation can be observed down to a depth of about 100 m in the Gulf of Bothnia /8-21/, which shows that approximately 100 m remain before the rebound has been completed.

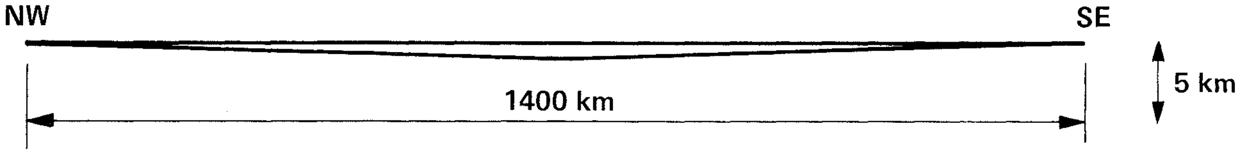


Figure 8-5. Maximal depression of the earth's crust in Fennoscandia during the most recent glaciation, according to data from N A Mörner /8-17/. The depression is magnified 20 times in relation to the length scale in order to render it visible.

The figures cited indicate that the remaining rebound corresponds only to about one tenth of the original total depression of the crust of the earth. Even this maximum depression during the most recent glaciation entailed extremely little deformation. According to recent studies /8-17/, the deformation was limited for the most part to a weak flexure in an area situated just off the Ångermanland coast and in a narrow zone from this area towards the NNE and SSW. Surrounding regions of Fennoscandia were only subjected to a very small tilt without appreciable deformation. The maximum tilt did not exceed 0.1 degree. Weaker flexures also occurred in the marginal zones of the area depressed by the ice. A vertical profile showing the maximum depression is given in figure 8-5.

The effects of a land uplift upon the bedrock have been analyzed /8-22/. The authors distinguish three different aspects:

- When the upper part of the bedrock is removed or an ice sheet retreats, an unloading occurs. This results in an elastic expansion of the underlying bedrock.
- The uplift involves a displacement radially away from the centre of the earth, which provides room for an expansion.
- The uplift moves the bedrock towards lower temperatures in the geothermal field. Cooling leads to thermal contraction.

The calculations show that the two latter aspects dominate so that the thermal contraction and the radial displacement provide more space than is consumed by the elastic expansion. This may lead to fracturing.

It is therefore clearly necessary to differentiate between effective land uplifts, which actually bring the bedrock to a higher level, and restoring uplifts, which merely return the crust of the earth to a previous position. The latter can take place, for example, when sedimentary rocks that were originally deposited on an erosional surface are once again eroded away or when an ice sheet melts, both of which would restore the crust to the higher level it had before loading. This may naturally activate the fractures that were formed when the crust of the earth first assumed the higher position, but the conditions required for a new extensive fracturing are not created by this kind of restoring uplift.

Against this background, the uplifts in Sweden can be grouped in the following manner:

- The uplifts during the period of formation and denudation of the basement more than 650 million years ago. Aggregate uplift amounts to approximately 10 km, and the temperature fall to about $700^{o}C$.

- A series of later land uplifts which have also given rise to new erosional surfaces on the basement approximately 300 and 110 million years ago and in several stages during a period that preceded the glaciations but may have started less than 55 million years ago. The total uplift is difficult to estimate but probably does not exceed two or three kilometres. The decreases in temperature were insignificant. The uplifts from around 110 million years ago and later (Cretaceous and Tertiary) are connected with the formation of the Alps and the North Atlantic.

- A number of restoring uplifts which did not lead to any true new uplift or cooling. Of these, those that occurred during the retreat of the ice sheets lie closest in time, and the most recent is still in progress.

For natural reasons, the present-day land uplift has attracted great attention. In terms of geometry, rock mechanics and geodynamics, however, it is a restoring uplift. It can clearly only have had an insignificant effect on the bedrock, in particular inasmuch as the bedrock has already undergone similar movements repeatedly in connection with previous glaciations. The insignificant role of the present-day land uplift for the quality of the bedrock is confirmed by a comparison between the different investigated sites. The site at Sternö is characterized by insignificant uplift, while Gideå is located close to the absolute maximum of the Fennoscandian uplift and Kamlunge is located near the area for the most rapid present-day uplift. These differences in uplift are not at all reflected in the quality of the bedrock at the sites.

Instead, it is clear from the magnitude of the uplift and the temperature changes that the aggregate land uplift more than 650 million years ago is the one that has had the dominant influence on the bedrock. For the same reasons, more recent effective land uplifts can only have contributed insignificantly to the fracturing in the bedrock. The new erosional surfaces that were formed in connection with these uplifts generally correspond to a further removal of the Precambrian rock of a few hundred metres. Today's land surface is still located fairly near the Subjotnian surface. In large areas of western Dalarna and the Baltic Sea depression, where the uppermost bedrock consists of Jotnian sandstone, the bedrock has still not reached the elevation it had at the time of the formation of the Subjotnian land surface, despite all later uplifts. In areas of the Precambrian shield rock where the Subcambrian peneplain is preserved, the past 600 million years have only witnessed the deposition and subsequent removal of an approximately 1 km thick series of overlying rocks. All of this shows that both the uplift and the depressions have been small and erosion very limited, on the average less than 3 m per million years. Taken together, this shows that the Fennoscandian Precambrian shield has been near a state of equilibrium in terms of elevation for about 650 million years.

The large composite uplift leading finally to the formation of the Subcambrian peneplain corresponds to the ultimate planation of the Precambrian mountain chains. However, the small uplifts during the past 650 million years represent disturbances in the state of equilibrium of the crust that occur simultaneously with orogenies and associated crustal movements in surrounding regions and the North Atlantic. This association with the orogenies and their time frames leads to the conclusion that this type of uplift will not appreciably alter the conditions for the safety of a repository in Swedish basement rocks either. As far as a new uplift following a future glaciation and its depression of the crust are concerned, this would only entail insignificant deformation and, in essence, one more repetition of crustal movements that have already been repeated several times in connection with preceding glaciations. Zones of earlier movement in the bedrock would be activated once again, but no great change in the properties of the bedrock can be expected.

8.5 BLOCK MOVEMENTS AND VOLCANISM

A characteristic feature of the basement is that it is intersected by numerous fracture zones in different directions. In many places, the largest zones appear as distinct, rather narrow but long and almost straight valleys. In a classic study of these conditions in Östergötland /8-23/, it was shown that the fracture valleys in the region run in four distinct directions: northeast, east-west, southeast and southsoutheast to south. Fracture-filling volcanic rocks, diabases, also run in these same directions. This shows that the fractures in some cases went so deep that they reached down to molten rock material, which was able to intrude and solidify in the fractures. In other words, there is a close relationship between the regional fracturing and volcanic activity, where the diabases still give evidence of how intensive and deep the fracture formation has been. The same relationships are also found in present-day volcanic areas on earth, which are similarly characterized by large and recurrent earthquakes and other signs of intensive fracture movements in the bedrock.

Diabases and closely-related volcanic rocks occur widely in the Precambrian shield at least from western Blekinge and up to northern Västerbotten. Datings indicate at least four separate periods of volcanism of this type with ages of around 1 550, 1 250, 1 150 and 880 million years.

The activity 1 250 million years ago is of particular interest. Its extent alone makes it one of the most remarkable of its kind in Europe. In addition, it can be shown that it is closely related regionally and chronologically to the deposition of the Jotnian sandstones on a platform area east of the Sveconorwegian orogeny, roughly concurrent with the formation of the Hästefjord granite /8-24/.

In a similar manner, the diabases that were formed around 880 million years ago are contemporary with the Bohus granite in the west. It is therefore plausible to assume that they are related to the large block movements that depressed the preserved areas with Jotnian sandstone, mainly within the Baltic Sea area and the Gulf of Bothnia, through vertical movements of some kilometres. More recent block movements of a similar type and magnitude, around 700 million years ago, are marked by the preservation of the Visingö series in the Lake Vättern rift /8-25/.

No such large and extensive block movements developed on a similar regional scale from later times are found in the Precambrian shield, apart from its margins, and the same applies to the related volcanism. On the contrary, it is found that the large vertical differences that arose during earlier block movements had been completely obliterated at the time of the Subcambrian peneplain /8-4, 8-25/ around 650 million years ago, see figure 8-2. Since that time, both block movements and manifestations of volcanism have been relatively limited in extent, few in number and only of local importance. The following episodes can be distinguished:

- Alkali-volcanic activity at Alnön, near Sundsvall, around 550 million years ago. Related block movements are marked by variations in the thickness of Cambrian sandstones off the coast /8-4/. Vertical movements amounted at the most to a hundred metres or so.

- Smaller block movements, with vertical displacements on the order of ten metres, and activation of older block boundaries, at the time of the formation of the Scandinavian mountain chain /8-4/.

- Large block movements and extensive volcanism in the Oslo field and northern Skåne around 280 million years ago. Outside of these belts, block movements with vertical displacements of a few hundred metres occurred locally and volcanic activity is known from south of Lake Vänern and at Särna.

- Volcanism and block movements in Skåne 170 and 110 million years ago. Smaller block movements locally within the Swedish Precambrian shield area.

- Block movements in Skåne and signs of volcanism in the Hanö Bay /8-10/, probably culminating around 55 million years ago in connection with volcanism of this age off the Norwegian coast. Probably repeated movements in connection with the uplift of the Scandinavian mountain chain and the Norrland terrain.

- Local block movements of up to 30 metres vertically in connection with the Quarternary glaciations.

Of these, the Alnö activity is an isolated and local phenomenon, while the volcanic formations and block movements 280 million years ago, despite their clearly local character, show a widespread activity in the Precambrian shield in connection with the Hercynian orogeny in Europe. More recent episodes mainly involve the margins of the North European platform. It is difficult to find their counterparts within the Precambrian shield and whether any real volcanic activity occurred at all here during the past 250 million years is a matter of dispute.

Special interest has been devoted in recent years to the block movements that have occurred since the most recent glaciation, postglacially. General orientation studies covering most of the country /8-26, 8-27/ indicate that such recent movements are most frequently found in upper Norrland and northern Finland. More detailed local studies have been conducted in Norrland, Västergötland and Blekinge. Continued studies will probably reveal similar movements elsewhere.

The studies in western Blekinge /8-28/ concern an area only 8 km from KBS's previous drillings on the Sternö penninsula. There, evidence has been found of a displacement in the bedrock that occurred about 10 900 years ago, approximately 1 500 years after the retreat of the ice sheet from the area. The movement raised the terrain east of the Mörrumså River valley more than 5 m in relation to the terrain west of the valley. The fault zone is assumed to lie in the valley itself and to continue at a depth of approximately 500 m below the surface on the Sternö penninsula.

There are five boreholes on northern Sternö, four of which reach a vertical depth of more than 500 m. All end in sound rock after 128 to 579 m long sections with very low hydraulic conductivity. This means that the presumed fault zone has not measurably affected the bedrock in the area. It therefore appears probable that the movement did not take place below Sternö but followed instead the zone marked by a valley out to the coast south of Karlshamn just east of Sternö. The same zone can be traced more than 40 km inland and belongs to a series of shear zones in the bedrock, which tectonic studies /8-29/ show are more than 880 million years old. Western Blekinge provides a good example of a recent block movement along a pronounced fracture valley, which constitutes an older zone of movement, and for that reason is naturally avoided as a prospective site for a rock repository. At the same time, drillings on the Sternö penninsula show that the rock quality in bedrock blocks in the immediate vicinity of the zone of movement has not been measurably affected by the postglacial movement. The investigated site at Kamlunge, near the region with postglacial movements in upper Norrland, is also characterized by very good rock quality.

More extensive investigations of the recent block movements have been conducted in Norrbotten County /8-30, 8-31/. The rock movements there have also as a rule occurred in connection with the local deglaciation. The fracture zones in question normally have a northnortheasterly orientation with a steep or medium-steep easterly dip. In many cases, the bedrock east of the zone of movement has been raised and thrust towards the west, indicating a compression. The direction of the zones coincides with one of the most important older fracture systems in Norrbotten. The largest vertical displacement found in upper Norrland is about 30 m.

The largest known of these zones of movement in Fennoscandia is the Pärvie zone, which starts just south of the Lule River and then runs 150 km in a northnortheasterly direction along the mountain border up towards Råstojaure. The Pärvie zone alone accounts for half of the length of all such known zones of movement in Norrbotten County and is accompanied by a number of shorter parallels on its eastern side. Rock fractures filled with minerals such as actinolite, epidote and zoisite have been found at a number of places distributed along its length. These minerals are formed at pressures and temperatures which show that the fracture zones must have been formed more than 850 million years ago. Fracturing in what appears to be completely fresh rock occurs at a number of places along this zone. A geophysical study in the Tjårrojåkka measurement area shows, however, that the movement here has also taken place in an older zone of movement.

A postglacial zone of movement has been found northwest of Kärkejaure whose different branches together are 15 km long. It follows a much older superregional zone of movement in the northnortheasterly direction which is more than 125 km long and up to 3 km wide. Parallel to this zone is a 25 km wide swarm of diabase-filled fractures which can reach up to 10 km in length.

Extensive investigations have been conducted in the Lansjärv district. The bedrock structures there have been examined with detailed interpretations of primarily regional geophysical measurements. They indicate a network of older fracture zones. The mean distance between these indicated zones in the belt around the postglacial movements is around 2 km. A comparison with conditions in areas with well-exposed bedrock, and in boreholes, where the distance between major fracture zones is 0.4 km or less as a rule, shows that the geophysically indicated fracture network may correspond to 10-20% of the actual one. Despite this limitation, it is found that the postglacial movements with a northnortheasterly direction conform entirely to geophysically detectable regional zones of movement or secondary fractures of such systems. On the other hand, more northeasterly oriented movements have, at least in part, gone through areas where older fracture zones have not been detected with currently employed regional geophysical methods.

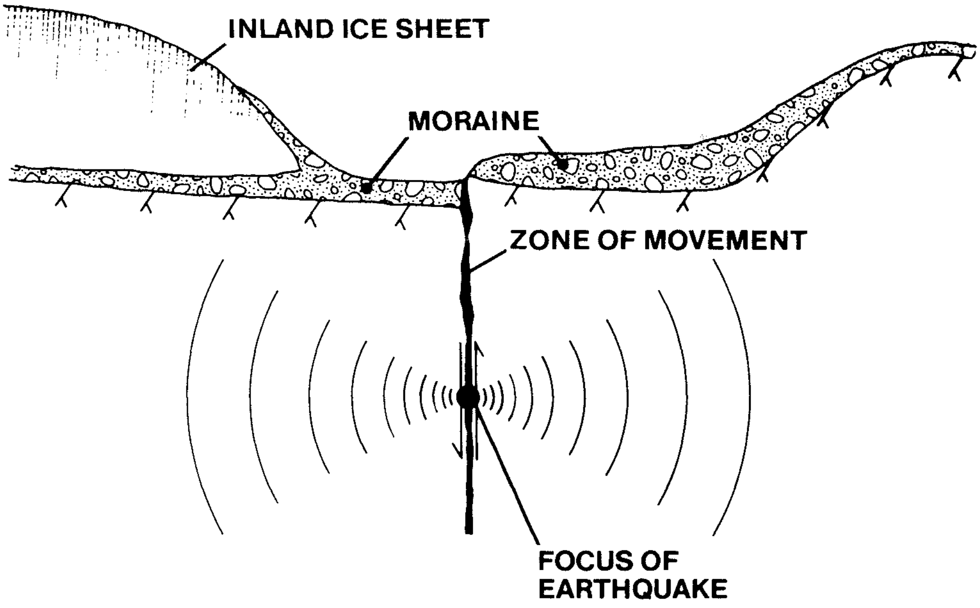


Figure 8-6. Schematic drawing explaining postglacial block movements, from Lagerbäck /8-30/. The ice sheet has retreated from the right-hand part of the illustration, so that its load on the earth's crust has been removed here /8-32/.

An explanation for these recent movements in the Precambrian shield must reasonably include an interaction of a number of different factors. The following can be mentioned at the present state of knowledge:

- The association of the movements with the time of the deglaciations points towards the special stress situation that prevails at the edge of a thick ice sheet. Its importance from the viewpoint of rock mechanics has been examined by Pusch /8-32/. Similar situations may also have existed during the advance of the ice sheet.

- The prevailing uplift of the blocks east of the zones of movement in Norrbotten County also appears to be associated with the load situation in connection with the retreat of the ice. Before this, the ice cap was regionally thicker in the east, but when it retreated, these previously more depressed parts were relieved of their load before the western parts, which included the much more recently deglaciated mountain districts, figure 8-6. The location of the dominant Pärvie zone east of and parallel to the northern high mountain range points towards the same situation. In this area, the thickness variation in the ice cap towards the high mountains in the west was the greatest and the deglaciation in the west was also the most recent.

- The compression in the zones of movement corresponds to the present-day rock stresses, which now have existed at least during the past 55 million years. They have recently been given an explanation based on plate tectonics /8-33/.
- The more frequent occurrence of the movements in upper Norrland and northern Finland may be related to the later retreat of the ice cap in these districts. There may also be a connection to the fact that the Swedish earthquake zone ends here and is divided into a northerly and an eastnortheasterly branch (intraplate triple function).

Renewed bedrock movements in existing fracture zones are, in actual fact, a common phenomenon. They have been reported by many scientists from many parts of the country and they have also been encountered in the KBS sites /8-34/. Most of these movements occurred long before the ice ages. One case has been described where it has been possible to analyze the movements in time with unusual detail /8-35/.

The fact that the movements are actually concentrated to the existing zones of weakness while adjacent bedrock blocks remain virtually unaffected is exemplified above by the results from the Sternö penninsula. This is a natural consequence of the block structure of the bedrock. This is confirmed by corresponding observations at other KBS sites and in rock caverns, tunnels and mines from all parts of the Precambrian shield. Everywhere, and especially at great depth, it is found that groundwater inflow takes place in isolated narrow zones, while large intervening sections of the bedrock provide extremely small contributions. As a example, it can mentioned that 80% of the seepage into the tunnel system at Juktan, with a total length of 25 km, comes from seven main zones, which together only have a width of 0.7 km in the

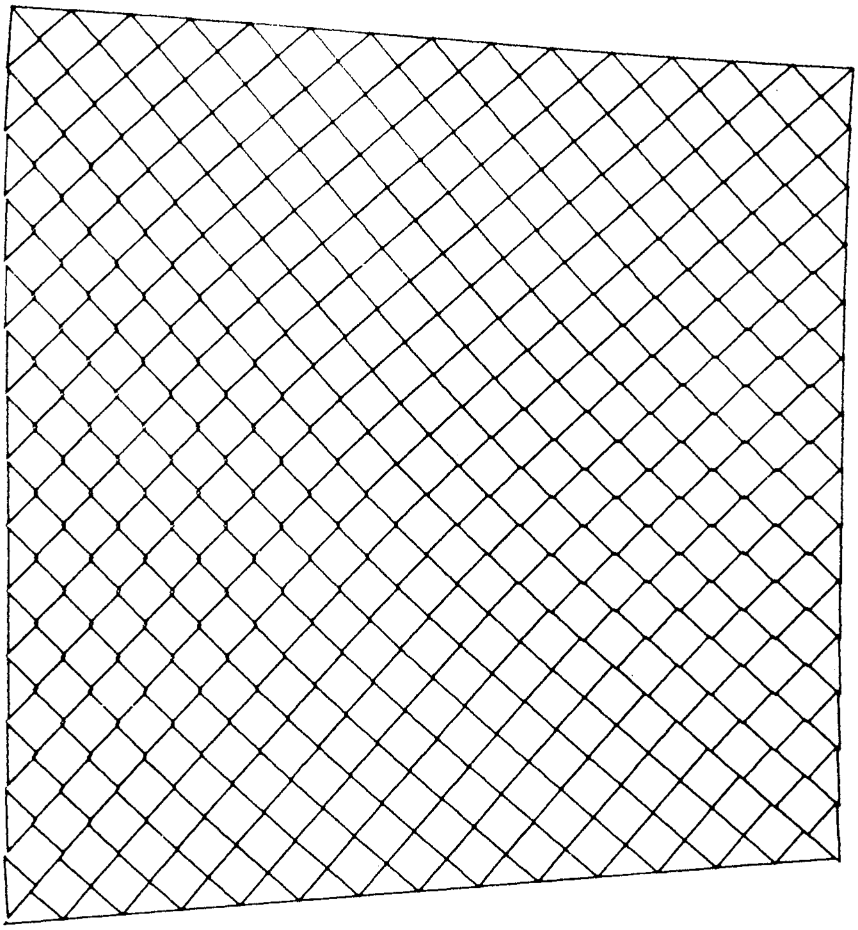


Figure 8-7. Deformation structure in a block-structured rock mass, from model calculations according to Stephansson et al /8-40/.

tunnels. The remaining seepages here can also be attributed to other, smaller fracture zones and individual fractures in an otherwise apparently impervious rock mass /8-36/. A supplementary detailed study of leakage zones in a tunnel is published in /8-37/.

Further illustrations of how existing fracture zones control later movements are provided by impact structures in the Precambrian shield. These have occurred as a result of large meteorite impacts and similar events at different times since the formation of the Subjotnian land surface. A review of the Swedish examples has recently been published /8-38/. In many cases, for example at Mien, Hummeln and Dellen, these younger impact structures have not visibly altered the block structure of the surrounding region. On the contrary, it is found that the major fracture zones in each area run through the impact structures, which has made their interpretation considerably more difficult. Special measurements show that movements at such fracture zones are still taking place /8-39/.

The reasons for why the recent movements take place to such a high degree in older zones of movement and affect to such a small degree the bedrock in adjacent bedrock blocks are connected with both the origin of the block structure and its deformational properties. Large block movements occurred already during the orogenies in the Precambrian and many regional zones of movement in the bedrock can be traced to late phases of this development. As shown above, however, the main block formation can be attributed to post-orogenic development, when the earth's crust essentially reacted as a rigid and brittle plate in which displacements on a km scale took place accompanied by regional volcanism. From the time of this stage, which ended more than 650 million years ago, the earth's crust in the shield can move as a set of smaller blocks, bounded by larger and smaller fracture zones. Renewed bedrock movements, around 280 million years ago, were approximately ten times weaker than the preceding ones and were accompanied only locally by volcanic activity. The post glacial block movements, without volcanism, were yet again ten times smaller. It is then natural that these more recent deformations, which are small both in relation to the preceding ones and to the thickness of the earth's crust (about 40 km), do not break up the crust once again, but merely cause displacements in already existing zones of weakness. Small blockages, such as the bedrock homogenization in connection with the aforementioned impact structures, do not, on the other hand, appear to constitute any obstacle to the renewed propagation of the older fracture zones.

One question in this context concerns the orientation of the bedrock-deforming forces in relation to existing fracture zones. New forces in an unfavourable direction might possibly cause renewed fracturing. However, the results of model calculations /8-40/ show that a rock mass divided up into blocks at right angles can adjust flexibly to shear forces that act at 45° angle to the fractures, see figure 8-7. In the Precambrian basement, which normally exhibits a number of different fracture directions, the angle to an arbitrary shear force will always be less than this. Moreover, a number of large structures - such as the Hyperite zone, the Vaggeryd syenite zone, the Koster-Orust-Göteborg dykes, the Karlshamn dykes, the Lake Vättern and Baltic Sea depressions, the Oslo field and the present-day Norwegian Atlantic coast - show that the main forces of tension over the past 1 550 million years have only rotated about

30° from the direction east-west to westnorthwest in Scandinavia. The direction of the Sveconorwegian compression structures, as well as the Scandinavian mountain chain and the present-day rock stresses, complete this picture and indicate times with forces of opposite effect (compression) but with similar orientation. Detailed analyses of the structure of Fennoscandia are given in references /8-41/ - /8-44/. However, it is already evident from the main features cited above that the orientation of the forces acting on the Precambrian shield has been established for a very long time. It is ultimately associated with the location of surrounding mountain chains and marine areas, as well as with the margins of the North European platform. The possibility that essential changes could take place in these major structures during a period of one million years can be regarded as non-existent.

Finally, the question remains as to whether the repository itself can alter the conditions for the present-day block structure and its continued existence. However, the individual tunnels in the repository are so small that they are neglible in relation to the size of the bedrock blocks that will be considered for hosting a final repository. Calculations based on elasticity theory, as well as stress measurements in tunnels and mines, show that the stress situation in the rock at a distance of more than three tunnel radii outside a circular tunnel in a stress field corresponds very closely to that which prevails in the undisturbed rock /8-45/. The thickness of the zone of shattering which is created in connection with construction of the tunnel must be added to this radius. This means that the tunnels in a repository are surrounded at a relatively short distance by rock with a stress situation virtually unaffected by the tunnelling. The importance of the tunnels for the survival of the block structure is therefore negligible from this point of view.

The spent fuel in the storage holes below the tunnels gives off heat. The repository is so designed that the temperature in the rock mass does not reach 80°C. Practical experience of similar heating is available from heavy oil storage in rock caverns and has not caused any serious problems in the much larger rock caverns used for such storage. On the other hand, it has been observed that water leakage decreases to around half in connection with this heating. This indicates that the thermal expansion of the rock reduces the width of the water-conducting fractures, but that they are not closed completely. Carefully instrumented heating tests in the Stripa mine have, in addition, shown that the temperature distribution in the rock can be predicted with good reliability, but that the rock stresses around the source of heat increase less than expected /8-46/. This, as well as the reduced water leakage, is basically due to the fact that the rock originally crystallized at around 700^{o}C. The renewed slight heating therefore utilizes only part of the contraction volume that corresponds to a previous cooling. The remaining water leakage indicates that some of the contraction volume is still left even after subsequent mineral formation and after the renewed heating has caused an expansion of the rock once again.

In summary, it can be said that in order for a new stage of large block movements and regional volcanism of the type that originally gave rise to the block structure in the Swedish part of the Precambrian shield to take place, nearby orogenies must occur, and this cannot be expected to take place within one million years. The smaller but locally important block movements of the type that took place in connection with local volcanism within the Swedish shield at the time of the Hercynian orogeny culmination around 280 million years ago cannot be expected either. Nor are block movements associated with volcanism in the margins of the Precambrian shield and a renewed opening of an ocean west of Scandinavia likely events within one million years. Particular attention has therefore been devoted to the postglacial block movements. They are close to us in time and can also be expected to occur in connection with new glaciations. As regards their number, size and effect on the bedrock, however, they are without practical importance in the present context. The large, older fracture zones in which they would tend to occur are avoided in the preliminary choice of sites. Smaller fracture zones within a repository site, where future block movements of this kind could also conceivably take place are avoided as far as possible in the laying out of the tunnels, and in any case in the subsequent siting of storage holes in a repository.

8.6 EARTHQUAKES

Perceptible earthquakes in Sweden are unusual, and where they occur they arouse general interest. Major earthquakes that cause damage to building structures on the ground are rare, and records of such quakes that have occurred in populated districts exist from the end of the Middle Ages. No earthquake catastrophes have occurred in Sweden in historical time. No reports have been found of damage underground, in mines and tunnels, despite the fact that mining has been conducted in the country for many hundreds of years.

In certain other countries, especially those affected by recent orogenies or volcanism, severe earthquakes are relatively common and large earthquake catastrophes occur. Scattered information on the effects of earthquakes on tunnels and mines are available from such countries. Recently, data on how rock caverns are affected by large blasts and underground nuclear weapons tests have also been added to the existing body of information. All such data have recently been compiled and analyzed /8-47, 8-48/.

The material covers a total of some 70 major earthquakes and some 80 underground facilities. It includes, for example, the 1960 earthquake in Chile, one of the largest that has ever been recorded, which caused the death of many thousands of people at the surface. Miners who were working at the time of the earthquake in nearby coal mines that extend out underneath the sea noted unusual sounds, but felt nothing of the quake. The 1964 earthquake at Anchorage, Alaska, which caused extreme damage at the surface and was one of the largest in the 20th century, caused no significant damage to railway and power station tunnels and mines in the afflicted area. Similar results are reported for the large 1970 earthquake in Peru, and the catastrophe at Friuli in 1976. Minor damages are noted in other cases, primarily in tunnels in loose deposits, especially at the portals or in existing fracture zones. In addition, damage occurred in coal mines and deep gold mines, which often have stability problems due to the fact that large rock volumes are taken out and the surrounding rock is of poor strength or under high rock stresses. However, several cases show that the damage was small even under such unfavourable circumstances. A diagram of damage in mines and tunnels without backfill in crystal-

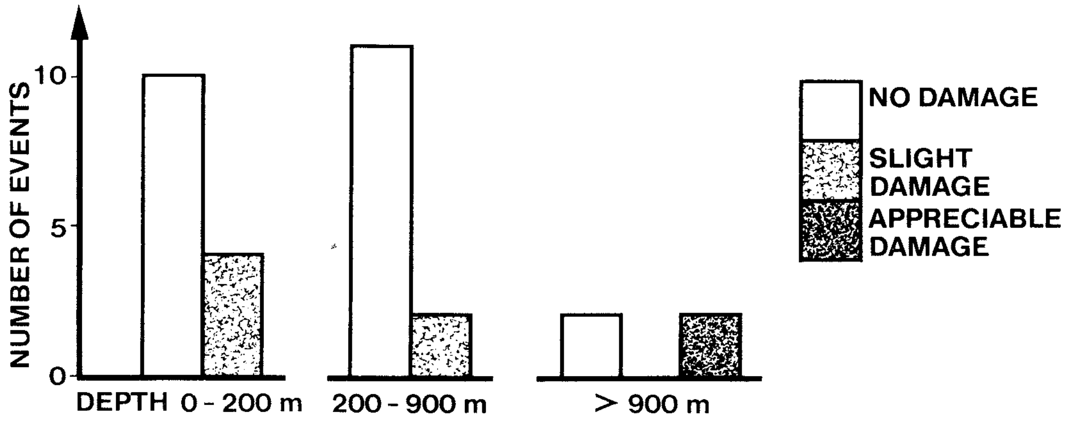


Figure 8-8. Bar graph of observed damages in connection with large earthquakes in North and South America, Japan, India and the Mediterranean area in 30 open rock caverns in crystalline bedrock and limestone, in three different depth zones, according to data from /8-48/.

line bedrock and limestone, and their distribution in depth, is presented in figure 8-8. It shows that massive damage tends to occur at depths greater than 900 m, while slight damage is somewhat more common at shallow depths than at depths of between 200 and 900 m. No damage was reported in the majority of cases.

In summary, it can be said that small rock caverns such as railway and power station tunnels in sound rock provide good protection even at moderate depths against the severest earthquakes that have been observed in the earth's most earthquake-prone areas. Large extracted volumes, extreme depths and complex rock conditions can reduce the stability of the rock caverns to different degrees. However, the greatest stresses in this respect occur, as a rule, in connection with the blasting work during excavation and not with the earthquakes. The stability of the rock caverns is a question that primarily concerns the working environment in the repository, but not its function. In this respect, the working environment is better in principle in a repository than in an equivalent mine, since there is no extraction of ore and the quality of the bedrock has already been a determining factor in the original choice of the site. The quality of the bedrock as it is found in the site investigations reflects, despite some new mineral formation, the cumulative effects of many millions of years. It shows the effect - with respect to the local situation and bedrock conditions - of uncounted earthquakes, totally beyond the scope of all human earthquake statistics. Naturally, this also includes increased earthquake activity in connection with repeated glaciations.

Against this background, it is clear that the small earthquakes in Sweden cannot be expected to harm the function of a backfilled repository of narrow tunnels in sound rock, even if more infrequent large earthquakes should occur. The quality of the rock at the investigated sites does not show any correlation with today's regional distribution of quakes. Areas such as Fjällveden, Kråkemåla and Sternö are located in regions with low present-day quake activity, and Gideå and Kamlunge in regions with, by Swedish standards, high activity, but the variations in rock quality between the areas reflect nothing of this. The overall conclusion therefore is that earthquakes cannot have any direct importance for the safety of a rock repository. They are, however, of interest in the present context for the insight they provide into present-day bedrock movements and into the deeper structure of the earth's crust. A brief account of their occurrence may therefore be of value here.

The total number of earthquakes in Sweden, mainly instrumentally recorded, during the years 1951-1976 includes slightly over 200 quakes with regional magnitudes M_L of between 1.5 and 3.8 /8-49/. The quakes usually occur at depths of around 15 km, less often around 25 km, and diminish in number both upwards and downwards from these two maxima /8-50/.

During the period from December 1979 to December 1981, 53 quakes with regional magnitudes of 0.4-3.4 have been recorded in a dense network of instrument points in southern and central Sweden. They have roughly the same distribution geographically and with respect to depth as previously recorded quakes.

A detailed analysis of the 53 quakes shows the following /8-51a, 8-51b/:

- An interpretation of the quakes indicates rock movements that correspond to the direction of the rock stresses prevailing in Sweden (and the rest of Europe north of the Alps), see figure 8-9.

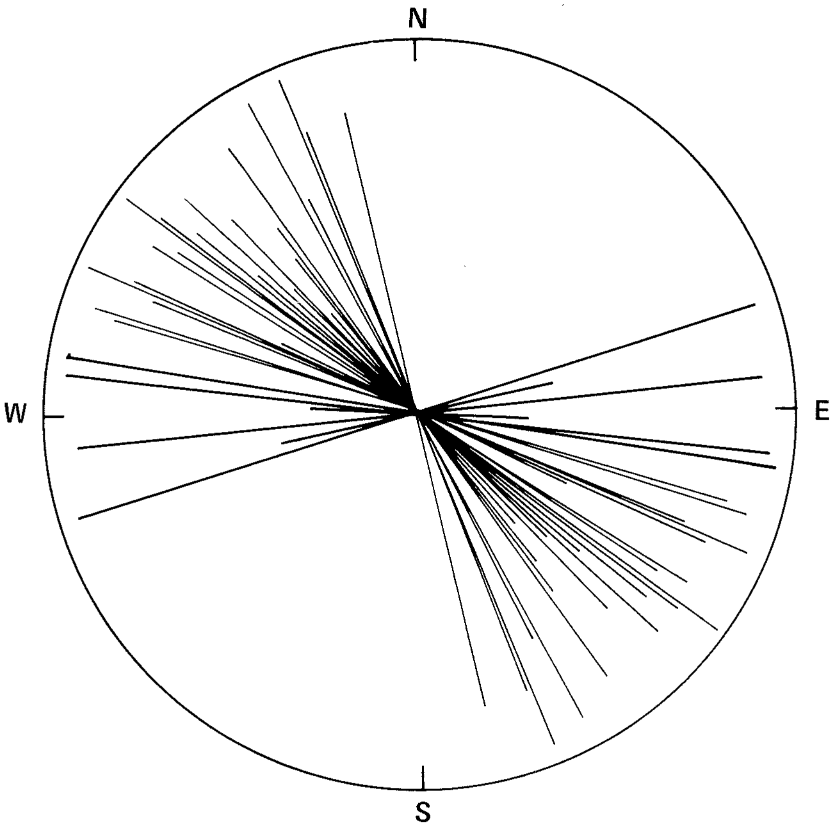


Figure 8-9. Interpretation of Swedish earthquakes. Each line indicates the direction of the horizontal deviator stress for a single quake, from Slunga /8-51a, b/.

- With given assumptions, the displacements in the rock are calculated to have reached a maximum length of 10 cm along fracture planes with radii of between 30 and 150 m at the depth where the particular quake occurred (at the focus of the quake).

- At the free rock surface above the focus of the quake, the amplitude of the movement may amount to a maximum of a few tenths of a millimetre.

It is further found that the movements have usually taken place along steep fracture planes and, in roughly half of the cases, have essentially been horizontal displacements along the fracture direction. The others have primarily involved movements along the slope of the fracture planes. In half of these cases, the rock block above the fracture plane has been thrust upward, and in the other cases it moved downward (normal faults). In many cases, the quakes can be correlated with fracture lineaments that are also visible in the terrain.

The quakes in Skåne (four in number) differ from the others in that they are for the most part normal faults that can be related to major faults in the bedrock, where they have produced smaller drops in stress than other quakes.

The Swedish earthquakes appear clearly grouped along a nearly linear belt between Gothenburg and Luleå, see figure 8-10. West of the central part of the belt, very few quakes take place; east of it, the number of quakes diminishes more gradually. Towards the north, the belt divides into a northerly branch, which roughly follows the Kalix and Torne river valleys, and an eastnortheasterly branch, which extends through Finland. On a larger scale /8-52/, an area with extremely few quakes emerges in the middle of Scandinavia, surrounded by seismically more active zones, which, in addition to the aforementioned belt, also include Kattegatt, Skagerak, the Oslo district and parts of the Norwegian coast and the Norwegian Sea.

Within the Swedish belt, the quakes appear to be concentrated to some extent to an area near Lake Vänern, and another between Skellefteå and Luleå. 95% of the quakes in Sweden between 1951 and 1976 were found to be distributed between the Lake Vänern area and along 26 linear fracture zones, which are often marked by river valleys /8-53/, see figure 8-11.

A number of factors have been mentioned as a explanation of the origin and geographical distribution of earthquakes in Sweden. These include the ongoing land uplift, whose stored-up deformation energy has been shown to be equal to the amount of energy that is released by the quakes /8-54/. In addition, the earthquake belt follows the zone where the earth's crust is supposed to have been deformed the most by the ice cap /8-17/, and where the lines of equal uplift rate show the greatest curvature /8-16/. The same zone, however, also constitutes a topographical border zone /8-11/, which, at an elevation of about 100-150 m, separates the highland western part of Scandinavia with the mountains and the Norrland terrain from the flat lowland and the Baltic Sea basin in the east. This line was activated in connection with the land uplift before the glaciations, and goes back to zones of movement of Precambrian

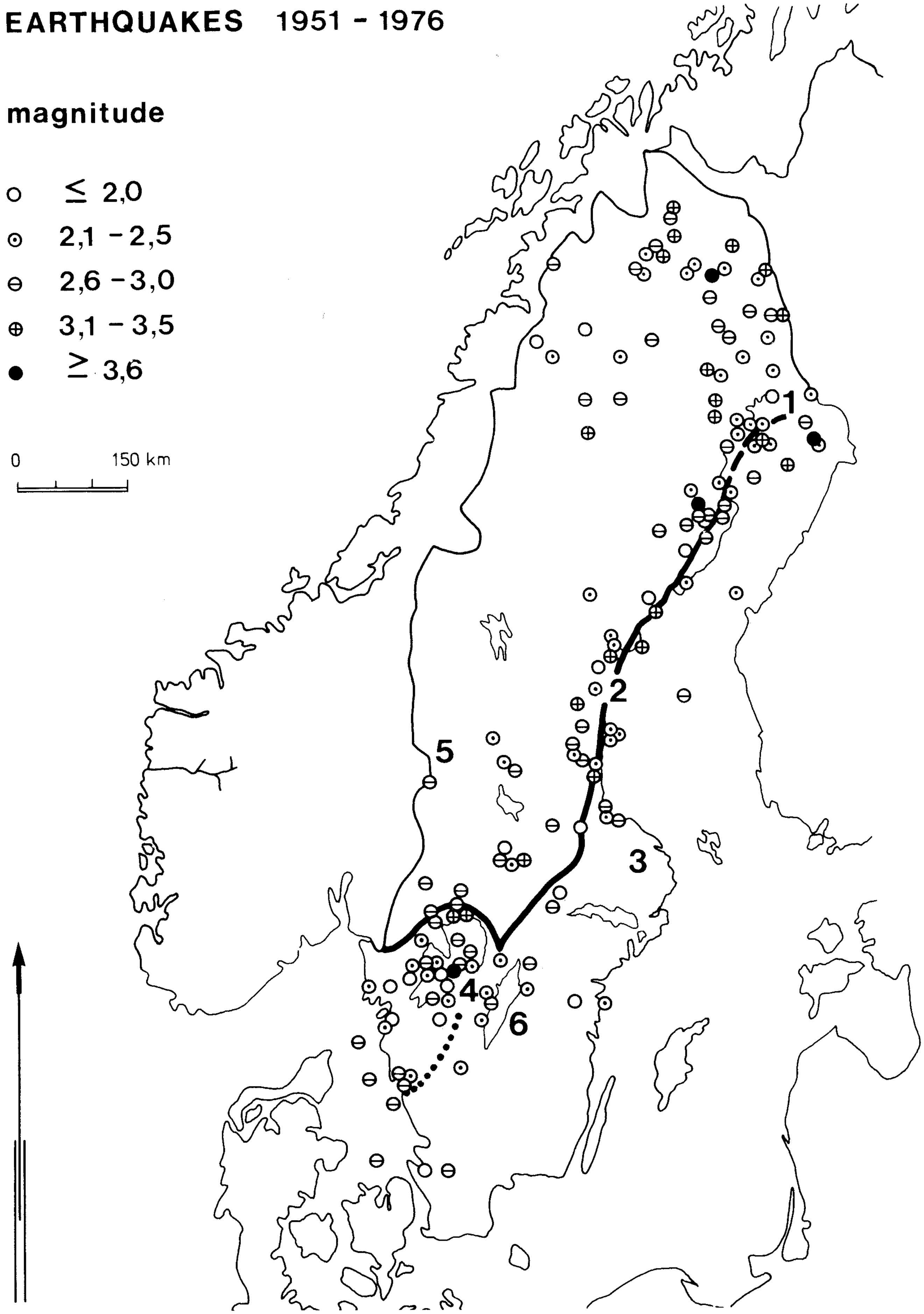


Figure 8-10. The geographic distribution of Swedish earthquakes during the period 1951–1976 according to Båth [8-49]. The map shows the western boundary of the Subcambrian peneplain, solid line, and of the Subpermian to the Subsenonian land surfaces, dotted line. The numbers 1–6 indicate the location of »volcanic» formations in Kalix, Alnön, Almunge, the Västgöta mountains, Särna and Norra Kärr.

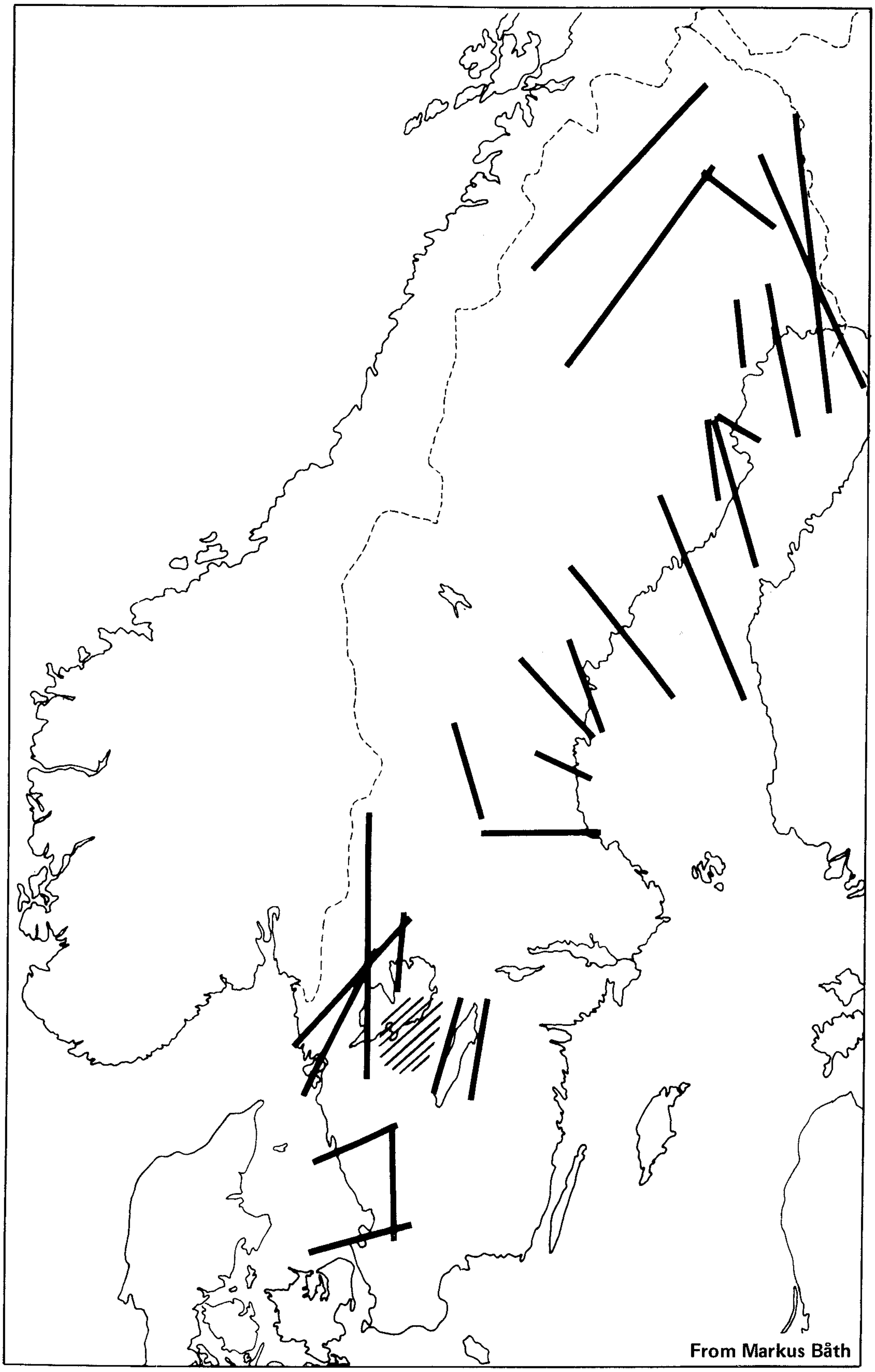


Figure 8-11. 95 % of all earthquakes which were recorded in Sweden during the period 1951–1976 took place within 26 linear zones plus the hatched area next to Lake Vänern /8-53/.

age. The elevation differences within the glaciated area have also caused the thickness of the ice caps to decline by approximately one kilometre west of this line and up to the highest parts of the mountain chain. Finally, the same line marks a boundary in the clearly elevation-dependent gravitational conditions. A gravity excess (free air) in the west changes along this line into a gravity low reflecting the Baltic Sea-Lake Mälaren-Lake Vänern depression /8-18/.

Earlier indications that the Swedish earthquake belt corresponds to a thinning of the crust have not been confirmed by later measurements /8-55, 8-56/. On the other hand, there appears to be a geographical relationship to the occurrence of alkaline rock bodies in Sweden, although these are of widely varying age. The north end of the belt is marked by the 1 150 million year old "Kalix kimberlites", and their orientation towards the north coincides with the northerly branching of the belt. The Kalix centre, together with other alkaline bodies and the young volcanism (280 million years ago) south of Lake Vänern, mark the present-day boundaries of the Swedish earthquake belt, which, moreover, points in its orientation towards similar deposits on the Kola penninsula. Finally, it can be noted that the location of the Scandinavian earthquake belt inside of and parallel to the Scandinavian mountain chain is reminiscent of an earthquake belt in the USA at New Madrid, with a similar location inside the Appalachians.

In summary, it can be said that earthquakes in Sweden appear to reflect present-day rock stresses and land uplift, but that they are controlled by structures in the bedrock that were created back during the period of formation of the Precambrian crystalline rocks and that have been activated many times since then.

8.7 DISPLACEMENTS WITHIN THE BEDROCK BLOCKS

The canisters in a rock repository are surrounded by a bentonite buffer mass that reacts plastically to mechanical stresses. In this manner, the canisters are protected against damages caused by minor displacements. Displacements along horizontal or flat fracture planes that exceed a centimetre or so in length would, however, entail the risk of canister damage. In order to shed light on this problem, observable displacements have been studied on well-exposed, clean-washed shore outcrops at nine places along the coast between Öregrund and Sternö, see figures 8-12, 8-13.

Displacements along fractures have been measured where they have exceeded 1 mm. A total of 1 385 fractures with lengths of between 2 and 60 m are included in the material. None of these displayed any displacement of glacial striae. A total of 67 older displacements have been observed. The lengths of the observed horizontal displacements within all areas, except one, can approximately be described as a log-normally distributed population with a frequency maximum between 30 and 65 mm, see figure 8-14. The average distance between the displacements exceeds 50 m. The observed deformation patterns show a variation in the sense of shear among the different areas, which does not agree with today's uniform rock stress situation and the pattern of movements that has been demonstrated for earthquakes. Several of the fractures with displacement in each area contain mineralizations, which indicate that they are older than 650 million years. In the area at Lönö, the displacements can be related to diabases that probably have an age of around 1500 million years, and at Flatvarp the displacements are even older, see figure 8-12. Thus, the field observations indicate that most of the displacements within the bedrock blocks, and possibly all, occurred during the period of formation and denudation of the Precambrian basement. In this case, no displacements can be expected during the next million years.

It has not been possible to determine the age of each individual displacement, however. It might therefore be of interest to examine the consequences of an unfavourable, completely hypothetical case where all observed displacements have occurred during the past 650 million years with a random distribution in time. It is further assumed that the frequency and magnitude of the displacement in the horizontal plane and the vertical plane are the same. The probability (P) that a 5 m canister will be hit by a displacement larger than 1 mm during a million years, assuming the average spacing of the displacements to be 50 m, can then be calculated with the aid of the Poisson distribution, which gives

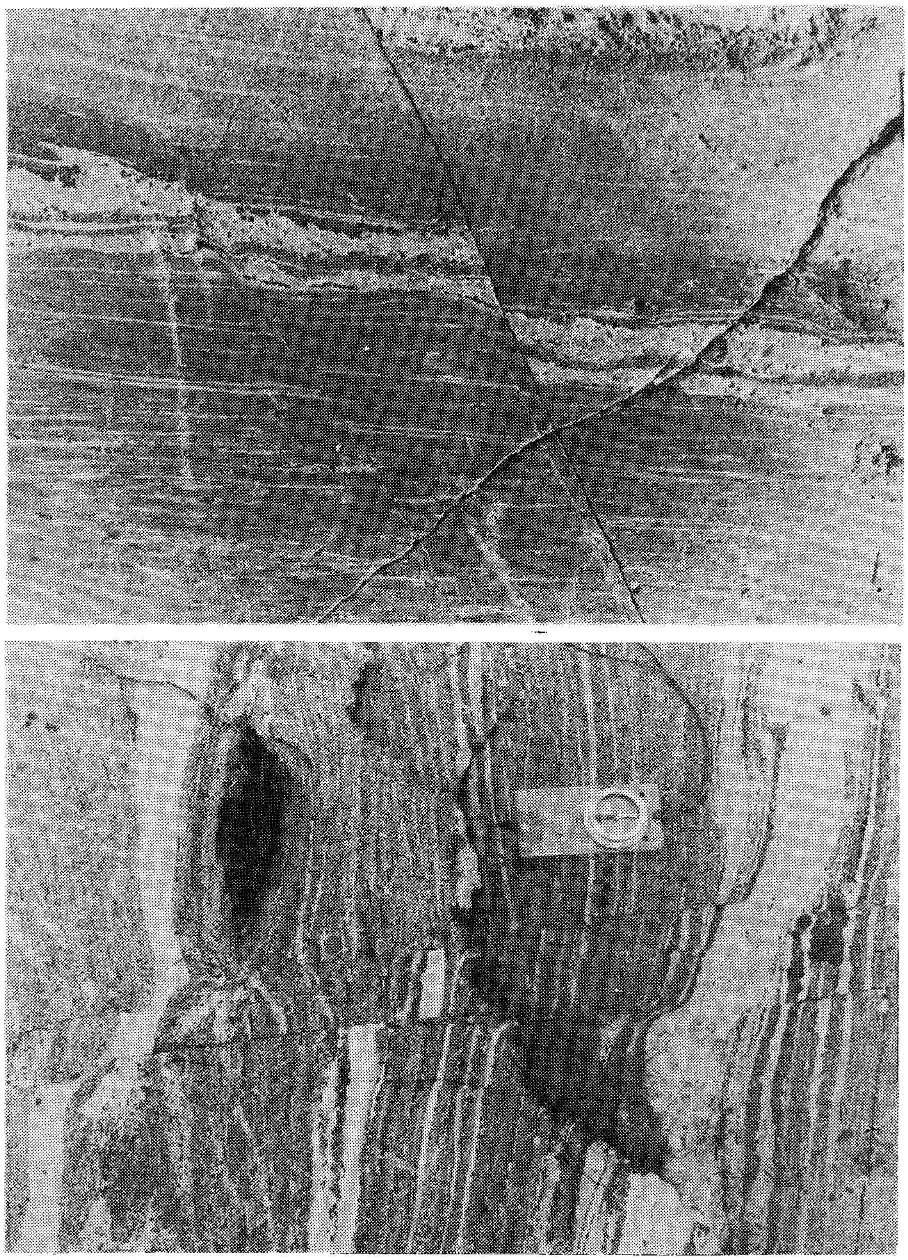


Figure 8-12. Displacements within the bedrock blocks. The lower picture shows that the light bands in the rock could still react plastically to the deformation, and to some extent intrude into the newly-formed fractures. This indicates an age of the displacements of around 1600 million years. Flatvarp, photo C G Rydén.

$$P = 1-1:e^{5:(50 \times 650)} = 1.5 \times 10^{-4}$$

This probability means that one of approximately 5000 canisters in a final repository can be expected to be affected by a displacement larger than 1 mm during one million years.

A number of circumstances indicate that the probability figure given above is too high. Thus, earthquake studies show that of 53

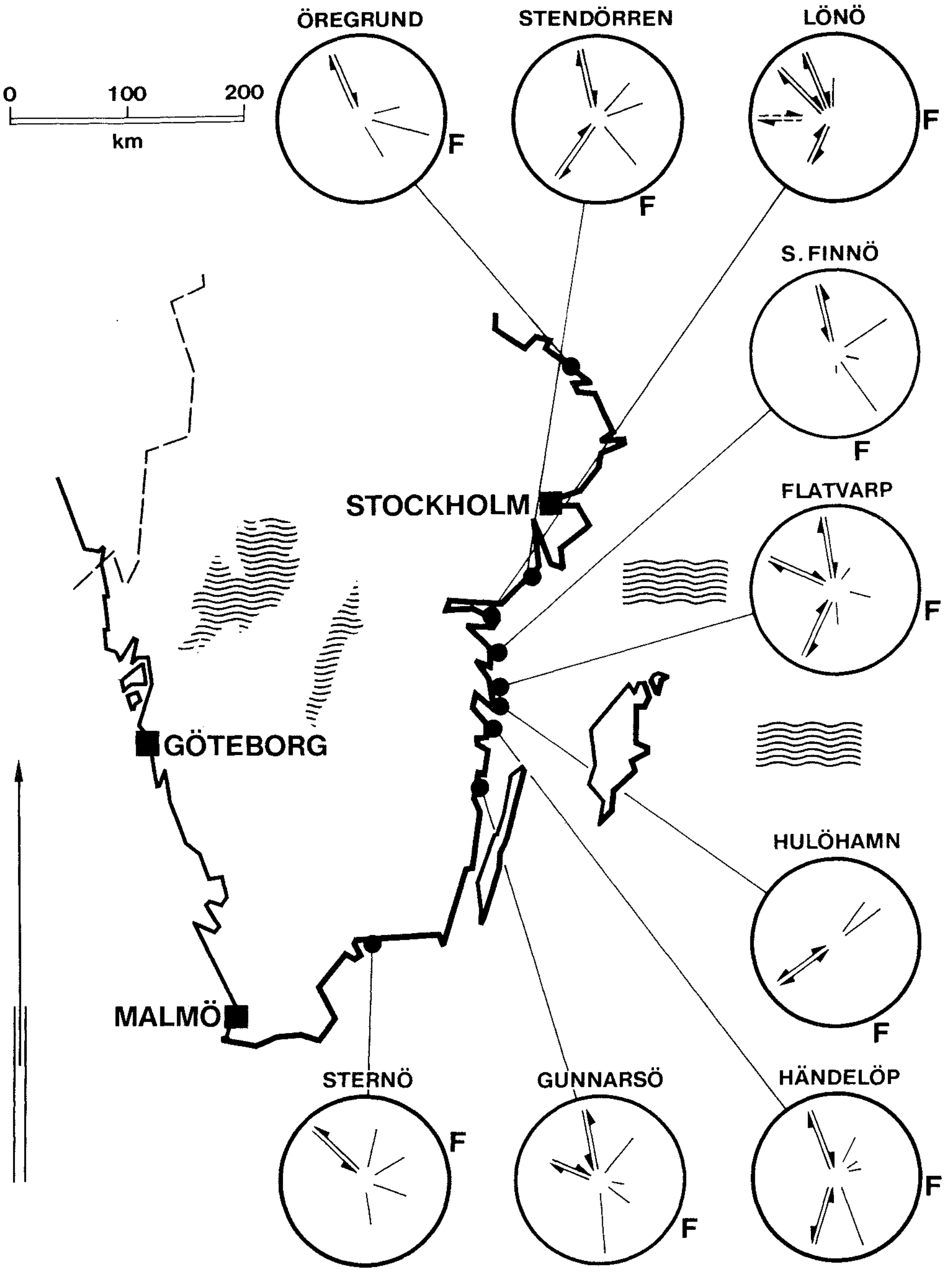


Figure 8-13. Location of the study areas concerning displacements and the results. The left-hand part of each circle diagrams shows the prevailing displacement directions and the right-hand part the prevailing fracture directions. The length of the fracture vector is inversely proportional to the average distance in m, one whole radius corresponds to the average distance 1 m, a tenth of a radius to the average distance 10 mcF indicates the prevailing direction of foliation.

displacement planes, all were steeper than 30^o while 46 had a dip between 45^o and 90^o.

The calculation given is not claimed to represent a strict risk assessment. It does, however, illustrate numerically the practical

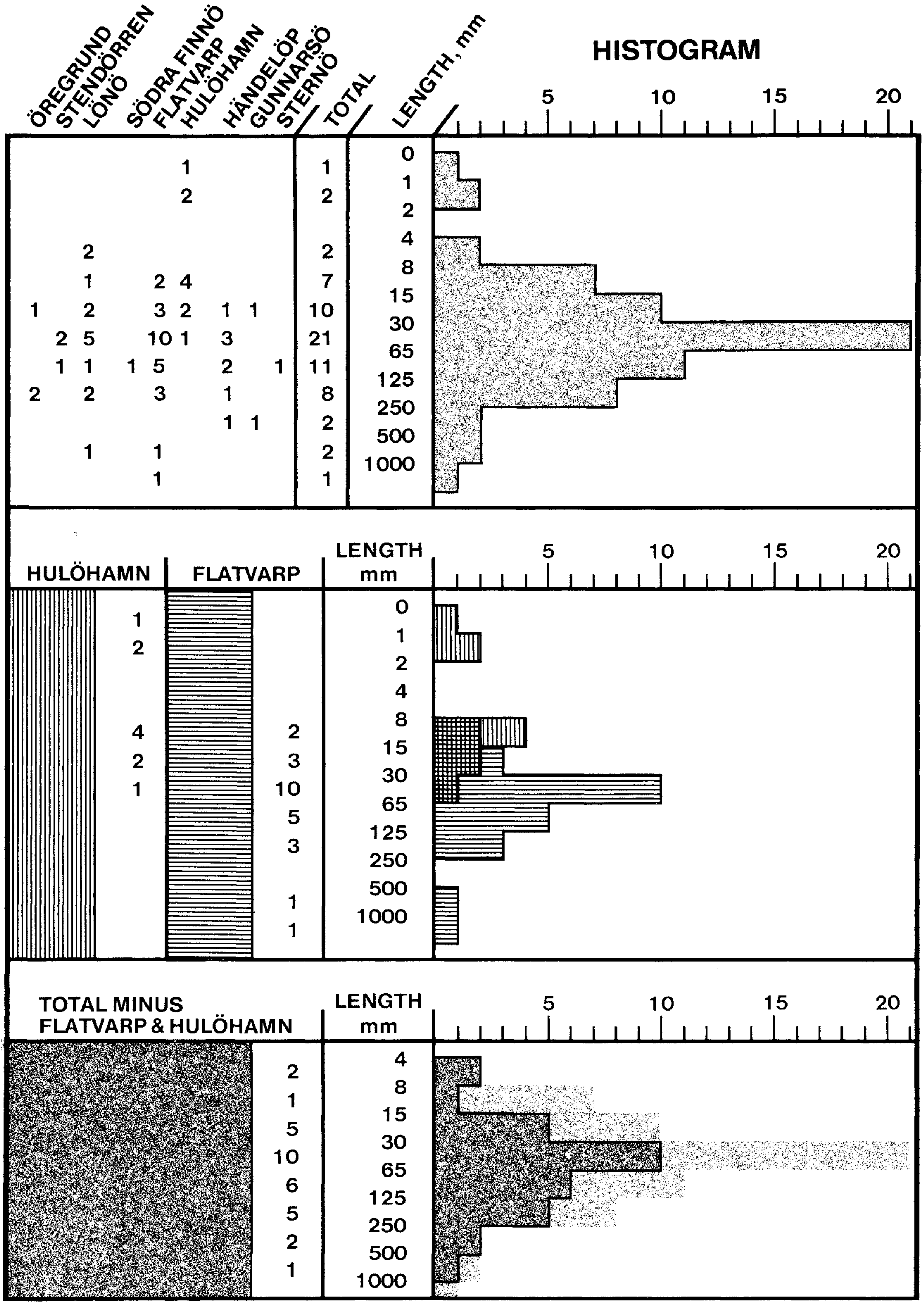


Figure 8-14. Distribution of observed displacement length, number of observations plotted against length classes in mm.

importance of the block structure of the bedrock. The characteristic contrast between the bedrock blocks and intervening narrow fracture zones, which is most clearly demonstrated by their different groundwater contents, shows that the bedrock displacements since the block structure was established have primarily been released along existing fracture zones between the blocks. Mineral fillings of the type shown in figure 8-12 indicate that the displacements within the bedrock blocks primarily occurred towards the end of the period of formation of the Precambrian bedrock in the area.

8.8 MINERALIZATION

In addition to the mechanical stresses to which the crystalline basement has been subjected, chemical changes have also affected its mineral composition. In terms of volume, this effect is insignificant. The new minerals have mainly been formed in the grain boundaries, pores and fractures of the rocks.. Hereby, the permeability, porosity and strength of the rock are affected, see chapter 6. Since the new minerals largely constitute the rock's contact surface with the groundwater, they affect the chemical composition of the groundwater as well as the reactions that can occur between the rock and radioactive substances in the water, see chapter 7. For these reasons, the fracture minerals have been studied from the start in KBS' site investigations and in Stripa. The literature contains much important information from other sources as well regarding the background and chronology of the mineralogical changes. The following points are important for an evaluation of the future evolution of the bedrock.

- The metamorphic fracture minerals, see section 7.3.1, were formed in connection with the cooling of the Precambrian rock from about 700°C and its simultaneous movement from a depth of about 10 km to a near-surface position corresponding to its present-day location (retrograde metamorphism). This development was concluded in large parts of Sweden prior to the formation of the Subjotnian land surface approximately 1 300 million years ago and for other parts of the basement outside the area of influence of the mountain chain more than 650 million years ago. This type of mineralization is therefore of no importance for a forecast period of one million years.

- Hydrothermal mineralizations have occurred repeatedly. Considerable mineralizations with quartz, calcite, fluorspar (CaF_2), baryte ($BaSO_4$) and sulphides, mainly galena (PbS) in southeastern Skåne can be structurally and geographically linked to diabases that are around 280 million years old. Similar mineralizations occur scattered in the sedimentary cover rocks in the Baltic Sea area, at Lake Siljan and in the eastern margin of the Scandinavian mountains as well as in the form of fracture fillings in the Precambrian basement. Many of them may be of a similar age, while others may be older. No more recent formations of this type are known, however. The special conditions for hydrothermal mineralization, with extensive block movements and local volcanism, which prevailed 280 million years ago have not existed since that time within the Precambrian shield area, nor can they be expected to appear within one million years.

- Weathering and mineral precipitation are still going on, however, and require closer analysis.

Chemically, weathering takes place when the water in the ground, with its content of oxygen and carbon dioxide, attacks existing minerals. These minerals can go entirely into solution or remain in part in the form of new, more stable phases. Biological activity, particularly in the root zone of the plants, as well as temperature stresses, frost action and other near-surface phenomena are believed to contribute to the process of weathering. Mineral precipitation takes place when the water, with its content of dissolved substances, becomes saturated or supersaturated with respect to new phases as it continues on its way. Equilibrium conditions and stable mineral associations for the systems in question can be calculated on the basis of thermodynamics and solution chemistry for both weathering and precipitation.

The main weathering that has taken place since the latest glaciation is represented by a centimetre-thick zone of leaching (A_2 horizon) in the dominant podsolic soils of Sweden. Precipitation, primarily of iron and aluminium compounds and certain organic substances, takes place in a zone with a thickness of several decimetres below the zone of leaching. It is known as the B horizon. Below this the soil is virtually unaffected by recent weathering processes . Some leaching of calcite occurs. At greater depth in the bedrock, calcite is again precipitated. This is indicated both by datings of fracture fillings of calcite and by a certain supersaturation in deep groundwaters /8-34/. As a rule, the deeper parts of the soil contain neither kaolinite nor smectite, which are typical weathering products. The clay mineral illite is, however, often found here, together with the unweathered rock minerals that constitute the larger part of the soil. The mineral composition here thus shows that the water sinking through the ground has lost most of its ability to oxidize the rock minerals and to transform them to kaolinite or smectite at a depth of less than one metre below the ground surface.

The bedrock below the soil overburden is therefore essentially unaffected by recent weathering and has been protected by the soil cover ever since the latest glaciation. As a rule, it exhibits an ice-polished surface with preserved striae. On exposed outcrops, without soil and particularly above the highest postglacial sea level, however, decomposition of the surface has often reached a depth of several centimetres and removed all traces of the glacial striae. In these cases, the weathering products have been washed away entirely.

During construction work in rock, as well as in KBS' investigations, oxidized, reddish-coloured as well as clay-altered kaolinite- and smectite-bearing zones are found in Precambrian rocks virtually all over the country. As has been shown above, it cannot be a question of modern postglacial formations to any great extent. Various periods of weathering before the glacial period may, on the other hand, have contributed to these changes in the bedrock. The reddish colouration, for example, might possibly be related to a deep, oxidizing groundwater circulation down below the Subjotnian land surface some 1300 million years ago. A Subcambrian to Cambrian (650-600 million years) kaolinite formation has been demonstrated at a number of places, and a more recent intensive kaolinite weathering occurred in at least parts of the Swedish Precambrian shield more than 100 million years ago. Its occurrence has recently been discussed /8-12/. Data are cited from drillings in the Kristianstad area that show that the proportion of kaolinite of the weathered rock diminishes with increasing depth while the proportion of smectite increases. The occurrence of the two minerals in different areas should therefore probably be regarded in the light of, among other things, the erosional level of the areas and the time of the removal of the cover rocks. It can also be mentioned that many groundwater samples from greater depths in the bedrock have a chemical composition that is close to the equilibrium of coexisting kaolinite and smectite /8-57, 8-34/. Even younger, tertiary, clay weathering in the bedrock has been suggested /8-58/.

All of these traces of deep chemical changes in the bedrock correspond to exposures of long duration, long before the ice age, with strongly levelled-out land surfaces, deep groundwater circulation and climatic conditions far different from those of today. Chemically, this deep weathering also deviates greatly from what is seen in the soil. The weathering that takes place in the soil corresponds to a uniform attack on exposed mineral grains with removal of the reaction products, leading to a rapid decomposition to what is a pure end product - the zone of leaching, which consists mainly of quartz. At greater depth in the basement rocks, the weathering instead occurs in the form of a slow propagation of a reaction front. This involves material transport in two directions over an interface represented by the walls of the water-bearing fractures. Water is supplied to the rock and bound in water-containing aluminosilicates, clay minerals, while cations are leached out or retained to some extent in the newly-formed minerals. The net effect is a volume increase, which can eventually lead to a complete cessation of the flow of groundwater in the fracture. Clay veins and clay zones underground are therefore often completely dry when they are first encountered and before their exposure provides a new supply of water. Both field observations and thermodynamic analysis /8-59/ show that the end product in these cases is a combination of a few mineral phases in local equilibrium or a series of monomineralic zones. The local equilibrium mechanism provides an explanation of why the bedrock next to the weathering zones is essentially unaffected and why the chemical composition of the groundwater in granitic bedrock is not in equilibrium with its essential minerals, feldspars and quartz.

Although recent weathering is taking place for the most part in the uppermost metre of the topsoil and its further progress is dependent to a high degree on an unknown future climatic development, the future effects of weathering in the bedrock can nevertheless be predicted on the basis of the study of older weathering products and underlying chemical principles. Ongoing processes are causing the zone of leaching in the ground to grow slowly downward until the available soil has been "consumed". In the meantime, the hydraulic conductivity of the deeper bedrock may decline further due to calcite precipitation. Subsequently, the weathering may attack calcite-filled fractures and the grain boundaries in the upper part of the bedrock, which is followed by a beginning kaolinite formation. The higher erosional surfaces in Västerbotten County, see section 8.3, that were formed some ten million years ago show that this process has there reached at the most about ten metres down into the bedrock and has been almost completely removed by the subsequent glaciations. It therefore appears unreasonable to expect that an even more extensive kaolinite formation corresponding to the present clay zones at depth in the bedrock, which are insignificant in themselves, should occur within one million years.

8.9 GLACIATION

There is no reason to believe that the most recent glaciation will be the last. A new glaciation would cause the bedrock to once again be burdened with an ice cap that might reach a thickness of a couple of km. Human beings, animals and plants would be displaced to ice-free regions. Precipitation would be stored in the ice mass and the ice cap, which is plastic and impenetrable to water in its interior would prevent melt water from reaching down to the ground over the entire area covered by the ice cap, except in the marginal zones.

Thus, the ice cap prevents infiltration into the bedrock and the rate of groundwater turnover will be less, if any. On the basis of what is known about previous glaciations, the duration of this ice age can be estimated at from several tens of thousands to a hundred thousand years or more.

The effects of the ice cap on the groundwater in the bedrock and the influence of this on a repository are difficult to predict in detail. One main effect of the long-lasting shielding must be that hydraulic gradients in the ground will approach zero and that the deep groundwater movements will tend to cease altogether. As a result, chemical reactions and transport processes in the bedrock will also tend to cease. This will delay the corrosion of the copper canisters in the repository and lengthen their life.

During periods of glacial retreat, the melt water on top of the ice moves out to its thinner margins, where it can find its way down through cracks and meltholes, finally flowing out in short ice tunnels next to and underneath the edge of the ice. Our eskers, as well as studies of present-day glacier tunnels, provide a good picture of these processes. The size of the stones in certain esker layers indicates short periods with very high water pressure and great transport capacity in the ice tunnels. Since the eskers largely follow the fracture valleys in the landscape, i.e. the groundwater's normal outflow zones, it can be envisioned that locally high water pressures might lead to situations with "reversed" groundwater flow, i.e. inflow in these zones. At such times, heavy melting occurs, and then the retreat of the edge of the ice will also be rapid. The effects will therefore be relatively brief and local. During the melting stage, the rate of surface water turnover increases and higher dilution effects are obtained on any groundwater outflows than under present-day conditions. This applies to an even greater degree to those parts of the country that are covered by the sea or large ice-dammed lakes. However, these favourable effects are without importance as long as the canisters are intact.

The depression of the earths' crust underneath the ice sheet, as well as its uplift during the retreat of the ice sheet, and the block movements that can occur in this context have been dealt with previously. During the advance and retreat of the ice, both block movements and elevated earthquake activity can be expected. The increased load of the ice should reduce the hydraulic conductivity and pore volume of the bedrock, which also is expected to lead to reduced groundwater flow during the glaciation.

A continental ice sheet also affects the bedrock mechanically. The result of earlier glaciations have left their imprint on the detailed forms of our present-day landscape, but the general topography derives largely from earlier stages. In the type of flat terrain that characterizes most of our country, the cumulative erosion caused by the glaciers has normally been limited to a few tens of metres. A total removal of younger cover rocks and exposure of the Precambrian bedrock may have occurred in certain areas. Wherever the cover rocks were already gone before, the ice sheets, with rare and local exceptions, have removed the uppermost weathered portions of the Precambrian rocks. If a renewed weathering takes place before a new glaciation, the weathered portions will probably once again be removed.

An elevated hydraulic conductivity has been observed in the upper part of the bedrock at all investigated sites. It is considered to be primarily due to the near-surface reduction of the load from overburden in combination with horizontal stresses in the rock. To some extent, the mechanical action of the ice during previous glaciations may also have contributed to this effect. If so, some further increase of the near-surface conductivity values and some deepening of the fractured zone might occur. Because the present-day quality and thickness of the near-surface rock represents the cumulative effect of several previous glaciations and the fractured shallow zone protects deeper levels, these effects of further mechanical action should be marginal. In this context, it should be borne in mind that most of the country's rock facilities are located in what has here been called near-surface rock and that the rock quality in these facilities is good in comparison with corresponding locations in areas that have not been glaciated. The hydrological effects of the ice ages and the processes of weathering are dealt with in chapter 6.

In summary, it can be concluded that a future glaciation would create an extra barrier which will exist in many thousands of years. Groundwater movements would tend to cease and associated corrosion and transport processes be delayed. Conditions at the end of and immediately following a glaciation are locally highly varying and difficult to predict in detail. During the period of glacial retreat, the groundwater recipients would generally be considerably larger than now and characterized by a higher rate of water turnover. Minor block movements can occur, but the general land forms, as well as the quality of the rock, will not be altered significantly. It is evident from the present-day quality of the bedrock that the effects of repeated glaciations are primarily restricted to its upper part, while the bedrock at a depth of several hundred metres remains virtually unchanged.

REFERENCES

CHAPTER 5

5-1 AHLBOM K, CARLSSON L, CARLSTEN L-E, DURAN O, LARSSON N-Å, OLSSON
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Fjällveden.
Swedish Geological KBS TR 83-52, May 1983.

5-2 AHLBOM K, ALBINO B, CARLSSON L, NILSSON G, OLSSON O, STENBERG L, TIMJE H
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Gideå.
Swedish Geological
KBS TR 83-53, May 1983.

5-3 AHLBOM K, ALBINO B, CARLSSON L, DANIELSSON J, NILSSON G, OLSSON O, SEHLSTEDT S, STEJSKAL V, STENBERG L
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Kamlunge.
Swedish Geological
KBS TR 83-54, May 1983.

5-4 AHLBOM K, CARLSSON L, GENTZSCHEIN B, JÄMTLID A, OLSSON O, TIREN S
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Svartboberget.
Swedish Geological
KBS TR 83-55, May 1983.

5-5 SCHERMAN S
Förarbeten för platsval, berggrundsundersökningar.
("Preliminary studies for site choice, bedrock studies.")
KLOCKARS C-E, PERSSON O
Berggrundvattenförhållanden i Finnsjöområdets nordöstra del.
("Groundwater conditions in the northeastern sector of the Finnsjö district.")
Geological Survey of Sweden.
KBS TR 60, January 1978.

HULT A, GIDLUND G, THOREGREN U
Permeabilitetsbestämningar.
("Permeability determinations.")
MAGNUSSON K-Å, DURAN O
Geofysisk borrhålsmätning.
("Geophysical borehole survey.")
Geological Survey of Sweden
KBS TR 61, January 1978.

ALMÉN K-E, EKMAN L, OLKIEWICZ A
Försöksområdet vid Finnsjön. Beskrivning till berggrunds- och jordartskartor.
("The test area at Finnsjön. Description for bedrock and soil maps.")
Geological Survey of Sweden
KBS TR 79-02, November 1978.

OLKIEWICZ A, SCHERMAN S, KORNFÄLT K-A
Kompletterande berggrundsundersökningar inom Finnsjö och Karlshamnsområdena.
("Supplementary bedrock studies within the Finnsjö and Karlshamn areas.")
Geological Survey of Sweden
KBS TR 79-05, 1979-02-02.

AHLBOM K, CARLSSON L, GIDLUND G, KLOCKARS C-E, SCHERMAN S, THOREGREN U
Utvärdering av de hydrogeologiska och berggrundsgeologiska förhållandena på Sternö
("Evaluation of the hydrogeological and bedrock geological conditions on the Sternö peninsula.")
Geological Survey of Sweden, Bedrock Bureau
KBS TR 79-09, February 1979.

AXELSSON C-L, CARLSSON L
Model calculations of groundwater conditions on Sternö peninsula.
Geological Survey of Sweden
KBS TR 79-10, September 1979.

DURAN O, MAGNUSSON K-Å
Geofysisk borrhålsmätning
("Geophysical borehole measurement.")
Geological Survey of Sweden
KBS TR 79-12, February 1979.

5-6 CARLSSON L, GIDLUND G, HESSELSTRÖM B
I: Evaluation of the Hydrogeological Conditions at Finnsjön.
II: Supplementary Geophysical Investigations of the Sternö Peninsula
Swedish Geological
KBS TR 83-56, May 1983.

5-7 THOREGREN U
Final Disposal of Spent Nuclear Fuel - Standard Programme for Site Investigations.
Swedish Geological
KBS TR 83-31, April 1983.

5-8 AHLBOM K, CARLSSON L, OLSSON O
Final Disposal of Spent Nuclear Fuel - Geological, Hydrogeological and Geophysical Methods for Site Characterization.
Swedish Geological
KBS TR 83-43, May 1983.

5-9 ALMEN K, HANSSON K, JOHANSSON B-E, NILSSON G, ANDERSSON O, WIKBERG P, ÅHAGEN H
Final disposal of Spent Nuclear Fuel - Equipment for Site Characterization
Swedish Geological, IPA-Konsult AB, Royal Institute of Technology, SKBF/KBS
KBS TR 83-44, May 1983.

CHAPTER 6

6-1 DE WIEST R J M
Geohydrology
John Wiley & Sons Inc, New York 1967, second printing.

6-2 NORTON D, KNAPP R
Transport phenomena in hydrothermal systems: The nature of porosity.
Am Journal of Science, Vol 277, pages 913-936, Oct. 1977.

6-3 ÖQUIST U
Measurements of Electrical Properties of Rock and its Application
to Geophysical Investigation of Ores and Waste Disposals.
Doctoral Thesis, Royal Institute of Technology, 1981.

6-4 CARLSSON L, GIDLUND G, HESSELSTRÖM B
I: Evaluation of the Hydrogeological Conditions at Finnsjön.
II: Supplementary Geophysical Investigations of the Sternö Peninsula. Swedish Geological
KBS TR 83-56, May 1983.

6-5 GUSTAFSSON E, KLOCKARS C-E
Studies on Groundwater Transport in Fractured Crystalline Rock under
Controlled Conditions using Non-radioactive Tracers
Geological Survey of Sweden
KBS TR 81-07, April 1981.

6-6 CARLSSON L, GIDLUND G, HANSSON K, KLOCKARS C-E
Estimation of Hydraulic Conductivity in Swedish Precambrian
Crystalline Rock.
Proc Workshop on Low Flow Permeability Measurements in Largely
Impermeable Rocks, OECD Paris March 19-21 1979, pages 97-115.

6-7 KLOCKARS C-E, PERSSON O, LANDSTRÖM O
The Hydraulic Properties of Fracture Zones and Tracer Tests with
Non-reactive elements in Studsvik.
Geological Survey of Sweden, Studsvik Energiteknik AB
KBS TR 82-10, April 1982.

6-8 LUNDSTRÖM L, STILLE H
Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test
Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns in Crystalline Rock.
SAC-02, 1978.

6-9 AHLBOM K, CARLSSON L, GENTZSCHEIN B, JÄMTLID A, OLSSON O, TIREN S
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Svartboberget
Swedish Geological
KBS TR 83-55, May 1983.

6-10 CARLSSON L, WINBERG A, GRUNDFELT B
Model Calculations of the Groundwater Flow at Finnsjö, Fjällveden, Gideå and Kamlunge.
Swedish Geological, Kemakta Konsult AB
KBS TR 83-45, May 1983.

6-11 FREEZE A R
A Stochastic-Conceptual Analysis of One-Dimensional Groundwater Flow in Non-uniform Homogeneous Media.
Water Resources Research, Vol 11, No.5, October 1975, pages 725-741.

6-12 WARREN J E, PRICE H S
Flow in Heterogeneous Porous Media
Soc of Petroleum Engineers Jour. Sept 1961, pages 153-169.

6-13 DAGAN G
Models of Groundwater Flow in Statistically Homogeneous Porous Formations.
Water Resources Research Vol 15, No.1, February 1979, page 47-63.

6-14 DAGAN G
Analysis of Flow through Heterogeneous Random Aquifer by Method on Embedding Matrix 1. Steady Flow Water Resources Research, Vol. 17, No.1, pages 107-121, Feb 1981.

6-15 CARLSSON A, OLSSON T
Hydraulic Properties of Swedish Crystalline Rocks. Hydraulic Conductivity and its Relation to Depth
Bull Inst Univ Uppsala. N S Vol 7, Uppsala 1977.

6-16 WALSH J B, GROSENBAUGH M A
A New Model for Analyzing the Effect of Fractures on Compressibility
Journal of Geophysical Research, 84, page 3532-3?36, 1979.

6-17 WALSH J B
Effect of Pore Pressure and Confining Pressure on Fracture Permeability
Int J Rock Mech Min Sci & Geomech Abstr, Vol 18, pages 429-435, 1981.

6-18 AHLBOM K, ALBINO B, CARLSSON L, DANIELSSON J, NILSSON G, OLSSON O, SEHLSTEDT S, STEJSKAL V, STENBERG L
Evaluation of the Geological, Geophysical and Hydrogeological Conditions at Kamlunge
Swedish Geological
KBS TR 83-54, May 1983.

6-19 AHLMEN K, HANSSON K, JOHANSSON B-E, NILSSON G, ANDERSSON O, WIKBERG P, ÅHAGEN H
Final Disposal of Spent Nuclear Fuel - Equipment for Site Characterization
Swedish Geological, IPA-Konsult AB, Royal Institute of Technology, SKBF/KBS
KBS TR 83-44, May 1983.

6-20 EARLOUGHER R C JR
Advances in Well Test Analysis
Soc Pet Eng Monograph Series Vol 5
Dallas 1977.

6-21 THUNVIK R, BRAESTER C
Hydrothermal Conditions around a Radioactive Waste Repository.
Royal Institute of Technology, Stockholm
Institute of Technology, Haifa, Israel
KBS TR 80-19, December 1980.

6-22 STOTTLEMYRE J A, WALLACE R W, BENSON G L, ZELLMER J T
Perspectives on the Geological and Hydrological Aspects of Long-Term Release Scenario Analyses
Battelle Pacific Northwest Laboratory PNL-2928, June 1980.

CHAPTER 7

7-1 TULLBORG E-L, LARSON S Å
Fissure Fillings from Finnsjön and Studsvik Sweden.
Identification, Chemistry and Dating.
Swedish Geological
KBS TR 82-20, December 1982.

7-2 ALLARD B, TULLBORG E-L, LARSON S Å, KARLSSON M
Ion Exchange Capacities and Surface Areas of some Major Components and Common Fracture Filling Materials of Igneous Rocks.
Chalmers University of Technology, Swedish Geological
KBS TR 83-64, May 1983.

7-3 JACKS G
Groundwater Chemistry at Depth in Granites and Gneisses
Royal Institute of Technology
KBS TR 78, April 1978.

7-4 ALLARD B, LARSON S Å, TULLBORG E-L, WIKBERG P
Chemistry of Deep Groundwaters from Granitic Bedrock
Chalmers University of Technology, Swedish Geological,
Royal Institute of Technology
KBS TR 83-59, May 1983.

7-5 WIKBERG P, GRENTHE I, AXELSEN K
Redox Conditions in Groundwaters from Svartboberget, Gideå, Fjällveden and Kamlunge.
Royal Institute of Technology
KBS TR 83-40, April 1983.

7-6 ALLARD B
On the pH-Buffering Effects of the CO_2-CO_3^{2-} System in Deep Groundwaters
Chalmers University of Technology
KBS TR 82-25, 1982-12-10.

7-7 RENNERFELT J
Sammansättning av grundvatten på större djup i granitisk berggrund.
("Composition of groundwater deep down in granitic bedrock.")
Orrje & Co
KBS TR 36, 1977-11-07

7-8 JACKS G
Kemi hos berggrundvatten i Blekinge
("Chemistry of groundwater in Blekinge.")
Royal Institute of Technology
KBS TR 79-07, February 1979.

7-9 LAURENT S
Analysis of Groundwater from Deep Boreholes in Kråkemåla, Sternö and Finnsjön
Swedish Environmental Research Institute
KBS TR 82-23, 1982-12-22.

7-10 LAURENT S
Analysis of Groundwater from Deep Boreholes in Gideå
Swedish Environmental Research Institute
KSB TR 83-17, 1983-03-29.

7-11 LAURENT S
Analysis of Groundwater from Deep Boreholes in Fjällveden
Swedish Environmental Research Institute
KBS TR 83-19, 1983-03-29.

7-12 LAURENT S
Analysis of Groundwater from deep boreholes in Svartboberget.
Swedish Environmental Research Institute
KBS TR 83-41, April 1983.

7-13 LAURENT S
Analysis of groundwater from deep boreholes in Kamlunge
Swedish Environmental Research Institute
KBS TR 83-70, May 1983.

7-14 HULTBERG B, LARSON S Å, TULLBORG E-L
Grundvatten i kristallin berggrund
("Groundwater in crystalline bedrock.")
Geological Survey of Sweden
SGU Dnr 41.41-81-H206U, Uppsala 1981.

7-15 ALLARD B
Actinide Solution Equilibria and Solubilities in Geochemical Systems
Chalmers University of Technology
KBS TR 83-35, April 1983.

7-16 TORSTENFELT B, ALLARD B, JOHANSSON W, ITTNER T
Iron Content and Reducing Capacity of Granite and Bentonite
Chalmers University of Technology
KBS TR 83-36, April 1983.

7-17 MEANS J
The Organic Geochemistry of Deep Groundwaters
Battelle Columbus Ohio
ONWI-268, 1982.

7-18 NORDSTROM D K
Preliminary Data on the Geochemical Characteristics of Groundwater at Stripa
OECD-NEA Symposium on Geological Disposal of Radioactive Waste.
In Situ Experiments in Granite
Stockholm 25-27 October 1982.

7-19 FRITZ P, BARKER J F, GALE J E, ANDREWS J N, KAY R L F, LEE D J, COWART J B, OSMOND J K, PAYNE B R, WITHERSPOON P K
Geochemical and Isotopic Investigations at the Stripa Test Site (Sweden)
IAEA-SM-243/6
International Symposium on the Underground Disposal of Radioactive Waste, Otaniemi, Finland, July 1979.

7-20 JOHANSSON B
Groundwater Dating by Means of Isotopes. A Brief Review of Methods for Dating Old Groundwater by Means of isotopes.
A Computing Model for Carbon-14 Ages in Groundwater.
University of Uppsala
KBS TR 80-08, August 1980.

7-21 ALLARD B, TORSTENSFELT B, ANDERSSON K
Sorption Studies of $H^{14}CO_3^-$ on some Geological Media and Concrete
3rd International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, November 1980.
Proceedings Plenum 1981 p 465.

7-22 NERETNIEKS I
Age Dating of Groundwater in Fissured Rock: Influence of Water Volume in Micropores
Water Resources Research 17, 2 (1981) 421.

7-23 TORSTENFELT B, ITTNER T, ALLARD B, ANDERSSON K, OLOFSSON U
Mobilities of Radionuclides in Fresh and Fractured Crystalline Rock
Chalmers University of Technology
KBS TR 82-26, 1982-12-20.

7-24 ALLARD B
Sorption of Actinides in Granitic Rock
Chalmers University of Technology
KBS TR 82-21, 1982-11-20.

7-25 ANDERSSON K, TORSTENFELT B, ALLARD B
Sorption and Diffusion Studies of Cs and I in Concrete
Chalmers University of Technology
KBS TR 83-13, 1983-01-15.

CHAPTER 8

8-1 WELIN E
Tabulation of Recalculated Radiometric Ages Published 1960-1979 for Rocks and Minerals in Sweden
Geol Fören Stockholm Förh 100, 309 (1980).

8-2 KNOLL A H, VIDAL G
Late Proterozoic Vase-shaped Microfossils from the Visingsö Beds, Sweden
Geol Fören Stockholm Förh 102, 207 (1980).

8-3 KRILL A G
Tectonics of the Oppdal Area, Central Norway
Geol Fören Stockholm Förh 102, 523 (1980).

8-4 FLODEN T
Seismic Stratigraphy and Bedrock Geology of the Central Baltic
Stockholm Contr Geol 35, 240 p (1980).

8-5 PRINGLE I R
Rb/Sr Age Determinations on Shales Associated with the Varanger Ice Age
Geol Mag, 109, 6 (1972).

8-6 KVALE A
Major Features of the European Caledonides and their Development. In Ager, D V and Brooks, M: Europe from crust to core, 81. J Wiley & Sons, London (1977) 202 p.

8-7 KRESTEN P, PRINTZLAU I, REX D, VARTIANEN H, WOOLLEY A
New Ages of Carbonatitic and Alkaline Ultramafic Rocks from Sweden and Finland
Geol Fören Stockholm Förh 99, 62 (1977).

8-8 RUDBERG S
Geomorfology i Atlas över Sverige
("Geomorphology in Atlas of Sweden.")
Sv Sällskap Antropol Geogr Generalstaben, Stockholm (1970).

8-9 KRESTEN P, SAMUELSSON L, REX D
Ultramafic Dykes on the Northern Skagerrak Coast of Sweden
Geol Fören Stockholm Förh 103, 285 (1981).

8-10 KUMPAS M G
Mesozoic Development of the Hanö Bay Basin, Southern Baltic
Geol Fören Stockholm Förh 101, 359 (1980).

8-11 RUDBERG S
Västerbottens berggrundsmorfologi
("Bedrock morphology of Västerbotten.")
Geographica, 25 (1954) 457 p.

8-12 LIDMAR-BERGSTRÖM K
Pre-quaternary Geomorphological Evolution in Southern Fennoscandia
Sveriges Geol Unders Ser C, 785 (1982) 202 p.

8-13 HOLLANDER N
Oral communication (August 1982).

8-14 STÅLHÖS G
A Tectonic Model for the Sveco-Karelian Folding in East Central Sweden
Geol Fören Stockholm Förh. 103, 33 (1981).

8-15 LINDOUIST K, LAITAKARI I
Glass and Amygdules in Precambrian Diabases from Orivesi; Southern Finland
Bull Geol Soc Finland, 52:2, 1 (1980).

8-16 EKMAN M, ELIASSON L, PETTERSSON L, SJÖBERG L
Bestämning av landhöjningen i Sverige ur upprepade precisionsavvägningar
("Determination of Land Uplift in Sweden from Repeated Precision Levellings.")
Landhöjning och Kustbygdsförändring. Symposium, 1, 26,
University of Luleå (1982), 282 p.

8-17 MÖRNER N A
The Fennoscandian Uplift in Earth Rheology, Isostasy and Eustasy
N A Mörner ed J Wiley & Sons, New York (1980), 251.

8-18 BALLING N
The Land Uplift in Fennoscandia
Ibid p 297 (1980).

8-19 BJERHAMMAR A
Postglacial Uplifts and Geopotentials in Fennoscandia.
Ibid, p 323.

8-20 BERGQVIST E
Postglacial Land Uplift in Northern Sweden
Geol Fören Stockholm Förh 99, 347 (1977).

8-21 TULKKI P
The Bottom of the Bothnian Bay, Geomorphology and Sediments
Havsforskn inst (Finland) skr 241, 5 (1977).

8-22 HAXBY W F, TURCOTTE D L
Stresses Induced by the Addition or Removal of Overburden and Associated Thermal Effects
Geology, 4, 181 (1976).

8-23 ASKLUND B
Bruchspaltenbildungen im südöstlichen Östergötland
Geol Fören Stockholm Förh, 45, 249 (1923).

8-24 GORBATSCHEV R, SOLYOM L, JOHANSSON I
The Central Scandinavian Dolerite Group in Jämtland, Central Sweden
Geol Fören Stockholm Förh 101, 177 (1977).

8-25 AXBERG S, WADSTEIN P
Distribution of the Sedimentary Bedrock in Lake Vättern, Southern Sweden.
Stockholm Contr Geol 34(2), 15 (1980).

8-26 RÖSHOFF K, LAGERLUND E
Tektonisk analys av södra Sverige, Vättern - N Skåne
("Tectonic Analysis of Southern Sweden, Lake Vättern - Northern Skåne.")
University of Lund, University of Luleå
KBS TR 20, September, 1977
Röshoff K: The tectonic fracture pattern in Southern Sweden
Geol Fören Stockholm Förh 100, 255 (1978).

8-27 LAGERBÄCK R, HENKEL H
Studies of Neotectonic Activity in Central and Northern Sweden
Geological Survey of Sweden
KBS TR 19, September, 1977.

8-28 BJÖRKMAN H, TRÄDGÅRDH J
Differential Uplift in Blekinge Indicating Late-Glacial Neotectonics
Geol Fören Stockholm Förh 104, 75 (1982).

8-29 LARSSON I, LUNDGREN T, WIKLANDER U
Blekinge kustgnejs, geologi och hydrologi
("The Blekinge Coastal Gneiss, Geology and Hydrogeology.")
Geological Survey of Sweden
KBS TR 25, August, 1977.

8-30 LAGERBÄCK R, WITSCHARD F
Neotectonics in Northern Sweden - Geological Investigations
Geological Survey of Sweden
KBS TR 83-58, May 1983.

8-31 ERIKSSON L, HENKEL H, HULT K, JOHANSSON L
Neotectonics in Northern Sweden - Geophysical Investigations
Geological Survey of Sweden, Swedish Geological
KBS TR 83-57, May 1983.

8-32 PUSCH R
Inverkan av glaciation på en deponeringsanläggning belägen i urberg 500 m under markytan
("Influence of Glaciation on a Waste Repository situated in Primary Bedrock 500 m below the Surface of the Ground.")
University of Luleå
KBS TR 89, 1978-03-16.

8-33 RICKARDSON R M, SOLOMON S C, SLEEP N H
Intraplate Stress as an Indicator of Plate Tectonic Forces
J Geophys Res 81, 1847 (1976).

8-34 ALLARD B, LARSON S Å, TULLBORG E-L, WIKBERG P
Chemistry of Deep Groundwaters from Granitic Bedrock
Chalmers University of Technology, Swedish Geological,
Royal Institute of Technology
KBS TR 83-59, May 1982.

8-35 SAMUELSSON L
Palaeozoic Fissure-fillings and Tectonism of the Gothenburg Area, South western Sweden.
Sveriges Geol Unders Ser C 711 (1975) 43 p.

8-36 OLSSON T
Hydraulic Properties and Groundwater Balance in a Soil-Rock Aquifer System in the Juktan Area, Northern Sweden
Striae 12, 1 (1979).

8-37 CARLSSON A, OLSSON T
Water Leakage in the Forsmark Tunnel, Uppland, Sweden.
Sveriges Geol Unders Ser C 734, (1977) 45 p.

8-38 BERGSTRÖM J, BRUUN Å, EK J, GOLD T H, GRANAR L, HENKEL H, KRESTEN P, LARSSON K, LINDEN A, LUND C-E, OLSSON T
Deep Earth Gas in Sweden
Swedish State Power Board, Stockholm 1983.

8-39 VERIÖ A
På jakt efter den obekanta mekanismen i landhöjningen
("Searching for the Unknown Mechanism in the Land Uplift.")
Landhöjning och Kustbygdsförändring
Symposium, 1, 79, University of Luleå (1982) 282 p.

8-40 STEPHANSSON O, BÄCKBLOM G, GROTH T, JOHASSON P
Deformation of a jointed rock mass
Geol Fören Stockholm Förh 100, 287 (1978).

8-41 BERTHELSEN A
Towards a Palinspastic Tectonic Analysis of the Baltic Shield.
Publ of the 26th Intern Geol Congress, Colloque C G, Geology of Europe, Villeneuve D'Ascq (1980).

8-42 STRÖMBERG A G B
A Pattern of Tectonic Zones in the Western Part of the East European Platform
Geol Fören Stockholm Förh 98, 227 (1976).

8-43 TALVITIE J
Seismo-tectonics in Finland
Geol Fören Stockholm Förh 100, 247 (1978).

8-44 GORBATSCHEV R
The Precambrian Development of Southern Sweden
Ibid, 102, 129 (1980).

8-45 PUSCH R
Bergmekanik
("Rock Mechanics.")
Almqvist & Wiksell, Stockholm (1974).

8-46 WITHERSPOON P A, COOK NGW, GALE J E
Geologic Storage of Radioactive Waste: Field Studies in Sweden
Science, 211, 894, 1981.

8-47 PRATT H R
Earthquake Damage to Underground Facilities and Earthquake Related Displacement Fields in Proc Workshop on Seismic Performance of Underground Facilities, ed Marine, I W, du Pont de Nemours & Co, BP 1623, Savannah River Lab, Aiken, SC, 43, (1981), 370 p.

8-48 McCLURE, C R
Damage to Underground Structures during Earthquakes
Ibid, p 74.

8-49 BÅTH M
Earthquakes in Sweden 1951-1976.
Sveriges Geol Unders Ser C, 750 (1979) 79 p.

8-50 BÅTH M
Focal Depth Distribution of Swedish Earthquakes.
Tectonophysics 53, T 29 (1979).

8-51a SLUNGA R
Research on Swedish Earthquakes 1980-1981.
FOA Rapport C 20477-T1, Swedish Defence Research Institute, Stockholm (1982), 189 p.

8-51b SLUNGA R
Fault Mechanisms of Fennoscandian Earthquakes and Regional Crustal Stresses
Geol Fören Stockholm Förh 103, 27 (1981).

8-52 BUNGUM H, FYEN J
Hypocentral Distribution, Focal Mechanisms and Tectonic Implications of Fennoscandian Earthquakes 1954-1978.
Geol Fören Stockholm Förh 101, p 261 (1980).

8-53 BÅTH M
Deep-seated Fracture Zones in the Swedish Crust
Tectonophysics 51(3/4), T47 (1978).

8-54 BÅTH M
Zum Studium der Seismizität von Fennoscandia
Gerlands Beitr Geophys 81(3/5), 213 (1972).

8-55 LUND C-E
Crustal Structure along the Blue Road Profile in Northern Scandinavia
Geol Fören Stockholm Förh 101, 191 (1979).

8-56 HUSEBYE E S, BUNGUM H
New Crustal-thickness Results for Fennoscandia
Ibid, 103, 1(1981).

8-57 GARRELS R M
Genesis of some Groundwaters from Igneous Rocks.
In Researches in Geochemistry, 2, 405, Abelson, Ph ed, J Wiley, New York 1967.

8-58 GEIJER P, MAGNUSSON N H
Mullmalmer i svenska järngruvor
("Earthy ores in Swedish Iron Mines.")
Geol Survey of Sweden series C, 338, 1926.

8-59 THOMPSON J B Jr
Local Equilibrium in Metasomatic Processes in Researches in Geochemistry, 427 Abelson, Ph ed, J Wiley, New York 1959.