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# Final disposal of spent nuclear fuel - geological, hydrogeological and geophysical methods for site characterization

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Swedish, Geological, Sweden May 1983

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## SUMMARY

Investigations for the siting of a final repository for high-level radioative waste are currently being conducted in crystalline rock formations in Sweden. A repository will be located at a depth of about 500 m, and investigations are being carried out in drill holes to below that level.

A standard program has been established for the site investigations, comprising a number of phases:

1. General reconnaissance for selection of study site
2. Detailed investigation on the ground surface
3. Depth investigations in drill holes
4. Evaluation and modelling

After completion of the reconnaissance studies, which include geological and geophysical reconnaissance measurements and drilling of one deep drill hole, the detailed investigations of the selected site begin. These investigations include surface and depth investigations within an area of approximately 4-8 $km^2$.

The surface investigations consist of geophysical measurements including electrical resistivity, magnetization, induced polarization and seismic measurements. Together with geological and tectonic mapping, the surface investigations yield information on the composition and fracturing of the bedrock in the superficial parts of the study sites.

Mapping of the superficial parts of the bedrock are concluded with short percussion and core drillholes down to 150-250 metres in order to determine the dip and character of fracture zones and rock boundaries.

The depth investigations are carried out to characterize the rock at depth from the geological and hydrogeological points of view. The investigations comprise core drilling to vertical depths of about 600 m, core mapping, geophysical well-logging and different hydraulic downhole measurements.

In core mapping, the emphasis is placed on fracture characterization of the core. The geophysical logging includes three resistivity methods, natural gamma, induced polarization, spontaneous potential and temperature, salinity, pH and Eh of the drill hole fluid. Geophysical measurements are made on the core samples in the laboratory.

The hydraulic measurements include: measurements of hydraulic conductivity by single-hole and cross-hole testing, determination of the hydraulic fracture frequency and determination of groundwater head at different levels in the bedrock.

The single-hole hydraulic tests are performed in 25 m sections as transient tests with injection and fall-off phases. The hydraulic head is calculated from Horner plots and from direct measurement over a long period.

The hydraulic conductivity values obtained are used in descriptive hydraulic models based on geologic-tectonic models of each site under consideration. In the hydraulic models, the bedrock is subdivided into different hydraulic units. The conductivity values obtained in each unit are used to describe the frequency distribution of the conductivity and to calculate an effective hydraulic conductivity versus depth to be used in further numerical groundwater model calculations.

# 1 BACKGROUND

High-level radioactive waste from nuclear power generation will be terminally stored in underground caverns in the bedrock at a depth of about 500 m, which will be sealed after disposal. The waste will be surrounded by a number of barriers, whose purpose is to prevent radionuclides from reaching the surface of the ground and the biosphere in harmful quantities. The rock comprises one, the last, of these barriers. Studies in connection with the final disposal of radioactive waste have therefore been aimed at finding suitable host rock for the construction of a repository as well as a rock that possesses good properties as a barrier. The properties of the rock that are of importance for storage of radioactive waste are in principle as follows:

- Good stability from a rock mechanics point of view
- Low groundwater turnover
- High sorptive capacity for nuclides
- Stable geological conditions.

Massive research efforts over the past 10-year period have greatly increased our knowledge of the bedrock and its hydraulic characteristics at great depth. This applies in particular to knowledge that is of importance for the storage of radioactive waste.

In order to obtain a broad spectrum of data from deeper parts of the Swedish bedrock, a broadly conceived program of geological, geophysical and hydrological investigations is currently being carried out on the ground surface and in deep drill holes on different investigation sites, known as study sites (Thoregren 1982). The goal is to investigate 10-20 sites with different geological conditions by the year 1990. At the end of the investigation program, an overall evaluation will be made of the Swedish crystalline bedrock which will eventually lead to recommendations that one or more sites be subjected to more detailed studies, including shaft sinking. These detailed studies will serve as a basis for the final design of the repository.

Experience from previous investigations (Hult et al 1978, Olkeiwicz et al 1979, Gidlund et al 1979, Ahlbom et al 1979, Magnusson and Duran 1978, Ekman and Gentzschein 1980, Carlsson et al 1980, Gustafsson and Klockars 1981) has served as a basis for the choice of methods and the scope of the investigations at the study sites. The work has been carried out largely in accordance with a standardized program (Thoregren 1982), with minor changes being made in the work procedures as new experience has been gained.

The sites that have been investigated in accordance with the "Standard Program' are Svartboberget, Gideå, Fjällveden and Kamlungekölen, see figure 1. Certain supplementary studies and data evaluations have been conducted on two previously investigated study sites, Finnsjön and Sternö.

The investigations within each study site have mainly been aimed at shedding light on the safety of the geological barrier in a repository for high-level nuclear waste. The most important factors in this respect are:

- the large-scale fracturing of the bedrock
- the groundwater flow in the bedrock at different depths
- the chemical composition of the groundwater
- the chemical composition of the rock types and the fracture minerals

Groundwater in bedrock occurs and moves mainly in fractures and fracture zones. The properties and orientation of these fractures and fracture zones are of great importance in studies of the groundwater flow in the rock. The chemistry and mineralogy of the bedrock and the fracture fillings are also important factors in studies of the influence of sorption (retention) on radionuclides.

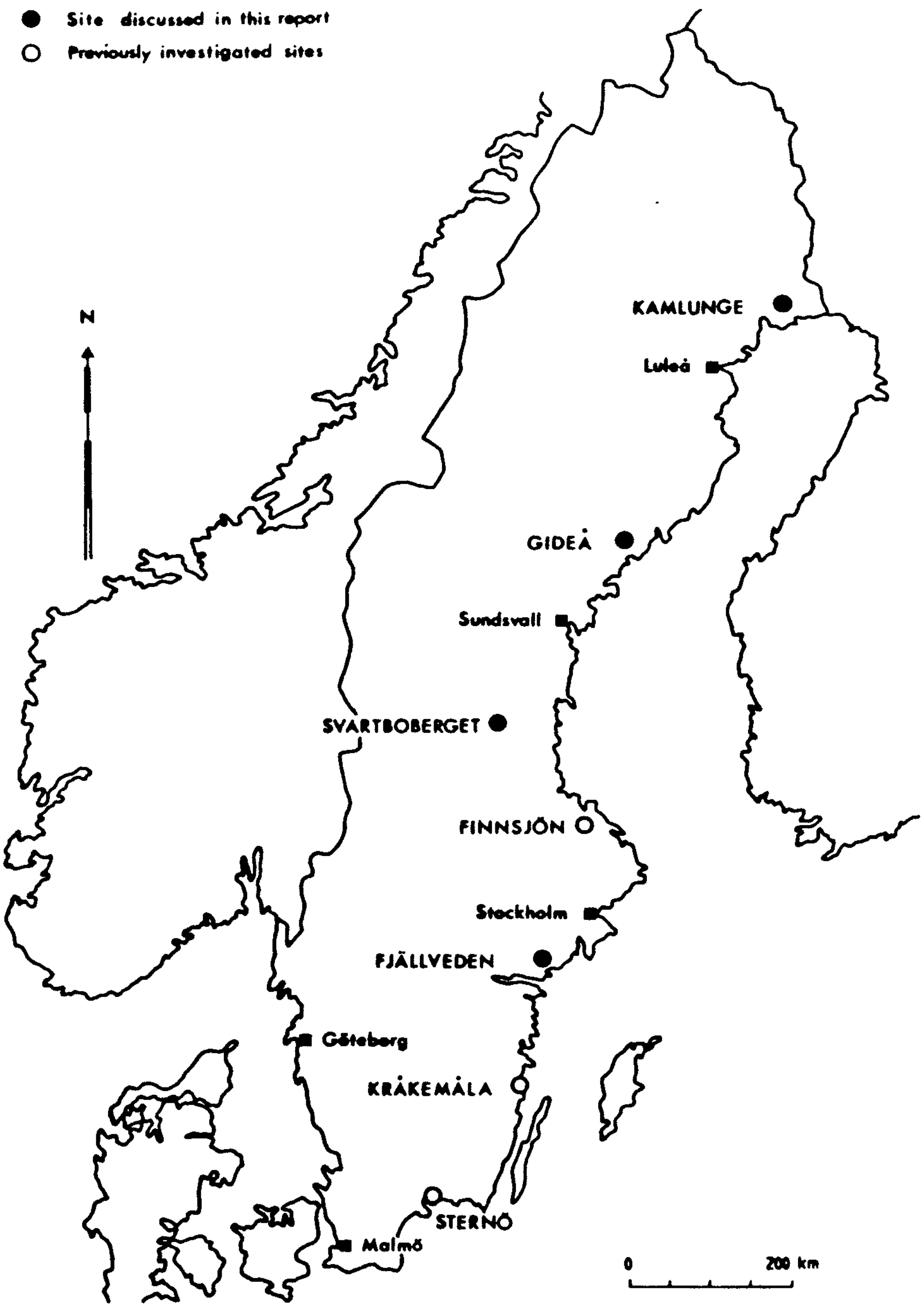

Figure 1 Map of the location of the study sites.

# 2. INVESTIGATION PROGRAM

## 2.1 Different investigation phases

The investigations at the study sites have been carried out in accordance with a standard program (Thoregren 1981). This program is divided into a number of phases that can be described in principle as follows:

1. General reconnaissance for selection of study site
2. Detailed investigations on the ground surface
3. Depth investigations in drill holes
4. Evaluation and modelling

## 2.2 Selection of study site

Reconnaissance studies are carried out for the purpose of selecting one or more study sites during one year. The sites are selected on the basis of a number of factors, the most important of which are:

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

Other factors that also influence the choice of a study site are previous experience from study sites and other underground work, land ownership, access to roads, population structure etc.

After examination of a large number of tentatively selected sites, a smaller number are selected for geological and geophysical reconnaissance studies. On the basis of the results of these studies, a decision is made to drill a reconnaissance drill hole in order to obtain information on the character of the bedrock at depth within the site in question. All gathered information is then evaluated and a decision is made as to whether the area is sufficiently interesting for complete study site investigations, phase 2 of the standard program. The size of the site that is chosen for detailed investigations is approximately 4-8 $km^2$. General geologic-tectonic studies are simultaneously carried out within a larger region encompassing the study site.

## 2.3 Investigations within each study site

### 2.3.1 Surface investigations.

The purpose of surface investigations within the study sites is to determine the bedrock composition and the occurrence of fracture zones and fractures in the superficial parts of the bedrock.

The program includes a detailed mapping of existing rock types plus air-photo interpretation and ground surveys of fracture zones and fractures. At the same time, surface geophysical 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 areas. These surface geophysical measurements include:

- Determination of the electrical resistivity of the bedrock by means of geoelectrical and electromagnetic methods.
- Determination of the magnetization of the bedrock through measurements of variations in the earth's magnetic field.
- Determination of the bedrock's content of metallic minerals by measurement of induced polarization.
- Determination of regions in the bedrock of reduced strength, fracture zones, by means of seismic measurements.

Data from these surface investigations are compiled and a drilling program with short drill holes is carried out in order to study changes in bedrock composition and determine the character and orientation of indicated fracture zones. The technique used for these drill holes is usually percussion drilling, the same technique that is used for drilling water wells in rocks. The length of the drill holes is normally 50-180 metres. Short core drill holes are also used for this purpose. The drill holes are logged by means of different methods, and the results of these loggings, together with the results of other surface investigations, serve as a guide for locating and aiming the deep core drill holes.

In summary, the surface investigations provide knowledge of the composition and fracturing of the bedrock in the superficial parts of the study sites. The fracture zones' manifestation on the ground surface, their character and orientation are also largely determined.

### 2.3.2 Depth investigations

The purpose of the depth investigations is to characterize the rock at depth within the study site from the geological and hydrogeological viewpoint. In particular, the character and water-conducting capacity of the fracture zones as well as the chemistry of the groundwater are studied at great depth.

On the basis of the surface investigations, a number of core drill holes are drilled to a vertical depth of about 600 metres. The drill holes are normally inclined about 60 degrees from the horizontal plane and are about 700 metres in length. In most cases, the core drill holes have been directed towards fracture zones to penetrate them 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 drill cores are mapped and geophysical measurements are made in the drill holes to supplement and add to geological knowledge of the site. Through different hydraulic measurements in the drill holes, the hydraulic properties of the bedrock and the fracture zones are determined. Groundwater samples are taken from various depths in the drill holes for chemical analyses. These analyses are used for dating of the groundwater and for calculations of canister corrosion, nuclide sorption etc.

In summary, the depth investigations yield information on the composition of the bedrock, including its fracture zones and fractures, down to great depth. The capacity of the rock and the fracture zones to conduct groundwater is determined by means of different hydrogeological tests. These data - together with groundwater chemistry, fracture mineralogy etc. - are compiled and evaluated.

## 2.4 Evaluation and modelling

In the evaluation and modelling work, the collected material is processed and the results are compiled into a model of the rock's different hydraulic units. This model then serves as a basis for numerical model calculations of groundwater flow, travel times and transport pathways for the groundwater from a conceived repository up to the biosphere. In addition, the quantities of groundwater that flow through a conceived repository per unit time are calculated (Carlsson, Winberg and Grundfelt 1983).

# 3 SURFACE INVESTIGATIONS

## 3.1 Geological investigations

### 3.1.1 Bedrock geology

The geological investigations on a study site begin with literature studies and, to the extent that modern geological maps are lacking, a regional geological survey of an area of approximately 50-100 $km^2$ around the study site. The bedrock is mapped on exposed outcrops, in particular along existing roads.

A topographical map of the study site is produced from aerial photographs on a scale of 1:5 000 covering an area of 4-8 $km^2$. The elevation contour lines on the map have an equidistance of 2 m. The size of the map is dependent on local geological and tectonic conditions and is chosen so that it includes known rock type boundaries and delimiting fracture zones around a defined rock volume. The size and location of the study site are then defined by the area described by the map.

On the basis of aerial photographs and the detailed topographical map of the study site, a map is made of existing rock outcrops within the study site. These outcrops are checked in the field and newly-discovered outcrops are added to the map. The bedrock is mapped on all outcrops and a geological bedrock map is drawn up on the basis of the detailed topographical map. Rock outcrops, rock types, structures and core drill holes are indicated on this map. An example of a detailed geological map from the Kamlunge study site is shown in figure 3.1.1.

Samples of existing rock types are taken for chemical analysis and for making microscopically thin sections. The number of samples within a study site is normally 10-20. The samples are taken from rock outcrops by extracting rock specimens with a hammer. Besides providing information on the general chemical content of the rocks, the chemical analyses yield information on degree of oxidation, sulphide minerals and the origin and degree of alteration of the bedrock. The rocks' mineral content, grain boundaries, microfissures etc. are investigated by studies of miscroscopically thin sections.

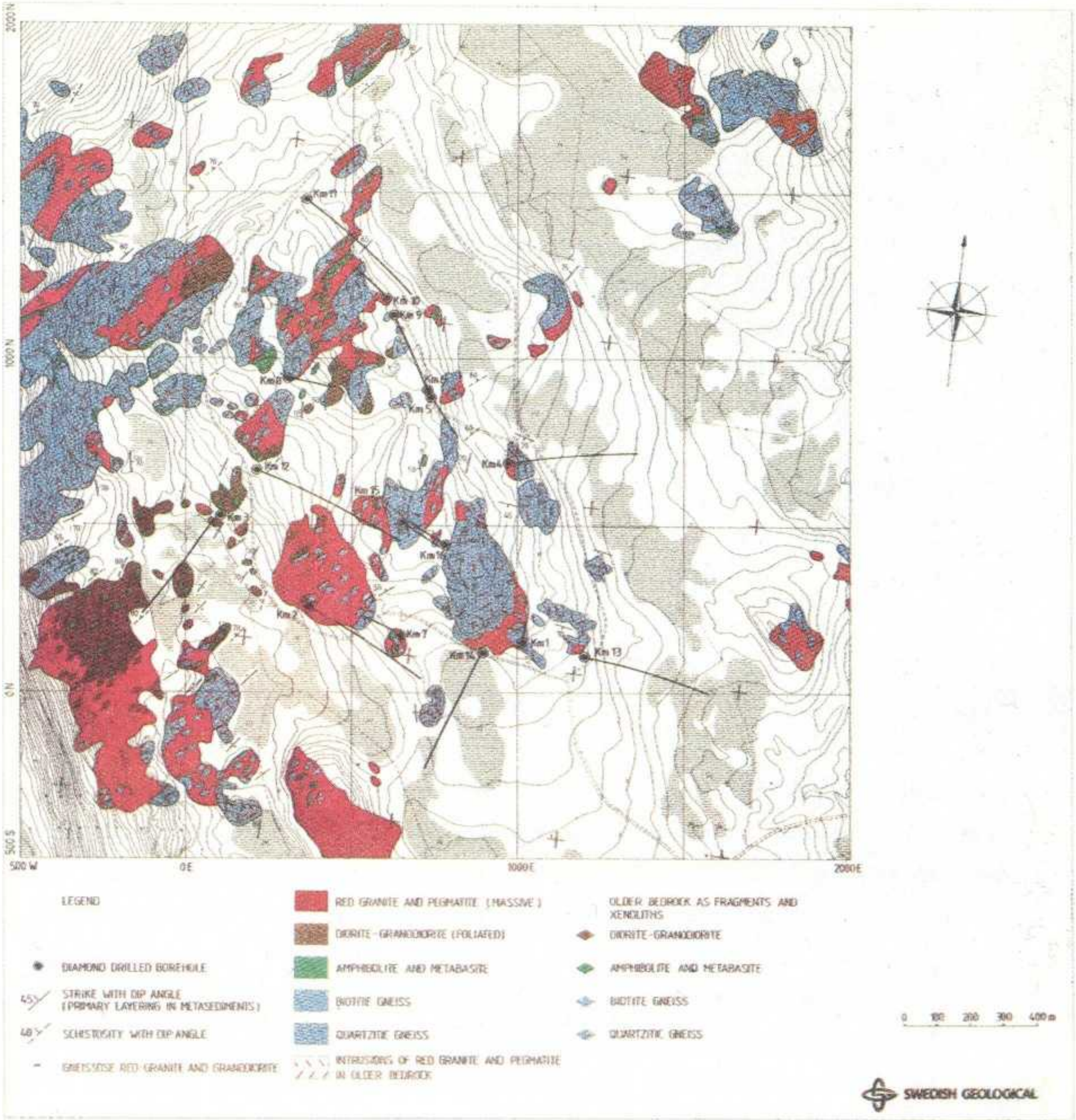

Figure 3.1.1 Detailed map of the bedrock at the Kamlunge site.

### 3.1.2 Regional fracture zones

Regional lineaments around a study site are studied from aerial photographs and topographical maps. The lineaments that are studied are valleys and other topographical indications of fracture zones. The lineaments are divided into well-defined and poorly-defined lineaments and are presented on lineament maps of the study sites. The orientation of the glacial striae is of importance in lineament studies of this type and is therefore indicated on the lineament maps. The eroding effect of the inland ice in fracture zones and other readily-eroded portions of the bedrock can exaggerate the proportions of lineaments in the direction of the glacial striae. Sediments deposited in connection with deglaciation can be incorrectly interpreted in some cases as indications of fracture zones. An example of an air-photo interpreted lineament map for the Fjällveden study site is presented in figure 3.1.2.

### 3.1.3 Fracture zones at the study sites

The position, orientation, continuity and water-conducting capacity of the fracture zones are of the utmost importance in studies of groundwater conditions in the bedrock. Most of the investigations on the study sites are therefore aimed at locating and characterizing existing fracture zones.

Fracture zones are located from the results of geological and geophysical investigations. The latter investigations are described in section 3.2. The principal geological method for locating fracture zones is detailed aerial photo interpretation. This interpretation is performed on black-and-white and infra-red aerial photographs with stereo coverage on a scale of 1:30 000. The instruments used for aerial photo interpretation are the stereoscope and the interpretoscope.

All air-photo interpreted lineaments that are judged to be manifestations of fracture zones are transferred to an interpretation map. The map is then supplemented and revised with information on fracture zones from the geological field studies and the surface geophysical measurements. The geological indications of fracture zones that can be studied on outcrops are primarily an increase of the fracture frequency and reddening and tectonization of the bedrock. Normally, however, these indications cannot be observed directly in

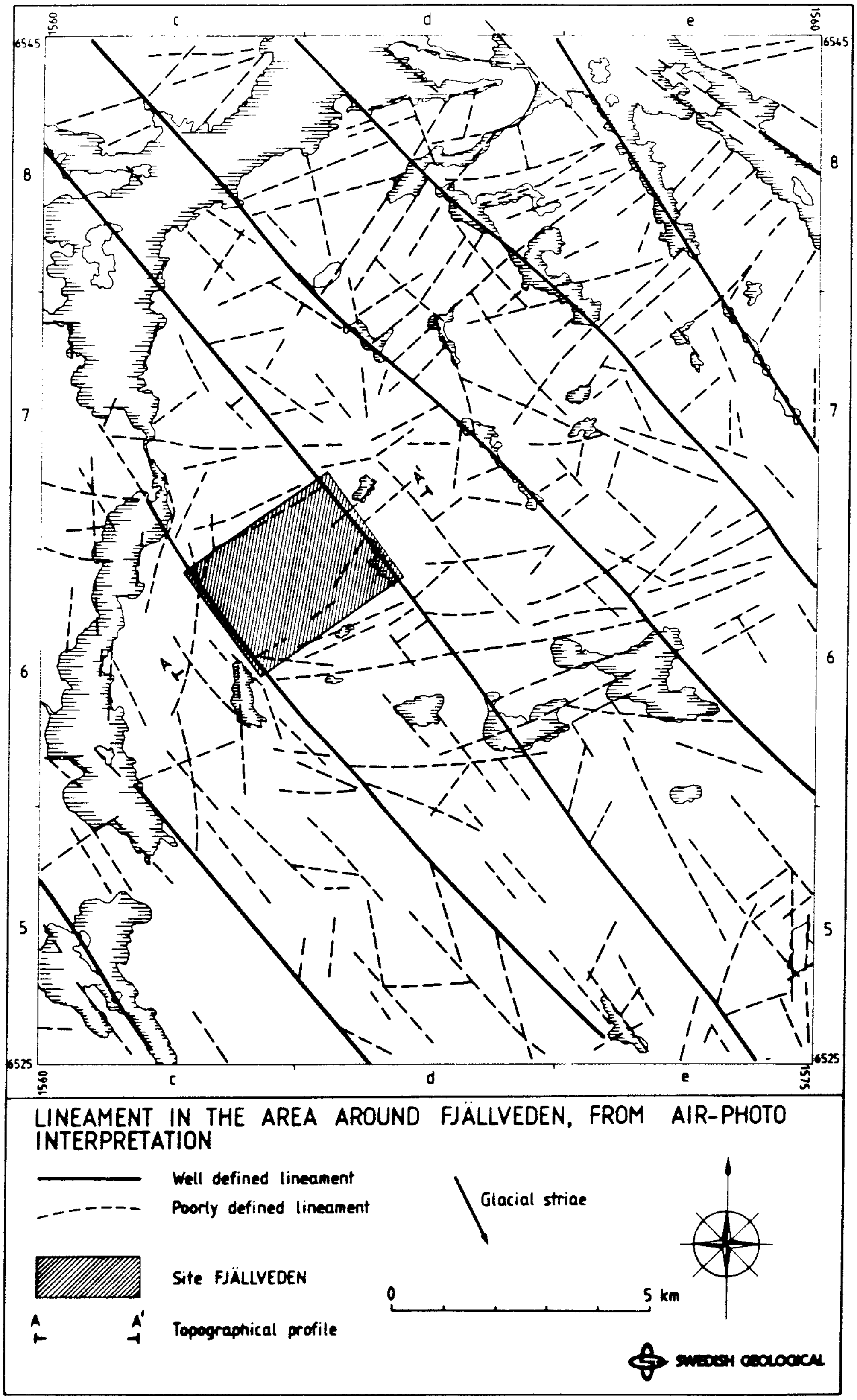

Figure 3.1.2 Lineaments at the Fjällveden site mapped from aerial photos.

the field. It is more common for fracture zones to emerge through topographical indications such as valley depressions, soil-filled dikes through outcrop areas, jags in the bedrock topography etc.

### 3.1.4 Percussion drill holes and short core drill holes

The surface investigations are concluded with short percussion and core drill holes. These drill holes are used to investigate probable fracture zones and to determine the dip, width and character of the fracture zones.

The percussion drill holes are of the same type as ordinary drilled rock water wells. Their diameter is 115 mm and the holes are usually made 50-180 metres long.

Fracture zones are normally investigated by means of at least two percussion drill holes drilled from either side of the fracture zone in towards it. At certain places, the dip of the fracture zone can be calculated on the basis of geophysical measurements. In these cases, a percussion drill hole is drilled from the hanging side of the fracture zone towards the zone. If the fracture zone is encountered at the calculated depth, the zone is considered to be defined. The method described above means that the drill holes are normally inclined, between 45 and 60 degrees from the horizontal plane.

Percussion drilling yields information on the water-conducting capacity of fractures and fracture zones at different depths by regularly measuring how much water flows per unit time into the drill hole after the drill hole has been blown clean. This estimate is only a very rough qualitative evaluation of the hydraulic properties of the bedrock adjacent to the drill hole.

The drilling rate is measured in connection with percussion drilling. Variations in this rate provide information on fractures and fracture zones as well as certain changes in rock type. An example of a record of the drilling rate and water inflow during percussion drilling in Fjällveden is shown in figure 3.1.3.

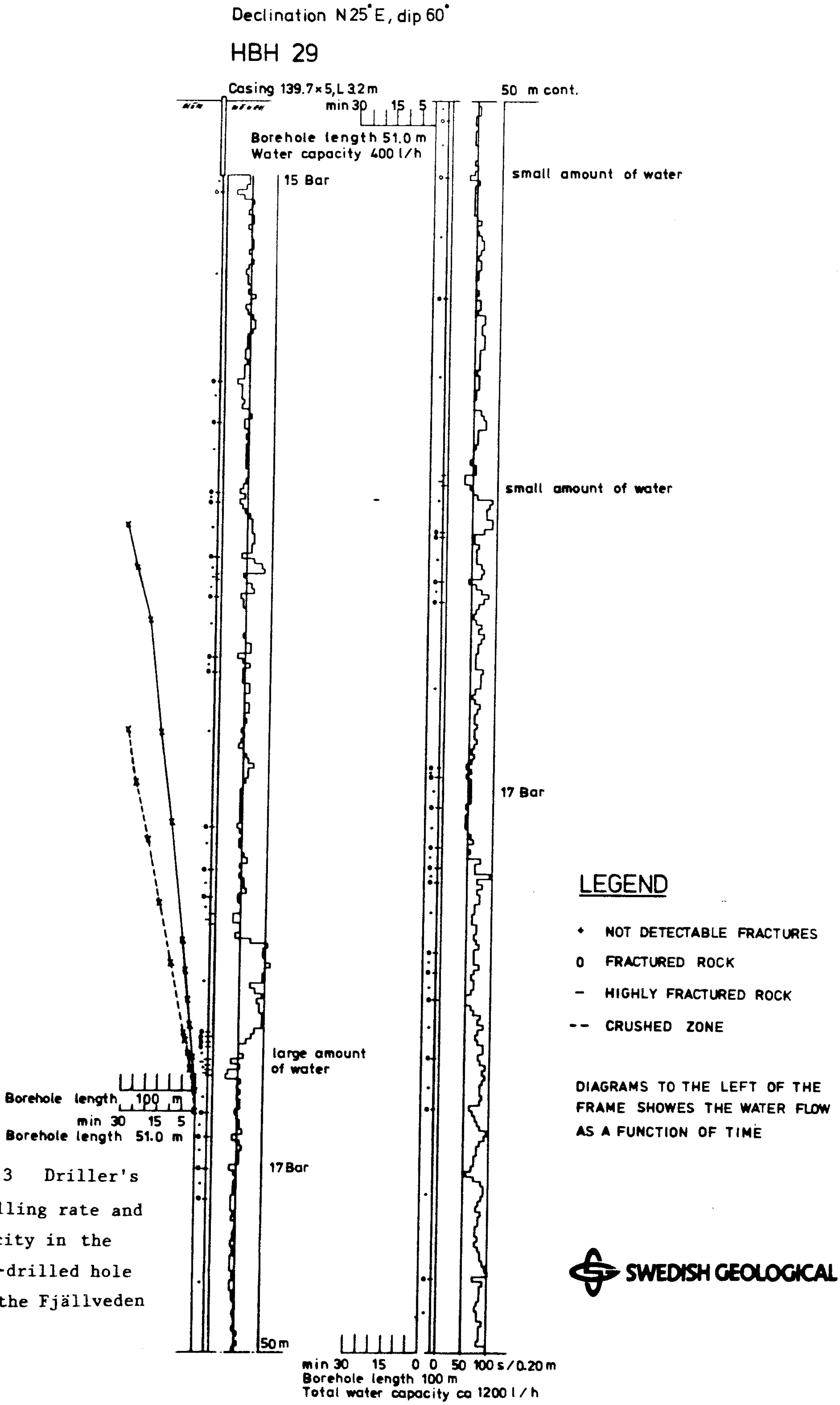

Figure 3.1.3 Driller's log of drilling rate and water capacity in the percussion-drilled hole HFj 29 at the Fjällveden site.

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Drill cuttings are sampled at regular intervals, usually every 25 metres, and when a change in the colour of the cuttings or the drilling water is observed. Information on rock type composition is then obtained by means of chemical and mineralogical analyses of cutting samples.

In order to obtain supplementary information on fracture zones and rock type changes, the percussion drill holes are investigated by means of the geophysical methods of point resistance and natural gamma radiation. These methods are described in greater detail in section 4.2.

Percussion drill holes are also drilled in order to supply the core drilling machines with drilling water, to obtain observation holes for determining groundwater level or to obtain pump holes or observation holes for hydraulic interference tests. These latter measurements are described in section 4.3.

An example of how percussion drill holes are used to study fracture zones is given in figure 3.1.4. This example shows how a valley in Gideå has been systematically investigated by means of percussion drill holes and how this has permitted the location of a shallow dipping fracture zone. The rate of water inflow for the different percussion drill holes is also indicated in the figure. Water inflow varies widely between different drill holes in the same fracture zone and is associated not only with the hydraulic conductivity of the fracture zone, but also with its continuity.

Short core drill holes have also been used to study fracture zones and rock type variations. The diameter of the core drill holes is 56 mm and their length varies between 50 and 250 metres. The same technique is used for setting out the core drill holes as for the percussion drill holes. The drill core is mapped with respect to rock type and fractures (see section 4.1) and the drill hole is logged with the standard complement of geophysical logs (see section 4.2). These core drill holes, with loggings, end up being more costly than equivalent percussion drill holes. However, the results are more reliable for the interpretaton of fracture zones and rock type variations. Valuable information on water-conducting fractures and fracture zones is obtained from records of drilling water losses during drilling. No measurement is made of the hole's water capacity, however.

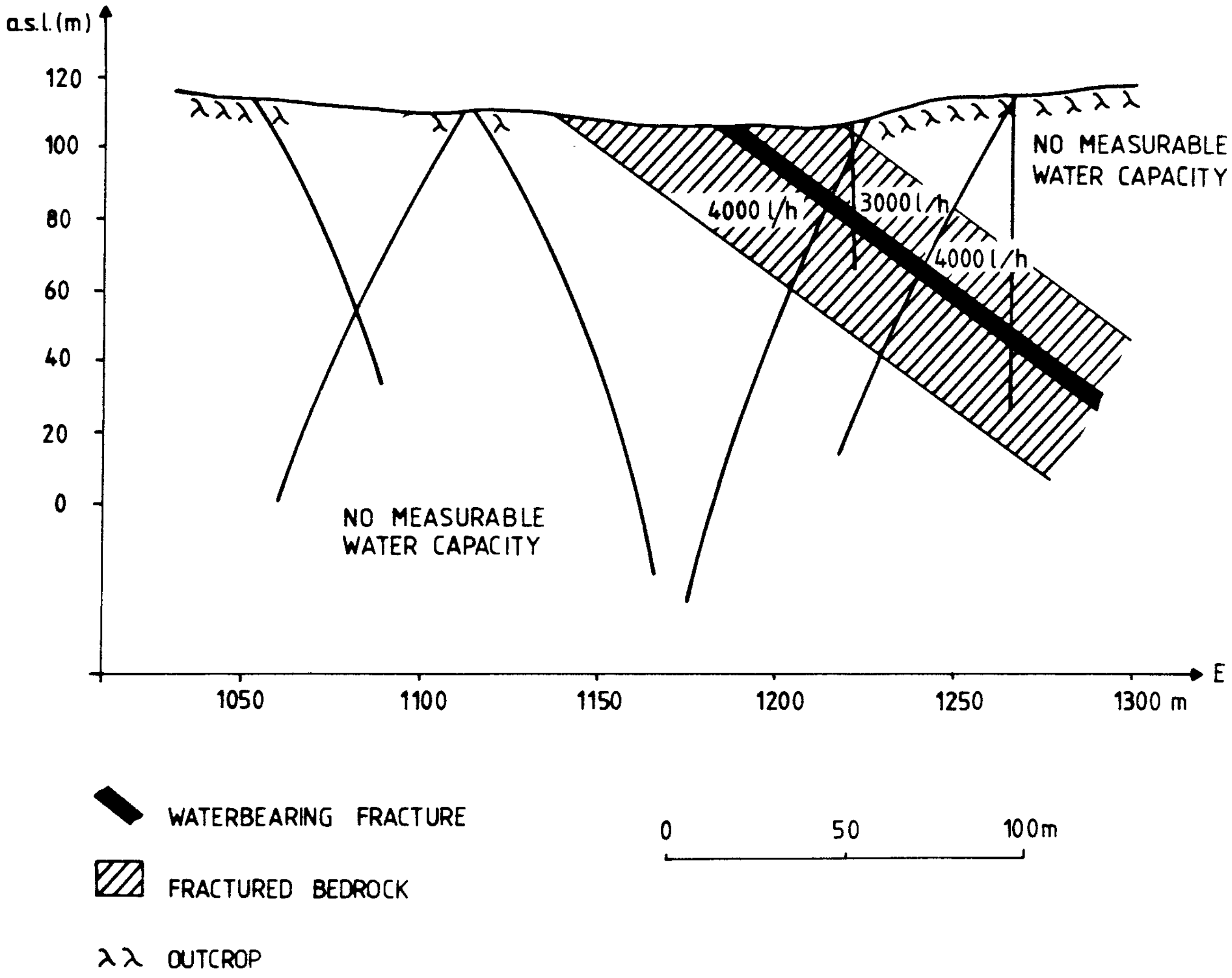

Figure 3.1.4 Results from percussion drilling in a fracture zone at Gideå.

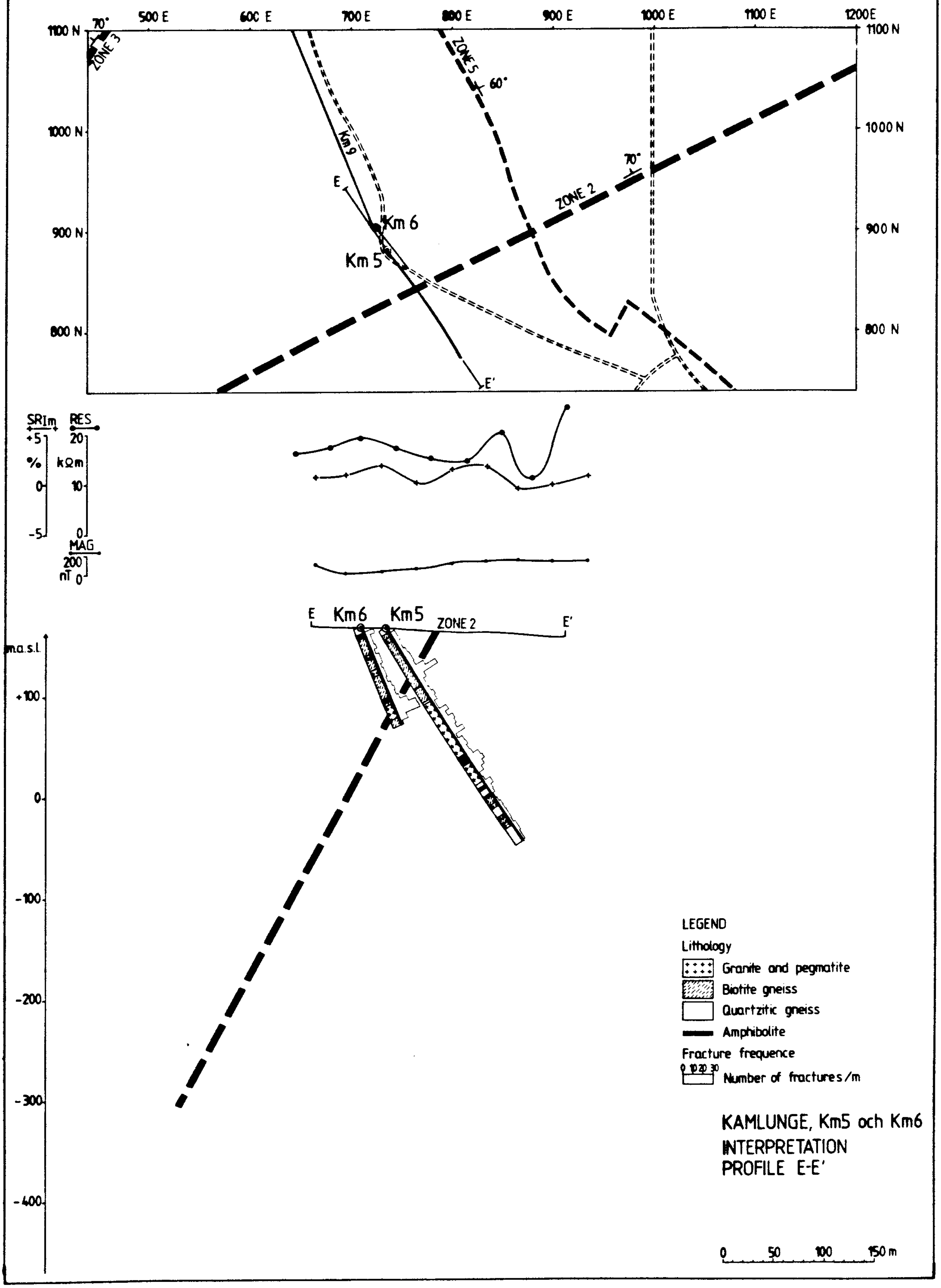

Figure 3.1.5 Investigation of a fracture zone at Kamlunge by means of two short core-drilled holes.

A fracture zone has been penetrated by core drill holes at two different levels on the Kamlunge study site, see figure 3.1.5. This permits the fracture zone's variation in width, fracturing, chemical alteration etc. to be studied. In addition, variation in hydraulic capacity in the zone can be studied by means of water injection tests (see section 4.3).

## 3.2 Geophysical investigations

### 3.2.1 Scope

The surface investigations within a study site are aimed at obtaining information on fracture zones and rock type distribution. Such knowledge must also be obtained within soil-covered areas and for bedrock at greater depth. For this purpose, different geophysical methods are used. The use of the geophysical methods to investigate the bedrock is based on the fact that physical differences that are measurable by means of different instruments exist between different rock types and between intact and crushed rock. Measurements on the ground surface can yield information on the properties of the rock beneath the soil cover and some distance down into the bedrock. A description of the properties and location of fracture zones in the rock where groundwater transport may possibly occur is of particular interest.

A fracture zone is a zone in which the bedrock is crushed. Chemical changes normally occur along the zones. These conditions usually cause changes in different properties in a fracture zone, such as:

- a reduction of seismic velocity due to increased fracturing, i.e. reduction in mechanical strength.

- an increase of electrical conductivity due to increased water content.

- a change in magnetic properties due to e.g. oxidation.

- a decrease in density due to crushing.

A number of geophysical methods can be used to detect such zones. However, the possibility of detecting and characterizing fracture zones is dependent upon the type of rock in which the measurements are made. This is due to the fact that there are different minerals in the bedrock with certain properties similar to those of fracture zones. A brief account of the principles on which the geophysical methods are based and which properties can be measured is presented in the following sections. As a general reference to the methods used, see Parasnis (1979) and Telford, Geldart, Sheriff and Keys (1976).

The scope of the geophysical program consists in the normal case (the Standard Program) of:

- dense surface measurement (40 x 20 metre grid) on an area of 4 $km^2$ by means of the slingram (horizontal loop EM), magnetometer, resistivity and induced polarization (IP) methods.

- regional profile measurements, 40 km with VLF (H-mode far-field EM), slingram and magnetometer.

- refraction seismic profiles 4 km.

- physical parameter measurements on rock samples.

A modification of the standard program is made depending on actual conditions within the study site.

The dense measurement within the study site is carried out within a staked-out and clearly marked area. The stake system is geodetically anchored in the terrain and has been reproduced on the topographic map, so that the measurement results can be assigned to specific locations on the topographic map with great accuracy, on the order of 5 m.

### 3.2.2 Magnetic measurements

In magnetic measurements, variations in the natural magnetic field of the earth are measured. Anomalies in the total magnetic field are caused by the fact that different types of rock have different magnetizations. The appearance and size of the anomalies depend on the difference in magnetization between different rock types and variations of magnetization within a rock type.

The magnetization of a rock is primarily determined by the rock's content of magnetic minerals, mainly magnetite and magnetic pyrhotite. The distribution of these magnetic minerals in a rock gives rise to a pattern of anomalies that is characteristic for the rock type, which may be banded or irregular.

From the magnetic anomaly map, it is possible to determine rock type boundaries, dips of contacts, intrusions of e.g. dolerite etc. Magnetic minima caused by an oxidation of magnetite to haematite usually occur over fracture zones which pass through magnetic anomalies (Henkel and Guzman, 1977). Interruptions, deformations and side shifts in magnetic anomaly structures can reveal faults, magnitude of displacements and existence of fracture zones (Henkel 1979). In general, these magnetic zones of disturbance today reflect both open and closed fracture zones. They can, for example, consist of older fractures that have sealed.

The magnetic field is measured with a proton magnetometer, and data is stored directly in the field in a digital memory. The magnetic field can be measured to an accuracy of 1 nT. The daily variations in the magnetic field are generally much greater than the measuring accuracy of the instrument. By measuring the magnetic field at a permanent station, known as a base station, at the same time as the measurement is being carried out along a measurement profile, it is possible to make a correction for the daily variation of the magnetic field. After these corrections, the measuring accuracy that is achieved in practice is better than 10 nT.

The depth extent or vertical range of the magnetic method is primarily dependent on the susceptibility contrast and size of the magnetic rock formation. In some cases, large rock complexes located at a depth of several kilometres can be detected. In general, however, the vertical range in the case of a surface measurement within a small area is limited to a few hundred metres.

The magnetic measurements are evaluated by studying the overall pattern of the anomalies in order to be able to draw conclusions on the geological causes of the anomalies. In addition, model calculations are carried out using well-known formulae (e.g. Parasnis 1979, Telford, Geldart, Sheriff and Keys, 1976) by means of which it is possible to calculate the depth, width, dip and magnetization of a magnetic body.

### 3.2.3 Electromagnetic measurements

Electromagnetic measurement methods include VLF (Very Low Frequency H-made far-field EM) and slingram (horizontal loop EM).

In VLF measurement, the magnetic field strength is caused by remote military radio transmitters with low frequency (15-25 kHz). The electromagnetic field from a VLF transmitter has a magnetic vector that is essentially horizontal and perpendicular to the direction of the transmitter and an electrical vector that is virtually vertical. The properties of the bedrock affect the propagation of the electromagnetic wave and give rise to anomalies that provide information on the structure of the bedrock.

The anomalies in the magnetic field are mainly caused by induction in geological structures that are better conductors than their surroundings. An increase in electrical conductivity in the bedrock occurs either when there is a mineralization with good electrical conductivity or when the amount of water increases, for example in fracture zones. On the basis of the characteristics of the anomaly, it is possible to estimate the location, dip and relative conductance of a conductive structure. The magnetic field does not give rise to any induction in geological structures with a strike perpendicular to the direction of the transmitter. This direction is therefore also called the "dead angle". In surface measurement, it is possible to avoid the problem of the directional dependence of the VLF method by using two different transmitter stations. In the measurements performed in connection with the study site investigations, one transmitter station in England (GBR) and one in Norway (JXE) have generally been used. The direction to these two stations is then roughly southwest in the first case and northwest to north in the second case, depending on where in the country the study site is located.

A small radio receiver with two perpendicular coils is generally used for measuring the VLF field. The coils are oriented in a given manner in relation to the VLF transmitter, and the ratio between the field strength in the coils is measured (Paterson and Ronka, 1971), figure 3.2.1. In principle, the measurement yields a value of the vertical component of the anomalous field in the measuring point as a percentage of the primary field, i.e. the field that would have existed if there had been no disturbances (fracture zones). A division of the secondary field into a real (in phase) and an imaginary ($90^{o}$ out of phase) component is also obtained. The accuracy of the measurement is approximately one per cent.

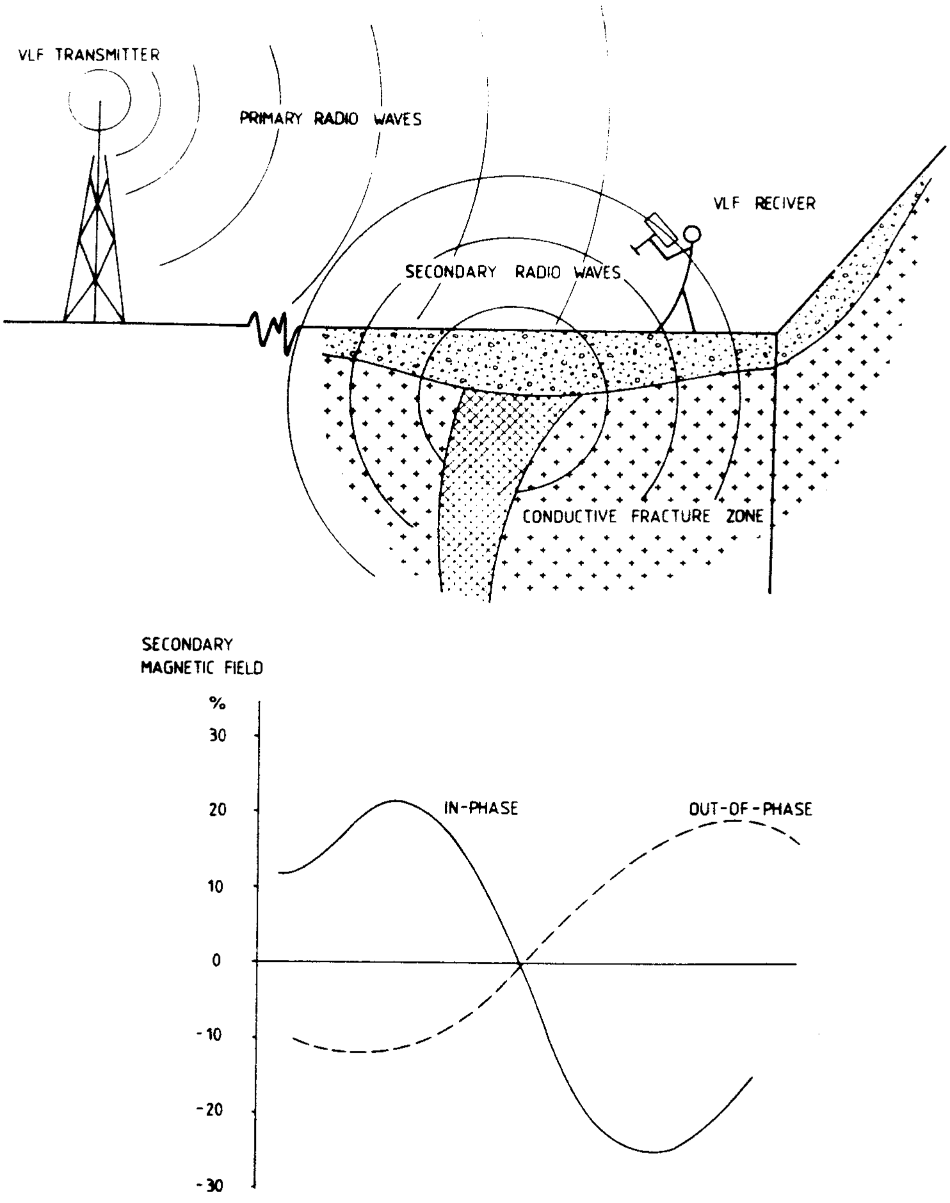

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Figure 3.2.1 The principle of VLF measurements with the expected anomaly of a fracture zone.

The VLF measurements are evaluated by comparing the results obtained with type curves and described interpretation algorithms (Olsson, 1980, 1983, Saydam, 1981). With these measurements, it is then possible to estimate the location, dip and conductance (thickness multiplied electrical conductivity) of the fracture zones.

Slingram (horizontal loop EM) is a system with two portable coils, one of which constitutes a transmitter and the other a receiver, figure 3.2.2. As in VLF, the field that is transmitted in slingram measurement gives rise to, by means of induction in electrically conductive zones, a field of disturbance that is registered as an anomaly. A measurement is made both of the field that is in phase with the transmitted field (real component) and of the field that is $90^{o}$ out of phase (imaginary component). Approximately the same frequency is used in slingram measurement as in the VLF measurements: 18 kHz. This relatively high frequency permits detection of formations such as fracture zones with only a slightly elevated conductivity in relation to their surroundings. Fracture zones normally give rise to relatively small anomalies in the imaginary component and no measurable anomaly in the real component. Anomalies are also caused by the presence of electrically conductive soil strata, e.g. clays, which can conceal anomalies caused by fracture zones. Slingram measurement gives a greater resolution than VLF, but has a shorter vertical range.

A slingram system with a frequency of 18 kHz and a distance between transmitter and receiver coil of 60 m is used for the measurements on the study sites. The real and imaginary components are measured as a percentage of the primary field. In practice, the accuracy of the measurement is 0.5 per cent in the real and 0.2 per cent in the imaginary component for values in the range -10% to 10%. The measuring accuracy for larger absolute values is approximately one per cent. Measuring errors in the real component are caused above all by variations in the distance between the transmitter and receiver coils and by misalignment between the coils. The corresponding error in the imaginary component is considerably smaller. The vertical range of the slingram system can be estimated to be approximately 3/4 of the distance between transmitter and receiver, i.e. 45 m.

The slingram measurements are evaluated by identifying anomaly structures and drawing conclusions as to their geological causes, for example whether the anomaly is caused by fracture zones, clays, mineralizations, peat bogs or

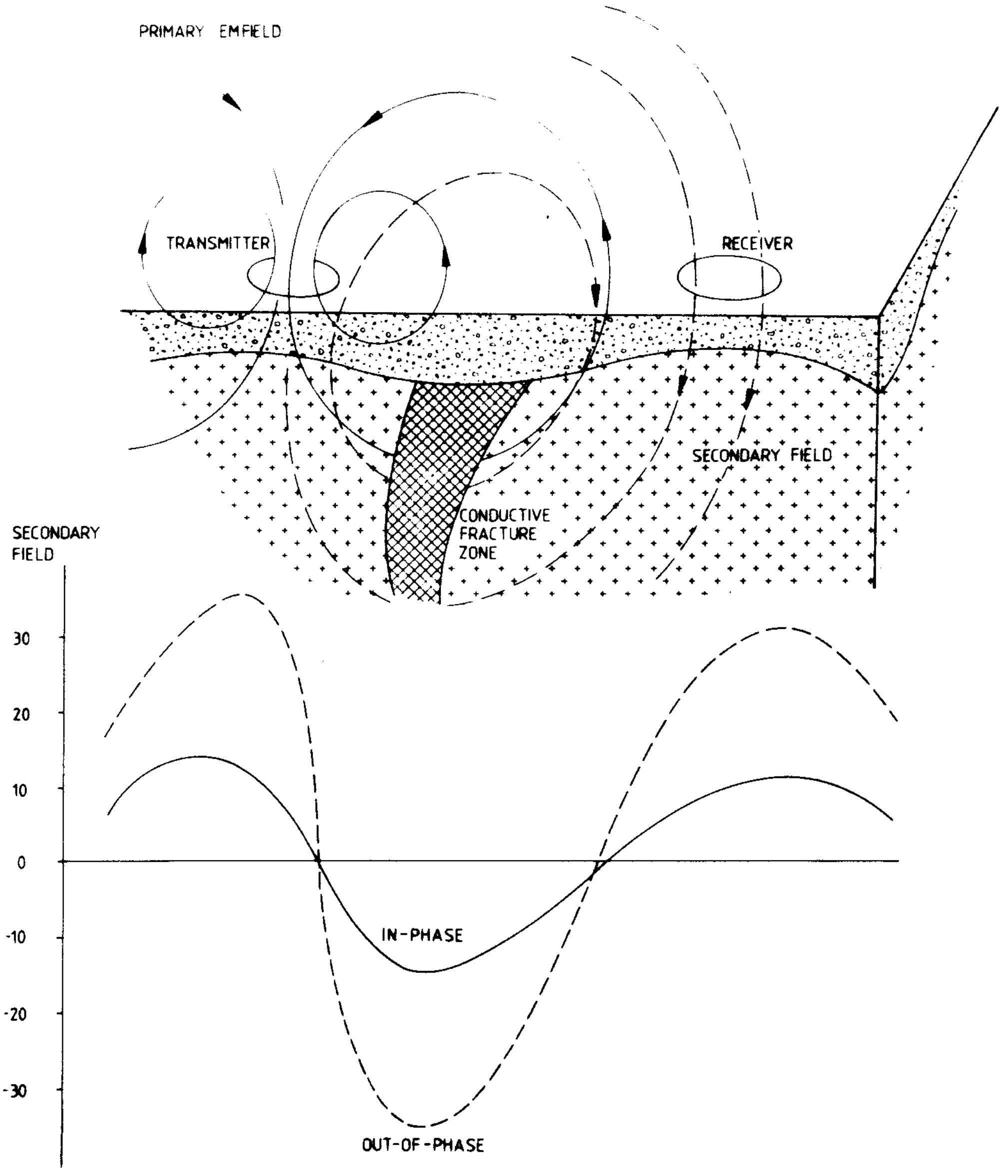


Figure 3.2.2 The principle of the slingram (horizontal loop EM) method with the expected anomaly of a fracture zone.

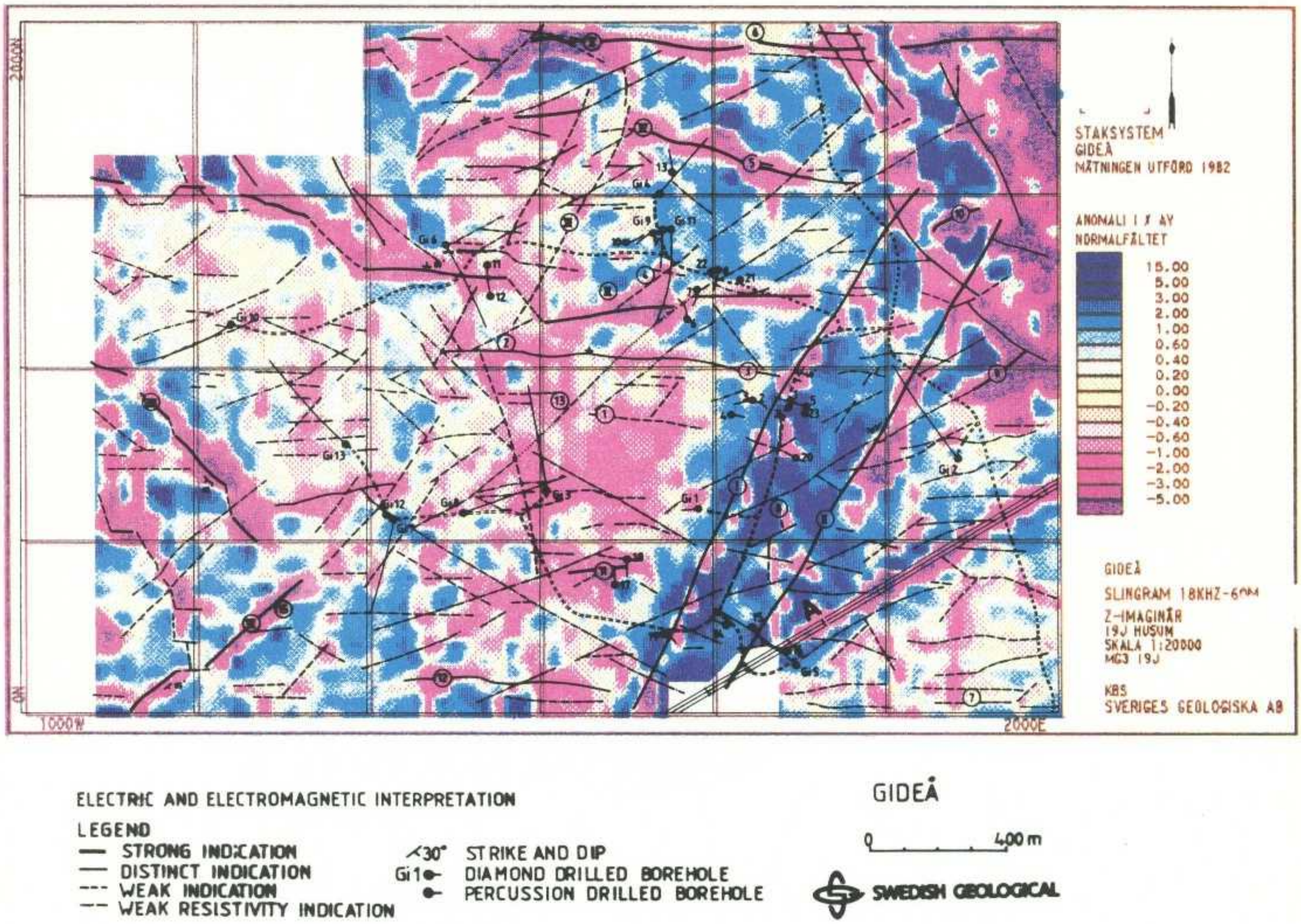


Figure 3.2.3 The imaginary component of a slingram survey at Gideå. Areas of elevated conductivity appear in red. The interpreted fracture zones have been indicated. A power line, A, causes a large anomaly.

electrical cables. Profiles of measured anomalies are compared with calculated profiles of different configurations of strata with varying properties (Nair, Biswas and Mazumdar, 1968). The comparisons yield, among other things, a basis for calculating the width, dip and conductance of existing fracture zones as well as the depth to the zone in question. One problem in evaluating both slingram and VLF measurements is the anomalies that can be caused by different kinds of electrical lines and cables. As a result, it may be advisable to restrict the use of these methods in densely populated and built-up areas.

Figure 3.2.3 shows an anomaly map of the imaginary slingram component together with an interpretation of the measurement results. Note in particular the anomalies caused by fracture zones. There is also an anomaly, A, caused by a power line.

### 3.2.4 Electrical measurements

The electrical measurements include both the resistivity and the induced polarization methods. Measurements made within the study site include simultaneous determination of resistivity and induced polarization.

In the electrical measurements, two electrodes are used to send a current through the bedrock that gives rise to an electric potential field. The potential distribution on the ground surface is measured by means of two measuring electrodes, and with knowledge of the size of the current, the apparent resistivity or electrical resistance of the bedrock can be calculated, figure 3.2.4. Differences in resistance above all provide information on water-conducting fractures in the bedrock, but also on the occurrence of electrically conductive minerals, such as graphite or sulphide minerals such as pyrite, pyrrhotite, chalcopyrite etc.

The reason why certain structures in the bedrock, such as faults and crushed zones, can be detected by means of electrical methods is that they are normally relatively permeable to groundwater and are therefore more electrically conductive than the surrounding bedrock, since ions of the salts that are present in varying quantities in the groundwater give rise to an electrolyte-based conductivity.

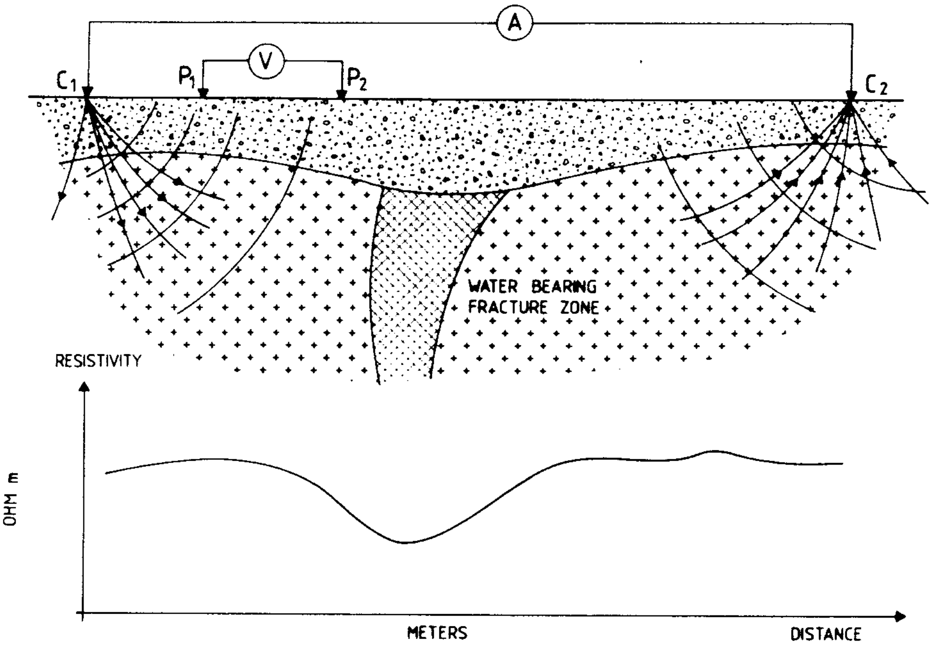


Figure 3.2.4 The principle of resistivity and IP measurements with the expected resistivity anomaly of a fracture zone. The current electrodes are marked 'C' and the potential electrodes 'P'.

In IP (induced polarization) measurements, the same electrode configuration is used as in the resistivity method. While the current is being transmitted through the bedrock, potential differences are built up on either side of electrically conductive mineral grains - they are polarized. When the current is suddenly cut off, this potential difference persists and gradually decays with time. In IP measurement, the magnitude of the potential left after a given period of time is measured. IP measurements mainly indicate the presence and distribution of electrically conductive minerals in the bedrock. By comparing IP measurements with resistivity measurements, it is possible to distinguish mineralized zones from water-conducting fracture zones. Fracture zones are visible as elongated bands of low resistivity (low electrical resistance). But low resistivity can also be due to the presence of electrically conductive minerals in the bedrock. In contrast to fractured, permeable rock, these regions should give rise to high IP values.

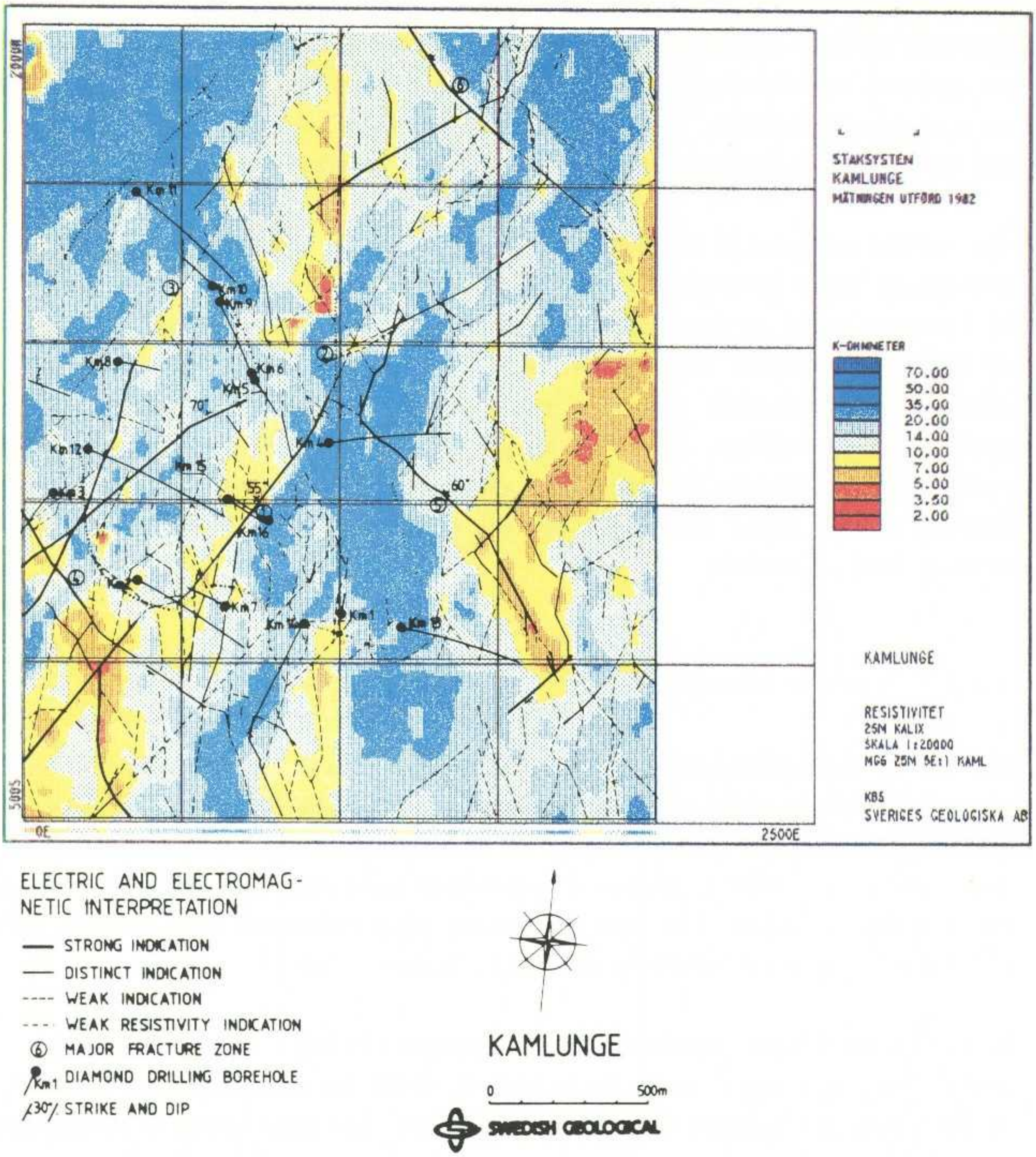


Figure 3.2.5 Resistivity measurements from Kamlunge with interpreted fracture zones.

The equipment employed in the measurements carried out on the study sites permits simultaneous measurement of resistivity and IP effect. Normally, an electrode configuration called the gradient configuration is used. In this configuration, the two current electrodes are positioned approximately 1 500 m apart, and the potential field is measured by two electrodes, 'P', spaced 20 m apart along the measuring lines in the stake system, see figure 3.2.4. For each placement of the current electrodes, an area of about 1 $km^2$ is measured. A study site, which normally covers an area of 4 $km^2$ is thus measured in four set-ups. The measured potential differences are then converted to apparent resistivity and IP effect. The accuracy of the method is dependent on a number of factors. The relative accuracy that is obtained in practice can be estimated at 3% of the resistivity and IP value obtained.

The evaluation entails classifying the anomalies in order to draw a conclusion concerning their geological cause. In addition, the location, width and dip of fracture zones is determined. An example of measurement results obtained at Kamlunge and their interpretation is given in figure 3.2.5. The vertical range of the electrical method is relatively large due to the use of the gradient configuration. It should be possible to identify large electrically conductive formations, for example a sulphide ore at a depth of several hundred metres, while fracture zones can only be detected at a depth of several tens of metres.

### 3.2.5 Seismic measurements

The use of the seismic methods is based on differences in the elastic properties of different types of rock and soil. Small explosive charges (shots) generate sound waves that propagate at different velocities in different rocks and soils. With geophones or seismometers spaced at a given distance, the time that elapses from when the seismic sound wave has been induced until it reaches a given geophone is measured, figure 3.2.6.

Rocks, in particular impervious ones, propagate seismic waves better than soils. The sound waves reach their highest velocity in crystalline bedrock. If the rocks are crushed or weathered, however, the wave velocity diminishes considerably. This means that the seismic methods can be used to indicate fracture and crush zones in the bedrock. The method is relatively costly and is, as a rule, carried out in the form of individual profiles along selected sections.

In order to obtain a high resolution so that even small fracture zones can be detected, the geophones are spaced 5 m apart. Normally, 24 geophones are placed in a row along the centreline and small dynamite charges are exploded at regular intervals. The signals from all geophones are recorded on a trace tape with a marking to indicate when the charge was shot. The travel times from shot point to geophone can be read off in this manner down to approximately one millisecond (ms). On the basis of these travel times, the soil depth and the seismic velocity in the soil stratum and in the bedrock are then calculated. Normally, fracture zones with a thickness of more than 5 m can be detected.

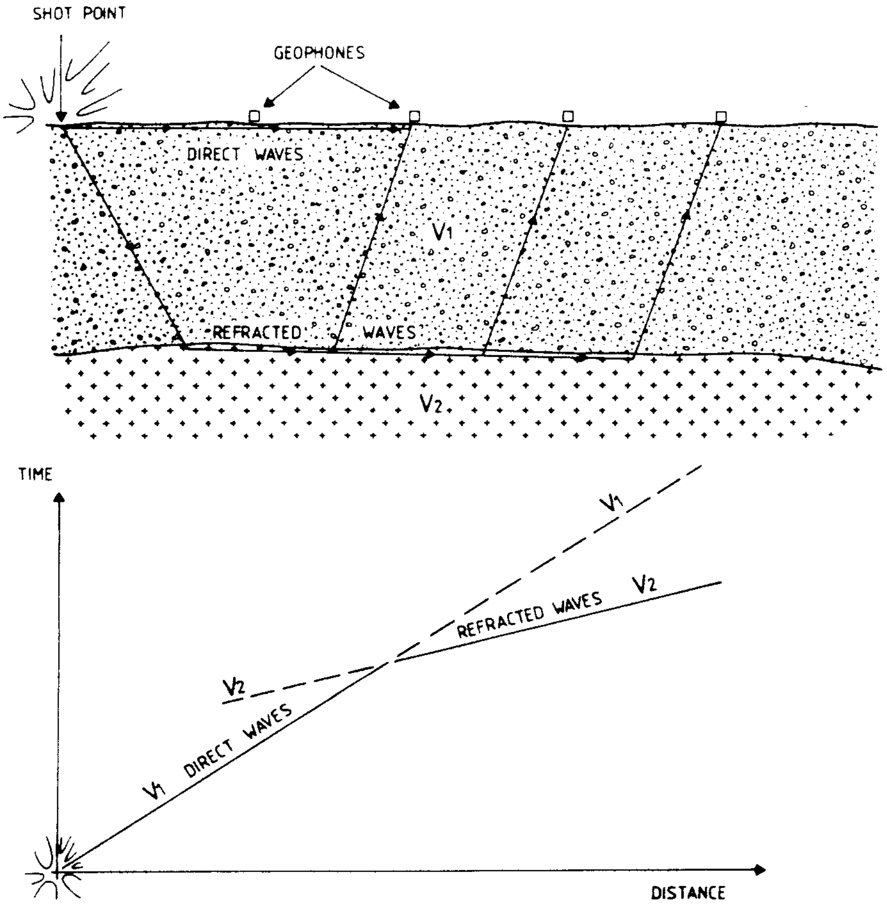


Figure 3.2.6 The principle of a refraction seismic profile.
A time-distance graph is shown of the travel time of the seismic wawe from the shot point to the geophones.

# 4. DEPTH INVESTIGATIONS

## 4.1 Geological investigations

### 4.1.1 Scope

Geological depth investigations involve drilling of core drill holes down to depths below a conceived repository. The drill cores are mapped with regard to rock type, fracturing and fracture fillings. The geological depth investigations yield information on the location and orientation of existing fracture zones at a depth of 500 m or more. In addition, an overall picture is obtained of the rock type distribution and fracture frequency at great depth.

### 4.1.2 Deep core drill holes

Deep core drill holes are drilled in order to obtain information on the bedrock and its hydraulic properties at great depth. The drill holes have a diameter of 56 mm and are usually 700 - 1000 metres long. The first drill hole that is drilled within a study site, the reconnaissance drill hole, is normally vertical and is drilled in those parts of the bedrock where the reconnaissance investigations have indicated that the bedrock is free of major fracture zones and rock boundaries. If this drill hole indicates that the bedrock at repository depth could be suitable for a repository, the other drill holes are directed towards the fracture zones and boundaries between different rock types that have been indicated by the surface investigations. The deep core drill holes are aimed in such a manner that the fracture zones are penetrated at great depth, more than 300 metres. Drill holes are also directed towards parts of the study site where the surface investigations have yielded inconclusive results. Water losses and any losses of drill core are noted during the drilling operation.

### 4.1.3 Drill core mapping

The obtained drill cores are mapped with respect to rock type, fractures and fracture minerals. Samples are taken of rock types and fracture minerals for mineral determination in microscopically thin sections and for chemical analyses. The number of samples varies between 10 and 30, depending on how the composition of the bedrock varies. Rock samples are also taken for determination of the physical parameter's density, susceptibility, magnetic remanence, IP, resistivity and porosity. The number of samples for this purpose varies between 200 and 300.

Drill cores are mapped visually. All information, with the exception of a detailed description of rock types, is stored directly on a disc memory with the aid of a microcomputer system (Almén et al 1983). Thus, after core mapping, the data exist in such a form that processing and correlation with other drill hole loggings can easily be done with the aid of different computer programs. Printout and graphical presentation of the core mapping data can also be done directly after the survey is concluded.

In core mapping, an emphasis is placed on the fracturing of the core. The occurrence and character of fractures is noted as follows:

- Location of the fracture along the drill core. The drill core's length is used as a positional coordinate. This is then converted to vertical depth coordinate with knowledge of the orientation of the drill hole (section 4.2.2).

- Orientation of the fracture in relation to the axis of the drill core and the structure of the rock type.

- Character of the fracture. Here, a differentiation is made between:

    - coated fracture, which means that the fracture is coated with fracture minerals and/or that weathering and colouration around the fracture have occurred. In addition, there may be signs of rock movements, slickensides or shear indications.

    - sealed fracture, which means that the fracture is not open, but rather filled with fracture minerals. The drill core exhibits no break in the case of a sealed fracture.

- fresh fracture, which means that the faces of the fracture are fresh and rough and lack coatings. This type of fracture in the core has probably been created in connection with the drilling work.

Sections where the fracture frequency exceeds 10 fractures per metre are termed fracture zones in the fracture log. Existing fracture minerals, the angle of the fractures to the drill core axis and the number of fractures within the fracture zone are noted. Furthermore, a note is made of whether the fractures are parallel or intersecting.

Sections where the drill core is so crushed that it cannot be combined to a complete core are termed crushed zones in the fracture log. Recovered core length, core losses (if any) and comments are also noted in the fracture log.

A description of symbols and codes used in the reporting of rock type and fracture data, plus an example of a printout of the mapping of a drill core from Km 8, are shown in figures 4.1.1 and 4.1.2.

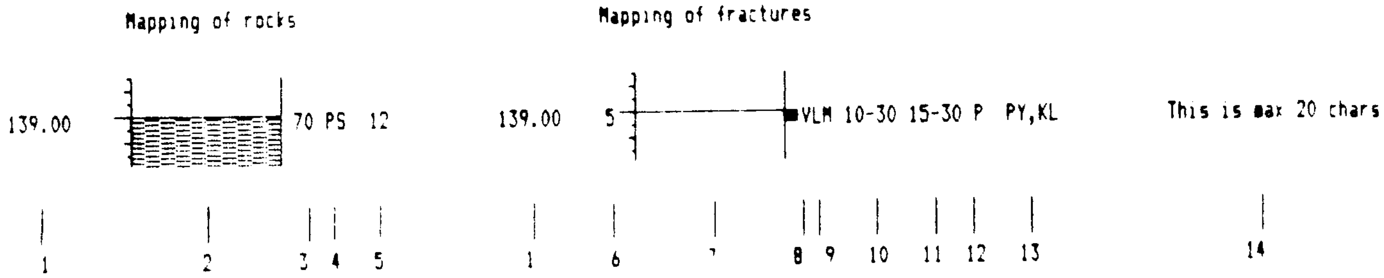
Fracture frequency and cumulative number of fractures for the drill cores are reported in graphic form for 10 metre sections, see figure 4.1.3. In calculating fracture frequency, 50 fractures per metre are assumed for crushed zones and core losses. Otherwise, the number of fractures noted in the core mapping has been used.

Figure 4.1.4 presents a record of the essential information obtained from drill core mapping that is reported for each drill hole within a study site. Such a record shows existing rock types, sections with increased fracture frequency, core losses, crushed zones, shear indications, weathered and clay-altered sections and drilling water losses during the drilling work. Fracture frequency diagrams for a study site are plotted on the basis of the results from all core drill holes. The bedrock is hereby divided into rock mass and local fracture zones.

Fracture zones in a drill core are correlated with fracture zones in other drill holes and with fracture zones on the ground surface. In connection with correlation between fracture zones in different drill holes, similarities between the widths, fracture angles, fracture minerals and other characteristic data (such as any brecciation, clay alteration, physical properties etc.) of

# Description

## of used symbols and codes during plotting



1 - Depth
2 - Rock classification
3 - Angle to core axis
4 - Code for rock type
5 - Prefix code for rock type
6 - Number of fractures
7 - Type of observation
8 - Marking for core uptake
9 - Marking for weathered (V), slickenside (L) and coated (M) fractures
10 - Angles from-to for parallel fractures
11 - Angles from-to for crossing fractures
12 - Marking for parallel foliation (P)
13 - Type of minerals, 1 to 5
14 - Comment

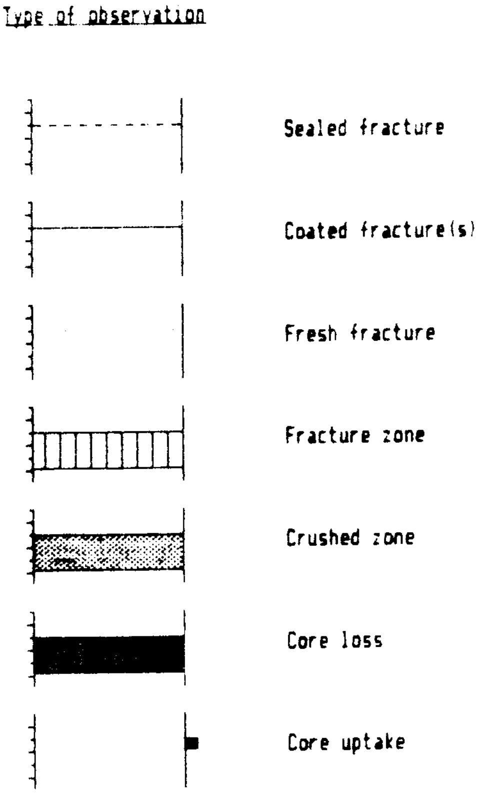


Figure 4.1.1 Symbols and codes used in mapping of cores from drill holes.

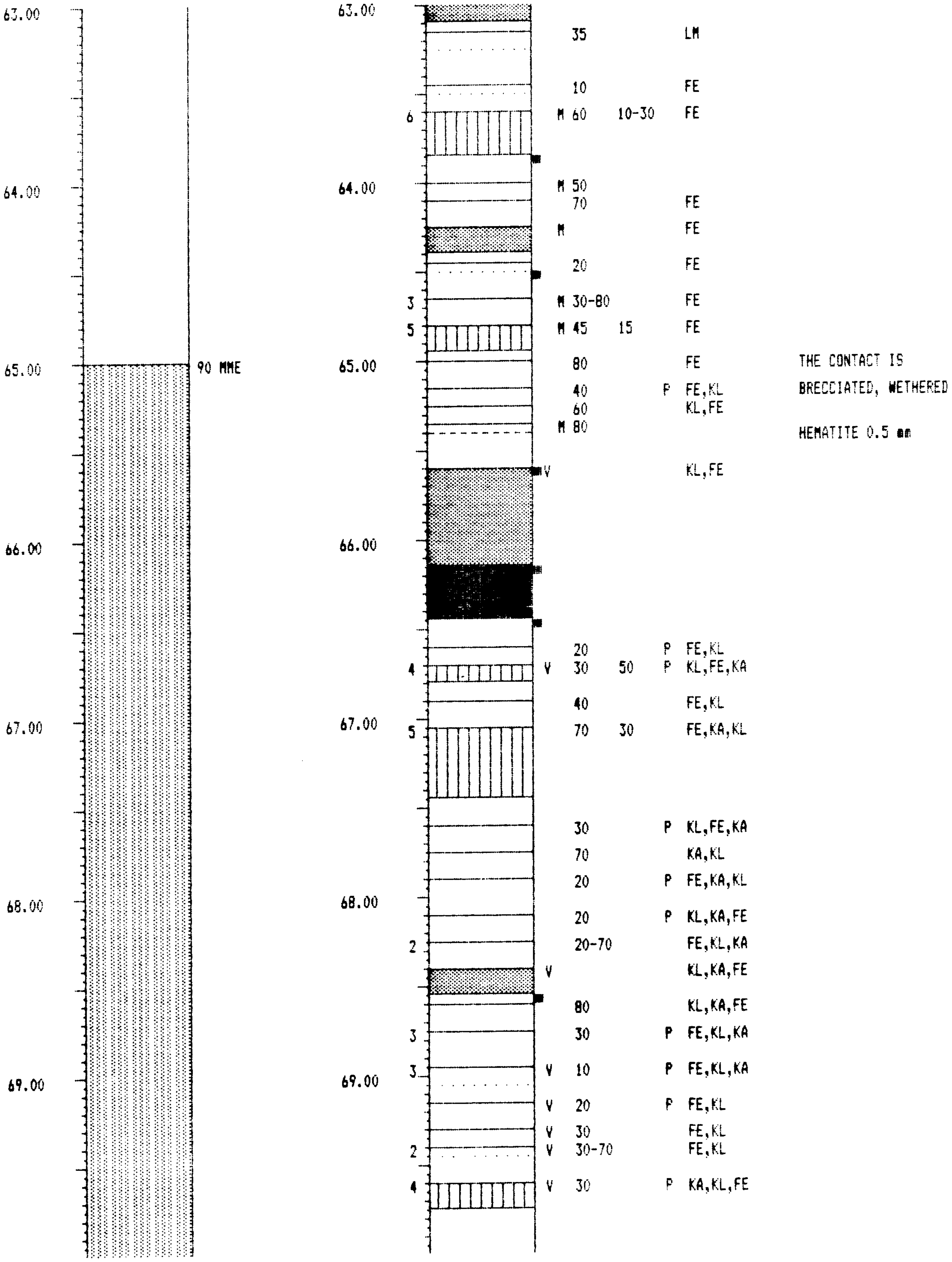


Figure 4.1.2 An example of a printout of computer-based core-mapped data.

observed fracture zones are studied. In addition, the results of geophysical and hydrogeological drill hole loggings are utilized (sections 4.2. and 4.3). The results are compiled into a descriptive model of the occurrence and extent of fracture zones within the study site. Figure 4.1.5 shows a model of the extent of fracture zones with depth on the Svartboberget site.

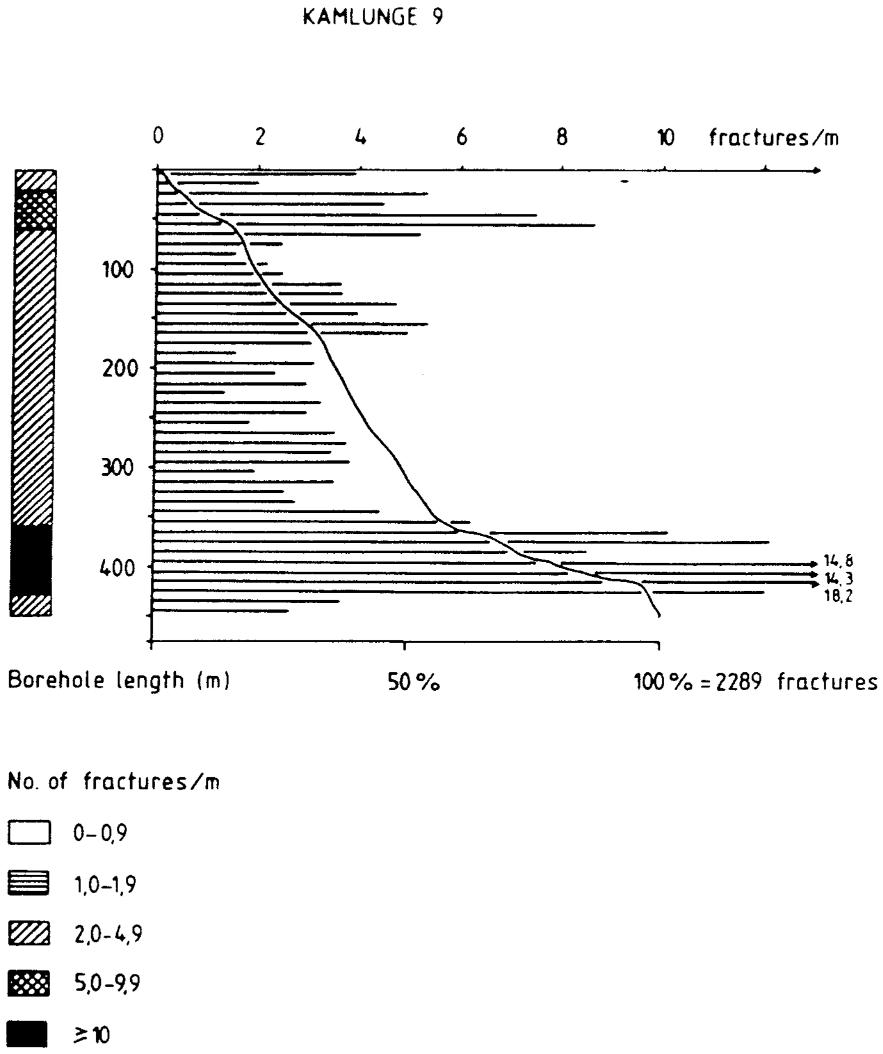


Figure 4.1.3 Fracture frequency in 10 m sections and cumulative number of fractures from drill hole Km 9 at Kamlunge.

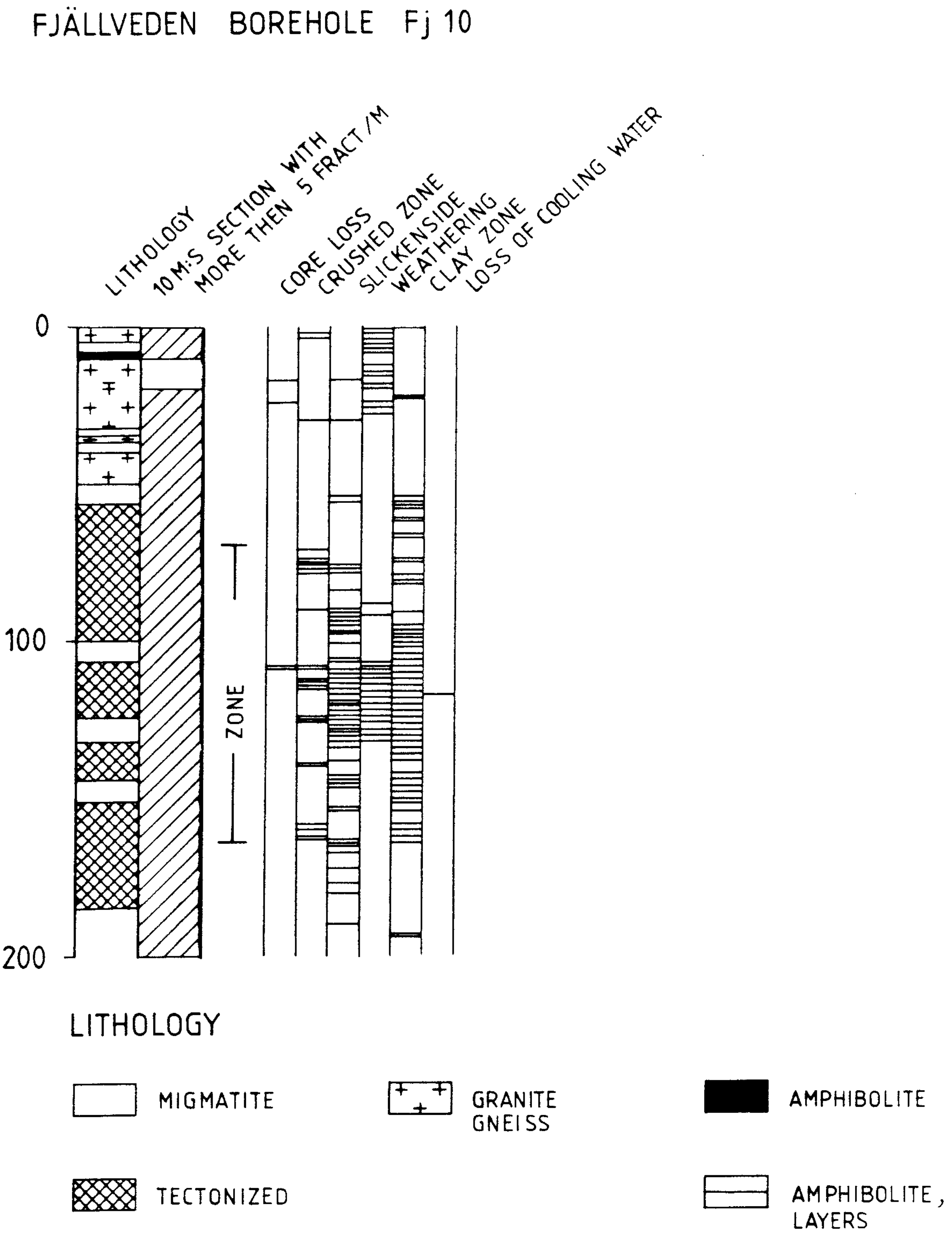


Figure 4.1.4 Data obtained during drilling and from core mapping of drill hole Fj 10 at Fjällveden.

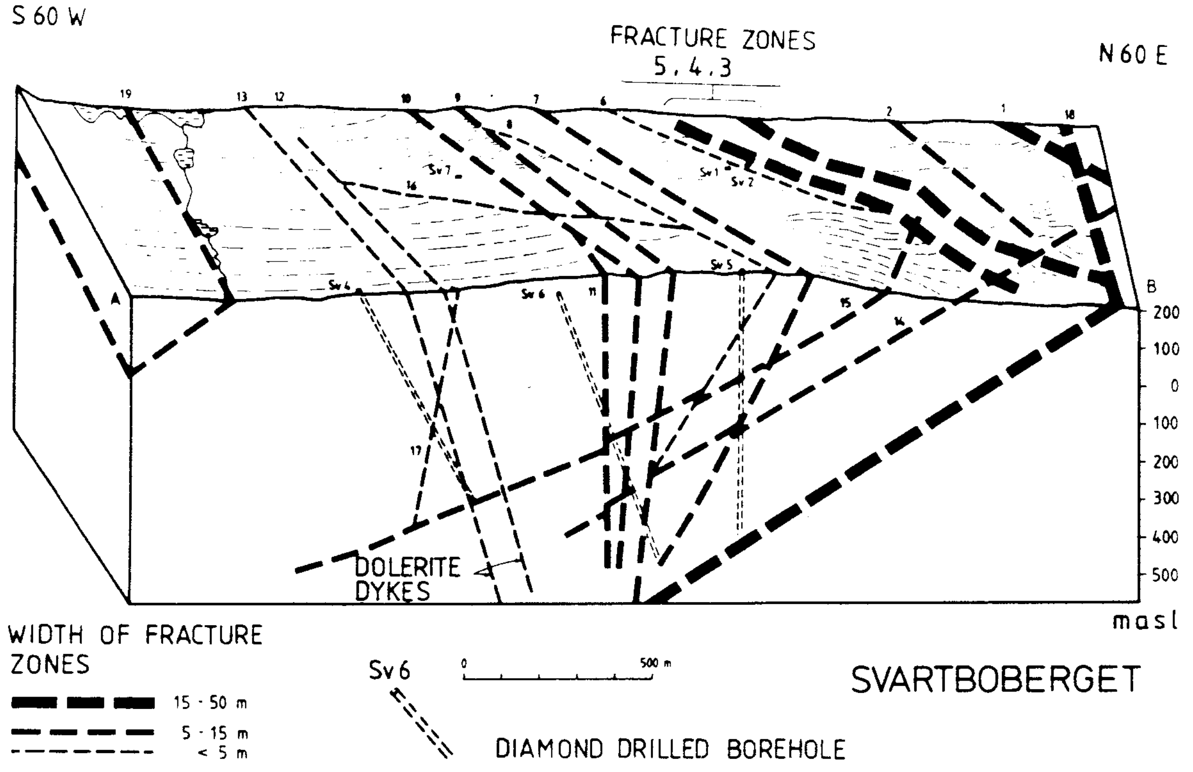


Figure 4.1.5 Fracture zones at Svartboberget.

## 4.2 Geophysical drill hole measurements

### 4.2.1 Scope

Measurements using different geophysical methods are also made in drill holes. The principles behind the use of these methods are the same as those described in the section on surface geophysical investigations, but the premises for the measurements are slightly different. Because the measurements are performed in drill holes, the technical requirements on the measuring equipment are different; the instruments have to be made small, at least as far as diameter is concerned. In addition, some form of communication is necessary between the measuring probe in the drill hole and the part of the measuring equipment on the ground surface.

The downhole geophysical measurements provide information on porosity variations in the rock, the occurrence and character of fractures, certain chemical properties of the drill hole liquid, groundwater flow along the drill hole and the presence of electrically conductive and radioactive minerals. In addition, a measurement is made of the drill hole's deviation from the calculated direction. A detailed description of the methods used has been published by Brotzen, Magnusson and Duran (1980). A brief description of these methods follows below.

In general, the measurements only yield information on the bedrock closely surrounding the drill hole, and thereby provide support for the description of the geological structure of the site as well as its hydrological and chemical conditions.

The Standard Program includes measurements in all core drill holes by means of the following methods:

- Drill hole deviation
- Natural gamma radiation
- Point resistance
- Resistivity
- Induced polarization (IP) (only performed in a small number of holes)
- Spontaneous (self) potential(SP)

- Temperature
- Resistivity (salinity) of the drill hole liquid
- Measurement of the pH and Eh of the drill hole liquid

In order to provide further support for the description of the properties of the bedrock and to back up the evaluation of the downhole geophysical measurements, the following properties are also measured on selected samples from the drill core:

- Density
- Porosity
- Resistivity
- IP effect
- Magnetic susceptibility and remanent magnetization

In order to supplement the information that is obtained from the ground surface and from measurements in individual drill holes, crosshole measurements are also carried out. The purpose of these measurements is to determine where a crushed zone observed in a drill hole exits on the ground surface or where it intersects another drill hole. Several different techniques are currently being developed for crosshole measurement e.g. seismic, electrical and electromagnetic. However, only electrical crosshole measurements have been performed to any extent within the study site investigations.

### 4.2.2 Drill hole deviation measurement

When a hole is drilled, it is normally assumed that the hole is to be straight. In practice, however, drill holes deviate from their intended direction. The deviation of the drill hole is due, among other things, to the structure of the rock, and the drill hole tends to either cut across the structures as steeply as possible or to follow them. For this reason, there is usually a tendency in the deviation that is characteristic for each study site. In Gideå, the drill holes tend to become steeper at greater depth, while those in Fjällveden tend to level off, figure 3.1.4. The structure in the rock (veined gneiss) is essentially horizontal in Gideå and vertical in Fjällveden.

In order to determine the deviation of the drill holes, a measurement is made of the drill hole's direction at regular intervals along the drill hole. From these data, the actual position of the drill hole can then be calculated along its entire length. The deviation instrument that is used employs a plumb-bob wheel, in principle a pendulum, to determine the slope of the drill hole i.e. its dip. A magnetic compass is used to determine the orientation of the drill hole in the horizontal plane. The presence of magnetic minerals in the bedrock can naturally lead to local declination. However, deviations in occasional measurements from the actual direction of the drill hole are of minor importance, since the drill hole can be considered to be straight over a shorter distance. The rock types on the study sites investigated to date consist primarily of granite or gneiss, and the occurrence of magnetic minerals in these rock types is relatively low and their influence on the compass negligible.

The accuracy in reading the angle in the vertical plane is 0.1 degree and in the horizontal plane 1 degree. Irregularities in the drill hole wall can also cause small errors in measurement. A determination of the location of the drill hole can in practice be estimated to better than 1 m per 100 m of drill hole length.

### 4.2.3 Radiometric methods

In order to obtain an idea of the mineral composition of the rock, a measurement is made of the natural gamma radiation in the drill holes. Total radiation is measured, coming for the most part from the radioactive isotopes potassium, thorium and uranium. In general, minor variations in the concentrations of these isotopes indicate changes in the composition of the rock. Basic rock types usually have lower radiation intensities than granites, to take one example, fig. 4.2.1.

Natural gamma radiation is measured in units of R/h with a relative accuracy better than 10% for the low radiation intensities that normally occur in gneisses. Accuracy is better at higher radiation intensities. Radiation can be measured from a distance of a decimeter or so into the rock (Gregory and Harwood, 1961). In this manner, an idea is obtained of the mineral composition of the rock only in the immediate vicinity of the drill hole.

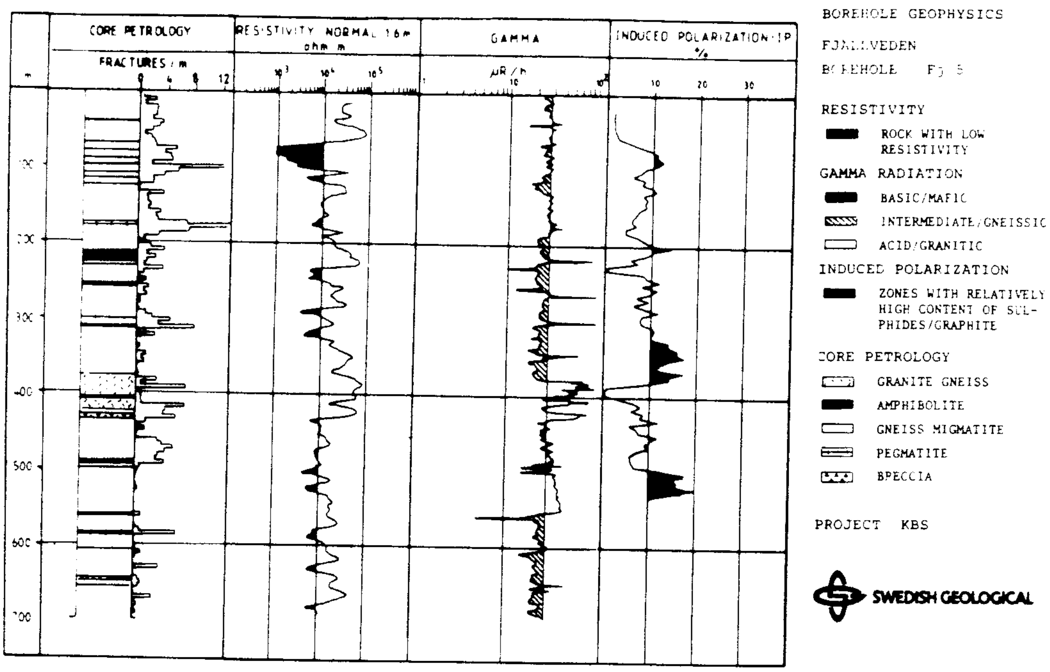


Figure 4.2.1 Results from logging of drill hole Fj 5. Granite gneiss shows up as parts with higher natural radiation levels.

### 4.2.4 Electrical methods

Variation in the resistivity of the bedrock is due primarily to the porosity of the rock and the presence of certain electrically conductive minerals. Most of the minerals present in different rock types are electrically nonconductive. Any detectable electrical conductivity can usually be attributed to the pore water present in the voids between the individual mineral grains. The water between the mineral grains generally contains dissolved salts, making it electrically conductive. Electrical conductivity is then dependent on the porosity of the rock. An empirical relationship known as Archie's Law between porosity and electrical conductivity for sedimentary rocks has been derived by Archie (1942) and measurements have been performed on rock samples from crystalline rock by Brace, Orange and Madden (1965). A theoretical calculation of the relationship between porosity and conductivity (Sen, Scala and Cohen, 1981) shows that conductivity is roughly proportional to porosity raised to a power of 3/2. The experimental studies by Brace et al (1965) indicate that conductivity is proportional to the square of porosity for crystalline rocks.

Measurements of the resistivity of the rock can thus be used to calculate its porosity. In order to obtain a good estimate of porosity, it is necessary to compare the resistivity measurements in the drill holes with measurements of resistivity and porosity performed on drill cores. The porosity obtained from measurements of drill cores is the porosity that is available for diffusion and cannot be directly related to the effective porosity, i.e. the volume in which water flow takes place (Norton and Knapp, 1977). The resistivity loggings also provide an idea of the properties of the fracture zones, for example resistivity is relatively well correlated to fracture frequency (Magnusson and Duran, 1983).

High conductivity (low resistivity) in the rock is due to, besides high porosity, the presence of certain minerals, above all clay minerals, which bind electrical charges to the surface layer of the grains so that electrical conduction can take place along the surfaces. In addition, some minerals are electrically conductive in themselves, mainly sulphide minerals such as pyrite. In the presence of large amounts of sulphide and/or clay minerals, calculations of the porosity of the rock and the resistivity loggings become unreliable.

The resistivity of the rock is measured with three different configurations, figure 4.2.2:

- Point resistance measurement

  The contact resistance is measured between an electrode in the drill hole and the drill hole wall. The electrode is approximately 5 cm long and has a diameter of 53 mm. On both sides of the electrode is an insulating plastic tube, as a result of which the contact resistance is sensed very locally. In other words, the point resistance gives a high resolution of detail (approximately 5 cm) in fracture zones, and it is possible in many cases to detect individual fractures.

- Normal configuration

  Resistivity is measured with a current electrode and a potential electrode in the drill hole. The distance between these electrodes is 1.6 m. This measurement produces an average value of the resistivity within a volume that extends approximately one metre from the drill hole. The results of this measurement can be used, after certain corrections, to calculate porosity.

- Lateral configuration

  Resistivity is measured with one current electrode and two potential electrodes in the drill hole. The distance between the current electrode and closest potential electrode is 1.6 m and the distance between the two potential electrodes is 0.1 m. The lateral configuration is used to obtain a better resolution of the location of fracture zones and the contact between rock formations of different conductivity than that obtained with the normal configuration.

Measurement with lateral and normal configuration is done with the same drill hole probe. This probe is 53 mm in diameter, which is only three mm smaller than the diameter of the drill hole. Since the water volume between the probe and the drill hole wall is small, no correction need be made of the resistivity values for the influence of the drill hole liquid. The equipment that is used has been specially designed to permit measurement of the very high resistivities that occur in crystalline rock. Relative accuracy is better than 3%.

By measuring the induced polarization (IP effect) in the drill hole, an estimate is obtained of the occurrence of electrically conductive minerals, above all sulphides, in the rock. The background of the IP effect has been discussed in the section on geophysical surface measurements and is not dealt with further here. A downhole measurement of the IP effect is performed with one current electrode and two potential electrodes in the drill hole. The distance between all of these electrodes is 5 m, a so-called half Wenner configuration, figure 4.2.2. Since a measurement of the IP effect is very sensitive to capacitive couplings in the measuring cables, a special drill hole cable is used for these measurements.

Measurement of spontaneous or self potential, the SP effect, is another electrical logging method. The spontaneous potential is obtained by measuring the potential between a potential electrode on the ground surface and one in the drill hole. In order to prevent the influence of electrode effects (electro-chemical reactions on the electrodes), non-polarizing electrodes are used both on the ground surface and in the drill hole. These electrodes consist of a copper electrode in a saturated solution of copper sulphate, where the

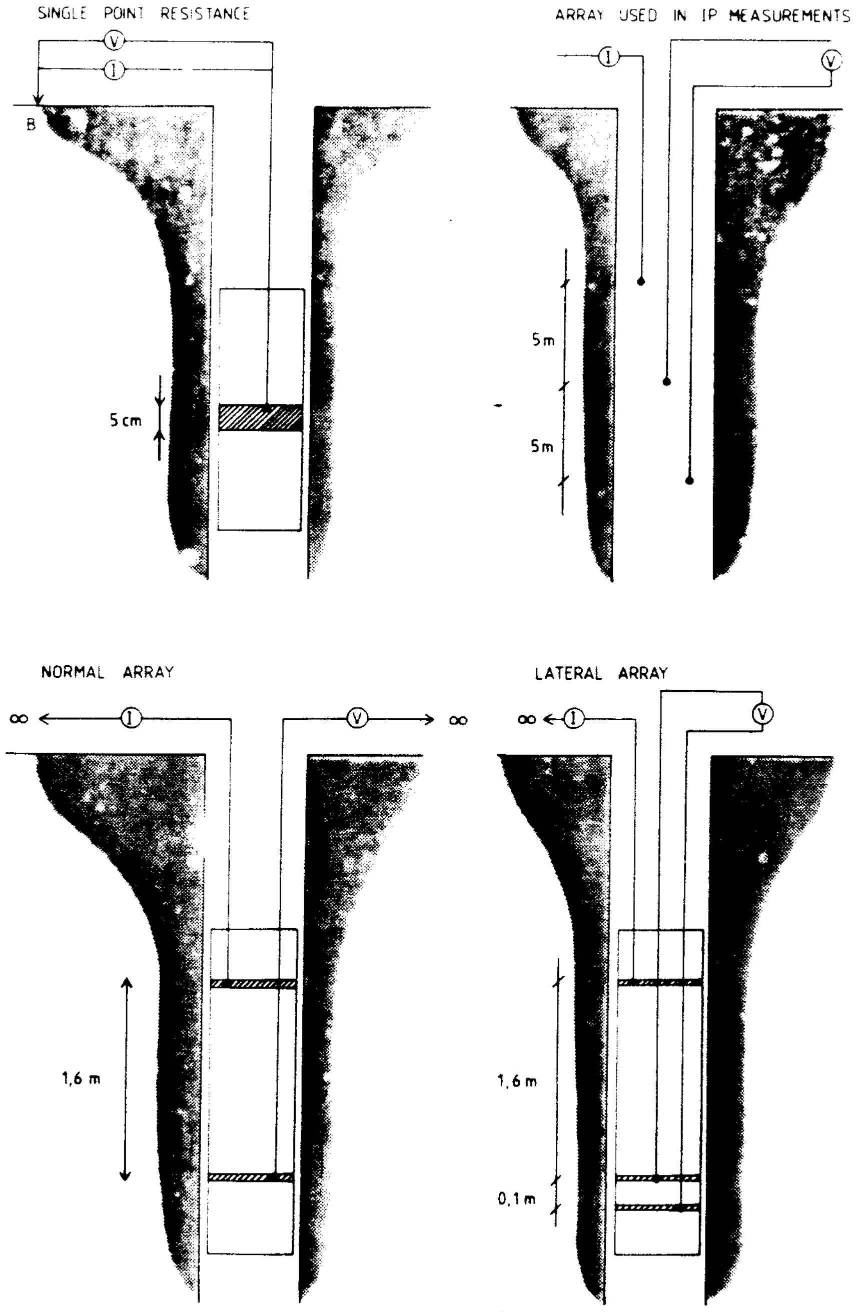


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Figure 4.2.2 Electrode configurations used for the electrical logs.

solution is in contact with the surroundings through a porous plug. In this way, very accurate SP measurements are obtained with a resolution of approximately 1 mV.

The spontaneous potentials (SP) in the ground are caused by various electrochemical processes. These are: diffusion of dissolved salts from the pore liquid in the rock to the less saline drill hole liquid, oxidation-reduction processes at the surface of various solid minerals and flow of water between the rock and the drill hole. By far the largest SP anomalies are caused by the presence of sulphides and/or graphite, giving rise to SP anomalies on the order of -200 mV to -500 mV. SP anomalies due to water flow between the rock and the drill hole are generally on the order of several tens of mV. Thus, the SP measurements give information primarily on the presence of electrically conductive and reducing minerals such as sulphides and graphite.

Examples of results obtained from the different electrical logging methods are given in figure 4.2.3, where the causes of different types of anomalies are indicated.

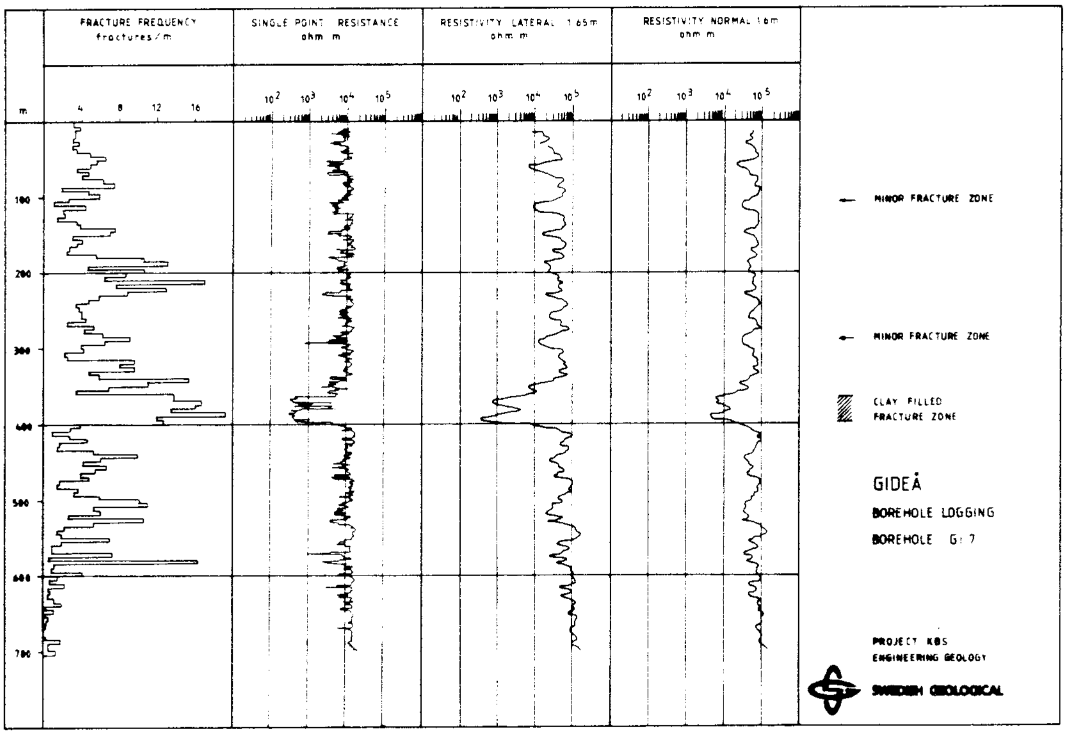


Figure 4.2.3 Electrical logs and fracture frequency from drill hole Gi 7 at Gideå.

### 4.2.5 Temperature logging

Measurement of the temperature in the drill holes serves two purposes: to obtain a value of the temperature and temperature gradient at great depth and to obtain an idea of existing water flows along the drill hole. When a drill hole intersects water-conducting fracture zones with different water pressures, an equalization of the water pressure takes place between the zones. This can lead to a flow of water along the drill hole from one fracture zone to another. Since water transports heat, the temperature in the sections of the drill hole where the water flow is equalized, i.e. the temperature gradient decreases. It is also possible to calculate the flow per unit time to some extent. (Drury, 1982). A clear example of the influence of a water flow along the drill hole is provided by the results from drill hole Gi 2 on the Gideå study site. In this case, relatively cold surface water flows into a fracture zone at a depth of 80 m and flows upwards out of the drill hole, figure 4.2.4. The temperature is virtually constant along the uppermost 80 m of the drill hole.

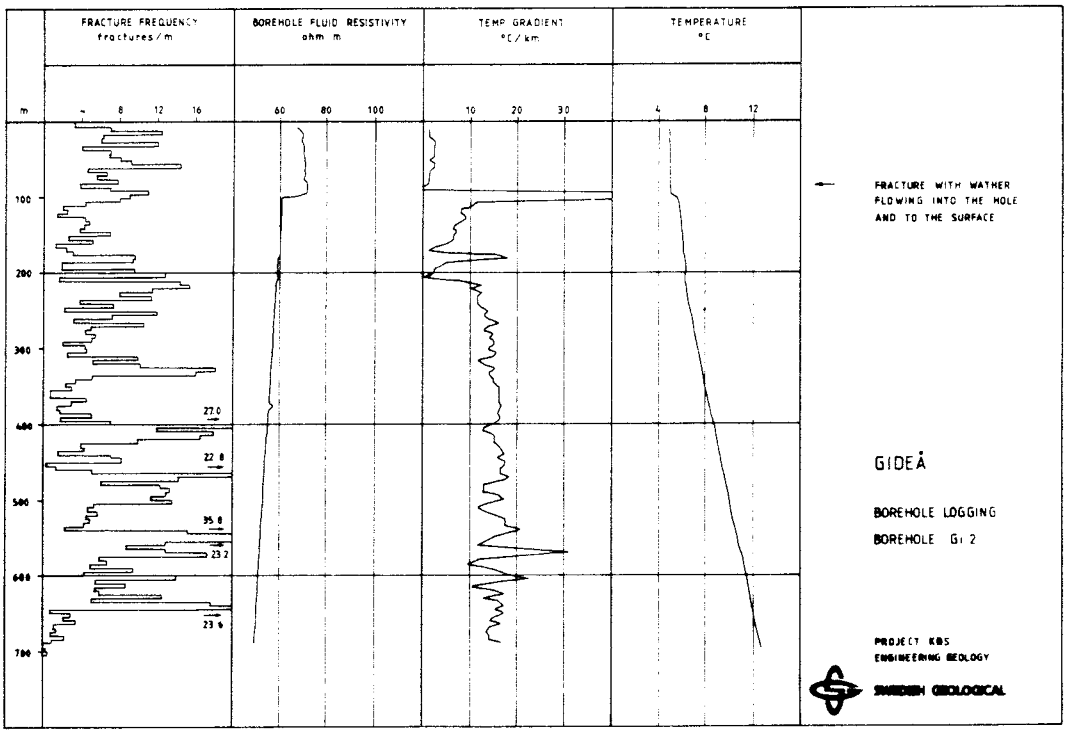


Figure 4.2.4 Temperature and temperature gradient in drill hole Gi 2 at Gideå.

The temperature is measured with a thermistor with a relative accuracy of 0.01 degree. The distance between the measuring points along the drill hole is 1-5 m. During drilling, the rock along the drill hole is heated in some parts and cooled in other parts. In the near-surface parts of the drill hole, the water is heated, while it is cooled in the deeper parts (Jaeger, 1961). Since the rock is a poor conductor of heat, it takes a relatively long time (one to two months) before the rock around the drill hole has assumed its natural temperature after the termination of drilling. The temperature is occasionally measured a relatively short time after the termination of the drilling, which introduces an error into the determination of the absolute temperature and temperature gradient at the depth in question. The heat generated by drilling can also give rise to characteristic anomalies at fracture zones (Drury, 1982).

### 4.2.6 Salinity of the drill hole liquid

The electrical conductivity of the drill hole liquid is measured at the same time as the temperature. This electrical conductivity can then be converted to the salinity of a solution of known composition, for example NaCl, taking into consideration the temperature in the drill hole (McNeill, 1980). The measurement furnishes, among other things, important data for determining the corrosion rate of metals at great depth. Variations in salinity also yield important information for determining water flow and diffusion between the rock and the drill hole.

The conductivity of the drill hole liquid is measured with a probe consisting of five electrodes, three of which are used to send out current and two to measure the potential. This electrode configuration prevents the measurement from being influenced by the presence of electrically conductive minerals in the rock. The determination of the conductivity of the drill hole liquid have a relative accuracy of 2%.

### 4.2.7 Geochemical logging

A special measuring probe has been developed for in-situ measurement of certain chemical properties of the groundwater. Since the measurement must be carried out at great depths in drill holes, special pressure-compensated electrodes and special electronics are required for data transmission and measurement of small potentials (Axelsen and Wikberg, 1981, Johansson and Lund, 1981). The probe contains ion-selective electrodes for the measurement of Eh, pH, $P5^{-2}$ (sulphide content) and spontaneous potential (SP). Eh is measured with three different inert electrodes: graphite, gold and platinum. In addition, the temperature is measured. The measured chemical properties of the groundwater are of importance for the corrosion tendency of e.g. copper and the solubility of radioactive nuclides.

Logging is done in open drill holes where water flow can take place between different levels. In some cases, the measuring results will therefore not apply to the chemical properties of the groundwater at the level where the measurement was carried out. Furthermore, contaminated drill hole water from the drilling process may be present and affect the natural groundwater.

The measurements performed within the study site investigations during 1981-1982 were done using a prototype apparatus which underwent successive development during the measuring period. The measurement results are therefore of varying quality, and certain technical problems remain to be solved. An evaluation of the reliability of the measurement results and their relation to the chemical properties of the groundwater is currently in progress (May 1983), and before it is completed, the obtained results must be used with great caution.

### 4.2.8 Petrophysical investigations

The use of geophysical methods is based on differences in physical properties between different rock types and between intact and fractured rock. In order to evaluate measurement results, it is essential to have data on the physical properties of the bedrock and their relation to various geological conditions. For this purpose, the following parameters are measured on drill core samples:

- Density
- Magnetic susceptibility and remanence
- Resistivity
- Induced polarization
- Porosity

The density of the samples is measured by weighing in air and in water. The magnetic properties of the samples are determined by measuring the magnetic field that is induced in the sample by the earth's magnetic field. The magnetic field is measured at four points and for a number of different sample orientations. Sensitivity in the determination of magnetic susceptibility is on the order of $3x10^{-5}$ SI units (Henkel and Nisca, 1978).

Resistivity and IP effect are determined by measuring the electric potential over the sample when the current flowing through the sample is known. In determining the IP effect, the potential is measured at a given time after the current has changed direction through the sample (Öquist, 1982).

In order to determine porosity, the sample is dried in an oven, after which the weight of the sample is measured. The sample is then placed under vacuum before being saturated with water. Vacuum is applied to ensure that the recharging of the pores with water will be as complete as possible. The weight of the sample is then measured with the pores filled with water. The porosity can be calculated from the weight difference and the known volume of the sample.

The measured porosity comprises the sum of the effective (kinematic) flow porosity and the diffusion porosity, which has been defined by Norton and Knapp (1977). The total porosity also consists of residual porosity, i.e. pores that are not connected with the other types of pores. Somewhat too low porosity values can be obtained in these measurements if the recharging of the pores with water is not complete. In certain cases, the recharging is only 65% (Öquist, 1982). However this problem can be considerably reduced by reducing the volume of the samples. Measurements are performed on 2 cm thick slices of the drill core.

## 4.3 Hydrogeological investigations

### 4.3.1 Scope

Hydrogeological investigations include:

- Determination of the hydraulic conductivity of the bedrock.
- Determination of the hydraulic fracture frequency of the bedrock.
- Determination of groundwater head at different levels in the bedrock.

The investigations have been carried out in one or more drill holes and the results are primarily representative for the bedrock adjacent to the tested drill hole or between several simultaneously tested drill holes (interference test).

The bedrock constitutes a heterogeneous medium in which fractures and fracture zones constitute the water-conducting elements. The principal aim of hydrogeological investigations is to determine the ability of the rock to conduct water, i.e. its hydraulic conductivity, which constitutes a direct measure of the openess, number and continuity of fractures in the rock. Only a certain proportion of the fractures in the bedrock are hydraulically conductive. The frequency of these fractures constitutes an important parameter in the analysis of flow paths as well as nuclide migration and sorption.

Groundwater flow is determined not only by hydraulic conductivity but also by prevailing hydraulic pressure conditions in the bedrock. This groundwater pressure or head varies in the bedrock and differences in water pressure within a rock formation constitute the driving force for the groundwater.

### 4.3.2 Choice of method

Extensive literature studies have been conducted of theories concerning, and application of, hydraulic tests in fractured formations (Andersson and Carlsson 1980, Andersson and Carlsson 1981, Almén et al 1982). The studies showed that tests performed under transient conditions give the most relevant value of hydraulic conductivity. At the same time, information is obtained on other hydraulic parameters of the tested section as well.

A number of different methods have been tested to permit the choice of the most suitable method for the production measurements within each study site. Table 4.3.1 presents the selected methods and the information that can be obtained from them. The tests have been carried out in drill hole Fi 6 within the Finnsjön study site. The tested sections in the drill hole have been selected to obtain a wide spread of hydraulic conductivity values. The results showed, like the results of the literature studies, that test methods with short duration, for example pulse response tests and short-duration water injection tests, provide limited information on the hydraulic properties of the bedrock. The long-duration transient tests, on the other hand, affect larger rock volumes and are applicable within a wider conductivity range. The criteria that have been established for choice of test method are summarized in table 4.3.2.

Table 4.3.1 Data that can be obtained from different hydraulic tests.

| Test method | Hydraulic conductivity | Skin | Piezometric head | Fracture character | Hydraulic boundaries |
|---|---|---|---|---|---|
| A1. Transient constant head | X | X | | X | X |
| A2. Transient constant flow | X | X | | X | X |
| B. Fall-off | X | X | (X) | X | X |
| C. Water loss | X | | | | |
| D. Slug test | X | (X) | | | |
| E. Pulse test | X | (X) | | X | |
| F. Drill stem | X | X | X | | |

The results in table 4.3.2 show that transient injection tests at constant head and subsequent pressure fall-off tests are the hydraulic methods that best meet the established criteria and are therefore best suited for production measurements.

Table 4.3.2 Criteria for selection of hydraulic testing method for production measurements within the study sites.

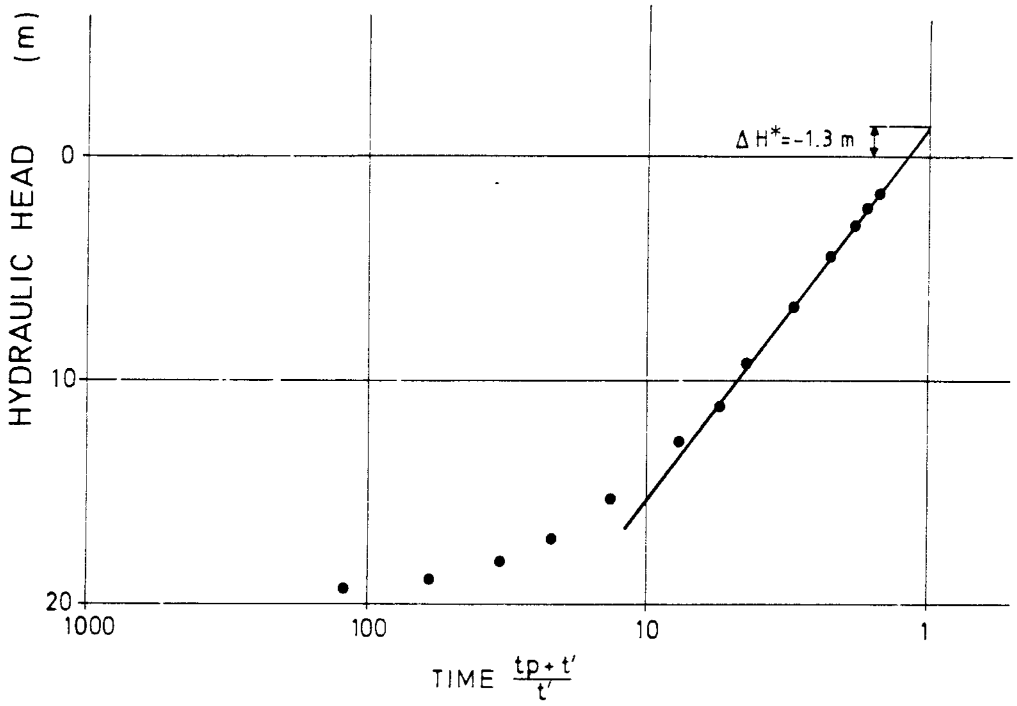
| Criteria | Test method A1 | A2 | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| Applicable within a wide range | X | X | X | X | | | |
| No deformation of the test section | | X | | X | | | |
| Easy to evaluate | X | X | X | X | | | |
| Large radius of influence | X | X | X | (X) | | | |
| Additional information | X | X | X | | | | X |
| Short testing time | | | | X | X | X | X |

Some of the advantages of the transient injection tests are:

- Possibility of measuring within a wide range of hydraulic conductivity.
- The pressure head is constant in the measuring section and in the entire measuring system. This means negligible effects of well-bore storage and small deformations of equipment during the measuring period.
- Evaluation is done on the basis of a large number of measured values, and the results have great relevance.
- Large radius of influence, i.e. the test result is valid for a comparatively large rock volume.
- Opportunities to determine other hydraulic parameters such as skin, effective drill hole radius, fracture lengths etc.

- Certain qualitative information can be obtained, for example identification of hydraulic boundaries and different flow regimes.

In order for a transient injection test to yield maximum information, it should be of such long duration that conditions become steady-state. For production measurements, a testing time of at least two hours of injection with subsequent pressure fall-off for an additional two hours is recommended. The choice of a combination method enables hydraulic conductivity to be calculated from two consecutive tests as a check of the reasonablesness of the values. A combination method also enables the natural hydrostatic pressure head in the tested section to be calculated by means of a so-called Horner diagram (Almén et al 1982), figure 4.3.1.



4.3.1 Evaluation of hydraulic conductivity and piezometric head using Horner plot.

### 4.3.3 Determination of hydraulic conductivity

The hydraulic conductivity of the bedrock has been determined through tests both in single drill holes and between different drill holes (interference tests). The former tests, water injection tests, have been carried out in different sections of the core-drilled holes. These sections have been sealed off by means of inflatable packers. The length of the sections has been 25 m. In addition, 5 and 10 m sections have been used within parts of the drill holes that contain major crushed and fracture zones. The results of the water injection tests constitute a basis for calculations of the groundwater conditions within the different study sites (Carlsson, Winberg and Grundfelt 1983).

Two types of equipment, steel mandrel and umbilical hose outfits, have been used in the water injection tests. The equipment and the testing procedures are described in detail by Almén et al (1983).

Interference tests have been carried out at Svartboberget, Fjällveden, Gideå and Kamlunge. The tests have been aimed at determining the hydraulic conductivity within a large rock volume and have been carried out in the form of test pumpings at constant pump capacity. For practical reasons, the interference tests have been performed within the upper part of the bedrock (0-150 m). The changes in groundwater head caused by the test pumping have been recorded in different sections in adjacent drill holes. The tests have been carried out and evaluated in accordance with theories for transient conditions.

The water injection tests have been carried out in three consecutive phases, figure 4.3.2:

| | |
|---|---|
| - Packer sealing | (about 30 min.) |
| - Water injection | (about 120 min.) |
| - Pressure fall-off | (about 120 min.) |

The packers are sealed by means of nitrogen and water to a pressure of 1.5 MPa above the hydrostatic pressure (Almén et al 1983). In connection with packer sealing, a certain amount of excess water pressure is created in the measuring section due to expansion of the packers. In the case of very tight and short measuring sections, this pressure equalizes slowly with time.

After completed packer sealing, a constant water pressure is applied to the tested section. This pressure is normally 200 kPA (20 m water gauge) above the prevailing natural water pressure head. The pressure is measured within the test section and kept constant by regulation of the water flow. This water flow is recorded as a function of time after the start of water injection.

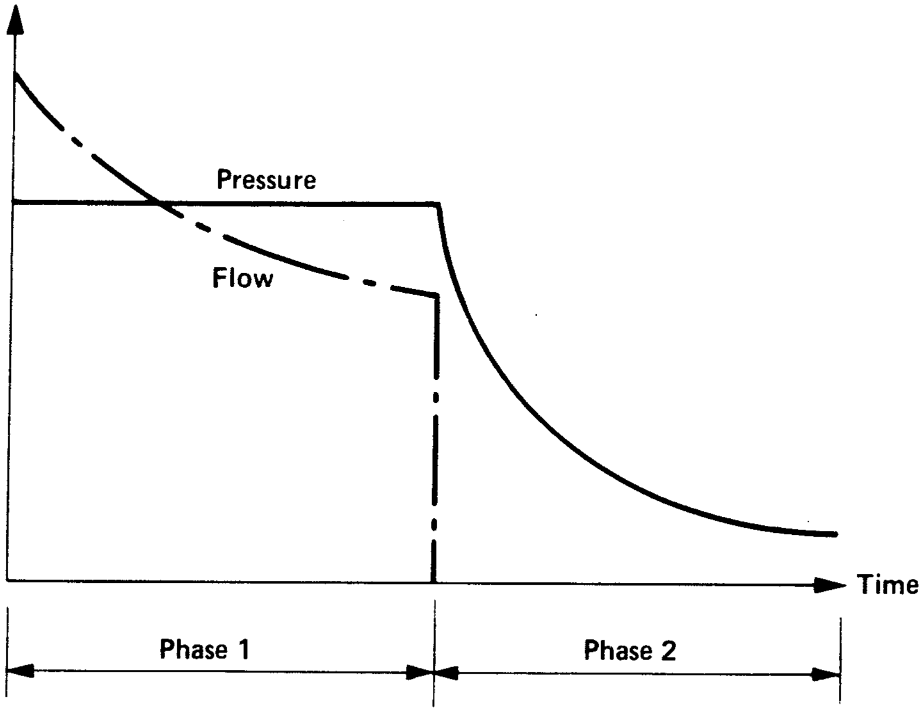


Figure 4.3.2 Different phases in hydraulic testing in individual drill holes.

The water flow is recorded both by a flowmeter of the rotameter type and by measuring the rate of descent of a water column in a tube of known diameter. The former method has been used in the majority of the measurements (Almén et al 1983).

The injected water flow enters the bedrock all around the test section. This flow diminishes with time as the water pressure in the bedrock increases. The flow reduction proceeds linearly on a logarithmic time scale, where the slope of the function curve constitutes a measure of the hydraulic conductivity of the tested section.

The theoretical function curve can be disturbed by factors associated with the drill hole and the bedrock, for example:

- Reduced or elevated hydraulic conductivity in the immediate vicinity of the drill hole due to clogging or flushing (skin effect).

- Volume changes in the measuring section or changes in the volume of water (temperature and salinity).

- Variations in hydraulic conductivity in the radial direction (nearness to major water-conducting zones etc.)

Due to the fact that the tests are carried out under transient conditions, it is possible in most cases to evaluate disturbing factors from resultant function curves. In certain cases, the curves also make it possible to quantify these factors and to analyse, for example, the hydraulic connection of major fracture zones with the adjacent rock mass.

The measurement limit in the tests is dependent upon the ability of the equipment to register small flows and changes in flow. The steel mandrel equipment that has been used has made it possible to achieve a measuring limit of $5 \times 10^{-12}$ m/s, while the measuring limit of the umbilical hose outfit is around $1 \times 10^{-11}$ m/s. For practical reasons, the highest measurement limit has been used in processing data from the different drill holes.

The size of the volume that is affected around the drill hole in an injection test is generally dependent on the hydraulic conductivity and the specific storage coefficient of the rock as well as the length of the testing period.

At low hydraulic conductivity, a smaller area is affected than at high conductivity. The reverse applies to the specific storage coefficient. The radius of influence increases with increasing testing time. The testing time used has been less than 2 hours and the tests are estimated to influence a region with a radius of 15 cm at a hydraulic conductivity of $1 \times 10^{-11}$ m/s. At $K = 1 \times 10^{-9}$ m/s the equivalent value is 1.5 m.

The hydraulic conductivity value obtained from the measurement constitutes a mean value for the entire tested section. Hydraulic conductivity varies within a test section. Fracture zones have a higher conductivity than portions with normal or low fracture frequency. Thus, the radius of influence will vary along the tested section in relation to hydraulic conductivity.

Detailed measurements of hydraulic conductivity in 5 or 10 metre sections have been carried out in order to obtain information on and delimit formations with high conductivity within, certain 25 m sections. These measurements also provide a means to check the results of measurements in 25 m sections. By comparing the transmissivity, i.e. the hydraulic conductivity multiplied by the length of the section, obtained from different measurements, an idea is obtained of the reliability of the results. Only in a few cases have discrepancies greater than a factor of 2 been noted.

A further check of the reliability of the measurement results is obtained by comparing the hydraulic conductivity from the injection phase with that from the subsequent fall-off phase. The evaluation principle for the latter phase is similar to that for the injection phase, i.e. the evaluation is made on the basis of theories for transient phenomena. This evaluation also provides a determination of the original natural groundwater head in the tested section, see section 4.3.5. Calculation of hydraulic conductivity from the injection and fall-off phases gives values that are generally in agreement.

Sources of error in the injection tests related to the equipment have been estimated to give a total relative measurement error of 28% (Almén et al 1982). These sources of error do not include leakage that can arise due to incomplete sealing between the packer and the drill hole wall. Such an error results in a higher hydraulic conductivity than the actual conductivity of the test section. The errors, which are usually associated with malfunctioning packers etc., can be observed by the fact that consecutive measurement sections exhibit the same fictive hydraulic conductivity, usually higher than normal.

### 4.3.4 Determination of hydraulic fracture frequency

The hydraulic fracture frequency of the rock mass has been determined from the results of water injection tests in sealed-off 2 or 3 m sections in core-drilled holes within the study site. The tests have been carried out during a limited period of 10-30 minutes and evaluated under the assumption of steady-state flow conditions. This means that calculated values of the hydraulic conductivity are normally slightly higher than values obtained from equivalent calculations from transient tests. The total relative measuring error has been estimated at 12% for K-values $>=10^{-9}$ m/s and 20% for K $<10^{-9}$ m/s (Almén et al 1982).

Of the tested sections in the rock mass, those that have a total of 8 fractures or less per section have been studied. These sections have been subdivided into different 100 m depth intervals. The proportion of all test sections with a given fracture frequency that have a hydraulic conductivity lower than the measurement limit has been calculated. This proportion constitutes a statistical estimate of the non-conductive proportion of the test sections with the given fracture frequency. These estimates for different fracture frequencies are weighed together to obtain a representative value of the probability of one hydraulically conductive fracture for every 100 m interval considered. With knowledge of the total fracture frequency within each interval, this probability can be converted to a hydraulic fracture frequency.

A 95% confidence interval for the hydraulic fracture frequency has been calculated from the obtained values. This interval consitutes a maximum of +- 30% of the calculated mean value.

The magnitude of the hydraulic fracture frequency is dependent on the measurement limit for the hydraulic tests in the 2 or 3 metre sections. This measurement limit has varied between the investigated sites depending upon differences in the measuring equipment used. Table 4.3.3 gives the measurement limits used and the number of tested sections and drill holes.

Table 4.3.3 Drill holes, vertical depths and number of measurement values used in calculating the hydraulic fracture frequency.

| Study Site | Drill hole | Vertical depth m | No. of values | Measuring limit K m/s |
|---|---|---|---|---|
| Fjällveden | Fj2 | 200-600 | 126 | $1.3\ 10^{-10}$ |
| Gideå | Gi7 | 200-600 | 162 | $1.0\ 10^{-11}$ |
| Kamlunge | Km2 | 200-600 | 175 | $1.3\ 10^{-10}$ |
| Finnsjön | 1-5 | 0-600 | 817 | $2.5\ 10^{-9}$ |
| Sternö | 1-5 | 0-600 | 1056 | $4.0\ 10^{-10}$ |

### 4.3.5 Piezometry

The groundwater head in the bedrock has been measured as follows:

- Recording of the level of the groundwater table in drill holes.
- Recording of the groundwater head at different levels in drill holes (piezometry).
- Calculations based on data from the hydraulic tests.

Recording of the level of the groundwater table in drill holes has been done continuously by means of registering water-level gauges and soundings. The water level recorded in a drill hole constitutes mean value for the drill hole. Different groundwater levels in the bedrock are 'short-circuited' due to a drill hole, so that groundwater can flow into a drill hole at one level and flow out at another. Such conditions can be recorded by means of measurements of the temperature and resistivity of the water along the drill hole (section 4.2.5).

Packers have been installed in the drill holes approximately 5-10 m below the groundwater table in order to section off the upper part of the bedrock and obtain values representative for this part. Measurements employing water-level gauges and soundings have been carried out with an accuracy of +- 2 cm. The number of observations within each study site is reported in table 4.3.4.

Table 4.3.4 Number of drill holes used for measurement of groundwater head in the study sites.

| Site | Measurement by | | |
|---|---|---|---|
| | Sounding | Gauge | Piezometry |
| Fjällveden | 60 | 3 | 2 |
| Gideå | 37 | 3 | 1 |
| Kamlunge | 35 | 2 | 2 |
| Svartboberget | 13 | 3 | 2 |

Piezometric measurements have been carried out by sealing off sections in the drill holes by means of packers. The sealed-off sections have primarily been zones of high conductivity, for example fracture or crushed zones. The equipment used has permitted the sectioning-off of 5 measurement sections by means of 7 packers. The measurements have been carried out with a pressure gauge to which the different measurement sections are connected via solenoid valves. These valves are controlled by a computer code, which permits different measuring intervals during different times.

The water injection tests have been carried out in three phases, figure 4.3.2. During the second phase, after packer sealing, a constant injection pressure is maintained and the injected flow rate is recorded. During the subsequent phase, the flow is stopped and the fall-off of the pressure with time is recorded. The residual water pressure diminishes linearly with the logarithm of the ratio between the total testing time and the recovery time. Providing that the injection phase is sufficiently long, the data points describe a straight line in this graph. Determination of the natural hydrostatic pressure head (piezometric head) of the test section is done by extrapolating the straight line to 'infinite time', i.e. when the above ratio is equal to 1 (Andersson and Carlsson 1981), figure 4.3.1.

Groundwater level maps have been produced for the study sites. The maps are based on observations of the level of the groundwater table in existing drill holes as well as on topographical conditions. The groundwater level maps serve as a basis for numerical model calculations of the groundwater conditions within the different study sites. The maps provide information on the location of the water table within and adjacent to the study sites under conditions that can be said to represent average conditions during the year. Thus, deviations can occur during certain times of the year, especially in connection with extreme drought or precipitation and snowmelt.

The groundwater level maps are virtually identical to the topographical maps of the respective study sites, but with lower levels within elevated areas. In producing the maps, certain assumptions have been made based on measured conditions:

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

- The groundwater table coincides with the lake surface at and under lakes.

- Low-lying sections of the terrain with major water courses, large peat bogs and tectonic zones constitute discharge areas for groundwater, and here the groundwater table coincides with the ground surface.

Figure 4.3.3 shows a groundwater level map of the Fjällveden study site.

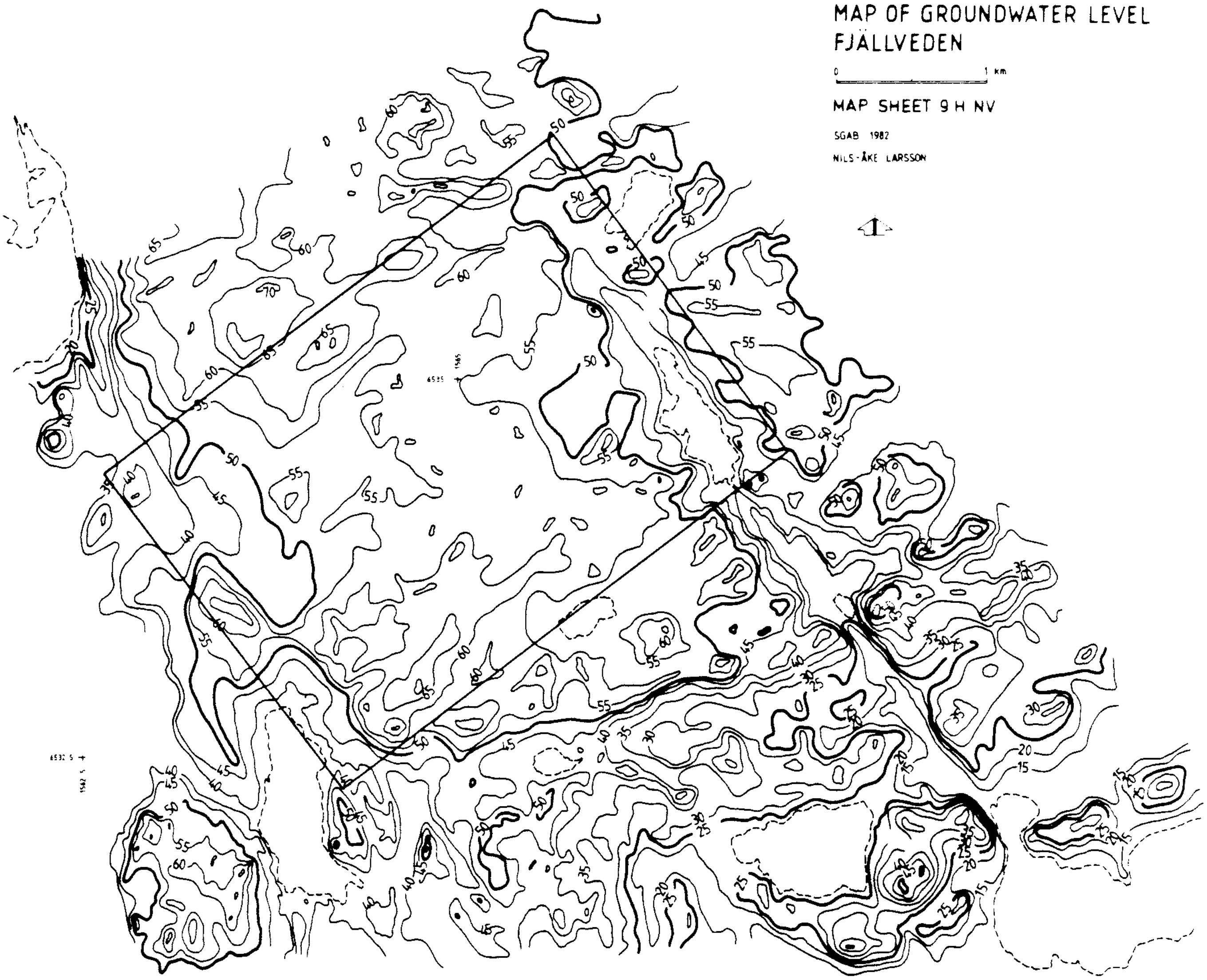


Figure 4.3.3 Map of the groundwater level at the Fjällveden study site.

# 5. EVALUATION AND MODELLING

## 5.1 Scope

Measurement data obtained from the surface and depth investigations within each study site have been compiled and evaluated for the purpose of constructing

- a geologic-tectonic model of the study site
- a descriptive hydraulic model of the study site

The descriptive hydraulic models that are developed must be quantified with respect to, among other things, groundwater flow and groundwater turnover. This is done by means of numerical modelling techniques, making use of three-dimensional models. Data for these calculations consist of the hydraulic properties of the bedrock and existing fracture zones obtained from the hydraulic tests. These data are processed in accordance with existing theories on models for groundwater conditions in crystalline bedrock. The methods and results of this processing and model calculations are reported by Carlsson, Winberg and Grundfelt (1983).

## 5.2 Geologic-tectonic models

A geologic-tectonic model provides a description of existing fracture zones and the geometric extent of existing rock types. Such a model can be made more or less accurate depending on available data and the actual purpose of the model. A model whose purpose is to indicate the presence of zones that can entail problems from a civil engineering point of view includes only those fracture zones that contain large crushed formations. A model intended for groundwater calculations will also include zones that do not have to entail problems from the viewpoint of civil engineering. Fracture zones unrelated to possible civil engineering problems are also included in view of the fact that the safety analysis for the waste repository spans a period of 10 000 to one million years.

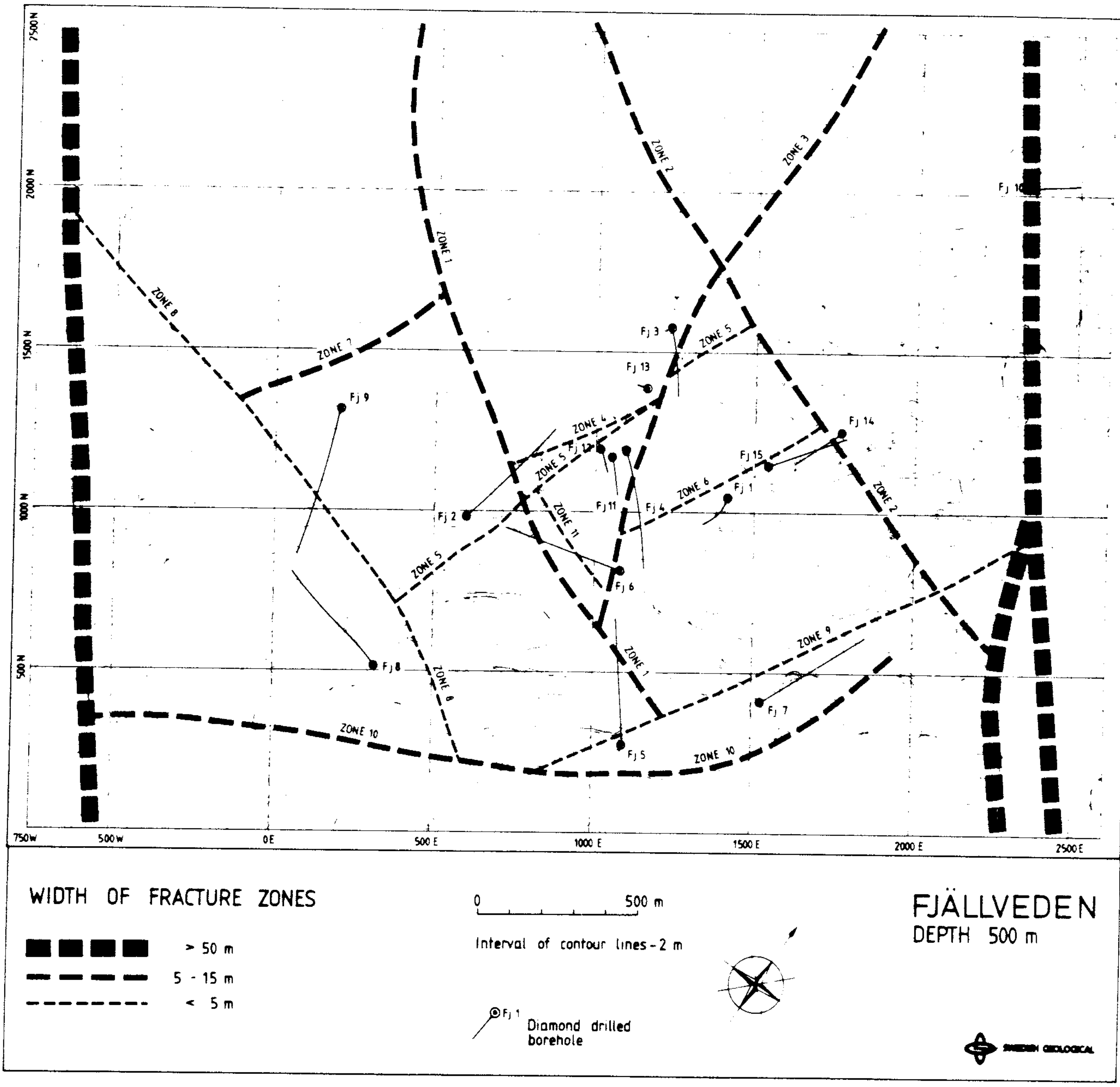


Figure 5.2.1 Map of the fracture zones at 500 m depth at Fjällveden study site.

The width of existing fracture zones is determined both from surface geophysical measurements and from drill core mappings and downhole geophysical loggings. Extensive fracture zones generally have a highly varying manifestation. An increase of the normal fracturing in the zones is nevertheless noticed in the drill core. In some cases, the fracturing is so extensive that the rock in the zone is crushed to fragments (crushed zone). The number and width of crushed rock formations within a zone can vary.

In order for a fracture zone to be distinguished and mapped with regard to location and extent, it must be of such a size that it is detected by the investigations from the ground surface or is encountered in one or more drill holes. The bedrock also contains a number of fractures and fracture zones of limited extent. These are considered to form part of the 'normal' fracturing of the bedrock.

The geologic-tectonic models that have been developed of the different study sites are intended to serve as a basis for descriptive hydraulic models of groundwater conditions in the bedrock with time aspects applicable for the safety analysis of a conceived repository at a depth of approximately 500 m, figure 5.2.1. The results obtained from hydraulic measurements in the different zones have therefore also been taken into account in determining the extent and width of existing fracture zones.

## 5.3 Descriptive hydraulic models

A descriptive hydraulic model of existing hydraulic units in the bedrock has been devised for each study site. The bedrock has been subdivided into the following hydraulic units:

A. Regional fracture zones
B. Local fracture zones
C. Rock mass

This subdivision has been based on the geologic-tectonic models developed. The different units have been assigned different hydraulic properties based on all the measurement values obtained within each unit. Data from all local fracture zones, regardless of orientation and width, have been used for group B. Information on width obtained from the drill core logs has been utilized to calculate the hydraulic conductivity of the individual fracture zone from the K value obtained for the entire tested section.

A limited quantity of data is usually available for regional fracture zones. In general, however, these zones have been assumed to have a higher hydraulic conductivity than the local fracture zones. The relationship between depth and conductivity has been assumed to be similar to that which applies to the local fracture zones.

An effective hydraulic conductivity has been used to characterize the hydraulic properties of the different hydraulic units in connection with the numerical model calculations. This effective hydraulic conductivity constitutes a mean value of individually measured conductivities based on all measurement results within a given unit (Carlsson, Winberg and Grundfelt 1983). An example of hydraulic conductivity versus depth for rock mass, local and regional fracture zones is shown in Figure 5.3.1.

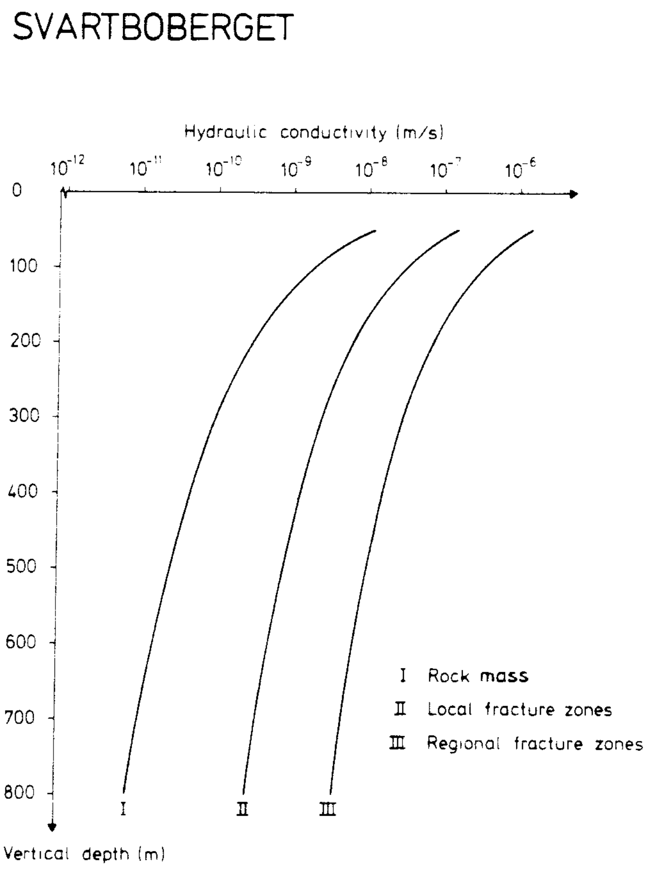


Figure 5.3.1 Hydraulic conductivity versus depth for rock mass, local and regional fracture zones at Svartboberget.

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