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Geophysical investigations at the Klipperås study site

Stefan Sehlstedt
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Luleå, July 1986

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ABSTRACT

The Swedish Nuclear Fuel and Waste Management Co (SKB) currently performes investigations in crystalline bedrock formations in Sweden to find a suitable location for a repository for storage of high level radioactive waste.

The Klipperås study site is situated 45 km west-north-west of Kalmar, Småland County, southern Sweden. From ground surface geophysical measurements, suspected fracture zones were located at the Klipperås study site. The methods used were, the following:

- Horizontal Loop EM (HLEM or slingram)
- Magnetic measurements (proton magnetometer)

The zones indicated became drilling targets for a slim borehole (56 mm) drilling program. After the drilling, each borehole was surveyed by 10 different geophysical methods. These were:

- Borehole orientation
- Natural gamma radiation
- Resistivity, normal and lateral
- Single point resistance
- Self potential (SP)
- Sonic
- Magnetic susceptibility
- Temperature/ liquid resistivity

The logging was performed in 14 slim boreholes, totally 6931 metres. All strong indications, suspected to be zones could be identified as fracture zones or as mafic dykes in the boreholes from geological core mapping and borehole logging. The investigation shows that surface geophysical measurements and borehole logging is a powerful combination to identify tectonic features, i.e. fracture zones, if the physical conditions are favourable. Magnetic bedrock, rather thin overburden, small quantities of clay in the overburden and distinct fracture zones, are examples of such favourable physical conditions.

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SUMMARY

The Swedish Nuclear Fuel and Waste Management Co (SKB) currently performes investigations in crystalline bedrock formations in Sweden. The purpose is to find a suitable location for a repository for storage of high level radioactive waste.

This report deals with the geophysical investigations performed within the Klipperås study site, located approximately 45 km west-north-west of Kalmar in the southern part of Sweden. The investigations comprise ground surface measurements and borehole loggings.

The object of the geophysical investigations is to obtain information on the location of large fracture zones and on the fracturing and groundwater conditions at depth. The ground surface measurements, performed over an area of 9 km^2 were as follows;

- Total magnetic field (Proton Magnetometer)
- Horizontal Loop EM (HLEM or Slingram)

These measurements were performed along parallel profiles with a separation of 40 m between the profiles. The station spacing used was 20 m (10 m for the magnetic method). The Horizontal Loop EM measurements were performed in two orthogonal directions (E-W and N-S).

The results of the ground surface measurements were utilized when the drillings were sited. In total, 14 core and 14 percussion boreholes were drilled. In all core boreholes, a standard borehole logging program was conducted comprising the following methods;

- Borehole deviation
- Natural gamma radiation
- Magnetic susceptibility
- Sonic
- Single point resistance

- Resistivity, normal and lateral
- Self Potential
- Temperature
- Salinity (Borehole fluid resistivity)

In the percussion boreholes the logging methods performed were as follows;

- Borehole deviation
- Natural gamma radiation
- Magnetic susceptibility
- Single point resistance

The borehole logs provided data for the identification of fracture zones as well as different lithological units and gave qualitative information of the hydraulic conditions in the vicinity of the boreholes.

All strong indications suspected to be zones could be identified as fracture zones or as mafic dykes in the boreholes by means of geological core mapping and borehole logging. The investigation shows that surface geophysical measurements and borehole logging is a powerful combination to identify tectonic features, i.e. fracture zones, if the physical conditions are favourable. Magnetic bedrock, rather thin overburden, small quantities of clay in the overburden and distinct fracture zones, are examples of such favourable physical conditions.

1 INTRODUCTION

The Swedish Nuclear Fuel and Waste Management Co (SKB) currently performes investigations in crystalline bedrock formations in Sweden. The purpose is to find a suitable location for a repository for storage of high level radioactive waste. A repository is planned to be located at a depth of about 500 m, and investigations are being carried out in boreholes exceeding that depth.

A standard program has been established for the site investigations, comprising a number of phases (Anlbom et. al., 1983):

- General reconnaissance for selection of study site
- Detailed investigation on the ground surface
- Depth investigations in boreholes
- Evaluation and modelling.

After completion of the reconnaissance studies, which include geological and geophysical reconnaissance measurements and drilling of one deep borehole, 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 conductivity and magnetization 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 conducted with short percussion and core drillholes down to 100-250 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, susceptibility, spontaneous potential and temperature, resistivity and salinity of the borehole fluid. Geophysical measurements are also made on 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 20 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.

This report deals with the geophysical surface and depth investigations performed within the Klipperås site. The geophysical laboratory investigations performed on core samples have been reported separatly (Stenberg, 1986).

2 SITE DESCRIPTION

2.1 Location and topography

The Klipperås study site area is located approximately 45 km west-north-west of Kalmar in the southern part of Sweden (Figure 2.1). The area is situated on a more than 100 km^2 plateau about 180 m above sea level. The topography is relatively flat, gently dipping about 0.5 percent to the east. Elevation within the area varies between 170 and 200 m above sea level.

The location is forested and includes small peat bogs. The overburden covering the Precambrian bedrock is mainly of moraine origin, 3-5 m thick. Rock exposures occur very rarely, only about 0.5 percent of the area consists of exposed bedrock.

Morphological lineaments are rare due to the flat topography within the area. Thus, ground surface geophysical measurements play a major role for detecting major fracture zones within the area.

The locations of the different boreholes within the Klipperås study site are presented in Figure 2.2.

2.2 Geology

The main rock type within the study area is a grey-red to red, coarse to medium grained, granite. The mineral assemblage is plagioclase, microcline, quartz and biotite. A few thin aplites and pegmatites occur also within the granite.

Porphyry dykes of acidic to intermediate composition have been observed within the area. The strike direction of the porphyries is WNW-ESE and dips steeply to the south ($75-90^o$). Different types of porphyry dykes occur within the area according to colour and macroscopic texture. Phenocrysts of feldspar and quartz occur within a fine-grained wine red to reddish brown matrix.

Greenstones have often been observed at the margins of the porphyries with a strike and dip direction parallel to the porphyry dykes. However, greenstones have also been observed elsewhere within the granite. The greenstone is often dark grey, sometimes with feldspar grains within a very fine grained, epidote rich matrix.

Dolerite and mafic-ultramafic dykes have been observed within the area. The location and extent of these dykes have mainly been interpreted from the ground surface geophysical measurements. The strike direction for the dolerite dykes is NNE-SSW and dips steeply to the east ($65-90^o$). The mafic dykes strike in N-S direction and dip steeply to the west ($80-90^o$).

Deformed sections of the bedrock consist of tectonized rock, breccias and mylonites, which occur together in a complex pattern of deformation. Alteration occur within the deformed sections or in discrete zones within the undeformed granite. The following type of alteration has been observed; chloritization, red colouring of the rockmass and along fractures, hematite stained fracture surfaces and alteration skin on fractures such as hydrate iron oxides alteration.

2.3 Other investigations

Several kinds of investigations on the surface and in the boreholes have been conducted in the Klipperås study site. Some of these are:

- Geological and tectonic description of
  the Klipperås study site.
  SKB Technical Report TR 86-06.
  A. Olkiewicz and V. Stejskal.
  Swedish Geological, 1986.

- Hydrogeological investigations at the Klipperås study site.
  SKB Technical Report TR 86-08.
  B. Gentzschein.
  Swedish Geological, 1986

- Geophysical laboratory investigations on core samples from the Klipperås study site.
  SKB Technical Report TR 86-09.
  L. Stenberg.
  Swedish Geological, 1986

- Fissure fillings from the Klipperås study site.
  SKB Technical Report TR 86-10.
  E-L. Tullborg.
  Swedish Geological, 1986

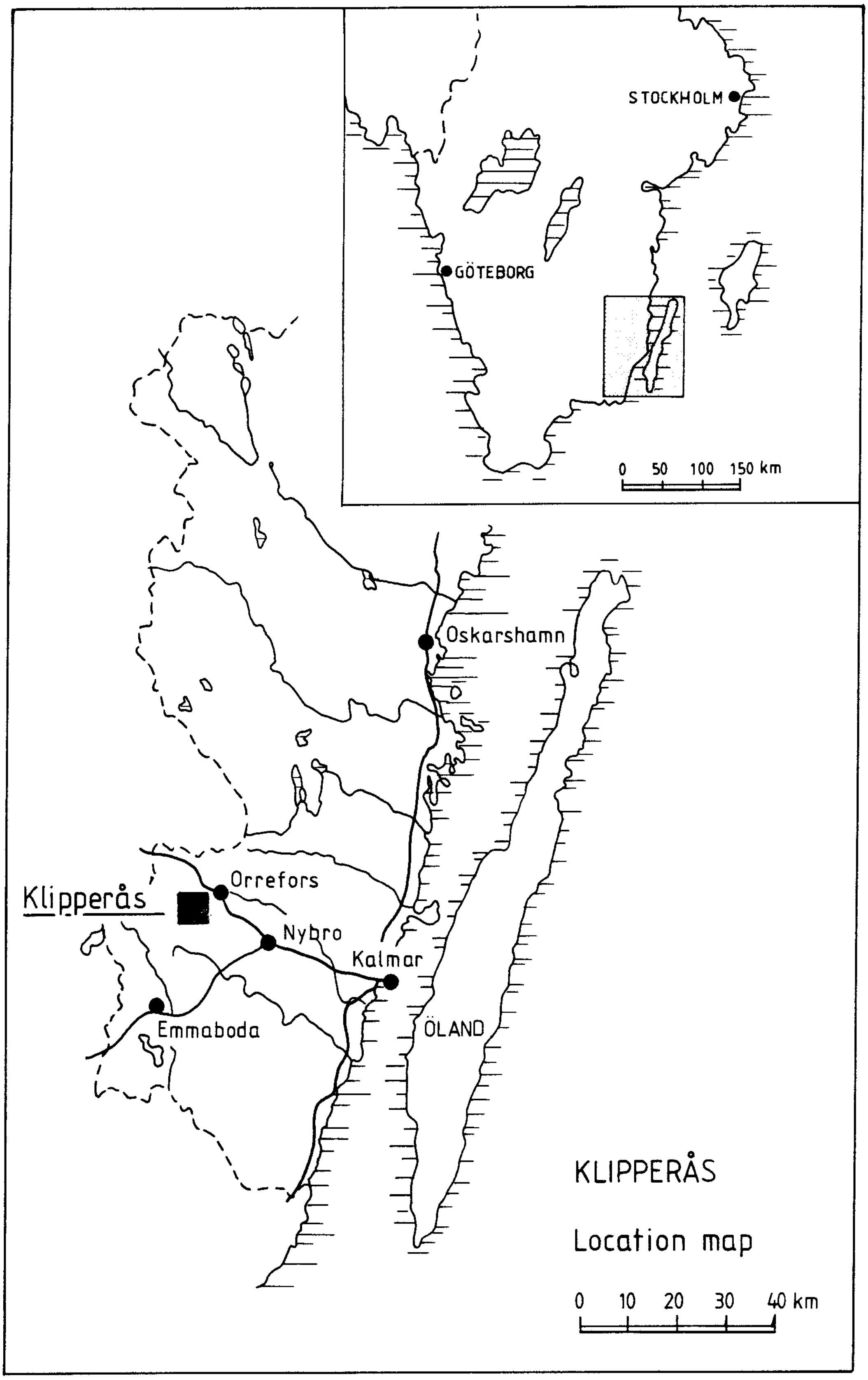


Figure 2.1 Location of the Klipperås study site.

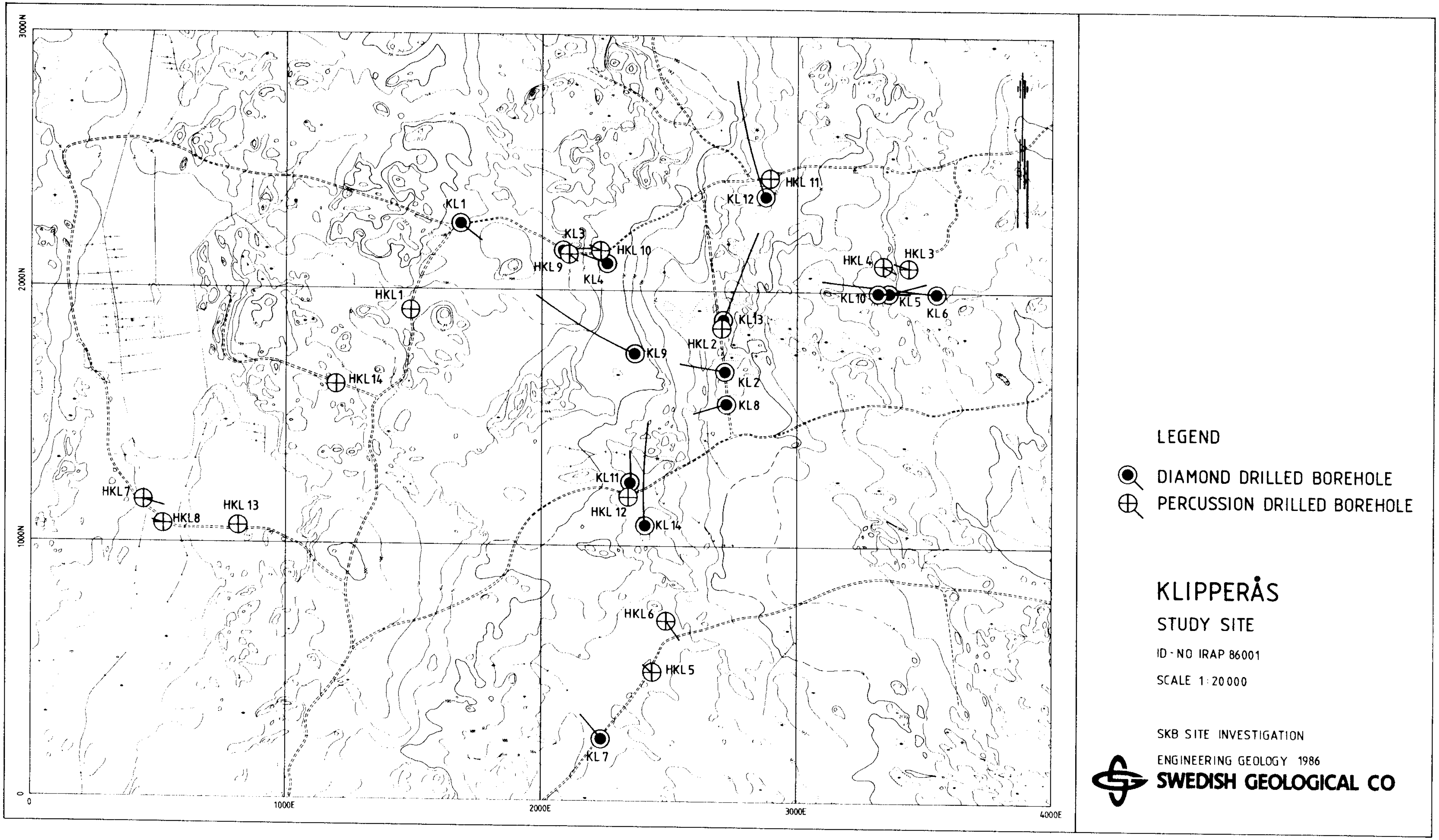


Figure 2.2 Borehole locations at the Klipperås study site.

3 GEOPHYSICAL INVESTIGATION PROGRAM

The geophysical investigation program carried out for the prospective sites for radioactive waste disposal in Sweden has been described by Olsson et. al., 1984. The following presentation of the geophysical surface and depth investigations has been presented elsewere (Ahlbom et. al., 1983). However, modifications in the standard program have been made following the experience gained from previous investigations. In the following presentation attention will be paid to the methods used within the Klipperås study site. A description of the equipment used for the geophysical measurements has been presented by Almen et. al., 1983.

3.1 Surface investigations

3.1.1 Scope

The surface investigations within a study site gives information of fracture zones and rock type distribution. This 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, measurable by 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 also at some depth down into the bedrock. A description of the properties and location of fracture zones in the rock where groundwater transport may occur is of particular interest.

A number of geophysical methods can be used to detect fracture zones. However, the detection and characterization of the fracture zones depends on 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. For a general reference to the methods used, see Parasnis, 1979 and Telford et. al., 1976.

The intensive 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, (to within ± 5 m).

3.1.2 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 magnitudes and pattern 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 determined principally by the content of magnetic minerals in the rock, mainly magnetite and magnetic pyrrhotite. 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 boundaries, dips of contacts, intrusions of e.g. dolerite etc. Magnetic minima caused by oxidation of magnetite to hematite 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 displacement and the existence of fracture zones (Henkel, 1979). In general, these zones of magnetic disturbance today indicate both open and closed fracture zones. The zones could, for example, consist of older fractures that nave sealed.

The magnetic field is measured with a proton magnetometer, and field data is stored directly in a digital memory. The magnetic field can be measured to an accuracy of 1 nT. Daily variations in the magnetic field are generally much greater than the measuring accuracy of the instrument. Measurements of the magnetic field at a permanent station, known as a base station, are made simultaneously with those made along a measurement profile. It is then possible to make a correction for daily variations in the magnetic field. Having applied these corrections, the measuring accuracy often exceeds 10 nT, in practice.

The vertical range of the magnetic method depends principally on the susceptibility contrast and size of the magnetic rock formation. In some cases, large rock complexes located at depths of several kilometres can be detected. In general, however, the vertical range for 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. Conclusions on the possible geological origin of the anomalies can then be drawn. In addition, model calculations might be done using well-known formulae (e.g. Parasnis, 1979, Telford et. al., 1976). From these, the depth, width, dip and magnetization of a magnetic body, can be calculated.

3.1.3 Electromagnetic measurements

Slingram (horizontal loop EM) is a system with two portable coils, one transmitter and one receiver coil, Figure 3.1. The transmitted field in slingram measurement generates, (by induction in electrically conductive zones) a field of disturbance 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). The frequency used in slingram measurement within the site investigation program is 18 kHz. This relatively high frequency permits the detection of formations such as fracture zones with only a slightly elevated conductivity relative 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.

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 of the field are measured as percentages 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 respectively, for values in the range -10 % to 10 %. The accuracy for larger absolute values is approximately one per cent. The major sources of errors in measurement of the real component arise from variations in the distance between the transmitter and receiver coils and also from misalignment between the coils. The corresponding error in the measurement of the imaginary component is considerably smaller. The vertical penetration of the slingram system can be estimated to be approximately 3/4 of the distance between transmitter and receiver, i.e. 45 m.

The interpretation of the slingram measurements consists of identification of anomaly structures and their geological origin, for example whether the anomaly is caused by fracture zones, clays, mineralizations, peat bogs or electrical cables. Profiles of measured anomalies are compared with calculated profiles of different stratigrafic configurations with variable properties (Nair et. al., 1968). These comparisons yield, among other properties, a basis for calculating the width, dip and conductance of existing fracture zones as well as the depth to the zone in question. The interpretation of slingram measurements can be hampered by interference from electrical lines and cables. Hence, it may be advisable to restrict the use of these methods in densely populated and built-up areas.

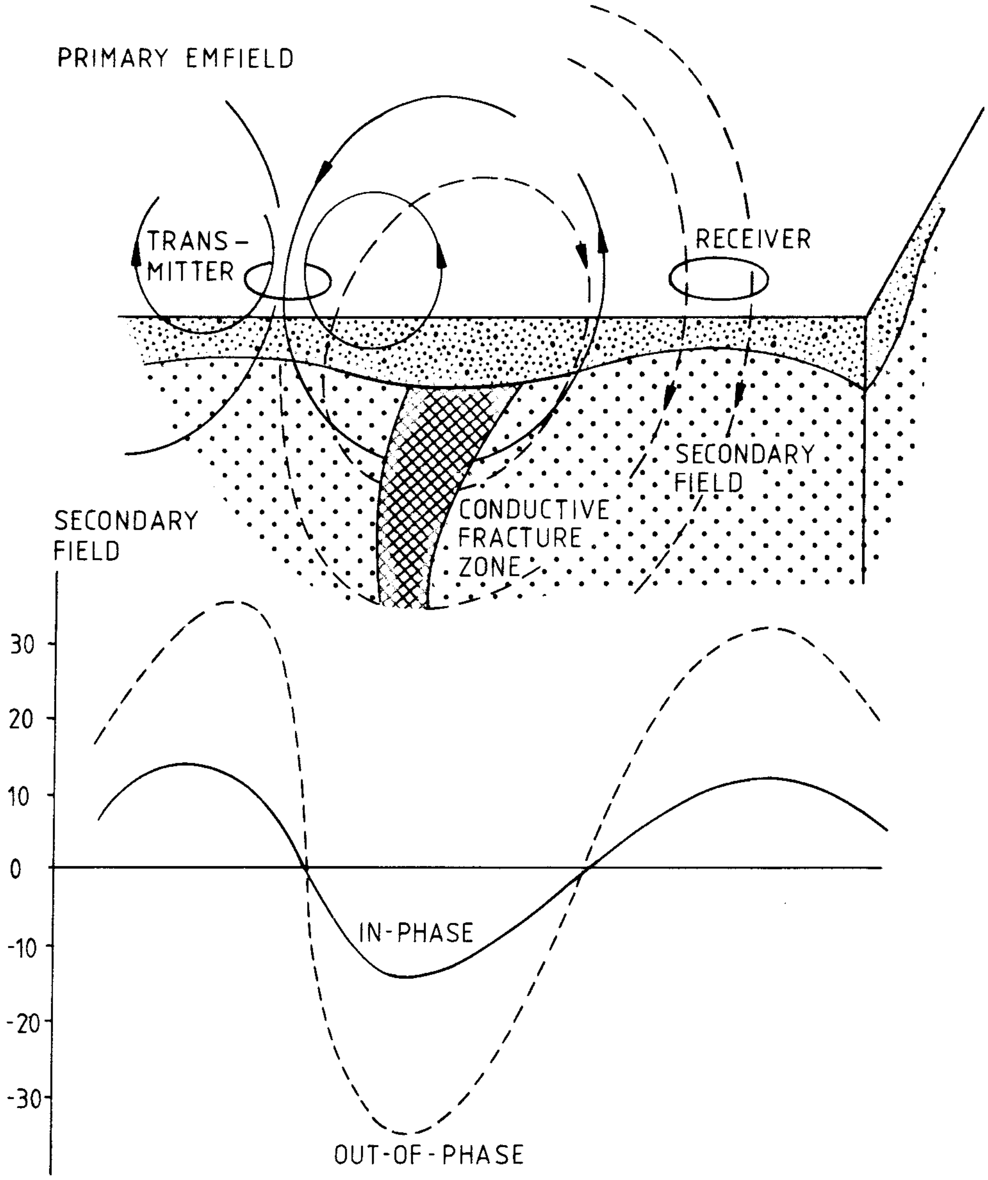


Figure 3.1 The principle of the horizontal loop EM method (HLEM or slingram method) with the expected anomaly of a fracture zone.

3.2 Depth investigations

3.2.1 Scope

Measurements using different geophysical methods are also made in boreholes. Since the measurements are performed in boreholes, the technical requirements on the measuring equipment are different. For instance, the dimensions of the instruments are constrained by the borehole diameter. Some form of communication between the measuring probe in the borehole, and the surface equipment is necessary.

Downhole geophysical measurements provide information of:

- rock formation porosity variations
- occurrence and character of fractures
- certain chemical properties of the borehole liquid
- groundwater flow along the borehole
- presence of electrically conductive and radioactive minerals

A detailed description of the methods used has been published by Brotzen et. al., 1980. The following description of the logging program and the logging methods used have been presented elsewere (Carlsten et. al., 1985). In the following presentation, attention will be paid to the logging methods used within the Klipperås study site.

In general, the measurements only yield information on the bedrock close to the borehole, and hence provide support for the description of the geological structure of the site as well as its hydrological and chemical conditions.

3.2.2 Logging program

To describe the rock mass in the vicinity of a borehole adequately, a number of independent logs are used. Each log measures a physical property of the rock which is directly or indirectly related to the mechanical, hydrogeological or geochemical properties of the rock or the borehole fluid. The following logs have been run in the boreholes:

Borehole deviation log

This log is used to determine the deviation and inclination of the borehole.

Susceptibility log

This log measures the induced magnetization. Rocks are characterized by two types of magnetization: induced and remanent magnetization. The induced magnetization requires the presence of an external magnetic field, whilst remanent magnetization does not. In a weak magnetic field (like the geomagnetic field), induced magnetization is proportional to the field strength; the constant of proportionality is called susceptibility. The susceptibility of a rock depends on the nature and concentrations of magnetic minerals present in the rock.

The magnetization of a rock is carried by three types of magnetic minerals, namely ferro-, para- and diamagnetic minerals. Ferromagnetic minerals such as magnetite or pyrrhotite have magnetization magnitudes which are of the order of 10^4 to 10^6 times larger than those of the para- and diamagnetic minerals. The susceptibility of most rocks is therefore determined principally by the presence o ferromagnetic minerals. Even if the ferromagnetic minerals are present in such minute concentrations as 0.1 vol-%, they will tend to mask the magnetization of the para- and diamagnetic minerals. Iron-rich mafic minerals such as olivine, pyroxene, amphibole and biotite form the most commonly paramagnetic mineral components in the rock, while the most commonly occuring diamagnetic mineral components are quartz and feldspar.

Gamma log

This log is used to investigate the natural gamma radiation of the rock. The natural gamma radiation depends on radioactive K, U and Th isotope components. Variation in the natural gamma radiation level usually corresponds to mineralogical changes in the rock. In general, high radiation values correspond to acid rocks and low to mafic rocks. Also, infiltration of radon-charged water can cause very high gamma ray radiation levels in boreholes.

Sonic log

The sonic log records the time required for a compressional sound wave to travel between a transmitter and a receiver. The speed of sound in the sonic probe and in the borehole fluid is less than that in the bedrock, and the compressional sound wave propagated through the bedrock will arrive at the receiver earlier than that propagated through the probe and borehole fluid.

The sound energy emitted is propagated as elastic waves through the surrounding bedrock, i.e. as an elastic deformation of the bedrock. The velocity of propagation of an elastic wave is a function of the deformation properties (elastic moduli) and the density of the media. The energy is propagated in the form of different types of elastic waves. However the compressional wave type (P-wave) has higher velocity than the other waves. Thus the first wave recorded at the receiver is the compressional wave. The receiver records the travel time for the first arrival.

One of the principal applications of the sonic log is the determination of porosity of sedimentary rocks. However, the log is very sensitive to the presence of fractures in a formation and it is therefore also useful for the detection of fractures in igneous rock. The travel paths of the elastic waves recorded follow the borehole wall closely. The tool is therefore more sensitive to features close to the borehole wall.

Single point resistance log

This log measures the contact resistance of the borehole wall.

The contact resistance will decrease in the presence of conducting minerals or fractures in the borehole wall. Narrow spike like anomalies occur on this log where the borehole has intersected fractures (Nelson et. al., 1982). These fractures constitute an enlargement in the borehole wall. Also, loss of small chips from the borehole wall will be enhanced at an intersection between the borehole wall and an open fracture.

Resistivity log

This tool have two different configurations called normal (1.6 m) and lateral (1.6-0.1 m). The resistivity logs indicate the presence of fracture zones and conducting minerals. The resistivity logs have greater penetration depth but a lower resolution than the single point resistance log. A quantitative estimate of rock porosity and the width and resistivity of fracture zones may also be obtained (after that lateral correction and correction for the influence of the borehole water have been applied). The lateral correction is a correction for the influence of the adjacent sections on the measured resistivity.

Self-potential log

This log measures the natural potential in the rock. Natural potentials can be caused by redox processes, ionic diffusion ions and kinematic processes. Thus the SP-log gives information on conducting minerals, ion concentration variations and groundwater flow in or out of the borehole. The occurrence of conductive minerals can cause large SP anomalies of several hundreds of mV, while the other factors generally cause anomalies which are less than one hundred mV. In crystalline rocks, the SP log has been used mainly as a diagnostic tool for the occurrence of conductive minerals (Brotzen et. al., 1980).

Temperature and borehole fluid resistivity logs

This is a combinated tool used to detect water movements in the borehole.

In rather stagnant water the temperature of the borehole water will correspond to the temperature of the surrounding rock. However, water flow along the borehole might not allow the water temperature to adjust to the temperature of the surrounding rock, i.e. thermal equilibrium between the water and the rock, will not be obtained in this case.

The boreholes often intersect water bearing zones with different piezometric heads. Water from zones with a higher head will then flow along the borehole into zones with a lower head, i.e. the borehole will then provide a "hydraulic shortcircuit". For example water with a lower temperature, which enters the borehole from zones at the upper part, and flows down the borehole to zones at greater depth will result in an apparent lower vertical temperature gradient.

Flow along the borehole is often made evident by the fact that the temperature-depth curve exhibits a change in slope at different sections along the borehole. The depth at which the slope of the temperature curve changes will indicate a zone with water flow between the zone and the open borehole. Such a change in slope is often accompanied also by an abrupt, "step-like" change in the temperature.

To enhance local temperature variations, the gradient is calculated from the temperature measurement. The gradient is calculated from nine adjacent measurements. Changes in the temperature gradient occur mainly in sections where there is waterflow between an intersecting zone and the open borehole.

The measurements were made a short time after completion of the drilling. The cooling of the drill bit in some cases has resulted in a temperature drop at the bottom of the borehole.

A simultaneous measurement of temperature and borehole fluid resistivity makes an accurate determination of the groundwater salinity possible. The salinity probe is calibrated against known NaCl solutions, and the measurements are expressed in equivalent content of NaCl (ppm). The salinity log can also indicate waterflow between intersecting zones and the open borehole. For example, a change in the resistivity often occurs where water with different salinity enters or leaves the borehole.

3.2.3 Logging equipment

Ancillary equipment

The surface unit of the SGAB logging system is constructed as a modular system, which enables flexible use of the different tools. The tools manufactured by other companies are adapted to the system. The measurements are registered on an analog chart recorder and the data are also stored on cassette tapes by a digital data collection system.

A motor driven cable winch is used to lower the probes into the borehole. If the motor failes, the hoisting may also be performed manually. The borehole length is registered by a measuring wheel. There are also calibration marks on the cable for every 10 m.

Borehole deviation

The borehole direction in the vertical plane is measured by a pendulum. The direction in the horizontal plane is measured by a compass needle. The direction of the compass and the position of the pendulum is measured electrically. Compensation is made for resistance changes in the borehole cable, e.g. changes due to temperature variations. The compass is sensitive to magnetic disturbances, e.g. magnetic orebodies or local concentrations of magnetic minerals. However, if magnetic minerals are concentrated in a few (and the length of each section is not excessive) a good estimate of the borehole geometry may still be obtained. The measured declination of the borehole in disturbed sections will, of course, be inaccurate. However, since each measurement is independent, the borehole may be assumed to be straight for shorter sections, and the locally disturbed values may thus be excluded. Corrections for larger concentrations of magnetic minerals are not easily performed.

Susceptibility log

The sensor is an air coil of very high impedance. The coil constitutes a part of a bridge circuit tuned to a frequency of 1450 Hz. The susceptibility of the surrounding rock influences the inductance of the coil which puts the bridge out of balance. The bridge is balanced by adjusting the frequency of the applied signal. Thus, the change in frequency is a measure of susceptibility. The frequency is adjusted electronically in the probe, and transmitted to the surface. The frequency is converted to a DC-voltage which is registered continuously on a chart recorder and a digital display. The measurements are calibrated against samples with known susceptibility.

The resistivity of the surrounding rock attenuates the amplitude of the signal. This effect is electronically compensated in the probe by adjusting the resistance of the bridge. The attenuation is a measure of the resistivity of the rock. Data on the attenuation is also transmitted to the surface and registered on the chart recorder. However, it is sensitive only for very low resistivities, i.e. 0.0001 to 1 ohm-m.

Natural gamma log

Natural gamma radiation is measured by a scintillation detector with a NaI crystal. The results are recorded continuously on a strip chart recorder. The equipment is calibrated to display the radiation intensity in micro R/h.

Sonic log

The probe is equipped with an acoustic source and two dual spaced receivers. The two piezoceramic receivers are mounted above the source, the closest (near) at a distance of 3 feet, while the other (far) can be mounted at 4 to 6 feet from the source. It is therefore possible to select a receiver spacing which varies between 1 to 3 feet. In our case, a receiver spacing of 1 foot was used.

The acoustic pulses are generated by a magneto-strictive source. The sound pulses are triggered with a frequency of 15 Hz. The frequency spectrum of the pulses has a range between 20 to 40 kHz.

The wave form from both receivers can be displayed on an oscilloscope. The oscilloscope is also used for calibration of both travel time and amplitude registration. Only the travel time was registered in this investigation.

The travel time is calibrated by placing markers in the oscilloscope registration for both receivers. The markers are connected to a timer. When the first P-wave arrives at the closest spaced receiver, the timer starts and the timer is stopped at the first P-wave arrival to the second receiver. The value is registered digitally and is converted by a D/A converter to an analog signal, which is registered on a chart recorder. Sometimes, however, the first arrival, although sufficiently strong to trigger the receiver closest to the transmitter, may be too weak to trigger the near receiver. The near receiver may be triggered instead by a later arrival in the sonic wave train. When this occurs, the sonic log shows very abrupt and large spike-like excursions towards higher travel time values. This process is known as "cycle skipping". Such skipping is more likely to occur when the signal is strongly attenuated.

When the amplitude is registered, only the first receiver is used. A time window is selected on the oscilloscope. Within this time window, the largest amplitude of the wave train is picked out for registration.

Point resistance log

The contact resistance is measured by a two-electrode system, where one electrode is situated in the borehole and the other is placed on the surface, some distance from the borehole, Figure 3.2. The resistance is recorded continuously with a strip chart recorder. The equipment is calibrated to display directly the resistance (in ohm) on a log scale. The borehole probe consists of a plastic tube, one metre in length, with a metallic electrode in the middle. The electrode has a diameter of 53 mm (which is only 3 mm smaller than the diameter of the borehole) and a length of 50 mm.

The resistance can be recorded at four different frequences, 3, 11, 33 and 100 Hz. For the current measurements a frequency of 11 Hz was used.

Resistivity log

Two different electrode configurations are used, normal 1.6 m and lateral 1.6-0.1 m. For the normal array one current and one potential electrode are placed on the surface some distance from the borehole, Figure 3.2. The other two electrodes are situated in the borehole and have (in our case) a separation of 1.6 m.

The lateral configuration has three electrodes in the hole, one current and two potential electrodes, Figure 3.2. The separation between the current electrode and the closest potential electrode is in our case 1.6 m. The separation between the potential electrodes is 0.1 m. Thus, the configuration length for the lateral array is 1.65 m.

When lowering the sonde through a zone of conductive material such as a fracture zone, the normal array gives symmetric anomalies, and the lateral array gives asymmetric anomalies. The lateral array has better resolution than the normal array but the normal resistivity approximates closer to the true resistivity of the rock. When a low or high resistive zone intersects the borehole at an angle less than 30 degrees, the normal and lateral configurations will both show anomalies which are nearly symmetric (Olsson and Jämtlid, 1984).

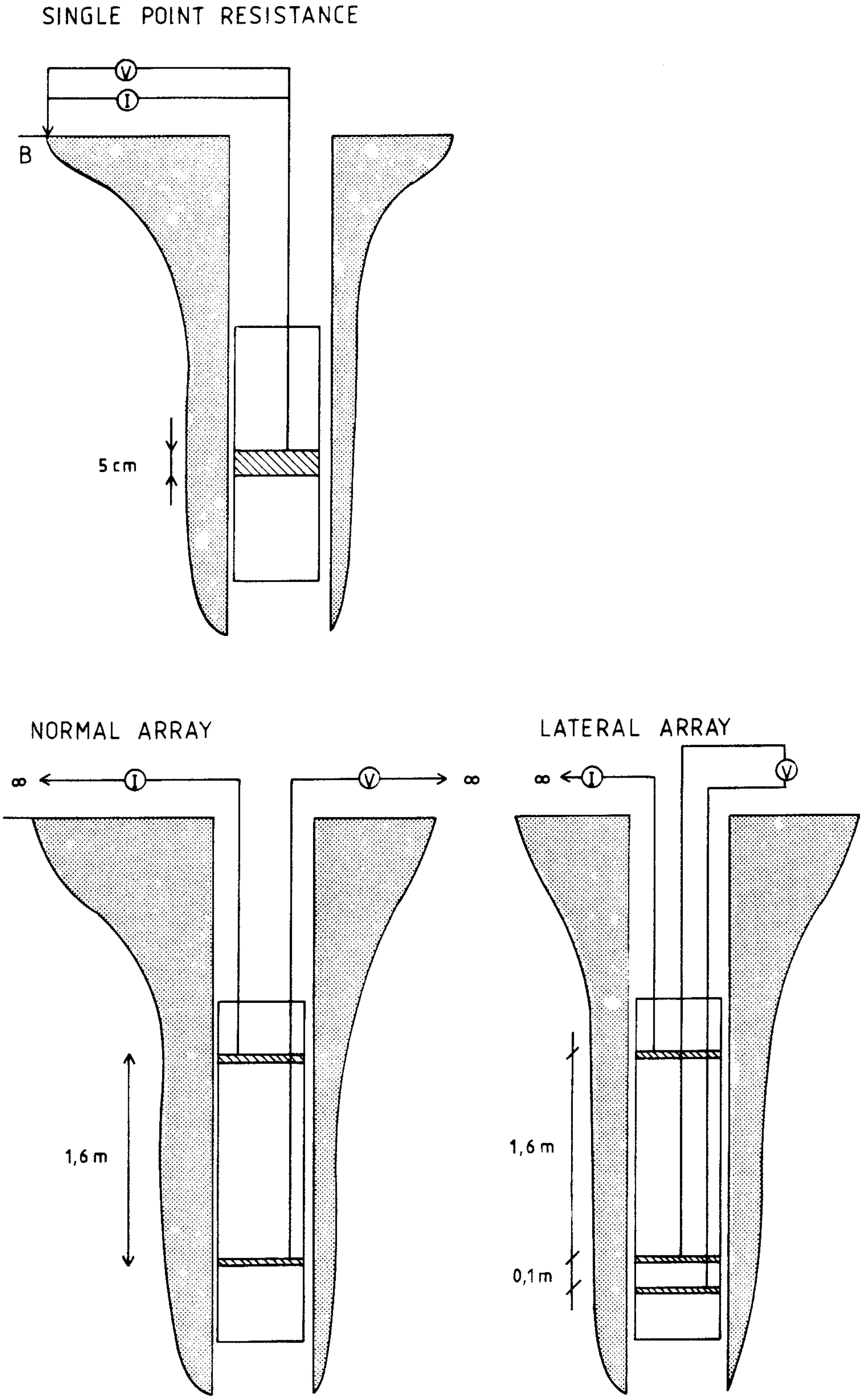


Figure 3.2 Configuration of resistivity tools used.

Self-potential log

The self-potential (SP) is obtained by measuring the potential between an electrode placed on the surface some distance from the borehole, and an electrode situated in the borehole. To minimize electrode effects, non-polarizable electrodes are used. The electrodes consist of a copper wire immersed in a saturated coppersulphate solution, which is in contact with the borehole fluid through a porous wooden plug. The SP is recorded continuously on a strip chart recorder in mV.

Temperature and borehole salinity log

The temperature is measured with a thermistor, to within an absolute accuracy of 0.01 ^{o}C.

The borehole fluid resistivity is measured by a five-electrode system installed in a plastic tube open at both ends. Three of the electrodes are used to emit the electric current and two are used to measure the potential. This electrode configuration prevents the measurement from being influenced by the presence of electrically conductive minerals in the rock.

The electrical conductivity of the borehole fluid may be used to calculate the salinity of the borehole fluid. The salinity calculated is expressed as equivalent contents of NaCl (ppm) after that a correction for the temperature in the borehole has been applied (McNeill, 1980).

4 RESULTS AND INTERPRETATION OF SURFACE INVESTIGATIONS

4.1 General

The reconnaissance studies performed at Klipperås in 1983-1984, included geophysical ground surface measurements over an area of 14 km^2. The following methods were used:

- VLF (two transmitter stations JXZ and GBR)
- Horizontal Loop EM (18 kHz, 60 m coil separation)
- Magnetometer

In all these measurements, a line separation of 100 metres, and a station spacing of 20 metres (5 metres for the magnetic measurements) were used.

As a result of the reconnaissance studies, detailed geophysical investigations were performed over an area of 9 km^2. The results and interpretation of these measurements are discussed below. The earlier results from the reconnaissance studies were taken in account.

The ground surface geophysical measurements performed during the detailed investigations were as follows:

- Total magnetic field (Proton Magnetometer)
- Horizontal Loop EM (HLEM) also called slingram

The measurements were performed with a line separation of 40 metres and a station spacing of 20 metres (10 metres for the magnetic method). A frequency of 18 kHz, and an intercoil spacing of 60 m was used in the horizontal loop EM method.

The horizontal loop EM measurements were performed in two orthogonal directions (E-W and N-S). This was due to the fact that the method is more sensitive to fracture zones which strike in a direction approximately perpendicular to the measuring profile. For fracture zones which strike nearly parallel to the measuring profile, only a slight change in the background level is observed.

The results of the measurements are presented in coloured ink maps in scales 1:10 000 and in profiles. In the report, the map scales used are 1:20 000. The Figures 4.1 and 4.2 show the quadrature (imaginary) component of the secondary magnetic field for the horizontal loop EM (HLEM) method performed in E-W and N-S directions respectively. No useful information is available on the real (in phase) component, due to the low conductivity of the fracture zones. The larger fracture zones are indicated in the range of minus 3-5 percent on the quadrature component. The magnetic field is presented in Figure 4.4.

4.2 Electromagnetic interpretation

The HLEM method provides information of tectonic significance. Fracture zones are indicated as low values on the imaginary component due to their lower electric resistivity, Figures 4.1-4.2. Mafic dykes may also be indicated as will be described below.

4.2.1 Fractures

The interpretation of the electromagnetic measurements are presented in Figure 4.3. The zone indications have been divided into strong, distinct and weak, depending on the anomaly strengths recorded. Continuous anomalies of -3 % or lower are called strong. Shorter anomalies of the same strength are called distinct, as well as longer indications not exceeding -3 %. Weak indications are often short and not easily distinguished. Anomalies described as strong or distinct, were considered to be of greater significance and interest was focused on them. Each of these zones has its own number. The zones interpreted together with their anomaly strength and principal direction, and also the boreholes intersecting each zone, are compiled in Table 4.1.

The detailed interpretation, Figure 4.3, indicates that most zones are built up by shorter sections of two or more directions. Together these directions give a main direction. A generalized map from the detailed interpretation is presented in Figure 6.1.

Table 4.1. Zones interpreted from ground surface geophysical measurements. Anomaly strength and strike direction.

Zone number	Anomaly strength	Strike	Intersected by borehole
1	strong	N20°E	Kl 3, Kl 4, Kl 9
2	strong-weak	N25°E	Kl 9, Kl 12
3	strong	N50°E	Kl 7
4	strong	E-W	Kl 11, Kl 14
5	distinct	N70°W	Kl 13
6	distinct	N75-85°W	Kl 12
7	distinct	N60°E	Kl 12
8	distinct	N85°W	Kl 12
9	distinct-weak	N65°E	Kl 12
10	distinct	N45°E	Kl 1
11	strong	N0-35°W	
12	strong	N-S	

Not all indications in the HLEM measurements are due to fracture zones. A dolerite dyke, also visible on the magnetic map (Figure 4.4), follows partly zone 2 and partly zone 1. The dolerite dyke is intersected by several boreholes, i.e. Kl 4, Kl 9 and Hkl 10.

One N-S trending strong indication, appearing on the measurement performed in the E-W direction, Figure 4.1, are mainly due to a mafic dyke. This indication has been identified by interpretation of logging results from the boreholes Kl 5, Kl 6 and Kl 10.

An indication in the western part of the study site area is due to a broad magnetic dolerite dyke. This is indicated by the magnetic reconnaissance measurements. Indications, zones 11-12, occur in an area having peat bogs superimposed on clay. These are electrically conductive and interferes with the response from the fracture zones. This makes interpretation difficult.

The effect of strike direction of the fracture zones to the measuring profile direction is clearly visible on the maps. The fracture zones which strike close to the E-W direction, i.e. zones 4, 5, 6, 7, 8, 9 are almost undetected by the measurement performed in the E-W direction (Figure 4.1). The fracture zones which strike close to the N-S direction, i.e. zones 1 and 2 are almost undetected by the measurement performed in the N-S direction (Figure 4.2). Only a small increase in background level is observed in connection with the N-S trending mafic dyke.

Although the measurements are fairly good, the station spacing (20 metres) is too large for reliable dip calculations. The response from the fracture zones is small and appears only on the quadrature component. Noise and disturbances from other small conductors influence the anomalies and hamper interpretation. In some cases, however, it has been possible to make estimations of the dip direction. The dolerite dyke following zones 1 and 2 and the zones themselves were interpreted to dip steeply towards E. Zone 3 was interpreted to dip towards SE. Drilling later confirmed the dip directions of both zone 3 and the dolerite dyke (between zones 1 and 2) to 65^{0} towards SE and E respectively. The dips of zones 1 and 2 were found to be nearly vertical.

A few profiles, with a station spacing of 5 metres, were also performed, to obtain improved dip estimations. Zone 4 was traversed with two HLEM profiles, indicating a steep dip towards south. One profile crossed the mafic dyke. The dip was estimated to be close to vertical. Drilling subsequently confirmed the dip of zone 4 to be 80^{0} towards S and the dip of the mafic dyke to be nearly vertical.

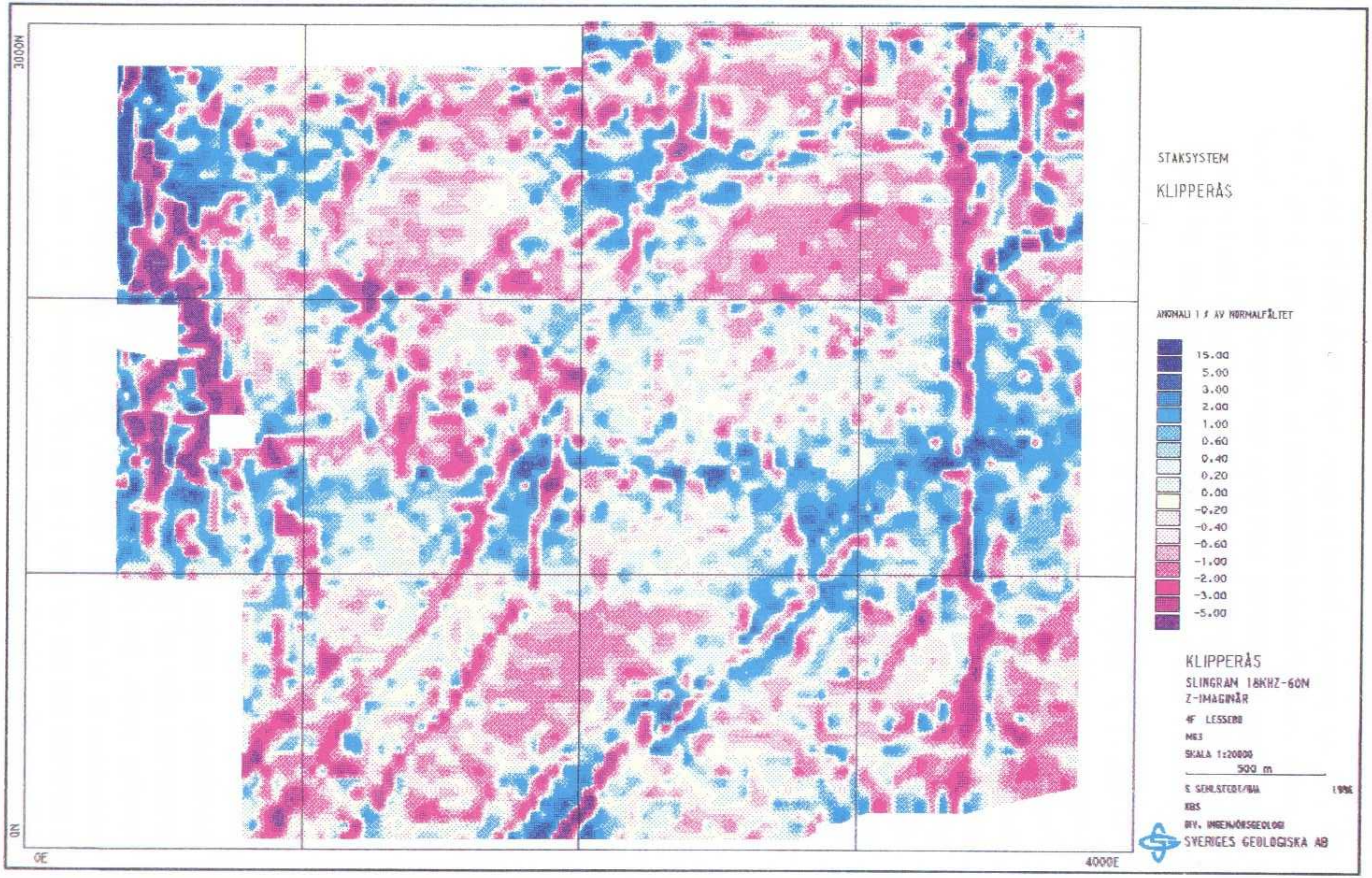


Figure 4.1 Horizontal loop EM, quadrature component, measurement performed in E-W direction.

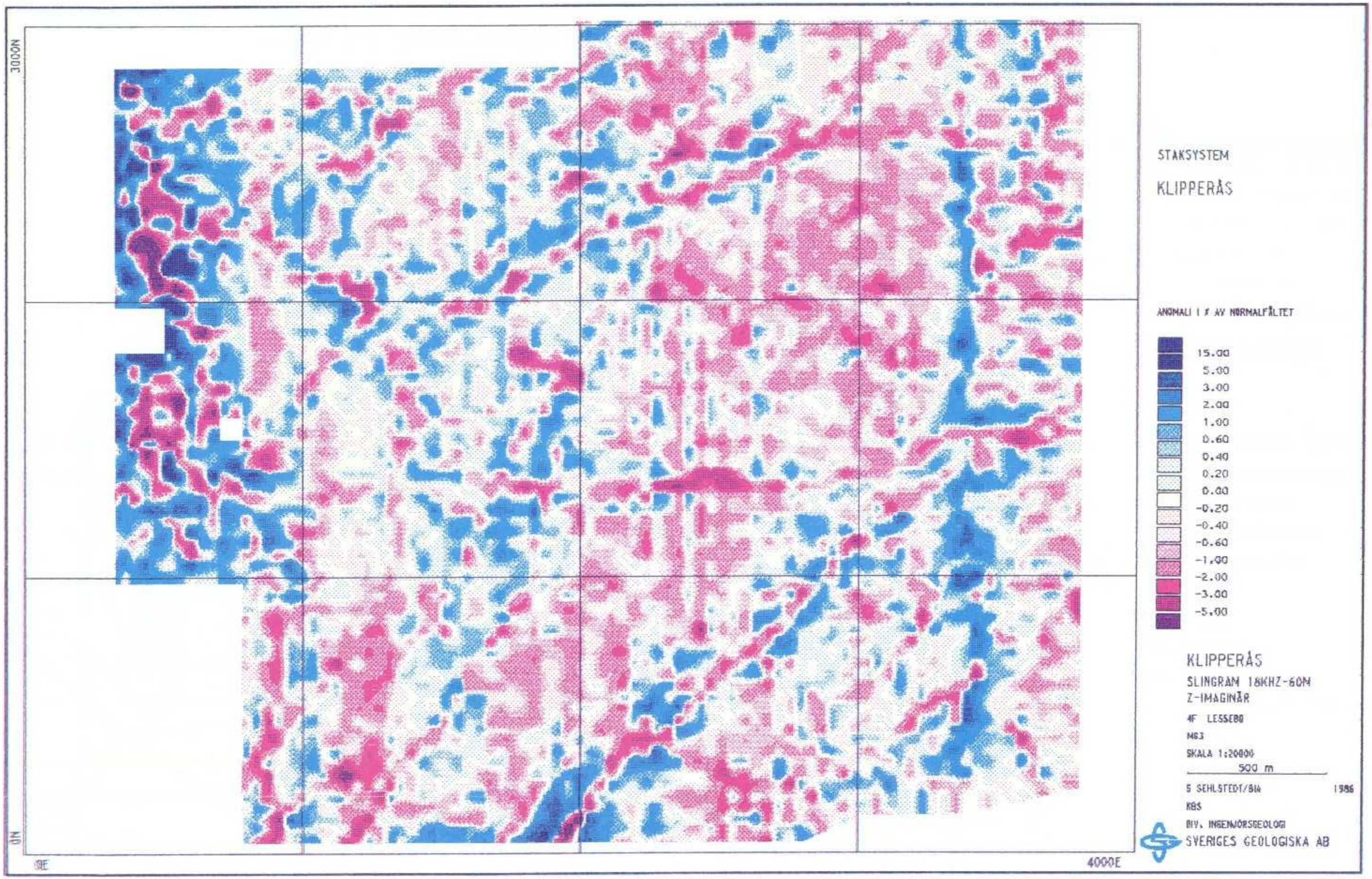


Figure 4.2 Horizontal loop EM, quadrature component, measurement performed in N-S direction.

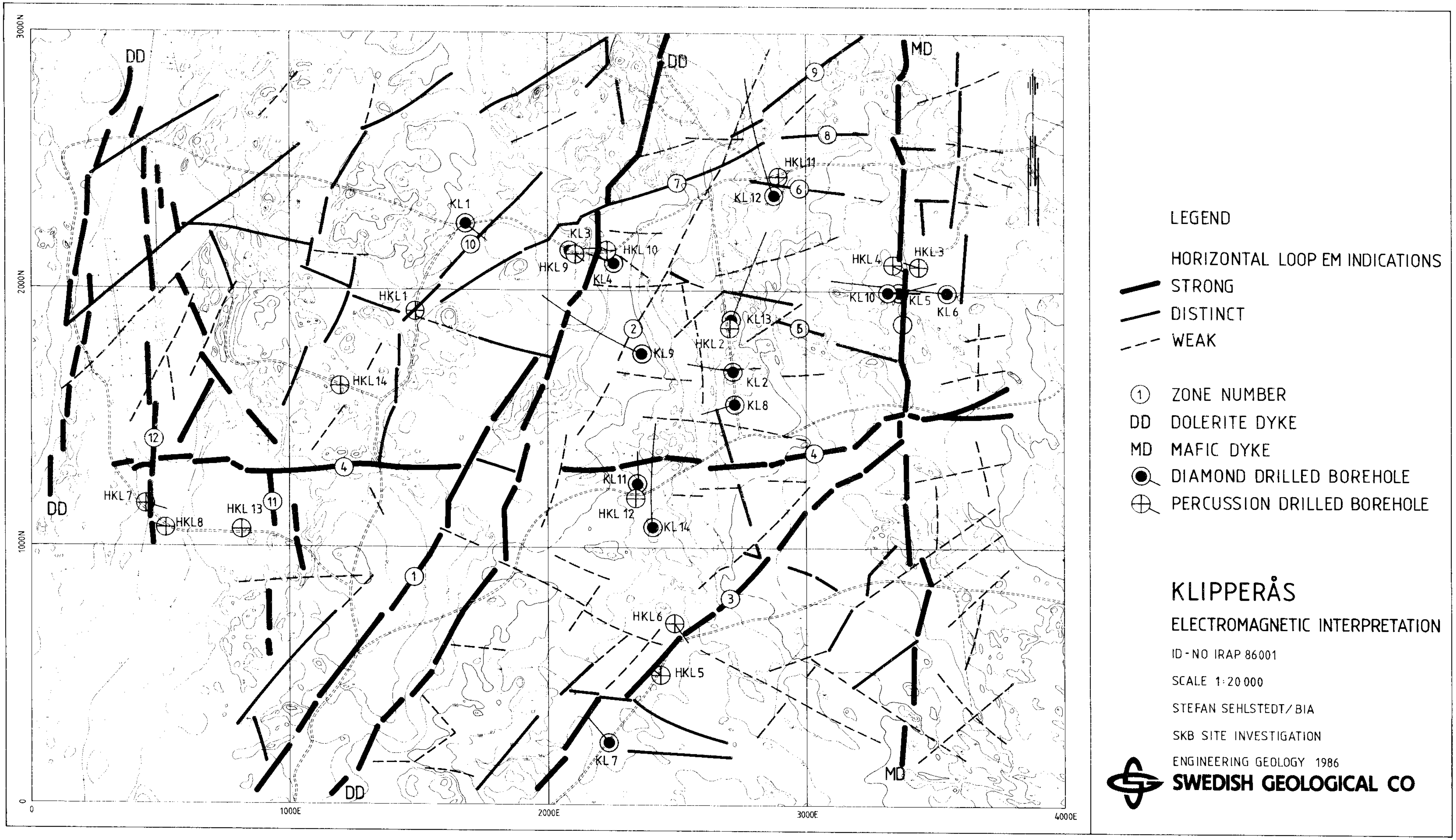


Figure 4.3 Interpretation of Horizontal loop EM measurements.

4.3 Magnetic interpretation

The magnetic method provides information of geologic and tectonic significance. Rock types richer in magnetic minerals, mainly magnetite, will show higher magnetic intensity. In areas with medium to high magnetic rock types, indication of fracture zones is possible. In these cases, the magnetite is oxidized to hematite.

The magnetic measurement is presented in Figure 4.4.
The interpretation of the electromagnetic and magnetic measurements is shown in the form of a generalized map of the fracture zones and mafic dykes occurring within the area in Figure 4.5.

The interpretation map, Figure 4.5, is divided into areas with high, medium and low magnetization. This is a relative classification. The magnetization or magnetic intensity is moderate, with a maximum value of around 1000 nT.

Areas with higher magnetic intensities can be divided into the following three groups:

- continuous dyke like patterns which follows the N 20^{0} E direction (approximately).
- dyke like or banded patterns, faulted into shorter sections. These strike E-W to WNW-ESE.
- areas with higher magnetic intensities.

According to the laboratory investigations performed on core samples, the porphyries have the highest magnetic susceptibility, i.e. $1 - 6 \times 10^{-2}$ SI- units (Stenberg, 1986). This would correspond to a magnetic intensity of 300 - 1800 nT (Parasnis, 1979). The dolerite has a magnetic susceptibility of about 2×10^{-2} SI- units, which would correspond to a magnetic intensity of about 500 nT. The magnetic susceptibility of the granite varies between 2×10^{-4} and 1×10^{-2}, which would correspond to a variation of the magnetic intensity between 0 and 250 nT. The background value of the magnetic intensity, subtracted from the anomaly map, is around 49 750 nT.

4.3.1 Dykes

Two magnetic dykes are indicated by the magnetic measurements. In the central part of the area investigated, one dyke like anomaly is detected. This dyke was interpreted as a dolerite dyke. This was later confirmed by drilling, i.e. Kl 4 and Kl 9. Part of the dolerite dyke follows zone 1 and part of it follows zone 2.

The other magnetic dyke detected is situated in the northwest corner of the area investigated. The appearance and direction were discovered during the reconnaissance work mentioned earlier. This dyke has a direction of N 15^{o} E. It has not been intersected by any borehole, but is suspected to be a dolerite.

Another mafic dyke, striking in N-S, has not been detected by magnetic ground surface measurements. However, susceptibility logging in the boreholes Kl 5, Kl 6 and Kl 10, show that this dyke is much more magnetic than the surrounding granite. The mafic dyke must therefore have a remanent (permanent) magnetization with a direction opposite to the present magnetic field of the earth at this location. This would explain why this dyke was not detected by the magnetic ground surface measurements.

The magnetic dykes mentioned above are also strongly indicated by the electromagnetic measurements.

4.3.2 Magnetic blocks

The areas with medium to high magnetization have been divided into different magnetic blocks. Each magnetic block has been characterized by its own properties, i.e. magnetic intensity, magnetic gradients and pattern, Table 4.2. Dyke like or banded patterns striking in E-W to WNW-ESE are mainly due to porphyry dykes. Areas with otherwise high magnetization are mainly due to granite with a higher content of magnetite. In areas with low magnetization, in the vicinity of fracture zones where weathering and alteration occurs more frequently, the granite may have lost its magnetization, due to oxidation of magnetite to hematite (Henkel and Guzman, 1977). The fracture zones surrounding each magnetic block are also listed in Table 4.2.

Table 4.2. Properties of magnetic blocks interpreted.

Block	Magnetization	Gradient	Magnetic pattern	Limited by zones
A	high	low	irregular	1
B	high	high	dyke like	1-9-2
C	high	high	banded	2-5-8
D	high	high	irregular	2-3-4
E	high	high	irregular	3-4

Block A West of zone 1, the magnetic intensity is rather high, stable and with small gradients. This might indicate an overburden, which is thicker than the one for the area east of zone 1. However, according to drilling results, there seems to be no significant difference in overburden thickness within the two areas. Another possible explanation of the difference in magnetic patterns is that tectonic displacements may have occurred along zones 1 and 2.

East of zone 2, the bedrock is divided into several blocks with medium to high magnetization. These blocks have high gradients and show somewhat different character.

Block B A small block, in the northern part of the measured area, surrounded by the zones 1-9-2. The block has a well developed dyke like pattern striking in E-W. These dykes are abruptly intersected by zones 1 and 2 on both sides. Within the block, there are distinct magnetic anomalies between the two zones. This might indicate that the block is better preserved than other parts, between zones 1 and 2. The dyke-like pattern is probably caused by magnetic porphyries and greenstones, as in block C.

Block C This block is surrounded by zones 2-5-8. It shows a banded pattern, especially in the northern part. The banding strikes N10-20° W. The banding is caused by thin sections of magnetic porphyries and greenstones, according to the core mapping and susceptibility logging in the boreholes, Kl 12 and Kl 13.

Block D This block is surrounded by zones 2-3-4. It shows an irregular pattern. Relatively unaltered granite probably forms its major constituent.

Block E Similar to block D. The block is surrounded by zones 3 and 4.

4.3.3 Fracture zones

As mentioned earlier, fractured zones can in some cases be detected by magnetic measurements. If a fracture zone permits circulation of water, alteration may occur in and around a fracture zone. When the magnetite component of a rock is exposed to oxidizing water, the magnetite will oxidize into hematite. The magnetic properties of the hematite and magnetite differ substantially. The zones will therefore be characterized by low magnetization.

In Figure 4.5 the fracture zones interpreted from the electromagnetic measurements are compiled, together with the intensity of magnetization.

In general, the widths of low magnetization zones are much larger than those of the fracture zones indicated by horizontal loop EM measurements. This is partly due to differences in response for the two methods. The horizontal loop EM method is an induction method, where eddy currents are generated close to the boundaries of the conductor. Hence, as a rule, only the boundaries of a fracture zone will be detected. There may also be differences in the conductivity within a fracture zone due to water content, fracture alteration, clay weathering and mylonitization. The magnetic method will also respond to fracture zones which may be healed but with no significant conductivity contrast to the surrounding bedrock.

An example of a wide section with low magnetization is the section between fracture zones 1 and 2. The horizontal loop EM method has indicated that fracture zones 1 an 2 are rather narrow. According to the magnetic measurements however, the whole section is characterized by low magnetization. Another example is fracture zone 3, which appears as a wide region on the magnetic measurements, but was rather narrow on the horizontal loop EM method.

Also fracture zone 4 is characterized by low magnetization. A rather broad section with low magnetization is indicated within the area where fracture zones 2 and 4 intersect. However, differences in magnetization intensity may also be due to mineralogical differences within the granite, i.e. differences in magnetite content.

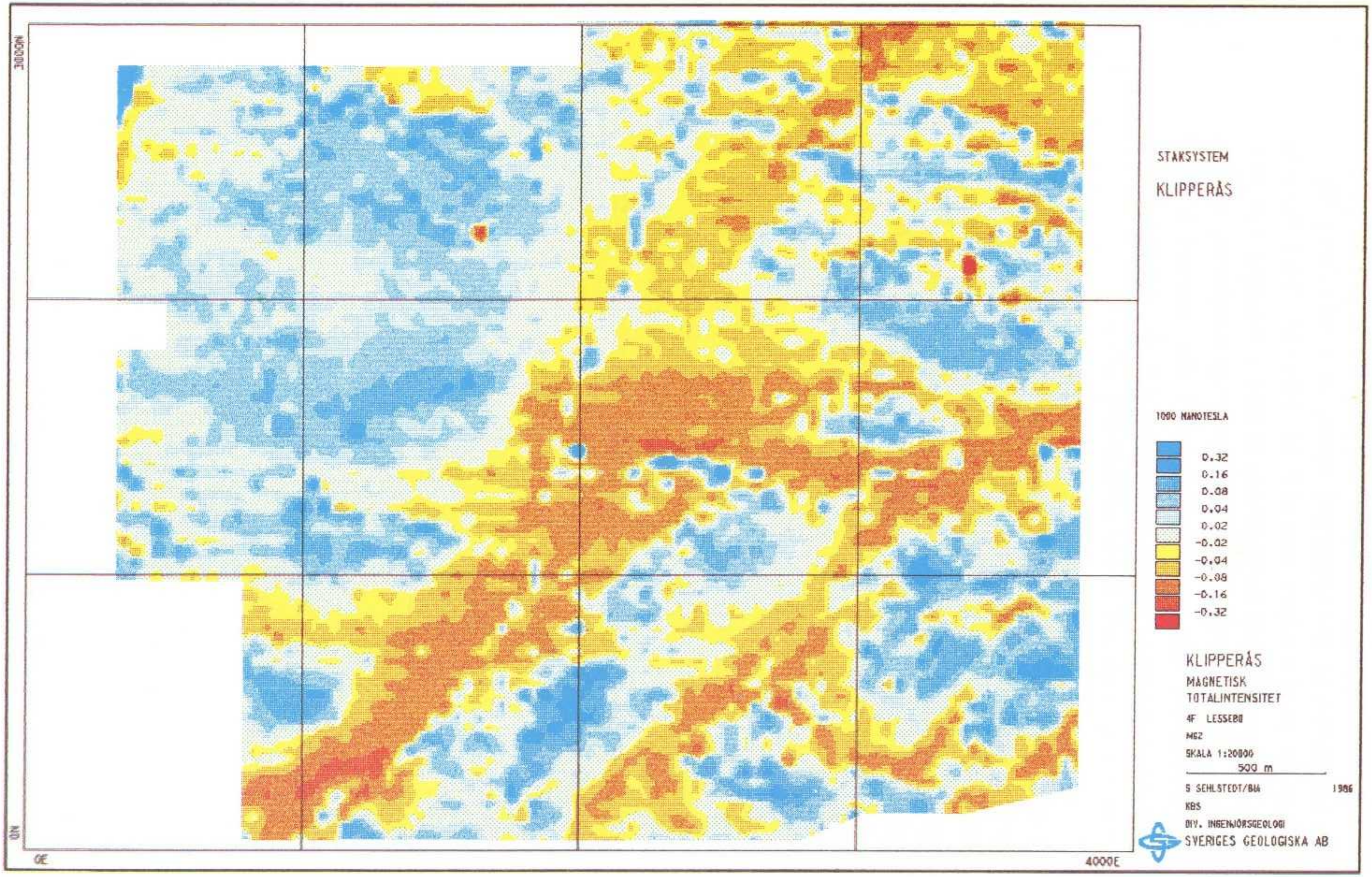


Figure 4.4 The magnetic field of the Klipperås study site.

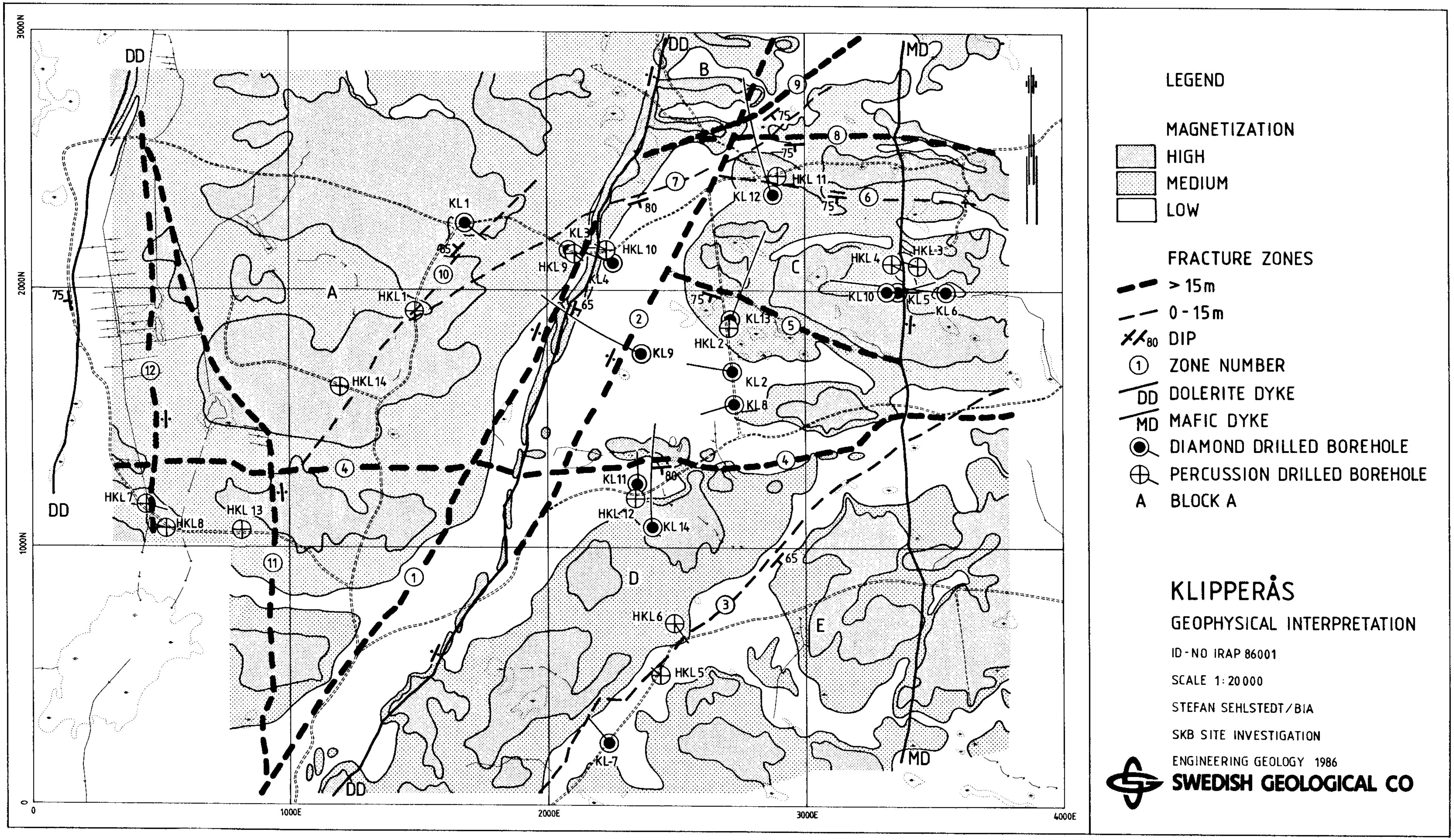


Figure 4.5 Interpretation of the magnetic and the electromagnetic measurements at the Klipperås study site.

5 RESULTS AND INTERPRETATION OF DEPTH INVESTIGATIONS

5.1 Presentation of results from borehole logging

To present the results from the borehole logging, three figures, composite logs, have been compiled for each borehole. These figures have a remarks column, were interpretation and/or comments are presented. These composite logs present methods sensitive to fractures, lithology (rock type) and borehole fluid properties. The text describes the same features but in more detail. All depths mentioned in the text, and in the length column in the figures, refers to borehole length, not to vertical depth.

5.1.1 Lithology

In the standard program, the following logging methods sensitive to lithological changes are used:

- natural gamma radiation
- susceptibility
- single point resistance

The geological core mapping (Olkiewicz, Stejskal, 1986), together with the geophysical logging is presented as a composite log. The scale of presentation gives some generalizations in the core mapping. In some cases sections of alternating granite and bands of mafic rock have been presented as wider mafic rock sections.

Some rock sections whose physical properties differ from those of the surrounding bedrock are coloured black in each log and commented on the REMARKS column.

5.1.2 Fractures

In the standard program, the following logging methods sensitive to fracture occurrence and fracture alteration are used:

- resistivity normal (1.6 m) and lateral (1.6-0.1 m)
- single point resistance
- sonic (acoustic)
- self potential (SP)

The fracture frequency from the geological core mapping, (Olkiewicz, Stejskal, 1986), together with the geophysical logs are presented as a composite log. The fracture frequency is presented as number of fractures per meter.

The geophysical logs mentioned above are not only sensitive to fracture occurrence and fracture alteration but also to lithological changes. Hence, it may be difficult to separate responses due to alteration and fractures, from those due to primary lithological changes.

Sections interpreted as more fractured or altered are marked black for the methods used. Capital letters in the MAJOR UNITS column refer to sections described in the text. Figures in the same column correspond to zone numbers from the interpretation of the ground surface geophysical measurements. The lineaments indicated from ground surface measurements are called zones. Geological mapping of the core intersecting such a zone, reveals that it consists of alternating sections of fresh rock, fracture zones and crushed rock (Olkiewicz, Stejskal, 1986).

5.1.3 Borehole fluid properties

In the standard program, the following logging methods sensitive to formation and borehole water temperature, water salinity and water movements in the borehole, are used:

- temperature
- fluid resistivity

From these two logs, the following properties are calculated:

- vertical temperature gradient
- salinity

The vertical temperature gradient is calculated from the temperature and vertical depth from surface. The salinity is calculated from the temperature and the borehole water resistivity.

The hydraulic conductivity is presented together with the geophysical logs. The hydraulic conductivity is obtained by constant head water injection tests with a straddle packer system (Gentzschein, 1986). A separation of 20 or 25 metres between the packers is used.

Interpretation of water movements in boreholes by means of temperature logging are based on Drury, 1984. These results have been compared with borehole fluid resistivity, piezometric pressure (Gentzschein, 1986) and drillwater loss during drilling. The piezometric pressure is calculated as the difference between the pressure obtained from the fall of phase of the water injection test and the hydrostatic pressure in the borehole at the corresponding level. While interpreting the temperature logs, the measurements in Kl 14 were used as a reference log.

5.2 Description of logging results obtained from the boreholes

5.2.1 Borehole Kl 1

Borehole Kl 1 was drilled as a preliminary reconnaissance borehole at the Klipperås site. This was done to obtain a preliminary picture of the rock composition, the fracturing and the hydrological conditions in the vicinity of the borehole.

Data for borehole Kl 1 are presented below.

Table 5.1. Borehole data for Kl 1.

Local coordinates x(m) y(m) z(m.a.sl):	2253N 1674E 199.38
Length (m):	563.95
Diameter (mm)	56
Inclination (°):	80
Declination (°)	134
Drilling period:	830608-830904
Logging period:	830920-830921 841001,841212

Lithology

The gamma radiation is produced by three elements, U, Th and K. Changes in potassium content provide information on lithologic changes (West et. al., 1975). Silic rocks often produce more gamma radiation than mafic rocks. Gamma radiation mainly originates from K in the orthoclase and biotite. U and Th are usually associated with biotite, (Davidson et. al., 1982).

All core mapped greenstones are detected by gamma measurements as low gamma intensities, Figure 5.1. These sections are marked black in the gamma log. The greenstones are nonmagnetic in Kl 1.

The aplites are detected with higher gamma intensities (50-100 micro R/h).

Other peaks are probably caused by uranium or radon enrichments in fractures.

Several sections with dark grey acid porphyry, between 449 and 561 metres, show a high magnetic intensity on the susceptibility log, and a gamma level which is slightly lower than the granite. If these sections have a nearly vertical dip as indicated from geological mapping (Olkiewicz et. al., 1986), they should be clearly indicated by ground surface magnetic measurements. This has not been observed, Figure 4.4, which implies that these sections/dykes do not reach the surface.

Fractures

Geophysical logs sensitive to fracture occurrence and fracture alteration are presented together with fracture frequency (1/m), in Figure 5.2.

The casing extends down to a borehole length of 33 metres, and no logging results are available above this level.

In the upper part of the borehole the background resistivity seldom exceeds 100 000 ohm-m. The normal background resistivity below 200 metres in Klipperås is about 200 000 ohm-m. This, and a fluctuating sonic curve indicates either a rather high fracture frequency, or that many fractures are open. Alteration commonly occurs down to 42 metres, and occational occurrences of ironoxide are found throughout the borehole. Ironoxide occurs only in sections with very low susceptibility and probably causes low resistivity in several sections.

The correlation between the logs and the core mapped fracture frequency is rather good down to 332 metres. At this borehole length the composition of the fracture angles changes drastically. Above 332 metres, fractures perpendicular to the core axis dominates, and below that level, subparallel fractures dominate. The hydraulic conductivity is very high above this location but its value falls below the detection limit at borehole lengths exceeding 332 metres. All logs change character at borehole lengths exceeding 332 metres, Figure 5.2. At this level the sonic curve becomes smoother, the resistivity increases, and the SP curve do not fluctuate so rapidly. The dominating fractures, subparallel to the core-axis, below 332 metres concentrate the current flow and give low resistivity values even for moderate fracture frequencies. These fractures also have a strong effect on the sonic travel time. This makes it difficult to indicate increased fracture frequency. In the section below 332 metres borehole length it appears that the presence of the ironoxide has a stronger effect on the resistivity than the fracture frequency.

Below 449 metres, granite, greenstone and porphyre alternate. Since the greenstone itself has a low resistivity and the porphyry has a high resistivity, this further complicates the interpretation.

Two major structural units are described below.

Unit A 64-88 m	A granite section (24 m) with three thin greenstones (totally 6.9 m). The most fractured parts are concentrated in the greenstones and the contacts between granite and greenstone. Increased fracture frequency is indicated mainly by the sonic measurements. The low resistivity is caused both by the rock type and the fracturing.
Zone 10 280-310 m	A unit dominated by granite (33.7 m) but which also consists of greenstone (14.3 m). Both rock types are fractured or crushed. The granite is red coloured and partly mylonitized and brecciated, (Olkiewicz et. al., 1986). Ironoxide is a common fracture mineral. This oxide, along with high fracture frequency gives a low apparent resistivity. In pure granite, the single point resistance gives a good picture of the fracture frequency. When greenstones occur they influnce the measurements considerably, giving low resistance,

even if they are not fractured.

A greenstone, at 316-325 metres borehole length, is also strongly indicated by resistivity. An indication of its presence is mainly due to its chemical composition. It has fewer fractures than the surrounding granite.

Borehole fluid properties

Interpretation of temperature logging gives an inflow of water at 81 metres in unit A, Figure 5.3. An increase in salinity is also registered at this level. A total water loss at 80-81 metres has been recorded during the drilling. The entering water follows the borehole downwards and leaves it at 309 metres. A gradient shift at 309 metres is caused by the water flow above this level.

According to the hydrogeological investigations performed (Gentzschein, 1986), however, the directions of water flow should be in the opposite direction. In the corresponding section, 56-81 m, the piezometric head is below zero, i.e. underpressue, which would imply an outflow of water from the borehole. In the section between 81-106 m, the hydrostatic pressure is close to zero. In the section 306-331m, the piezometric head is greater than zero, i.e. overpressure, which would imply an inflow of water from the formation into the borehole.

The hydraulic coductivity is high, 10^{-7}-10^{-5} m/s, in the 30-330 metres section. At borehole lengths exceeding 330 metres the conductivity falls below the detection limit.

Drillwater loss during the drilling was recorded at 20 m, 29 m, 80-81 m (total), 213 m and 289 m.

5.2.2 Borehole Kl 2

The second reconnaissance borehole, Kl 2, was drilled in an area where no ground surface geophysical indications of fracture zones were found.

Data for borehole are presented below.

Table 5.2. Borehole data for Kl 2.

Local coordinates x(m) y(m) z(m.a.sl):	1687N 2717E 182.33
Length (m):	958.62
Diameter (mm)	56
Inclination (°):	78
Declination (°)	278
Drilling period:	840427-840628
Logging period:	840701-840703 840930,850414

Lithology

Geophysical logs mainly sensitive to lithology variations are presented together with a schematic lithology log in Figure 5.4.

Of the greenstones mapped from this borehole, two were not clearly indicated from the gamma measurements. These sections were probably too thin to be detected.

All greenstones mapped are nonmagnetic, with one exception, Figure 5.4. The thickest greenstone in Kl 2, 586-618 metres, is highly magnetic in the lower part, moderately magnetic in the upper part, and nonmagnetic in the central part.

The core section 764-796 metres is missing. According to the logging results this section consists mainly of granite with two very thin magnetic mafic sections, 768 and 770-773 metres, which are also highly fractured.

A magnetic dolerite, 944-952 metres, was interpreted as an apophyse to the dolerite west of the borehole (Olkiewicz, Stejskal, 1986), Figures 4.4 and 4.5.

Fractures

The borehole Kl 2 is characterized by high background resistivity, 300 000 ohm-m, and a calm sonic curve, Figure 5.5. This indicates a general low fracture frequency relative to other boreholes in the area. This is in good agreement with the core mapped fracture frequency.

In a comparison of the resistivity and natural gamma radiation, it appears that almost every low resistivity indication is associated with lithologic variations, i.e. mafic rock types.

A moderate resistivity anomaly, caused by two greenstones, occurs in the 99-113 metres section. The granite between the two greenstones, and the upper contact of the lower greenstone is relatively fractured. This can be observed from both sonic and resistance measurements.

Unit A 586-618 m	A greenstone section with, slightly increased fracture frequency. The unit is indicated by lower resistivity, low sonic travel time and different SP character. This is typical for a mafic rock type, which is not too fractured.

A resistivity anomaly at 673-686 metres is due to a greenstone.

Unit B 768-774 m	Two thin mafic and magnetic sections surrounded by granite are indicated by natural gamma measurements, Figure 5.4. The unit is very fractured according to the sonic measurements and the very low resistivity, 4 000 ohm-m. No geological information is availible, since the core is missing.

Zone H1 792-804 m	This unit is dominated by granite, but also contains two thin greenstones. This unit is indicated by anomalies identical to unit B. The first four metres of the unit are missing. Altered fractures occur between 801 and 804 metres. The zone is distinctly indicated by all methods except SP. This section is very interesting from a hydrological point of view (Gentzschein, 1986).

At 866 m, a distinct but narrow sonic and resistivity anomaly is indicated. It is described as a shearzone by Olkiewicz and Stejskal, 1986.

Borehole fluid properties

At 804 metres, there is a temperature step, Figure 5.6, which is typical for water movements in a borehole. Comparing the temperature log with Kl 1, which has the same inclination, a displacement in temperature level can be observed. Obviously cooler water flows downwards in Kl 2 and leaves the borehole at 804 metres. A negative piezometric pressure and a drillwater loss during the drilling at the same level supports this interpretation. The highest hydraulic conductivity, 10^{-6} m/s, was measured in the section 790-810 metres. The lower temperature gradient above 804 metres is probably caused by the water flow in the borehole.

The 740-787 metres section has the highest salinity recorded in the borehole. This is probably caused by saline formation water. In this section, there is a negative piezometric pressure, which is correlated to this salinity change. Still it is difficult to give an explaination to this anomaly.

Down to 140 metres the hydraulic conductivity is approximately 10^{-7} m/s. Below 140 metres few sections have a detectable conductivity ($>10^{-11}$ m/s). The 740-810 metres section shows a higher conductivity, 10^{-9}-10^{-6} m/s.

The geothermal formation gradient is 14.5-15 ^{o}C/km.

5.2.3 Borehole Kl 3

The drilling target for this borehole, like Kl 4, was the dolerite dyke indicated from geophysical ground surface measurements (chapter 4). This dyke is oriented N30°E. Part of this dyke follows zone 1 and part of it follows zone 2, Figure 4.3.

Logging was performed down to 200 metres only, due to collapse of the borehole.

Data for borehole Kl 3 are presented below.

Table 5.3. Borehole data for Kl 3.

Local coordinates x(m) y(m) z(m.a.sl):	2160N	2079E	197.25
Length (m):	249.96		
Diameter (mm)	56		
Inclination (°):	60		
Declination (°)	85		
Drilling period:	840701-840709		
Logging period:	841212,841219 850111-850113		

Lithology

The core from this borehole consists mainly of granite, Figure 5.7. None of the other very thin rock sections caused significant anomalies.

One gamma anomaly at 200 metres could possibly be a mafic section, which was not observed during the mapping (Olkiewicz, Stejskal, 1986).

The susceptibility level is very low in the borehole, and no magnetic anomalies whatsoever were recorded. This indicates that the magnetite has been oxidized to hematite. The geological core mapping shows that iron oxide is a common fracture mineral throughout the borehole, which supports this view.

Fractures

Low background resistivity is caused by a combination of high fracture frequency and an common occurrence of iron oxide as fracture mineral, Figure 5.8.

Three major structural units are described below.

Unit A 13-37 m	This unit is geological core mapped as granite. Throughout the length of the borehole, calcite is a common fracture mineral. In unit A the lower contact resistance and the higher sonic travel time is recorded where calcite is missing. These fractures are more open and they contain more water. Alteration in fractures is commonly observed in this unit.
Unit B 48-77 m	This unit is also formed by granite. The correlation between low contact resistance, high sonic travel time and lack of calcite is very good. Again, open fractures give good response on the different logs. Several fractures in the upper half of the unit are altered according to the core mapping (Olkiewicz, Stejskal, 1986).
Zone 1 140-195 m	This zone is mainly built up by granite, with only one very thin section of greenstone. The zone consists of many fractured zones and also some crushed zones. Excellent correlation between low contact resistance and lack of calcite can be observed in this zone. Altered fractures are common in the central part of the zone.

Clay alteration in fractures occurs at 203 metres.

Borehole fluid properties

The low temperature gradient, less than 7 °C/km, indicates a waterflow in the borehole, Figure 5.9. A distinct temperature anomaly can be observed between 60 metres and 176 metres. This is caused by water entering the borehole at 60 metres, flowing downwards and leaving the borehole at 176 metres. The interpretation is in accordance with a stabilization of the salinity at 60 metres and downwards. The temperature level below the temperature step is exactly the same as in Kl 14 at the corresponding depth. This supports the interpretation of flow direction.

The temperature gradient do not stabilize in Kl 3.

5.2.4 Borehole Kl 4

The drilling target for this borehole, like Kl 3, was a dolerite dyke indicated by ground surface geophysical measurements, Figure 4.3.

Data for borehole Kl 4 are presented below.

Table 5.4. Borehole data for Kl 4.

Local coordinates x(m) y(m) z(m.a.sl):	2110N 2243E 195.80
Length (m):	200.01
Diameter (mm)	56
Inclination (°):	59
Declination (°)	289
Drilling period:	840710-840718
Logging period:	840929-841002 850111,850422

Lithology

The background susceptibility is extremely low with no anomalies within the granite, Figure 5.10. This implies that the bedrock is altered. This is confirmed by the geological core mapping.

A magnetic dolerite, 78-91 metres, is indicated from all the methods used. This dolerite is also indicated distinctly from ground surface measurements.

Some greenstones are also indicated but thin sections give only weak gamma anomalies.

Two porphyry sections, 167-178 and 192-193 metres, are indicated by a gamma radiation level somewhat lower than the granite. They are both surrounded by greenstones giving an even lower gamma radiation.

Three positive gamma peaks, at 11, 24 and 171 metres are probably caused by uranium enrichments in fractures. At 11 metres, strong tectonization has been observed, and at 171 metres there is a brecciation. The highest of these peaks, at 171 metres depth, is situated in a porphyry section.

Fractures

The low background level on the resistivity log, 30 000 ohm-m, and the violently fluctuating sonic curve indicate a very high fracture frequency, Figure 5.11. This is confirmed by the geological core mapping, which reveals that alteration is of common occurrence (Olkiewicz, Stejskal, 1986) . At core lengths exceeding 110 metres the bedrock is commonly brecciated and altered. This along with high fracture frequency explains the low resistivity encountered in this part of the borehole.

Unit A 78-91 m	This unit is a dolerite dyke indicated by ground surface geophysical measurements. The logs gives distinct indications due to its magnetic, electric and nuclear properties, Figures 5.10-5.11. At 91 metres borehole length clay alteration in fractures occurs.
Zone 1 110-180 m	This zone is dominated by granite, with several greenstones, some quartz veins and one porphyry section. Zone 1 contains many fracture zones and several crushed ones. The zone is brecciated. There is a correlation between a lack of calcite in the fractures, low contact resistance and low sonic travel time. This correlation is not so strong as that obtained from Kl 3.

Borehole fluid properties

The extremely low vertical temperature gradient, 2°C/km, indicates a water flow in the borehole. Temperature anomalies correlating with changes in salinity further supports this idea. Temperature interpretation implies that water enters the borehole at depth and moves upwards. Temperature indications of this type can be seen at 195, 164, 153, 119 and 98 metres. Increasing salinity is observed between 164 and 153 metres, when following the borehole upwards, and at 120 metres. The temperature for the last few metres is the same as in Kl 14 at the corresponding depth. This supports the interpretation.

The higher salinity in the upper part of the borehole might be due to higher content of formation water, which should be more saline than the drillwater.

The temperature gradient do not stabilize along this borehole.

5.2.5 Borehole Kl 5

The drilling target for this borehole, as for Kl 6 and Kl 10, was a suspected fracture zone, as indicated from ground surface geophysical measurements.

All logs were not measured due to collapse of the borehole and loss of equipment.

Data for borehole Kl 5 are presented below.

Table 5.5. Borehole data for Kl 5.

Local coordinates x(m) y(m) z(m.a.sl):	2000N 3361E 175.77
Length (m):	246.44
Diameter (mm)	56
Inclination (°):	56
Declination (°)	76
Drilling period:	840721-840730
Logging period:	841212-841213

Lithology

Due to collapse in the borehole, susceptibility logs was not measured.

All greenstones are indicated as low gamma values, Figure 5.13.

A mafic dyke, 19-29 m, one of the distinct indications on the HLEM method, Figure 4.1, was first suspected to be a fracture zone. The mafic dyke is indicated by natural gamma radiation and strongly indicated by low contact resistance.

A section, 34-66 m, with a slightly lower gamma radiation than the granite, was mapped as plagioclase porphyry (Olkiewicz, Stejskal, 1986).

Some brecciated sections, such as those at 66-79 and 152-155 metres, have a higher gamma radiation than the background.

Fractures

A fracture figure is not compiled for this borehole since several logs not were run in this borehole. Of the methods sensitive to fracture occurrences, only single point resistance was measured. Comparing this method with natural gamma radiation, Figure 5.13, a close correlation between mafic rocks and fractured parts can be seen.

In pure granite, the fracture frequency is low. Increased fracturing has been mapped in and around other rock types, mainly mafic rocks.

The low resistivity section, 19-29 metres, was indicated from ground surface geophysical measurements. Geological core mapping showed it to be an mafic dyke. The dyke is highly fractured and extensively crushed. Alteration and clay fillings occur in several fractures. This dyke has also been found in Kl 6 and Kl 10. With logging, it is indicated by low gamma radiation intensity and low resistivity.

A porphyry section, 34-66 metres, has the same contact resistance as the granite, even if it is much more fractured than the granite.

A mylonitized and tectonized section, 200-244 metres, with many fractures shows lower resistance.

Borehole fluid properties

Borehole fluid resistivity and salinity are presented together with formation temperature and vertical temperature gradient in Figure 5.14.

In the upper part of the bedrock, the first 100-200 meters, the vertical teperature gradient seldom stabilizes. Only distinct anomalies might be localized and interpreted. No significant anomalies were recorded in Kl 5. However, compared with the temperature in Kl 14, the temperature at depth is lower in Kl 5. This might indicate a downward water movement.

5.2.6 Borehole KL 6

The drilling target for the borehole was a suspected fracture zone, as indicated by ground surface geophysical measurements. This borehole was first drilled down to 267 metres and then logged. When the zone not was found, the drilling commenced down to 808 metres. The rest of the borehole was then logged.

Data for borehole Kl 6 are presented below.

Table 5.6. Borehole data for Kl 6.

Local coordinates x(m) y(m) z(m.a.sl):	2000N 3539E 173.11
Length (m):	808.00
Diameter (mm)	56
Inclination (°):	56
Declination (°)	276
Drilling period:	840802-840810 850222-850316
Logging period:	840928-841001 850114 850410-850412

Lithology

As usual, most mafic rock sections exept for the thinnest, are recorded with the gamma log as low values, Figure 5.15.

Where single point resistance shows a high background level, the rock is magnetic, while low contact resistance often correlates with nonmagnetic sections. This is due to oxidation of magnetite to hematite in fractured parts of the rock.

Several strongly magnetic mafic sections are recorded at borehole lengths between 338 and 371 metres.

Within the 450-522 metres section, several red quartz porphyries are indicated with higher gamma level (33 micro R/h) than the granite (23 micro R/h). These porphyries are somewhat magnetic. Most of the porphyries have greenstones on either or both sides. This is nicely illustrated on the gamma log in the section 465-526 metres where several porphyries and greenstones alternate.

Another red quartz porphyry, 702-749 m, is magnetic but has the same gamma level as the granite. A section, 713-722 metres, with lower gamma radiation correlates with somewhat lower resistivity and low sonic travel time. This indicates a more mafic composition within this porphyry section.

Fractures

The 0-110 metres section has a somewhat lower resistivity, Figure 5.16. Both sonic and resistivity curves here are more disturbed than in the rest of the borehole. Most fractures in the section have iron oxide as a fracture mineral, but no calcite. At borehole lengths exceeding 110 metres the background resistivity increases. The sonic curve is still disturbed but not to the same extent as earlier. Spike-like sonic and resistance anomalies are due to narrow fracture zones or single fractures.

In Kl 6 high fracture frequency is closely correlated to the occurrence of greenstones and other mafic rock types.

Unit A 219-300 m	This unit consists mainly of greenstone. The upper part has been mapped as highly fractured, which is clearly indicated by low apparent resistivity and high SP. The lower part, 258-300 metres, contains far fewer fractures, which is also clearly indicated by sonic and resistivity logs.

The 300-338 metres section consists of fresh granite with few fractures and no signs of alteration. In this section, the apparent resistivity is high at about 200 000 ohm-m. The sonic travel time is about 160 micro secs/m, corresponding to a velocity of 6 250 m/s. Very small sonic and resistance spikes are caused by single fractures. Similar granite sections are found at 372-407 and 578-690 metres.

Unit B 338-372 m	In this unit sections of granite and mafic rock alternate. These mafic sections are indicated by ground surface geophysical measurements and was first believed to be a fracture zone. These sections are of the same type as an mafic dyke found in KL 5 and KL 10 (Olkiewicz, Stejskal, 1986), and have been interpreted to be the same dyke.

The 407-424 metres section consists of a somewhat fractured greenstone. This section is moderately indicated compared with other highly fractured greenstones in the area.

Unit C 424-531 m	Granite, greenstone and porphyry alternate in this unit. Most of the fracture zones are localized in the contacts between different rock types. The resistivity clearly indicates fractured parts in granite and greenstone, but not in porphyry. This is due to its high resistivity. In this case, the sonic method is better adapted to detect fractured sections.
Unit D 552-569 m	This unit consists of granite and is the most significant zone from a hydrogeological point of view (Gentzschein, 1986). It is indicated as a moderate resistivity anomaly, but has a strong sonic indication. Several altered fractures have been observed in the unit. Temperature measurements indicate a water inflow into the borehole within this unit.

The 702-749 metres section is geologically core mapped as a porphyry. This section has the highest resistivity registered in the borehole, 500 000 ohm-m. A small decrease in resistivity correlates with lower sonic travel time and gamma radiation, in the central part of the porphyry, which indicates a more mafic composition.

A curious single point indication, 728-744 m, within the porphyry appears as very small fluctations at a high resistivity level. Ironoxide has been observed as a fracture mineral throughout this section. The anomalies might be due to surface conduction in ironoxide in highly resistive rock.

Borehole fluid properties

The geothermal formation temperature gradient is 13.7 ^{o}C/km, Figure 5.17.

Interpretation of temperature measurements, shows several indications of in- our outflow of water into or from the borehole at several depths. In this case, it is easier to describe the situation in the borehole if following the direction of water movement. At 570 and 558 metres (unit D, Figure 5.16) a change in temperature gradient and a steplike increase in salinity imply the entrance of water, which than moves upwards in the borehole. Several altered fractures have been observed between these two points of inflow. The two points are within a section of piezometric overpressure (Gentzschein, 1986).

A slight decrease of salinity, 700-654 metres, correlates with a section of uncertain negative piezometric values (Gentzschein, 1986). On either side of the section there is a positive pressure.

Three significant temperature anomalies at the locations 465, 443 and 423 m, indicates an in- or outflow of water. Here an inflow of water has been interpreted, but an outflow of water is also possible. According to the hydrogeological investigations performed (Gentzschein, 1986), there is an uncertainity in the piezometric values obtained within the sections between 420 and 480 m. The values obtained would imply an outflow of water here, but due to the uncertainity in the values obtained, an inflow of water still may be possible.

According to the salinity log, there is an increased salinity between the point of inflow at 558 m and the point of steplike change in temperature at 465m. Between 465 and 423 metres the salinity constantly decreases. Above 423 metres the salinity stabilizes and the temperature gradient indicates a waterflow upwards in the borehole.

A change in temperature gradient at 244 metres indicates that some water leaves the borehole at this depth. According to the hydrogeological investigations, there is also a piezometric underpressure in the section between 240-260 metres, (Gentzschein, 1986), which supports the interpretation of outflow here.

The borehole became artesian after that the borehole was deepend. This is nicely illustrated from a comparison of the two temperature logs performed before and after the deepening of the borehole. In the second measurement the water is about 1.5 ^{o}C warmer than the first measurement, performed before the borehole was deepend. This indicates that the borehole has reached fractures at depth standing under higher hydrostatic pressure. When the borehole reached these fractures at depth, warmer water started to flow upwards in the borehole. Some water also reached ground surface, and the borehole became artesian.

A displacement in salinity can also be observed when the two measurements are compared. The water has higher salinity in the second logging.

Sections where the temperature indicates an in- or outflow have a hydraulic conductivity which is 10-100 times higher than the surrounding sections.

Water loss during drilling was recorded at 424.4-424.8 metres.

5.2.7 Borehole Kl 7

The drilling target for this borehole was zone 3, Figure 4.3, indicated from ground surface geophysical measurements.

Loss of logging equipment in the borehole made it impossible to make measurements down to the bottom of the hole. Some of the measurements were therefore logged down to a borehole length of 170 metres only.

Data for borehole Kl 7 are presented below.

Table 5.7. Borehole data for Kl 7.

Local coordinates x(m) y(m) z(m.a.sl):	253N 2225E 185.97
Length (m):	250.28
Diameter (mm)	56
Inclination (°):	57
Declination (°)	320
Drilling period:	840814-840823
Logging period:	840929-841003 850114,850421

Lithology

Sections where altered fractures are common have lost most of their magnetite content, Figure 5.18. This is verified in the upper part of the borehole, where better sections with high resistivity and moderate susceptibility occur.

All greenstones in Kl 7 are thin, with one exception, 77-84 metres. This greenstone is also magnetic. Most thin greenstones are not indicated by gamma measurements.

Zone 3, 116-132 metres, consists of alternating granite and greenstone. This section is indicated diffusely with lower natural gamma radiation. Within the section there is a high gamma peak, at 120 metres borehole length, probably caused by an enrichment of uranium in the fractures. This peak occurs in a section, at 117.6-124.8 metres, composed of gravel.

Fractures

Geophysical logs sensitive to fracture occurence and fracture alteration are presented together with fracture frequency (1/m) in Figure 5.19.

Compared with other boreholes in the area Kl 7 has a rather low resistivity and relatively high sonic travel time, 175 micro secs/m (5700 m/s). In fresh granite the corresponding value is about 160 micro secs/m (6250 m/s). This indicates a high average fracture frequency. Altered fractures are common in this borehole. All altered fractures occur in sections where the apparent resistivity is less than 40 000 ohm-m. The apparent resistivity background value is about 100 000 ohm-m. In Kl 7 low resitivity correlates with fracturing and alteration and not strongly with the occurrence of mylonite.

Unit A 11-19 m	The unit contains granite and greenstone and is very fractured according to the geological core mapping. This can also be observed from high sonic travel time and low resistivity. A fracture zone, 15.6-16.7 metres, has altered fractures.
Zone 3 116-132 m	The unit is dominated by granite which alternates with several minor greenstone sections. The geological core mapping shows that most of this zone is crushed (Olkiewicz, Stejskal, 1986). Alteration is common in fractures and fracture zones, and both gravel, 117.6-124.8 metres, and sand, 125.0-126.0 metres, occur in this unit. At 128 metres some clay has been observed. This of course gives very distinct sonic and resistivity indications. The apparent resistivity is extremely low while the sonic travel time is quite high. There is no doubt that this causes the surface indications which formed the drilling target.

Borehole fluid properties

If the temperature measurements in Kl 7 and in Kl 14, Figures 5.20 and 5.41, are compared, the interpretation described below seems plausible. However, there are alternative solutions which may give the same anomalies.

Water seems to enter the borehole at 139 metres. It then follows the borehole upwards. Above 139 metres the temperature gradient falls to 9.5 °C/km. The water leaves the borehole at 123 metres in zone 4, Figure 5.19.

Water also enters the borehole at 66 metres and flows downwards. Some of it leaves the borehole at 108 metres. At 66 metres the salinity increases abruptly. The water above this level is probably less saline surface water, while the water below this level is formation water.

The vertical geothermal temperature gradient at borehole lengths exceeding 140 metres is 14 °C/km.

5.2.8 Borehole Kl 8

This borehole was drilled to check a possible correlation between a weak indication from the ground surface geophysical measurements, Figure 4.3, and a hydraulically conductive zone at 804 metres in Kl 2 (Gentzschein, 1986).

Data for borehole Kl 8 are presented below.

Table 5.2.8.1 Borehole data for Kl 8.

Local coordinates x(m) y(m) z(m.a.sl):	1557N 2722E 182.57
Length (m):	266.11
Diameter (mm)	56
Inclination (°):	58
Declination (°)	283
Drilling period:	841025-841030
Logging period:	841211-841213 850111-850113 850422

Lithology

Geophysical logs sensitive mainly to variations in lithology are presented together with a schematic lithology log in Figure 5.21.

No lithological changes have been recorded with logging. Granite was the only rock geologically core mapped in Kl 8 (Olkiewicz, Stejskal, 1986). The susceptibility increases with depth, but is within the variations for granite.

Fractures

Geophysical logs sensitive to fracture occurrence and fracture alteration are presented, together with fracture frequency

(1/m) in Figure 5.22.

Down to 50 metres borehole length the resistivity is low. This correlates with ironoxide on fracture surfaces and with high fracture frequency. In these fractures, calcite is not found. This shows that oxidizing water has circulated in the upper part of the bedrock.

At borehole lengths exceeding 50 metres, the background resistivity is high, 200 000 ohm-m, and the sonic is unusual calm, 160 micro sec/m (6 250 m/s). This indicate low fracture frequency at these depths in Klipperås. Few fracture zones are indicated.

Two major units are described.

Unit A 12-34 m	According to geological core mapping this unit is a granite with several fracture zones (Olkiewicz, Stejskal, 1986). Ironoxide is a common fracture mineral in this unit. Mylonite and breccia occur here and the rock has an altered appearance. The unit is clearly indicated from all logging methods. Distinct resistivity and sonic anomalies indicate high fracturing.
Unit B 92-96 m	According to geological core mapping this unit is a granite with several thin fracture zones and two thin crushed sections. In one section, 94.3-95.1 metres, 40 cm of the core is missing. The resistivity and sonic indications are very distinct. Strongly brecciated granite has been observed in the 76-104 metres section. This section is interesting from a hydrological point of view.

An indication at 139 metres, probably a single fracture, also carries a water flow. Below this depth the geologically mapped fracture frequency decreases, and small sonic anomalies are due only to single fractures.

Borehole fluid properties

Temperature interpretation is presented in Figure 5.23.

A temperature anomaly, 76-94 metres, indicates an inflow of water at 76 metres and an outflow at 94 metres. This is in good agreement with a water loss registered at 94.3-95.1 metres. In this section 40 cm of the core is missing.

However, the salinity do not coincide with this interpretation. At 94 metres a sudden change in salinity, indicates an inflow at this depth and water movement upwards. In this case the water would leave the borehole at 76 metres.

The temperature gradient gradually changes with depth and never stabilizes. In the lower parts of the borehole it is about 15.5 ^{o}C/km.

5.2.9 Borehole Kl 9

This borehole was drilled to intersect zone 2, and the dolerite dyke indicated by ground surface geophysical measurements (chapter 4).

Data for borehole Kl 9 are presented below.

Table 5.9. Borehole data for Kl 9.

Local coordinates x(m) y(m) z(m.a.sl):	1754N 2360E 192.20
Length (m):	801.03
Diameter (mm)	56
Inclination (°):	56
Declination (°)	300
Drilling period:	841005-841204
Logging period:	841218-841219 850112-850113 850415

Lithology

The variation of susceptibility for the granite depends mainly on the magnetite content within the granite, Figure 5.24. Hence, the lower susceptibility values are due mainly to oxidation of magnetite to hematite.

No alteration was observed in the 420-452 metres section. The granite is also almost unfractured within this section. The magnetic susceptibility within this section is high (250×10^{-5} SI).

Another section within the borehole where the granite still has a high susceptibility lies at 700-720 metres.

The two porphyries within the borehole have different susceptibility values. The upper porphyry, 269-300 m, is a reddish plagioclase quartz porphyry, while the porphyry between 731-780 m is a dark, grey plagioclase porphyry (Olkiewicz, Stejskal, 1986) . The two porphyries also have different gamma radiation levels. The red porphyry, 269-300 m, has a higher content of radioactive minerals than the adjacent granite, while the dark grey porphyry, 731-780 m, has a lower content of radioactive minerals than the adjacent granite.

The prominent susceptibility indication between 356-368 m and 371-374 m is due to the dolerite dyke, indicated by ground surface geophysical measurements.

All greenstones encountered in the borehole have a low magnetic susceptibility. The slight increase in magnetic susceptibility is due mainly to the content of mafic minerals within the greenstones. As usual, the mafic rock sections, i.e. greenstones and the dolerite, have a low gamma radiation.

There are some decreases in natural gamma radiation not associated with mafic greenstones. These are associated with mylonite and breccia occurrences in the rock mass. One example of this is the section between 142-152 m, where the granite is brecciated and partly mylonitized. Clay alteration has also been observed along fractures within this section. Another example is the section between 622-628 m, where the granite is strongly brecciated. Machine crushed sections and clay alteration occurs rather frequently within this section.

The slightly higher gamma radiation level of the granite in the upper part of the borehole may be due to small differences in mineral composition of granite above 200 m. However, radon enrichment in the borehole fluid may also give rise to a background level of radioactivity.

At the bottom of the borehole, below the porphyry, the granite has a low gamma radiation level. In this section, however, a mixture of mafic rock sections occur within the granite.

Fractures

In the upper part of the borehole, 0-200 m, strong fluctuations on both the sonic and resistivity logs occur rather frequently, Figure 5.25. Fracture alteration occurs in those sections where the resistivity is lower. Brecciation and sometimes also mylonitization correlates well with more prominent indications. Spike-like sonic and resistivity indications often occur in connection with clay altered fractures.

Zone 2 120-160 m	Tectonized, partly brecciated and mylonitized granite. Fracture alteration occurs throughout the section. Some clay alterered fractures have been observed in connection with spike-like sonic and resisitivity anomalies. An altered breccia occurs at 133 m. The 146-156 m section, where the resistivity and sonic indications are most prominent, is intensely altered. Hematite stained fracture surfaces and clay altered fractures occur frequently.
Unit A 356-374 m	One of the most prominent low resistivity indications within the borehole. This unit consists mainly of the dolerite dyke indicated by ground surface geophysical measurements. The dolerite is partly brecciated and crushed at the lower contact (364-368 m). Clay altered fractures occur within the dolerite which may explain the low resistivity. According to the resistivity measurement performed on the core samples, the resistivity of the matrix between the fractures is several orders of magnitude larger than the resistivity obtained from logging.
Zone 1 615-665 m	The section consists partly of strongly brecciated or mylonitized granite. Some parts within the section consist of greenstone. Within the most fractured sections, 622-627 m and 642-653 m, the rock is strongly brecciated or mylonitized. The core is intensely altered within these sections.

Clay altered fractures occur in connection with

peaks on the resistivity and sonic logs at 622 m and 648 m respectively.

Unit B
764-776 m

This prominent resistivity anomaly occurs within the plagioclase porphyry. Within this unit the porphyry is strongly mylonitized. A high content of pyrite has been observed within the mylonitized section. One interesting feature within this section is that the porphyry has partly lost its magnetization, as can be seen on the magnetic susceptibility log. This has also been observed from the geophysical laboratory investigation performed on the core samples (Stenberg, 1986). The resistivity of the porphyry is rather high, but the pyrite mineralized porphyry sample has low resistivity, low magnetic susceptibility and high density, due to the pyrite content.

Despite the major units described above there are several resistivity and sonic anomalies within the borehole. Some of these occur in connection with greenstones encountered in the borehole. Others are associated with increased fracturing together with fracture alteration.

The greenstones at the margins of the porphyry at 269-300 m give sharp resistivity anomalies. They are, however, partly mylonitized and crushed. The porphyry itself is rather fractured, as indicated by the sonic log. However, the matrix resistivity of the porphyry is 1-2 orders of magnitude higher than the matrix resistivity of the granite, as indicated by the core sample measurements. But, for high resistivity contrasts between the fluid and the rock, in the range of 10 000-100 000 ohm-m, there is a saturation effect on the apparent resistivity measured, depending on the configuration used and the borehole diameter (Olsson and Jämtlid, 1984).

Examples of resistivity and sonic anomalies which do not correspond to greenstones, but to fractured, altered sections are at 212 m, 394-406 m, 474-482 m, 519 m, 593 m and 699 m. The background apparent resistivity of almost unfractured, unaltered granite (0-2 fractures/m) for the normal array configuration is roughly 300 000 ohm-m and for the lateral array configuration it is roughly 250 000 ohm-m. After correction for the borehole fluid resistivity of 60 ohm-m, the true formation resistivity of the unaltered granite can be estimated to be 150 000 ohm-m (Olsson and Jämtlid, 1984).

The background apparent resistivity in the upper 200 m of the borehole is about 100 000 ohm-m for the lateral array, and about 80 000 ohm-m for the normal array. After the fluid resistivity correction has been applied, the true formation resistivity in this part can be estimated to be 50 000 ohm-m.

Borehole fluid properties

In the upper part of the borehole, 0-200 m, the hydraulic conductivity is rather high, close to or exceeding 10^{-7} m/s, Figure 5.26. As mentioned earlier, fracture alteration occurs rather frequently within this part of the borehole. Loss of drillwater has been reported during drilling at depths of 28 m, 42.45 m, 42.78 m, and 59.18 m. The hydraulic conductivity measurement (Gentzschein, 1986), shows a piezometric underpressure in the section 30-50 m, which would suggest an outflow of water from the borehole into the formation within this section.

In the section between 200 m down to the dolerite dyke, 356-374 m, loss of drillwater during drilling was reported at depths of 211.70 m, 244.75 m and 281.70 m respectively. The upper two locations correlate well with two spike-like anomalies on the sonic and resistivity logs. At both locations, temperature anomalies occur. These anomalies are due mainly to injection of drillwater during the drilling period.

Below the dolerite dyke, within the sections between 370-430 m, the hydraulic conductivity increase to about 10^{-7} m/s (Gentzschein, 1986). Altered fracture surfaces were reported within this section. A loss of drillwater was reported at

390.95 m. However, no temperature indication is observed here.

In the last section 690-710 m, the hydraulic conductivity increase to almost 10^{-6} m/s. Within this section, at the location of 698-699 m, a temperature anomaly occurs, strongly correlated with a prominent resistivity and sonic anomaly. Altered fractures have also been observed here. This temperature anomaly indicate an inflow of water from the fracture into the borehole. Together with the reduced temperature gradient observed above the fracture, the water would then flow upwards along the borehole. Also the hydraulic conductivity measurements show a piezometric overpressure within this section, which would imply an inflow of water into the borehole.

There is a sharp change in temperature gradient at the location of the dolerite dyke, marked with an "A" in the remarks column, Figure 5.26. The vertical temperature gradient above the dolerite dyke is greater than 15.5^{o}C/km, which is a normal value observed within the area. The vertical temperature gradient below the dolerite dyke is about 12.8^{o}C/km, which implies a decrease in the temperature gradient of about 17 %.

The reduced temperature gradient between the location at 699 m and the dolerite dyke at A, would imply a flow of water upwards along the borehole. However, the hydraulic conductivity measurements show a piezometric underpressure above the dolerite dyke and a piezometric overpressure below the dolerite dyke. The dolerite dyke would therefore act as a hydraulic barrier. Changes in temperature gradient can also be a result of heat flow by conduction, which has persisted for a long period of time. If the thermal conductivity of the dolerite is different than that of the granite, the dolerite itself would have transported or consumed heat. Also, water flowing along a dipping fracture zone transports heat, which increases or decreases the heat flow conducted above the fracture zone, depending on the flow direction of the water (Drury, 1984, Poikonen, 1983). However, according to the hydraulic injection tests, the hydraulic conductivity of the dolerite is below the measuring limit of the equipment within this section.

5.2.10 Borehole Kl 10

The drilling target for this borehole, like Kl 5 and Kl 6, was a suspected fracture zone indicated from the ground surface geophysical measurements.

Data for borehole Kl 10 are presented below.

Table 5.10 Borehole data for Kl 10.

Local coordinates x(m) y(m) z(m.a.sl):	2000N 3310E 176.06
Length (m):	202.88
Diameter (mm):	56
Inclination (°):	49
Declination (°)	90
Drilling period:	850105-850114
Logging period:	850227-850301 850413

Lithology

The granite in Kl 10 is quite magnetic, Figure 5.27, which indicates that the rock has not been tectonized to the same extent as in many other boreholes. The magnetic properties of the granite, the porphyry and the mafic rocks explain the relatively high magnetic intensity from the ground surface geophysical measurements.

One magnetic section, 78-104 metres, with low gamma radiation consists of a mafic dyke between two plagioclase porphyries. Outside the porphyries there are two thin greenstones on either side. The mafic rock is more magnetic than the porphyry.

One nonmagnetic greenstone is indicated by low gamma radiation and resistivity values, at 120-124 metres borehole length.

Fractures

Both resistivity and sonic logs indicate a large number of fractures, or more open fractures down to 50 metres, Figure 5.28. Comparing this with fracture minerals, it appears that iron oxide is common down to exactly this depth, while calcite is lacking. Alteration in fractures is common in this section. Clay alteration occurs at several depths. Clay horizons of 1 cm are distinctly indicated on the sonic log as spikes.

A fractured section, 42-46 metres, is interesting because of the drillwater loss recorded during the drilling.

Other thin fractured sections indicated by resistance and sonic logs are located at 74-78, 104 and 120-123 metres.

One major unit is described below.

Unit A 88-100 m	This mafic rock is identical to the one intersected by Kl 5 and Kl 6. According to the geological core mapping, this section is dominated by fractured and crushed zones (Olkiewicz, Stejskal, 1986). The unit is distinctly indicated by high sonic travel time and low resistivity.

Borehole fluid properties

In the upper part of the borehole the salinity is low and this is probably due to circulation of surface water, Figure 5.29. The temperature and salinity shows a complex anomaly pattern, which is not so easily interpreted. During the drilling, a water loss was noted at 24 metres.

At 99 metres, within the mafic dyke, there is a change in temperature gradient, marked "A" in Figure 5.29. This type of gradient shift may be due to prolonged downdip flow of cooler water in a dipping fracture zone. Also changes in heat flow due to differences in thermal conductivity between the mafic dyke and the granite, generates changes in temperature gradient.

If the change in temperature gradient are due to water flow, the water flowing in unit A, began to follow the borehole downwards, and left the borehole at 138 metres. This flow would explain the salinity step at 99 metres and the temperature step at 138 metres.

There is a change in the salinity log within the section 100-170 metres. It is possible that the piezometric pressure of this section differs from that of the surrounding sections.

At about 145 metres the geothermal formation gradient stabilizes to 15 °C/km.

5.2.11 Borehole Kl 11

The drilling target for this borehole was zone 4 indicated by ground surface geophysical measurements, Figure 4.3.

Data for borehole Kl 11 are presented below.

Table 5.11 Borehole data for Kl 11.

Local coordinates x(m) y(m) z(m.a.sl):	1252N 2347E 191.50
Length (m):	250.82
Diameter (mm)	56
Inclination (°):	57
Declination (°)	353
Drilling period:	850115-850122
Logging period:	850302,850422

Lithology

The susceptibility in the borehole is quite low, Figure 5.30. This is in good agreement with the magnetic ground surface geophysical mesurements, Figure 4.3.

All greenstones in Kl 11 are indicated by natural gamma radiation.

A gamma peak at 211 metres occurs within a section of mylonite and breccia.

One of the greenstones is very magnetic, 140-148 metres, while the others are nonmagnetic. The low susceptibility on either side of this section might indicate that this is dyke. When warm lava flows into a fracture, it will heat the surrounding rock above the Curie temperature. At this temperature the magnetic properties of the rock are destroyed.

Fractures

The low background resistivity and the fluctuent sonic shows that the bedrock is quite fractured, which is confirmed by the core mapped fracture frequency, Figure 5.31.

At 50 metres the sonic log stabilizes. Above this point it fluctuates due to weathered fractures. The dominating fracture mineral in the section is ironoxide. This in combination with lack of calcite shows that oxidizing water have circulated and dissolved the calcite in the fractures. Above 68 metres there are no calcite in fractures.

Throughout the borehole altered sections correlate well with low resistivity and high sonic travel time.

Zone 4 108-148 m	This unit is dominated of granite, but also have some other rock types. The upper 12 metres of this unit is dominated by greenstone (2.4 m porphyry) just like the last 9 metres. The upper greenstone and the following granite has many fracture zones and a few crushed ones. This is also indicated as the most fractured parts of the unit by sonic, 200 micro secs/m (5 000 m/s), and resistivity, 3 000 ohm-m. Altered fractures is common and clay alteration occurs in the most fractured parts. Several losses of drillwater have been recorded in this unit during the drilling. In the granite between 132 and 136 metres the SP measurements distincly indicates electric conducting minerals. This is accessory pyrite according to the geological mapping.

Borehole fluid properties

At 133 metres, zone 4, there is a temperature anomaly, Figure 5.32. Below this point the temperature gradient stabilizes. Loss of drillwater have been noted at this depth. The temperature anomaly indicates an outflow of water at 133 metres, from the upper part of the borehole.

During the drilling drillwater loss has been recorded at several depths, 19 m, 36 m, 124 m, 133 m, 137 m and 139 m. The latter four are all within zone 4.

Below 150 meter the geothermal temperature gradient stabilizes at 17.2 ^{o}C/km.

5.2.12 Borehole Kl 12

This borehole was drilled to intersect several minor and major zones, i.e. zones 2, 6, 7, 8, 9, indicated by ground surface geophysical measurements, (chapter 4).

Data for borehole Kl 12 are presented below.

Table 5.12 Borehole data for Kl 12.

Local coordinates x(m) y(m) z(m.a.sl):	2370N 2870E 183.82
Length (m):	730.14
Diameter (mm)	56
Inclination (^{o}):	50
Declination (^{o})	346
Drilling period:	850124-850219
Logging period:	850227-850301 850412, 850423

Lithology

Greenstones with high magnetic susceptibility are found at 147-148 m, 150-152 m, 166-172 m and 331-336 m, Figure 5.33. The other greenstones are non-magnetic, with low susceptibility.

Porphyries encountered in the borehole at 219-233 m, 281-298 m and 705-711 m, have a rather high magnetic susceptibility. However, the porphyries in the 74-94 m section have very low magnetic susceptibility. The porphyries in this section have lost their magnetization due to intense alteration and fracturing.

The variation of the magnetic susceptibility in granite lies in the range 25-500 x 10^{-5} SI-units.

In general, low gamma radiation is associated with greenstones. However, in some cases, low natural gamma radiation occur in association with mylonites and breccias. This behaviour appear in the 298-306 m section, where the granite is strongly deformed and brecciated. At 427-428 m and 446-452 m low gamma values occur in connection with mylonites. Occasionally an enrichment of radioactive minerals in the healing matrix of the breccias occurs. At 582-606 m, a positive gamma anomaly appear in the breccias, associated mainly with dark cloritic or epidotic material.

Fractures

In the upper part of the borehole, 0-195 m, strong fluctuations in both the sonic and resistivity logs occur rather frequently, Figure 5.34. Severe fracture alteration occurs in the sections with low resistivity.

Zone 6 70-88 m	Strongly deformed and mylonitized granite and porphyry. At 78 m a strongly foliated and crushed greenstone occurs. The most prominent spike like resistivity and sonic anomalies occur in connection with two brecciated and altered greenstones at 86 and 87 m. At 87 m, the greenstone is also crushed and 20 cm of clay alteration occurs within the greenstone.

The spike-like sonic and resistivity anomaly at 100 m occurs in connection with a 30 cm crushed zone and 10 mm of clay alteration. A prominent spike-like resistivity and sonic indication at 219 m occur in connection with the contact between a greenstone and a porphyry. Clay alteration has also been observed here.

The 233-280 m section, between the two porphyries, has a high background apparent resistivity greater than 200 000 ohmm and a calm sonic travel time of 160 micro secs/m. This gives a true resistivity of about 100 000 ohm m (Olsson and Jämtlid, 1984), and an acoustic velocity of about 6250 m/s . The rock consists of coarse grained, light grey to reddish granite, with a low fracture frequency, 0-2 fractures/m.

The main fractured section encountered in the borehole is at

288-384 metres. This section is strongly altered, partly crushed and mylonitized or brecciated. Strongly fluctuating sonic travel time, low resistivity and positive SP-indications characterize the section. To fit the ground surface measurements this wide section were divided into three separate zones. The zone dips were assumed to be close to the vertical, which is common in Klipperås.

Zone 7 288-306 m	The fractured section starts within a porphyry. The porphyry itself is rather resistive, but at the contact with the granite a thin clay altered greenstone occurs at 298 m. This is indicated by a prominent spike like resistivity and sonic indication. At 303 m a somewhat clay altered tectonic breccia occurs. The granite is strongly cataclastic in the 299-305 m section.
Zone 8 312-347 m	The section mainly consists of a fractured mylonitized granite. Intense alteration occurs, especially at 321-332 m and 336-342 m. One somewhat less fractured greenstone is indicated at 331-336 m. It has an increased acoustic velocity indicated by the sonic log.
Zone 9 362-384 m	The section consists of an intensely fractured mylonitized brecciated granite, with intense weathering and alteration, especially between 368-381 m. At 373 m, a partly crushed section occurs. The decrease in resistivity and increase in sonic travel time, correlates well with the intensity of fracturing.

In the section between zone 9 and zone 2, 384-595 m, most of the indications on the logs occur in connection with greenstones. Two prominent sonic and resistivity indications at 471-479 m and 582-584 m respectively, are however associated with a high fracture frequency having some alteration. Some low gamma log values occur in connection with mylonites. As mentioned earlier, some higher gamma log values are associated with breccias.

Zone 2 595-630 m	This zone consists mainly of granite. Two greenstones occur at 606 m and between 619-622 m. The section is characterized mainly by an increase in fracture frequency. Machine crushed core has been observed at 598 m and 602 m. The most prominent sonic and resistivity anomalies occur where the granite is mylonitized or brecciated, and where alteration occurs rather frequently.

From 630 m and down to the bottom of the borehole all resistivity and sonic indications are associated with greenstones.

Borehole fluid properties

In the upper part of the borehole, 0-220 m, the hydraulic conductivity is rather high, close to or greater than 10^{-6} m/s, Figure 5.35. As mentioned earlier, alteration occurs rather frequently in this part of the borehole. Loss of drillwater was reported during drilling at depths of 34.7 m, 34.9 m, 100.2 m, 141.0 m, 155.3 m, and 178.8 m.

The 220-280 m section has a very low hydraulic conductivity, (less than 10^{-10} m/s), which correlates well with the high resistivity and calm sonic travel time within this section, as mentioned previously.

The main fractured section 288-384 m, (zone 7-9), has a very high hydraulic conductivity, about 10^{-7} m/s. The borehole fluid resistivity log indicates three distinct jumps in the salinity of the borehole fluid at depths of about 303 m, 323 m and 373 m respectively. The hydraulic conductivity measurements show a piezometric overpressure within the sections 300-340, 360-380 m (Gentzschein, 1986), which would suggest an inflow of water into the borehole from the formation. Thus, more saline water would enter the borehole at the locations mentioned previously.

The temperature log shows a reduced temperature gradient at borehole lengths less than 303 m. This would imply a flow of water upwards in the borehole. Some of the water would leave the borehole at the locations where drillwater losses were observed, i.e. 34.7 m, 34.9 m, 100.2 m, 141.0 m, 155.3 m and 178.8 m respectively.

At borehole lengths exceeding 400 m, the hydraulic conductivity is still very high, about 10^{-7} m/s down to 520 m. The fractures and fracture zones within this section may thus be permeable and may be connected hydraulically with zones 7-9. Therefore, if the dip of the zones is nearly vertical, than the fractures encountered in this section are still permeable within a distance of 50 m from the fracture zones.

The small temperature anomalies below 400 m may be due to drillwater injection in fracture zones. The temperature injection anomalies, noted in the remarks column at 435 m, 473 m, 583 m and 616 m, occur in connection with sonic travel time indications. This implies that these fractures or fracture zones may be permeable. The last two, at 583 m and 616 m occur within or in connection with zone 2, 595-630 m.

The hydraulical investigations (Gentzschein, 1986), show a hydrostatic overpressure in the corresponding sections 460-480 m and 600-620 m. This would imply an inflow of water into the borehole at the locations 473 and 616 m respectively. In the sections 420-440 m and 580-600 m, the hydraulical investigations show a hydrostatic underpressure. This would imply an outflow of water from the borehole at the locations 435 m and 583 m respectively.

Below 620 m, the hydraulic conductivity is very low, less than 10^{-10} m/s or not measurable, which is consistent with the geophysical logs.

The vertical formation temperature gradient is $14.5^{o}C/km$ between 300-500 m. Below 500 m the temperature gradient is lower, around $13^{o}C/km$.

5.2.13 Borehole Kl 13

The drilling target for this borehole was zone 5, indicated by the ground surface geophysical measurements (chapter 4).

Data for borehole Kl 13 are presented below.

Table 5.13 Borehole data for Kl 13.

Local coordinates x(m) y(m) z(m.a.sl):	1866N 2703E 183.27
Length (m):	700.06
Diameter (mm)	56
Inclination (°):	55
Declination (°)	22
Drilling period:	850221-850313
Logging period:	850415-850421

Lithology

All mafic rock sections encountered in the borehole have low gamma radiation, Figure 5.36. These sections also show low magnetic susceptibility and resistivity.

In some sections low natural gamma radiation occurs in association with increased fracturing and alteration. One example of this occurs between 29 and 36 m, and another occurs at the crushed section 173-176 m.

The higher background radiation level between 0 and 252 m may be due to infiltration of radon charged water into the borehole.

The magnetic susceptibility log shows a variation in the range 25-500 x 10^{-5} SI-units. The higher susceptibility values occur in connection with almost unfractured (0-3 fractures/m) and unaltered granite. The higher susceptibility is due mainly to a higher content of ferromagnetic minerals, i.e. magnetite.

The lower susceptibility values occur where the granite is fractured and altered. Here, magnetite is oxidized to hematite or other unspecified iron oxides. Examples of sections where intense alteration occurs are located at, 0-36 m, 66-100 m, 150-190 m and 620-650 m.

The two porphyries encountered in tne borehole, 378-393 m and 483- 492 m respectively, have a uniform and high magnetic susceptibility. The granite in contact with the upper porphyry has lost its magnetization within 25 m from its contact with the porphyry.

Fractures

In the uppermost 190 m of the borehole fracture alteration occurs rather frequently. Strong fluctuations on the sonic log and low resistivity correlates with increased fracturing, Figure 5.37. Three sections with intense fracturing and alteration strongly influence the logs at 29-34 m, 76-99 m and 152-188 m. A 1.2 m thick greenstone at 117 m gives a sharp resistivity anomaly.

The 76-99 m section occurs within and adjacent to two greenstones. A 30 cm wide crushed section appears at 91 m borehole length.

The 152-188 m section is interpreted as the anomaly source in zone 5, indicated by the ground surface geophysical measurements.

Zone 5 152-188 m	The sections consist mainly of granite. Two 0.5 m thick greenstones appear at 164 and 165 m. The zone is strongly altered. The most intensely fractured part, 170-180 m, gives prominent low sonic and resistivity indications. The core is crushed between 173 and 176 m. A machine crush occurs at 183 m and a core loss at 188 m was reported . The resistivity contrast between the most fractured part and the surrounding unfractured granite is about 100.

In the 190-622 m section most low resistivity indications and high sonic values are correlated with greenstones. Sections containing greenstones or adjacent to the greenstones are often more fractured.

Greenstones often appear at the margins of the porphyries, 378-393 m and 483-492 m. The porphyries have high resistivity. However the margins are indicated by low resistivities and high travel times on the sonic log. The lower margin of the upper porhyry (378-393 m) is intensely fractured and altered. However, no greenstone was noticed here.

Some spike-like anomalies on the logs within the pure granite may be due to single open fractures. Examples of this are found at 281 m and 360 m.

At the bottom of the borehole, in the 622-660 m section, several low resistivity and high sonic peaks occur. These correlate well with high fracturing together with intense fracture alteration. However, one indication is due to a fractured greenstone.

Sections with high resistivity and no indications on the sonic log correspond to sections with uniform, almost unfractured granite. Examples of this are found at 190-230 m, 440-480 m and 600-620 m.

Borehole fluid properties

In the upper part of the borehole, 0-190 m, the hydraulic conductivity is rather high ($>10^{-7}$ m/s), Figure 5.38. As mentioned earlier, alteration occurs frequently in this part of the borehole. Loss of drillwater was reported during drilling at depths of 6.3 m, 173.0 m, 174.2 and 175.3 m. The last three depths lie within the crushed section between 173 and 176 m.

The formation temperature and temperature gradient log fluctuates sharply along this part of the borehole.

Between 190 and 610 m, only small fluctuations on the temperature log are present. There are some temperature anomalies along the section where water may have been injected into the fractures or fracture zones during the drilling period, at 183, 204, 273 and 284 m respectively. However,the last three occur in a section where the rock appears to be impermeable, according to the water injection tests.

In the bottom of the borehole, 610-680 m, the hydraulic conductivity is rather high, greater than 10^{-7} m/s. As mentioned earlier, fracture alteration occurs rather frequently in this section. A drillwater loss was observed during drilling at 624.1 m. At this location, a rapid change of formation temperature is observed. The temperature gradient decreases above, and increases below this location. An interpretation according to Drury (1984) suggests an outflow of water at this location.

There is a small change in temperature gradient at 514 m marked with an "A" in the remarks column. The temperature gradient decreases in the section below that point. The lower gradient between "A" and the outflow point at 624.1 m, would imply a flow of water downwards along the borehole in this section. The borehole has thus connected two fractures or fracture zones under different piezometric levels.

A comparison with the formation temperature log in Kl 14 shows that the temperature is lower in Kl 13 borehole down to 624 m borehole length. Together with the high borehole fluid resistivity, or low salinity of the borehole water, there is probably a minor flow of surface water downwards along the entire length of the borehole. A possible inflow occurs at 6.3 m, where loss of drillwater was reported during drilling.

The distinct change of borehole fluid salinity at the bottom of the borehole is probably due to an accumulation of cuttings at the bottom of the borehole.

The normal formation temperature gradient in the undisturbed parts between 210 and 515 m is 15.5^{0}C/km.

5.2.14 Borehole Kl 14

The drilling target for this borehole, like Kl 11, was zone 4, indicated by the ground surface geophysical measurements (chapter 4).

Data for borehole Kl 14 are presented below.

Table 5.14 Technical borehole data for Kl 14.

Local coordinates x(m) y(m) z(m.a.sl):	1084N 2400E 189.12
Length (m):	705.22
Diameter (mm):	56
Inclination (^{o}):	55
Declination (^{o}):	2
Drilling period:	850319-850408
Logging period:	850416-850419

Lithology

Granite dominates the upper part of the borehole (0-169 m). Some minor greenstone sections, 0.2-1.0 m thick, also occur, Figure 5.39. The susceptibility log fluctuates, indicating differences in the magnetization of the granite. Low susceptibility sections correlate well with low resistivity. In these sections higher fracture frequency and alteration of fracture surfaces have been observed (Olkiewicz and Stejskal, 1986).

The susceptibility of the dolerite (169-200 m) is lower than that of the adjacent sections. The upper part of the dolerite is less resistive than the lower part. Due to lower content of radioactive elements the dolerite has lower gamma radiation than the granite. The central part of the dolerite is slightly more radioactive than the margins. This part correlates with lower resistivity and sharp fluctuations on the sonic log, indicating responses due to secondary features, i.e. alteration or open fractures.

Two porphyry sections, 215-248 m and 271-305 m, have a higher susceptibility (500 x 10^{-5} SI) than adjacent sections. Some parts within each porphyry section have lower susceptibility due to increased fracturing and fracture alteration. Thin sections of greenstone within and at the margins of the porphyries have low susceptibility. The lower red quartz porphyry has a higher gamma radiation level than the feldspar porphyry above. Both the porphyries are rather resistive although fractured. The lower porphyry has the highest resistivity encountered in the borehole (400 000 ohmm). Low resistivity indications within the porpyhries are due mainly to greenstones.

The greenstone at the upper margin of the lower porphyry (264-271 m) has one of the more prominent resistivity indications within the borehole (less than 10 000 ohmm). The greenstone is intensely fractured at 264-265 m, and at 268-269 m the core is partly crushed. Clay alteration occurs at 264 and 269 m.

Below 306 m, the susceptibility of the granite is rather low compared with the upper part of the borehole. However, some sections of the granite below 306 m still have a higher susceptibility, indicating a higher content of mafic paramagnetic minerals or an occurance of ferromagnetic minerals, i.e. magnetite.

There are two prominent spike-like susceptibility indications (406-408 m and 520-527 m) which are due to a magnetic greenstone and a magnetic dolerite. The other greenstones and dolerites within the borehole are practically non-magnetic.

All the mafic rock sections, i.e. greenstones and dolerite have lower gamma radiation, due to a lower content of radioactive minerals. However, there is a narrow spike-like increased radiation within a dolerite section (571-575 m) at 573 m. This is an indication of radioisotope concentration, i.e. uranium, in a fracture or fractures sufficiently open to permit the migration of altering fluids.

Fractures

As mentioned earlier it may be difficult to separate responses due to fracturing and alteration from responses due to primary lithologic changes.

Low resistivity indications always appear at the mafic rock sections, i.e. greenstone and dolerite, encountered in the borehole, Figure 5.40. However, most of the greenstones are also intensely fractured.

In the upper part of the borehole (0-130 m) there are several low resistivity indications which correlate well with spike-like anomalies on the sonic log. Alteration occurs rather frequently in this section. Positive SP-indications with a magnitude of 10-20 mV correlate well with fracture frequency and low resistivity indications.

In the section between 131-169 m the fractures are not altered. This section has a high apparent resistivity of 200 000 ohm-m. After correction for borehole fluid resistivity and the array configuration used, the true formation resistivity of the formation can be estimated to be 100 000 ohm-m (Olsson and Jämtlid, 1984). Hence, the true formation resistivity is close to half the apparent resistivity in this borehole. The sonic travel time between the receivers is about 160 micro secs/m, which gives an acoustic velocity of 6250 m/s in this section.

Other sections with few fractures indicated by a high resistivity and a stabile sonic log are 306-368 m, 450-520 m and 583-638 m. Within these sections a few small but distinct sonic and resistance anomalies correlate with a mafic rock section. Such indications are found at 305-306 m, 355 m and 462 m.

The lower sonic travel time between 169-200 m is due to the mafic dolerite mentioned earlier. A travel time of about 150 micro secs/m gives an acoustic velocity of 6670 m/s for the dolerite.

In the section between 200-264 m the low resistivity indications are at, or in the vicinity of thin greenstones within the porphyry. Spike like anomalies on the sonic log correlate well with more intense fracturing.

The prominent low resistivity anomaly at 264-271 m correlates with the greenstone in the upper margin of a porphyry. This greenstone is intensely fractured and clay alteration occurs in connection with spike like anomalies on the resistivity and sonic logs.

The porphyry (271-305 m) has a very high apparent resistivity, although the fracture frequency is high, Figure 5.40.

The main fractured section between 368-450 m correlates well with low resistivity, a strongly fluctuating sonic travel time, positive SP-values with a magnitude of 25 mV and a reduced temperature gradient. Fracture alteration occurs throughout the section. However, the section is divided into two sub-units zone 4 and unit A, for better correlation with the width of zone 4 encountered in borehole Kl 11, situated some 50 m further west of this borehole.

Zone 4 368-410 m	The section is intensely fractured. Two greenstones occur between 368-375 m and between 406-408 m. Prominent alteration occurs between 378-383 m, 388-392 m and 400-410 m. Strong deformation and clay alteration correlate with significant anomalies on the resistivity and sonic travel time logs at 379 m.

The sections between zone 4 and unit A are also altered. A significant low resistivity indication together with a spike-like sonic travel time anomaly occur in connection with a greenstone at 419-420 m. At the upper contact, a core loss of 15 cm was reported (Olkiewicz, Stejskal, 1986).

Unit A 430-450 m	This section, like zone 4, is intensely fractured. Two greenstones occur at 440-442 m and 446-447 m respectively. Alteration occurs throughout the

section. Machine crushed core has been reported at 445 m.

A dolerite at 520-526 m causes a low resistivity and a low sonic travel time, corresponding to an acoustic velocity of about 6700 m/s.

Three spike like resistivity indications occur in the section between 520-583 m. Two are consistent with two dolerites at 571-575 m and 581-583 m. The third occurs adjacent to a porphyry (548-551 m), where the fracture frequency increases at borehole lengts between 550-554 m. A machine crush of 5 cm at 552 m correlates well with spikes on the resistivity and sonic logs.

Below 638 m, almost all low resistivity indications are consistent with mafic rock sections, i.e. greenstone and dolerite. However at 648 m there is a resistivity anomaly which coincides with increased fracturing and alteration. In connection with the greenstone at 656 m, intense fracturing and alteration together with a 40 cm wide crushed zone have been reported (Olkiewicz, Stejskal, 1986). At 666-667 m, intense fracturing and alteration also occur.

Borehole fluid properties

The entire borehole appear to be rather hydraulically conductive, Figure 5.41. There is only one section where the hydraulic conductivity is less than 10^{-10} m/s. Even the high resistivity sections, 131-169 m, 306-368 m, 450-520 m, and 583-638 m have a hydraulic conductivity close to 10^{-8} m/s.

However, there are some fluctuations in the temperature and temperature gradient log, which may be consistent with somewhat higher permeability. At 68 m and 107 m there are two temperature anomalies. Both of these occur at a location where water losses were reported during drilling. Drilling water has probably been injected into these fractures during drilling. Both these sections appear to be somewhat more permeable from the hydraulic injection tests (Gentzschein, 1986).

In the main fractured sections between 368-450 m, zone 4 and unit A, a change in the normal temperature log is observed. There is an anomalously low temperature gradient between 380 and 446 m. Temperature interpretation gives an inflow of water at 380 m and an outflow at 446 m. Fractures or fractured zones having different piezometric levels are interconnected by the borehole. There is a lower salinity below 380 m, and a drillwater loss at 446 m has been reported.

According to the hydrogeological investigations performed (Gentzschein, 1986), their is a slight overpressure in the section between 360-380 m, and an underpressure in the section between 380-400 m. In the section between 440-460 m, the piezometric head is close to zero. Therefore it is difficult to estimate the directions of flow from hydrogeological point of wiev. The hydraulic injection tests show higher hydraulic conductivity in the sections 360-380, 400-420 and 440-460 m.

The geothermal formation gradient is 15 ^{o}C/km in the undisturbed section below 150 m.

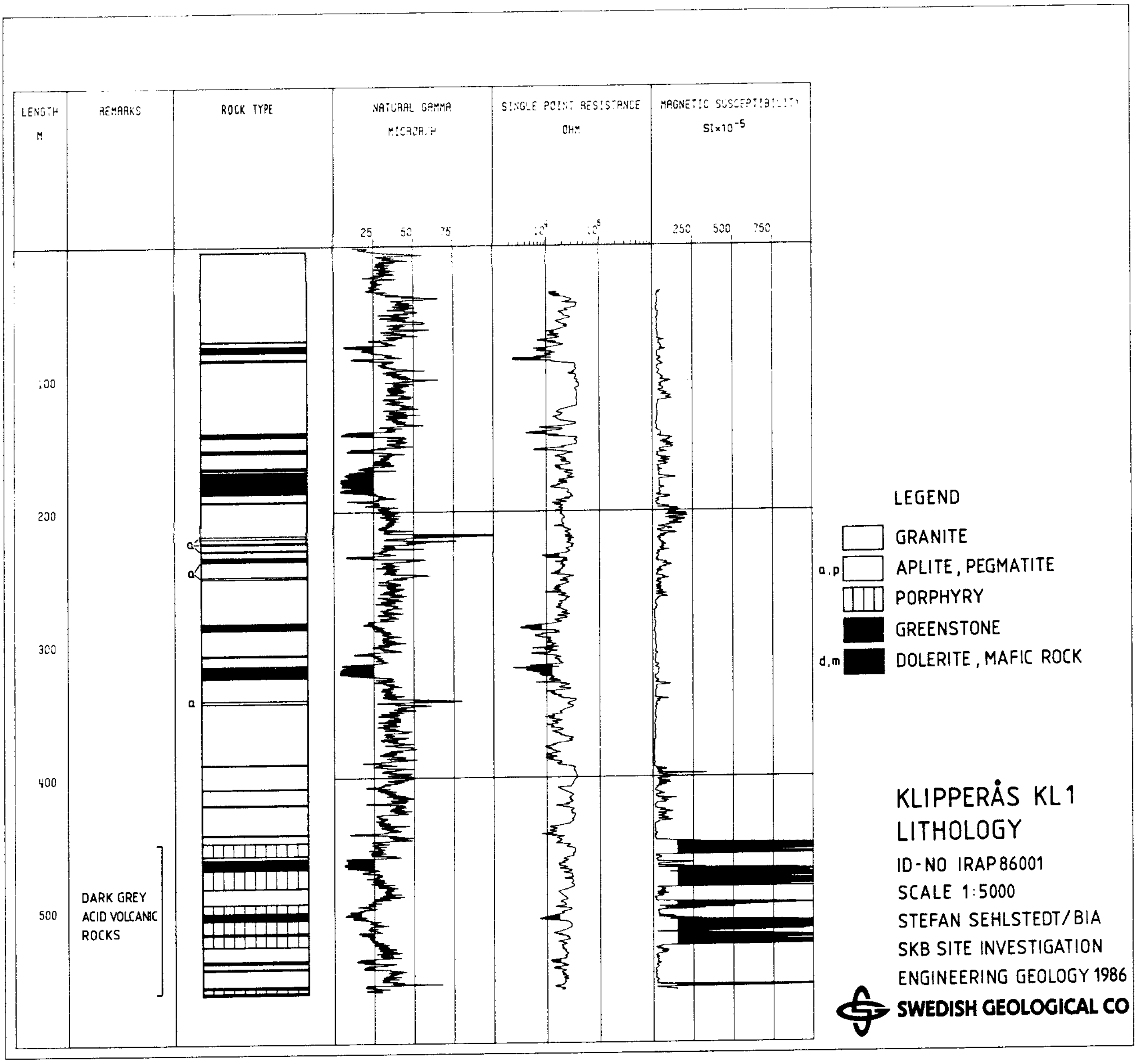


Figure 5.1. Geophysical logs sensitive to lithology variations, measured in borehole Kl 1.

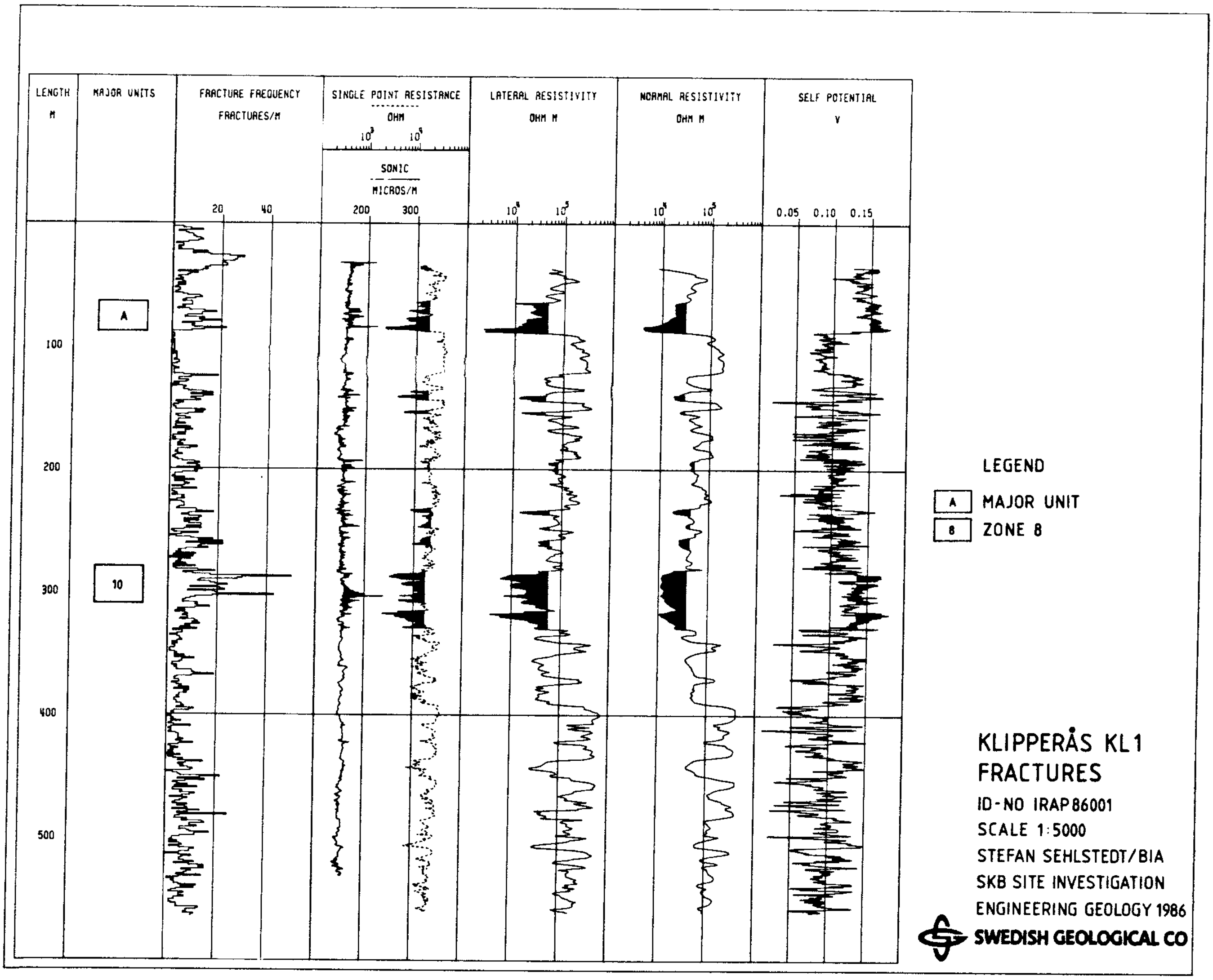


Figure 5.2 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 1.

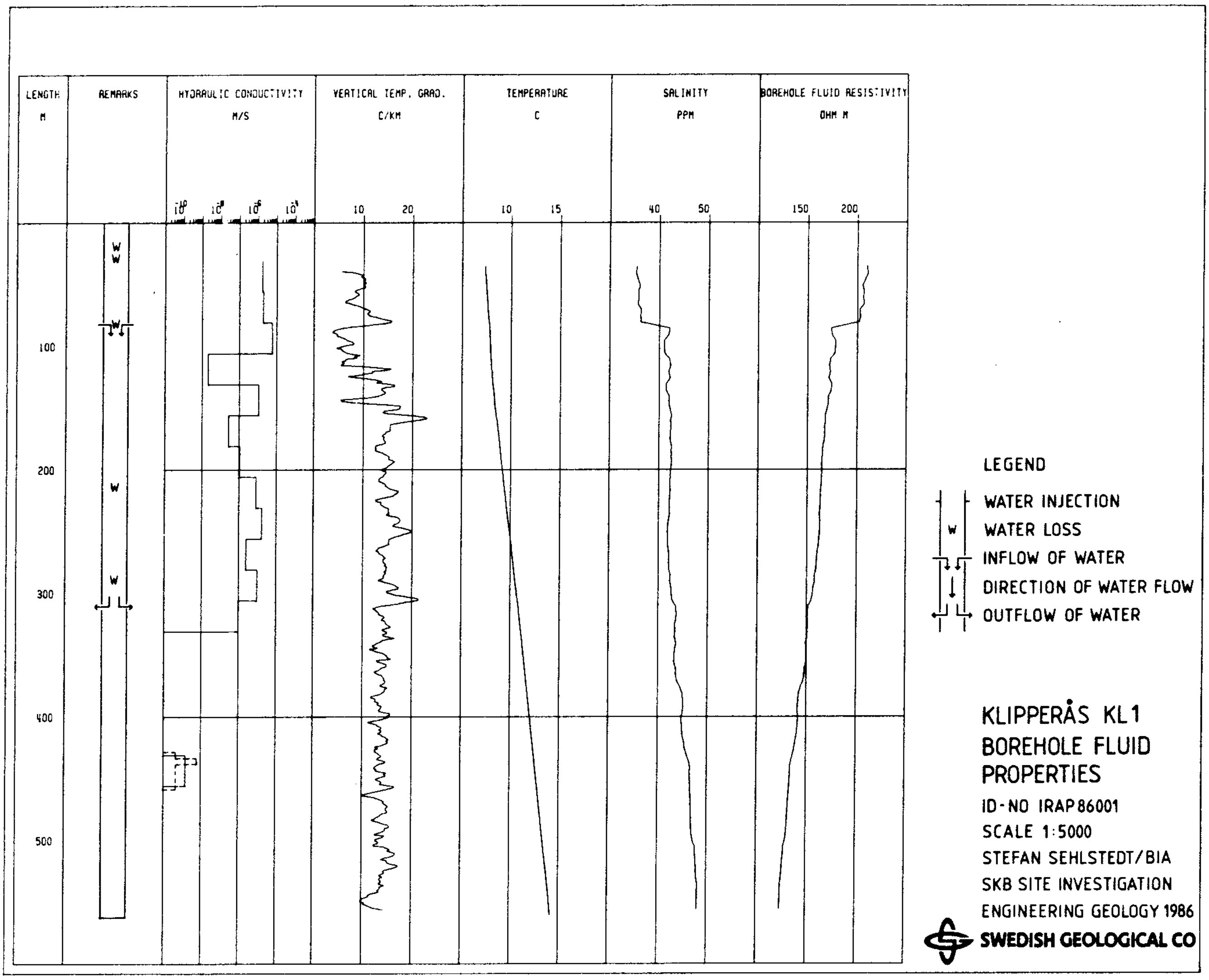


Figure 5.3 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 1.

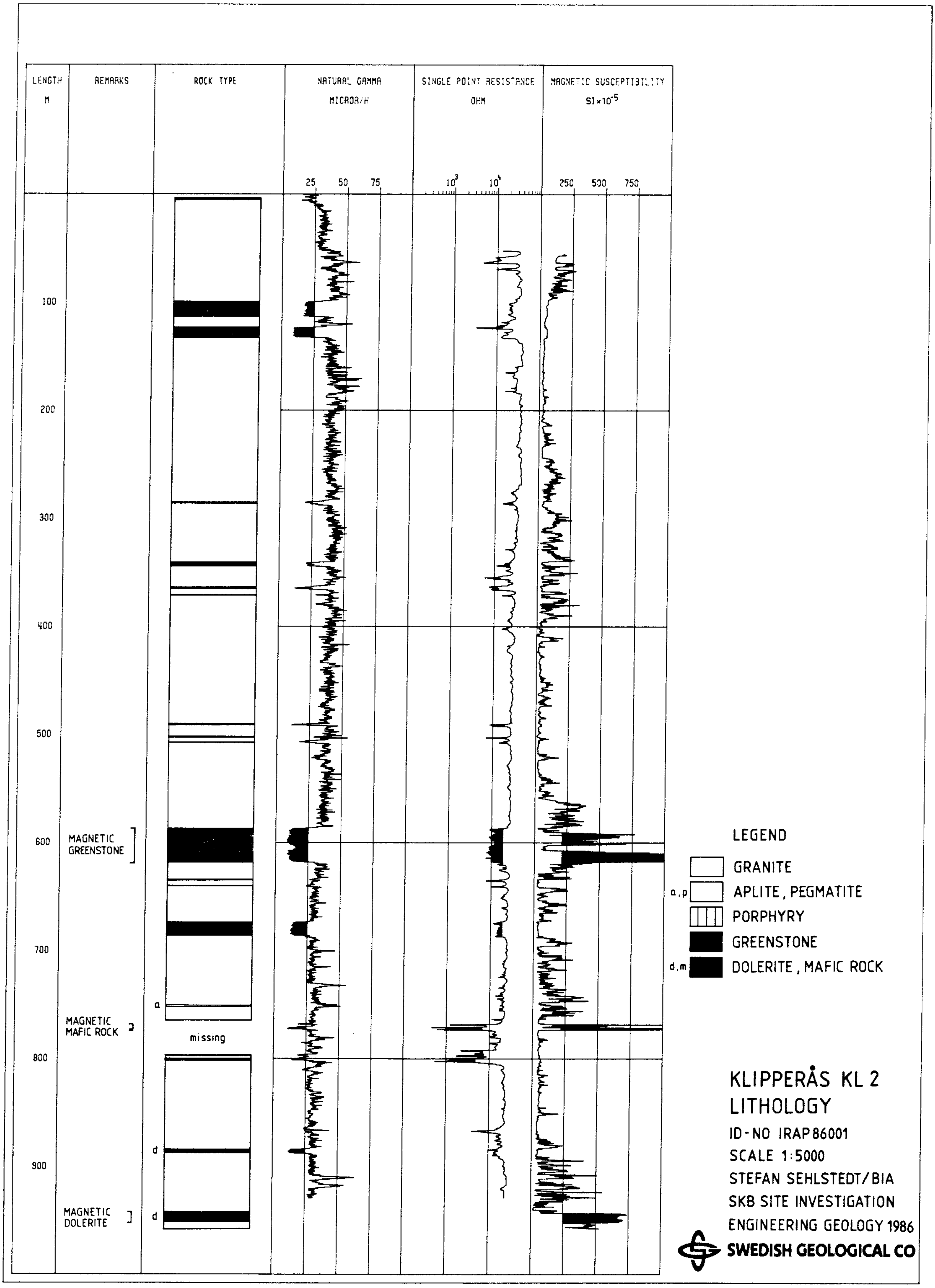


Figure 5.4. Geophysical logs sensitive to lithology variations, measured in borehole Kl 2.

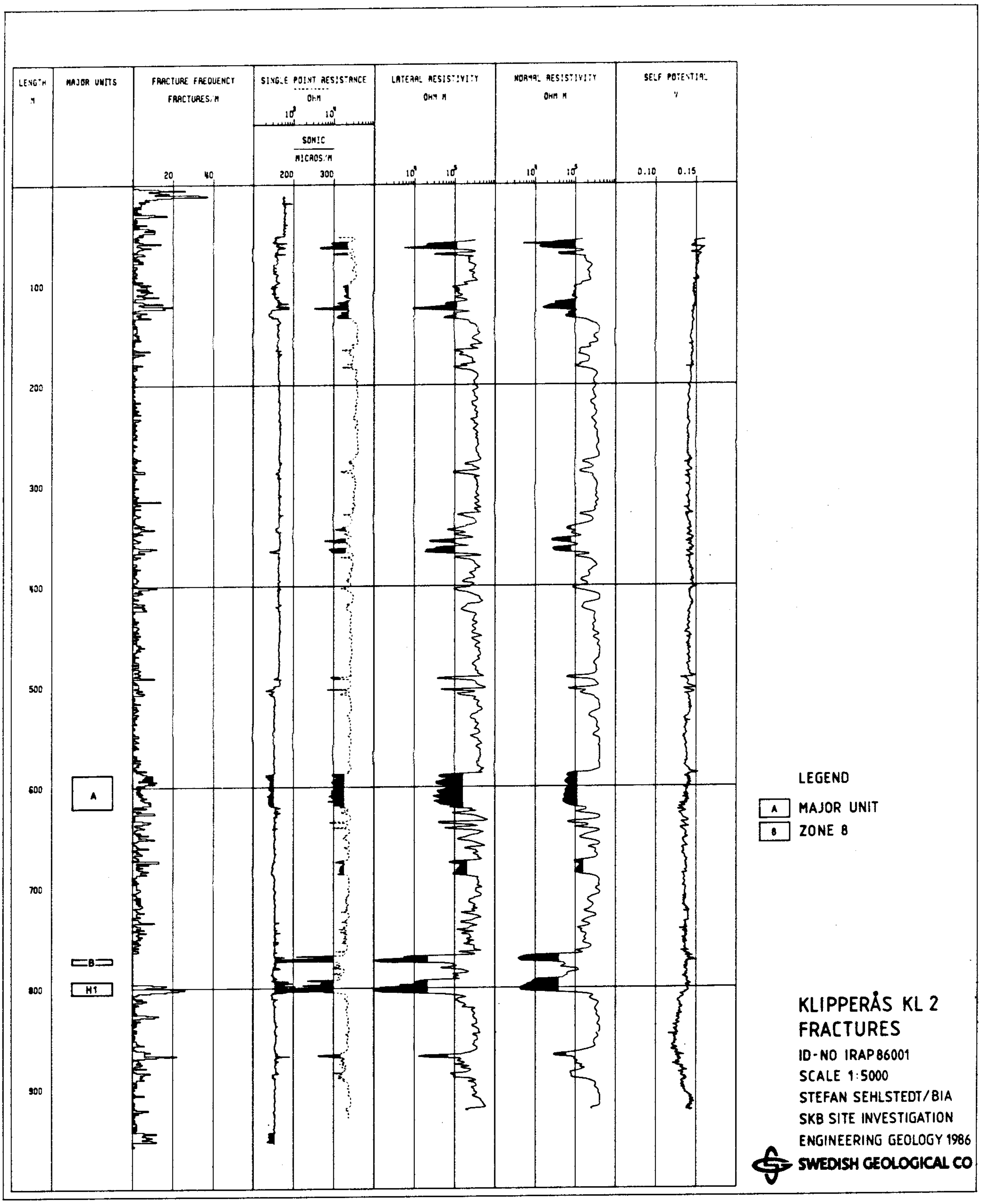


Figure 5.5 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 2.

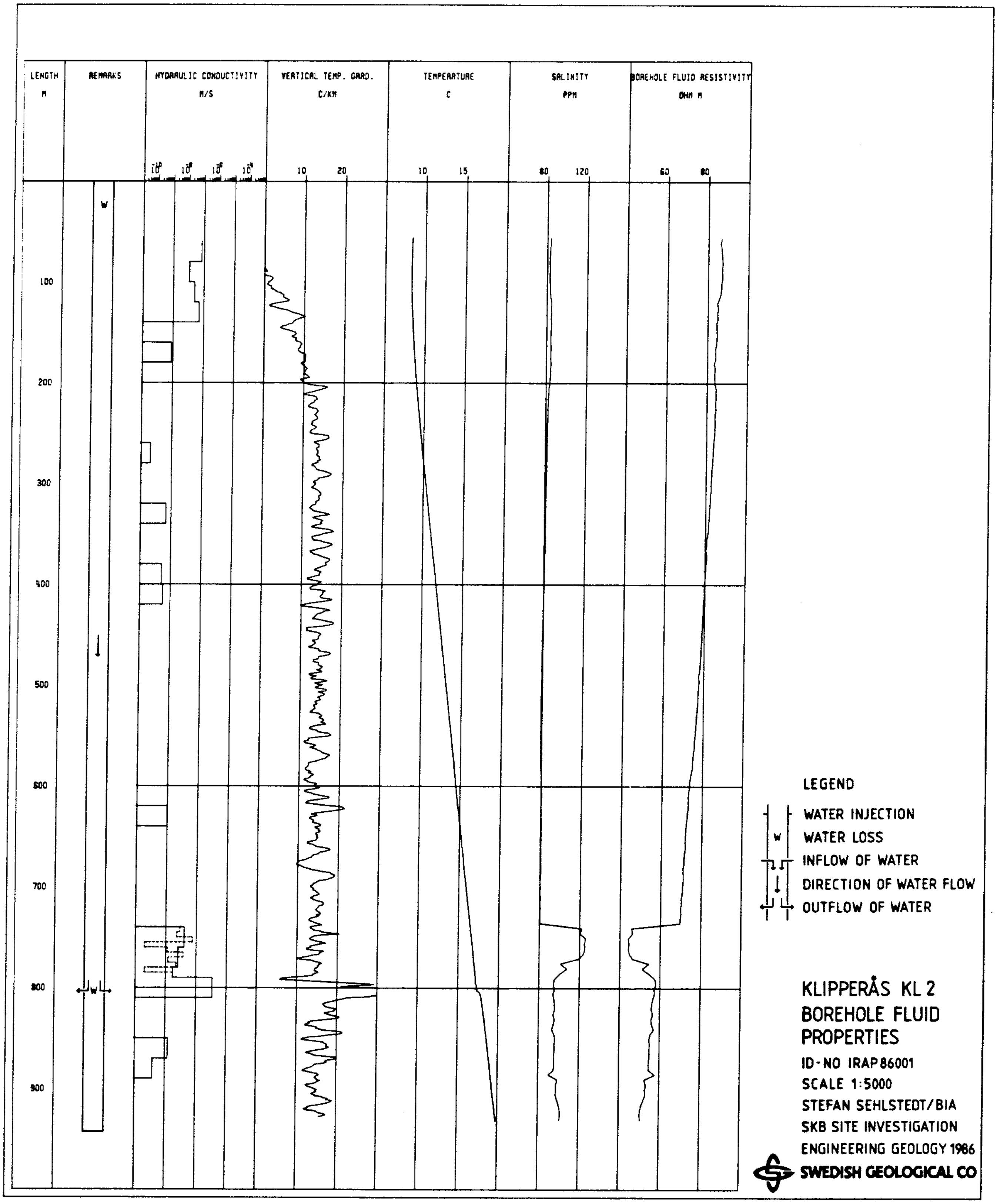


Figure 5.6 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 2.

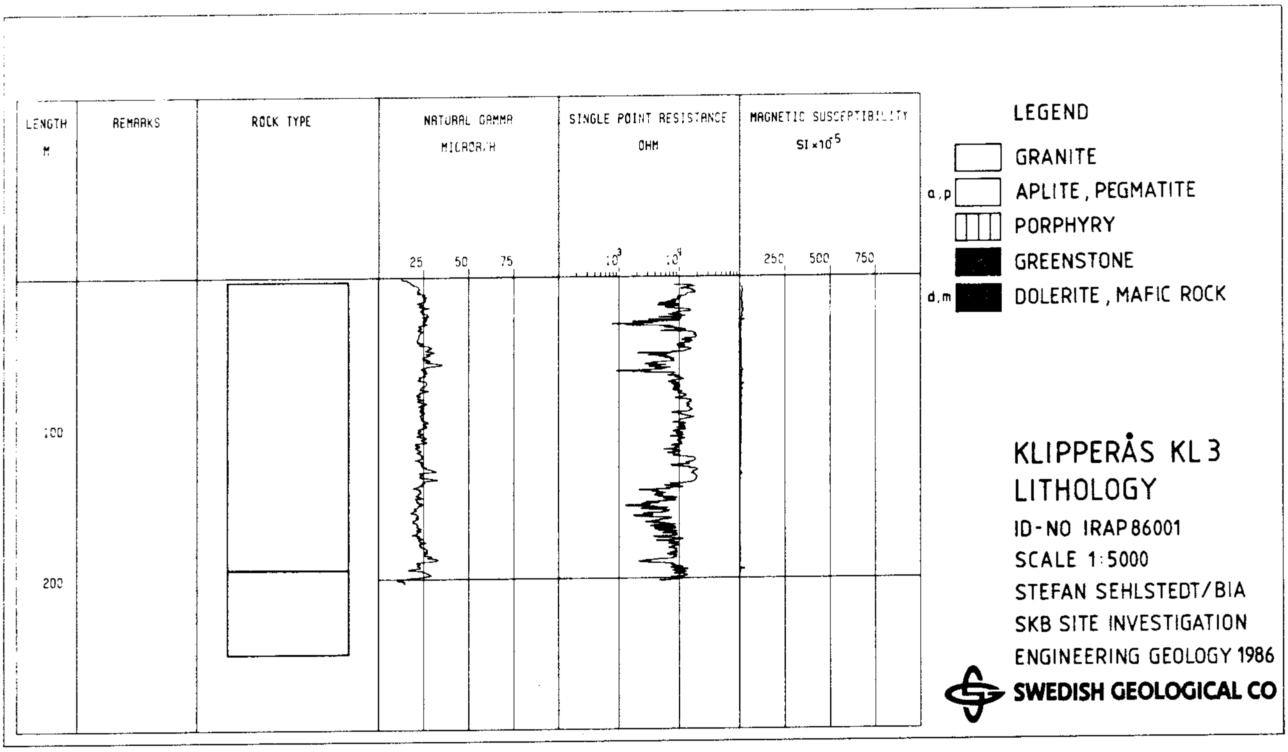


Figure 5.7 Geophysical logs sensitive to lithology variations, measured in borehole Kl 3.

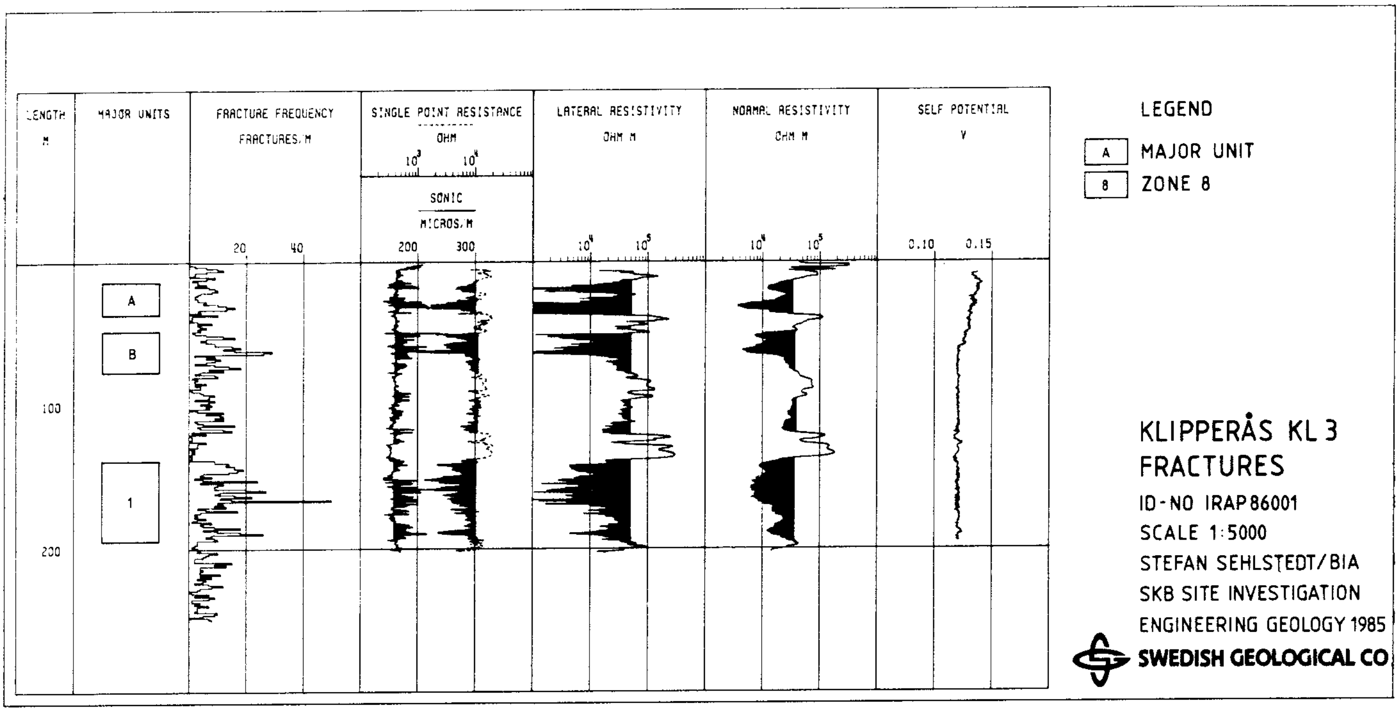


Figure 5.8 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 3.

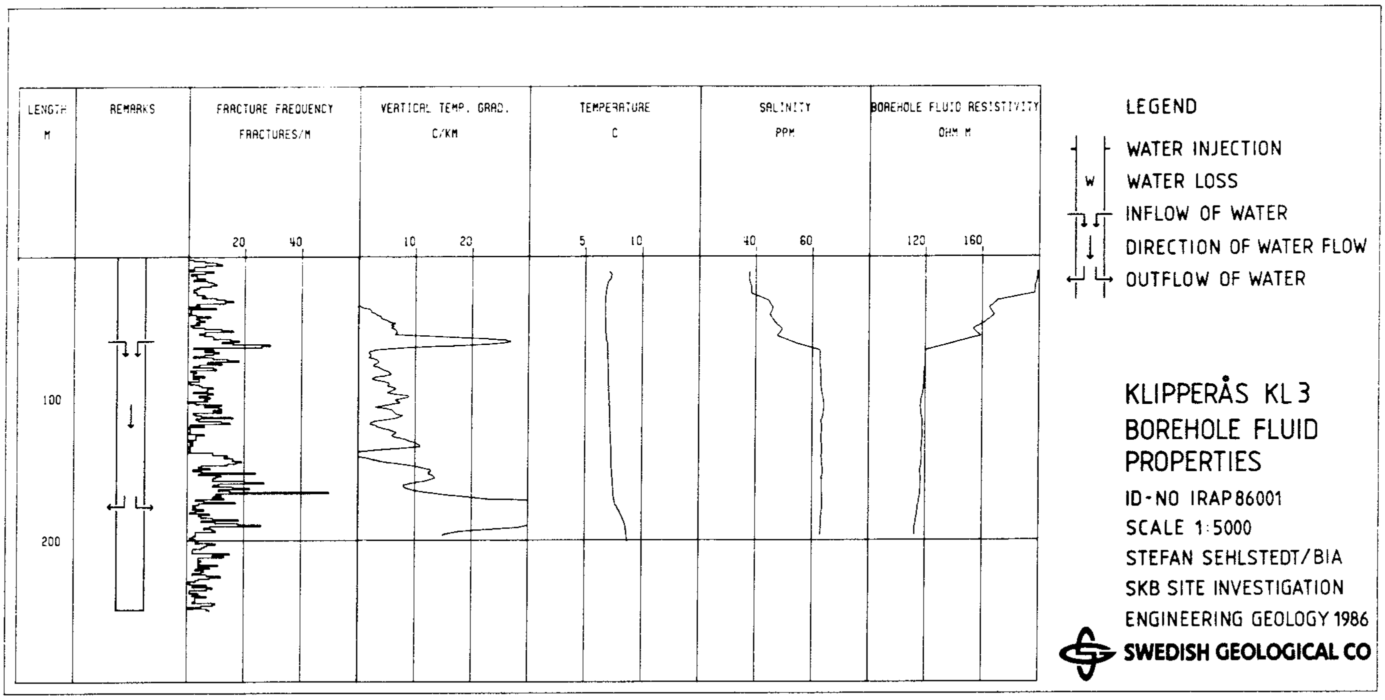


Figure 5.9 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 3.

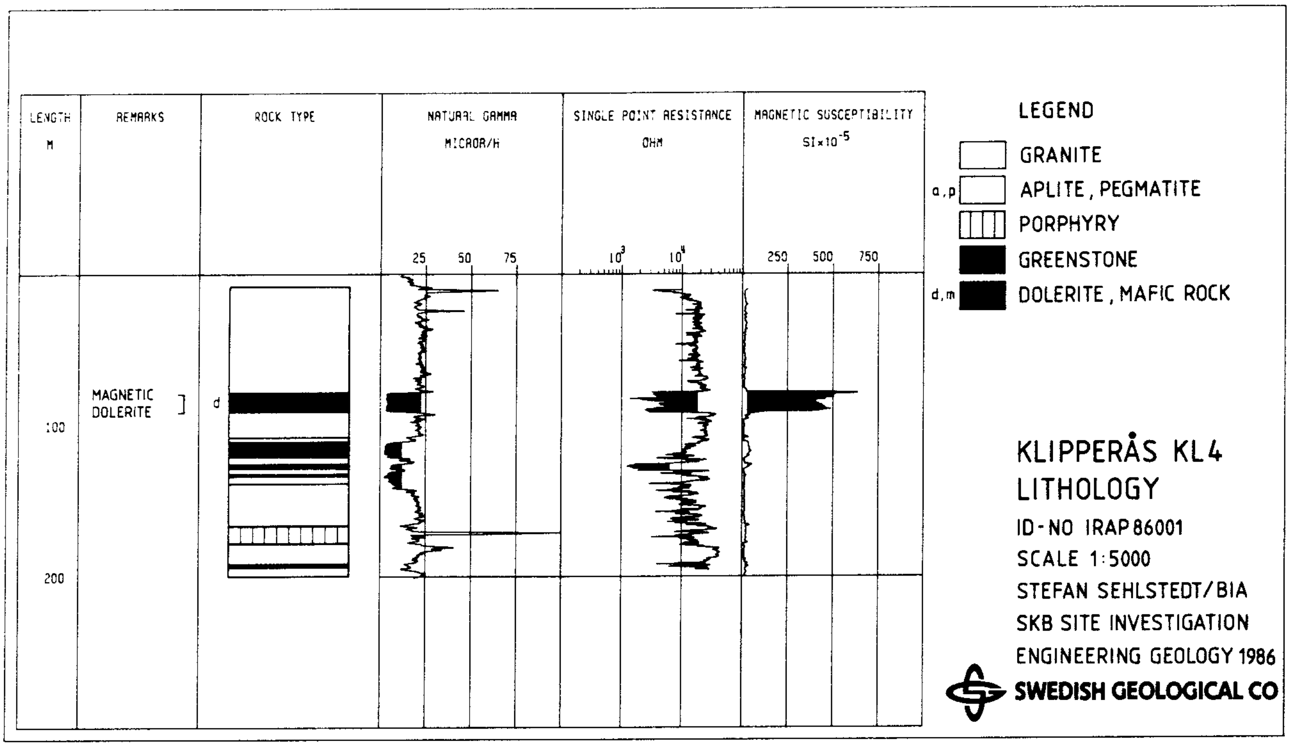


Figure 5.10 Geophysical logs sensitive to lithology variations, measured in borehole Kl 4.

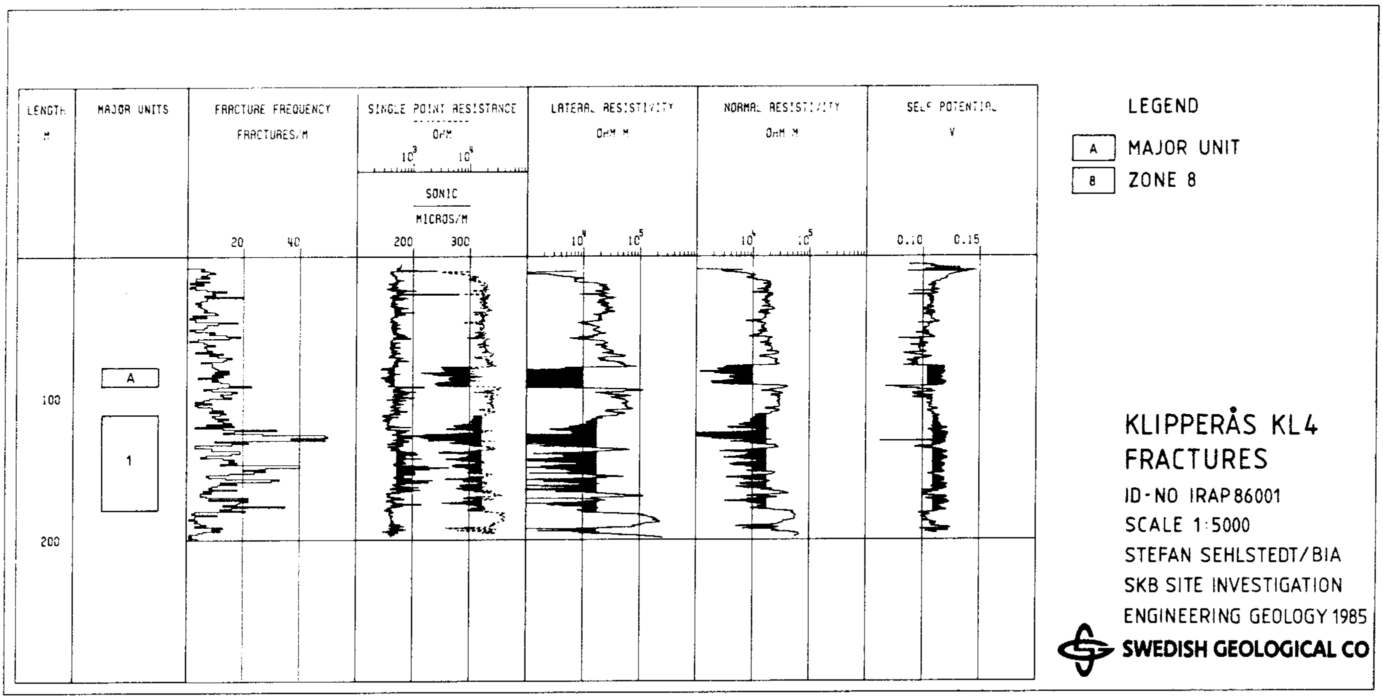


Figure 5.11 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 4.

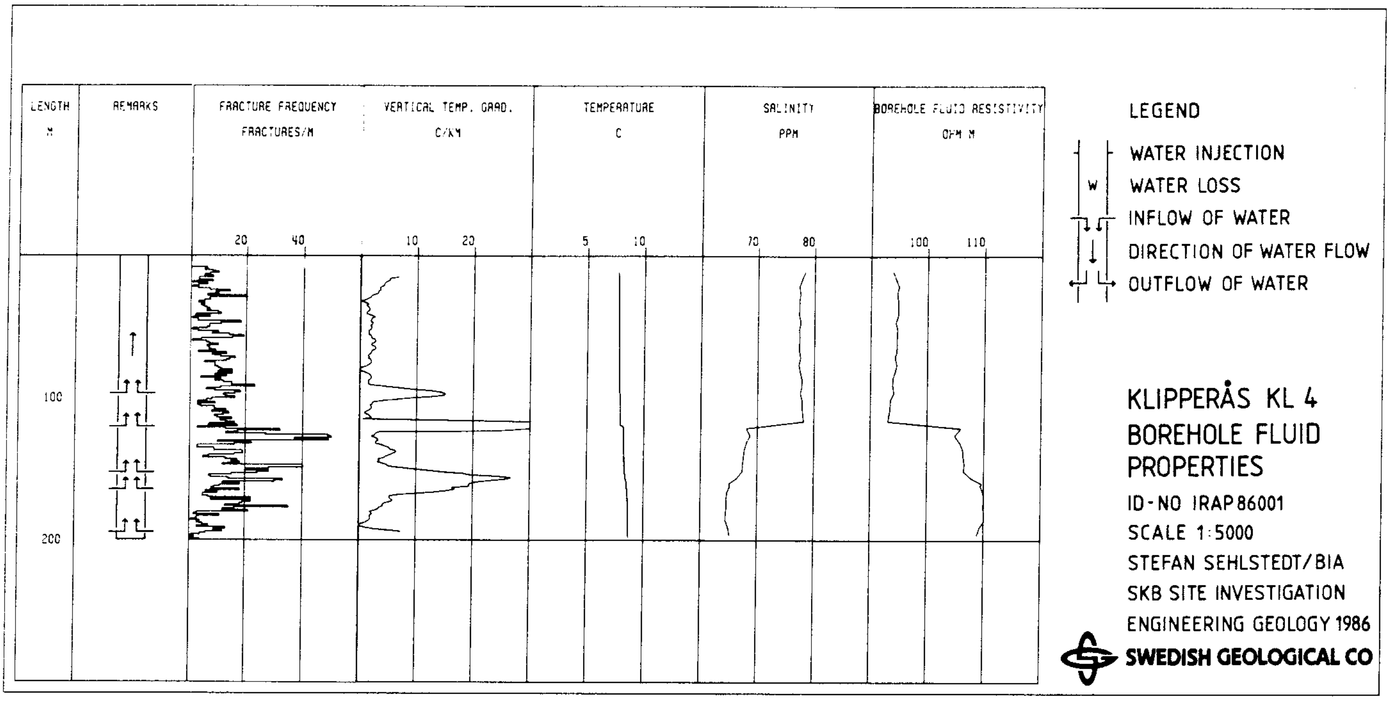


Figure 5.12 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 4.

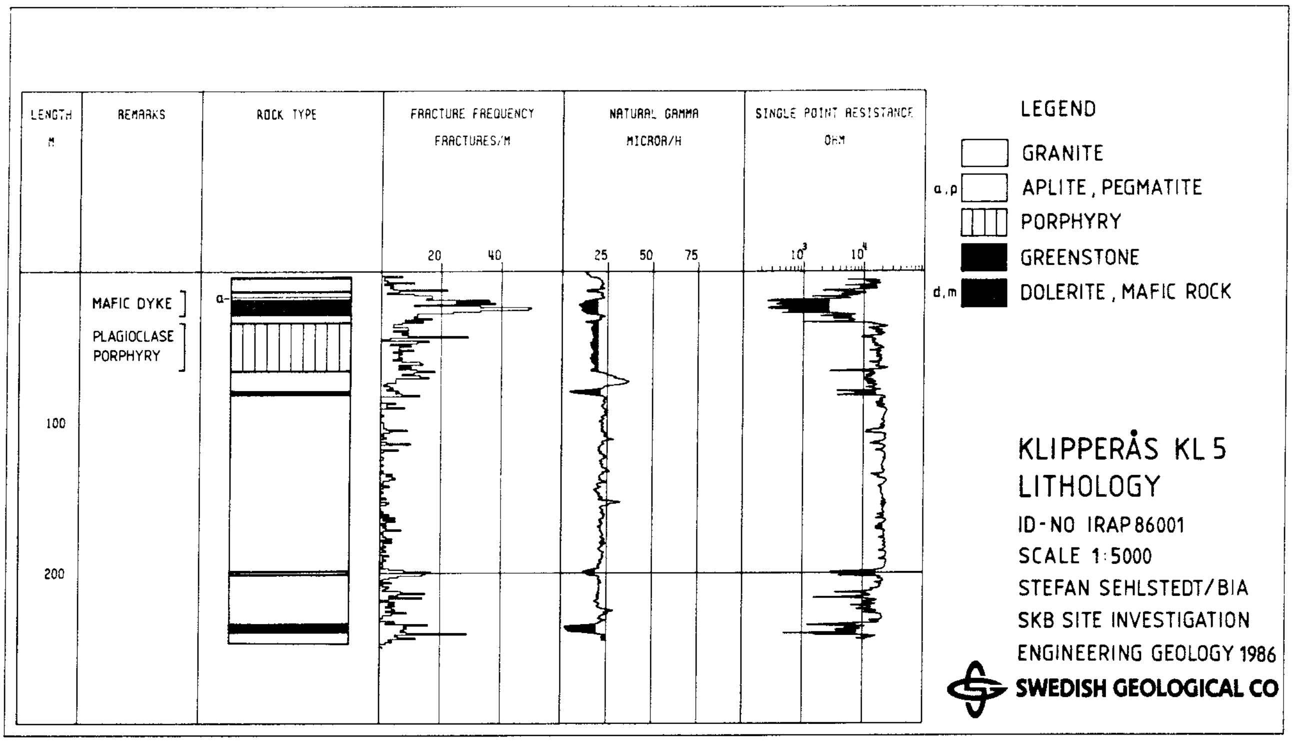


Figure 5.13 Geophysical logs sensitive to lithology variations, measured in borehole Kl 5.

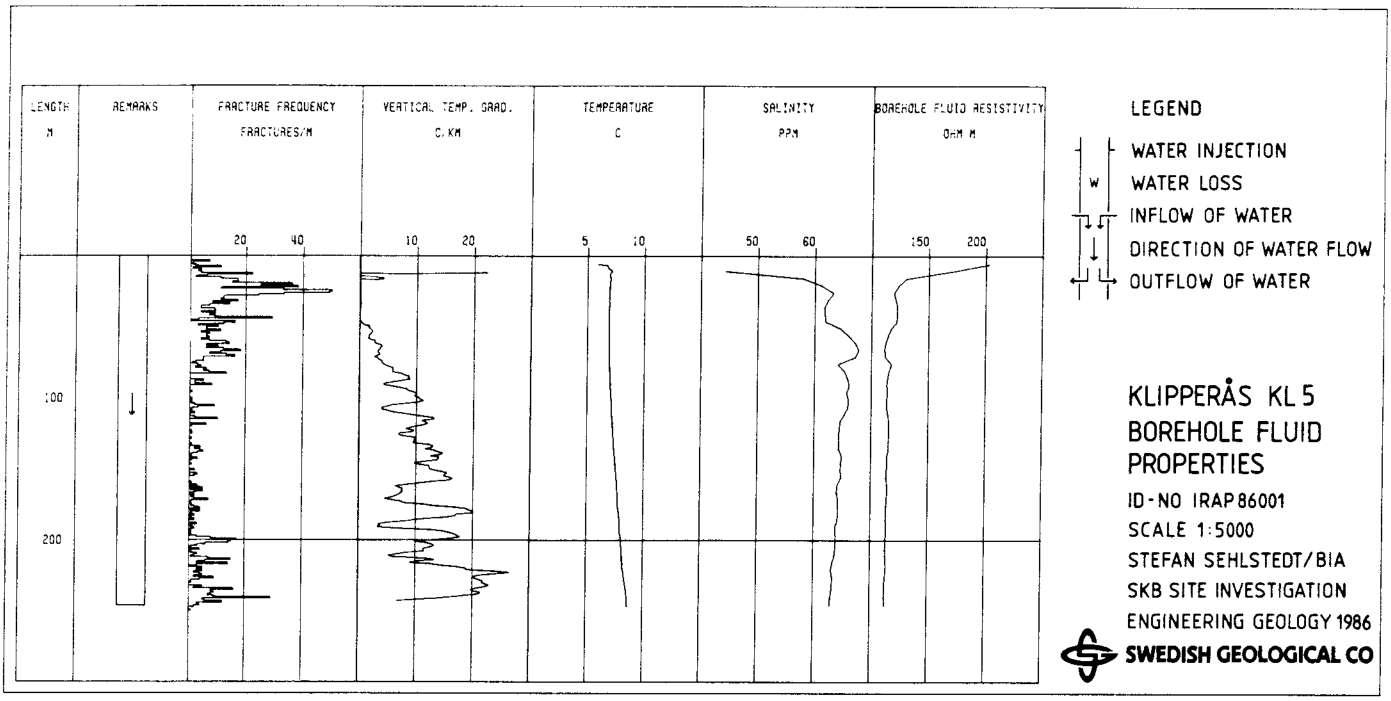


Figure 5.14 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 5.

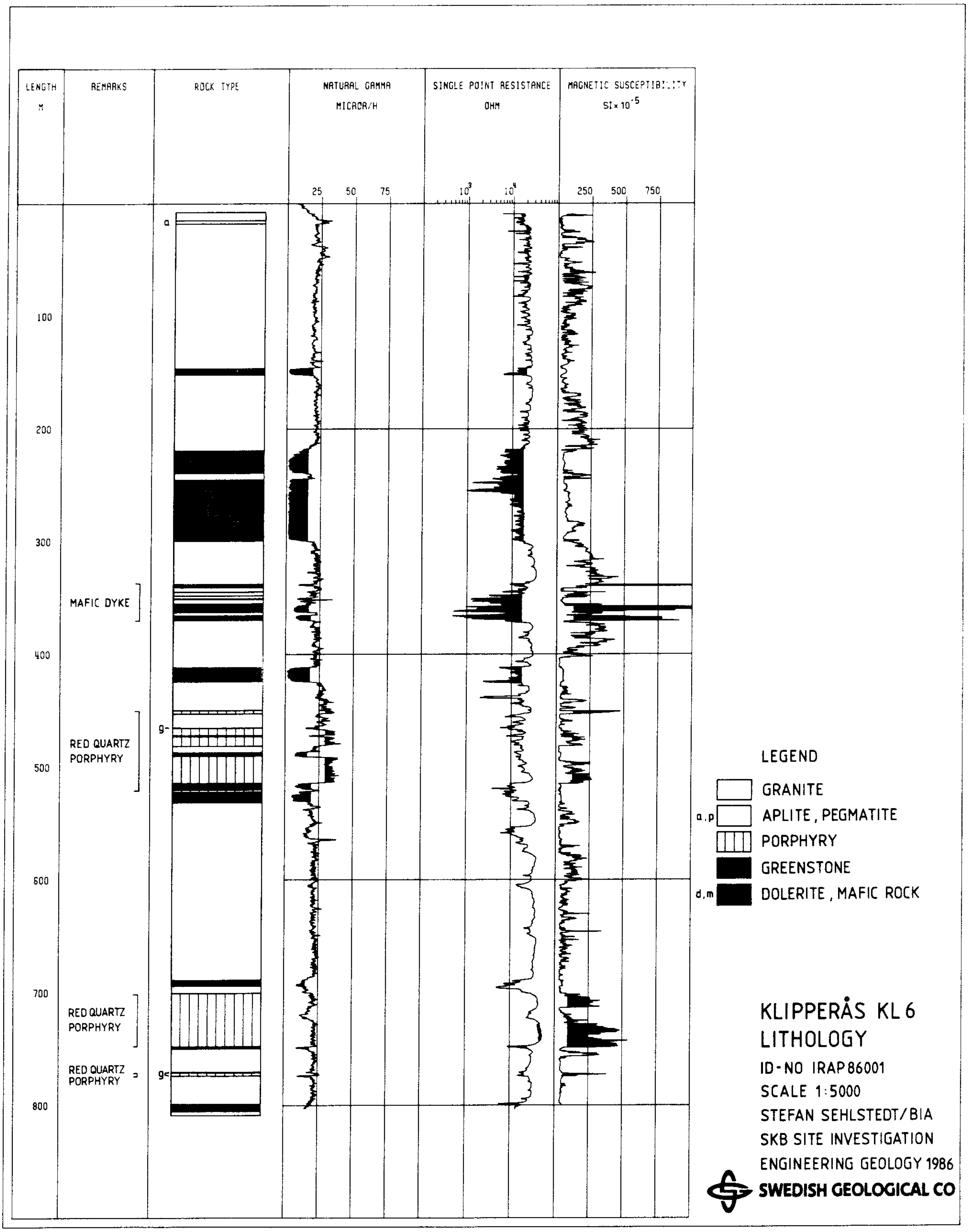


Figure 5.15 Geophysical logs sensitive to lithology variations, measured in borehole Kl 6.

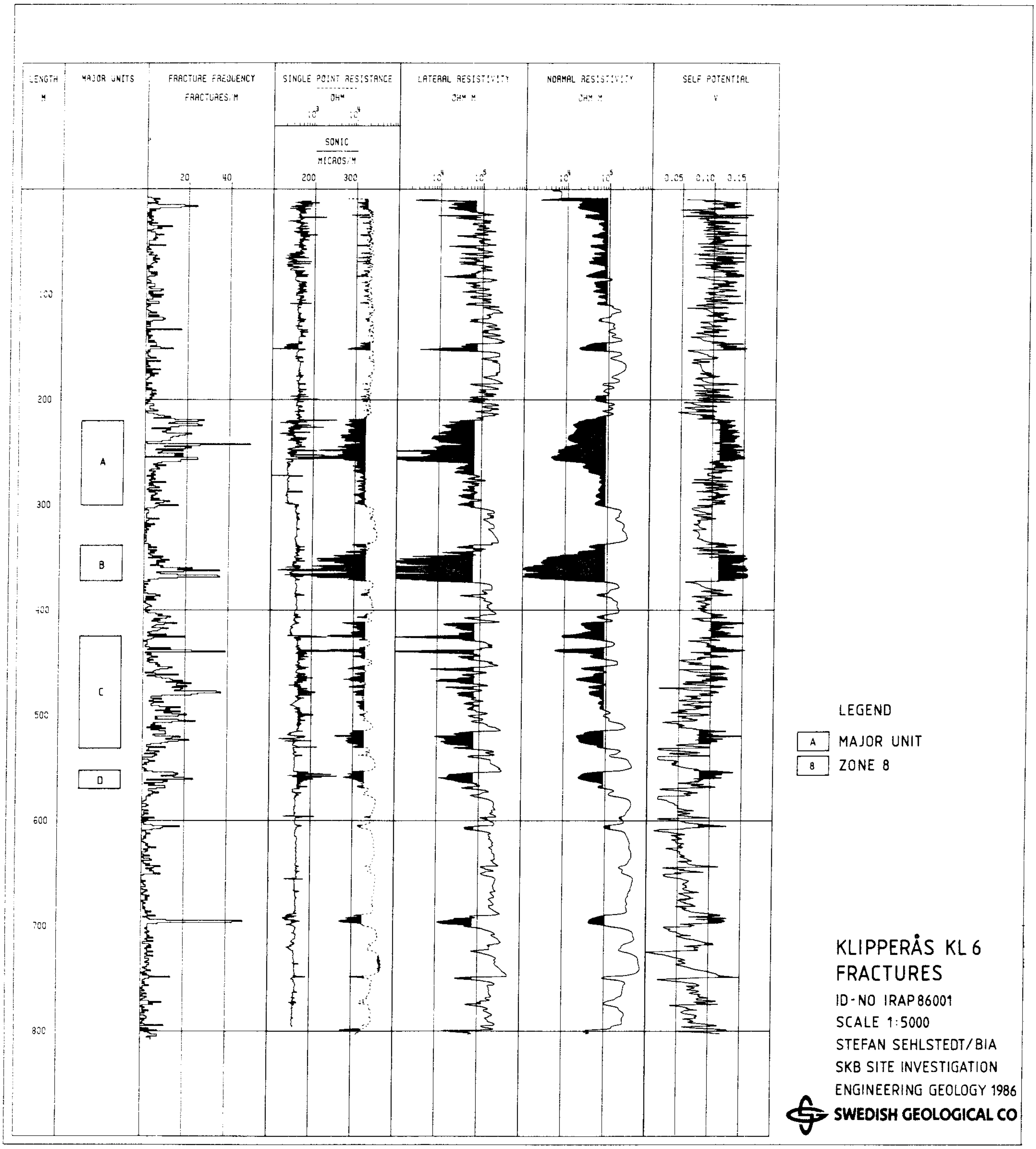


Figure 5.16 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 6.

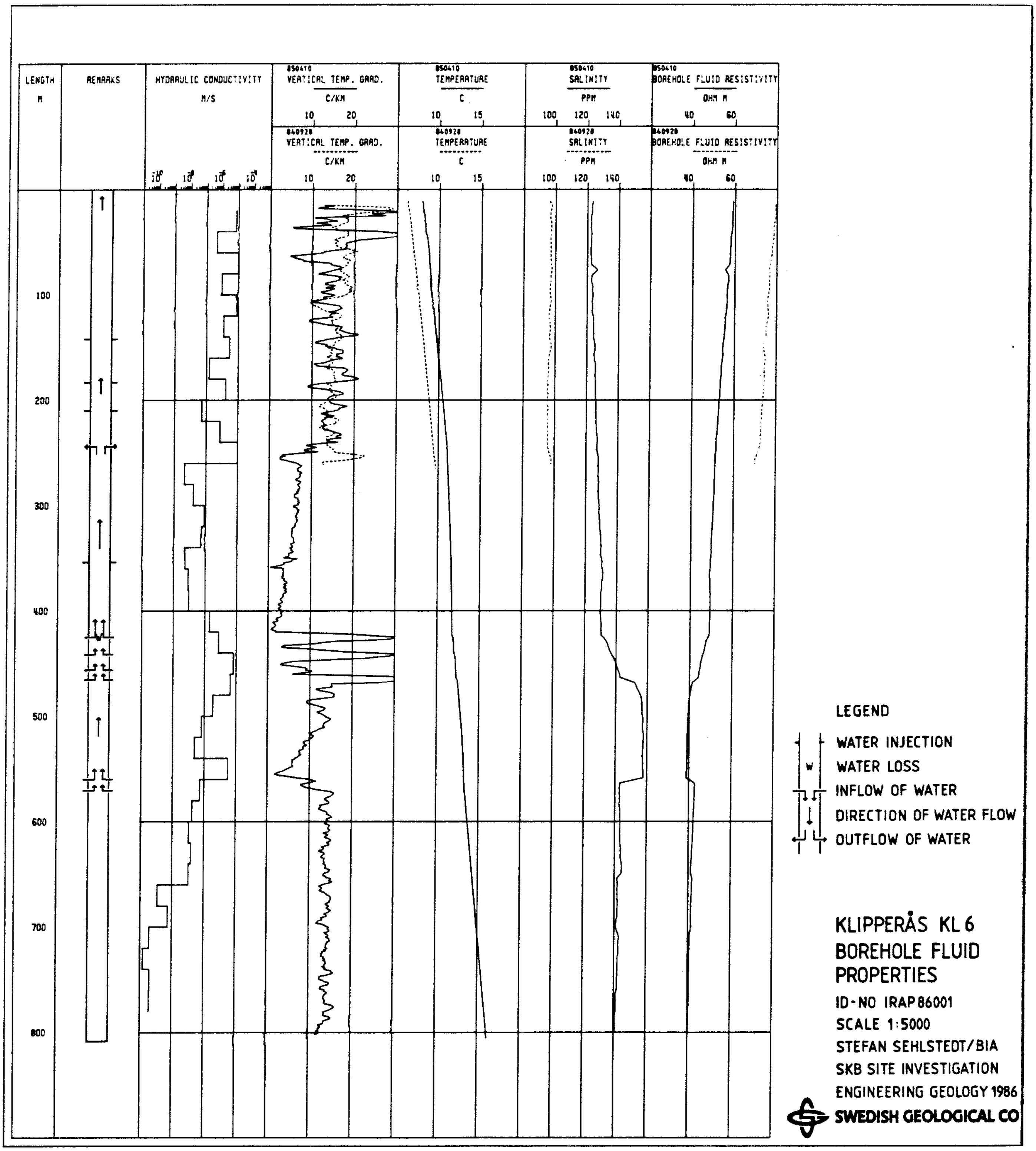


Figure 5.17 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 6.

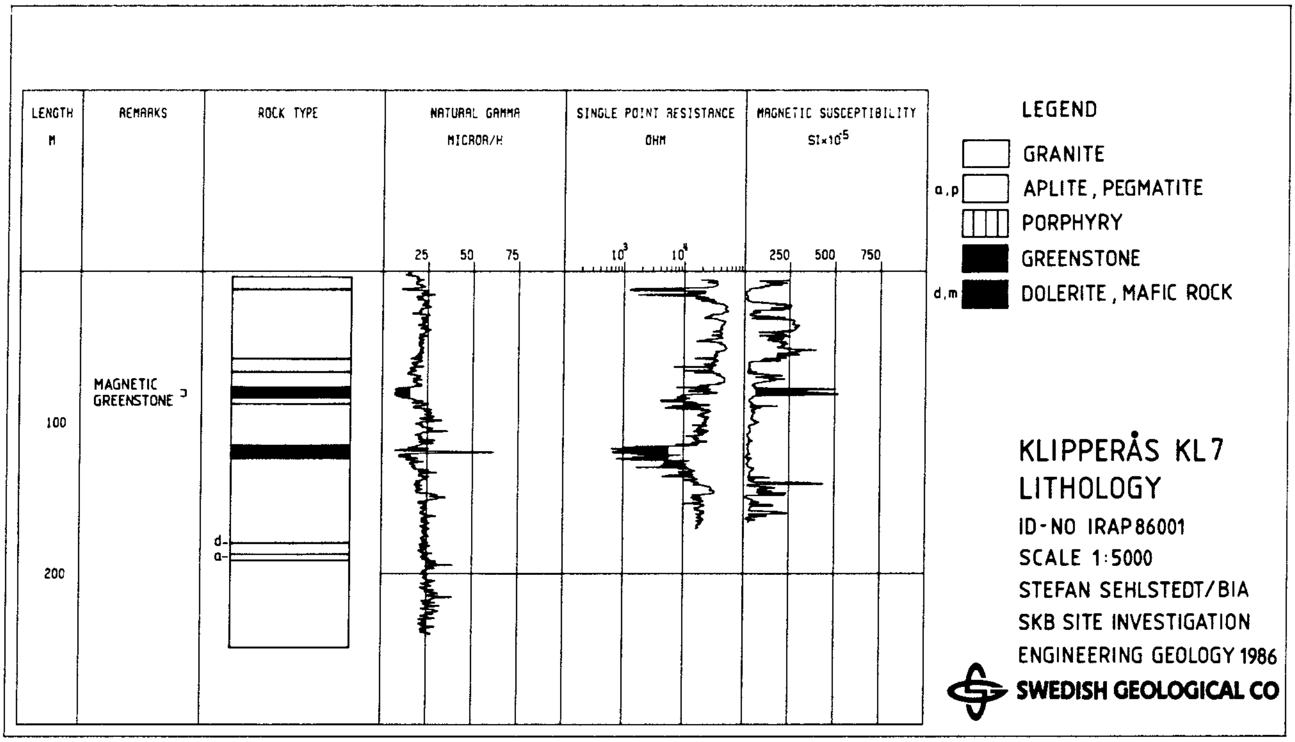


Figure 5.18 Geophysical logs sensitive to lithology variations, measured in borehole Kl 7.

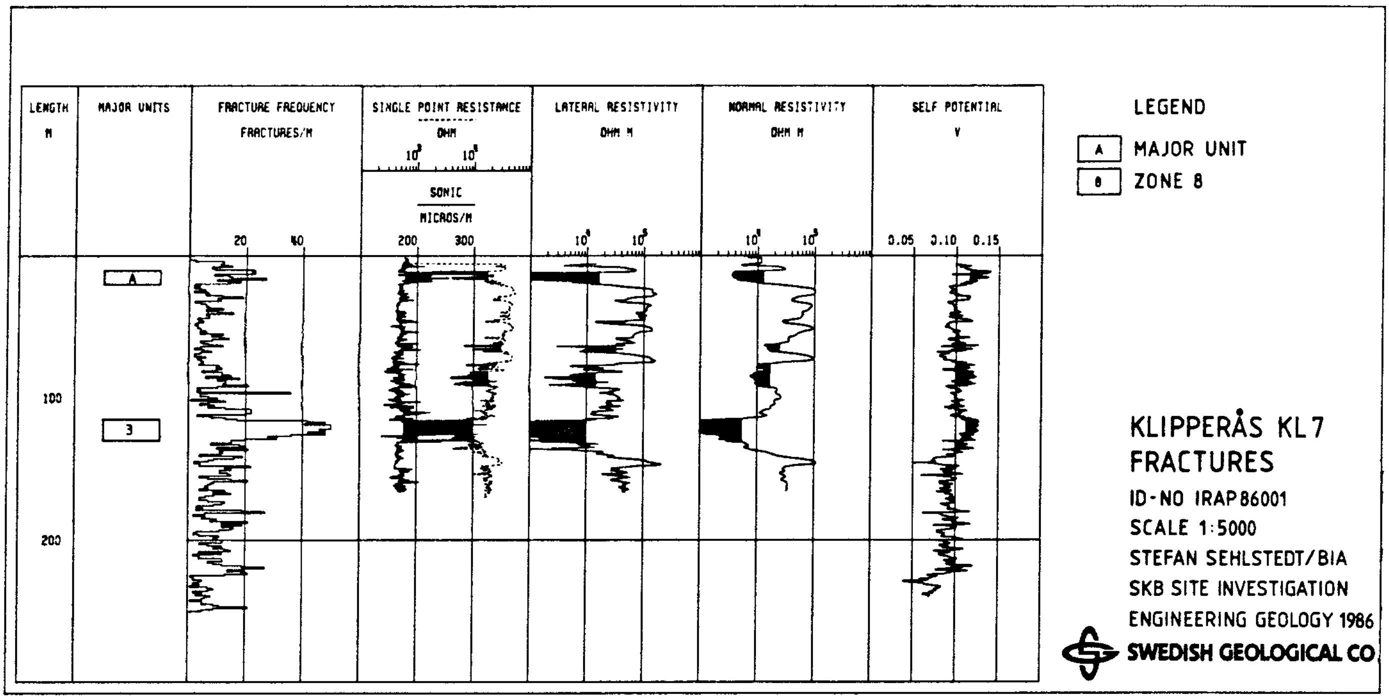


Figure 5.19 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 7.

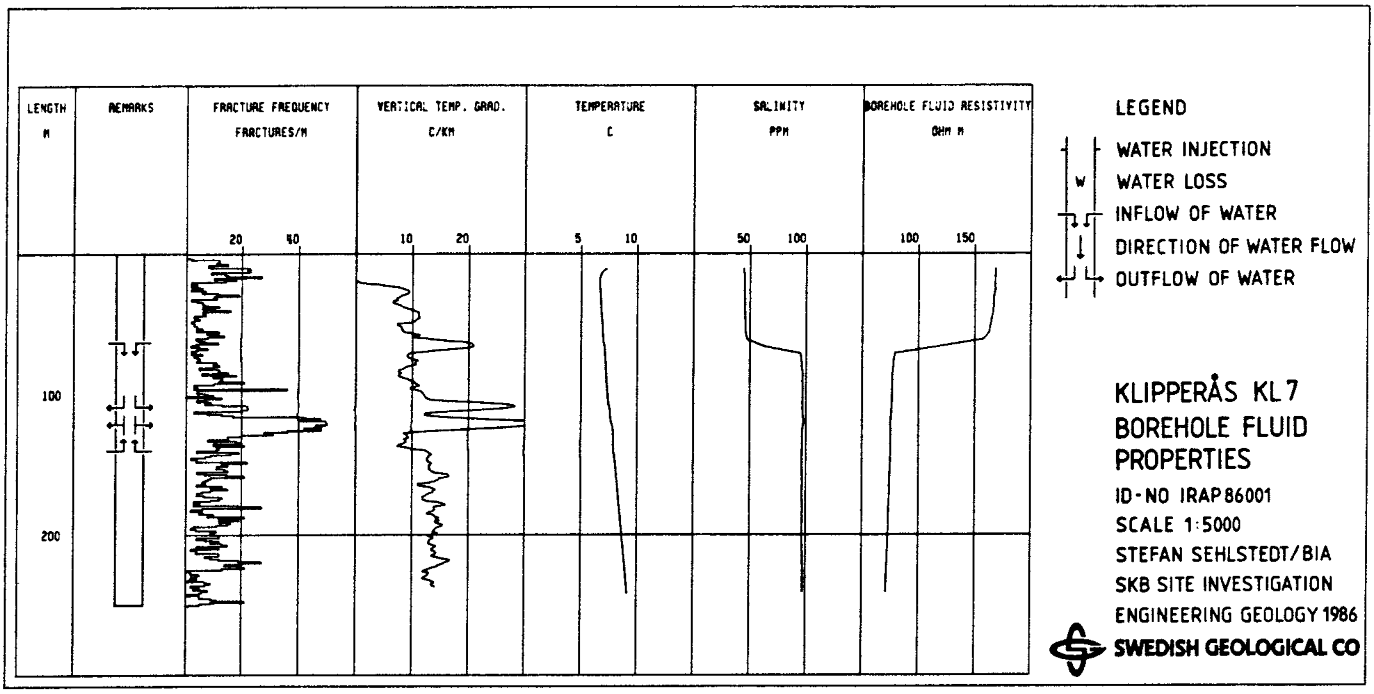


Figure 5.20 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 7.

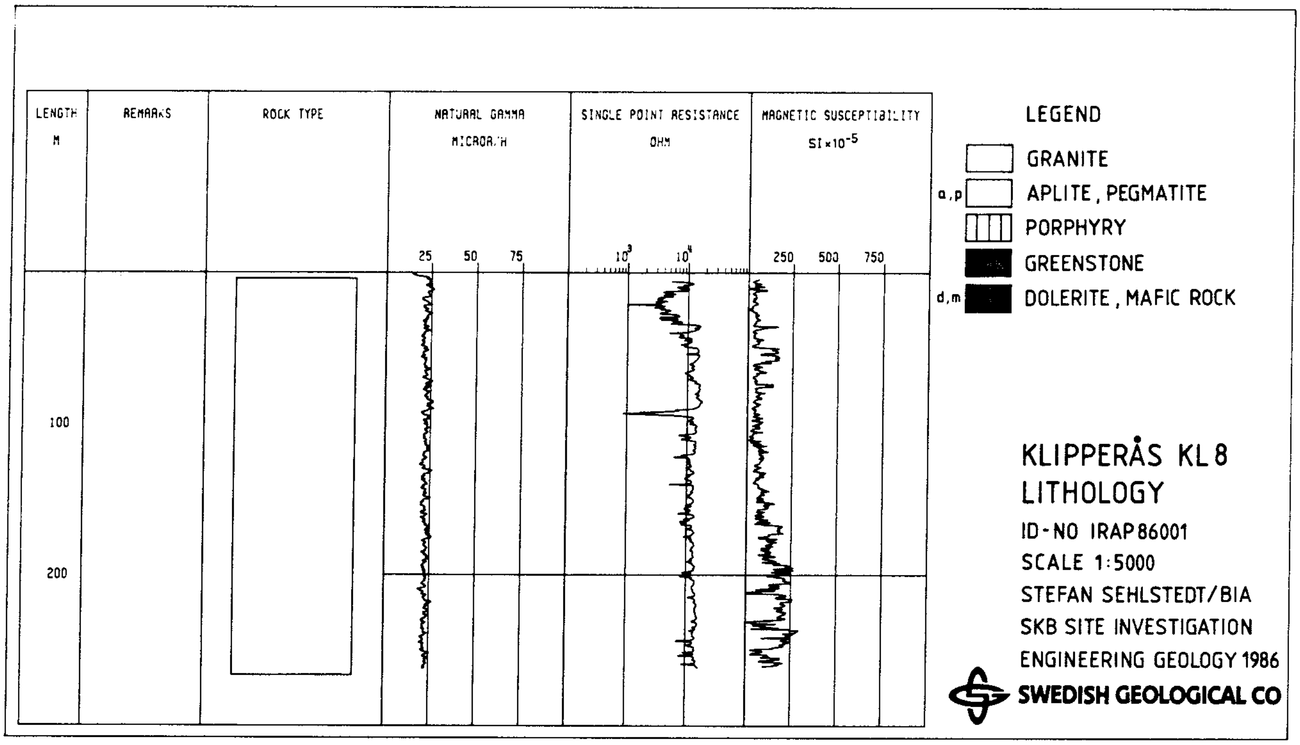


Figure 5.21 Geophysical logs sensitive to lithology variations, measured in borehole Kl 8.

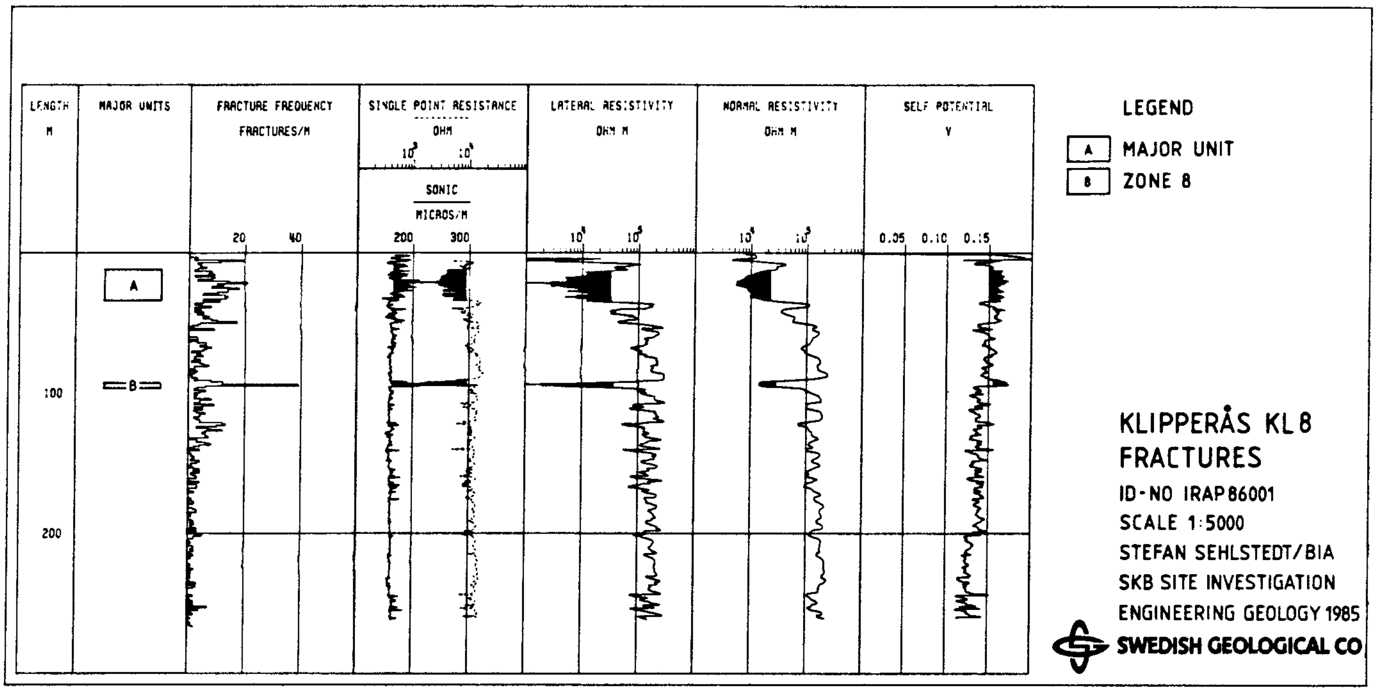


Figure 5.22 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 8.

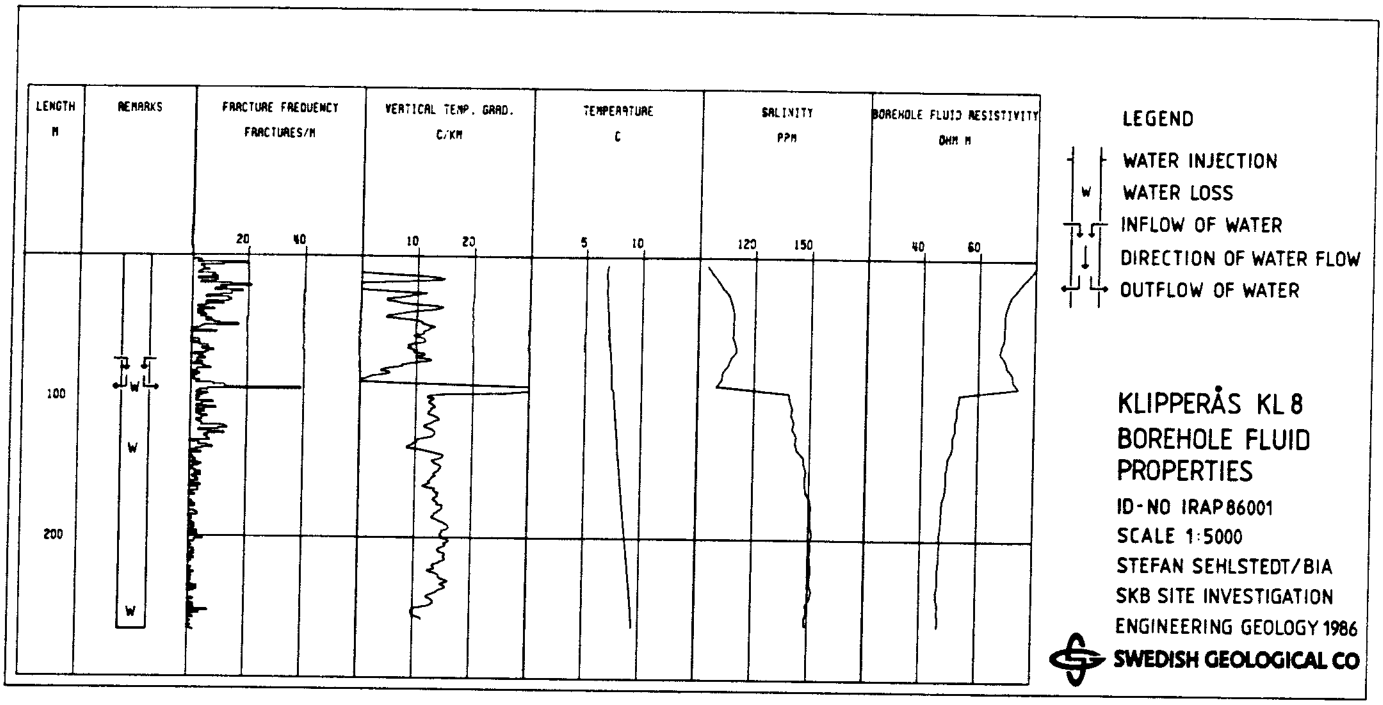


Figure 5.23 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 8.

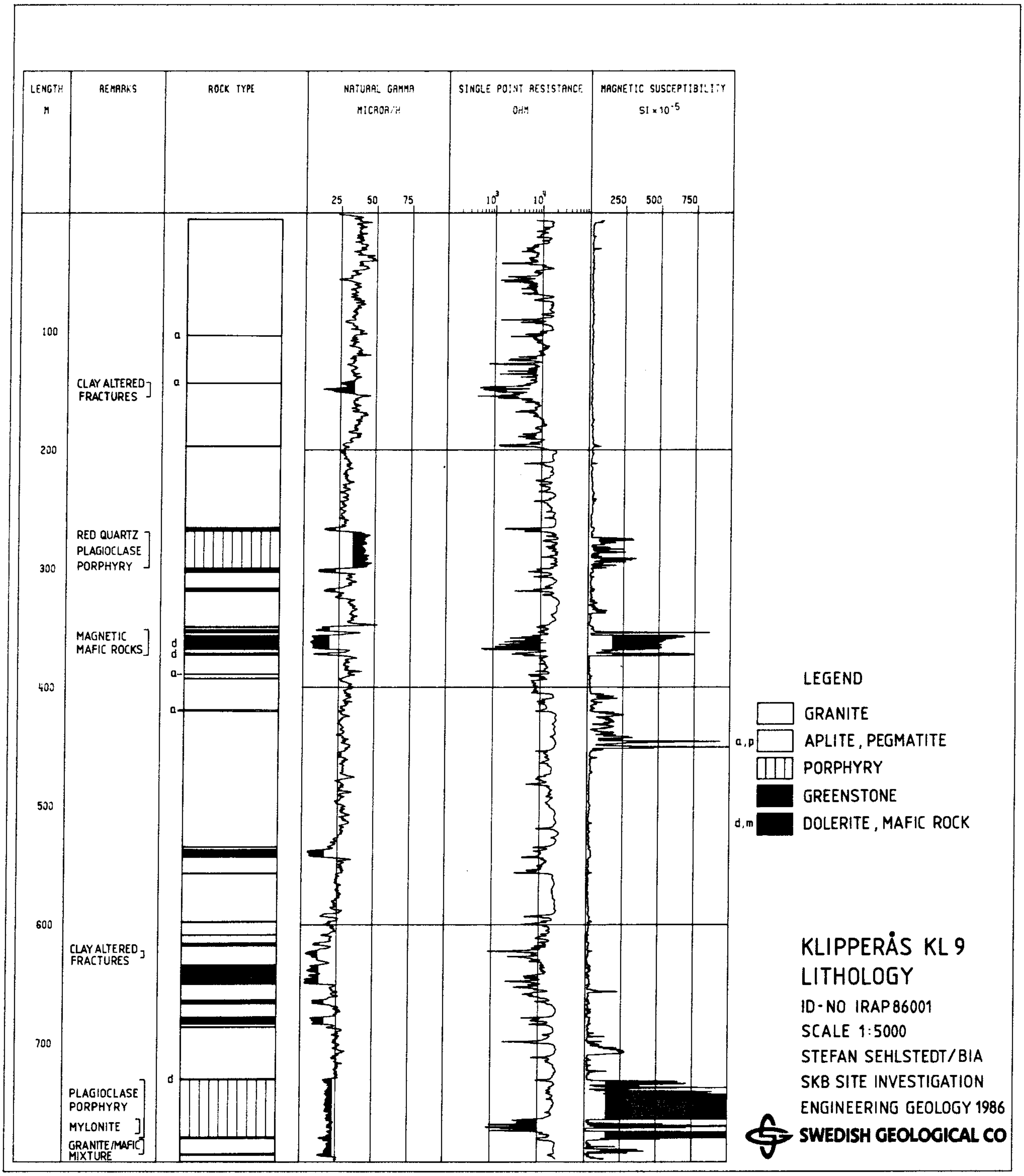


Figure 5.24 Geophysical logs sensitive to lithology variations, measured in borehole Kl 9.

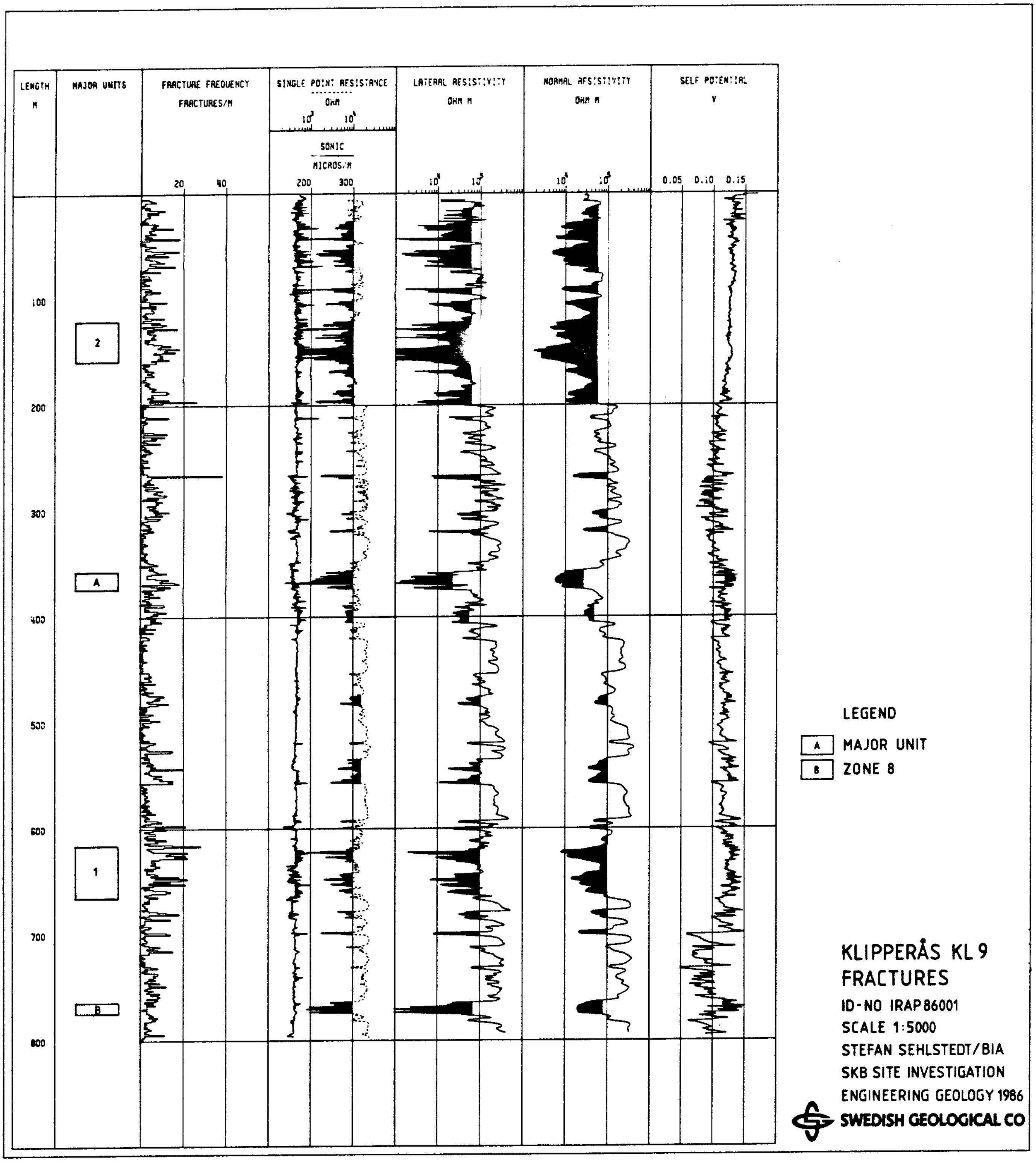


Figure 5.25 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 9.

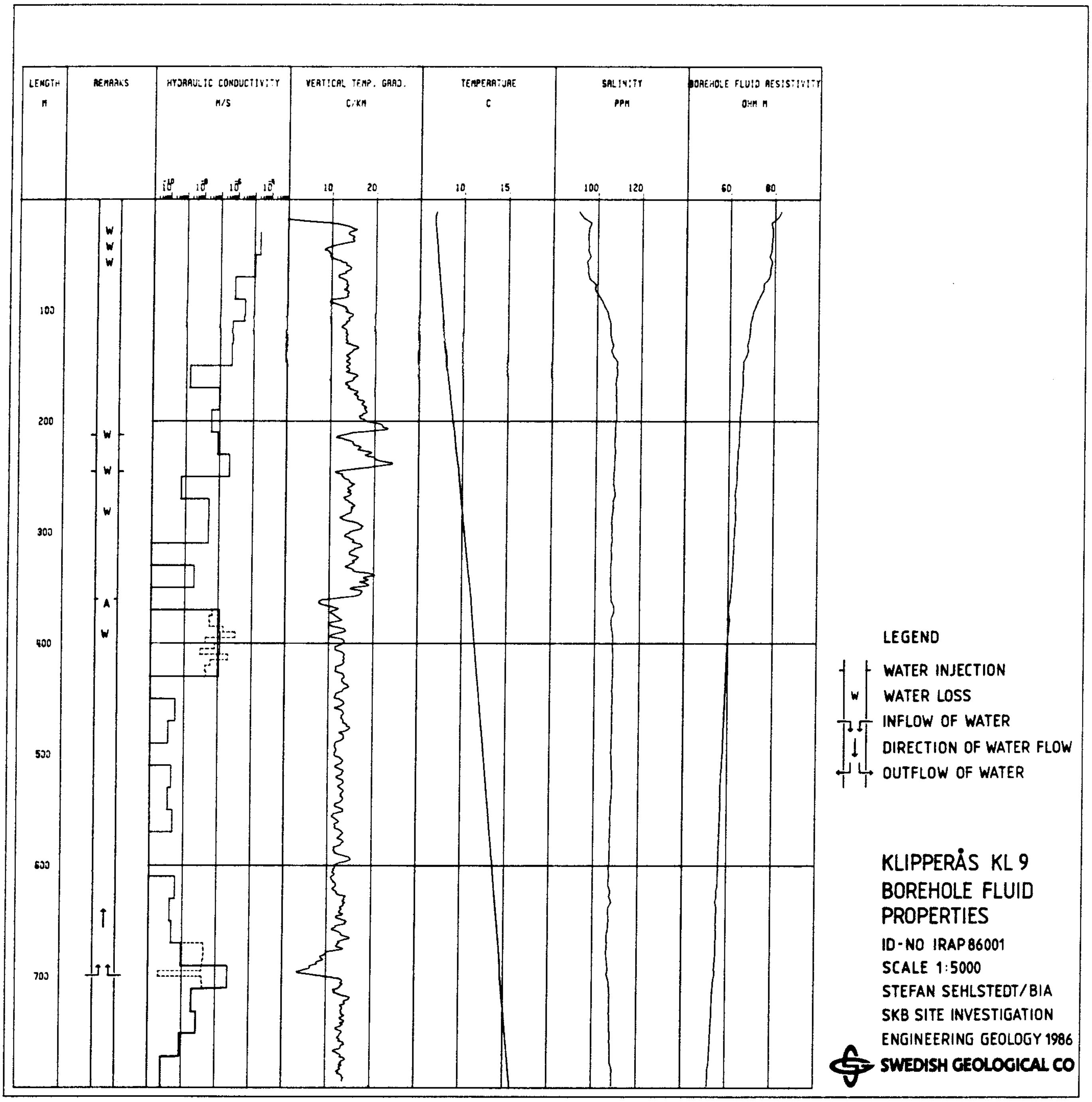


Figure 5.26 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 9.

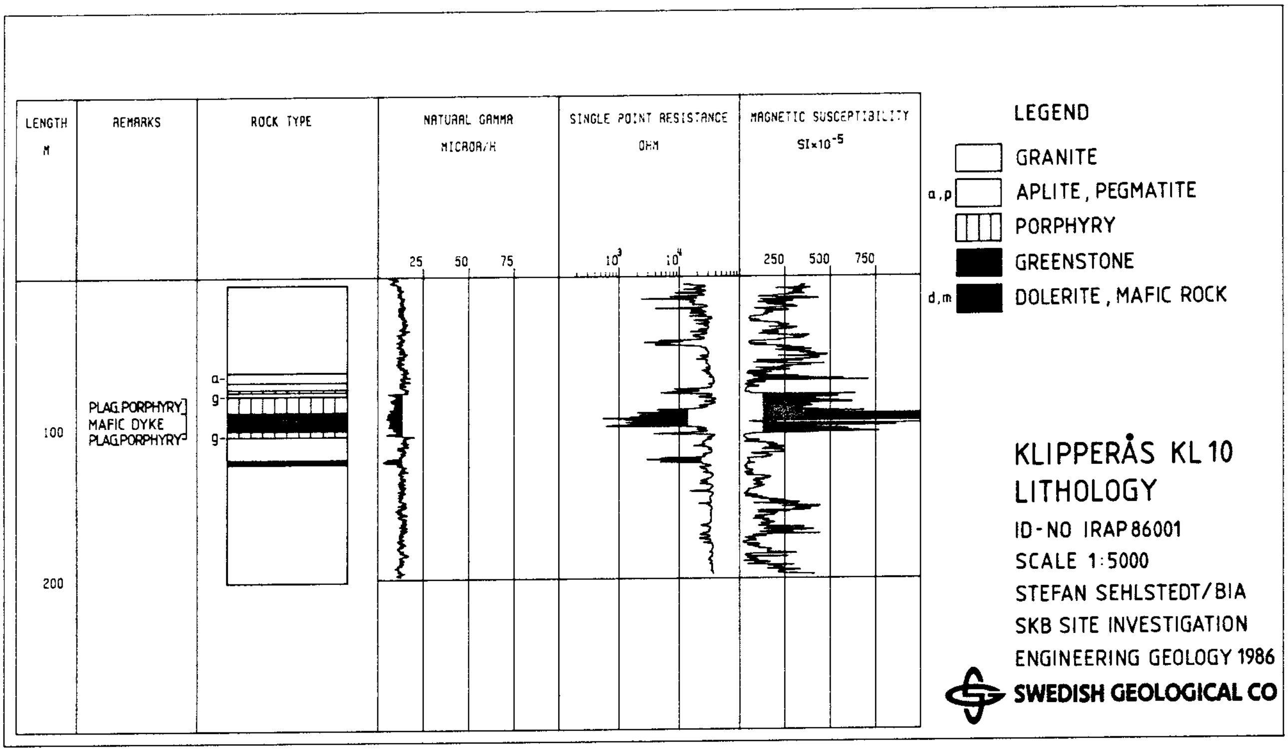


Figure 5.27 Geophysical logs sensitive to lithology variations, measured in borehole Kl 10.

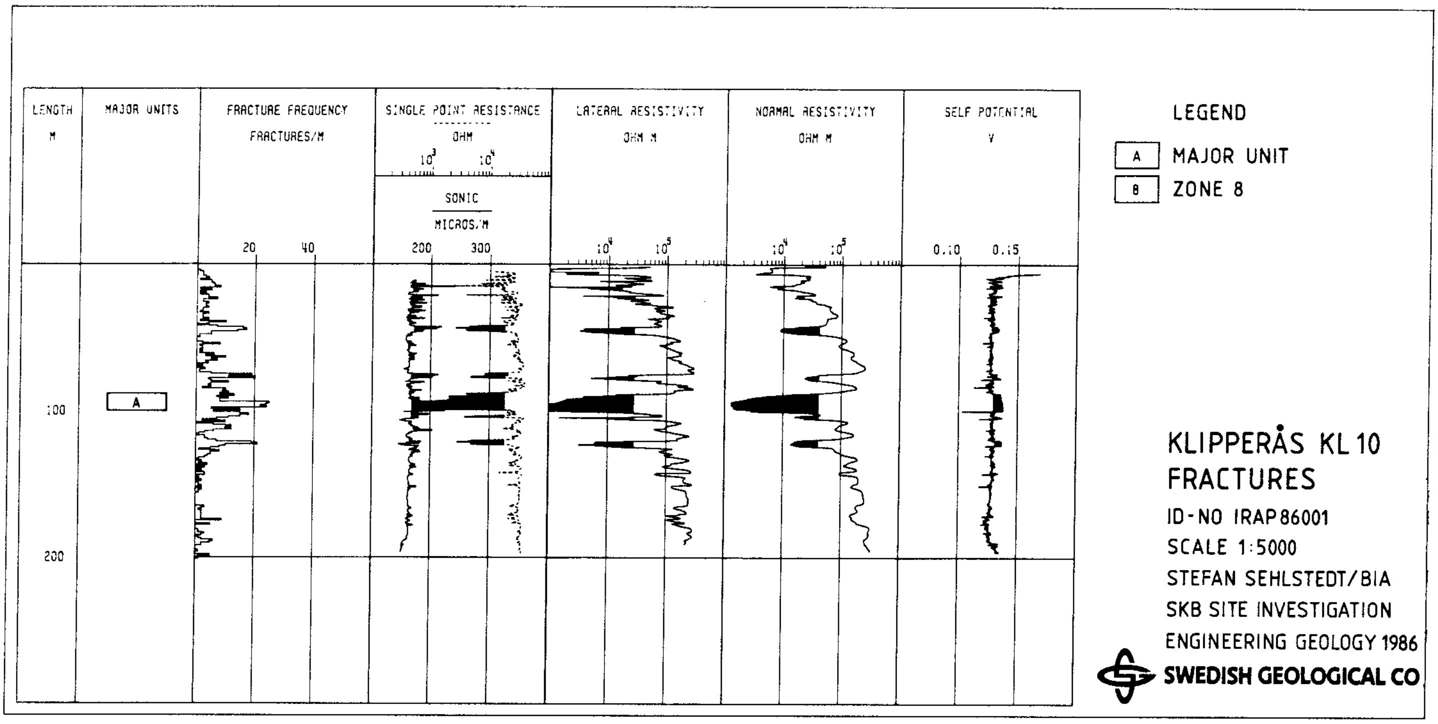


Figure 5.28 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 10.

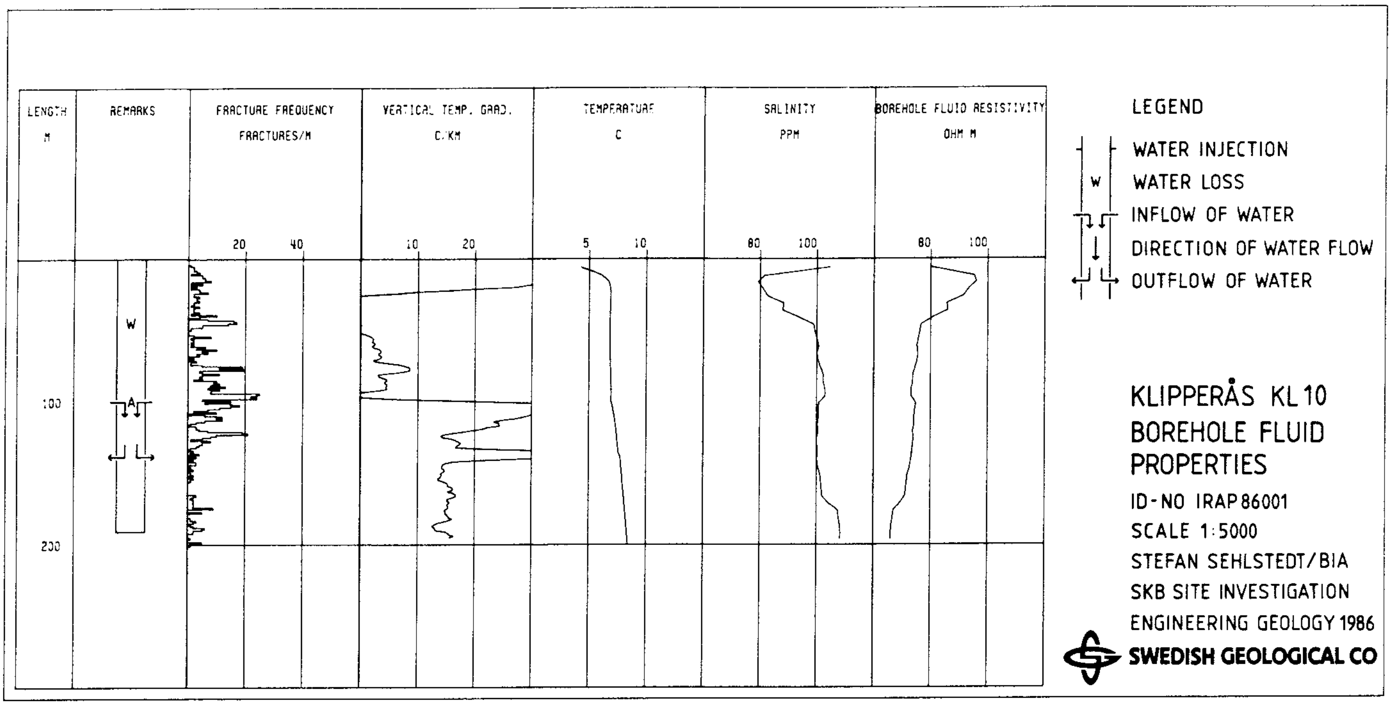


Figure 5.29 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 10.

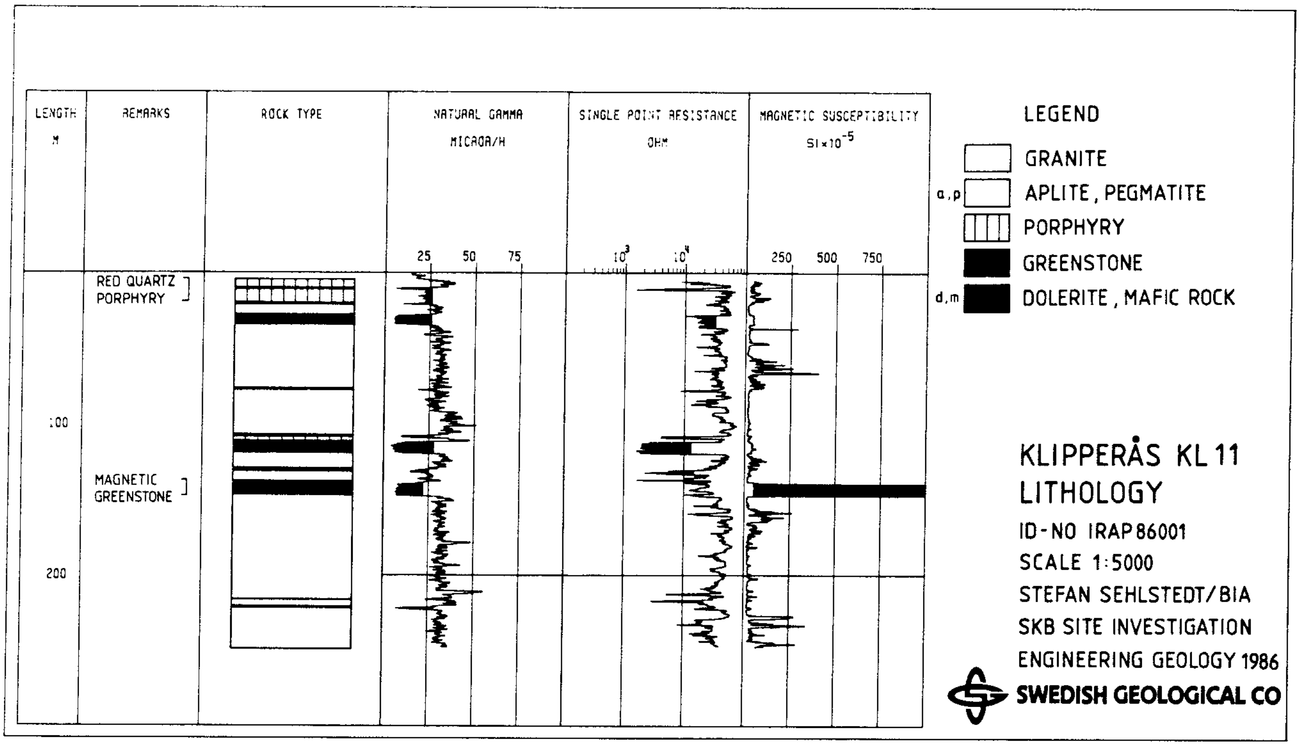


Figure 5.30 Geophysical logs sensitive to lithology variations, measured in borehole Kl 11.

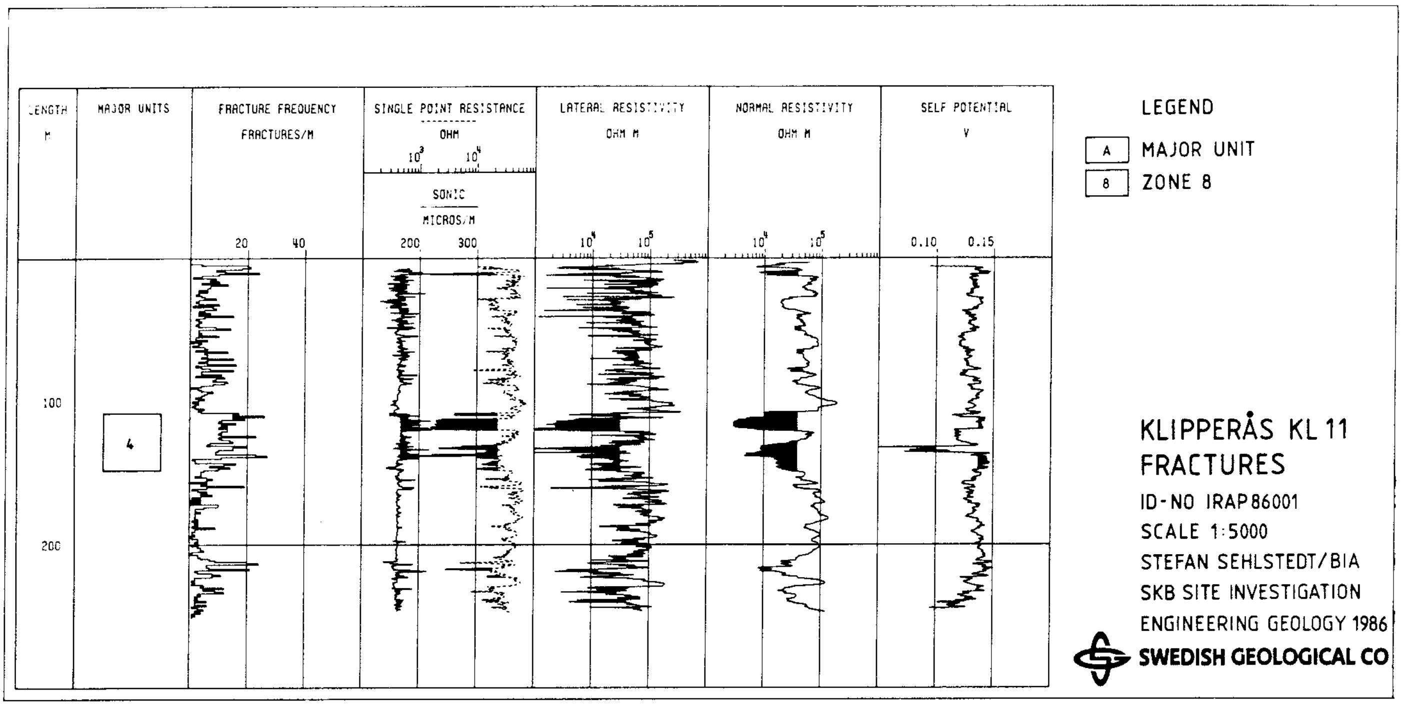


Figure 5.31 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 11.

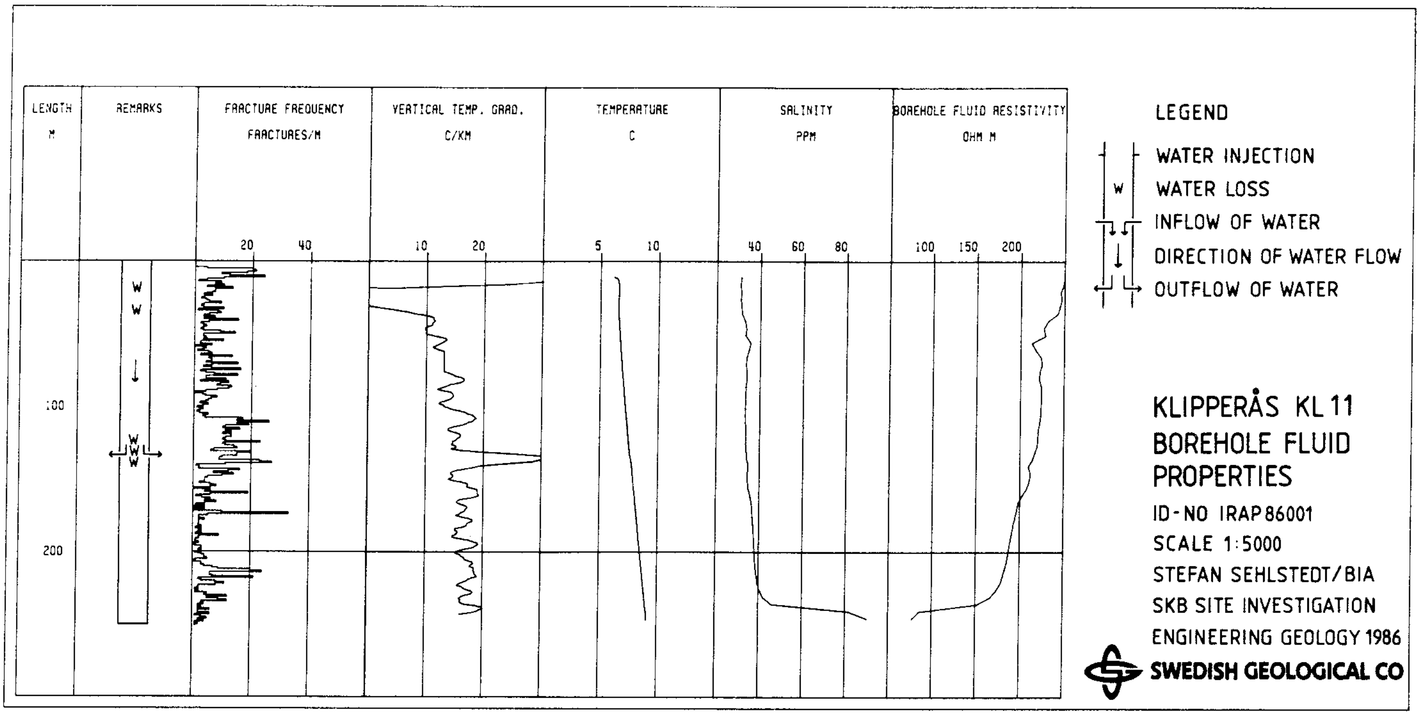


Figure 5.32 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 11.

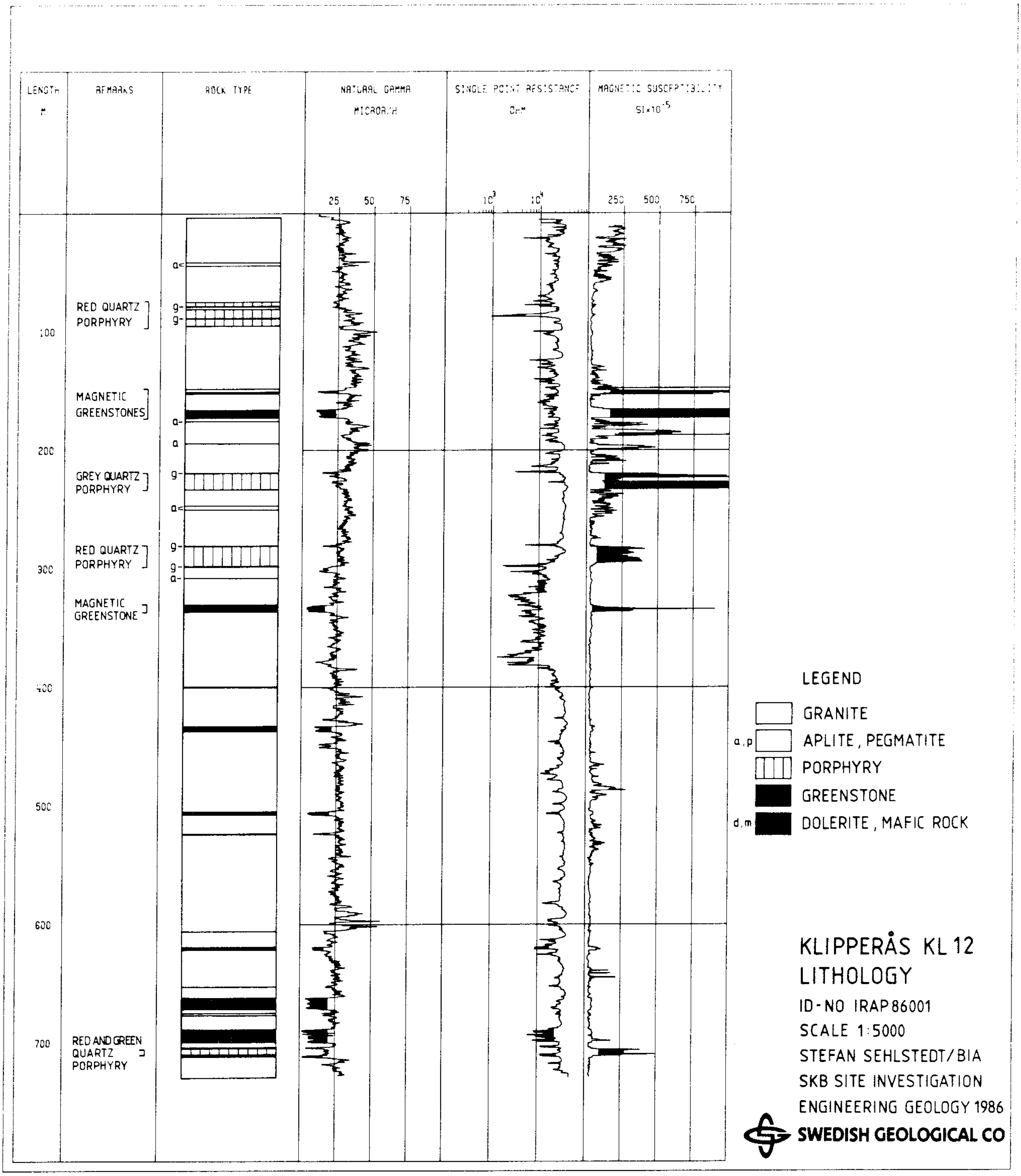


Figure 5.33 Geophysical logs sensitive to lithology variations, measured in borehole Kl 12.

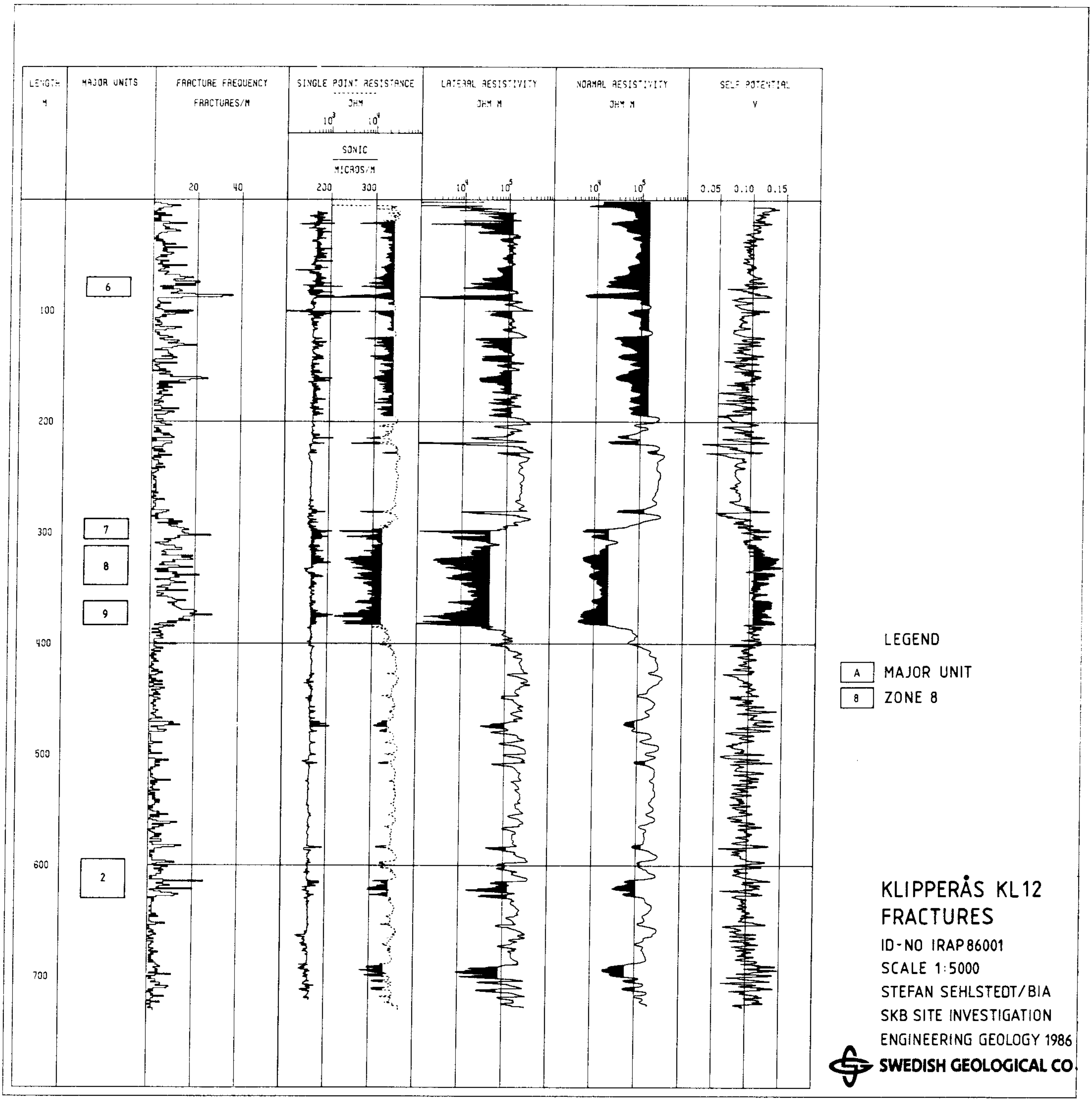


Figure 5.34 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 12.

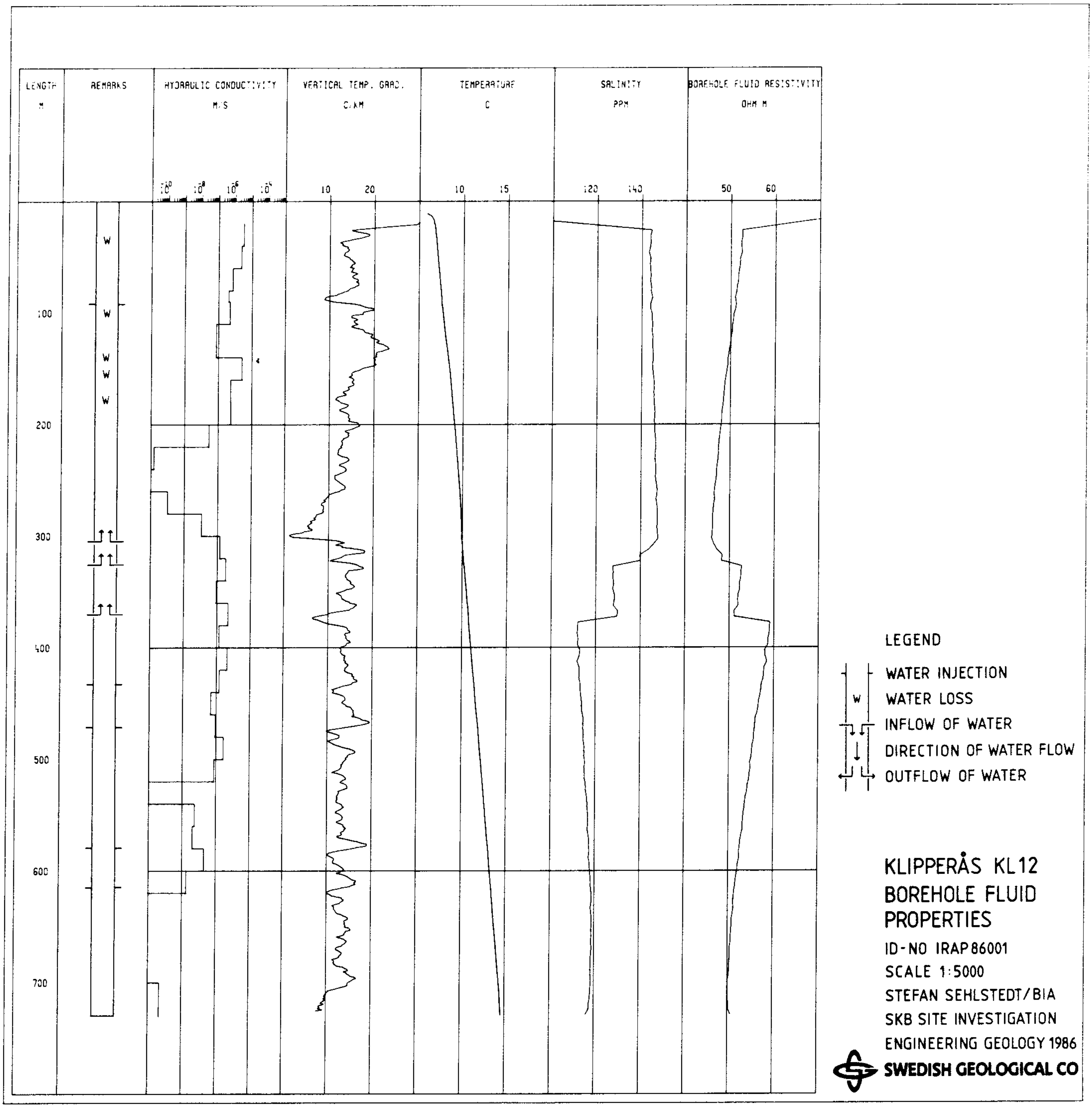


Figure 5.35 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 12.

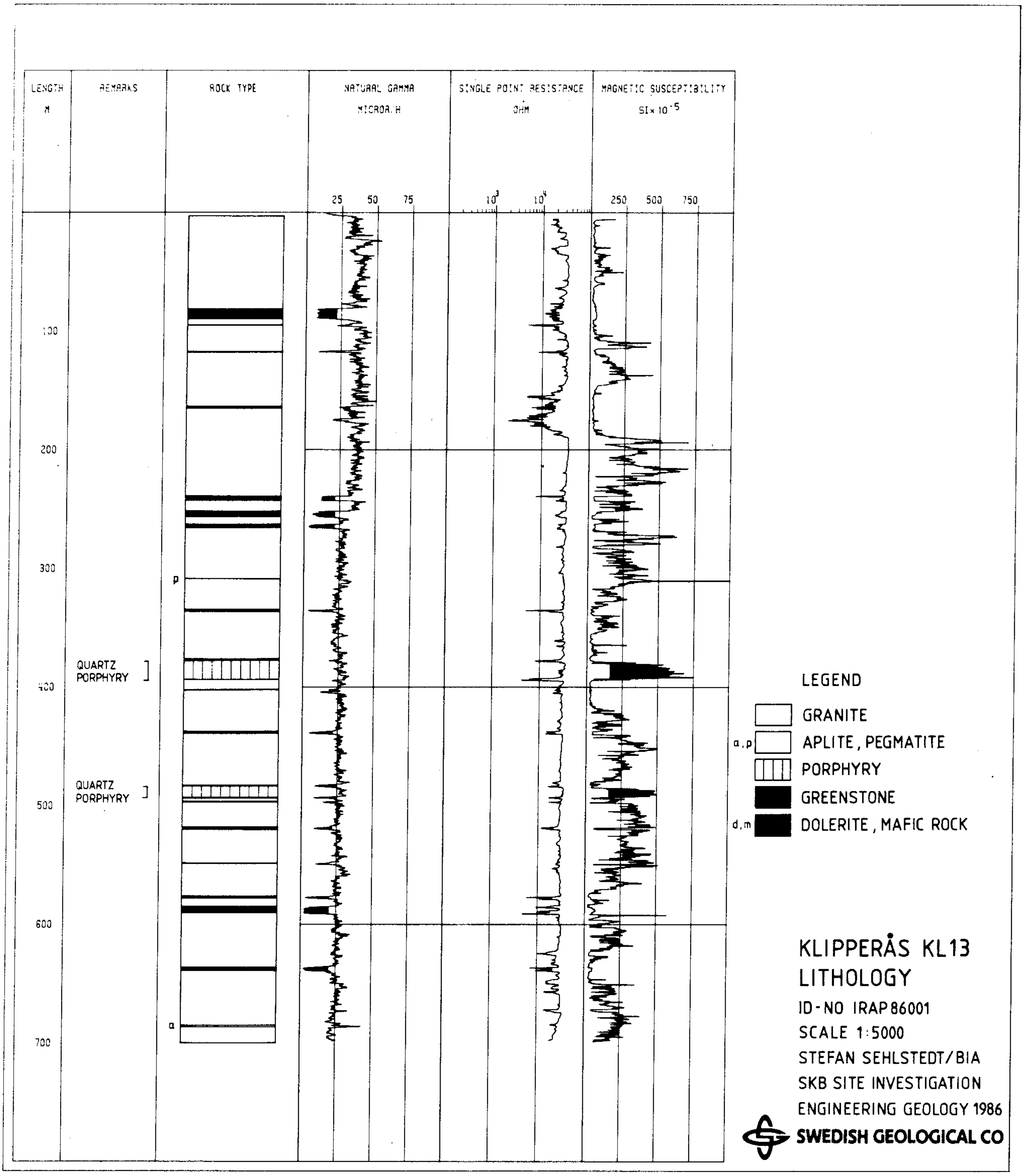


Figure 5.36 Geophysical logs sensitive to lithology variations, measured in borehole Kl 13.

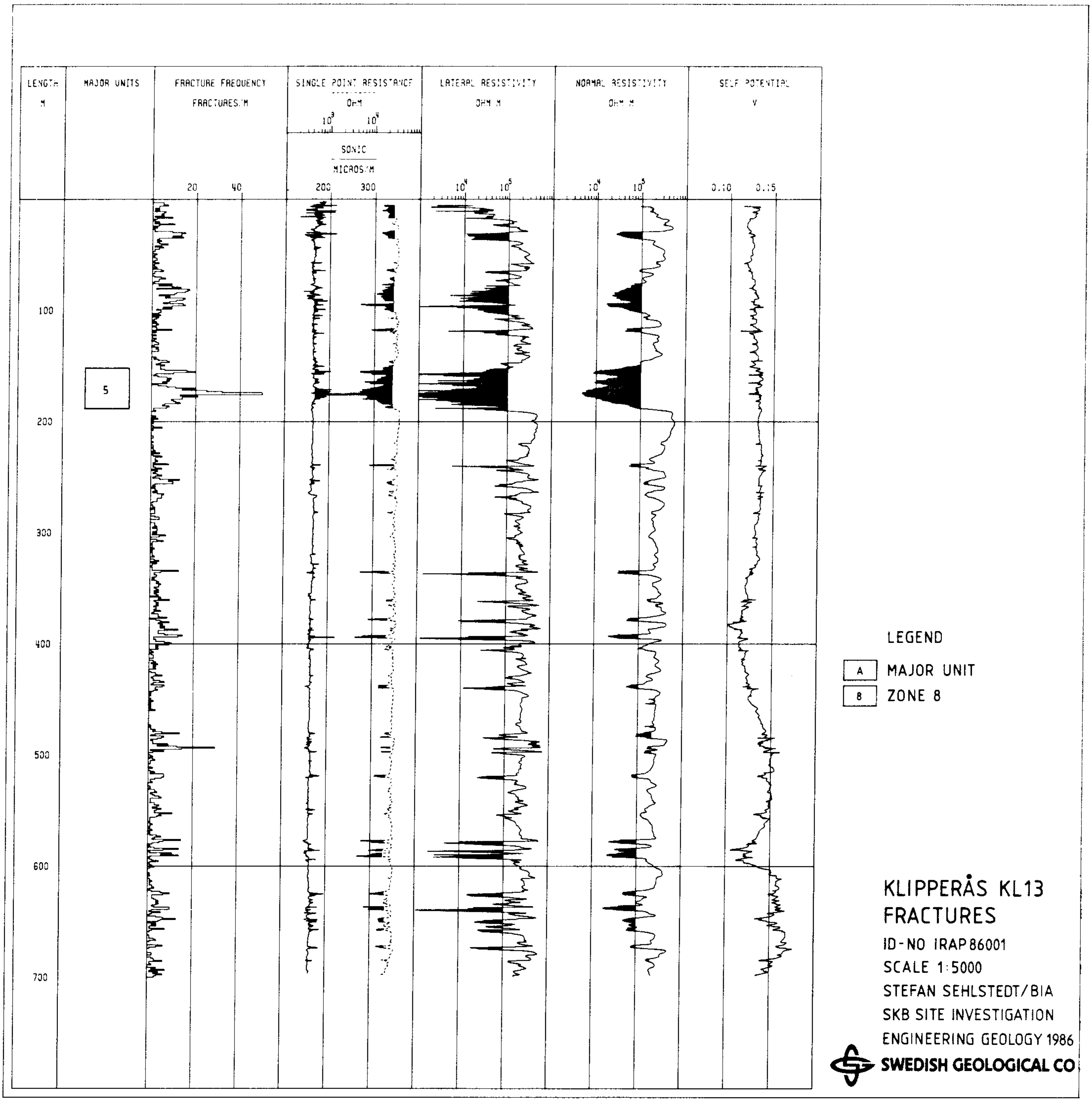


Figure 5.37 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 13.

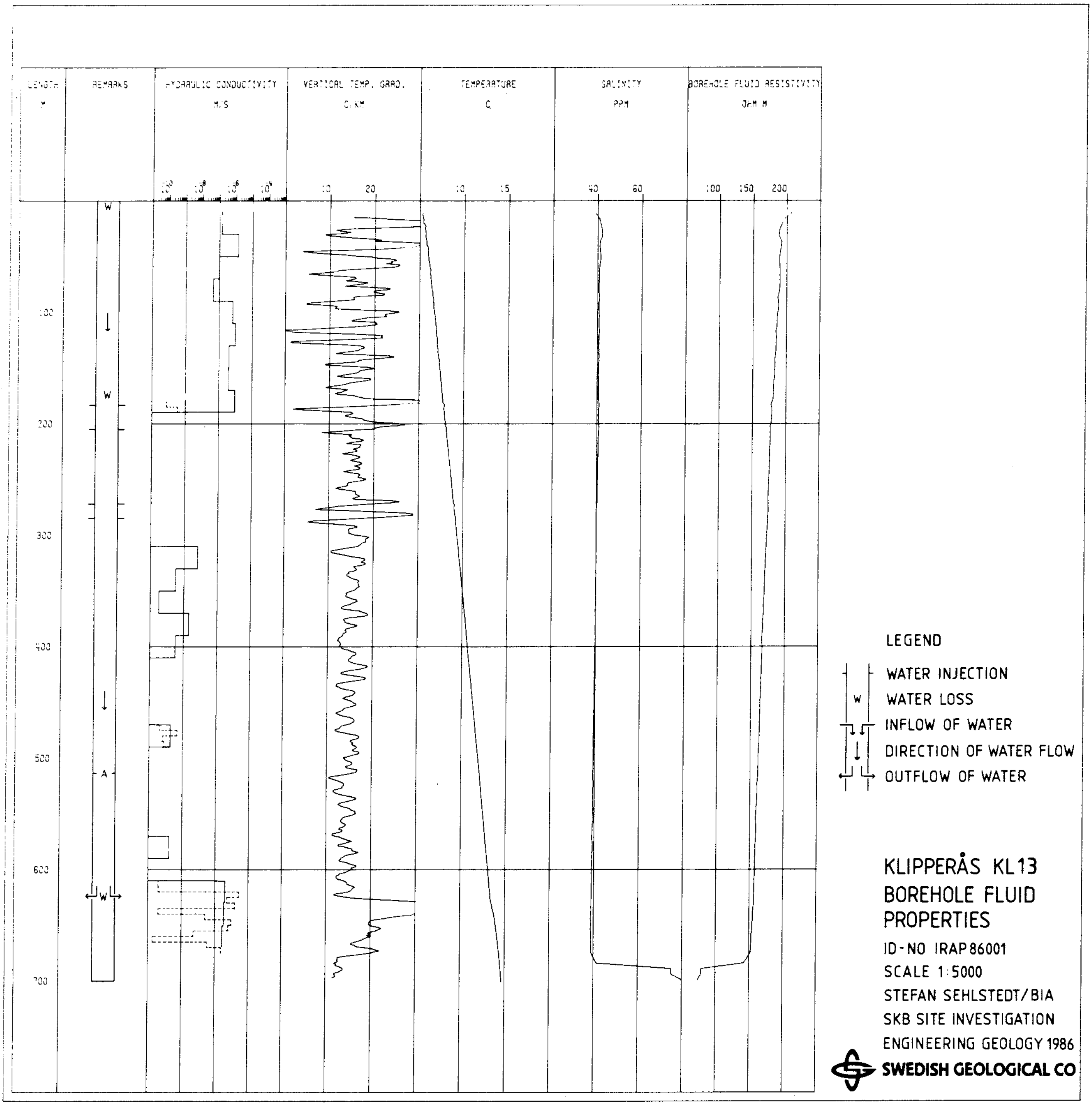


Figure 5.38 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 13.

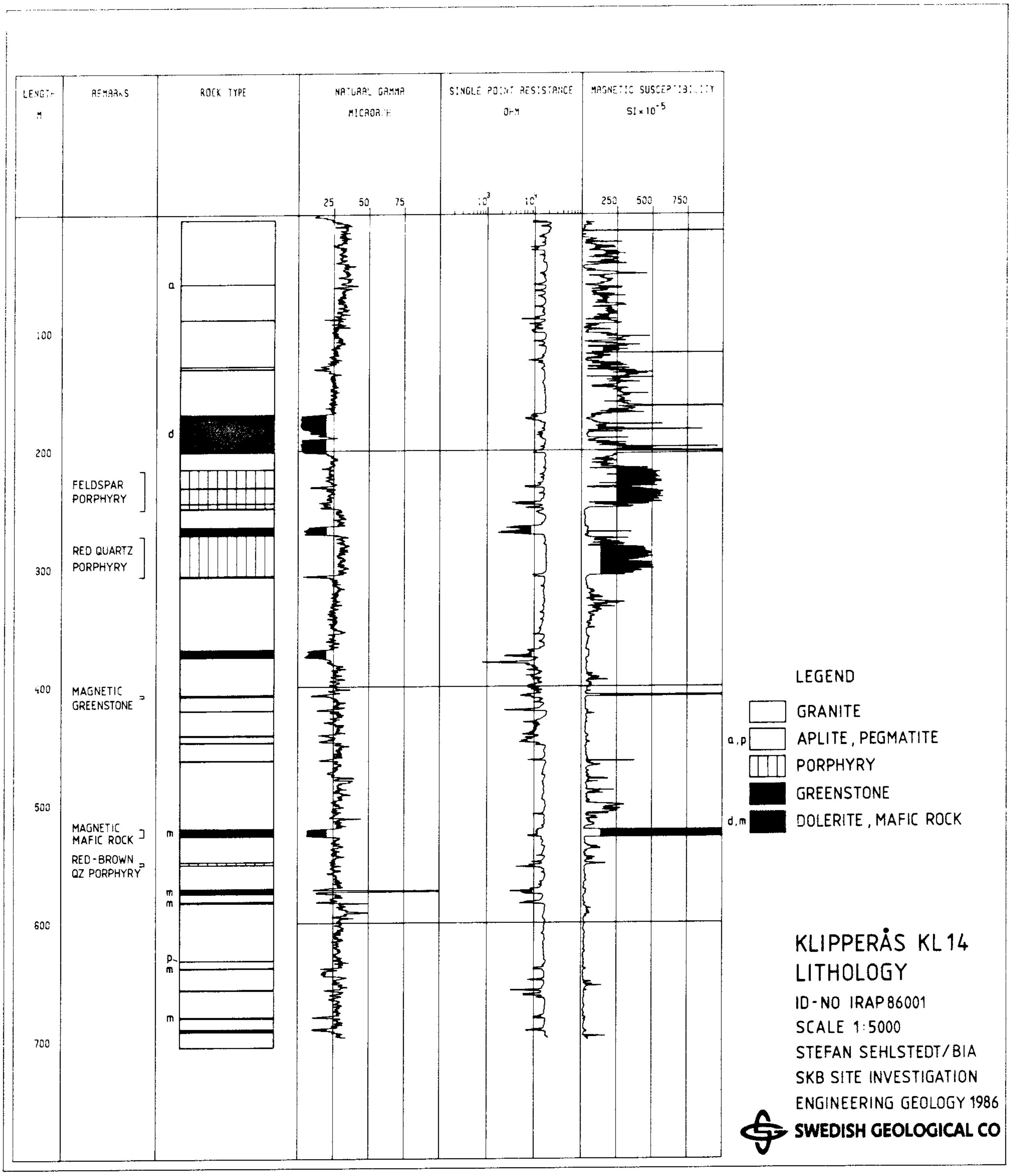


Figure 5.39 Geophysical logs sensitive to lithology variations, measured in borehole Kl 14.

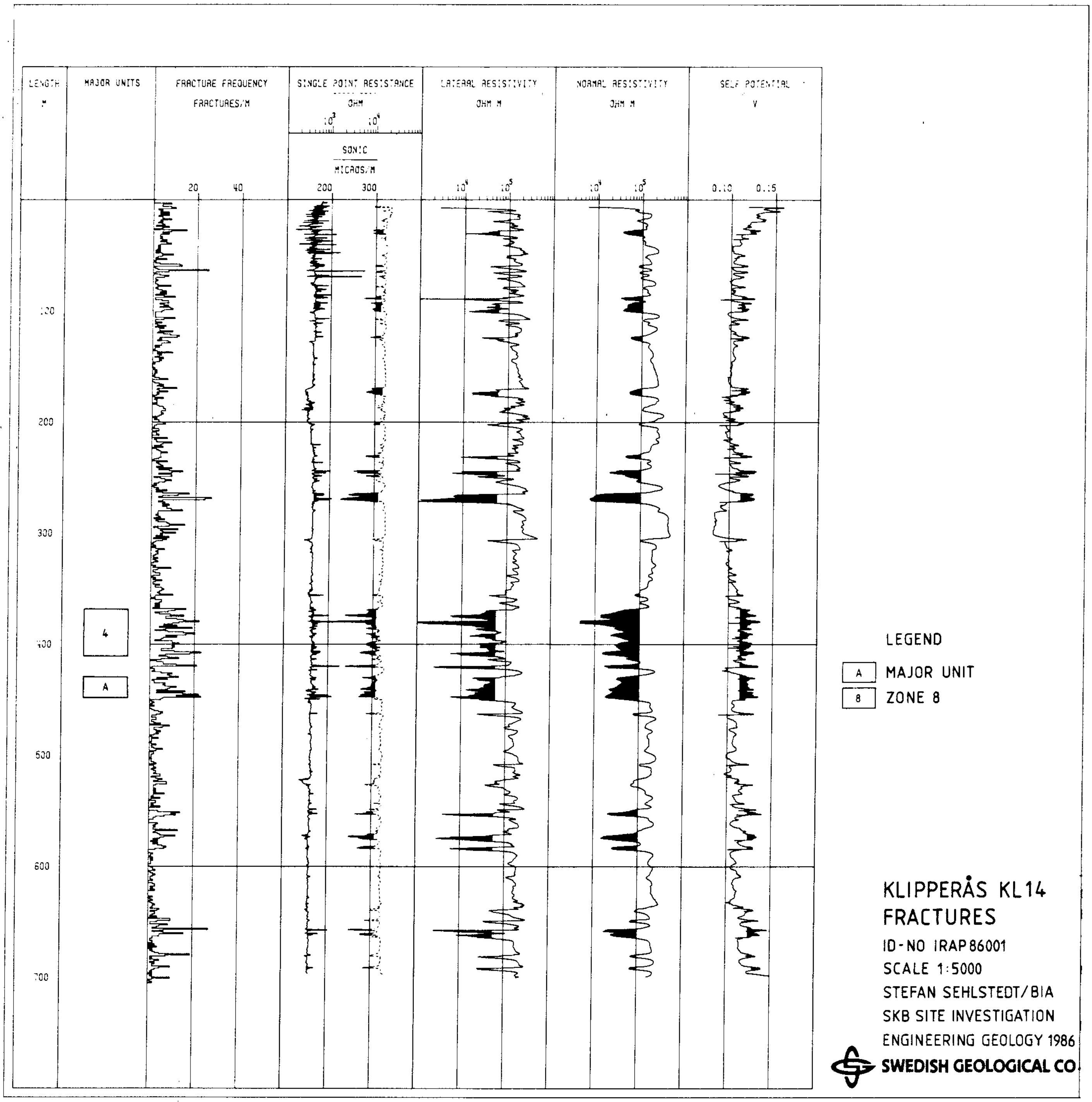
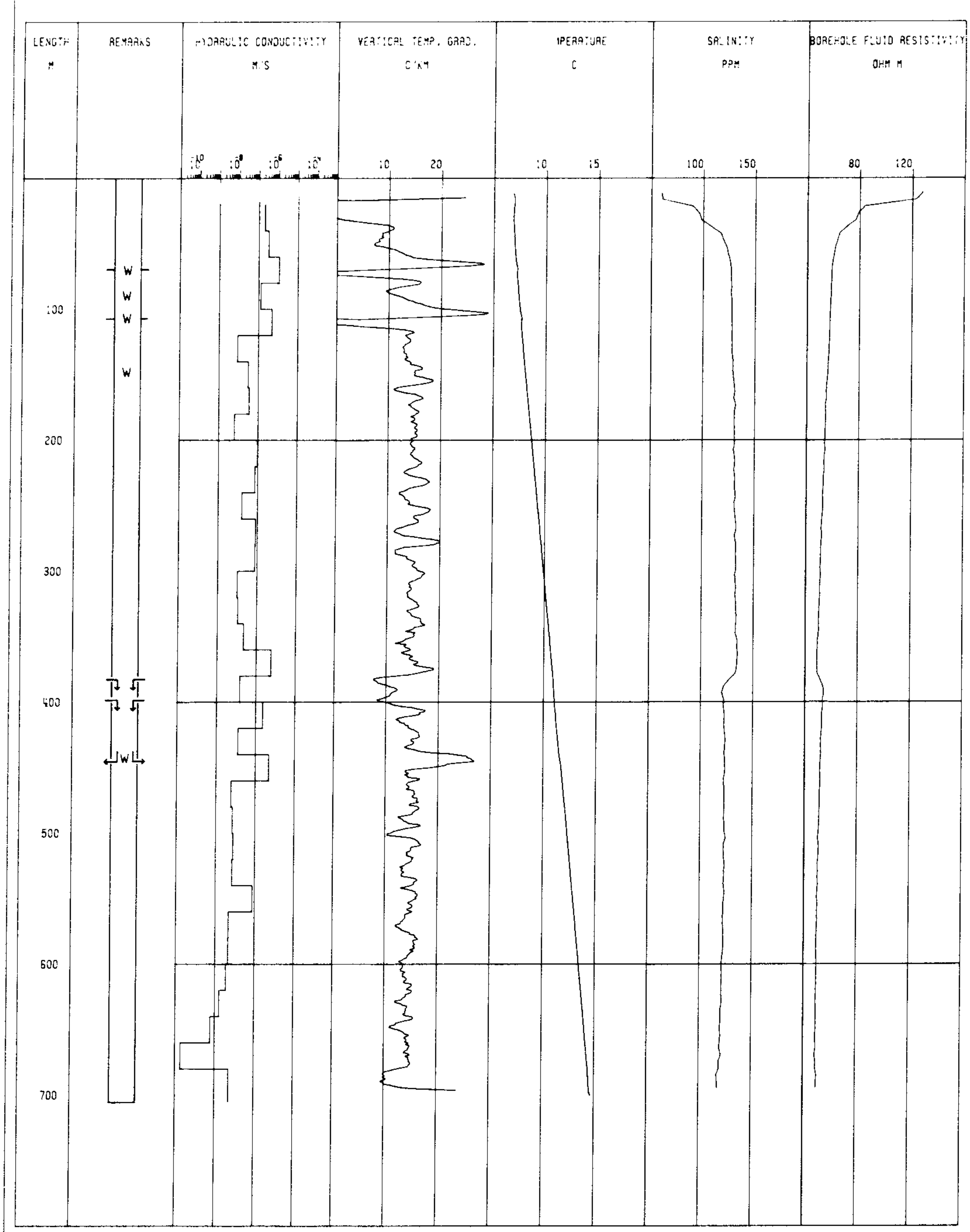


Figure 5.40 Geophysical logs sensitive to fracture occurrences, measured in borehole Kl 14.



LEGEND

WATER INJECTION
W WATER LOSS
INFLOW OF WATER
DIRECTION OF WATER FLOW
OUTFLOW OF WATER

KLIPPERÅS KL14
BOREHOLE FLUID
PROPERTIES
ID-NO IRAP86001
SCALE 1:5000
STEFAN SEHLSTEDT/BIA
SKB SITE INVESTIGATION
ENGINEERING GEOLOGY 1986
SWEDISH GEOLOGICAL CO

Figure 5.41 Borehole fluid and hydraulically sensitive logs measured in borehole Kl 14.

5.3 Physical properties of the rock types

The extensive borehole logging campaign at the Klipperås study site gives good knowledge on the physical properties of the different rock types in the area. However, logging methods sensitive to fractures often will be influenced by the lithology. Some general conclusions are compiled below. The resistivity levels mentioned below are only approximate.

A fresh granite either unfractured or with only a few fractures is characterized by the following properties;

- high apparent resistivity (normal) - about 200 000 ohm-m.
- stable sonic travel time - 160 micro secs/m (6250 m/s)
- variable magnetic susceptibility

When the granite is fractured, mylonitized, brecciated or altered the susceptibility falls to very low values. Simultaneously the resistivity drops and the sonic begins to fluctuate.

At the Klipperås study site it has been simple to distinguish mafic rock types from other rock types by gamma logging. This can be done so long as the mafic sections are sufficiently wide, i.e. about 0.5- 1 metres thick.

Fresh greenstone or other mafic rock, either unfractured or with only a few fractures, are characterized by the following properties;

- apparent resistivity (normal) lower than the granite - about 60 000 ohm-m
- low sonic travel time - 140 micro secs/m (7140 m/s)
- low gamma radiation

When these rock types are fractured, the resistivity quickly decreases and the sonic travel time increases. The resistivity of fractured granite and unfractured greenstone is approximately the same.

In general, the greenstones are nonmagnetic. However, some of the greenstones have a high magnetic susceptibility. The dolerites and mafic or ultramafic dykes encountered have, in general, a high magnetic susceptibility.

Porphyry sections generally have high resistivity, greater than 200 000 ohm-m, whether they are fractured or not. Some of these sections can be separated from granite due to a higher or lower natural gamma radiation. The porphyries encountered have, in general, a very high and stable magnetic susceptibility. In some cases, where alteration or mylonitization have occured, the porphyries have lost their magnetization.

5.4 Description of logging results obtained from the percussion boreholes

To provide information on the lithologic character in the percussion boreholes, logging was performed according to the the following program;

- natural gamma radiation
- single point resistance
- magnetic susceptibility

The percussion boreholes have a diameter of 110 mm (4 inches). The sondes are the same as those used in the cored boreholes. No correction for the borehole diameter has been performed on the logs. This gives smoother logs and weaker anomalies than in the 56 mm boreholes.

Due to the collapse of the boreholes Hkl 4 and Hkl 5, data is missing from Hkl 4 and no data is available from Hkl 5.

The results are presented in Figures 5.42-5.43 on a scale of 1:5 000. Brief comments concerning the lithology in each borehole are presented below.

All metre values refer to borehole length, and not to vertical depth.

5.4.1 Percussion borehole Hkl 1

One section, 32-40 metres, is distinctly indicated by the gamma log as a mafic rock type, probably a greenstone. Within this section there is a high positive gamma peak probably caused by an enrichment of radioactive elements, i.e. uranium.

5.4.2 Percussion borehole Hkl 2

Only one thin mafic section is indicated, in the upper part of the borehole. The remaining intersected bedrock is probably granite.

5.4.3 Percussion borehole Hkl 3

Logging results in Hkl 3 shows a porphyry section, 25-57 m, indicated by high gamma values and high resistance. This section is surrounded by two greenstones. At 85 m another mafic rock section begins. The lower contact is not registered. All mafic sections are indicated both on the gamma log and on the resistance log.

5.4.4 Percussion borehole Hkl 4

Due to collapse of the borehole very little information was obtained.

5.4.5 Percussion borehole Hkl 5

Due to collapse of the hole no information is available.

5.4.6 Percussion borehole Hkl 6

Some low gamma indications with low contact resistance correspond to mafic rock sections, probably greenstone.

5.4.7 Percussion borehole Hkl 7

Only thin mafic sections are indicated by the gamma log. The 35-55 metres section, with low magnetic and resistance properties, corresponds to higher fracture frequency.

5.4.8 Percussion borehole Hkl 8

Several minor mafic sections are indicated by the gamma log.

5.4.9 Percussion borehole Hkl 9

A typical greenstone, 33-37 metres, is indicated by low gamma and resistance values and a minor positive susceptibility indication. Within the section, a positive gamma indication corresponds to an enrichment of radioactive minerals in fractures. A similar peak is found further down the hole.

5.4.10 Percussion borehole Hkl 10

A dolerite dyke, 100-127 metres, also intersected by Kl 9 is indicated by all logging methods. The susceptibility and resistivity anomalies are of smaller magnitude than in Kl 9, due to the larger borehole diameter.

5.4.11 Percussion borehole Hkl 11

This percussion borehole probably intersects granite only.

5.4.12 Percussion borehole Hkl 12

Two mafic rock sections, probably greenstones, are indicated by the gamma log.

5.4.13 Percussion borehole Hkl 13

Two mafic rock sections, probably greenstones, are indicated mainly on the gamma log.

5.4.14 Percussion borehole Hkl 14

The combination of positive susceptibility and gamma radiation along with high resistance indicates a porphyry section at 88-98 metres.

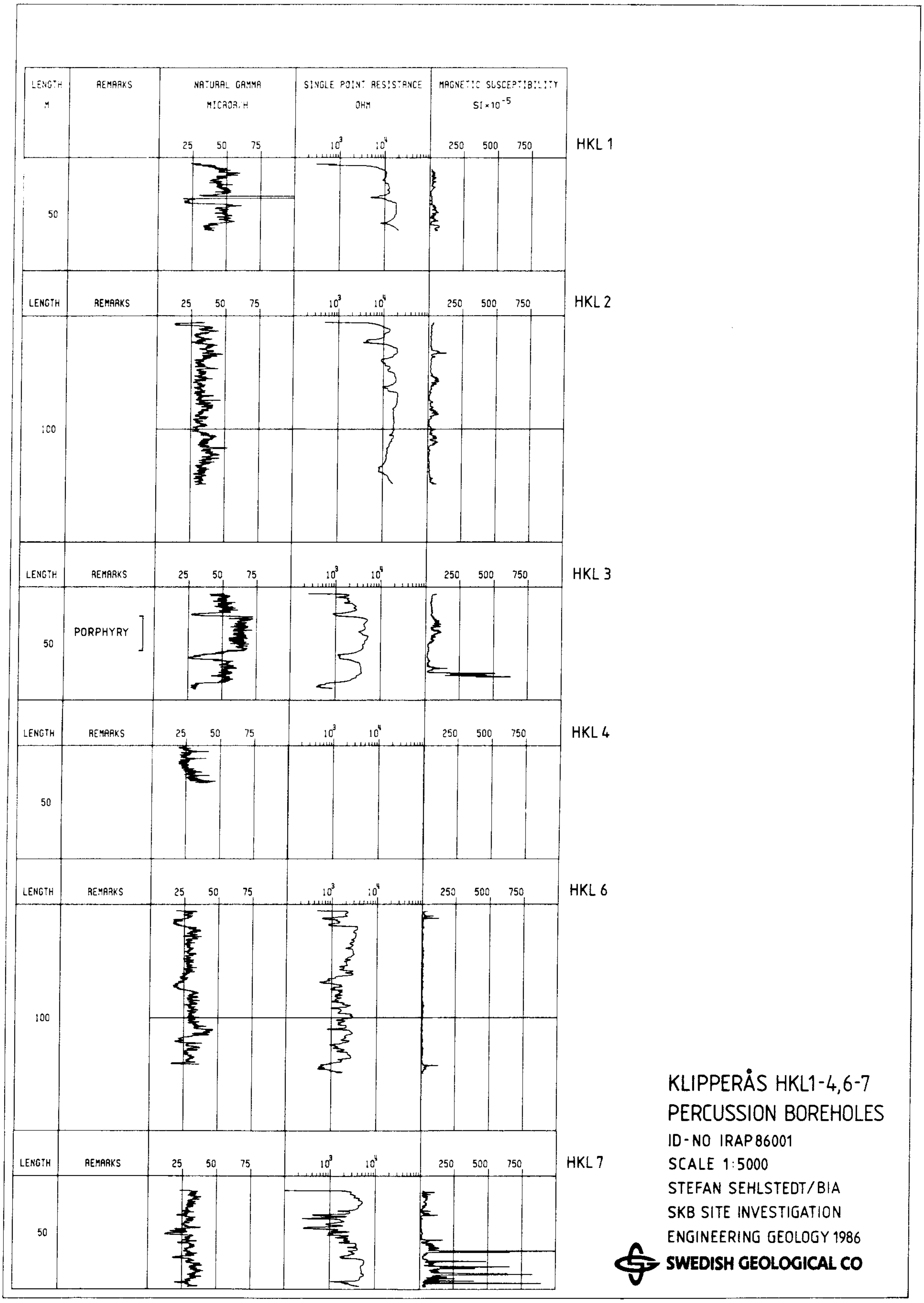


Figure 5.42 Borehole logging in the percussion boreholes Hkl 1-4, 6-7.

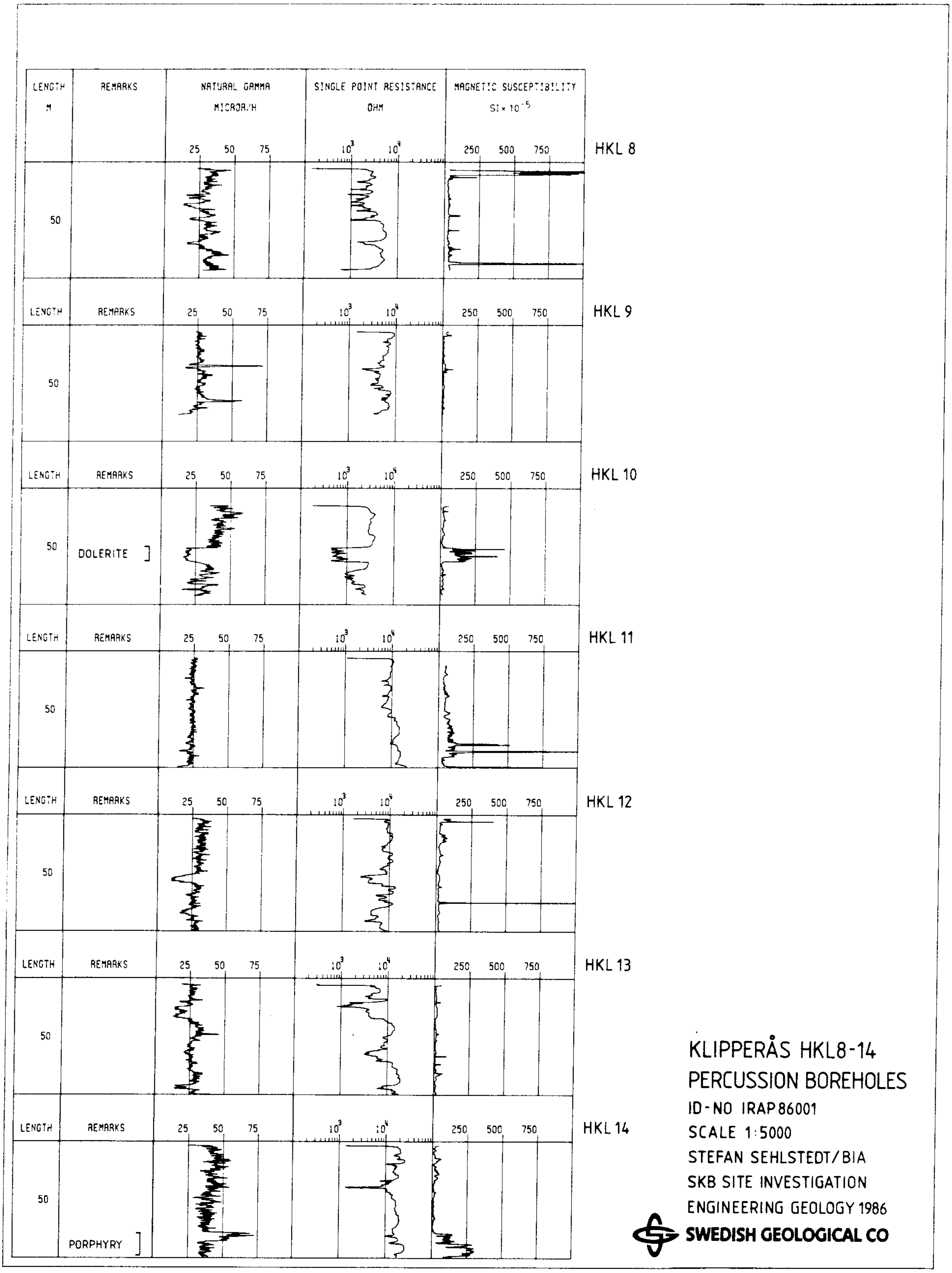


Figure 5.43 Borehole logging in the percussion boreholes Hkl 8-14.

6 FINAL RESULTS FROM GEOPHYSICAL MEASUREMENTS AT KLIPPERÅS

The very small number of outcrops and flat topography at the Klipperås study site make geophysical ground surface measurements the only possible way to obtain tectonic and geologic information from the bedrock surface. Combining these measurements with borehole logging and core logging (Olkiewicz and Stejskal, 1986), it is possible to obtain a three dimensional description of the fracture zones. This was the purpose of the investigation.

6.1 Fracture zones

To determine the strike of various fracture zones at surface, HLEM (slingram) measurements were used. From the detailed electromagnetic interpretation, Figure 4.3, a generalized fracture zone map was compiled, Figure 6.1. With this map, and by using geological core logging, geophysical borehole logging and trigonometric calculation, the dip of each zone was determined, Table 6.1. The dips of zones 2 and 6 should be classified as uncertain. If a fracture zone is strongly indicated at the surface it is usually recognized in a borehole by borehole logging, i.e. by resistivity methods.

Zone 1 is strongly indicated at the ground surface. This zone crosses the study site area. It has been intersected by three boreholes, Kl 3, Kl 4 and Kl 9, Table 6.1. The zone was identified in all boreholes by borehole logging and core logging. Trigonometric calculation gave a vertical zone dip in all three boreholes, which confirms the interpretation.

Zone 2 is weakly indicated at ground surface. It is parallel to zone 1 and crosses the study site area. It is believed to have the same dip as zone 1. If this is the case, the zone should be intersected by Kl 9 and Kl 12. Only weak anomalies are found in each borehole and the interpretation is rather uncertain. The interpreted zone sections give a dip that is vertical in Kl 9 and 85^{o}E in Kl 12.

Zone 3 is strongly indicated at ground surface. The zone is intersected only by Kl 7, but is strongly indicated by all logging methods and by an increased fracture frequency. The calculated dip in the intersected section is 65° E.

Zone 4 is strongly indicated at the surface and crosses the site area. The zone is intersected by Kl 11 and Kl 14. It is indicated distinctly by logging and by an increased fracture frequency in both boreholes. The dip is calculated to be vertical in Kl 11 and 80° S in Kl 14.

Zone 5 is shorter than the zones described earlier and is indicated distinctly at the surface. The zone is intersected only by Kl 13. It is indicated distinctly by resistivity logging in the borehole. The location in the borehole is confirmed by magnetic ground surface measurements and susceptibility logging. The dip is calculated to be 75° S.

Zone 6 is rather short and indicated distinctly. It is intersected by Kl 12. The zone is weakly indicated by logging and the interpretation is somewhat uncertain. The calculated dip is 75° S.

Zones 7, 8 and 9 are rather short and distinctly indicated at the surface. The three zones are intersected by Kl 12. From logging, these zones look like one wide, strongly indicated, fracture zone. To explain the surface indications and build an evaluation model, this wide section was devided into three zones. Zones 7 and 9 are almost parallel. They have nearly the same dip, 80° S and 75° S respectively. A vertical dip was calculated for zone 8.

Zone 10 is distinctly indicated at the surface. The zone is intersected by Kl 1. It is clearly indicated by borehole logging. The dip is calculated to be nearly vertical, 85° NW.

Zone H1 was encountered by borehole Kl 2 in the section between 792-804 m. This zone is interpreted as sub-horizontal. The surface investigation methods used are not likely to detect sub-horizontal fracture zones at some depth.

Table 6.1. Fracture zone data.

Zone number	Bore-hole	Zone section	Strike/dip	True width
1	Kl 3	140-195 m	N-S/90^o	28 m
1	Kl 4	110-180 m	N20^oE/90^o	36 m
1	Kl 9	615-665 m	N30^oE/90^o	29 m
2	Kl 9	120-160 m	N30^oE/90^o	22 m
2	Kl 12	595-630 m	N15^oE/85^oE	13 m
3	Kl 7	115-130 m	N35^oE/65^oE	12 m
4	Kl 11	108-148 m	N75^oE/90^o	23 m
4	Kl 14	368-410 m	N85^oE/80^o	27 m
5	Kl 13	152-188 m	N80^oW/75^oS	23 m
6	Kl 12	70- 88 m	N75^oW/75^oS	12.5 m
7	Kl 12	288-306 m	N65^oE/80^oS	13.5 m
8	Kl 12	312-347 m	N85^oW/90^o	28 m
9	Kl 12	362-384 m	N60^oE/75^oS	17.5 m
10	Kl 1	280-310 m	N45^oE/85^oNW	10.5 m
H1	Kl 2	792-804 m	Sub-Horizontal	12 m

6.2 Lithology

Some information concerning the rock types at the ground surface, i.e. 0-50 m depth, is availible from the magnetic ground surface measurements. These measurements show that the bedrock can be devided into different blocks with higher magnetic intensity and different patterns. Each block is surrounded by fracture zones. Within one of these blocks, a strike direction of WNW-ESE can be observed. Susceptibility logging and petrophysical measurements on core samples show that these patterns are caused mainly by magnetic porphyries and some magnetic greenstones. Whether this is caused by fragments or dykes of these rock types, can not be determined by the geophysical measurements made in the area. Borehole radar measurements may give an answer to these questions.

One specific dyke direction, N 25°E, is indicated by the magnetic ground surface measurements. Two dykes with this direction are indicated, and one of these was intersected by Kl 9. It was identified as a dolerite dyke (Olkiewicz and Stejskal, 1986).

A north-south trending mafic dyke was indicated by the electromagnetic (HLEM) method due to its lower resistivity compared with the surrounding granite. This dyke was also magnetic, but did not appear on the magnetic ground surface measurements. One explanation of this might be that the dyke has a remanent magnetization which is in opposite direction to the magnetization induced by the present magnetic field of the earth at this location.

6.3 Physical properties

According to the physical properties of the different rock types encountered within the Klipperås study site, some conclusions concerning the geophysical ground surface measurements can be examined:

- Fresh and unaltered granite should appear on the magnetic measurements within areas of medium to high magnetization, with an irregular pattern.

- Altered and fractured granite should appear within areas of low magnetization.

- Porphyries and magnetic greenstones should appear in areas with high magnetization, with banded or dyke like patterns.

- Dolerites and mafic dykes should appear as magnetic dykes, provided that they do not have a remanent magnetization, in the opposite direction to the present magnetic field. These dykes appear also on the electromagnetic measurements (HLEM) due to their lower resistivity compared with the granite.

- Major fracture zones should appear on the electromagnetic measurements (HLEM) due to their increased conductivity compared with the surrounding granite.

These fracture zones appear only on the imaginary component on the horizontal loop method (HLEM) at the freguency used (18 kHz) and with a coil separation of 60 m. A lower frequency gives an induction number in the fracture zones which is so small that the fracture zones will not be detected. A higher frequency gives less penetration depth and a conductive overburden obscures the measurements. However, an increased coil separation, to 100 m for example, will give a higher induction number within the fracture zones. At the same time, theoretically, the penetration depth will increase. However, poorer resolution of single fracture zones will be obtained.

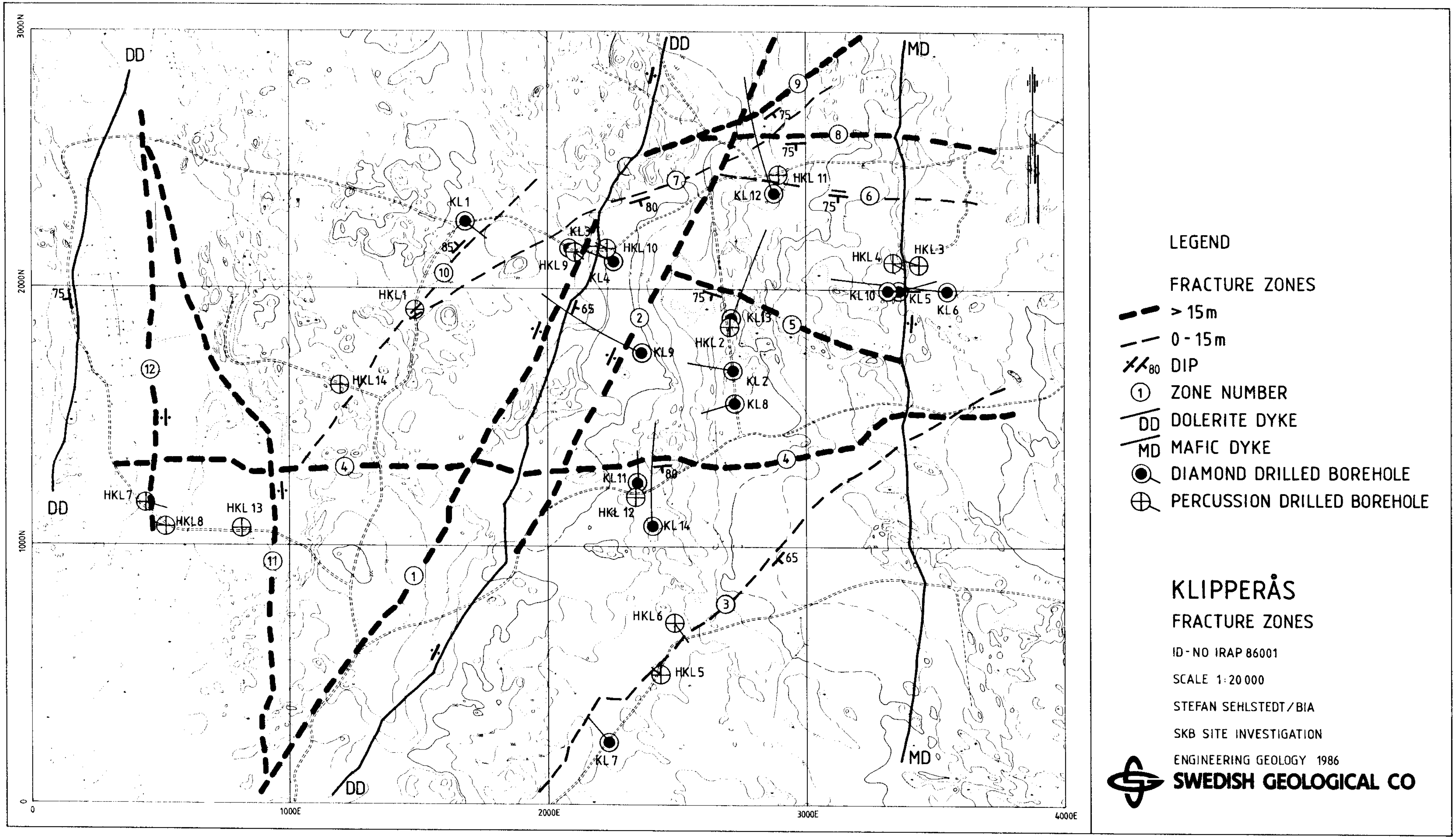


Figure 6.1 Fracture zones interpreted from ground surface geophysical measurements.

7 DISCUSSION

In the evaluation of the borehole data the results from the geological, geophysical and hydrological investigations in adjacent holes and from the surface measurements are correlated to build a three-dimensional model of the site. The orientation, extent and width of the fracture zones are inferred from the data. In some cases the data is ambiguous or incomplete, so that in some respects, the site model will not be reliable. In such a case complementary investigations should be made. The mise-a-la-masse method has been used with some success to find the extent and orientation of fracture zones (Jämtlid et. al., 1982).

However, a new borehole radar system has been designed as part of the Crosshole program of the International Stripa Project (Olsson, et. al., 1985a). Radar measurements have been used to identify fracture zones and to determine their position and orientation (Olsson, et. al., 1985b). By combining data from several boreholes in a step by step procedure, the orientation of fracture zones could be determined. In single boreholes, fractures could be observed more than a hundred metres from the borehole. In the borehole techniques currently used in the program, information on a relatively small volume around the borehole only (of the order of 1 m) was obtained.

Thus, a complementary program comprising borehole radar measurements are to be conducted within every borehole in the Klipperås study site. Several obscurities are still to be resolved. Some of these are the following;

- In some cases, high hydraulic conductivity values have been obtained in the rock mass at locations not identified as fracture zones. In such cases, it is possible that borehole radar measurements would identify the extent and character of these sections.

- The orientation and extent of some of the fracture zones are still uncertain.

- A general problem is the orientation of greenstones and porphyries. The boreholes Kl 1, Kl 6 and Kl 9 are orientated approximately parallel to the estimated strike direction, while boreholes Kl 12, Kl 13 and Kl 14 are orientated approximately perpendicular to this direction.

- The orientation and extent of fracture zone H1 encountered between 792-804 m in borehole Kl 2. This fracture zone is hydraulically conductive and appears distinctly on the geophysical logs. Cores from this section are missing. A greenstone sample from this location has a porosity of 19 % (Stenberg, 1986).

- It is possible that the porpyries encountered at the bottom of borehole Kl 1 are identical to the porphyries encountered at the bottom of Kl 9.

- The orientation and extent of the dolerite encountered between 78-92 m in Kl 4 and between 356-374 m in Kl 9.

- A greenstone has been encountered between 219-300 m in borehole Kl 6. This greenstone has not been detected in the adjacent borehole Kl 5. The greenstone can either be a thin dyke orientated almost parallel to the borehole extension, or an isolated fragment within the granite.

- In the same borehole, Kl 6, two porphyries are encountered between 450-520 m and between 700-747 m. It is possible that it is the same porphyry encountered at both sections. If the orientation of this porphyry is almost parallel to the borehole extension, then it is possible that the borehole penetrates the porphyry at two locations due to the deviation of the borehole itself.

- The orientation and extent of a significant geophysical indication between 92-96 m in borehole Kl 8. The correlation between this indication and a geophysical anomaly obtained on the surface measurements (HLEM) are to be examined. It is also possible that there is a connection with fracture zone H1 encountered in borehole Kl 2.

- The orientation and character of a prominent resistivity anomaly occuring within a porphyry at the borehole length of 764-776 m in Kl 9. The section is strongly mylonitized and contains large quantities of sulphides, i.e. pyrite.

- The orientation and extent of the mafic dyke encountered between 12-29 m in Kl 5, 88-100 m in Kl 10, and between 338-371 m in Kl 6.

- The occurrence of almost horizontal waterbearing single fractures within the rock mass.

Information from borehole radar measurements should make it possible to examine the extent and nature of many of these features. A valuable contribution to the evaluation of the geological, geophysical and hydrogeological conditions at the Klipperås study site is to be obtained with the borehole radar measurements.

The geophysical investigations give valuable data for the geological and hydrological characterization of a site. The geophysical logging techniques are normally useful in defining the fracture zones and different lithological units. In a detailed study by Magnusson and Duran (1984), a good correlation between fracture frequency and resistivity has been found. However, there was hardly any correlation between resistivity and the hydraulic conductivity. The logs which give the best hydraulic information are actually the temperature and the salinity logs.

However, the Tube Wave method proved to be an effective method for detection of permeable fracture zones in a borehole (Huang and Hunter, 1984). Within the Klipperås study site, the Tube Wave method, has been performed in borehole Kl 2 (Stenberg and Olsson, 1985). The result from this measurement shows that there is a very good correlation between tube wave sources and sections with increased hydraulic conductivity. For example, the main fractured section (zone H1) between 792-804 m, which has a high hydraulic conductivity, generates strong tube waves. Another significant tube wave source is the section 618-624 m, just below a greenstone. Several significant spike-like sonic and single point resistance anomalies correlates well with this tube wave source.

8 CONCLUSIONS

The geophysical program employed within the Klipperås study site has also been performed at several other sites in granitic and gneissic rocks in Sweden. In the case of a thin, resistive overburden the surface investigation program proved to be effective in the detection of the dipping fracture zones. The methods used are not likely to detect sub-horizontal fracture zones, at least not those at some depth.

In investigations of this type, there is a need for obtaining data on the properties of the bedrock and the fracture zones at considerable distances from the borehole. A valuable contribution to the evaluation of the geological, geophysical and hydrological data will be obtained from the borehole radar technique, e.g. the orientation, extent and width of fracture zones.

In summary, the investigation shows that ground surface geophysical measurements and borehole logging is a powerful combination for identification tectonic features, i.e. fracture zones, if the physical conditions are favourable. Magnetic bedrock, a rather thin overburden, small quantities of clay in the overburden and distinct fracture zones are examples of such favourable physical conditions.

REFERENCES

Ahlbom K., Carlsson L., Olsson O., 1983.
Final disposal of spent nuclear fuel - geological, hydrogeological and geophysical methods for site characterization. Technical Report 83-43.
KBS, Stockholm.

Almen K-E., Hansson K., Johansson B-E., Nilsson G., Andersson O., Wikberg P., Åhagen H., 1983.
Final Disposal of Spent Fuel. Equipment for Site Characterization. Technical Report 83-44.
KBS, Stockholm.

Archie G.E., 1942.
The electrical resistivity log as an aid in determining some reservoir characteristics.
Trans. A.I.M.E. Vol. 146, 54-62.

Brotzen O., Magnusson K-Å., Duran O., 1980.
Evaluation of geophysical drill hole studies.
Prav. report No. 4.14. Stockholm.

Carlsten C., Magnusson K.Å., Olsson O., 1985.
Crosshole investigations - description of the small scale site. Stripa project. Internal report 85-05.
KBS, Stockholm.

Davidson C.C., Keys W.S. and Paillet F.L., 1982.
Use of Borehole-Geophysical and Hydrological Tests to Characterize Crystalline Rock for Nuclear-Waste Storage, Whitshell Nuclear Research Estabilshment, Manitoba, and Chalk River Laboratory, Ontario, Canada.
ONWI-418, prepared jointly by Atomic Energy Canada Limited and the U.S. Geological Survey for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH, December.

Drury M.J., 1982.
Drill hole temperature logging for the detection of water flow. In "Geophysical investigation in connection with geological disposal of radioactive waste."
OECD/NEA, Ottawa.

Drury M.J., 1984.
Borehole temperature logging for detection of water flow.
Geoexploration. Vol. 22, pp. 231-243.

Duran O., Magnusson, K-Å., 1984.
Comparative study of geological, hydrological and geophysical borehole investigations.
Technical report 84-09, KBS, Stockholm.

Gentzschein B., 1986.
Hydrogeological investigations at the Klipperås study site. Swedish Geological Co.
Technical report 86-08, SKB, Stockholm.

Henkel H., Guzman M., 1977.
Magnetic features of fracture zones.
Geoexploration, Vol. 15, pp. 173-181.

Henkel H., 1979. Dislocation sets in northern Sweden.
Geologiska föreningen i Stockholm förhandlingar,
Vol. 100, pp. 271-278.

Huang, C.F., Hunter, J.A., 1984.
The Tube-wave method of estimating in-situ rock fracture permeability in fluid-filled boreholes.
Geoexploration, Vol. 22, pp. 245-249.

Jaeger J.C., 1961.
The effect of drilling fluid on temperatures measured in drill holes.
Journal of Geophysical Research, Vol. 66, 563-569.

Jämtlid A., Magnusson K-Å., Olsson O., Stenberg L., 1984.
Electrical borehole measurements for the mapping of fracture zones in crystalline rock.
Geoexploration, Vol. 22, pp. 203-216.

Magnusson K-Å., Duran O., 1984.
Comparison between core log and hydraulic and geophysical measurements in boreholes.
Geoexploration, Vol. 22, pp. 169-186.

McNeill J.D., 1980.
Electrical conductivity of soils and rocks.
Geonics Ltd., Technical note TN-5, Mississauga, Ontario, Canada.

Nair M.R., Biswas S.K., Mazumdar K., 1968.
Experimental studies on the electromagnetic response of tilted conductivity half-planes to a horizontal-loop prospecting system.
Geoexploration, Vol. 6, pp 207-244.

Nelson P.H., Magnusson, K-Å., Rachiele R., 1982.
Application of borehole geophysics at an experimental waste storage site.
Geophysical Prospecting, Vol 30, 910-934.

Norton D., Knapp R., 1977.
Transport phenomena in hydrothermal systems: the nature of porosity.
American Journal of Science, Vol. 277.

Olkiewicz A., Stejskal V., 1986.
Geological and tectonic description of the Klipperås study site. Swedish Geological Co.
Technical report 86-06, SKB, Stockholm.

Olsson O., Jämtlid A., 1984.
Hydrogeological and hydrogeochemical investigations - geophysical borehole measurements.
Stripa project. Internal report 84-03. KBS Stockholm.

Olsson O., Duran O., Jämtlid A., Stenberg L., 1984.
Geophysical investigations in Sweden for the characterization of a site for radioactive waste disposal - an overview.
Geoexploration, Vol. 22, pp. 187-201.

Olsson O., Forslund O., Lundmark L., Sandberg E., Falk L., 1985a.
The design of a borehole radar system for detection of fracture zones. NEA symposium on In Situ Experiments in Granite Associated with the Disposal of Radioactive Waste, Stockholm.

Olsson O., Falk L., Sandberg E., Carlsten S., Magnusson K-Å., 1985b.
Results from borehole radar reflection measurements. NEA symposium on In Situ Experiments in Granite Associated with the Disposal of Radioactive Waste, Stockholm.

Parasnis D.S., 1979.
Principles of Applied Geophysics.
Chapman and Hall, London.

Poikonen A., 1983.
Suitability of certain borehole geophysical methods for structural and hydrogeological studies of Finnish bedrock in connection with disposal of nuclear waste. Technical Research Centre of Finland. Geotechnical Laboratory. Report YJT-83-06.

Stenberg L., Olsson O., 1985.
The Tube Wave method for identifying permeable fracture zones intersecting a borehole. Swedish Geological. SKB AR 85-14, Stockholm.

Stenberg L., 1986.
Geophysical laboratory investigations on core samples from the Klipperås study site. Swedish Geological Co. Technical report 86-09, SKB, Stockholm.

Telford W.M., Geldart L.P., Sheriff R.E., Keys D.A., 1976.
Applied Geophysics.
Cambridge University, Cambridge.

Thoregren U., 1982.
Final Disposal of Spent Fuel - Standard Program for Site Investigations. Swedish Geological Co.
Technical report 83-31, KBS, Stockholm.

Tullborg E-L., 1986.
Fissure fillings from the Klipperås study site.
Swedish Geological Co.
Technical report 86-10, SKB, Stockholm.

West F.G., Kintyinger P.R. and Laughlin A.W., 1975.
Geophysical Logging in Los Alamos Laboratory, Geothermal Test Hole no. 2.
UC-66, LA-6112-MS, prepared by Los Alamos Scientific Laboratory for U.S. Energy Research and Development, Washington, DC, November.

Öqvist U., 1981.
Measurement of electrical properties of rocks and its application to geophysical investigations of ores and of waste disposal.
Royal Institute of Technology, KTH, Stockholm.

List of SKB reports

Annual Reports

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

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

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

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

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

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

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

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

Technical Reports

1986

TR 86-01
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February 1986

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Chalmers University of Technology, Gothenburg, Sweden
B Allard
University of Linköping, Sweden
March 26, 1986

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April 1, 1986

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Risö National Laboratory, Roskilde, Denmark
March 1986

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Kaj Ahlbom, Peter Andersson, Lennart Ekman, Erik Gustafsson, John Smellie,
Swedish Geological Co, Uppsala
Eva-Lena Tullborg, Swedish Geological Co, Göteborg
February 1986

TR 86-06

Geological and tectonical description of the Klipperås study site

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