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Comparative study of geological, hydrological and geophysical borehole investigations

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Uppsala September 1984

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This report concerns a study which was conducted for SKBF/KBS. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

A list of other reports published in this series during 1984 is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28) and 1983 (TR 83-77) is available through SKBF/KBS.

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APPENDIX A

ABSTRACT

The understanding of the permeability of the bedrock can be improved by supplementing the results of the water injection tests with information from core mapping, TV-inspection and borehole geophysics. The comparision between different borehole investigations encompasses core mapping, TV-inspection and various geophysical borehole measurements. The study includes data from two different study areas, namely Kråkemåla and Finnsjön. In these two areas have extensive geological, hydrological and geophysical investigations been carried out.

The fractures and microfractures in crystalline rock constitute the main transport paths for both groundwater and electric currents. They will therefore govern both the permeability and the resistivity of the rock. In order to get a better understanding of the influence of fractures on permeability and resistivity, a detailed comparison has been made between the hydraulic conductivity and resistivity, respectively, and the character of fractures in the core and the borehole wall.

The fractures show very large variations in hydraulic conductivity. Microfractures and most of the thin fractures have no measurable hydraulic conductivity (in this case $< 2 \times 10^{-9}$ $m\ s^{-1}$), while test sections which contain a single isolated fracture can have no measurable to rather high hydraulic conductivities ($> 10^{-7}$ $m\ s^{-1}$). Wide fracture zones often have hydraulic conductivities which vary from very low (less than 2×10^{-9} $m\ s^{-1}$) to high values (10^{-5} $m\ s^{-1}$). This indicates that the hydraulic conductivity is governed by a few discrete fractures.

The resistivity shows a continous variation in the range 1,000-100,000 ohm-m and a relatively poor correlation with hydraulic conductivities. The observed difference is considered to be the effect of restriction of water flow on a few channels, while electric surface condition, i.e. current transport through thin water films, makes current transport possible through fractures with very small aperatures.

1. INTRODUCTION

Swedish Geological AB (SGAB) has carried out a number of different borehole investigations in different study areas (Fig. 1:1). The borehole investigations have included core mapping, TV inspection, water injection tests and various geophysical borehole measurements such as resistivity, point resistance (including differential point resistance), SP, IP, VLF, natural gamma radiation and measurement of the temperature, resistivity, Eh and pH of the borehole liquid.

The purpose of the study is to improve our understanding of the permeability (hydraulic conductivity) of the bedrock by supplementing the results of water injection tests with information obtained from core mapping and borehole geophysics. Taken together, the supplementary information obtained from the different measurement methods will furnish additional and more comprehensive knowledge concerning the physical properties of the bedrock, which improves evaluation and interpretation of the results obtained.

An evaluation of the geophysical borehole logging methods has already been presented in PRAV Report No. 4.14 (Brotzen et al 1980), where the usefulness of the methods for characterizing different physical properties that can provide valuable geological information has been investigated. The study referred to above does not, however, deal with the usefulness of the geophysical borehole logging methods for supplying supplementary information for evaluating the permeability of the bedrock.

The present study encompasses two different study areas where extensive geological, hydrological and geophysical investigations have been carried out, namely Kråkemåla and Finnsjön. These areas were selected due to the availability of a very large body of borehole data.

Fractures and microfissures in the matrix constitute transport pathways for both groundwater and electrical currents in the bedrock. The water injection tests and the resistivity measurements have therefore been correlated with mapped fractures in the core and observed fractures in the borehole wall. This provides a picture of how these fractures affect permeability and current propagation. The water injection tests have also been correlated with the resistivity measurements, providing information on differences in the ability of the bedrock to transport electrical currents and groundwater in different types of fractures. Taken together, this provides a better picture of water movements in the fractures in the bedrock.

The investigated properties of the bedrock - i.e. fracture frequency, hydraulic conductivity and resistivity - have been analysed statistically. This provides an estimate of the average values and variation of these parameters.

In two TV-logged boreholes in Kråkemåla, a detailed comparison has been carried out between water injection tests, variations in the diameter of the borehole (differential resistance), observed fractures in the borehole wall and mapped fractures in the core. In the detailed study, the aforementioned parameters within each tested measurement section have been compared with injection tests of the section. These results are presented in a KBS report (Magnusson 1984).

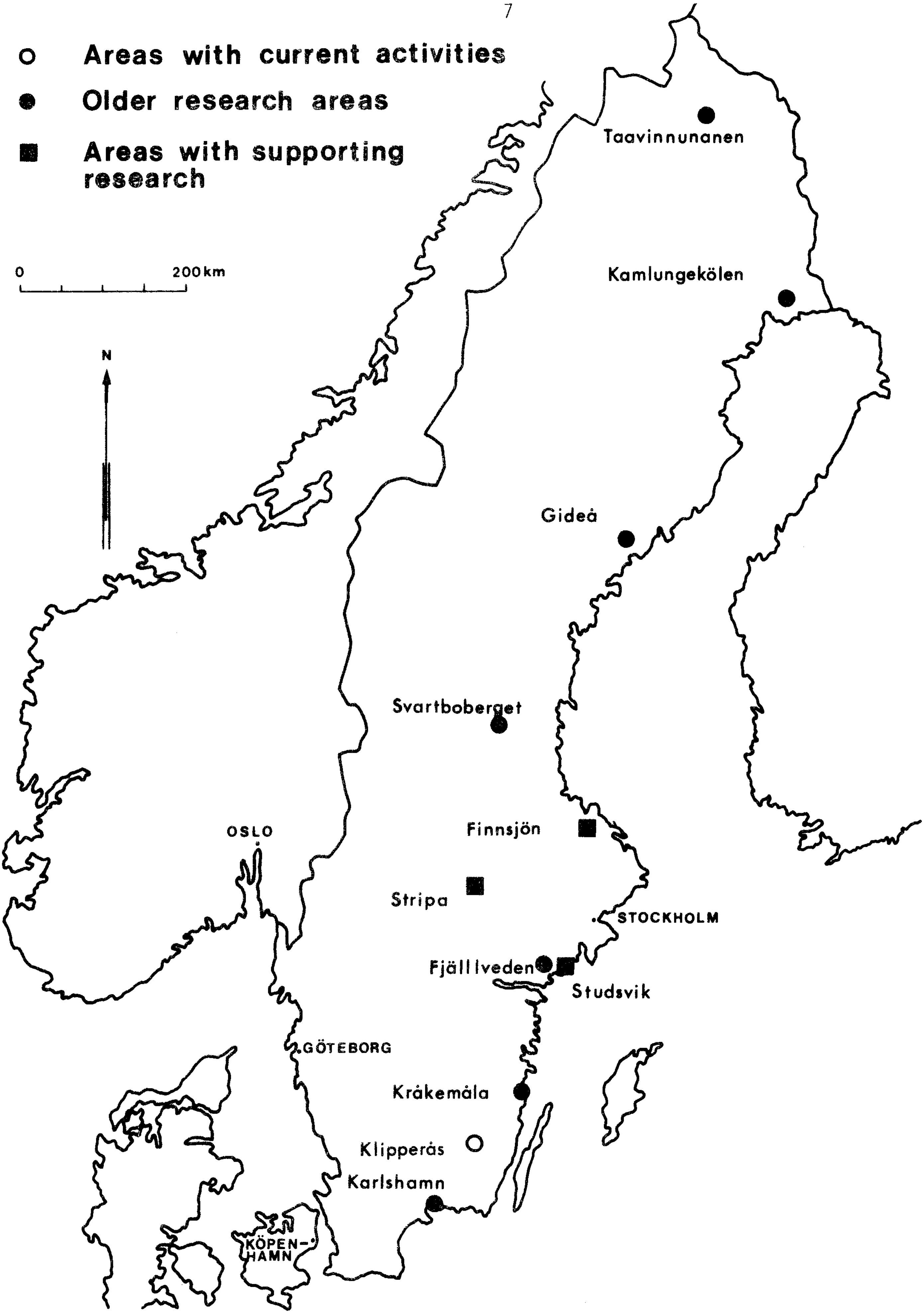


Fig 1:1. Investigated sites concerning the Swedish program for radioactive waste disposal.

2. DESCRIPTION OF THE PHYSICAL PROPERTIES OF THE BEDROCK

2.1 Major weak zones and fractures in the bedrock

The crystalline basement of Sweden is a part of the Baltic Shield, which belongs to the older part of the earth's crust. The Baltic Shield has undergone plastic deformation in connection with different periods of mountain chain folding. After plastic deformation and regional metamorphosis of the bedrock, the solid crystallized bedrock has undergone ruptural brittle deformation (i.e. fracturing). Block displacements caused by faulting have parted the crystalline bedrock into different blocks. Larsson (1967) assumed that once a well-developed ruptural deformation pattern has formed, subsequent deformations tend to follow the already existing pattern. Because subsequent deformations and fault movements take place for the most part in already formed major weak zones, the bedrock will consist of a mosaic of relatively well-preserved blocks bounded by surrounding weak zones. The different degrees of brittleness of the rock types have resulted in differences in fracturing and the formation of weak zones. Granites have reacted as brittle bodies by undergoing extensive fracturing, while folded gneisses with steeply-dipping serpentine foliation have constituted tough and more resistant units in the bedrock (Larsson 1977).

Larsson (1967) has developed two main types of models for ruptural deformation of the crystalline bedrock. The one model is applicable where the rock's anisotropy has little influence on the fracture pattern. This model has steeply-dipping tension zones in the direction of deformation (the principal stress direction) and less well-developed steep zones perpendicular to the deformation direction, as well as transverse steep shear zones and flat shear zones that may constitute zones of overthrust, see Fig. 2:1. In heavily foliated rock types, ruptural deformations take place primarily through overthrust movements along flat shear zones that follow the planes of foliation in the rock, i.e. the planes of foliation constitute suitable slide surfaces. On the other hand, tension zones do not seem to occur in the direction of deformation, while zones perpendicular to the direction of deformation occur sparsely (Larsson 1967). See Fig. 2:1. The movements in the shear zones can often lead to crushing of the rock. If this crushing leads to a fine-grained crushed material, which later undergoes mineral alterations (formation of clay minerals), this can lead to a low rate of water flow in the zones.

The blocks of bedrock delimited by major fracture zones in turn contain different fracture systems that divide the surface of the rock into a mosaic, where units of unfractured whole rock are surrounded by fractures, i.e. the rock is divided into smaller whole rock blocks bounded by surrounding fracture planes (Fig. 2:2). The fracture patterns observed in the bedrock are the result of fractures formed under the different conditions of stress undergone by the bedrock during its tectonic history. As a result, numerous fracture directions are represented, and in extreme cases virtually all fracture directions can be well represented, which in turn means that the bedrock has a homogeneous distribution of fractures. The Finnsjö area is an example of a bedrock with a complex, less well defined system of fractures where all fracture directions are well represented (S Scherman 1978). Bedrock where fractures have been formed under a primary state of stress have a few, more well defined fracture systems. As a result, the fractures have, for the most part, a few well represented directions, while other fracture directions occur very sparsely. An example of such a fracture system is the Götemar granite (Kråkemåla area), which for the most part has a primary system of fractures (Kresten & Chyssler 1977). In general, the fractures do not occur randomly, but rather in more or less well defined fracture systems (Brown et al 1982).

The whole blocks of rock bounded by fracture planes have in their matrix a network of small, thin fissures and microfissures (not visible to the naked eye). These microfissures are often formed in the grain boundaries of the minerals, see Fig. 2:3.

The distance between fractures along a line of measurement (e.g. along a borehole) is dependent on how the line of measurement is oriented to the bedrock's fracture system. For example, a line of measurement on the surface of the ground where the rock outcrop has two orthogonal steeply-dipping fracture systems exhibits the highest fracture frequency along a line that is oriented 45^{o} to the fracture systems. The fractures in the different fracture systems are therefore more or less well represented along the line of measurement, depending on the orientation of the line of measurement to the fracture systems, for example in vertical boreholes it is mainly the flat fractures that are intersected by the borehole. Fracture frequencies are calculated along a borehole and are thus influenced by the orientation of the boreholes. This applies especially to Kråkemåla, which has a well-defined system of fractures. But it applies to a lesser degree to Finnsjön. The results of studies of crystalline rock types in Canada (Brown et al 1982) show that the fracture frequency observed in boreholes does not differ appreciably from the frequency on outcrops on the ground surface.

A number of authors have shown that the distance between fractures along a line of measurement largely has an exponential distribution, where large distances between the fractures (fracture spacings) are common (Snow 1970; Hudson & Priest 1979; Wallis & King 1980). This type of fracture distribution is characterized by large fracture spacings randomly interspersed with fracture swarms (i.e. sections with high fracture density). For homogeneous granites, Snow (1970) and Wallis & King (1980) have shown that the distribution has a close fit to a Poisson distribution, which is characterized by the fact that the mean value and the standard deviation are equal. The surfaces of the outcrops are divided into a mosaic by the fractures. The distribution of the sizes of these mosaic surfaces exhibits a rapid decline with increasing surface size. The measured distribution of surface size on ten different rock types has indicated very good agreement with a theoretically calculated distribution based on orthogonal fracture systems with exponentially decreasing fracture spacing. This indicates that the distribution of unfractured block volumes bounded by fractures can be estimated by means of this method. (Hudson & Priest 1979).

The fracture apertures or openings are of great importance for the physical properties of the fractures, such as permeability. Measurements on outcrop surfaces have shown that the fracture apertures are logarithmically distributed. One investigated granite has a mean fracture aperture of approximately 1 mm (Snow 1970). The load on the fracture planes increases with increasing depth, which results in a reduction of the fracture apertures. But the compressibility of the fracture apertures is controlled by numerous other factors besides load. Since all surfaces possess some roughness, the real contact between two surfaces is extremely small compared to the nominal surface area, since it is primarily the asperities of the surfaces that come into contact with each other (Greenwood & Williamson 1966). Measurements of the topographical variations of metallic surfaces show that the height of the asperities and their distribution is largely normally distributed (Greenwood & Williamson 1966). A theoretical model for the contact between surfaces based on the assumption that the surfaces are rough and have numerous asperities that have the same radius and are randomly distributed has been devised by Greenwood and Williamson (1966). The model shows that the distance between two surfaces is chiefly dependent on the nominal load (i.e. the load divided by the nominal contact area), while the number of contact points and the total contact area are dependent solely on the load. The distance between the surfaces is thus not particularly sensitive to the pressure. It is primarily the number of contact points and their total area (the total contact area) that increases with increasing load, while the distance between the surfaces is affected to a lesser degree. The contact between the surfaces of solid substances is therefore controlled by two material properties (the modulus of elasticity and hardness) as well as by the topographical characteristics of the surfaces. This is the reason why even fractures under high load have pore spaces between the fracture planes. This means that the pore space mainly decreases as the result of an increased number of contact points and the fact that the area of these points increases with increasing load.

Walsh & Grosenbaugh (1979) apply a similar model to analyse the relationship between the load on rock samples and compressibility.

They assume that the surfaces of fractures and microfissures are rough and that it is primarily the asperities of the surfaces that are in contact with each other. This model shows that the compressibility of the rock types is mainly dependent on the total fracture area per unit volume and the standard deviation in height of the surfaces' asperities. This model provides good agreement with the rock samples' non-linear relationship between load and compressibility. The observed elastic properies of rock samples can also be reproduced by applying a different distribution of cavities, for example ellipsoidal pores (Mavko & Nur 1978). Crystalline rock samples under high magnification show that the microfissures constitute a network of interconnected cavities. Resistivity measurements and permeability measurements of loaded specimens show that the specimens' fractures and microfissures are sufficiently interconnected to constitute pathways for both electric current and water (Brace et al 1965; Zobeck & Byerlee 1975). This shows that Walsh & Grosenbaugh's (1979) model is closer to observed physical properties of rock samples than models with populations of cavities spread out in the samples. A large drill core (2 metres in height and 1 metre in diameter) with a complex fracture pattern has been sampled in the Stripa mine. This also shows a non-linear relationship between load and compression, which verifies the above model for deformation of a fractured medium (Thorpe et al 1980).

The fractures in the bedrock have different fracture-filling minerals. In Finnsjö and Sternö, for example, the following fracture minerals have been identified: Calcite, prehnite, quartz, chlorite, dolomite, wairakite, stilbite, laumontite, epidote, pyrite, zeolite minerals, polygorskite, gypsum and clay minerals. A fracture mineralogy study of drill cores from Finnsjön and Sternö (Larson et al 1981) show that all fracture-filling minerals, with the exception of calcite, were probably deposited under hydrothermal conditions. This shows that these minerals, with the exception of calcite, are not young, but were deposited during an older period of hydrothermal activity.

The investigation shows that many fractures have "healed" (become sealed with minerals) on repeated occasions; among other things, several generations of carbonate occur that alternate in places with prehnite generations. The prehnite appears to have been deposited prior to the corresponding calcite generation. The study also shows that there are many fractures (breaks in the core where the break surfaces are coated with fracture-filling mineral) that follow an older fracture plane at repeated intervals. This shows that fractures have often been generated along existing fractures healed or partially healed with fracture-filling material. The measurements performed on a large drill core from Stripa (2 metres in height and 1 metre in diameter) show that the fractures induced by loading follow already existing fractures (Thorpe et al 1980). If open fractures are generated in sound rock, water circulation in these fractures gives rise to mineral alteration of the fracture surfaces. All natural fractures in drill cores should therefore have either altered or mineral-coated fracture surfaces.

In the investigations performed at Finnsjön and Kråkemåla, the open fractures all exhibit a higher frequency of flat dips. (At depths of less than 400 m.) These flat dips are probably due to the fact that the present-day state of stress in the upper parts of the rock, which has been measured at several places in the Swedish crystalline basement, has a higher compressive component in the horizontal direction. In addition, there is a marked difference in the distribution of fracture-filling minerals between open and healed (whole drill core, i.e. no break of the core along the fracture-filling) fractures. Thus, quartz constitutes a main mineral in healed fractures along with carbonate. In the open fractures, quartz is mostly subordinate as a fracture-filling mineral, while carbonate and chlorite constitute the main minerals. This indicates that quartz-healed fractures have withstood the stresses better than e.g. fractures with pure carbonate filling (S-Å Larson et al 1981).

The open water-bearing fractures may consist in part of regenerated fractures along older fractures with hydrothermal fracture-filling minerals. In addition, the fractures may be generated through sound rock, in which case these fractures have fracture surfaces with a mineral alteration skin or possibly a relatively recently deposited carbonate coating. But young (recent) fractures with a very thin alteration skin may also be misinterpreted as a mechanical core break in connection with core mapping.

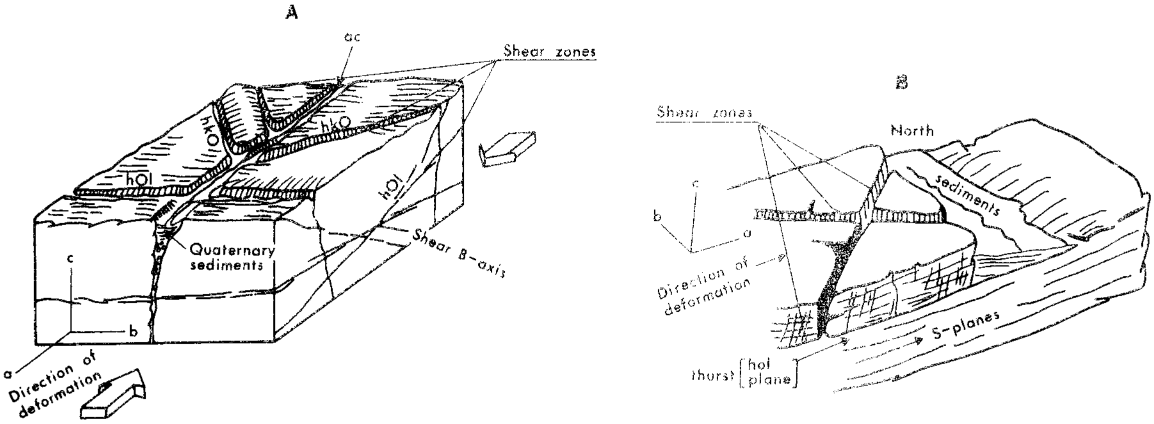


Fig 2:1. The intergrated deformation model of post-crystalline ruptural deformation. A = multiple shear type after Larsson (1963). B = single shear type after Larsson (1967).

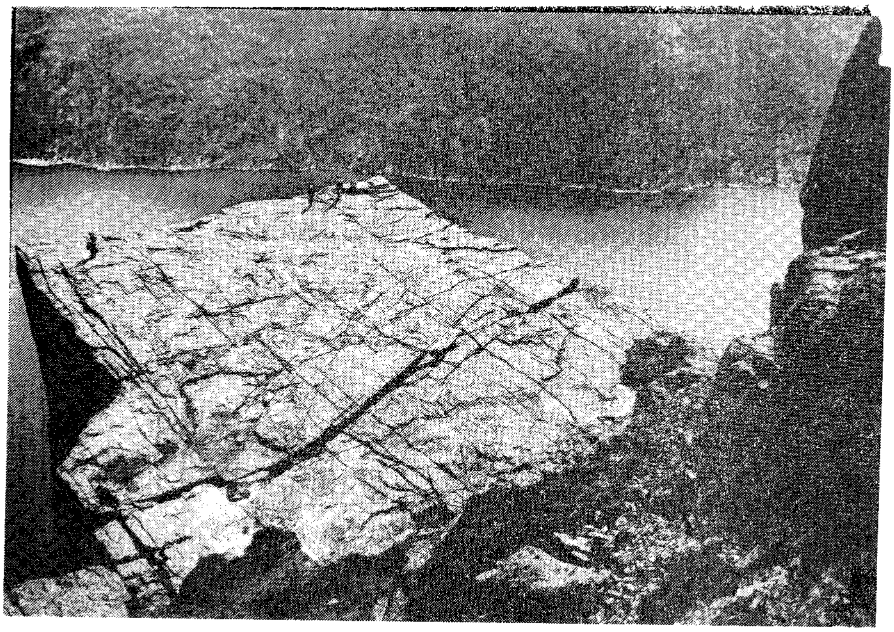


Fig 2:2. Photo of prekestolen (Pulpit Rock), Lysefjord, near Stavanger, Norway. The photo shows a nice example of a fracture pattern in the bedrock.

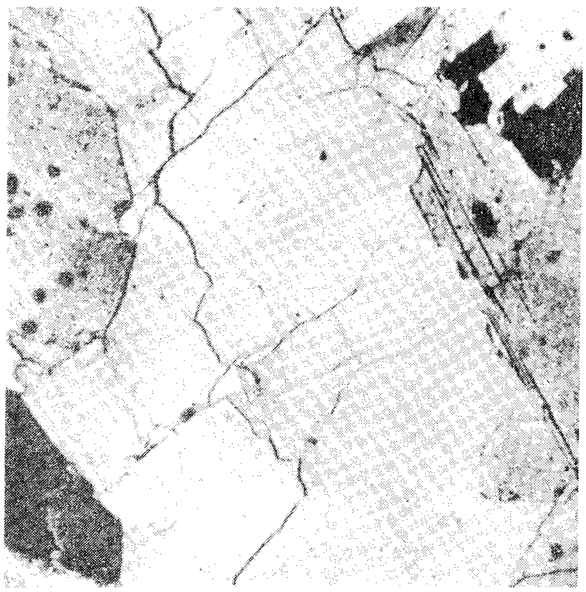


Fig. 2:3. Photo of a thin section (25 X magnefication) showing a fracture network in a quartz crystal. After Montoto et al (1978).

2.2 Electrical conductivity of the bedrock

With few exceptions, the minerals in the crystalline bedrock are generally good insulators, i.e. they have very low electrical conductivity. The most commonly occurring minerals with good electrical conductivity are graphite and sulphides (mainly pyrite). If electrically conductive minerals occur dispersed in a matrix of minerals with low conductivity, the conductive mineral grains are insulated from each other and therefore do not affect the electrical conductivity of the bedrock. In formations where the electrically conductive mineral grains are in contact with each other through a network of interconnected mineralizations or veins, these serve as pathways of electrical conduction, which gives the rock better electrical conductivity.

Minerals that serve as good electrical conductors occur relatively sparsely in crystalline bedrock. The conductivity is therefore determined mainly by the bedrock's content of mobile and diffusion-available groundwater. However, alteration products such as clay minerals also serve as good electrical conductors. The crystalline bedrock consists for the most part of silicate minerals with high resistivities (= the inverse of electrical conductivity, i.e. the electrical resistance of the bedrock) on the order of 10^5 to 10^9 ohm-m, which is considerably higher than the 10 to 50 ohm-m of the groundwater. Electric currents in the bedrock are therefore conducted mainly by the ions in the pore water in the bedrock (Brace et al 1965). The electrical conductivity of the bedrock is thereby determined by the character and geometry of the pores and by the conductivity of the pore water. In crystalline bedrock, it is chiefly the fractures that constitute the pores in the bedrock. Norton and Knapp (1977) propose that the porosity of a medium such as crystalline bedrock can be regarded as the sum of three types of porosity:

Effective flow porosity (Pf): The interconnected pores in the bedrock, those that constitute transport pathways for the groundwater.

Diffusion porosity (Pd): Pores that are interconnected with each other, but in which the transport of substances dissolved in the groundwater through water flow is insignificant. In these pores, transport takes place by chemical diffusion, i.e. chemical diffusion is a more important transport mechanism than the very slow and insignificant flow of water in these pores. The pores consist of thin fractures where water transport through flow is insignificant, or fractures with poor hydraulic contact with the fractures that constitute effective flow pores.

Residual porosity (Pr): Includes isolated pores that are not connected with effective flow pores or diffusion pores.

The pathways of electrical conduction in the bedrock consist of effective flow pores and diffusion pores, while the isolated residual pores do not constitute pathways of electrical conduction. The influence of porosity on the resistivity of the bedrock follows a relationship that is usually called Archie's law:

$$\frac{R_t}{R_w} = P^{-M}$$

R_t = Resistivity of the bedrock
R_w = Resistivity of the pore water
P = Porosity ($0< P<1$)
M = empirical coefficient

The measurements on crystalline rock specimens have shown that the coefficient M is approximately equal to 2 (Brace et al 1965). When the specimens are subjected to a load of 3 to 4 kilobar, the fractures usually close so that the fracture planes have good contact with each other. In spite of this, samples filled with pore fluid have considerably lower resistivity than dry specimens (Brace et al 1965; Brace & Orange 1968). This is probably due to the fact that there are thin films of water along cavities in the compressed fractures. This is in agreement with the fracture models described in chap. 2.2.

Despite the fact that the fracture planes are in good contact with each other, these films of water can constitute pathways of electrical conduction. However, thin skins of alteration products may contribute to the electrical conduction. This form of electrical conduction is termed surface conduction (Brace et al 1965). If the pressure on the samples is further increased beyond 3 to 4 kilobar, surface conduction decreases in a manner similar to volume conduction in the pore liquid at pressures below 4 kilobar. This indicates that at increasing pressure, some of the surface conduction pathways are cut off together with the water films that cause surface conduction (Brace et al 1965; Brace & Orange 1968). Thus, resistivity is affected by the load exerted on the fractures in the bedrock in such a way that increased load leads to increased resistivity. Bedrock samples where the pore liquid has lower resistivity than 10 ohm-m are completely dominated by volume conduction in interconnected pores. In pore liquids of higher resistivity, surface conduction accounts for a considerable portion of the electrical conductivity (Brace et al 1965; Öqvist 1982).

At high porosities, the influence of surface conduction declines due to the fact that there are more pores that are connected with each other and thereby increase volume conduction through the pore liquid. At porosities below 1%, surface conduction leads to a change in the relationship between resistivity and porosity. According to Brace et al (1965) and according to Nelson et al (1982), Archie's law can be rewritten as follows:

$$\frac{1}{R_t} = \left(\frac{1}{R_w} + \frac{1}{R_s}\right) P^2$$

$1/R_s$ = Electrical surface conductivity

2.3 Permeability of the bedrock

The major weak zones that surround and delimit the bedrock blocks normally constitute the principal transport pathways of the groundwater, see Fig. 2:1. Some of these zones may, due to clay alteration, have relatively low permeability. Movements along the shear or overthrust zones (Fig. 2:1) often lead to the formation of crushed material. Depending on the size of the crushed products and possible subsequent clay alteration the shear zones may be more or less sealed by the crushed material. In the bedrock blocks, the groundwater's transport pathways consist of open, unsealed fractures (Fig. 2:2). In comparison with the weak zones that surround the bedrock blocks, the groundwater flow is much smaller in the bedrock blocks' network of interconnected, unsealed fractures. Fracture zones with closely-spaced and very well interconnected fractures are expected to constitute the best transport pathways for the groundwater. The fractures in the bedrock may have highly varying water transport capacity depending on the fracture's aperture and its geometry and hydraulic connection with other fractures that constitute good transport pathways.

Whole rock samples without visible fractures have proved to be permeable due to movement of the water in networks of interconnected microfissures (Brace 1977). Thus, the bedrock's matrix is also permeable (Fig. 2:3). The hydraulic conductivity of unfractured crystalline rock samples is very low (10^{-9} - 10^{-15} m/s) compared to the larger permeable fracture or crushed zones in the crystalline bedrock, where hydraulic conductivity as measured in situ lies in the range 10^{-5} to 10^{-4} m/s (Brace 1980). The water flow in microfissures and other fractures of subcapillary size is too low to be measurable by means of conventional water injection tests in boreholes. It is therefore only open fractures with fracture apertures in excess of 35 µm that are of any significance as water transport pathways (Snow 1968). In the very thin fractures, chemical diffusion can constitute an important transport mechanism for substances dissolved in the groundwater, i.e. in very thin fractures water transport through flow is so insignificant that transport through chemical diffusion is a more important transport mechanism.

The degree of openness of the fractures is of very great importance for the flow of water through them. If a fracture model is applied where the fractures constitute plane-parallel joints of infinite extent and where water flow through the fracture is laminar, the hydraulical conductivity of the fracture is proportional to the cube of the fracture aperture (Snow 1965; Louis 1969; Bear 1972).

- $Q/h = c \times e^3$
- Q = flow
- h = differential pressure
- c = a constant
- e = fracture aperture

In the bedrock, the degree of openness of the fractures is dependent on the load on the fracture planes, which is determined by the prevailing state of stress in the rock. Due to the roughness of the fracture surfaces, water movements in the fractures are expected to take place in interconnected cavities between the fracture planes. With increasing load, the compressibility of the fractures declines as more of the asperities of the fracture surfaces are brought into contact with each other. This means that despite high loads, the fractures do not close entirely, and therefore cavities remain between the fracture planes. This is in agreement with measurements performed on whole rock samples and on samples containing induced tension fractures, which show that the samples and the induced tension fractures are permeable even at very high loads (Zoback & Byerlee 1975; Brace 1977; Brace et al 1968; Witherspoon et al 1980).

In the fractures in the bedrock, the water moves in interconnected cavities around the loaded parts of the fracture surfaces. In poorly interconnected or constricted cavities, the water moves very slowly in relation to the well-interconnected cavities. Water transport in these cavities is therefore insignificant in relation to the well-interconnected cavities. This is in agreement with tests performed on transparent imprints of natural fractures in araldite, where the injection of dyed water shows that water transport takes place primarily in channels between the fracture planes (Fig. 2:4) while large portions of the pore space between the fracture planes are filled with relatively stationary water (Maini 1971). When the applied pressure gradient increases, the area with relatively stationary water (dead water) decreases (Maini 1971). This is due to the fact that the increase of the flow velocity causes water to flow in sections with a smaller aperture between the fracture faces as well (Maini 1971).

Witherspoon et al (1980) have carried out permeability measurements on homogeneous crystalline bedrock samples containing an induced tension fracture. In order to investigate how permeability is affected by the degree of compression of the fracture, the measurements were carried out under different loads on the samples (from 0 to 17 MPa). The study shows that with laminar flow, the cubic law still applies for all loads used. The effect of the fact that the water actually moves in a complex pattern of interconnected channels causes only a reduction of the permeability that can be described by means of a factor (f), which varied in the tests between 1.04 and 1.65.

- $Q/h = (c/f) \times e^3$

Other measurements carried out on natural fractures (Gale 1982) or on fresh fractures where different degrees of roughness have been achieved artificially (Kranz et al 1979), exhibit more variable results. The results of these investigations are only in partial agreement with the cubic law.

Since the water, due to the roughness of the fracture planes, moves in a more or less complex pattern of channels between the fracture planes, the water transport pathways in the laboratory samples may be too short for a large surface. It can therefore be of interest to perform measurements on samples that have a sufficiently large fracture surface to represent the complex flow conditions in a fracture (Witherspoon 1981). In the measurements referred to above of the permeability of a fracture, an average fracture aperture has been determined indirectly by measuring the degree of compression over the fracture in question. Due to topographical variations on the fracture surfaces, the fracture may have large variation in the aperture along the fracture planes. For rough fracture surfaces, Witherspoon (1981) therefore proposes a model with a set of different distances between the fracture surfaces. Water transport takes place primarily through the larger well-interconnected cavities, i.e. with a large distance between the fracture planes. But slow water movements also take place through poorly interconnected cavities with small distances between the fracture surfaces. With a reduced average fracture aperture, permeability is reduced due to the fact that the water-bearing channels are narrower and some water transport pathways are closed off entirely. This means that permeability is heavily dependent on average fracture apertures, despite the fact that the water movements are more complex than in a model with two plane-parallel fracture surfaces.

Walsh (1981) has shown in a theoretical study that the permeability of the fractures increases with the cube of the aperture, while permeability is only inversely proportional to tortuosity (i.e. the complexity of the channel-shaped transport pathways). In other words, the fracture aperture has a much greater influence.

Studies in tunnels show that water seepage takes place primarily through point openings in otherwise closed fractures (Wolters et al 1972). This also indicates that the water in a rock mass primarily moves within a complex pattern of interconnected channels. This has been demonstrated by tracer tests carried out on natural fractures in rock samples (Neretnieks et al 1981).

Investigations on a large drill core (2 metres in height and 1 metre in diameter from Stripa) show that water movements in the fractures take place in a very complex pattern (Thorpe et al 1980). In these measurements, water was injected in sections along a small borehole drilled through the centre of the core.

In the water injection measurements, the seepage of the injection water was observed at the surface of the drill core (Fig. 2:5). The observations show that the fractures are hydraulically connected with each other in a very complex pattern and that the fractures in the core have very different flows. In addition, the flow along the same fracture plane also exhibits large variations. The water flow shows clear tendencies to move in channel-shaped openings. The channels occur along large cavities where the fractures are poorly closed and in intersections between water-conducting fractures (Fig. 2:5).

The large variations in the water flows in the fractures are due to the irregular presence of permeable cavities between the fracture planes and of hydraulic communication between water-bearing channels in different fractures. Wide fractures with relatively large pore spaces can therefore often have very low water flows owing to the fact that the fractures have poor hydraulic connection with each other. As an example, it can be mentioned that fractures observed in outcrops on the ground surface are often found arranged in a longitudinal sequence of parallel fractures slightly displaced in relation to each other, known as en echelon oriented fractures. Often, the fractures end in thin branchings that may be connected with a nearby en echelon oriented fracture. These branchings of fractures are called horsetails (O. Brotzen, in preparation). Interruptions and constrictions at the branchings reduce the hydraulic contact among these fractures. If en echelon fractures are not connected through a fairly well developed system of transverse or flat fractures, the en echelon arranged fracture systems will be in poor hydraulic connection with each other. But very slow water circulation takes place even in a poorly interconnected system due to the fact that the fractures are connected with each other through very thin fractures or through the microfissures in the matrix. However, the resistivity measurements are affected to a lesser degree by the hydraulic connection of the fractures than the water injection tests, owing to the fact that surface conduction permits current transport through very thin water films, see section 2.2.

The orientation of the fractures in relation to the prevailing stress field in the bedrock can be expected to influence the permeability of the fractures owing to the fact that the fracture planes are subjected to different loads, i.e. fractures oriented parallel to the highest compressive stress field are less compressed than equivalent fractures oriented perpendicular to the highest stress. Measurements in the Juktan tunnel performed by Olsson (1979) exhibit hydraulic anisotropy, where permeability is generally higher parallel to the highest stress field than perpendicular to it.

Shear deformation along a fracture can give rise to great changes in pore geometry (Barton 1971). Owing to the fact that the fractures have different degrees of undulation in the fracture faces, a displacement of the fracture planes in relation to each other leads to a poorer fit between them, see Fig. 2:6. Permeability measurements on samples with artificial tension fractures that have been subjected to shear displacement without compressive load show that even relatively small displacements give rise to a large increase in permeability (permeability can increase by up to 100 times the original value, Maini et al 1977). Natural fractures with coated fracture surfaces may, however, exhibit very different properties in connection with shear deformation due to the fact that the coating often consists of soft minerals. In addition, shear deformation can lead to a crushing of the sheared surfaces, which means that the cavities will be filled with crushed material to some extent.

Fig 2:4. Stream lines in an artificial fracture, after Maini (1971). a = at low gradient. b = at high gradient. Dark is dyed water.

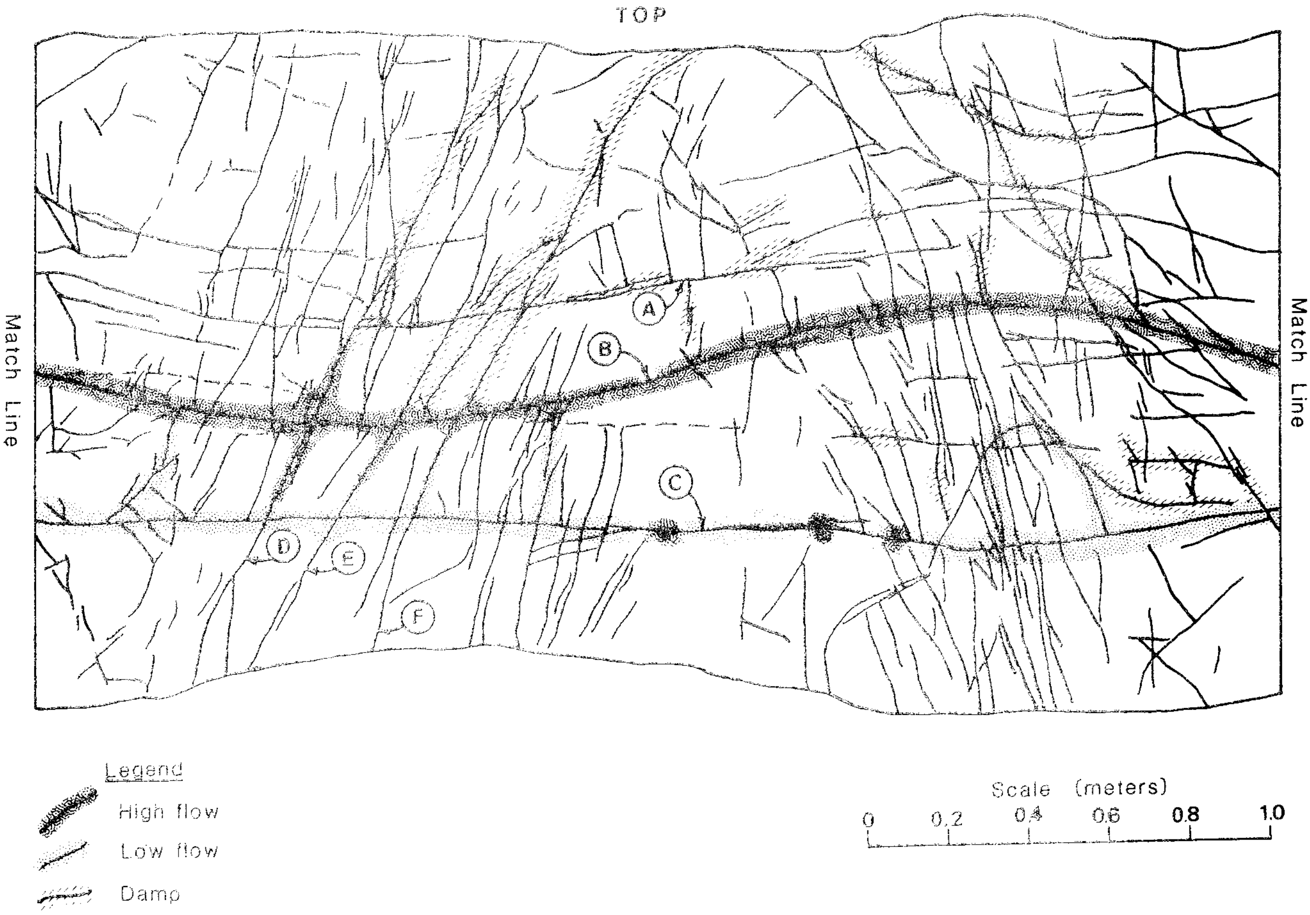


Fig 2:5. Seepage at surface of core from injection into center borehole after R. Thorpe, D.J. Watkins, W.E. Ralph, R. Hsu, and S. Flexser (1980).

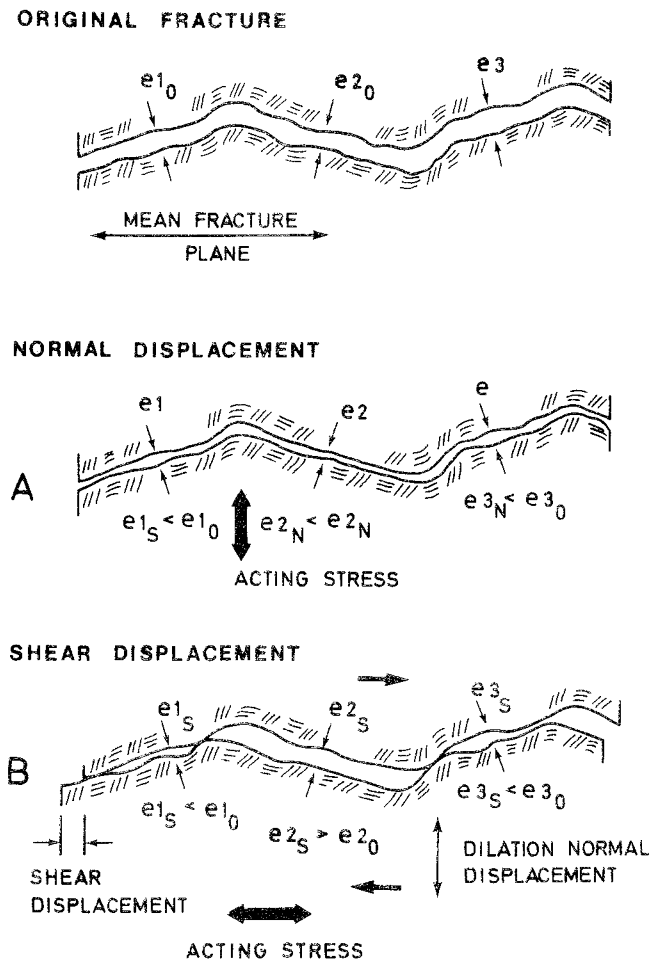


Fig. 2:6. Effective change in joint opening due to shear displacement, after Maini et al (1972).

3 THE KRÅKEMÅLA AREA

3.1 Geological description

The study area is situated west of the village of Kråkemåla, about 7.5 km NNW of the Oskarshamn Nuclear Power Station at Simpevarp, see map, Fig. 1:1 in Chap. 1.

The area consists of a younger granite (Leucocratic granite) of the Rapakivi type, the Götemar granite, which has penetrated through the surrounding Småland granites. The Götemar granite and the surrounding older Småland granites have been dated at 1.38 and 1.74 billion years, respectively (Wehlin 1966, Åberg 1977). On the ground surface, the Götemar massif occupies a circular area with a diameter of about 9 km.

The Götemar granite is a massive granite with homogeneous minerological composition. The dominant minerals are quartz, feldspar and mica minerals. The quartz content is remarkably high with accessory minerals, particularly fluorspar and pyrite. Fluorspar can occur in large quantities in connection with fractures. (Kresten & Chyssler 1976, Scherman 1978).

Studies performed by Kresten & Chyssler (1976) show that the Götemar granite has a high content of silicic acid and alkali and a low content of iron, calcium, magnesium and sulphur. A relatively low density of 2.60 g/cm^3 is also characteristic of the Götemar granite.

The Götemar granite exhibits a very well-developed primary system of fractures, where three main types of fractures can be distinguished, see Fig. 2, page 157 in Kresten & Chyssler (1976):

Tangential fractures concentric with the circular shape of the Götemar granite

Radial fractures oriented radially in towards the centre of the intrusion

Flat fractures

The investigated area occupies a surface area of about 2.5 km^2 and is characterized by a flat topography that is only interrupted by three continuous fracture valleys. The topography is somewhat more pronounced in the western valleys in the area, close to Lake Götemaren. The soil cover is thin and exposed rock constitutes about 50% of the site area.

The topographically indicated fracture valleys within the area have two main directions: northwesterly and about N70^{o} E. The near-surface fracture pattern has been mapped in outcrops and in three existing quarries in the Götemar granite. The steeply-dipping fractures have two very marked main directions, about N20^{o}W and N55^{o}E, while other directions occur very sparsely. The fractures that are oriented at about N55^{o} E are often filled with Cambrian sandstone. The fracture faces are coated with fluorspar and calcite. Fluorspar occurs occasionally in large quantities. Another remarkable feature is the horizontal release jointing that appear clearly in the vertical cuts. In the horizontal direction, these planes appear as a flakiness in the rock surface, probably aggravated by ice erosion. The strike is NE with a dip of about 15^{o} towards the east. The fracture filling is often coarse muscovite and pyrite. The thickness of such fracture fillings has been measured at a maximum of 10 cm. The capacity of a number of wells drilled in rock indicate that these planes can give a relatively high water flow. The highest reported value is 4 000 l/h.

There are three boreholes in the area called K1, K2 and K3. The first two are drilled vertically to 500 and 600 m, respectively, while K3 slopes 50^{o} towards the north with a borehole length of about 760 m. The vertical boreholes are located in the northern and western part of the area, respectively, and the sloping hole is located in the eastern part of the area.

The bedrock is built up mainly of massive medium-grained granite, red in places and known as the Götemar granite. The occurrence of coarse, quartz-rich pegmatite, conformable with the release joints and with thicknesses around 10 cm is not unusual, while aplite occurs more sparsely. Mapping of the fracture minerals in the drill cores shows that quartz, chlorite, illite and muscovite are the most common fracture-filling minerals. Small quantities of swelling clay minerals have been obtained in four samples (Scherman 1978).

3.2 Physical properties of the bedrock

3.2.1 Fracture frequency

TV inspection has been carried out in two of Kråkemåla's three core drilled boreholes (K1 and K2). The study of the fracture frequency in the boreholes has mainly been concentrated to the two TV-inspected boreholes.

The hydraulic tests in the boreholes have been carried out in two-metre sections along the boreholes. In corresponding two-metre sections, the fracture frequency along the boreholes has been expressed in the number of fractures in the water injection tested 2-metre sections (Figs. 3:1 and 3:2).

In figures 3:1 and 3:2, the frequency of fresh fractures (fresh break surfaces) and coated fractures (mineral-coated or altered break surfaces) along the drill core is presented along with the frequency of thick (>1mm) and thin (<1mm) TV-inspected fractures along the borehole wall. Fracture frequency in the borehole wall exhibits a very good correlation to the frequency of coated fractures in the core. Zones with a high frequency of coated fractures in the core coincide with high fracture frequency in the borehole wall. The fractured sections in K1 and K2 are characterized by a high frequency of coated fractures in the core and a high frequency of fractures in the borehole wall (Figs. 3:1 and 3:2). In borehole K1, the thin fractures in the borehole wall usually occur in wider zones compared to the thick fractures in the borehole wall and the coated fractures in the core. This may be due to the fact that the large fracture zones are often associated with thin fracture indications (these have not been mapped in connection with core mapping.) Fractures without an actual break in the core and with no visible fracture-filling material are called fracture indications, see appendix A.1.1.

The fractures in the borehole wall and the coated fractures in the core exhibit high fracture frequencies in certain few, discrete zones, while long borehole sections have no or only a few fractures. On the other hand, fresh fractures are found in virtually all 2-metre sections along the boreholes (Figs. 3:1 and 3:2). The frequency of fresh fractures along the drill core does therefore not show good correlation with the fracture frequency in the borehole wall or with the frequency of coated fractures in the core, exhibiting instead a more random variation along the drill core (Figs. 3:1 and 3:2).

The cores from all three core boreholes in the area have a similar distribution of fresh fractures. The fresh fractures exhibit a simple, relatively symmetric distribution, with some skewness towards higher frequences (Fig. 3:3). The distributions of the three drill cores' fresh fractures and the total distribution in all three boreholes have the following means and standard deviations:

K 1:	3.2 + 1.2	fresh	fractures/m
K 2:	2.9 + 1.4	"	"
K 3:	2.5 + 1.4	"	"
K 1 + K 2 + K 3:	2.9 + 1.3	"	"

This shows that fresh fractures occur with approximately equal frequency in all of the boreholes in the area. The distribution of fresh fractures, together with the fact that these fractures do not exhibit good correlation with coated fractures in the core or with observed fractures in the borehole wall, indicate that the fresh fractures have probably arisen through randomly induced breaks as a result of e.g. drilling and handling of the drill cores. The probability of induced breaks is dependent on the strength of the core and should therefore be the same for all the boreholes on the site. But the presence of weaknesses in the core, such as fracture indications, increases the possibility of an induced core break. The skewness in the distribution towards higher frequency (Fig. 3:3) may be caused by the fact that induced breaks occur more often in sections with a high frequency of weaknesses such as fracture indications, i.e. fresh fractures are caused by induced breaks along a fracture indication. Evidence in support of this is the fact that a high frequency of fresh fractures is often found where the core also has a high frequency of fracture indications.

The frequency of mineral-coated fractures in the three drill cores exhibits an exponential decreasing distribution, see Fig. 3:3. A large percentage of the 2-metre sections in the cores have no or only one coated fracture. In K1, K2 and K3, 70%, 29% and 24%, respectively, of the 2-metre sections have no mineral-coated fractures. Sections with higher fracture frequencies constitute a much smaller percentage of the boreholes, and the higher the fracture frequency the smaller the percentage.

Characteristic of an exponential distribution of fractures along a line of measurement (fractures that intersect the line of measurement) in the bedrock, such as a borehole, is the fact that large fracture spacings randomly interrupted by fracture swarms (sections with high fracture density) dominate along the line of measurement. If the fracture frequency is calculated for long borehole sections, a misleading picture is therefore obtained of the fracture distribution in these long borehole sections. A number of studies have shown that the bedrock usually has this type of fracture distribution (Snow 1970; Hudson & Priest 1979; Wallis & King 1980). The three drill cores have relatively similar fracture distributions, but borehole K3 has, on the average, more fractures than the other boreholes. See Fig. 3:3. This is due to the fact that K3 - unlike the vertical boreholes K1 and K2 - slopes 50^{o} towards the horizontal plane, which means that steeply-dipping fractures will be better represented. In comparison with both K2 and K3, borehole K1 also has a much higher percentage of fracture-poor borehole sections.

In an internal study at SGAB, Ahlbom has compared fracture frequency in the boreholes down to a depth of 100 m with fracture frequency in nearby outcrops:

Borehole	Inclination to horizontal plane	Fracture frequency in outcrop (fractures/m)	Fracture frequency in drill core (fractures/m)
Finnsjön 3	50^{o}	2.5	2.7
Finnsjön 4	80^{o}	2.4	2.3
Finnsjön 5	50^{o}	4.2	4.8
Karlshamn 1	80^{o}	0.7	1.1
Karlshamn 2	75^{o}	0.8	2.0
Kråkemåla 1	90^{o}	0.6	1.2
Kråkemåla 2	90^{o}	1.2	1.9
Kråkemåla 3	50^{o}	0.7	2.0

The fracture frequency in the Kråkemåla drill cores is approximately twice as great as in nearby outcrops. This indicates that the bedrock in Kråkemåla has a more pronounced horizontal fracturing (release jointing). The fracture frequency in the drill core has been calculated by adding up all fractures and dividing the sum by the length of the borehole section (i.e. 100 m). The boreholes are characterized by a high fracture frequency in certain narrow fracture zones, while long borehole sections have a very low fracture frequency where the distance between mineral-coated fractures mapped in the core can sometimes exceed 10 m. The above-calculated fracture frequency does not therefore provide a representative picture of the occurrence of fractures along the borehole.

There are fewer fracture-free sections in the borehole wall in the TV-inspected boreholes (K1 and K2) than there are sections without mapped coated fractures in the drill core. 72 two-metre sections in K1 and 16 in K2 lack fractures in the borehole wall, while the corresponding numbers of sections without coated fractures in the drill core are 156 and 65. Thus, there are a number of sections with fractures in the borehole wall that do not have any coated fractures in the drill core. This difference stems from the fact that unmapped sealed fractures and fracture indications have been observed in the borehole wall. Otherwise, the fracture frequency in the borehole wall and the frequency of coated fractures in the core exhibit a similar distribution (Fig. 3:4). On average, the sections also contain more observed fractures in the borehole wall than mapped coated fractures in the drill core. This may be due in part to the fact that the assumption that the fracture zones have one coated fracture per dm leads to some underestimation of the number of fractures in these zones, and in part to the fact that unmapped sealed fractures and fracture indications have been observed in the borehole wall.

With the aid of resistivity measurements, the bedrock along the boreholes has been divided into sections with different average resistivities. These sections have different lengths but are usually larger than 2 metres. The delimited borehole sections represent rock with different conductivities and thereby indirectly also rock with different degrees of fracturing.

In order to be able to correlate the fracture frequency in the boreholes with the resistivity measurements, the frequency of coated fractures in the core and the frequency of observed fractures in the borehole wall have been calculated for corresponding sections. A large fraction of these sections do not have any mapped coated fractures in the core or observed fractures in the borehole wall, see Figs. 3:5 and 3:6. On a logarithmic scale, the distribution of the fracture frequency of these measurement sections has the following mean and standard deviation:

Coated fractures (K1 + K2): 1.4 fractures/m + 0.54 parts of a decade.

Fractures in the borehole wall (K1 + K2): 2.0 fractures/m + 0.75 parts of a decade.

Because a logarithmic scale is used, the standard deviation is expressed in parts of a power of ten (i.e. a decade), see Figs. 3:6 and 3:7.

In calculating the fracture frequency, the thickness of the fractures has not been taken into account. In order to weigh in the thickness of the fractures, a fracture ratio has been calculated for the borehole sections that have a lower resistivity than the surrounding sections, i.e. for delimited fracture zones and not for fracture-poor high-resistivity borehole sections. The fracture ratio is the sum of the apparent fracture apertures of all fractures in mm (observed in connection with TV inspection) within a borehole section divided by the length of the borehole section in metres, i.e. how large a fraction the fracture apertures constitute of the borehole section. The borehole section's fracture ratio has a logarithmic normal distribution with the following mean and standard deviation (Fig. 3:7): 10.0 mm/m + 0.69 parts of a decade.

The relatively large fracture ratios in the fractured borehole sections are probably due to the fact that observed fracture apertures in the borehole wall lead to a gross overestimate of the actual fracture aperture. This is due to the fact that chips can be dislodged from the fracture edges and the borehole wall and that it is not possible by means of TV inspection to determine the degree to which the fractures have been sealed with fracture-filling material.

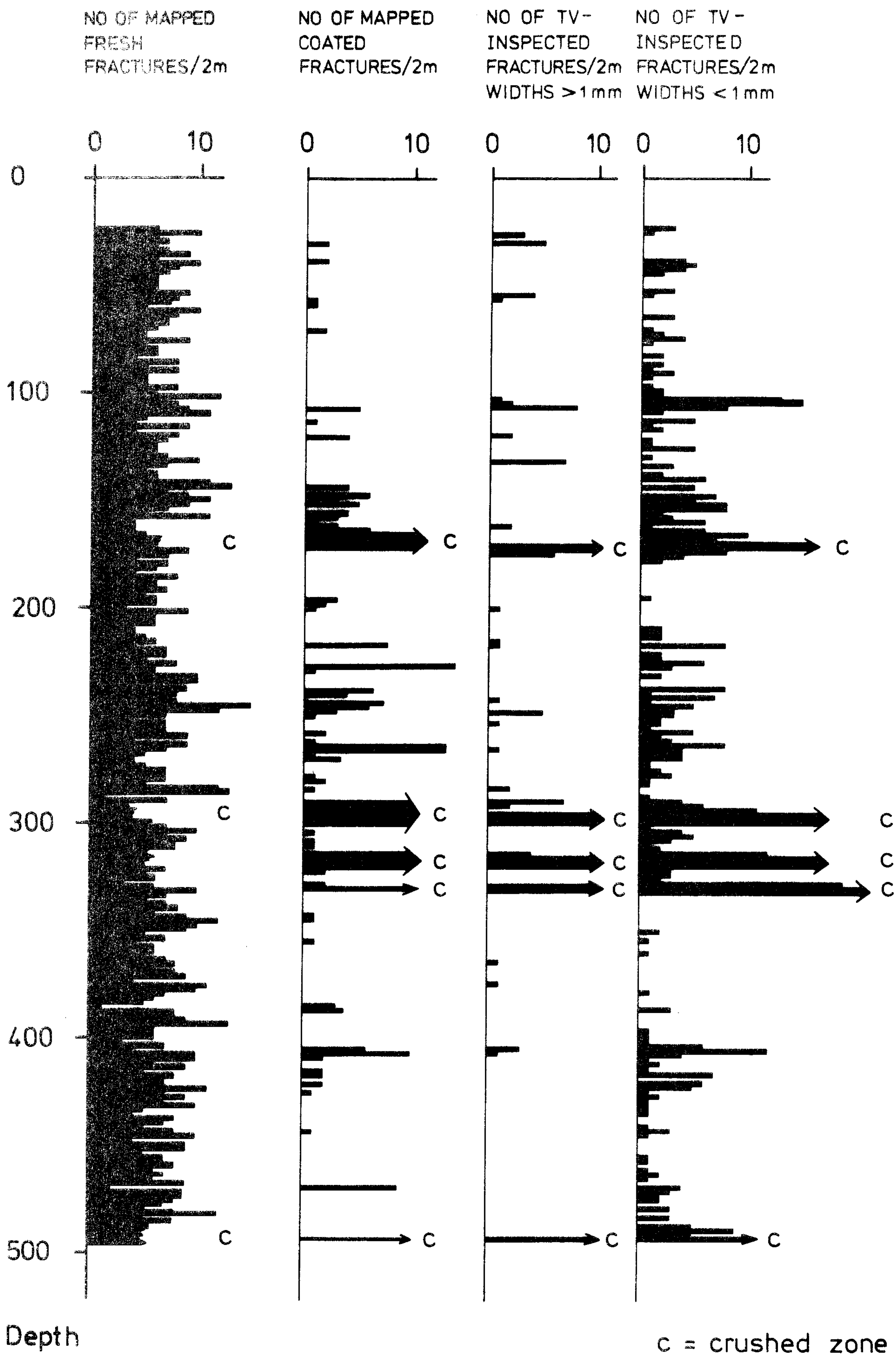


Fig 3:1. Borehole k1. No of mapped fractures in the core and TV-inspected fractures in 2 m sections along borehole K1. The sections coincide with the sections tested by water-injection tests.

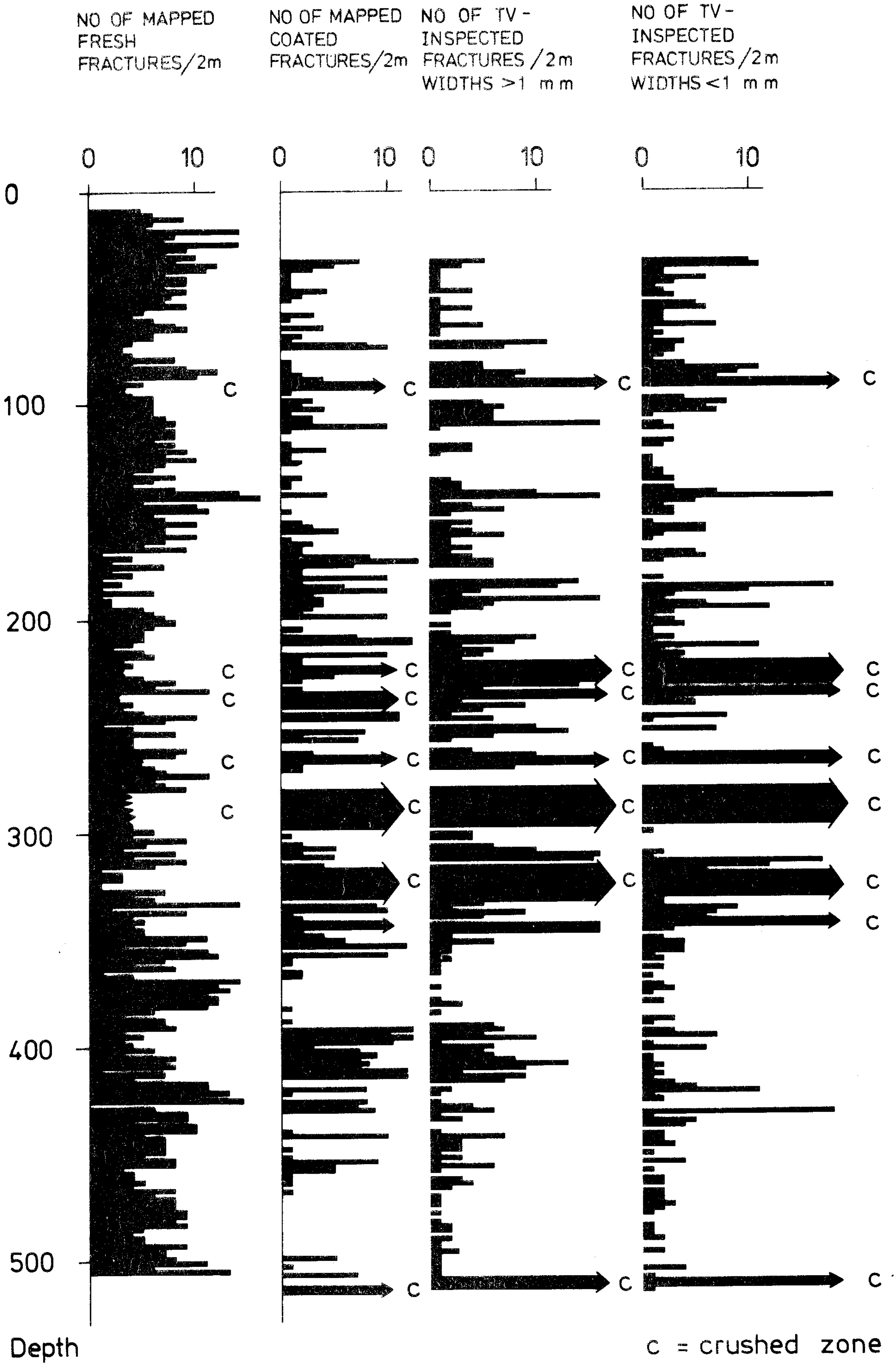


Fig 3:2. Borehole k2. No of mapped fractures in the core and TV-inspected fractures in 2 m sections along borehole k2. The sections coincide with the sections tested by water-injection tests.

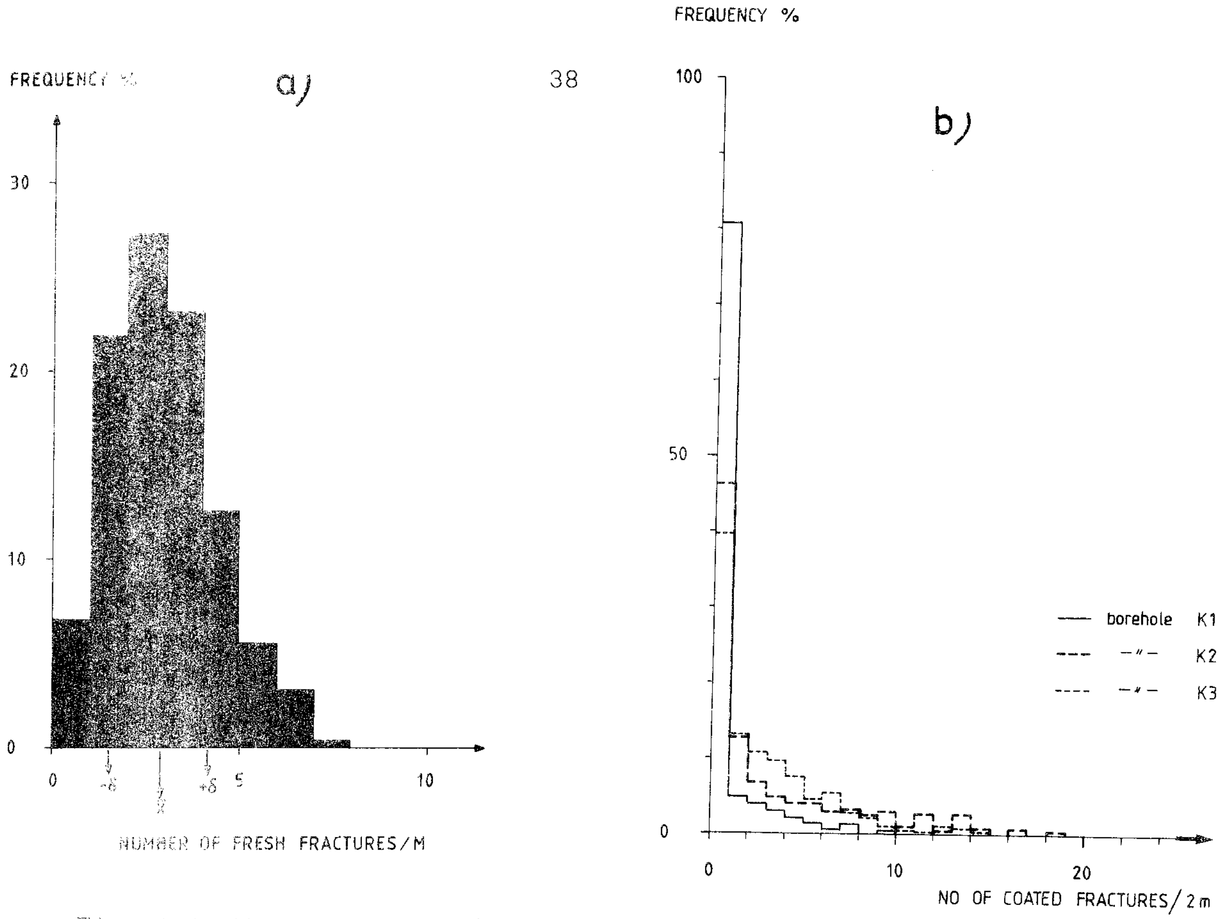


Fig. 3:3. Histogram of (a) fresh fractures/m in three approximately 500 m deep boreholes in Kråkemåla (K1,K2,K3) and (b) number of coated fractures in each of the water injection tested two metre sections in these boreholes.

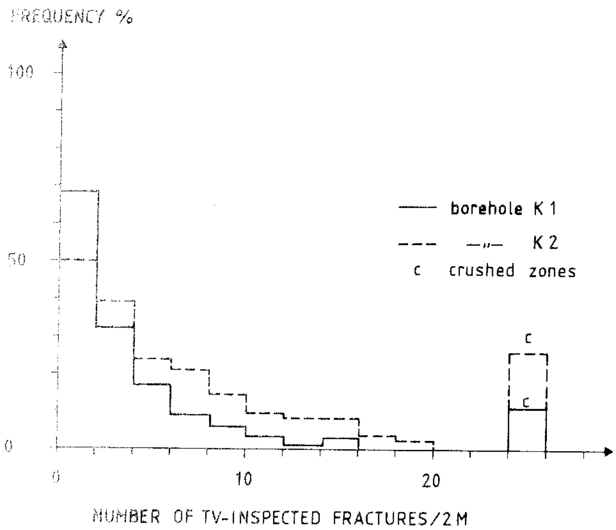
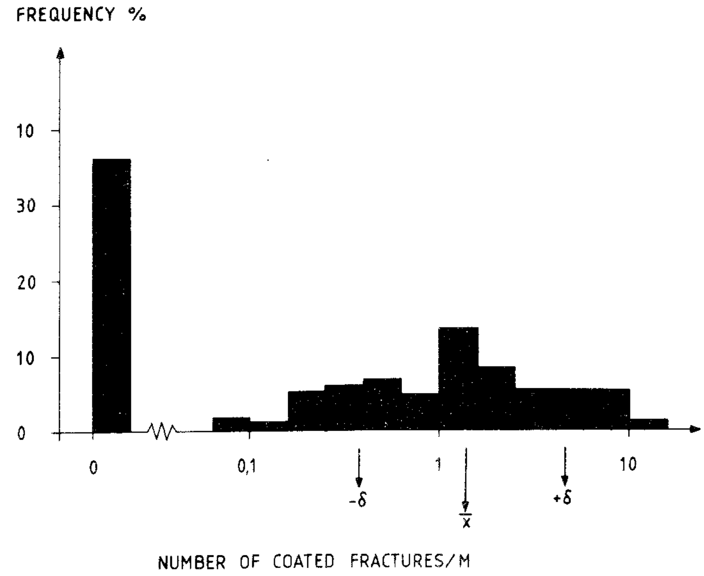


Fig. 3:4. Histogram of observed fractures in the borehole wall (TV-inspection) in each of the water injection tested two metre sections of two of the boreholes in Kråkemåla (K1,K2).

Fig. 3:5. Histogram of mapped coated fractures in sections defined by an average resistivity which differs from that of surrounding sections, i.e. the borehole has been divided into sections with different average resistivities. See Fig. 4:14.



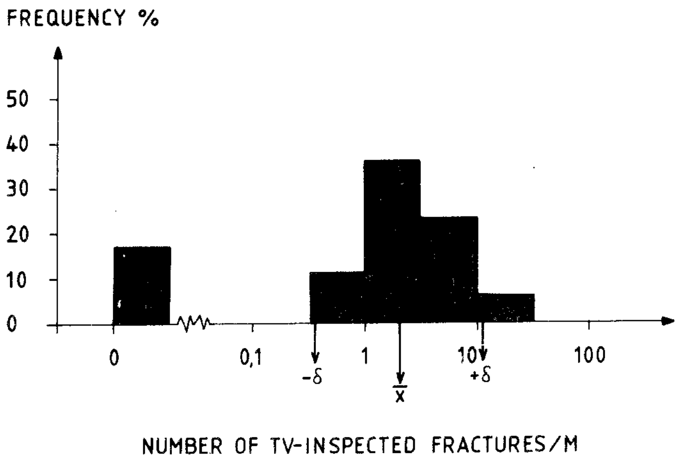
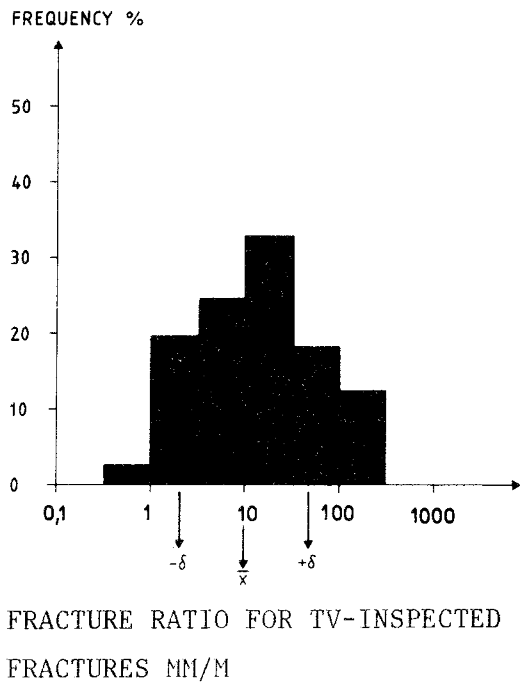


Fig. 3:6. Histogram of TV-inspected fractures in sections defined by an average resistivity which differs from that of surrounding sections, i.e. the borehole has been divided into sections with different average resistivities.

Fig. 3:7. Fracture ratio for TV-inspected fractures in fracture zones defined by a lower resistivity than surrounding sections.



3.2.2 Resistivity of the boreholes

The transport of current through the bedrock takes place through both existing fractures and the network of interconnected microfissures in the matrix. Over a large volume, the current transport through a complex network of microfissures will be equalized so that the current propagation can be regarded as homogeneous. Normally, fracture-poor or fracture-free borehole sections have high resistivities above 40 000 ohm-m, which shows that the matrix generally has low electrical conductivity (Fig. 3:8). In the fracture-free borehole sections (without mapped coated fractures), which can sometimes be up to several tens of metres long, current propagation takes place through the matrix. These borehole sections constitute the boreholes' high-resistivity sections, but in some cases a few of these sections may also have relatively low resistivities (approximately 10 000 ohms), see Fig. 3:8. Depending on the quantity of microfissures in the matrix, the matrix may have highly fluctuating conductivities. But normally, the matrix has low conductivity (high resistivity). The resistivity variations along the borehole are therefore caused mainly by the presence of fractures in the bedrock (i.e. the propagation of current through the bedrock's matrix and interconnected fractures).

The bedrock penetrated by boreholes in Kråkemåla possesses high average resistivity. The measured resistivity values exhibit a relatively symmetric logarithmic normal distribution, but with a few low-resistivity sections (<10 000 ohm-m) with values that deviate from those in the logarithmic normal distribution, see Fig. 3:9. The boreholes have very similar resistivity distributions with approximately the same mean and standard deviation:

K 1: 25 000 ohm-m + 0.28 parts of a decade

K 2: 25 000 ohm-m + 0.28 parts of a decade

K 3: 30 000 ohm-m + 0.20 parts of a decade

Total distribution (mean and standard deviation) of measured resistivity values for boreholes K1, K2 and K3: 25 000 + 0.27 parts of a decade.

The logarithmically normally distributed values above 10 000 ohm-m represent normal resistivity variations in the bedrock in the area and reflect the different degrees of fracturing in the drilled rock blocks, i.e. the current transport through both the matrix and the more compact rock's fracture mosaic.

The low-resistivity values below 10 000 ohm-m that deviate from the logarithmic normal distribution are found in extremely fractured or crushed borehole sections and in highly weathered borehole sections. In these sections, current transport takes place through a system of closely-spaced fractures that constitute a network of electrically well-interconnected fractures.

The Kråkemåla area is thus characterized by relatively high-resistivity rock with a few crushed zones with low resistivities. Borehole K3 has a higher fracture frequency along the borehole than K1 and K2. In spite of this, K3 has a higher average resistivity than K1 and K2. Borehole K3 slopes 50° towards the horizontal plane, while K1 and K2 are vertical boreholes, which means that steeply-dipping fractures are better represented in K3. This suggests that the vertical fractures are poorer conductors of electric currents, which is probably due to the fact that the state of stress in the bedrock is such that the vertical fractures in the upper parts of the bedrock (down to a depth of a couple hundred metres) are more compressed.

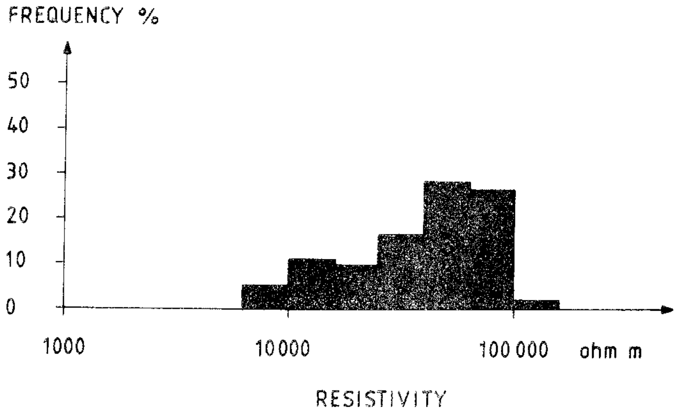


Fig. 3:8. Histogram of the resistivity of sections which have no mapped coated fractures in the core and no fractures observed by TV-inspection (after lateral correction and correction for the influence of the borehole fluid). These sections in boreholes K1 and K2 will therefore represent the resistivity of the matrix.

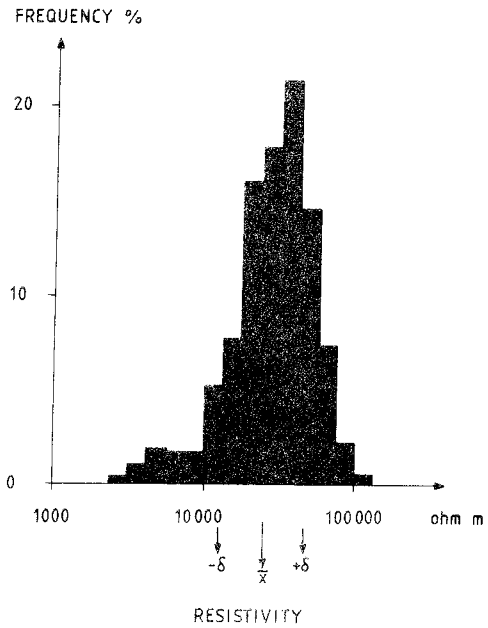


Fig. 3:9. Histogram of the resistivity values for the three boreholes in Kråkemåla K1, K2 and K3 (after correction for the influence of the borehole fluid).

3.2.3 Permeability of the boreholes

The water injection tests were carried out with different differential pressures (0.2, 0.4 and 0.6 MPa). The hydraulic conductivity of the measurement sections has been calculated for each differential pressure applied. The different differential pressures used usually give small differences in the hydraulic conductivity calculated for the measurement sections. But there are also certain differences in hydraulic conductivity. The clearest difference is that many measurement sections that do not have measurable permeabilities (2.4×10^{-9} m/s) at low differential pressures (0.2 MPa) can have measurable and sometimes high permeabilities at high differential pressures (0.4 and 0.6 MPa), see Figs. 3:10, :11 and :12. Many of these measurement sections are found in borehole sections situated directly adjacent to a large permeable crushed zone or fracture zone. At low differential pressures (0.2 MPa), these measurement sections situated directly adjacent to a large permeable zone do not have any hydraulic communication with the permeable fracture or crushed zone. This shows that high differential pressures can open the hydraulic connection between the fractures in the measurement section and the permeable fracture zone. The state of stress in the bedrock may be relieved next to a large fracture zone or crushed zone, which facilitates hydraulic connection between the zone and the fractures located adjacent to the zone.

It also happens that long borehole sections that do not have measurable permeabilities at a differential pressure of 0.2 MPa may contain isolated measurement sections that are permeable at 0.4 and 0.6 MPa, see Figs. 3:10, :11 and :12. These measurement sections are situated in borehole sections with a higher frequency of coated fractures in the core than the surrounding borehole sections. But some of the measurement sections are found in borehole sections that have a weathered drill core without coated fractures. The weathered borehole sections have a very high frequency of small fissures that are not visible to the naked eye (microfissures). The higher pressure sometimes causes water to be injected through this fine-mesh system of thin microfissures.

The other measurement sections have fractures that are impermeable at low differential pressures (no measurable water flows). But at high differential pressures (0.4 and 0.6 MPa), water can be injected through one or more of the fractures in the measurement sections. There are three possible explanations for why fractures that are impermeable at low differential pressures (0.2 MPa) can have high permeabilities at higher differential pressures (0.4 and 0.6 MPa).

- The higher differential pressure may flush out drillings that have clogged a permeable fracture.

- Water may be conducted past a sealing packer through fractures that are oriented along the borehole, i.e. if the water is forced a short way into the fracture, the longitudinal fractures can permit leakage past a sealing packer.

- The water flow through a fracture takes place through a more or less complex pattern of channels between the fracture planes (Maini 1971, Witherspoon 1980). This is due to the fact that the water moves through a system of channel-shaped cavities around the contact points between the fracture planes (Greenwood & Williamson 1966; Walsh & Grosenbaugh 1979). Therefore, fractures that are drilled through at a point where the loaded fracture faces are in good contact with each other do not have any measurable hydraulic conductivities at low differential pressures (0.2 MPa). If a borehole is drilled through a fracture plane that has a water-conducting tubular cavity in close connection with the borehole, a relatively low increase of the differential pressure - e.g. from 0.2 to 0.4 MPa - can cause a hydraulic connection to be opened up between the borehole and the water-conducting channel in the fracture plane. Since the applied differential pressure declines very rapidly moving away from the borehole, the injection tests have a relatively small radius of influence of approximately one to two dm from the borehole (Maini 1971). Thus, the water-conducting channels in the fracture planes must be situated very close to the borehole.

A differential pressure of 0.2 MPa has been used as a standard in the measurements, since this differential pressure has been considered to yield the most reliable results. Measurements with this differential pressure have therefore generally been selected for presentation (Gidlund et al 1979). The material presented in this and the following sections stems from measurements performed with a differential pressure of 0.2 MPa.

Most of the boreholes' measurement sections do not have measurable permeabilities. 73% of the measurement sections in all three boreholes do not have measurable permeabilities; the following percentages apply for the individual boreholes:

K 1: 64.3% K 2: 69.8% K 3: 86.3%

Compared to K1 and K2, K3 has a higher percentage of measurement sections with a high frequency of coated fractures. Nevertheless, K3 has a higher average resistivity and fewer permeable measurement sections than K1 and K2. Owing to the fact that K3, unlike K1 and K2 (vertical boreholes), slopes 50^{o} towards the horizontal plane, the steeply-dipping fractures are better represented. This shows that the borehole-penetrated steeply-dipping fractures in K3 generally constitute poorer transport pathways for electric currents and water than the borehole-penetrated fractures in the vertical boreholes (K1 and K2). This indicates that the vertical fractures on average have a lower pore water content and poorer hydraulic and electrical connection with each other than the more horizontally oriented fractures (cf. chap. 3.2.2). This may have several reasons or a combination of interacting reasons.

- The stresses in the Swedish bedrock have higher horizontal compressive components than vertical down to a depth of several hundred metres. As a result, the flat (horizontally oriented) fractures are less compressed than the steep (vertically oriented) fractures.

- Many of the mapped steep fractures in K3 may have been created by induced break along a sealed fracture.

The permeable measurement sections, which constitute 27% of the measurement sections, exhibit a relatively symmetric logarithmic normal distribution of hydraulic conductivity, see Fig. 3:13. The boreholes' permeable measurement sections have the following mean and standard deviation in hydraulic conductivity:

K1 + K2 + K3: 1.6×10^{-7} m/s + 0.7 parts of a decade.

The distribution of the permeable measurement sections' hydraulic conductivity shows some skewness towards the high hydraulic conductivities. Apart from four measurement sections in K3, all measurement sections with high hydraulic conductivities (above 10^{-5} m/s) are found in borehole K2. These measurement sections in K2 are, with the exception of one measurement section, situated in borehole sections with steeply-dipping fractures. The measurement sections are found primarily in borehole sections with large fracture or crushed zones, but in some of the measurement sections there are only a few isolated steep fractures. This indicates that steep fractures oriented along the borehole (K2 is a vertical borehole) can in some cases give rise to very high permeabilities. Measurement sections with high hydraulic conductivities (above 10^{-5} m/s) are found only in very few cases in borehole sections with fracture zones with only flat fractures. The reason for the high hydraulic conductivities of these measurement sections may be a combination of different interacting factors:

- Fractures oriented along the borehole can more easily cause water leakage past a sealing packer.

- Fractures oriented along the borehole have a larger contact surface with the borehole.

Owing to the fact that the water flow through the microfissures in the rock's matrix is too low to be measurable by means of the water injection test, the boreholes have many measurement sections with unmeasurable permeabilities. Most of the fractures that have been mapped in the core and observed in the borehole wall also have too low water flows to be measurable. The borehole sections with measurable permeability therefore represent the most permeable fractures.

The distribution of permeable measurement sections thus represents only the variation in permeability of large fractures and fracture systems, while microfissures in the bedrock's matrix do not make any measurable contribution to the permeability of the measurement sections.

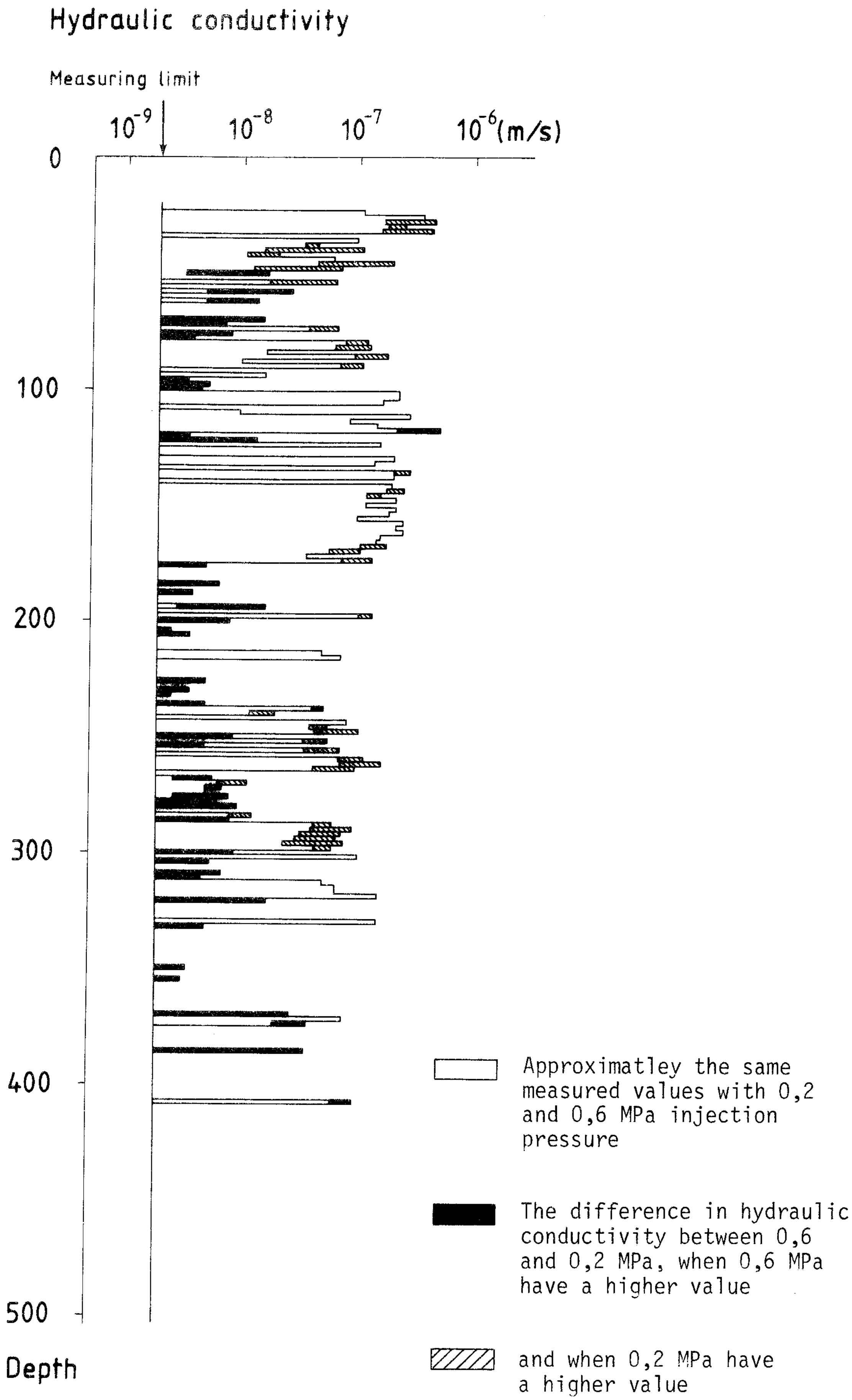


Fig 3:10. Water injection tests in 2 m sections along borehole K1.

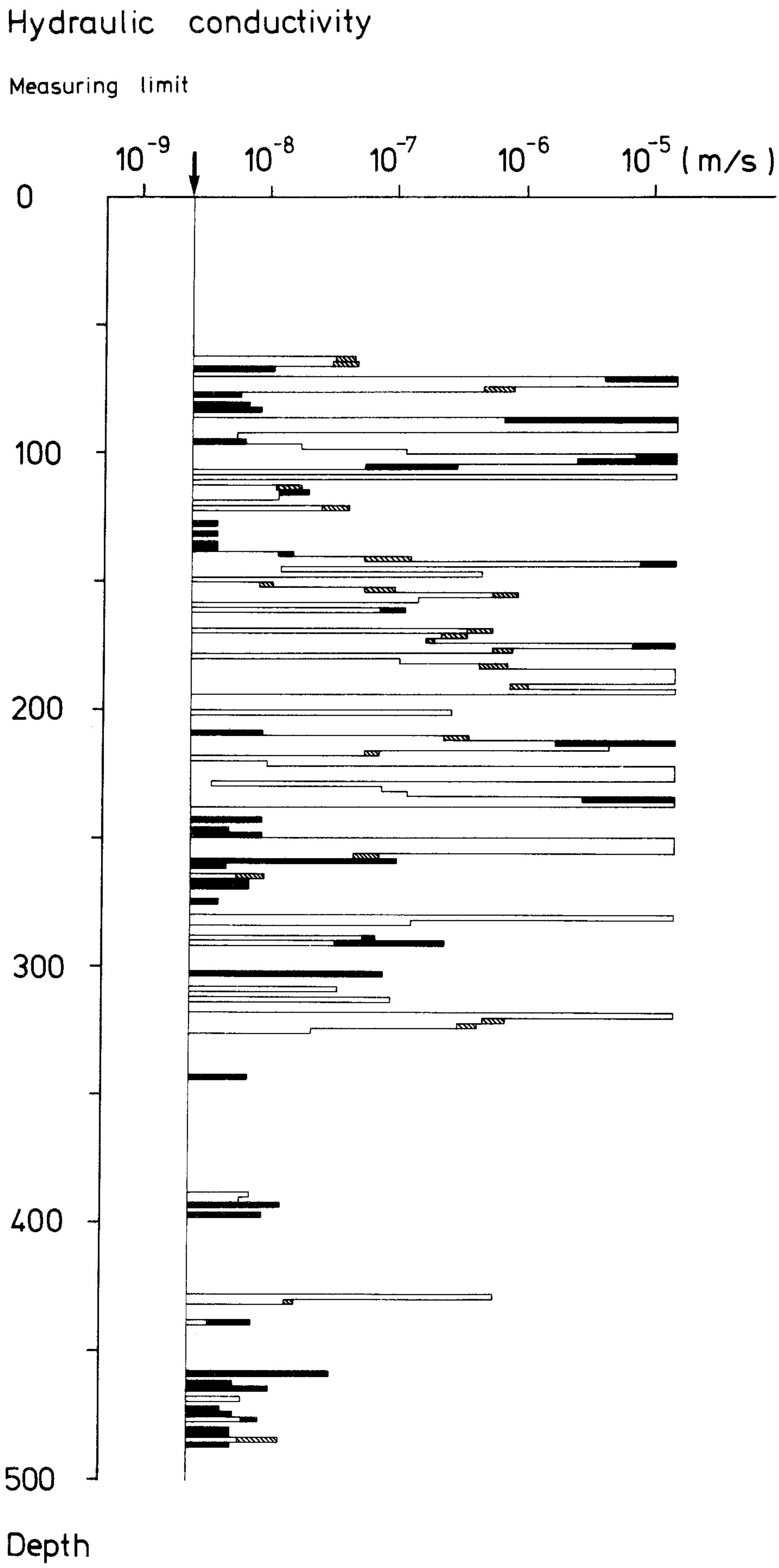


Fig. 3:11. Water injection tests in 2 m sections along borehole K2.

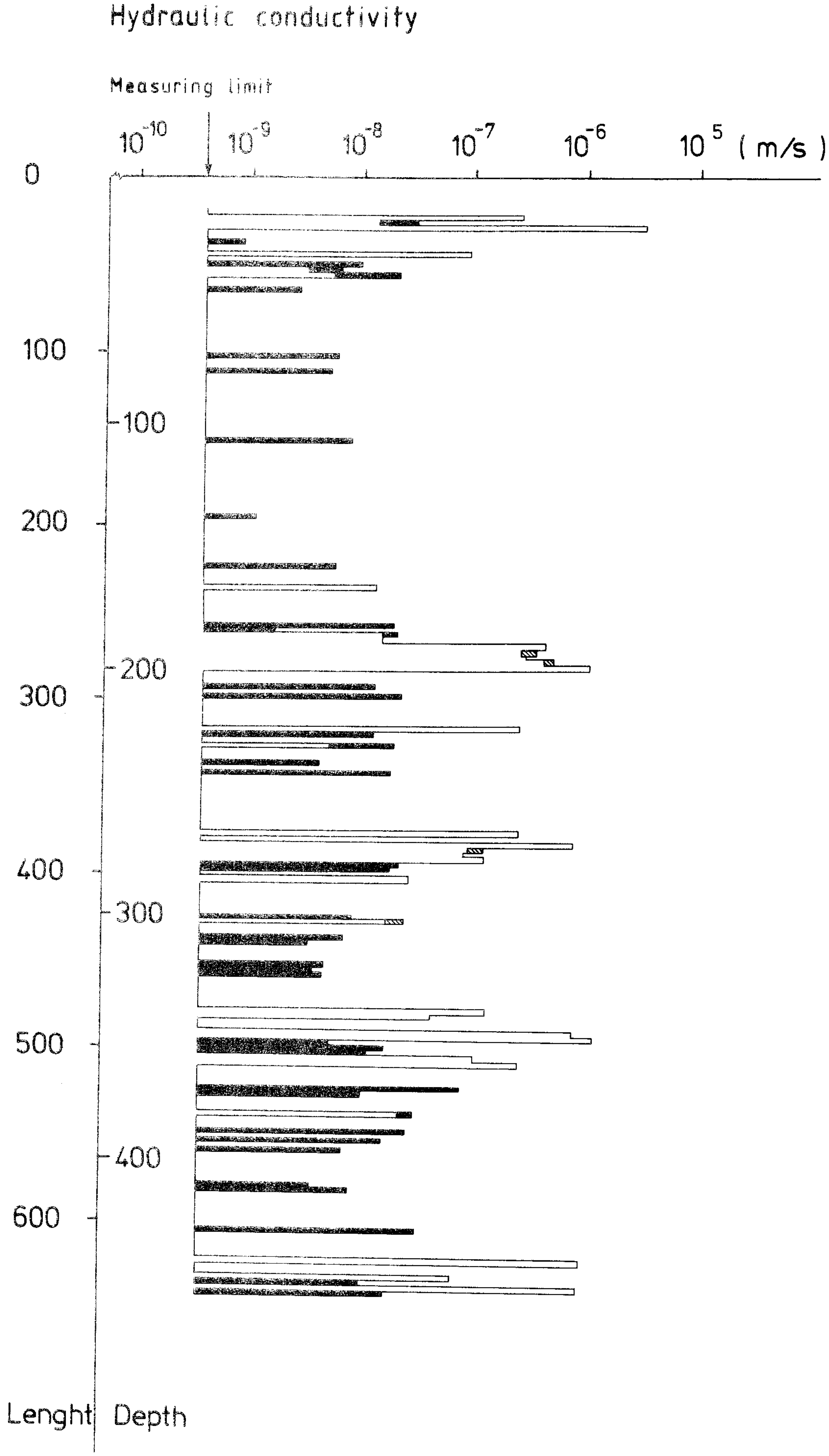


Fig. 3:12. Water injection tests in 2 m sections along borehole K3.

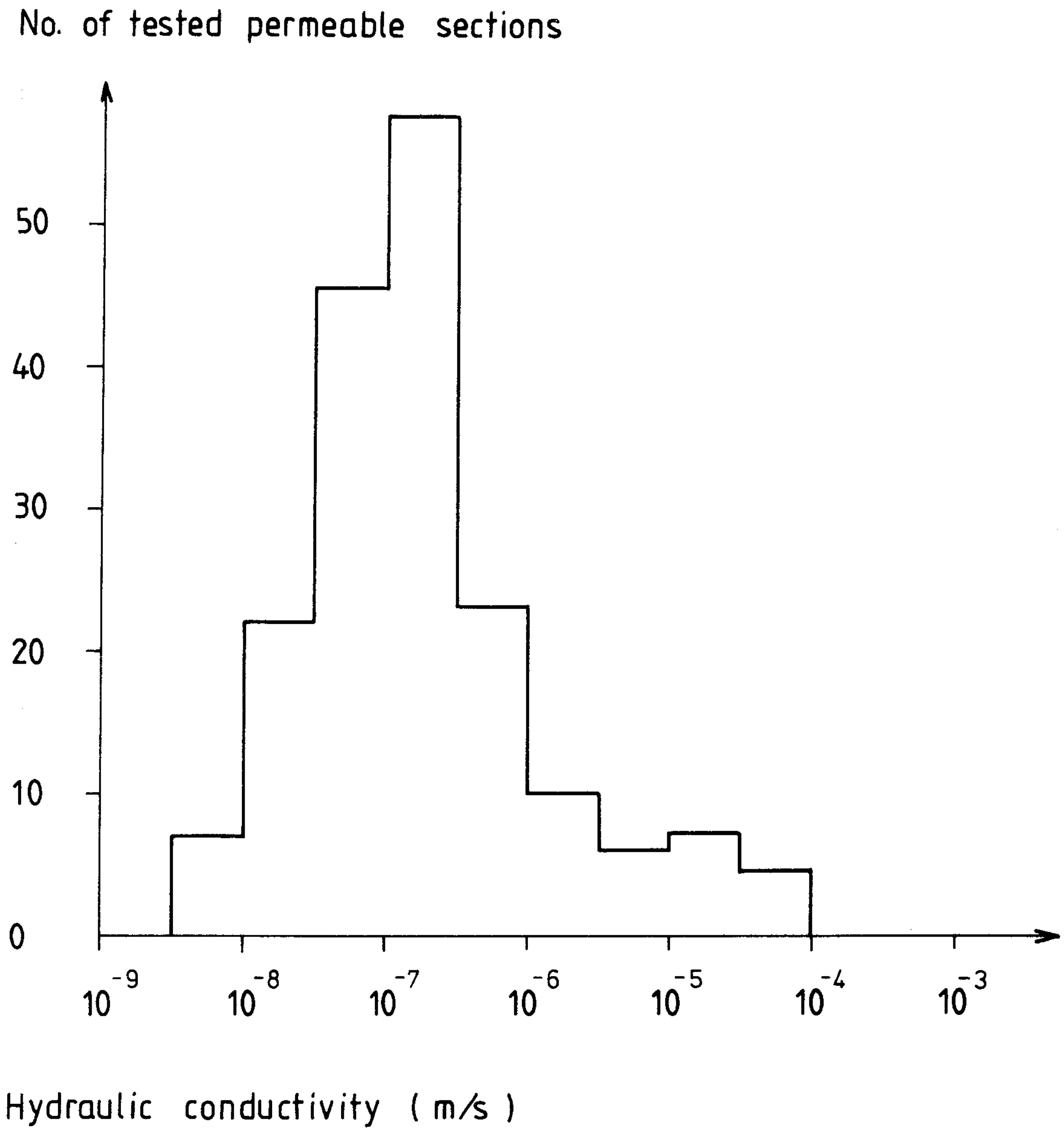


Fig. 3:13. Histogram of the tested permeable sections in K1, K2 and K3. The impermeable sections, i.e. below 2.4×10^{-9} m/s in hydraulic conductivity, constitute 73% of the tested sections in K1, K2 and K3.

3.3 Correlation of the borehole methods

3.3.1 Correlation of fracture frequency and resistivity

In order to be able more easily to compare the measured resistivity values with the fracture frequency along the boreholes, the bedrock along the boreholes has been divided into sections with different average resistivities. From the measured resistivity values (corrected for the influence of the borehole fluid), zones with different average resistivities have been defined and their average resistivity estimated. Lateral correction of thin zones (thinner than three times the configuration distance of 1.6 m) has also been carried out, see Appendix A. On the other hand, it is very difficult to estimate the resistivity in thin zones such as fracture zones that are considerably thinner (less than 0.5 m) than the configuration distance.

The resistivities along the boreholes exhibit a relatively good correlation with the fracture frequency in the drill core and the borehole wall, see Figs. 3:14, 3:15 and 3:16. Sections with lower resistivity than their surroundings are normally characterized by a higher frequency of coated fractures in the drill core.

Clusters of fractures thus normally give rise to a reduced resistivity in relation to surrounding sections. This is due to the fact that the fractures provide further pathways for current transport in addition to current propagation through the matrix. Since the matrix normally has high resistivities, the resistivity variations are controlled by the fracture zones in the bedrock, while variations in matrix resistivity give rise to variations in the background values of resistivity. The background values exhibit smaller resistivity variations than variations over the fractures.

The estimated resistivity of the sections has been compared with the fracture frequency in corresponding sections in the drill core and the borehole wall (fractures observed in the borehole wall in connection with TV inspection). The resistivity of the boreholes has been plotted on a log-log scale against the fracture frequency of corresponding sections in the core and the borehole wall. The frequency of fresh fractures in the core does not exhibit good correlation with resistivity, while coated fractures in the core exhibit a declining trend in resistivity with increasing fracture frequency, see Figs. 3:17 and 3:18. Generally the fresh fractures do not therefore have any influence on resistivity, which agrees with the assumption that these fractures have primarily arisen through induced core break.

Sections without coated fractures have not been included in the cross plot, owing to the fact that current transport in the fracture-free borehole sections takes place through microfissures in the matrix. In a similar manner, the resistivities in K1 and K2 have been plotted against the observed fracture frequency in the borehole wall, where resistivity also exhibits a declining trend with increasing fracture frequency, see Fig. 3:19. The boreholes have the following correlation coefficients between resistivity and fracture frequency in the core (coated fractures) and in the borehole wall:

Correlation coefficient between resistivity and fracture frequency in the core: -0.51.

Correlation coefficient between resistivity and fracture frequency in the borehole wall: -0.60.

The resistivity variations in the fracture-poor borehole sections (i.e. low fracture frequency) are controlled primarily by variations in the resistivity of the matrix, while fracture frequency is of less importance for the resistivity variations. This leads to a poor correlation between resistivity and fracture frequency. The resistivity of the matrix is controlled by the quantity of microfissures and their electrical interconnection. Zones with an extremely high frequency of microfissures, such as weathering zones, can have very low resistivities, below 5000 ohm-m. In these zones, the microfissures form a fine-mesh network of interconnected microfissures (Magnusson 1984).

In the boreholes in Kråkemåla, markedly low resistivities are found in some individual isolated fractures in an otherwise fracture-poor rock. This despite the fact that the fracture is several times thinner than the configuration distance (1.6 m). Besides good electrical conductivity, these isolated fractures are characterized by wide fracture apertures in the borehole wall as well as widening of the borehole's diameter (differential resistance log) and by high permeabilities. This means that individual highly electrically conductive fractures can have just as low resistivities as sections with a higher fracture frequency. Besides their good conductivity, the great influence of these large individual fractures can be caused by the fact that the fracture brings about a better electrical contact between closely-located systems of thin fractures (e.g. fracture indications and microfissures in the matrix) that are connected with the large fracture, i.e. the large fracture provides a better connection in a system with poor connection (i.e. creates a wider zone with low resistivity). This leads to poorer correlation between resistivity and fracture frequency (Magnusson 1984). Resistivity nevertheless exhibits a clear correlation with fracture frequency.

Resistivity has a somewhat better correlation with fracture frequency in the borehole wall than with the frequency of mapped coated fractures in the drill core. The difference between fracture frequency in the borehole wall and the drill core stems mainly from the fact that unmapped fracture indications in the core have been observed in the borehole wall. This indicates that current transport through the fracture indications also makes a small contribution to the total current transport in the bedrock.

Owing to the fact that the pores in crystalline bedrock consist for the most part of fractures, porosity is dependent on fracture frequency, which is clearly evident from the correlation between fracture frequency and resistivity (Figs 3:18 and 3:19). But in the fracture-poor borehole sections, most of the pores may consist of microfissures in the matrix. Fracture frequency does not take into account the different pore water contents of the fractures, which leads to a poorer correlation with resistivity.

Thin fractures in the borehole wall can be expected to have a lower water content than thicker fractures with a larger fracture width.

In order to achieve better correlation between resistivity and fracture frequencies in the bedrock, a fracture ratio has been defined by weighing in the apparent aperture of the fractures (observed by TV inspection). The fracture ratio is the sum of all fracture widths in mm within a section divided by the length of the section in metres, i.e. it provides a measure of how large a portion the fracture apertures constitute of the section. The fracture ratio has only been calculated for fracture zones with lower resistivity than their surroundings. A plot in a log-log scale of resistivity versus the fracture ratio shows a declining trend in resistivity with increasing fracture ratio. Compared to fracture frequency, the fracture ratio is related in a similar manner to resistivity, but gives a better correlation with resistivity, see Fig. 3:20.

Correlation coefficient between resistivity and fracture ratio: -0.76.

The relationship between resistivity and fracture frequency is dependent on the fractures' electrical contact with each other as well as their pore water content, i.e. individual fractures can have differing capacities for the transport of electric currents. The fractures can also be more or less sealed with fracture-filling material. Many mapped coated fractures may also have arisen through induced break along a sealed fracture. Taken together, this leads to a poorer correlation between resistivity and the fractures, e.g. fracture frequency. But because the current transport is distributed over the matrix and existing fractures within the measurement volume, an equalization of the differing capacities of the transport pathways to transport electrical currents is obtained. This leads to a more even distribution of current propagation over the measurement volume. Resistivity therefore provides a more average picture of the total number of transport pathways consisting of interconnected pores within the measurement volume. Thus, the resistivity measurements provide a picture of the bedrock's content of mobile and diffusion-available groundwater. Brace et al (1965) have shown through measurements on crystalline rock specimens that resistivity is inversely proportional to the square of porosity.

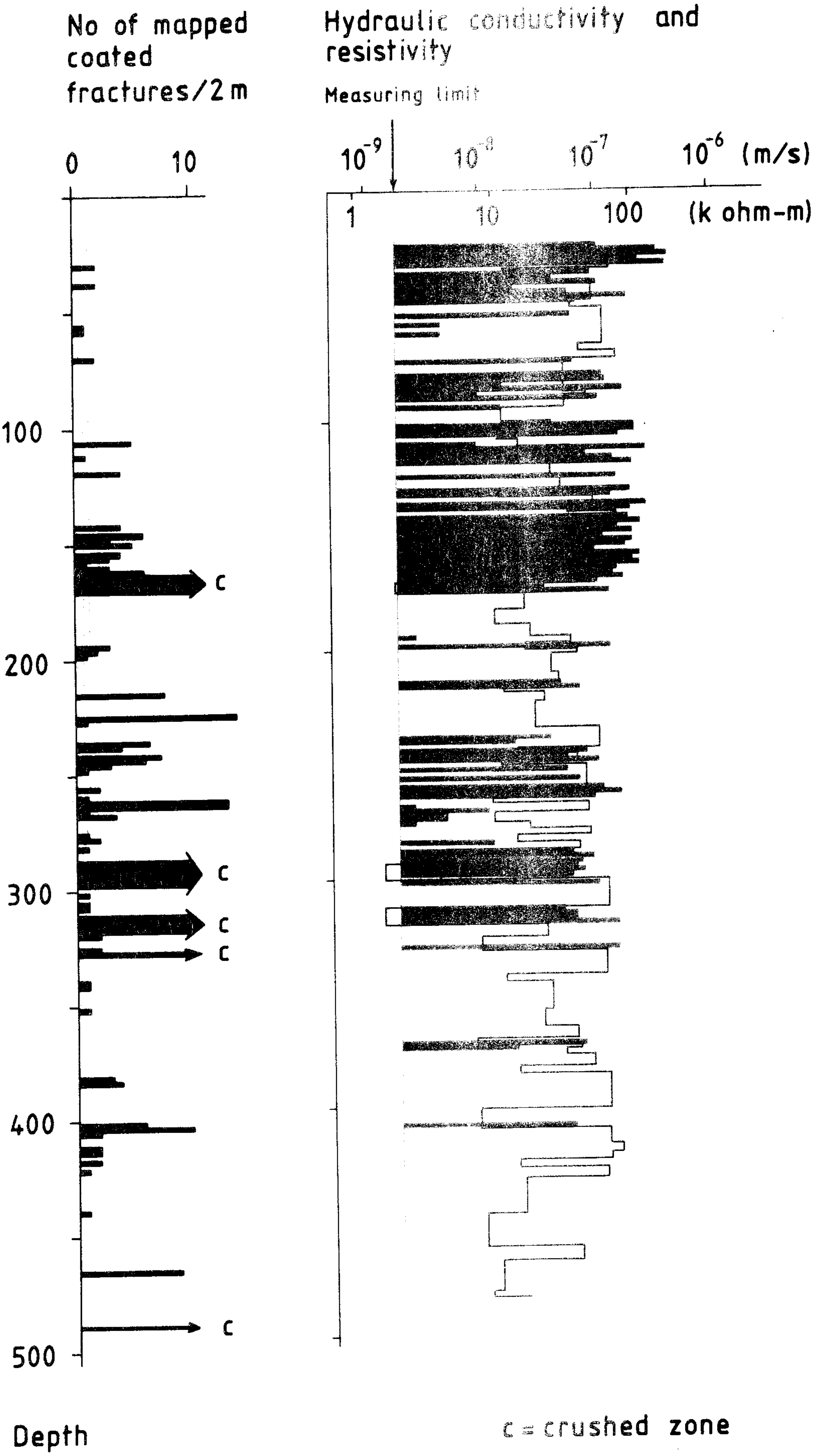


Fig 3:14. Borehole Kl. No of coated fractures in the injection tested 2 m sections along the core. Hydraulic conductivity of transmissive 2 m section (dark shade) along the borehole. Estimated resistivity along the borehole, after correction of the borehole fluid and lateral effects (solid line).

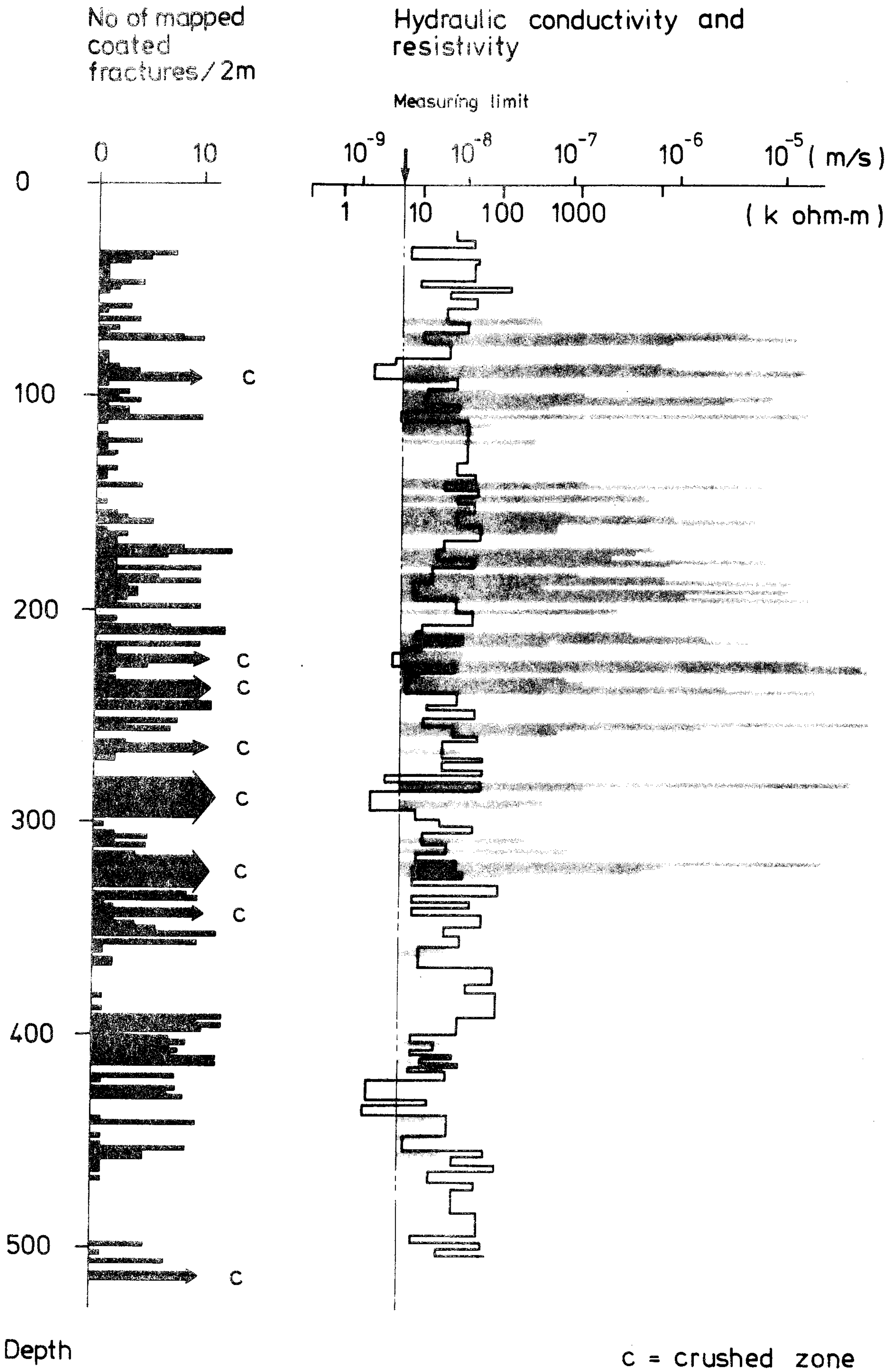


Fig 3:15. Borehole K2. No coated fractures in the injection tested 2 m sections along the core. Hydraulic conductivity of transmissive 2 m sections (dark shades) along the borehole. Estimated resistivity along the borehole after correction of borehole fluid and lateral effects (solid line).

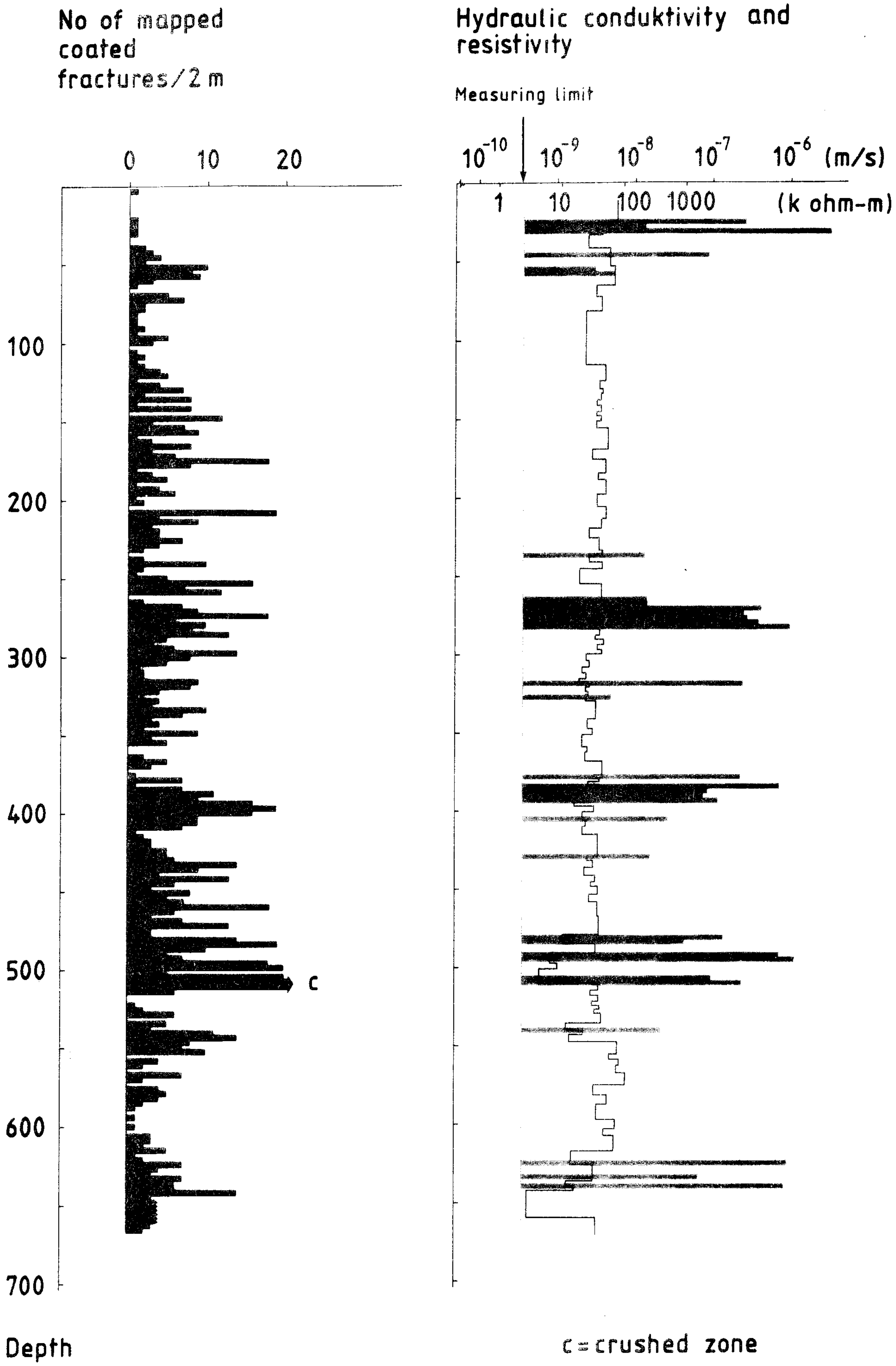


Fig 3:16. Borehole K3. No of coated fractures in injection tested 2 m sections along the core. Hydraulic conductivity of transmissive 2 m sections (dark shade) along the borehole. Estimated resistivity along the borehole after correction of the borehole fluid and lateral effects (solid line).

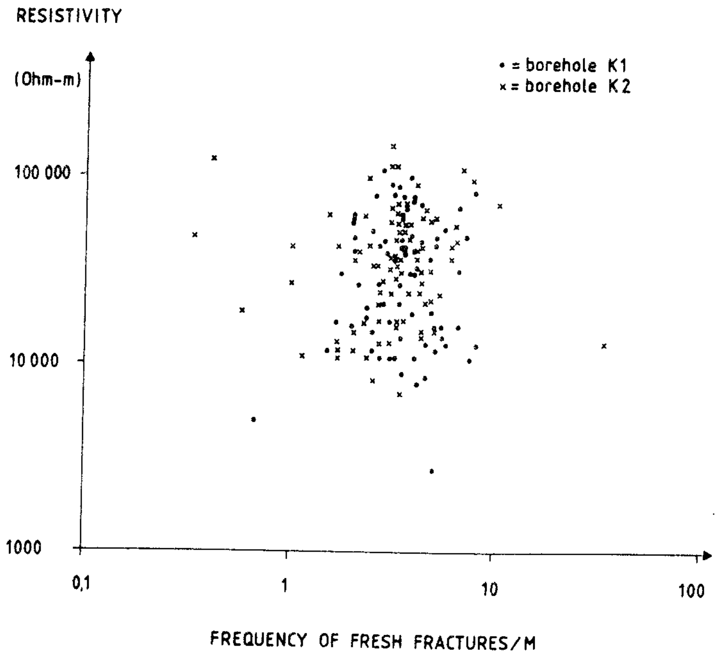


Fig. 3:17. Resistivity versus frequency of fresh fractures.

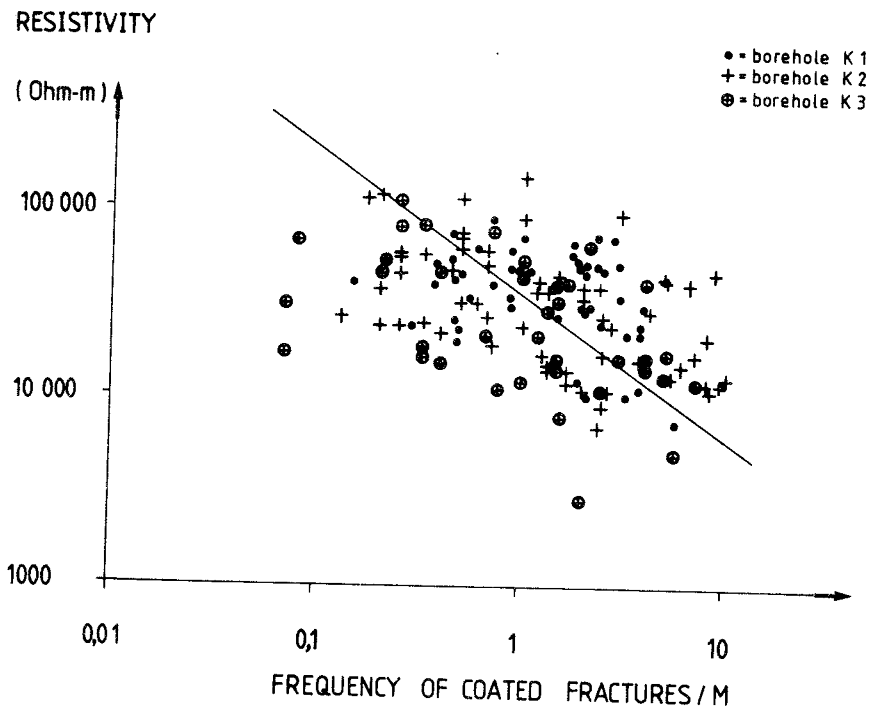


Fig. 3:18. Resistivity versus frequency of coated fractures.

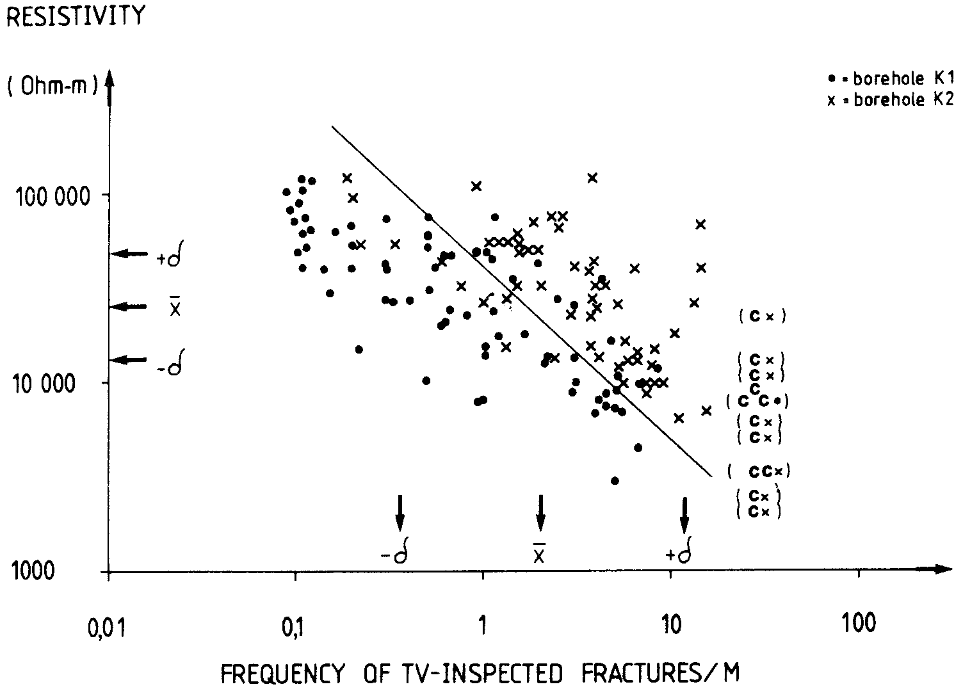
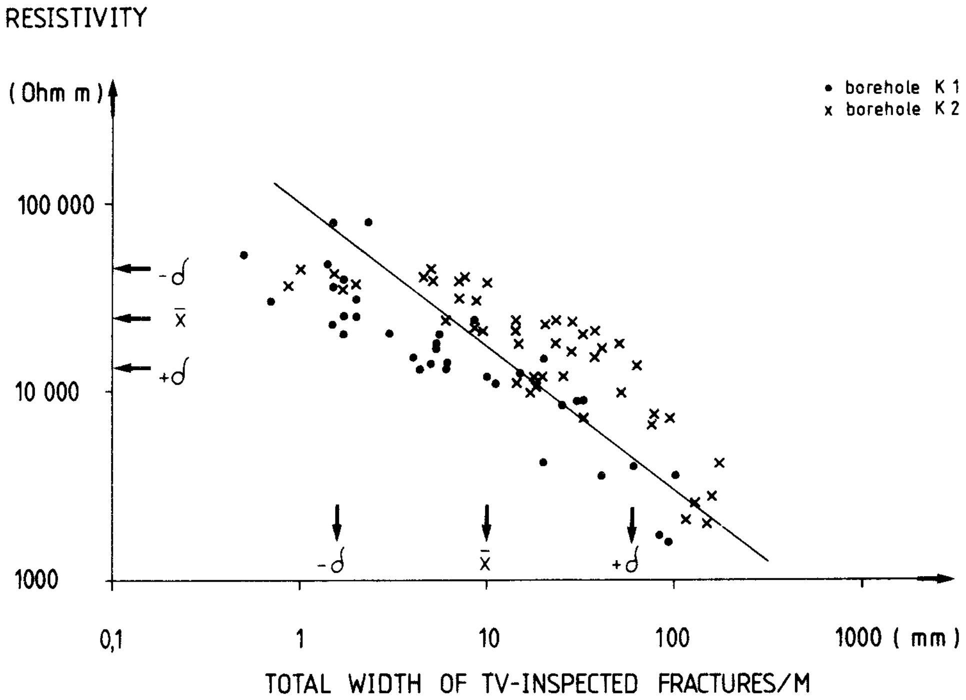


Fig. 3:19. Resistivity versus frequency of TV-inspected fractures.



FRACTURE RATIO = TOTAL WIDTH OF TV-INSPECTED FRACTURES/M

Fig. 3:20. Resistivity versus the sum of the width of all the fractures within a section with a defined resistivity.

3.3.2 Correlation of fracture frequency and permeability

The variation in hydraulic conductivity along the boreholes shows a relatively poor correlation with fracture frequency along the boreholes, see Figs. 3:14, 3:15 and 3:16. For example, measurement sections with a low fracture frequency, and in some cases with a few or a single isolated fracture in the borehole wall, may sometimes have high hydraulic conductivities that are comparable to those in measurement sections in crushed borehole sections. This indicates that in fractured formations, the injected water can primarily be channelled in a few, large, persistent and continuous fractures, while only an insignificant portion of the water is injected into other fractures in the section. This is also verified by the fact that different measurement sections within wide fracture or crushed zones can have very different permeabilities, with both high and low unmeasurable hydraulic conductivities (cf Magnusson 1984). Since the microfissures in the matrix and most of the mapped coated fractures have too low permeabilities to be measurable by means of the water injection tests, most of the measurement sections do not have measurable permeabilities. Thus, the water injection tests are controlled by individual large fractures. Boreholes K1 and K2 show a clear tendency towards having fewer permeable measurement sections with increasing depth. On the other hand, it is not possible to distinguish any tendency towards reduced fracture frequency with increasing depth, see Fig. 3:14, 3:15 and 3:16. But the permeable measurement sections show a tendency to occur primarily in connection with borehole sections with high fracture frequency.

Compared to the other boreholes (K1 and K2), K3 has much fewer permeable measurement sections, although it has, on average, more fractures in the measurement sections than K1 and K2. In addition, K1 has slightly more permeable measurement sections than K2, despite the fact that K1 is the fracture-poorest borehole. This also shows that there is no good relationship between permeability and fracture frequency in the boreholes.

Two of the boreholes in Kråkemåla (K1 and K2) exhibit large differences in permeability between their shallower and deeper parts. In the shallower parts of the boreholes, there are only a few impermeable measurement sections. These measurement sections contain only a few or no fractures. The shallow parts of these boreholes therefore have long borehole sections with an unbroken sequence of permeable measurement sections. This is due to the fact that, besides the fracture zones, a large portion of the fracture-poor borehole sections are also permeable. This shows that good hydraulic communication exists between the fractures in the upper parts of the boreholes. Unlike K1 and K2, K3 has few permeable measurement sections in the upper parts of the borehole as well. This despite the fact that K3 has, on average, a higher fracture frequency along the borehole than both K1 and K2.

In contrast, most measurement sections in the deeper parts (below 300 m) of all three boreholes (K1, K2 and K3) do not have measurable permeabilities, see Figs. 3:14, 3:15 and 3:16. Thus, the deeper parts of the boreholes are characterized by the presence of long borehole sections with unmeasurable permeabilities and by the fact that only a few isolated borehole sections are permeable. The permeable zones, which occur isolated in long impermeable borehole sections, generally have a relatively small width and encompass only one or a couple of measurement sections. In the deeper parts, the permeable measurement sections are generally limited to a few, well-defined fracture zones, but in some cases measurement sections that contain a single thick fracture can also be permeable, see Magnusson (1984). The fractures that occur in the borehole sections surrounding the permeable fracture zones therefore have poor communication with the fracture zone.

Since the water injection is controlled by large individual permeable fractures, the plot of hydraulic conductivity versus fracture frequency shows poor correlation (Fig. 3:21 and 3:22). Because the permeable fractures have a large span in hydraulic conductivity from unmeasurable ($<2.4 \times 10^{-9}$ m/s) to high hydraulic conductivities in excess of 10^{-7} m/s (measurement sections with a single isolated fracture have conductivities in excess of 10^{-7} m/s, cf. Magnusson 1984), the measurement sections exhibit abrupt and rapid fluctuations in hydraulic conductivity. This means that in measurement sections containing many fractures, the contribution of the different fractures to the measured permeabilities may differ widely, i.e. almost the entire permeability may stem from a single open permeable fracture. Thus, hydraulic conductivity is not directly dependent on the number of fractures within the measurement section, but rather on the hydraulic properties of the individual fractures.

Nevertheless, certain characteristic trends appear in the cross-plot diagrams (Figs. 3:21 and 3:22). Since hydraulic conditions change with increasing depth, the hydraulic conductivities and the number of coated fractures in the measurement sections are reported for each depth section of 100 metres, i.e. 0-100, 100-200, 200-300, 300-400 and 400-500 metres.

In the upper 100 metres of boreholes K1 and K2, virtually all measurement sections that contain one or more fractures are permeable, with the exception of two measurement sections in K1 and five in K2. However, even in this upper part of the borehole, K3 has - as in all other borehole sections along the borehole - few permeable measurement sections. Thus, even in the superficial parts of K3, measurement sections with a comparatively high fracture frequency can have unmeasurable permeabilities. In boreholes K1 and K2, even borehole sections without mapped coated fractures can have measurable hydraulic conductivities. Borehole K1 in particular has many such measurement sections. In some of these measurement sections, there are fractures with polished fracture surfaces (designated p in the cross-plot diagrams). These fracture surfaces have therefore probably had coated fracture surfaces where the mineral coating has been polished off. In other cases, these measurement sections may have water-bearing mineral-coated surfaces in adjacent measurement sections. Since displacements can occur in the depth determination of the core and the water injection tests, one of the 2-metre packers may have been placed next to a water-bearing coated fracture. But in some cases, long borehole sections without any mapped fracture may also have permeable measurement sections. In these borehole sections, there may sometimes be only a few fracture indications in the drill core and in some cases also a few thin fractures in the borehole wall (Magnusson 1984.) This shows that the prevailing stress conditions in the superficial parts of K1 and K2 permit injection of water even in closed discontinuities such as fracture indications, i.e. the differential pressure can cause water to be forced into these closed discontinuities as well, see Magnusson (1984).

Between 100 and 200 m depth, most of the measurement sections in K1 and K2 that contain one or more fractures are still permeable. But the number of impermeable measurement sections with few isolated fractures is much greater than in the shallower parts above 100 m.

Between 200 and 300 m depth in K1 and K2, the number of permeable and impermeable measurement sections that contain one or a few fractures is approximately equal. Within this section in the boreholes, there are also a greater number of impermeable measurement sections that contain relatively many fractures (11 sections with more than 5 fractures).

Below a depth of 300 metres, permeability in K1 and K2 differs drastically from the shallow parts of the boreholes. In the deeper parts below 300 m, there are few permeable measurement sections in all three boreholes, and several measurement sections that contain many fractures have unmeasurable permeabilities. The permeable measurement sections below a depth of 300 metres usually have a high fracture frequency. But there are also a few permeable measurement sections with few, isolated fractures (Magnusson 1984). These isolated fractures have large fracture apertures in the borehole wall (TV inspection) and large widenings in the diameter of the borehole (according to differential resistance).

The results of the comparison can be summarized as follows:

- In the shallower parts of e.g. boreholes K1 and K2, virtually all measurement sections containing one or more fractures are permeable. But with increasing depth, fewer and fewer of the measurement sections that contain one or a few fractures are permeable, and at greater depths (below 300 m), there are very few such measurement sections. In the deeper parts of the boreholes, these isolated fractures have large fracture apertures in the borehole wall (observed in TV inspection) and large widenings in the diameter of the borehole (according to differential resistance).

- With increasing depth, more and more measurement sections containing relatively many fractures also have unmeasurable permeabilities, and in some cases even highly fractured borehole sections can have unmeasurable permeabilities. Therefore, the permeable measurement sections in the deeper parts of the boreholes are mainly found in fractured borehole sections with a high fracture frequency.

The results from K1 and K2 show that in the shallower parts of the boreholes, water can be injected in virtually all mapped coated fractures. But with increasing depth, fewer and fewer of these fractures become permeable. This shows that with increasing depth, the state of stress in the bedrock leads to an increasing compression closure of the fractures, i.e. where the fractures are intersected by boreholes, the fracture surfaces are in good contact with each other (Greenwood & Williamson 1966; Walsh & Grosenbaugh 1979). A particularly distinct change in the permeability of the fractures take place below a depth of about 300 m. Below this depth, very few of the fractures are permeable. The upper parts of the bedrock have higher horizontal compression stresses than vertical. As a result, horizontal fractures in the upper parts of the bedrock are less compressed than vertical ones. Since K1 and K2 are vertical boreholes, the horizontal fractures are better represented in these boreholes. This is probably the reason why most of the measurement sections in the shallower parts of boreholes K1 and K2 have measurable permeabilities. In the upper parts of K3, even measurement sections with a relatively high frequency of coated fractures can have unmeasurable permeabilities, which indicates that these fractures are more compressed. Unlike K1 and K2, K3 slopes 50^{o} to the horizontal plane, as a result of which the vertical fractures are better represented in this borehole.

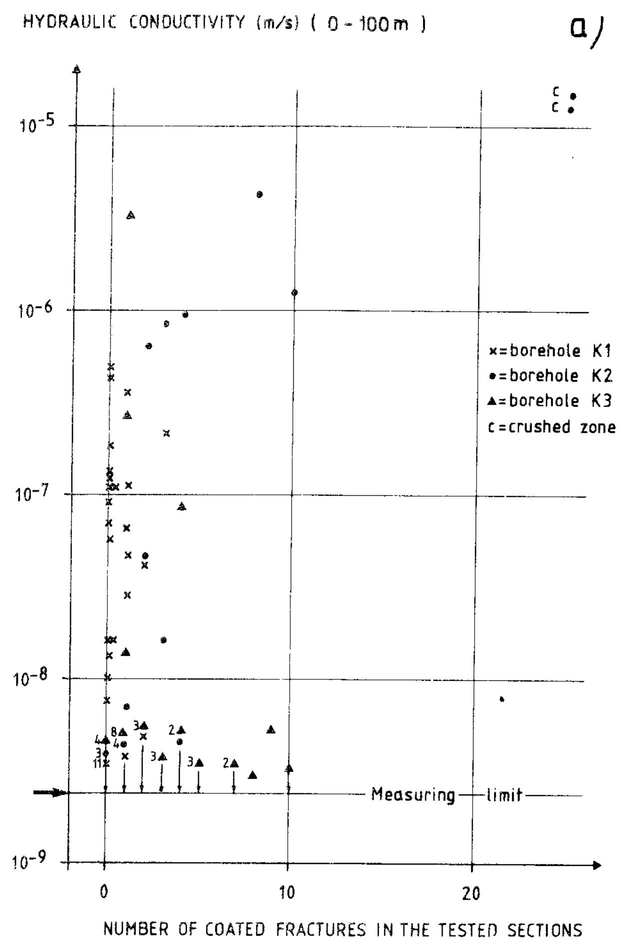
The fracture faces are rough and the fractures do therefore not close entirely, leaving cavities between the points where the fracture faces are in good contact with each other. But with increasing compression of the fractures, the points where the fracture faces are in good contact with each other increase, cutting off many water transport pathways. Compression of the fractures also leads to poorer hydraulic communication between the water transport pathways in interconnected fractures. If a fracture plane is drilled through so that permeable channel-shaped cavities occur in contact with the borehole, the fractures in the deeper parts of the boreholes can also give rise to high sums in hydraulic conductivity that are comparable to the values measured in the upper parts of the borehole. The cavities between the fractures are controlled by the irregularities on the fracture faces, which means that even loaded fractures can have large cavities in certain parts along the fracture planes. For this reason, measurement sections with a single thick isolated fracture (large fracture aperture in the borehole wall) have, in some cases, high permeabilities even in the deeper parts of the boreholes, comparable to those of measurement sections in crushed borehole sections, cf. Magnusson (1984).

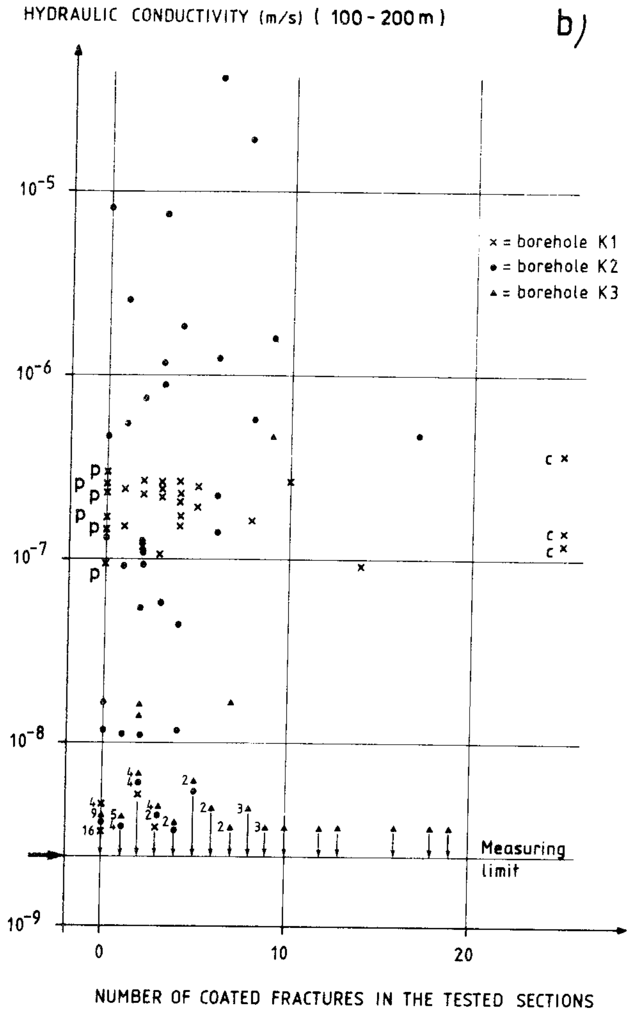
At greater depths, highly fractured borehole sections can also have unmeasurable permeabilities, which shows that none of the fractures penetrated by the borehole has any water-conducting channel in contact with the borehole, i.e. where the fractures are drilled through, the fracture faces are in good contact with each other. This shows that the permeability of the measurement sections is mainly controlled by isolated individual fractures that have permeable cavities in contact with the borehole, while most of the fractures in the deeper parts of the boreholes do not have any permeable cavities in contact with the borehole. But the greater the number of borehole-penetrated fractures that occur in a measurement section, the greater is the probability of encountering a permeable channel in contact with the borehole. A large number of fractures in the measurement section also increases the hydraulic communication between the transport pathways in different fractures.

The permeable measurement sections show no tendency towards having lower values of hydraulic conductivity with increasing depth. This may be due to the fact that the permeable fractures have a very large span of hydraulic conductivity, causing wide variation in the hydraulic conductivities measured in the measurement sections. In consequence, the spread in measured hydraulic conductivity may mask a tendency towards a declining value of hydraulic conductivity in the permeable measurement sections with increasing depth.

The water injection tests also show a poor correlation to the thickness of the fractures in the borehole wall. Thick fractures that constitute widenings in the diameter of the borehole according to differential resistance normally have measurable permeabilities, but in some cases, such fractures may also have unmeasurable permeabilities. Thin fractures less than 1 mm in width and with undetectable widenings in the diameter of the upper parts of the boreholes may also have high permeabilities (Magnusson 1984). But the fracture apertures calculated from the water injection tests are usually only a few tenths of a µm wide, which shows that the fracture widths in the borehole wall are several times greater. For example, in an investigation of a borehole in crystalline bedrock in Canada, it was found that the largest fracture aperture in the borehole wall (TV inspection and televiewer) was 1000 µm, while the fracture aperture calculated from the hydraulic tests was only 123 µm (Davidson 1980).

The fracture apertures calculated from the water injection tests are so small that they can only be observed with great difficulty with the naked eye, i.e. of microscopic size. But since permeable fractures are not microscopic discontinuities, but rather can easily be observed with the naked eye, these calculated fracture apertures probably constitute a very great underestimate of the width of the fractures. This also verifies the assumption that the flow of water in the fractures is restricted to a few permeable channels that constitute a very small fracture of the total fracture surface, i.e. the model with water flow through a plane-parallel joint does not provide a good picture of the average fracture aperture. Due to the fact that chips detach more readily from the edges of open fractures than from the edges of closed fractures, open fractures can often have apparently wider apertures and larger widenings in the diameter of the borehole. In any case, the results show that the fracture apertures in the borehole hole are merely apparent fracture apertures that do not represent the tubular cavities of the water transport pathways.





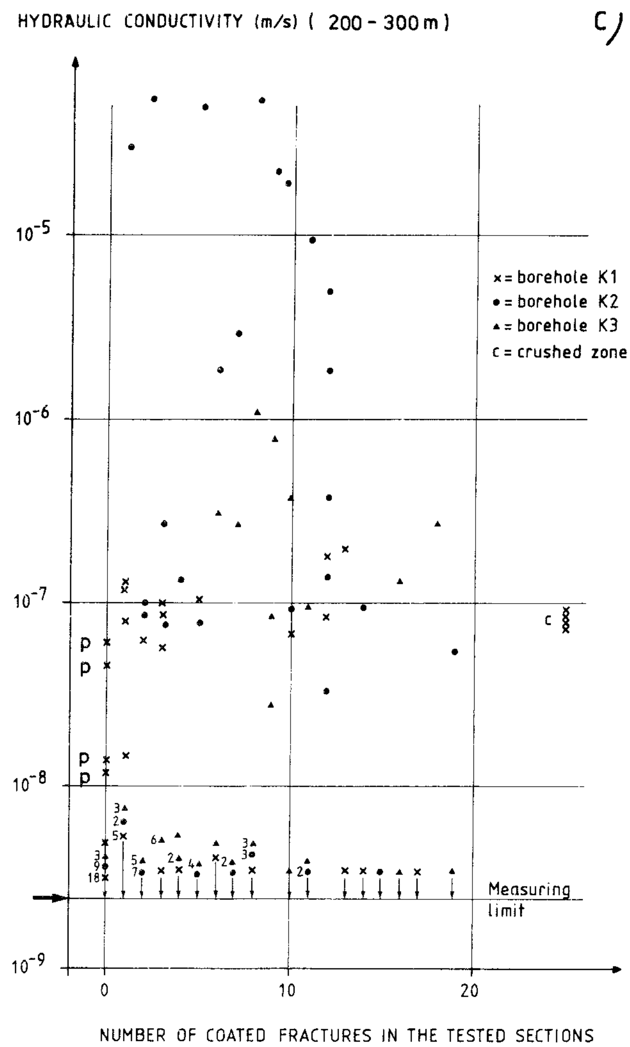
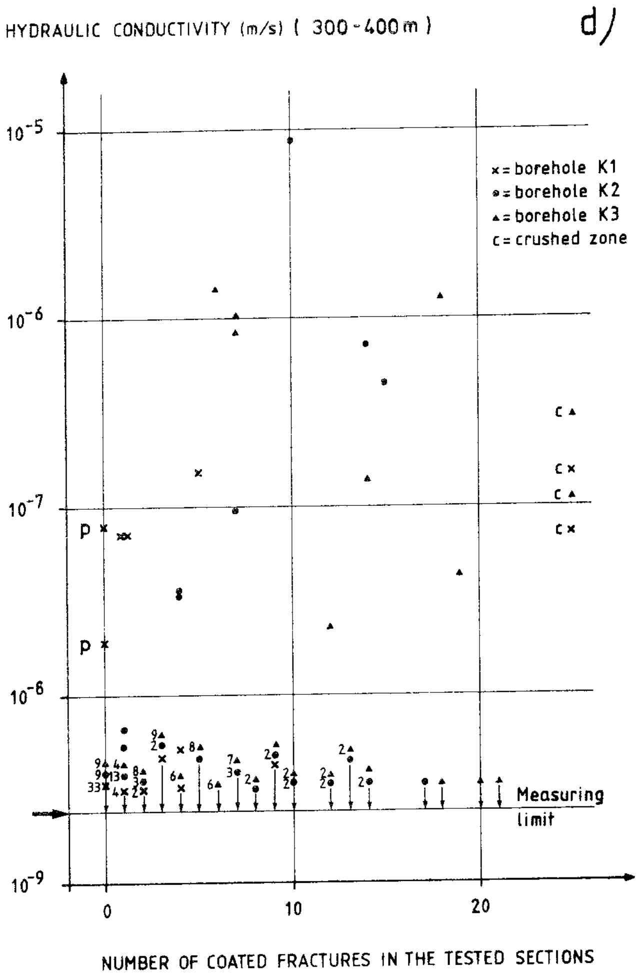


Fig. 3:21. Hydraulic conductivity vs the number of coated fractures in three boreholes in Kråkemala, (a) the sections from 0 to 100 m, (b) the sections between 100 and 200 m and (c) the sections between 200 and 300 m depth. P=tested sections containing polished fractures which were mapped as fresh fractures.



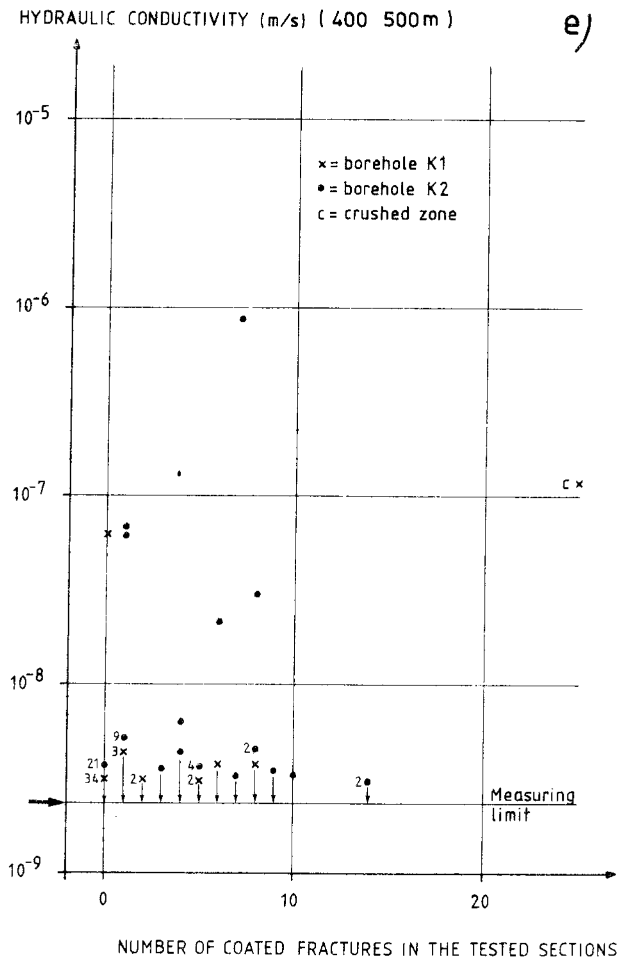


Fig. 3:2 2 Hydraulic conductivity vs the number of coated fractures in three boreholes in Kråkemala, (d) the sections between 300 and 400 m and (e) the sections between 400 and 500 m depth. P=tested sections containing polished fractures.

3.3.3 Correlation of resistivity and permeability

The water injection tests are controlled by individual large permeable fractures and therefore exhibit very rapid fluctuations in hydraulic conductivity along the boreholes. For example, measurement sections with high hydraulic conductivities can be followed directly by impermeable measurement sections. This means that permeable borehole sections do not exhibit a continuous transition to impermeable borehole sections. Because electric current transport in the bedrock is distributed over a number of transport pathways (both existing fractures and microfissures in the matrix), however, measured resistivities exhibit more continuous variations along the boreholes. Observe that figures 3:14, 3:15 and 3:16 have sectionalized resistivities, i.e. zones with different average resistivities have been delimited from the measured continuous resistivity values and their average resistivity estimated.

Owing to the very wide span in hydraulic conductivity of the permeable fractures, the boreholes exhibit a very large variation in measured hydraulic conductivity, from very permeable measurement sections with hydraulic conductivities on the order of 10^{-5} to 10^{-4} m/s to the measurement sections with unmeasurable permeability (2.4×10^{-9} m/s). Because electric current transport in the bedrock is distributed over a number of transport pathways, the effect of the differences in the highly varying capacities of the transport pathways to transport currents is evened out, as a result of which the resistivity has a smaller range of variation, varying only over two powers of ten, i.e. between 100 000 and 1 000 ohm-m, while the measurable hydraulic conductivities vary over at least five powers of ten (Figs. 3:14, 3:15 and 3:16). But because the impermeable parts of the bedrock have unmeasurable hydraulic conductivities, the bedrock's range of variation in hydraulic conductivity is considerably greater than that measured. Among other things, measurements performed on rock samples have shown that the matrix has hydraulic conductivities between 10^{-16} and 10^{-9} m/s, Brace (1980). In the matrix, water transport takes place through a network of interconnected microfissures.

The water injections also show a clear tendency towards fewer permeable measurement sections with increasing depth. The resistivity measurements, on the other hand, show no detectable tendency towards either lower average resistivity or fewer low-resistivity zones. But the greatest difference between the measurement methods is that in many borehole sections, the existing transport pathways for water have too low flows to be measurable by means of the water-injection tests, while there are no borehole sections that have too low current propagation to be measurable.

The permeable measurement sections exhibit, however, a tendency towards occurring in connection with borehole sections with low resistivity in relation to their surroundings. But the sum of the measured hydraulic conductivities does not exhibit any correlation with resistivity (Figs. 3:14, 3:15 and 3:16). In order to compare hydraulic conductivity with the resistivity, the hydraulic conductivity of the measurement sections has been plotted against the resistivity of corresponding borehole sections. Although the methods do not show any good correlation with each other, certain characteristic features emerge in the cross-plot diagrams. Owing to the fact that hydraulic conditions change with increasing depth, the boreholes have been divided into 100 m depth sections, i.e. 0-100, 100-200, 200-300, 300-400 and 400-500 m, see Figs. 3:23, 3:24 and 3:25.

In the upper parts of the boreholes, virtually all measurement sections that are situated in connection with low-resistivity borehole sections have measurable permeabilities. But there are also measurement sections with unmeasurable permeabilities (2.4×10^{-9} m/s) in connection with two relatively low-resistivity (20 000 ohm-m) borehole sections in K1 (97-107 m and 175-195 m). These borehole sections lack coated fractures in the core and have only a few thin fractures in the borehole wall, which indicates that the low resistivity is primarily caused by a higher number of microfissures in the matrix, cf Magnusson (1984). There are also high-resistivity borehole sections with high hydraulic conductivities in the shallower parts of the boreholes; for example, above a depth of 100 m, there are many permeable measurement sections in borehole sections that have resistivities higher than 60 000 ohm-m. But below a depth of 100 m, there are no permeable measurement sections in borehole sections that have a resistivity in excess of 60 000 ohm-m.

Between 200 and 300 metres, there are no permeable measurement sections in borehole sections that have resistivities in excess of 50 000 ohm-m. At this depth, even many relatively low-resistivity borehole sections (below 20 000 ohm-m) have measurement sections with unmeasurable permeabilities. In borehole K2, there is even a low-resistivity (200-300 ohm-m) crushed zone (K2:280-295 m) with four impermeable measurement sections (Magnusson, 1984).

There are very few permeable measurement sections below a depth of 300 m, and with the exception of one measurement section, the permeable measurement sections occur only in connection with borehole sections with resistivities that are lower than 30 000 ohm-m. The exceptional measurement section (K1:303 m) is situated in fracture-poor borehole section between two large crushed zones at 294-300 m and 214-318 m in K1, cf. Magnusson (1984). The crushed zones probably relieve the stress in the intervening rock mass, so that overlying measurement sections can contain a fracture with good hydraulic communication with one of the surrounding crushed zones. In the deeper borehole sections, even low resistivity borehole sections (with resistivities below 10 000 ohm-m) often have unmeasurable permeabilities. The results of the cross-plotting can be summarized as follows:

1. In the shallower portions of the boreholes, measurement sections that occur in very high-resistivity borehole sections often have high permeabilities. Current propagation therefore takes place primarily through the matrix, i.e. only an insignificant portion of the current is transported through existing fractures. The high resistivity therefore shows that the matrix also has a low content of electrically interconnected microfissures. The borehole sections thus consist of compact rock with very few to virtually no fractures, i.e. they contain individual isolated fractures

in an otherwise rather long fracture-free section, and in some cases even with long sections that do not contain any mapped coated fractures. In these measurement sections, the injected water is forced out into closed discontinuities such as fracture indications, cf. Magnusson (1984). This shows that the stress conditions in the near-surface parts of the bedrock enable water to be injected even in borehole sections that have large fracture spacings and are thereby characterized by very sparse fractures, and in some cases water can even be injected into sections which contain a few fracture indications. This shows that in these extremely fracture-poor and high-resistivity portions, the measured high hydraulic conductivity values cannot be regarded as giving a representative picture of the permeability of the bedrock.

2. With increasing depth, the permeable measurement sections show a clear tendency to occur primarily in low-resistivity borehole sections as well as a tendency to have a number of impermeable measurement sections, even in low-resistivity borehole sections. This shows that in deeper parts of the boreholes, even highly fractured or crushed borehole sections with low resistivities (about 10 000 ohm-m) can have unmeasurable permeabilities. In these low-resistivity borehole sections, the fractures constitute good transport pathways for the electric currents. The fractures constitute an electrically interconnected system of unclosed fractures, i.e. fractures with sufficient pore water content to serve as good transport pathways for electric currents.

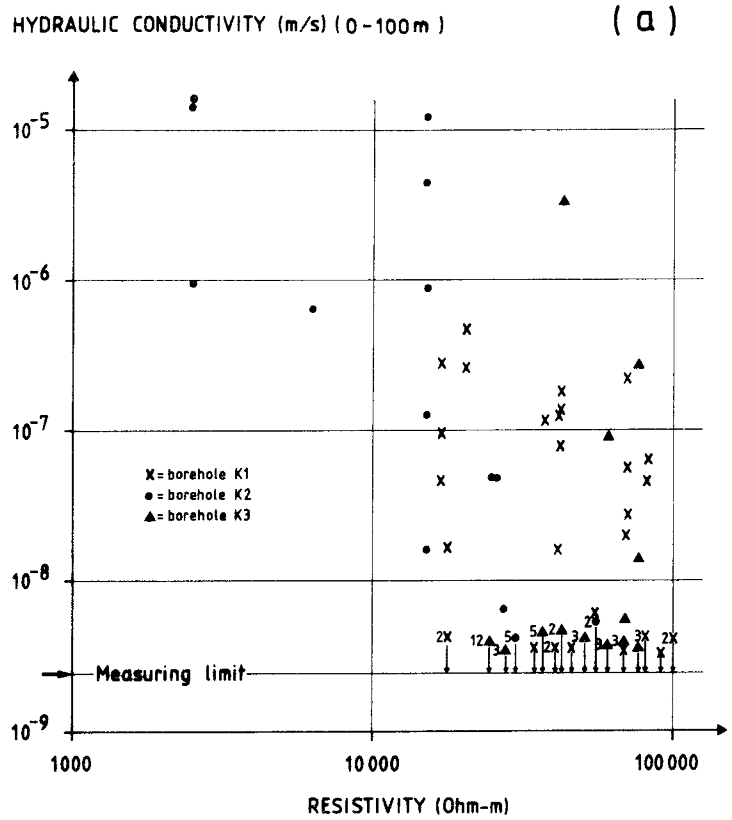
The big difference between the patterns of variation of permeability and resistivity along the boreholes is caused by differences in current propagation through the bedrock's fractures and microfissures compared to water injection into them. This shows that the fractures and microfissures that constitute transport pathways for both water and electric currents have very different transport characteristics for current and water.

In contrast to the water injection tests, the resistivity measurements do not show any detectable tendency towards either a lower average resistivity or fewer low-resistivity zones with increasing depth. This shows that the propagation of current through the matrix and the existing fractures does not exhibit any tendency to decrease with increasing depth. This suggests that, down to a depth of 500 m, increasing depth does not lead to any major change in the capacity of the fractures to transport electric currents. The clear tendency of the boreholes towards having fewer permeable measurement sections with increasing depth is caused by the fact that fewer and fewer of the borehole-penetrated fractures have measurable permeabilities, i.e. no measurable water volumes can be injected into many of the borehole-penetrated fractures. These differences between the resistivity and permeability of the boreholes are caused by the fact that with increasing depth, the stress conditions in the bedrock lead to increased compression (closure) of the fractures. This compression of the fractures has a very different effect on resistivity and permeability. This probably depends on the configuration of the cavities between the compressed fracture faces.

Owing to the rough surfaces of the fracture surfaces, cavities exist between the points where the fracture surfaces are in good contact with each other. As a result, it is mainly the number of contact points and their total surface area that increases with increasing compression of the fracture surfaces, while the distance between the fracture surfaces is affected to a lesser degree. For this reason, pore spaces occur between the fracture faces even under high load (Greenwood & Williamson 1966; Walsh & Grosenbaugh 1979). Maini (1971) has shown that water flow takes place primarily through channels consisting of large, well-interconnected cavities, while smaller and poorly interconnected cavities have relatively stationary water in comparison with the channels. Brace et al (1965) have shown that the propagation of electric current can take place even in thin water films between compressed fracture surfaces. This type of current conduction is termed surface conduction in contrast to volume conduction through the pore fluid in large, well-interconnected cavities.

A probable explanation for the differences between the water injection tests and measured resistivities is that the water is injected into the large, permeable channels, while smaller and poorly interconnected cavities do not have measurable water flows. Surface conduction, on the other hand, can take place even through smaller, impermeable cavities. Thin skins of alteration products such as clay minerals may also contribute to current propagation. This means that many impermeable fractures can constitute relatively good transport pathways for electric currents. Compression of the fracture surfaces leads to an increase in the number of contact points on the surfaces, which in turn cuts off many permeable channels. Compression of the fracture surfaces therefore often cuts off the borehole-penetrated fractures from larger, permeable channels situated in the vicinity of the borehole. On the other hand, compression of the fracture surfaces has no effect on alteration products and seems to have much less of an effect on the poorly interconnected cavities containing relatively stationary water, i.e. the quantity of pore water in the fractures is affected to a lesser degree by compression of the fracture surfaces. Brace et al (1965) have shown that increased loading of samples leads to reduced electrical conductivity and that surface conduction also declines because some of the thin water films are also cut off. But the measurement results in Krakemåla do not indicate any detectable tendency towards lower resistivity with increasing depth, which indicates that down to a depth of 500 m, compression of the fracture surfaces does not lead to any major change in the electrical conductivity of the fractures.

Compression of the fracture surfaces also leads to more complex hydraulic conditions where fewer and fewer cavities between the fracture planes constitute well-interconnected cavities that can carry high water flows. Thorpe et al (1980) have, by studies of a large drill core (2 m high and 1 m in diameter), shown that water flow takes place in a complex pattern where the fractures in the core have very different flows, and that the water flow in the fractures exhibits clear tendencies to occur primarily in channel-shaped cavities within certain parts of the fracture planes. Compression of the fracture faces leads to increased complexity as more large permeable channels are cut off, which thereby also leads to poorer hydraulic communication between water-bearing channels. Because water flow takes place within very limited parts of the rock volume (i.e. in a complex system of channels), bore-penetrated fracture zones often have not one single permeable channel in contact with the borehole. Owing to the fact that the applied differential pressure (water injection tests) declines very rapidly away from the borehole, measurement sections may have permeable channels a few dm beyond the borehole without this resulting in measurable permeabilities within the measurement section. The low-resistivity fracture zones that have measurement sections with non-measurable permeabilities do therefore not have to be completely impermeable zones, but rather may have permeable channels that have not been drilled through. In any case, the fractures constitute a system of good transport pathways for electric currents.



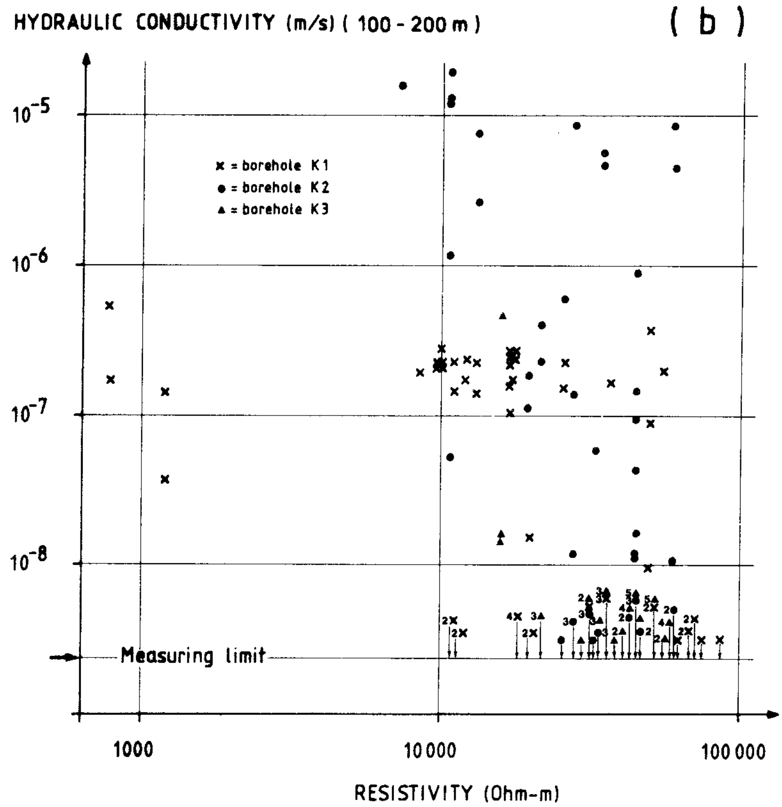


Fig. 3:23. Hydraulic conductivity vs estimated resistivity in three boreholes in Kråkemåla, (a) the sections from 0 to 100 m and (b) the sections between 100 and 200 m depth.

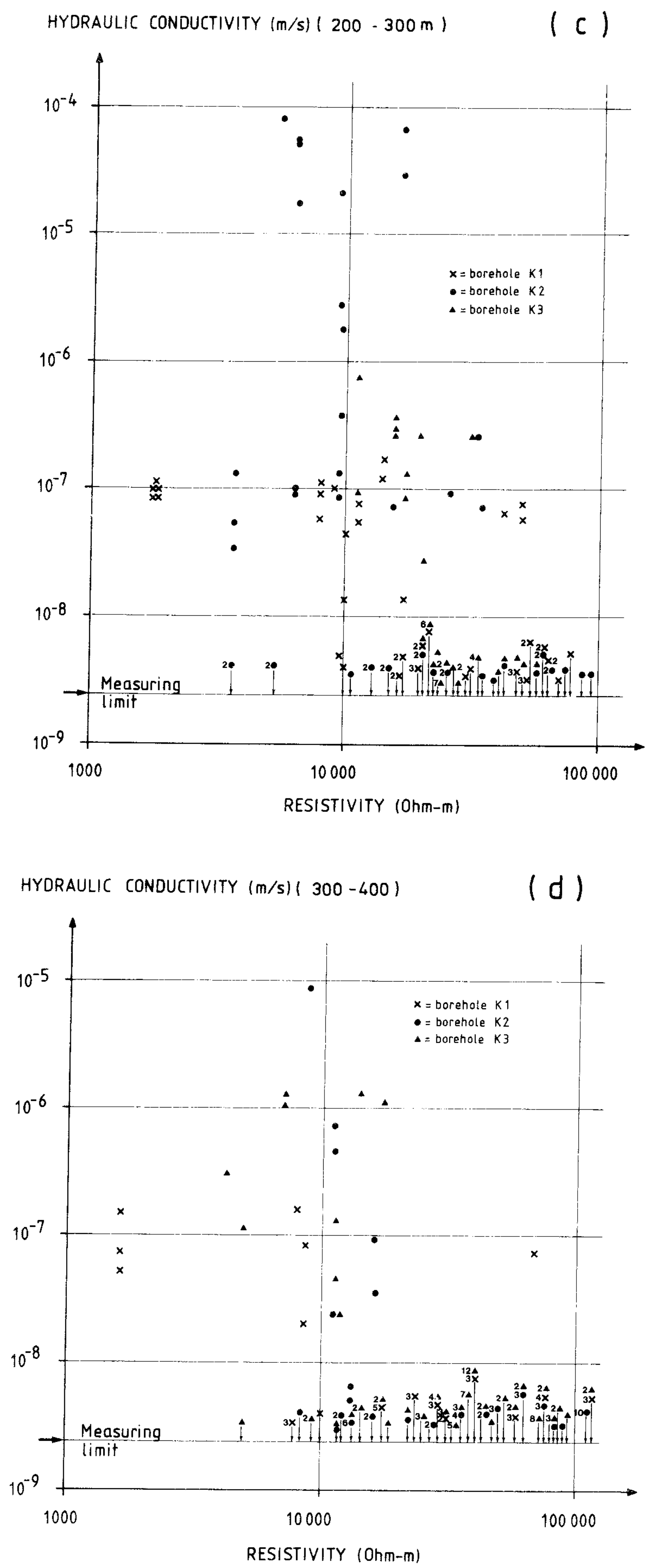


Fig. 3:24. Hydraulic conductivity vs estimated resistivity in three boreholes in Kråkemåla, (c) the sections from 200 to 300 m and (d) the sections between 300 and 400 m depth.

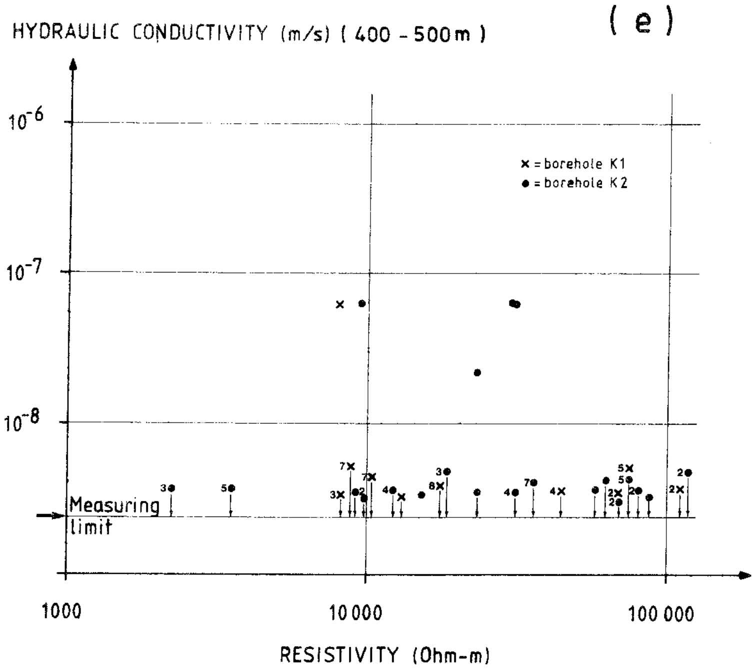


Fig. 3:25. Hydraulic conductivity vs estimated resistivity in two boreholes in Kråkemåla, (e) the sections between 400 and 500 m depth.

4. THE FINNSJÖ AREA

4.1 Geological description

The study area is situated in a region with flat topography about 10 km west-southwest of the Forsmark Nuclear Power Station in northeastern Uppland County. The Finnsjö area (see Fig. 1:1 in Chap. 1) consists primarily of grey granodiorite (Fig. 4:1). It is bounded on the east by a younger red granite and on the west by leptites.

In general, it can be said that the Finnsjö area is heavily tectonized: mylonite, breccia, foliation and secondary reddening are common. Fracture and crushed zones usually occur in connection with sealed mylonite and breccia zones. The rock within the tectonically affected portions is usually reddened and highly foliated in places (Olkiewicz et al 1979, 1981).

Metabasite occurs at numerous places within the study area in the form of dm-wide, partially continuous dykes. The gneissification, the metabasites and granite-aplite-pegmatite dykes constitute early structural features which - together with mylonite zones, where the granodiorite has been ground down and sealed together to a fine-grained, impervious rock - bear important witness to the structural evolution of the bedrock.

The Finnsjö area exhibits a very high fracture frequency. All fracture directions are well represented in outcrops, but there is some overrepresentation in the NE and NW directions. The fracture frequency measured on drill cores (8 boreholes approximately 500 m deep) is approximately the same as that measured on the outcrops. This indicates that the bedrock is fractured in a similar manner in both the vertical and horizontal directions (Olkiewicz 1981).

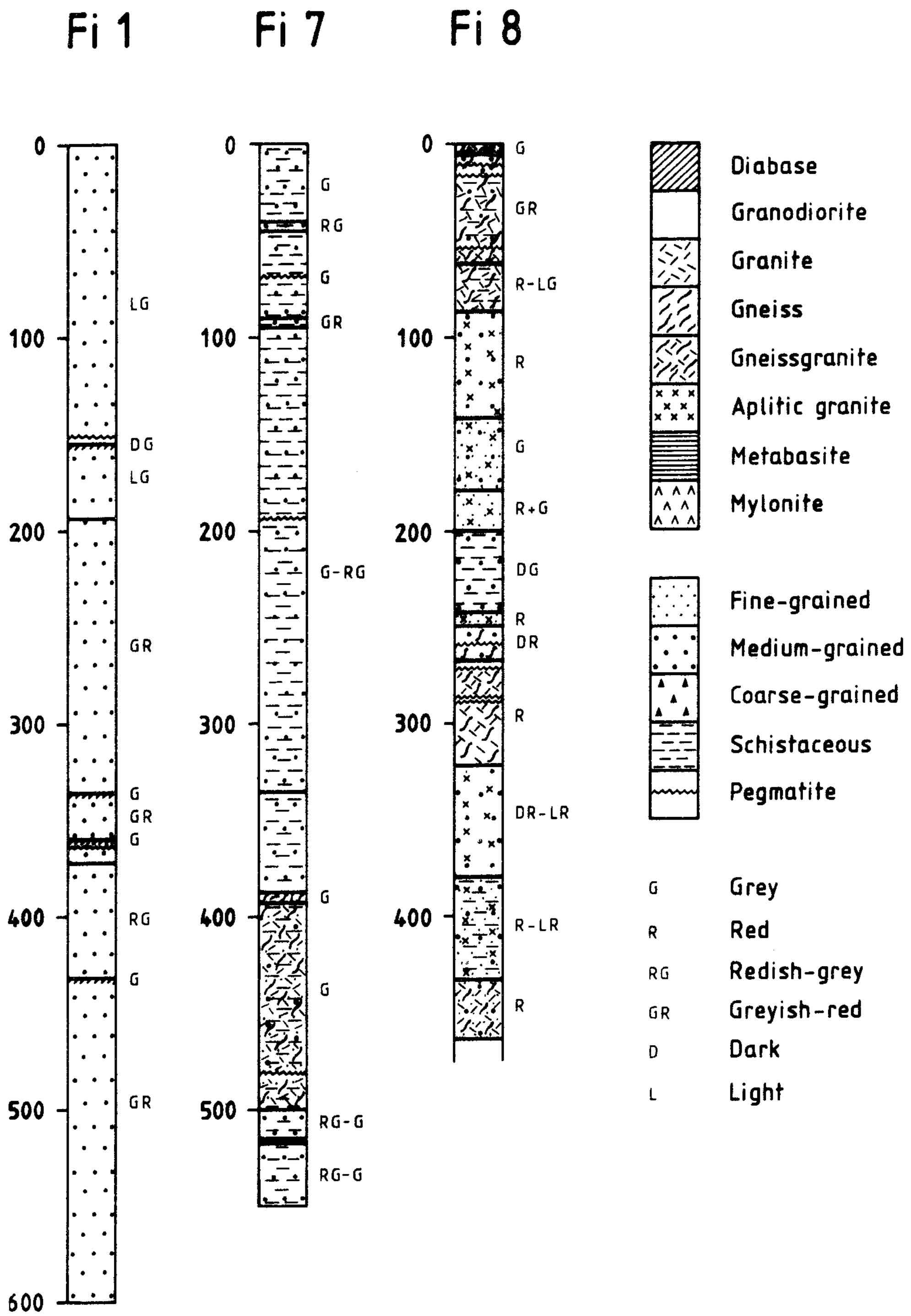


Fig 4:1 Petrographic description of the core

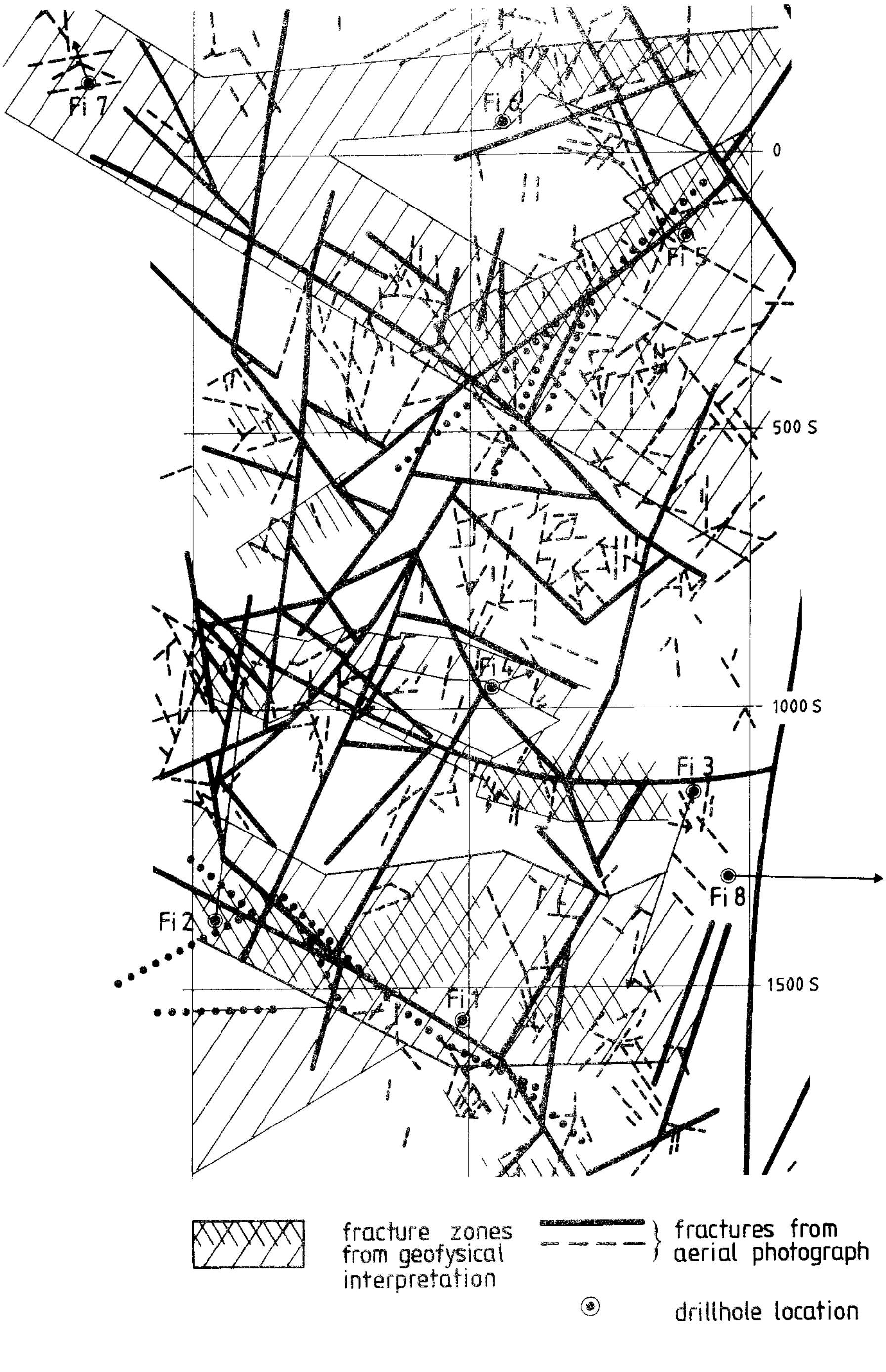


Fig 4:2 Map of the fracture pattern and borehole location in the Finnsjön area

4.2 Physical properties of the bedrock

4.2.1 Fracture frequency

The fractures in the drill cores (i.e. all breaks in the drill core) from Fi 1 and Fi 7 have been mapped in the same manner as in Kråkemåla, and the fractures have been classified with respect to the character of the fracture surfaces in coated fractures and fresh fractures. In the drill core from Fi 8, mineral-filled fractures without accompanying breaks in the drill core have also been mapped, and these fractures have been classified as "healed" fractures. The most common fracture minerals in Finnsjön are calcite, chlorite and quartz, while clay minerals, sulphides, biotite and muscovite are less common. Since TV inspection was not carried out in the core boreholes, a comparative study of the drill core and the fractures in the borehole wall has not been carried out in Finnsjön.

The hydraulic tests in the boreholes have been carried out in 2 m sections in Fi 1 and in 3 m sections in Fi 7 and Fi 8. The fractures in each section having been added up, the fracture frequency along the boreholes has been expressed in number of fractures per measurement section (Figs. 4:3, 4:4, 4:5). Compared to those from Kråkemåla, the Finnsjön drill cores have more coated fractures along the drill core, but like those from Kråkemåla, the drill cores from Fi 1 and Fi 7 exhibit high fracture frequency in several isolated delimited zones, which may be a few tens of metres wide, but are usually thinner than 10 m. Otherwise, these drill cores have, for the most part, long core sections with low fracture frequency (Fig. 4:3, 4:4). The drill cores from Fi 1 and Fi 7 do not exhibit good correlation between the frequency of coated and fresh fractures along the core. The fresh fractures exhibit a more random variation in fracture frequency and are not associated with the fracture zones in the bedrock.

The drill core from borehole Fi 8 differs from the other drill cores in that it has a high average frequency of coated fractures along the entire core with the exception of the core section between 130 and 300 m, which has a relatively low frequency (Fig. 4:5). The high frequency of coated fractures can be explained by the fact that the borehole has been drilled through one of the area's most morphologically marked fracture valleys (the Gåvastbo line). The fractured sections with a high frequency of coated fractures have, compared to the sections with a low frequency of coated fractures, a lower frequency of fresh fractures. This is probably due to the fact that a greater number of natural breaks along existing fractures reduces the chances of induced mechanical breaks occurring on the drill core.

The studied core from Finnsjön have different distributions of fresh fractures. But like the Kråkemåla cores, the drill cores exhibit relatively symmetric distributions, see Fig. 4:6. The distributions of fresh fractures in the three drill cores have the following means and standard deviations:

Fi 1: 1.7 +- 0.9 fresh fractures/m

Fi 7: 2.2 +- 0.9 fresh fractures/m

Fi 8: 1.4 +- 1.0 fresh fractures/m

The higher frequency of fresh fractures in Fi 7 compared to Fi 1 is probably accounted for by the fact that the drill core is more foliated. The higher frequency of fresh fractures is therefore probably caused by the fact that many fresh fractures result from mechanical break along the planes of foliation. The low frequency of fresh fractures in Fi 8 is probably due to the fact that this borehole has a high frequency of natural fractures.

The frequency of coated fractures in the three drill cores, as in the cores from Kråkemåla, exhibits an exponential distribution, see Fig. 4:7. Compared to the Kråkemåla drill cores, these drill cores have a much smaller fraction of sections with no fractures or only one fracture. However, the mean number of coated fractures/m differs less from the mean for Kråkemåla. This means that if fracture frequency is considered over larger sections where the fracture zones are represented, Finnsjön and Kråkemåla exhibit a similar fracture frequency, but in Finnsjön the fracture-poor sections have a slightly higher fracture frequency than in Kråkemåla. The more fracture-poor sections in Kråkemåla between the fractured zones have fewer fractures and thereby a greater fracture spacing. In Finnsjön's compact whole rock blocks, the fractures divide the rock into a denser mosaic than in Kråkemåla. The drill core from the Fi 8 borehole has a very high fracture frequency compared to the other boreholes. This is due to the fact that most of the borehole consists of fractured rock.

Fi 1: 1.9 +- 2.3 coated fracture/m

Fi 7: 1.4 +- 1.6 coated fracture/m

Fi 8: 5.4 +- 4.4 coated fracture/m

In Fi 1's drill core, 60-70% of the 2 m sections have fewer than five coated fractures, while in Fi 7 35% of the 3 m sections have fewer than five coated fractures. However, large portions of Fi 7 exhibit sparser fracturing than Fi 1. On the other hand, a smaller portion of the Fi 1 and Fi 7 drill cores consists of fracture zones with a high fracture frequency, e.g. only 15% of the sections in Fi 7 have more than 10 coated fractures per 3 m section. In Fi 8, there are only three measurement sections that lack mapped coated fractures (about 2% of the drill core), while the corresponding percentage in Fi 7 is 15%.

The frequency of healed fractures in the Fi 8 drill core also exhibits an exponential distribution, see Fig. 4:8. The mean number of sealed fractures in the drill core is approximately 0.8 fracture/m. Those parts of the drill core that have a high frequency of healed fractures also have a high frequency of coated fractures. A possible explanation for this may be that many coated fractures may have arisen through induced mechanical break along a healed fracture. This leads to a situation where zones with a high frequency of healed fractures occur together with a high frequency of coated fractures that have arisen through mechanical break in a healed fracture. When fracturing takes place in a solid crystalline bedrock, new fractures are often generated along already existing fractures sealed with fracture-filling materials (Thorpe et al 1980; Larsson et al 1981). This can also lead to a situation where zones with a high frequency of healed fractures also have a high frequency of coated fractures, compare with chapter 2.1. By this is meant that zones with healed fractures constitute weaknesses in the bedrock in which later tectonic events can generate new fractures along previously healed fractures.

The fracture-filling materials that occur most frequently in the drill core from Fi 8 are calcite and chlorite. Other minerals that occur are epidote, pyrite, gypsum, quartz etc. (Olkiewicz et al, 1979).

In certain sections, such as at 294 m and 315 m, marked fracture zones occur, most of which are characterized by the fact that the fractures have iron oxide coatings. The filling material also includes a reddish-brown clayey mass (294 m - 297 m).

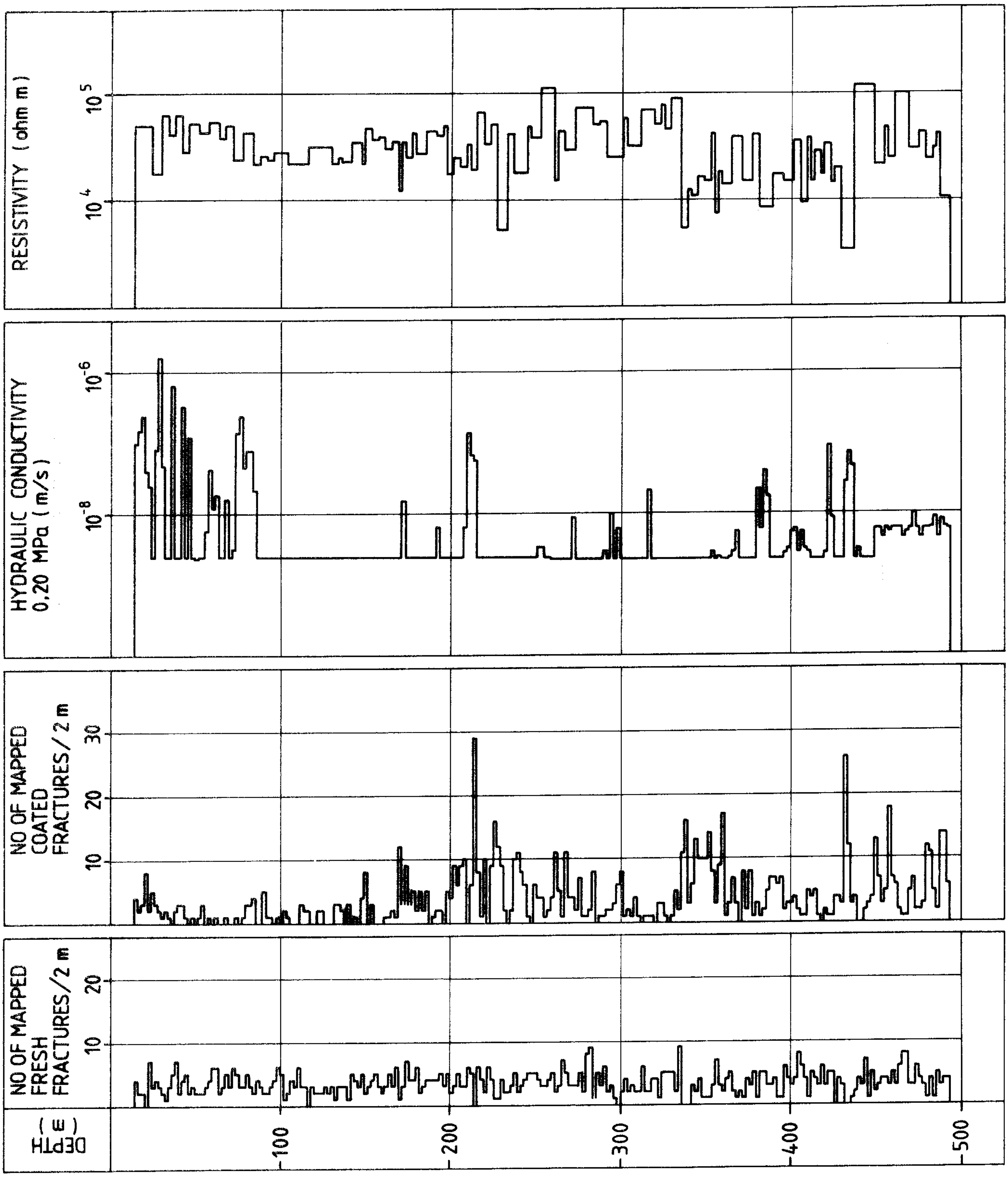


Fig 4:3 Borehole Fil, No. of maped fractures, hydraulic conductivity and resistivity.

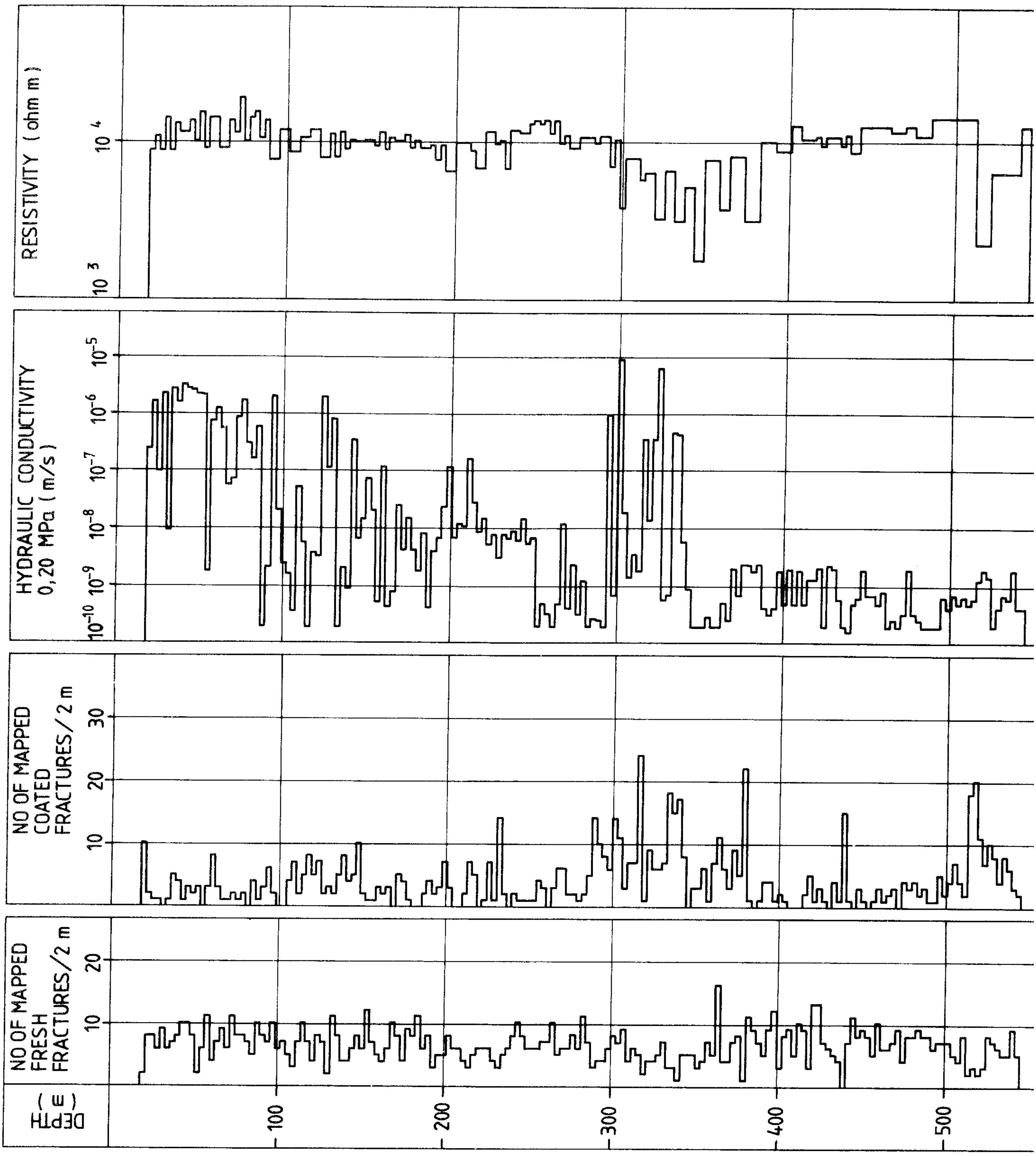


Fig 4:4 Borehole Fi7,No. of maped fractures, hydraulic conductivity and resistivity

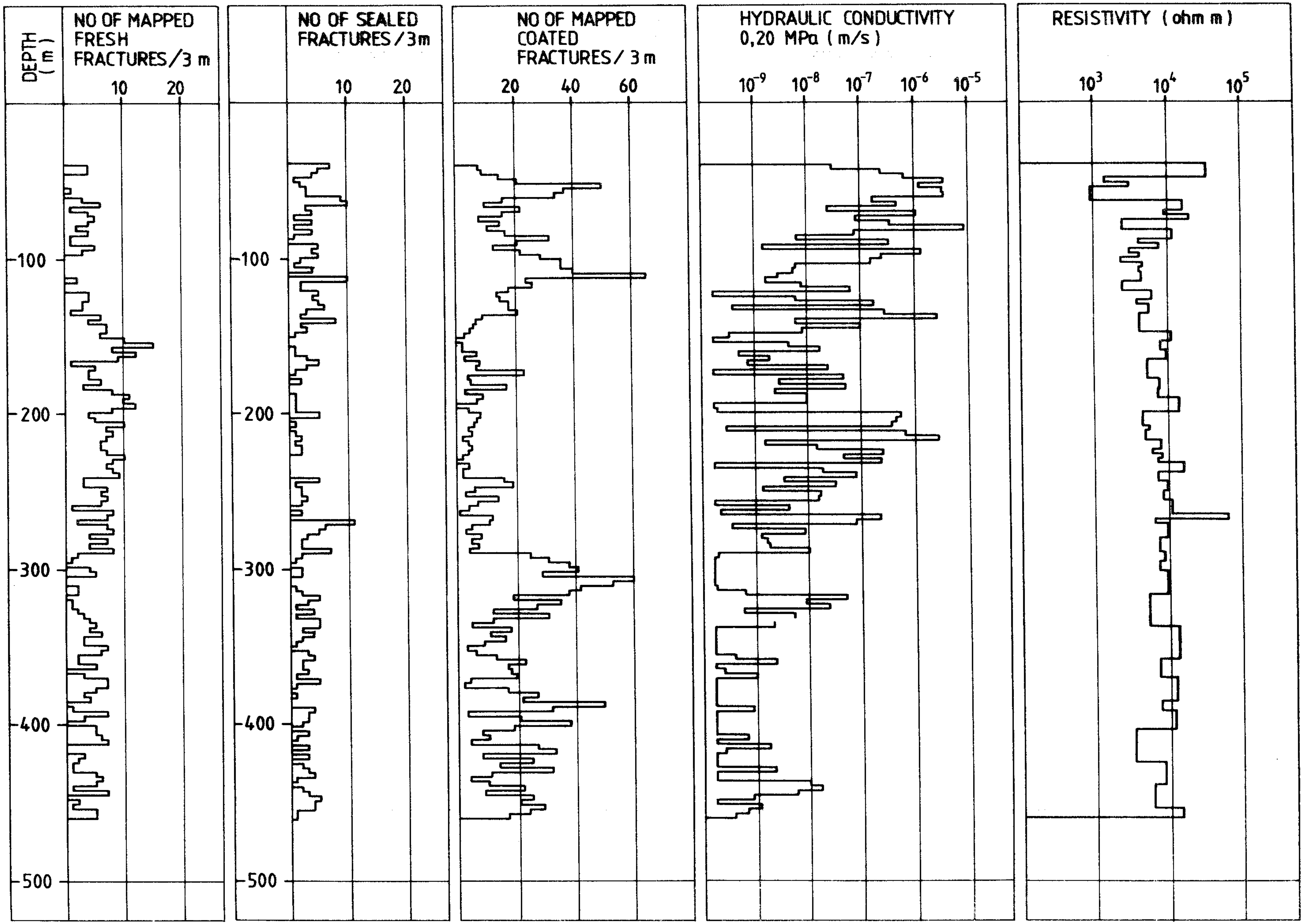


Fig 4:5 Borehole Fi8, No. of maped fractures, Hydraulic conductivity and resistivity

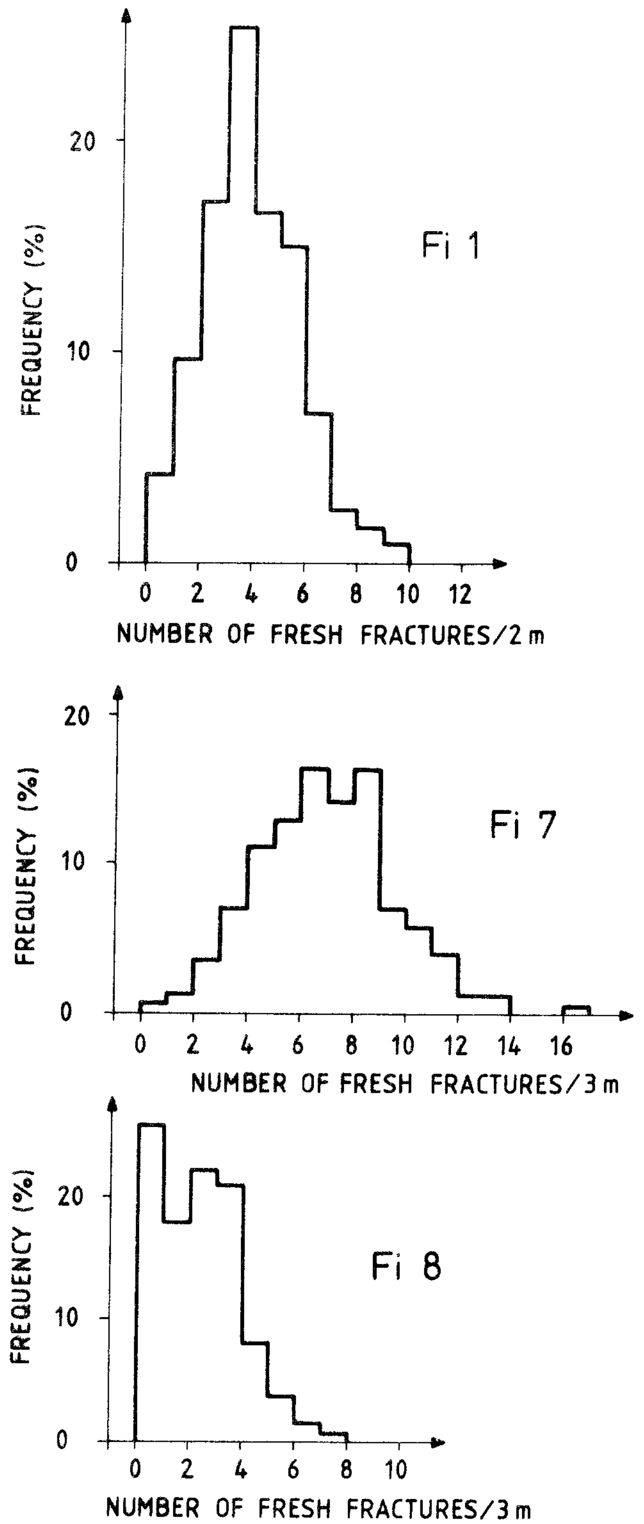
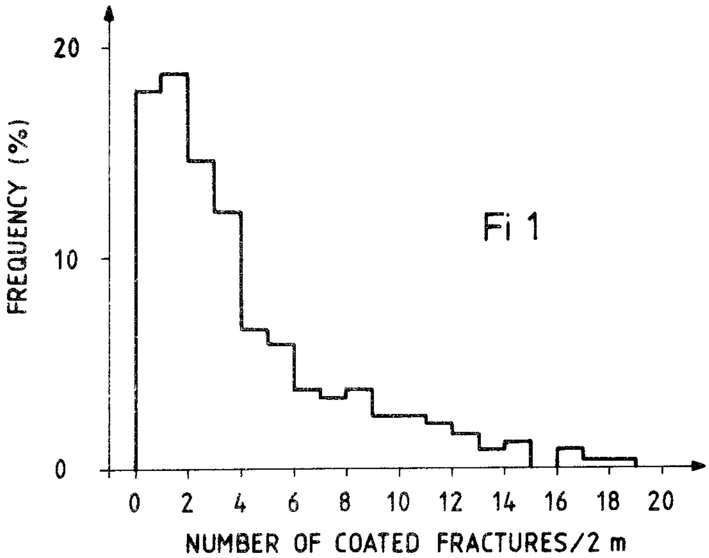
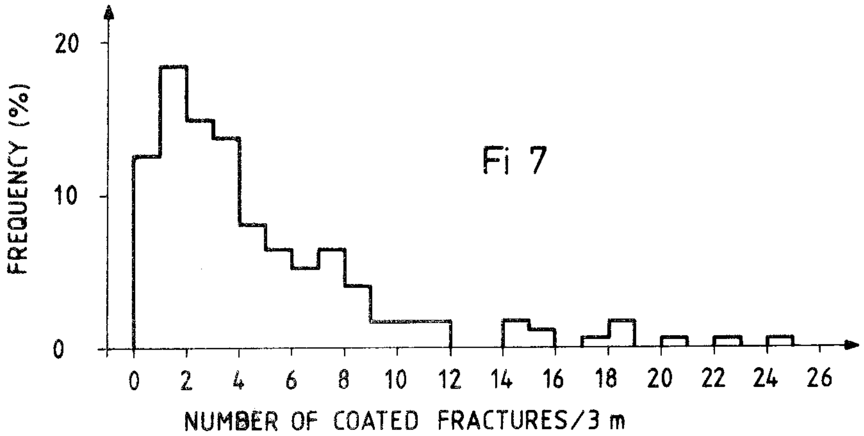


Fig 4:6 Histogram of the number of fresh fractures in each of the water injection tested sections (2 and 3m).





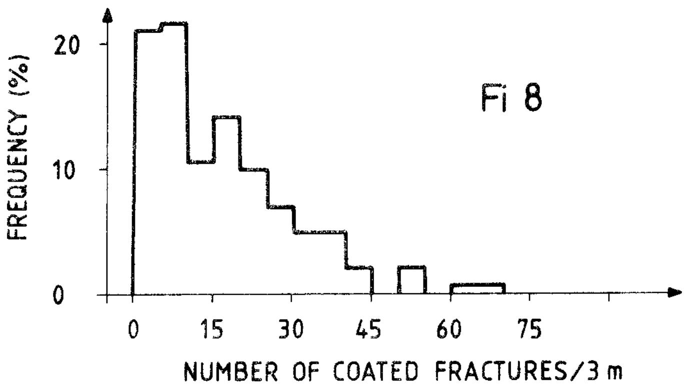


Fig 4:7 Histogram of the number of coated fractures in each of the injection tested sections (2 and 3m).

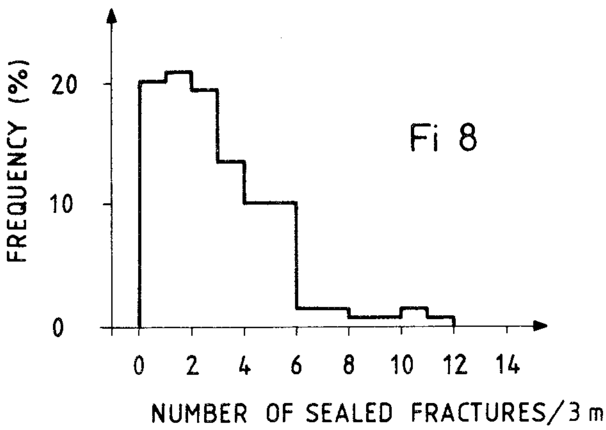


Fig 4:8 Histogram of the number of sealed fractures in each of the injection tested sections (2 and 3m).

4.2.2 Resistivity

Resistivity in the Finnsjön boreholes exhibits, as in Kråkemåla, relatively symmetric logarithmic normal distributions (Fig. 4:9). But in contrast to Kråkemåla, the three boreholes have very different resistivity distributions with different means and standard deviations:

Fi 1: 30 200 ohm-m +- 0.31 parts of a decade

Fi 7: 9 100 ohm-m +- 0.19 parts of a decade

Fi 8: 7 100 ohm-m +- 0.28 parts of a decade

Borehole Fi 1 has resistivities that are comparable to the resistivities in Kråkemåla. In both Fi 1 and Kråkemåla, the borehole-penetrated bedrock is thus characterized by high average resistivity.

Borehole Fi 8, on the other hand, has very low resisitivities, for the most part below 10 000 ohm-m. Such low resistivities (below 10 000 ohm-m) occur in Kråkemåla in only a few, well-defined crushed and fractured zones. Virtually the entire borehole Fi 8 intersects a heavily fractured rock.

Borehole Fi 7 has an average resistivity of around 10 000 ohm-m. Compared to Kråkemåla, Fi 7's resistivity values correspond to the relatively low-resistivity and fractured portions of the boreholes, but not to the extremely low-resistivity major fracture zones or crushed zones.

The mean value of resistivity for the intact fracture-poor rock formations (no mapped coated fractures) does not exhibit any appreciable difference

Fi 1 = 30 500 ohm-m +- 0.18 decades

Fi 7 = 10 000 ohm-m +- 0.18 decades

from the mean resistivity value for the entire borehole, see Fig. 4:10. This is probably due to the fact that the fracture-poor sections constitute most of the boreholes, while the fractured portions constitute a much smaller fraction of the boreholes (cf. chapter 4.2.9). Current propagation therefore takes place through the interconnected fractures, but also to a very large extent through the microfissures in the matrix.

The average resistivity in the two holes Fi 1 and Fi 7 is very different.

These differences are probably due to the fact that Fi 7 has a high frequency of microfissures in the matrix and a denser fracture mosaic than Fi 1. The core in Fi 7 exhibits high foliation in comparison with other cores; there are also sections of breccia and mylonitized granodiorite. Compared to Kråkemåla, Fi 1 has slightly lower resistivities in the matrix, which indicates that the rock mass in the Finnsjö area has a higher average content of microfissures. This may be due to the fact that the Finnsjö area is more tectonically affected than Kråkemåla.

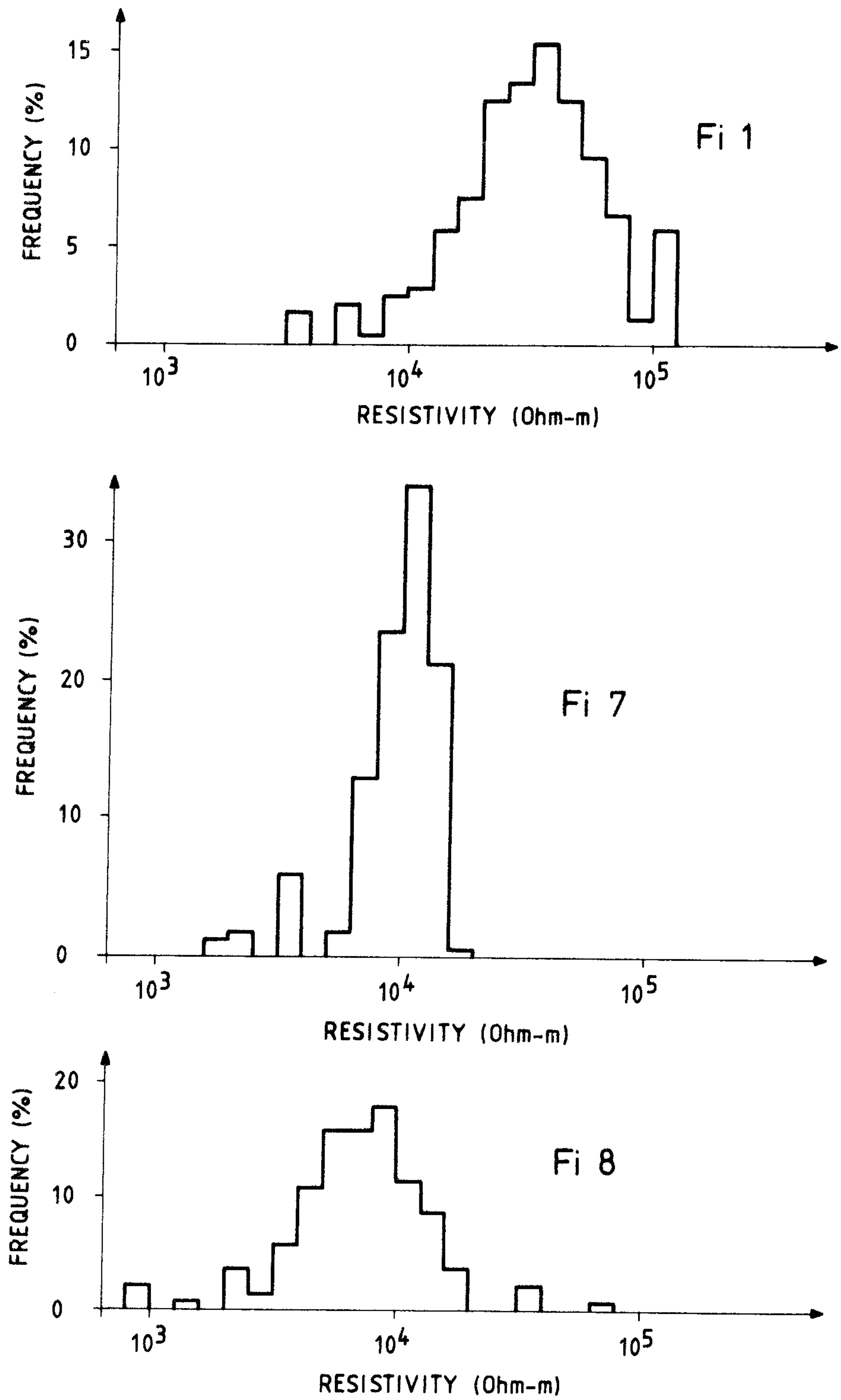
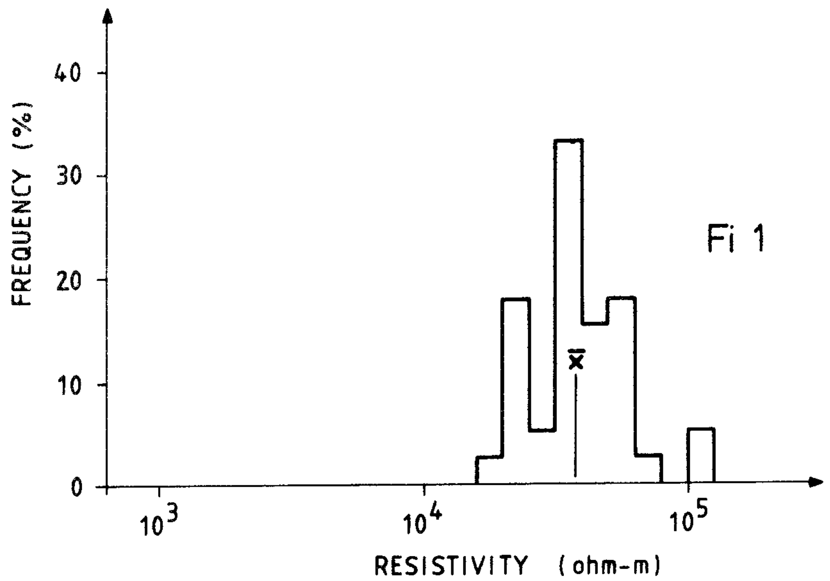


Fig 4:9 Histogram of the resistivities along the boreholes Fi1, Fi7, Fi8.



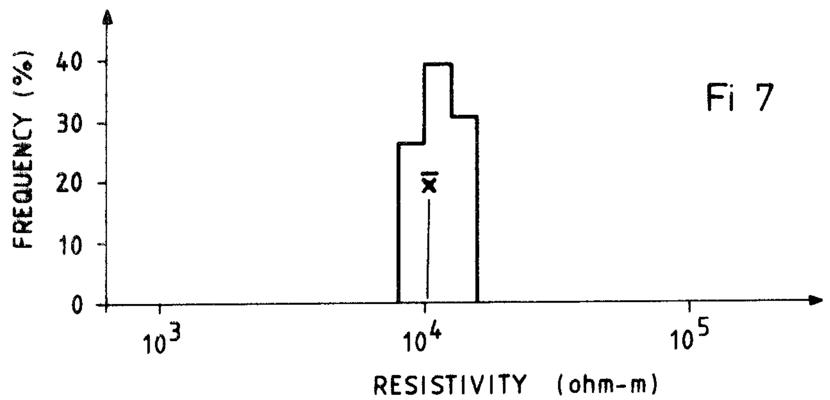


Fig 4:10 Histogram of the resistivities in sections without any mapped fractures.

4.2.3 Permeability

The water injection tests in Finnsjön have also been carried out with different differential pressures (0.2, 0.4 and 0.6 MPa). The different differential pressures usually give small differences in hydraulic conductivity in the measurement sections (Carlsson et al 1980). In borehole Fi 1, the hydraulic conductivities obtained in the measurement sections at different differential pressures have been compared with each other: 0.2 with 0.4 MPa and 0.2 with 0.6 MPa. See Fig. 4:11.

A Comparison of differential pressures 0.2 MPa and 0.4 MPa.

- 65% of the sections do not show any difference in hydraulic conductivity.
- 20% of the sections have higher conductivity at 0.4 MPa than at 0.2 MPa and 10% of the sections have lower conductivity at 0.4 MPa.

B Comparison of differential pressures 0.2 MPa and 0.6 MPa.

- 40% of the sections have no difference in hydraulic conductivity.
- 60% of the sections have higher conductivity at 0.6 MPa than at 0.2 MPa.

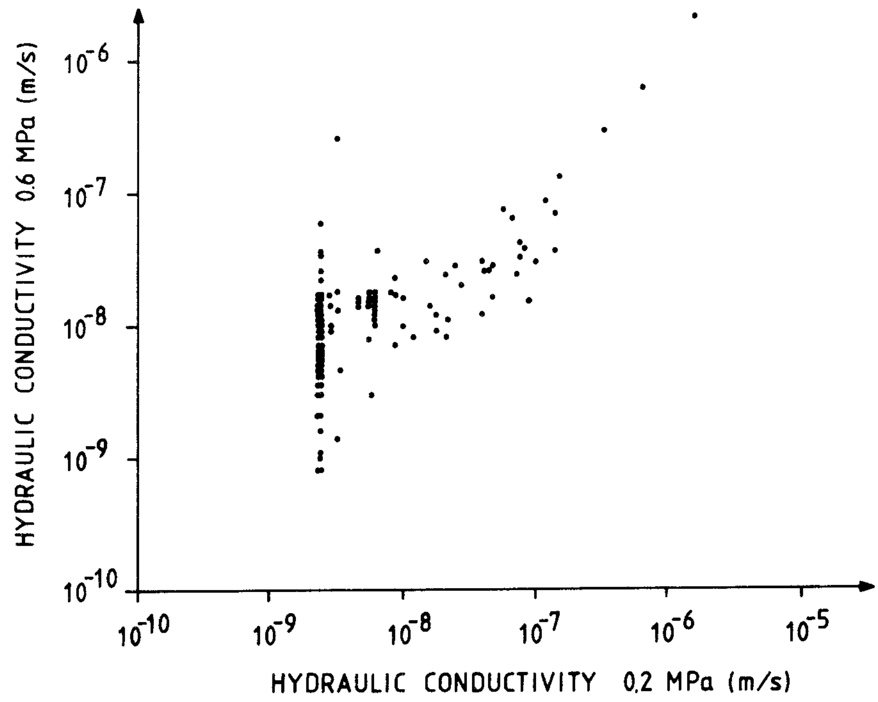
In comparison with the other boreholes in the area, borehole Fi 1 has relatively many measurement sections that have different hydraulic conductivities at different differential pressures. The higher differential pressures normally give higher conductivities. Factors that give higher conductivity at higher differential pressure have already been described in the comparison of measurements with different differential pressures in the Kråkemåla boreholes. But higher pressure increases the risk of affecting the actual flow channels in the rock, which can in many cases lead to higher conductivities being obtained.

One reason why higher differential pressures give lower conductivity in some cases may be that high water velocities increase the probability of turbulent flow in the fractures, which gives rise to excessively low permeability values. The material presented in this and following sections derives from the measurements carried out with a differential pressure of 0.2 MPa.

Borehole Fi 1 contains a slightly lower percentage (58%) of impermeable measurement sections (hydraulic conductivities too low to be measurable with the water injection equipment used, i.e. below 2.3×10^{-9} m/s) than in Kråkemåla (K1 = 64%, K2 = 70% and K3 = 86%). This is probably due to the fact that Kråkemåla has a sparser fracture mosaic in the more intact rock blocks, i.e. Kråkemåla has, on average, a larger fracture spacing than in Finnsjön. Boreholes Fi 7 and Fi 8 have been measured in 3 m sections, in contrast to Fi 1, which has been measured in 2 m sections. These boreholes have a lower measuring limit of 2×10^{-10} m/s. Consequently, these boreholes have fewer measurement sections with unmeasurable permeability (Fi 7 = 6% and Fi 8 = 31%). But the percentage of measurement sections with a hydraulic conductivity below 2.3×10^{-9} m/s is 57% for Fi 7 and 53% for Fi 8. Thus, all studied boreholes have a large percentage of measurement sections with very low permeability.

The permeable measurement sections exhibit an exponential distribution where high conductivity values occur less frequently, i.e. the percentage (frequency) of permeable measurement sections decreases exponentially with increasing conductivity (Fig. 4:12). The graph for borehole Fi 7 shows a bimodal distribution with a small frequency maximum at conductivity values of around 10^{-6} m/s.

The distribution of the permeable measurement sections in the Kråkemåla boreholes exhibits, on the other hand, a pronounced frequency maximum at 10^{-7} m/s. Thus, unlike the boreholes in Finnsjön, these boreholes have very few measurement sections with values between 2.3×10^{-9} m/s and 3.2×10^{-8} m/s. But like those in Finnsjön, the Kråkemåla boreholes also have very few measurement sections with conductivities above 10^{-6} m/s.



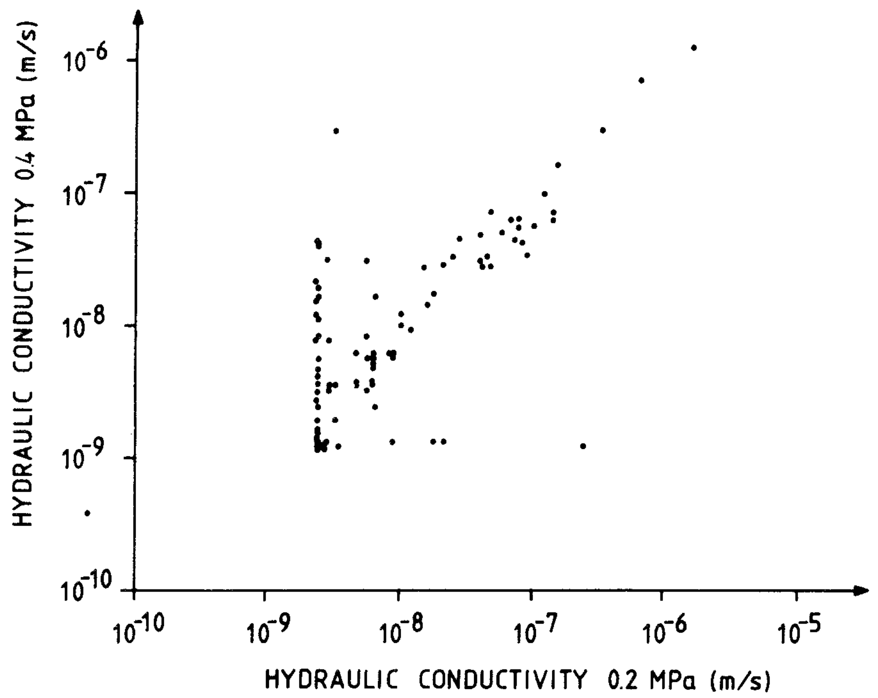


Fig 4:11 Comparison of hydraulic conductivity measured with 0.2MPa with hydraulic conductivities at respectively 0.4Mpa and 0.6Mpa.

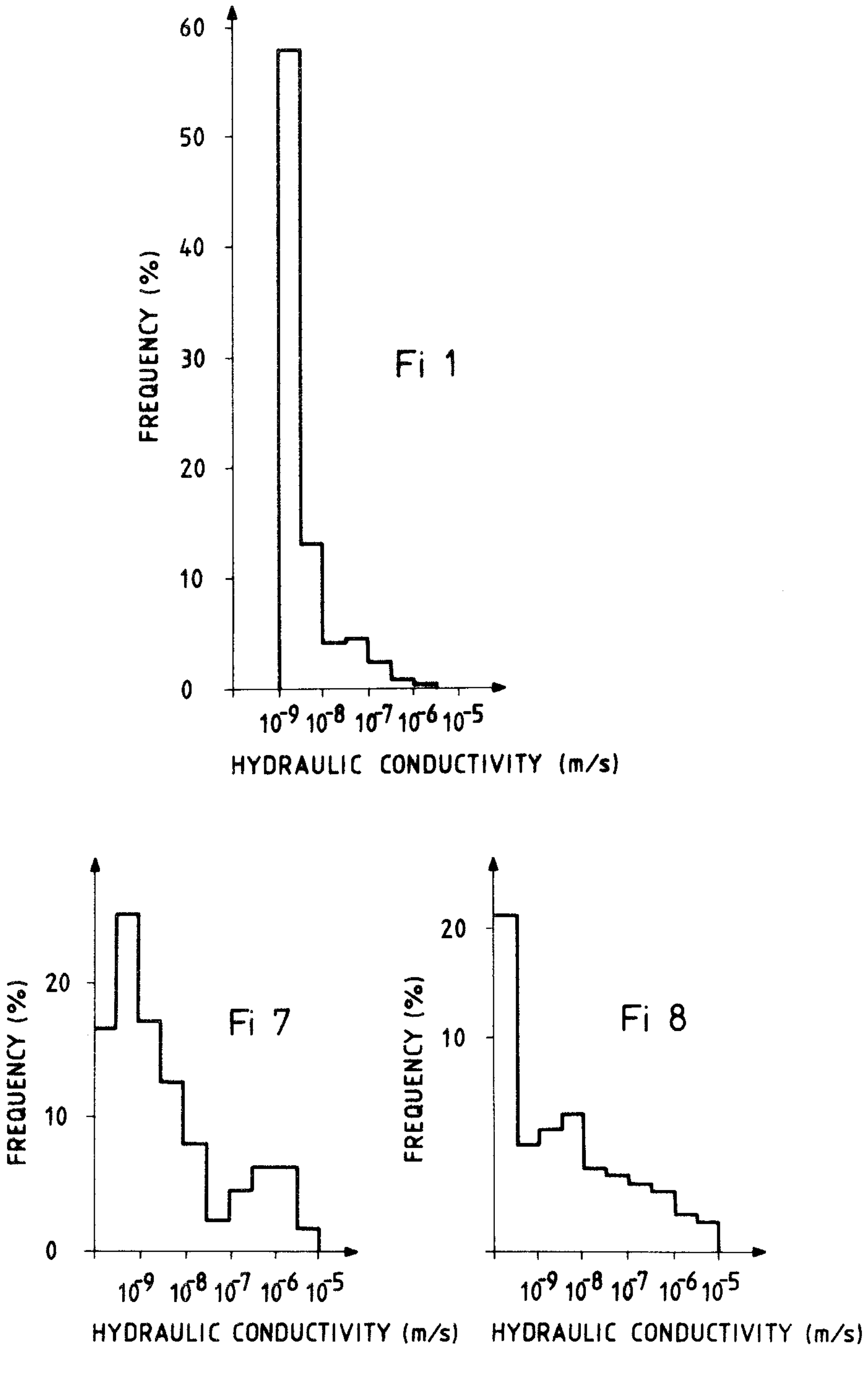


Fig 4:12 Histogram of hydraulic conductivities. The lower measurable limit for Fi1 is 2.3×10^{-9} m/s and 2.9×10^{-10} m/s for Fi7 and Fi8 respectively.

4.3 Correlation of the borehole methods

4.3.1 Correlation of fracture frequency and resistivity

In order to compare the measured resistivity values with the mapped fracture frequency along the drilled core, the bedrock along the boreholes has been divided into sections with different average resistivities, see Chapter 3.3.1. The estimated resistivity values (corrected for the influence of the borehole fluid) have been compared with the fracture frequency in corresponding sections in the drill core.

Fracture frequency along the boreholes shows a relatively poor quantitative correlation to resistivity, see Fig. 4:13. But sections with a high frequency of coated fractures are generally accompanied by a reduction of the resistivity values, normally to about 5 000 ohm-m. For the most part, fracture-free sections exhibit a higher resistivity than fractured rock sections, for the most part (10 000 ohm-m).

The resistivity of the bedrock in the Finnsjö area is much lower than in Kråkemåla. This points towards a higher frequency of microfissures in the matrix and a denser fracture mosaic in the Finnsjö area.

Figure 4:10 shows the distribution of resistivities for fracture-free zones (i.e. corresections with no mapped coated fractures). The average resistivity value for the fracture-free sections is about 30 000 ohm-m for borehole Fi 1 and 10 500 ohm-m for borehole Fi 7. This indicates that the matrix in the different boreholes has a widely differing frequency of microfissures. Borehole Fi 1 has been drilled in a less tectonically affected part of Finnsjön and therefore has a matrix with a lower frequency of microfissures.

The resistivity values in the three boreholes exhibit a relatively symmetric logarithmic normal distribution, see Fig. 4:9, while the fracture frequency exhibits an exponential distribution. This difference may be due to the fact that the resistivity changes along the boreholes exhibit a more uniform variation due to the influence of the microfissures, while the fracture frequency (visually mapped fractures) shows that large fracture spacings dominate, i.e. the distance between mapped coated fractures is large. The total fracture frequency in the three boreholes has a mean value of 3.2 fractures per metre, and the resistivity mean is 14 392 ohm-m.

In borehole Fi 1 (Fig. 4:3), the sections (Fig. 4:3) between 20 and 75 m and between 315 and 345 m exhibit very low fracturing (about 1 fracture/m), accompanied by very high resistivity (40 000 ohm-m). The section between a depth of 75 m and 150 m also exhibits a comparatively low fracture frequency, while the resistivity is slightly lower (about 20 000 ohm-m). This indicates higher porosity than in the above-mentioned rock sections. Otherwise, most low-resistivity sections are accompanied by zones with a high frequency of coated fractures.

Core borehole Fi 7 (Fig. 4:4) exhibits less variation in resistivity along the borehole, while the fracture frequency exhibits wider fluctuation.

The borehole section between 300 m and 380 m exhibits a higher fracture frequency, which is also accompanied by very low resistivity. It is possible that the zone's low resistivity is due in part to the presence of small sections of mylonite and breccia. At a depth of 512 m, in a fractured mylonized granodiorite, the resistivity values drop.

Fi 7 contains sections with a higher fracture frequency - for example at depths of 60 m, 90 m, 135 m, 170 m, 280 m, 410 m, 415 m, 420-450 m, 465 m and 485 m - which are not accompanied by a lower resistivity, which indicates that the fractures are more closed and have a smaller water content.

Core borehole Fi 8 (Fig. 4:5) exhibits on average the lowest resistivity and the highest fracture frequency in comparison with Fi 1 and Fi 7. The borehole's low resistivity is not only associated with the high fracture frequency of the area, but also appears to be dependent on the properties of the rock mass, i.e. microfissures in the matrix, as well as possibly a greater presence of electrically conductive minerals or alteration products. The section between 50 m and 150 m depth exhibits the most highly fractured zone, accompanied by very low resistivity. This zone consists of a medium-grained mylonitized granite-gneiss. The low background value of the resistivity indicates a high frequency of microfissures in this section.

The section between a depth of 150 m and 290 m exhibits the lowest fracture frequency, but is not accompanied by an expected high resistivity value, exhibiting instead a fluctuation between high and low values. The low values might conceivably be due to iron oxides filling the fractures (personal communication Stejskal, 1980).

Measurement sections with a higher fracture frequency occur at depths below 290 m. They differ from the upper fracture-free section in that the resistivity exhibits smaller fluctuations between high and low values.

No apparent correlation has been observed in borehole Fi 8 between healed fractures and resistivity values, with the exception of the zones that contain sulphides, iron oxides or clay minerals, which exhibit low resistivity values. Because Fi 8 is rather highly fractured, it is difficult to distinguish resistivity variations caused by pore water from those caused by electrically conductive fracture-filling minerals.

In the three boreholes investigated in Finnsjön, no correlation has been observed between the frequency of fresh fractures and resistivity, which agrees with the assumption that these fractures are mechanically induced core breaks.

The following summation can be made from the above observations.

- Fracture frequency and resistivity in the bedrock in the Finnsjö area have a heterogeneous character, with large differences in fracture frequency and porosity in all three boreholes.

- In rock blocks with a poorly interconnected fracture mosaic, current propagation takes place mainly through the matrix, i.e. a very small portion is transported through the poorly interconnected fractures.

- The resistivity values show no tendency to increase with increasing depth, except in borehole Fi 8, which exhibits a weak trend towards relatively higher resistivity values with increasing depth. This may indicate a relative decrease in the fracture porosity of the bedrock, which has also been found by porosity measurements on drill cores (Öqvist 1981). See Fig. 4:14.

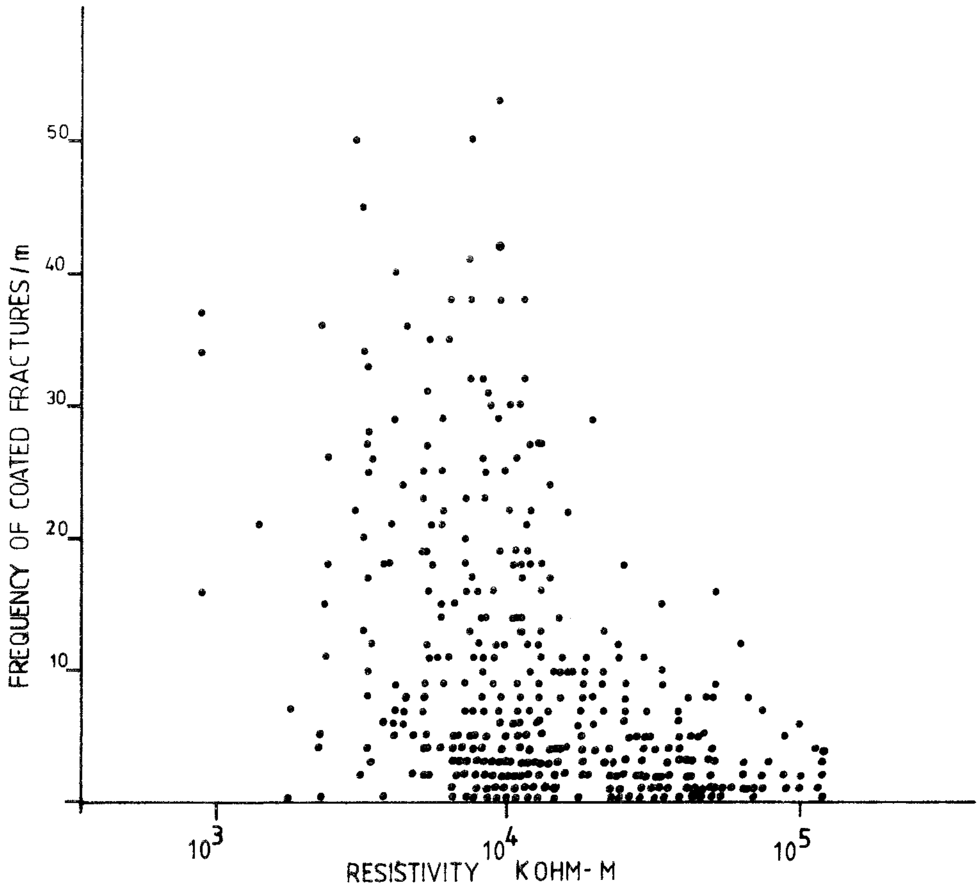


Fig 4:13 Resistivity versus frequency of coated fractures in boreholes Fi1, Fi7, and Fi8.

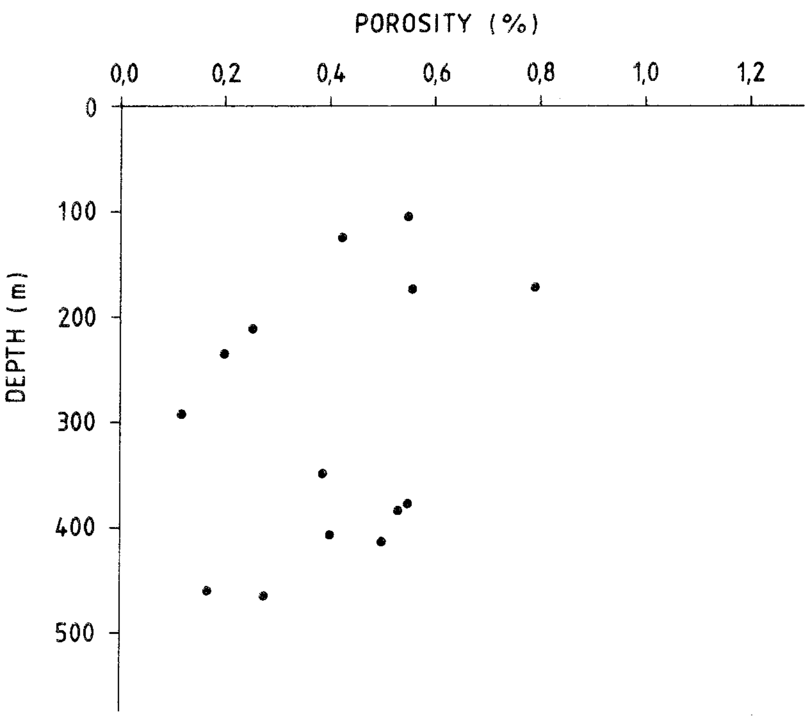


Fig 4:14 Porosities of selected core samples from borehole Fi8.

4.3.2 Correlation of fracture frequency and permeability

The variation in hydraulic conductivity along the borehole shows a relatively poor correlation with the fracture frequency along the borehole, see Fig. 4:15:a, b, d, e.

Measurement sections with low fracture frequency or, in some cases, with a single fracture can have high hydraulic conductivities, while it also happens that measurement sections with high fracture frequency have unmeasurable permeabilities, see Fig. 4:3, for example section 340-350 m in Fi 1. A poor correlation between water injection tests and fracture frequency can also be due to:

- Water leakage past the packers. One of the sealing rubber packers may be placed over adjacent steep fractures, and the applied differential pressure may cause the water to be forced past the packer.

- The geometric characteristics of the fractures have been altered along the fracture planes, for example constrictions, blockages and interruptions may occur. As a result, the permability properties of the fractures are very different. This illustrates the fact that there is not always a direct connection between fracture frequency and measured hydraulic conductivity. But certain characteristic trends nevertheless appear in the diagrams (Fig. 4:15), where the hydraulic conductivities have been plotted against the number of coated fractures in the measurement section for each depth section of 100 metres.

In the upper 100 m of boreholes Fi 1, Fi 7 and Fi 8, most measurement sections are permeable, with the exception of a number of sections in Fi 1 (Fig. 4:15, a).

Between depths of 100 and 200 m, most of the measurement sections that contain one or more fractures are still permeable, with the exception of Fi 1, where most of the measurement sections are not permeable (Fig. 4:15, b).

Between a depth of 200 and 300 m the number of permeable zones is fewer than above 200 m (Fig. 4:15, c).

Between a depth of 300 and 400 m, there are a large number of sections with high fracture frequency and even crushed rock that are not permeable (Fig. 4:15, d).

Between a depth of 400 and 500 m, there are a number of measurement sections with high fracture frequency, but despite this most of these sections are not permeable (Fig. 4:15, e).

Borehole Fi 1 (Fig. 4:3) exhibits the following fracture-poor sections: 30-170 m, 280-335 m and 400-435 m. These sections are accompanied by a relatively low or unmeasurable hydraulic conductivity, with the exception of the upper part of the borehole (0-85 m), which exhibits high hydraulic conductivity. The high hydraulic conductivity in spite of the low fracture frequency indicates that good hydraulic communication exists between the fractures owing to the fact that the state of stress in the bedrock in the shallower portions of the borehole is relieved to a higher degree than in the deeper portions.

Between depths of 150 and 280 m, 335 and 400 m and 445 and 500 m, the fracture frequency is relatively high (3-5 fractures/m), in spite of which only a few measurement sections exhibit high hydraulic conductivity. This indicates a decline in the permeability of the fractures in the deeper portions.

Borehole Fi 7 (Fig. 4:4) exhibits relatively low fracturing down to a depth of 200 m, but nevertheless has a high hydraulic conductivity, except for a few sections with lower permeability.

The value of the hydraulic conductivity exhibits a declining trend with increasing depth. This indicates that the permeability of the fractures decreases with depth, probably due to increased compression (i.e. closure) of the fractures.

Borehole sections down to 350 m differ significantly from deeper sections due to their higher hydraulic conductivity (up to 4 x 10^{-6} m/s). The section between 300 m and 350 m exhibits the highest fracture frequency (about 20 fractures/3 m) and is accompanied by high hydraulic conductivity (10^{-6} m/s). Fracture-rich sections with good water-conducting properties constitute about 10% of the borehole's measurement sections.

In the deeper parts of the borehole (350-550 m), there is no conductivity value greater than 6.7 x 10^{-9} m/s. Most values are less than 1.0 x 10^{-9} m/s). Moreover, these zones exhibit a relatively low fracture frequency, with the exception of the section between a depth of 320 and 330 m.

Borehole Fi 8 (Fig. 4:5) exhibits comparatively high hydraulic conductivities in comparison with borehole Fi 7, with a clearly declining trend in the value of the hydraulic conductivity with increasing depth.

The borehole's most permeable zone (3 x 10^{-6} m/s) exists down to a depth of 70 m, accompanied by borehole sections with very high fracture frequency (about 6 fractures/m). Then follow a number of sections with high fracture frequency and a declining trend in hydraulic conductivity (127-178 m, 430-470 m).

At greater depth, the following fracture zones therefore exhibit relatively low hydraulic conductivity values: 358-361 m, 367-370 m, 415-418 m, 436-439 m and 451-453 m. Besides the declining hydraulic conductivity, permeable zones became sparser with greater depth, i.e. fewer permeable measurement sections are found with increasing depth.

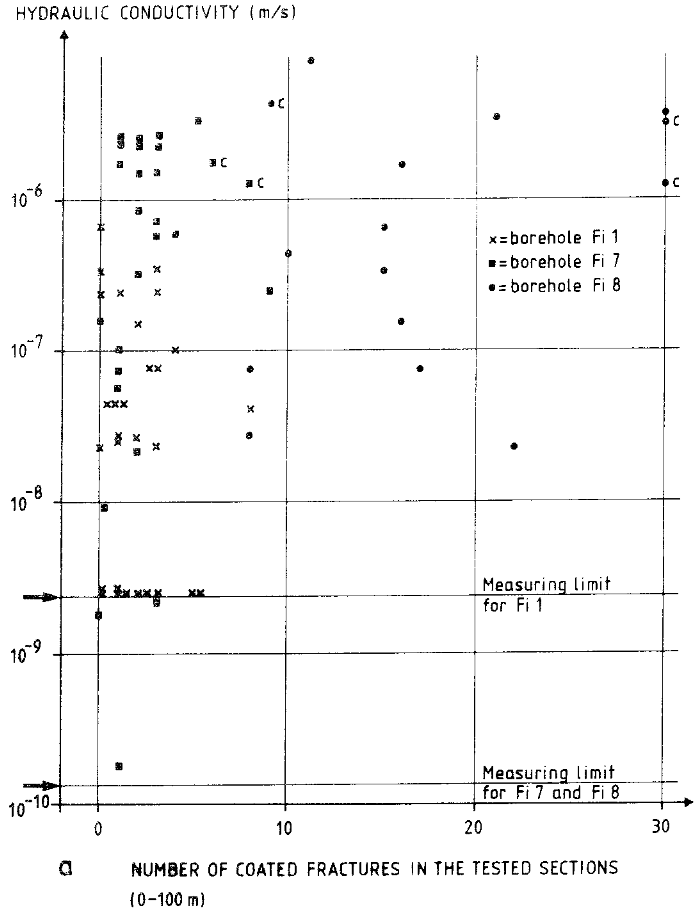
The borehole section 200-240 m exhibits relatively high hydraulic conductivity despite a low fracture frequency. The same applies to the section between 268 m and 271 m. The reverse relationship i.e. fracture-rich measurement sections with low permeabilities, exists in the following zones: 292-310 m, 373-380 m and 394-406 m.

The comparison between fracture frequency and hydraulic conductivity can be summarized as follows:

- In the shallower parts of the boreholes, virtually all measurement sections with one or more fractures are permeable.

- The permeable measurement sections exhibit a tendency towards having lower hydraulic conductivity values and a sparser occurrence with increasing depth. This indicates that with increasing depth, the state of stress in the bedrock causes increased compression of the fractures.

With increasing depth, the fractures become more compressed, as a result of which fewer and fewer fractures have measurable permeabilities, i.e. where the fractures are drilled through, the fracture planes are in good contact with each other and therefore have no permeable cavity in contact with the borehole. As a result, fewer and fewer of the measurement sections have measurable permeabilities. In contrast to Kråkemåla, the value of hydraulic conductivity also exhibits a declining trend with increasing depth. This indicates that as the average fracture apertures decrease due to increased compression and closure of the fracture planes, permeability decreases due to the fact that the water-conducting channels between the fracture planes become narrower and that some of the water transport pathways are cut off (Maini 1971, Witherspoon et al 1980). Thus, compression of the fractures causes the permeable fractures to have, on average, lower values of hydraulic conductivity with increasing depth. Kråkemåla has a very well defined system of fractures where only a few fracture directions are well represented; for example, Kråkemåla has heavy horizontal fracturing. Because the hydraulic conductivity of these fractures varies widely, any tendency towards a lower value of the fractures' hydraulic conductivity is masked by the variations in hydraulic conductivity of the individual fractures.



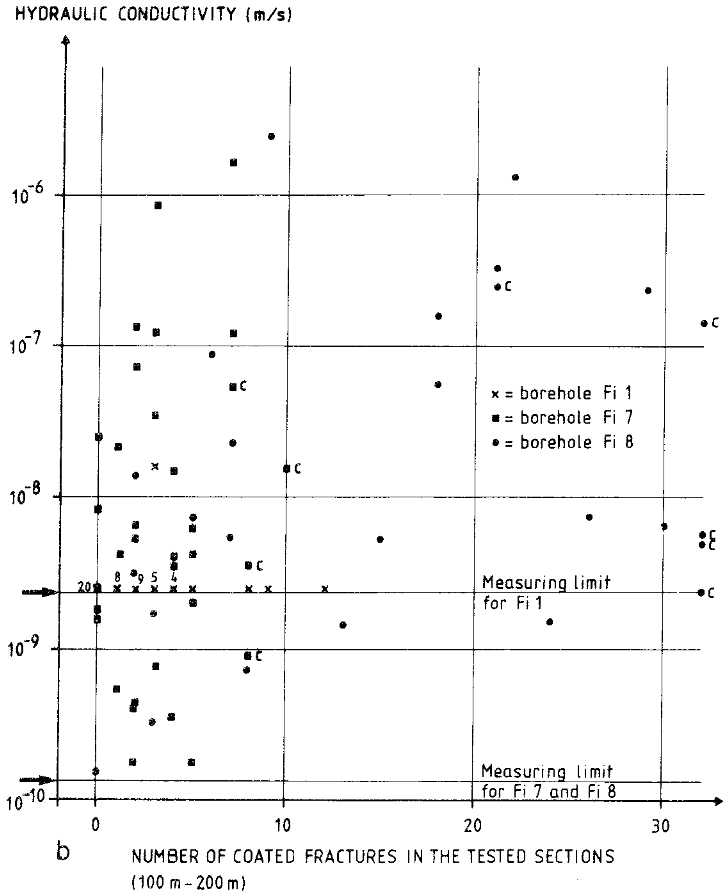
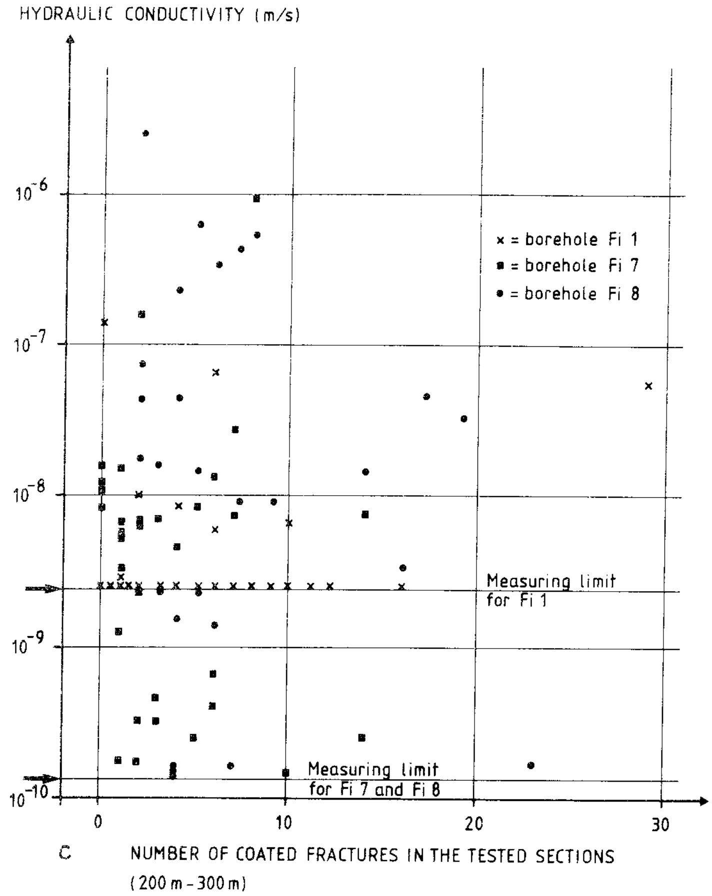
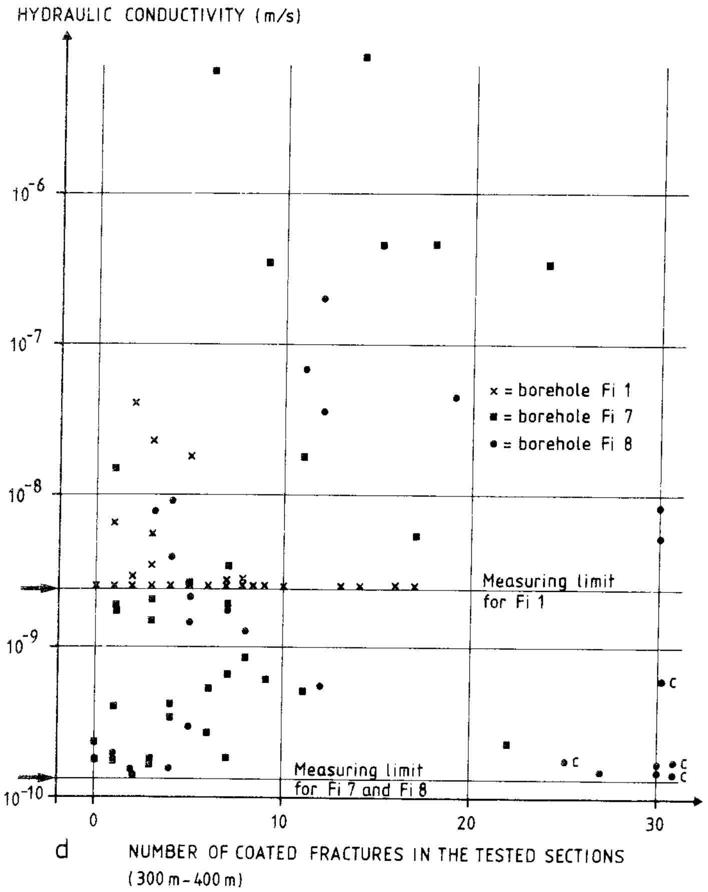


Fig 4:15.a,b. Hydraulic conductivity versus resistivity





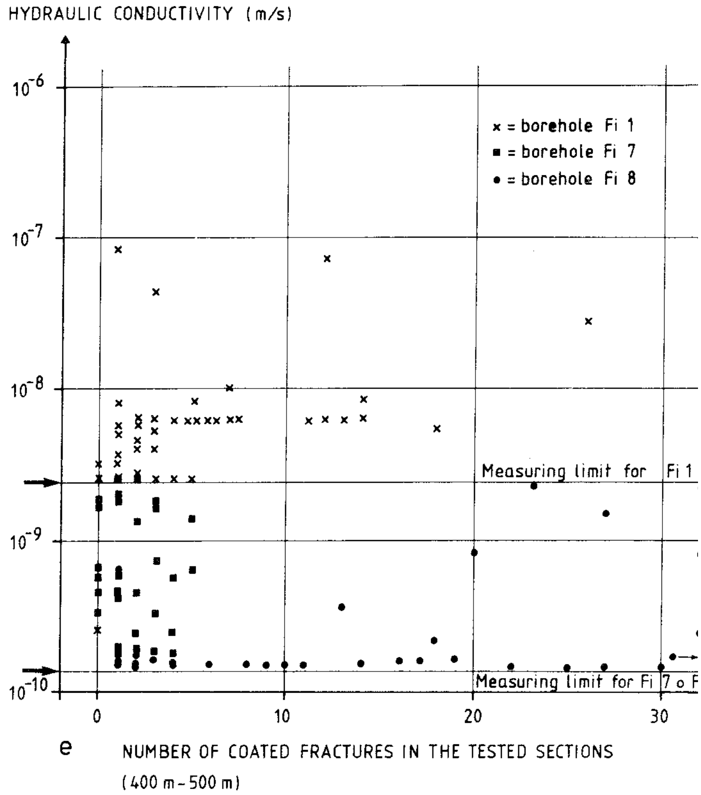


Fig 4:15 c,d,e. Hydraulic conductivity versus resistivity.

4.3.3 Correlation between resistivity, permeability and fracturing

The results of fracture mapping, water injection tests and resistivity measurements generally agree when it comes to large, pronounced permeable zones with a high fracture frequency. Otherwise, however, a relatively poor direct correlation exists between these three parameters. Fig. 16 presents a very schematic illustration of the implications of the different observations.

The boreholes in crystalline bedrock show a very wide variation in measured resistivity, usually between 1000 ohm-m for porous, fractured rock or rock with an extremely high frequency of microfissures (possibly with the occurrence of electrically conductive minerals and alteration products) and 100 000 ohm-m for compact, tight rock.

Despite the fact that the fracture faces can be in good contact with each other (unmeasurable permeability with conventional methods), these fractures can constitute pathways of electrical conduction (Brace 1968). If these fractures form a continuous network, the resistivity of the bedrock may be rather low.

Hydraulic conductivity varies along the boreholes between 10^{-10} m/s (measuring limit for tight rock) and 10^{-5} m/s. Since the tight parts of the bedrock do not have measurable hydraulic conductivities, the variation in hydraulic conductivity of the bedrock is considerably greater than that measured (Rocha 1977, Snow 1968).

Marine (1966) believes that the rock mass has two different types of fracture from the viewpoint of permeability. The first type consists of microfissures distributed throughout the entire rock mass that can only conduct water at very low flow rates. Rock mass that contains only this type of fracture is called non-transmissive impermeable rock. The second type of fracture, which exhibits a more well-defined extent in the rock mass and wider apertures, is, on the other hand, permeable.

Rock mass with such fractures is called transmissive or permeable rock (Marine 1980).

The bedrock's pore water content is of great importance for the mechanism of dispersal of the substances dissolved in the pore water, since it permits dispersal into the matrix of dissolved substances that are transported in the fluid along a flow path (Neretnieks 1980, 1981, Skagius 1981). This diffusion in the matrix can also be of importance for the physical and chemical interaction that takes place in the bedrock in connection with the migration and absorption of radionuclides (OECD, Newsletter 1, Paris 10 July 1979).

From in situ resistivity measurements, only qualitative estimates can be made of the bedrock's pore water content by estimating the background values of resistivity. Öqvist (1981) has performed laboratory measurements on selected drill core samples without visible coated fractures. The results (table 4:1) show that the porosity in Fi 8 varies between 0.1% and 0.6%.

The investigated boreholes do not show any correlation between the resistivity and permeability of the bedrock, except for a few zones, and then particularly in the more superficial parts of the boreholes. This may indicate that permeable fractures do not always occur in connection with the borehole sections that have the highest pore water content, but that permeable fractures may also occur in compact rock (low microfissure content and low water content in the large fractures) with low fracture frequency.

More homogeneous and fracture-poor sections in Finnsjön have a resistivity span that ranges from 3000 ohm-m to 100 000 ohm-m. Permeability values for such zones lie for the most part around the measuring limit, i.e. between 2.4×10^{-9} and 1.6×10^{-10} m/s.

Fig. 4:17 shows the result of an attempt to arrive at a composite interpretation of water injection tests, fracture mapping and resistivity measurements as well as a highly simplified classification of borehole sections with respect to their permeability.

The length of the borehole has been divided into permeable (hydraulically conductive) sections and sections that are impermeable or have very low permeability (hydraulic conductivity).

The limit value chosen to differentiate borehole sections with very low hydraulic conductivity from borehole sections with higher hydraulic conductivity is 1×10^{-8} m/s. This value has been chosen in view of the statistical distribution of hydraulic conductivity, where the tendency towards a bimodal distribution has been utilized in order to distinguish low-conductivity zones from high conductivity sections.

The limit that distinguishes zones with low resistivity from zones with high resistivity has been set at 20 000 ohm-m, which is very close to the mean value for Finnsjön and Kråkemåla.

Drill core sections with two coated fractures/m or less have been regarded as sections with low fracture frequency, while zones with more than two fractures per metre have been regarded as sections with high fracture frequency.

Impermeable rock (i.e. rock with very low hydraulic conductivity) has in turn been classified into four different section types as follows:

A_L Measurement sections without visible fractures or with low fracture frequency (fewer than 2 fractures) and characterized by high resistivity. This indicates a tight matrix with few microfissures.

B_L Measurement sections with high fracture frequency and high resistivity. These zones consist of compressed, non-transmissive fractures. The high resistivity also indicates a very low pore water content in the fractures and possibly also that the fractures are more or less sealed. This is a more probable condition for deeper parts of the boreholes.

C_L Measurement sections with low low fracture frequency and low resistivity, indicating a relative high frequency of microfissures in the matrix. In some cases, the presence of clays or electrically conductive minerals such as sulphides accounts for the lower resistivity.

D_L Measurement sections with high fracture frequency characterized by low resistivity. These zones are often found in deeper parts of the boreholes. These fractures have sufficient pore water content to constitute good transport pathways for electric current.

Permeable (hydraulically conductive) rock has also been classified into four types of sections:

A_H Measurement sections with high fracture frequency and relatively low resistivity. This situation characterizes highly fractured sections.

B_H Measurement sections with low fracture frequency and relatively low resistivity. This indicates that the borehole section has a few highly electrically conductive fractures, with a high pore water content and possibly also a high frequency of microfissures in connection with isolated transmissive fractures.

C_H Measurement sections with high fracture frequency and high resistivity. The presence of transmissive fractures in rock with a tight matrix and fractures that constitute poor pathways of electrical transport can explain this combination.

D_H Measurement sections with low fracture frequency and high resistivity. This indicates rock sections with low fracture porosity and less of a load on the fractures and possibly a higher content of microfissures. These conditions are most often found in shallower parts of the borehole and sections with steeply-dipping fractures.

The above proposed classification and interpretation from Fig. 4:17 can be used as a basis for detailed hydrogeological or geophysical evaluation.

In some cases, the above-described picture of fracture frequency, resistivity and water injection tests can be complicated considerably. This can be due to the presence of sulphides, iron oxides, graphite or clay minerals that can affect resistivities.

The following summation can be made from the above:

- In most cases, the upper parts of the boreholes exhibit high hydraulic conductivities.
- Transmissive (i.e. permeable fractures occur in both low-resistivity and high-resistivity rock.
- The geometric properties of the fractures change along the fracture planes; blockages, closures and interruptions can occur. As a result, the hydraulic and electrical conductivity of the fractures vary considerably.

TABLE 4:1

Borehole Fi 8 Finnsjö area

SAMPLE	POROSITY(%)	SAMPLE	POROSITY(%)
105.85	0.54	289.00	0.11
105.80	0.55	289.05	0.11
		289.10	0.15
105.75	0.60		
		350.50	0.39
125.75	0.47	350.55	0.39
125.80	0.40	350.60	0.36
125.85	0.41		
125.90	0.44	376.00	0.54
125.95	0.41	376.05	0.54
		376.10	0.56
172.00	0.62	376.15	0.56
172.05	0.61		
172.10	0.66	382.40	0.51
172.15	0.87	382.45	0.55
172.20	1.20		
172.25	1.00	408.40	0.42
		408.40	0.38
175.25	0.56		
175.30	0.56	411.05	0.53
175.35	0.55	411.10	0.48
		411.15	0.52
211.90	0.25		
211.95	0.25	459.20	0.19
		459.25	0.19
238.80	0.19	459.30	0.14
238.85	0.24	459.35	0.18
238.90	0.19		
238.95	0.9	461.00	0.19
		461.05	0.26
239.00	0.24	461.10	0.40

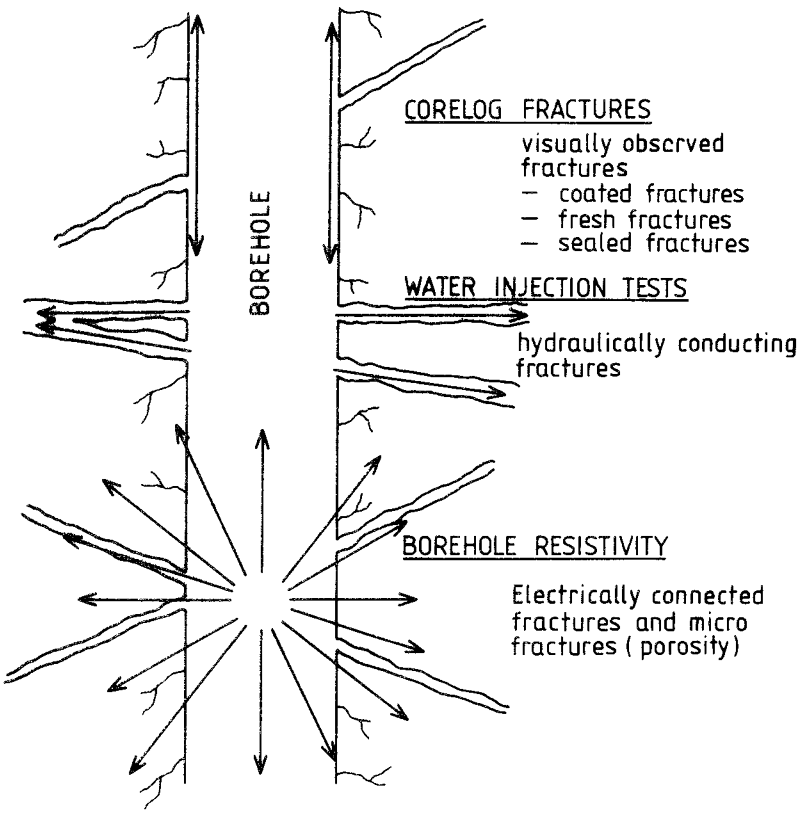


Fig 4:16 Schematic representation of the zone of investigation for the fracture mapping, water injection tests and borehole resistivity.

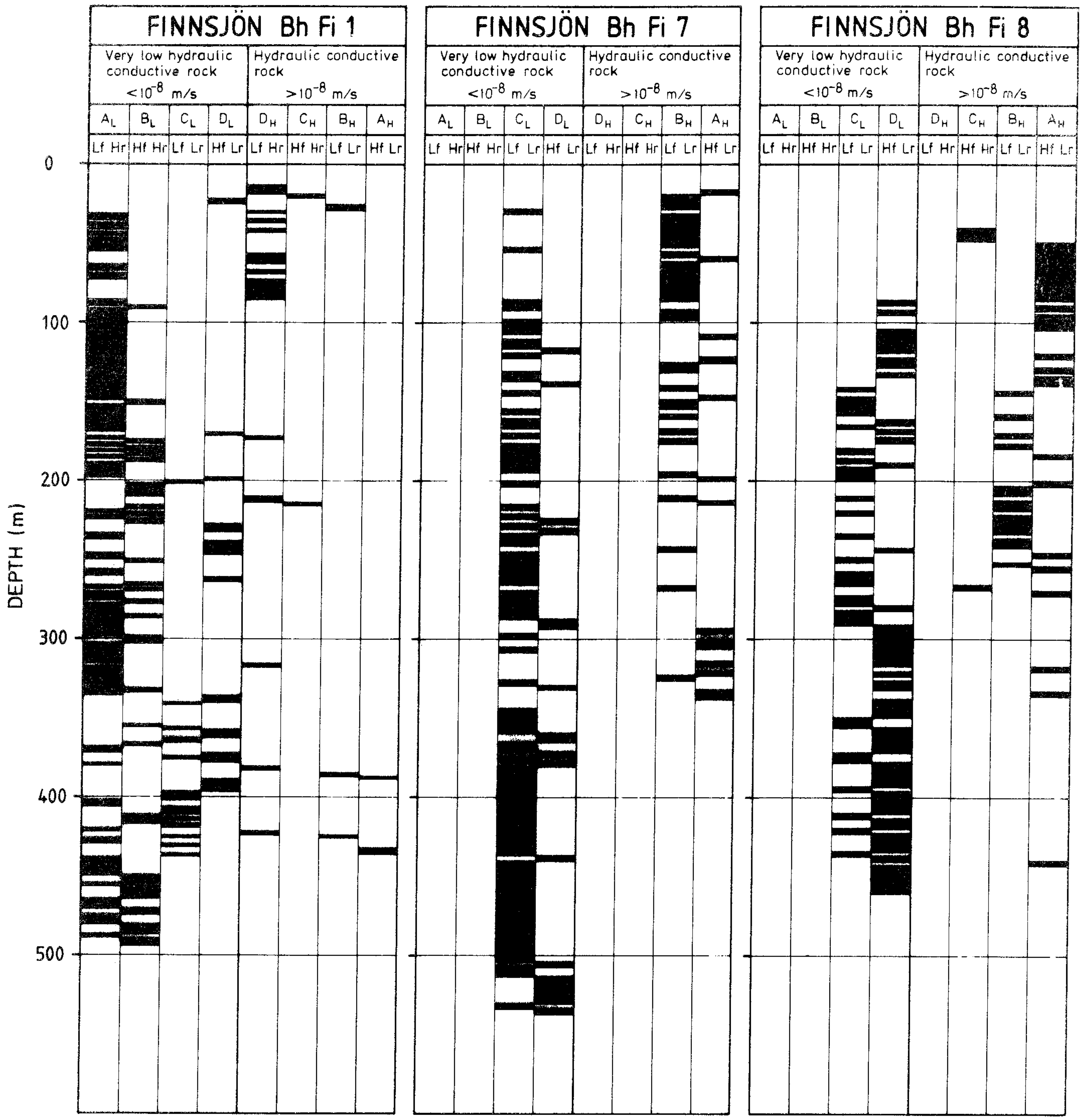


Fig.4:17 CLASSIFICATION OF THE ROCK MASS IN FUNCTION OF THEIR HYDRAULIC CONDUTIVITY, RESISTIVITY AND FRACTURE FREQUENCY.

VERY LOW HYDRAULIC CONDUCTIVE ROCK

A_L -Section with low fracture frequency(Lf) and high resistivity(Hr).

B_L -Section with high fracture frequency (Hf) and high resistivity (Hr).

C_L -Section with low fracture frequency (Lf) and low resistivity (Lr).

D_L -Section with high fracture frequency (Hf) and low resistivity (Lr).

HDRAULIC CONDUCTIVE ROCK

A_H -Section with high fracture frequency (Hf) and low resistivity (Lr).

B_H -Section with low fracture frequency (Lf) and low resistivity(Lr).

C_H -Section with high fracture frequency (Hf) and high resistivity (Hr).

D_H -Section with low fracture frequency (Lf) and high resistivity (Hr).

5. CONCLUSIONS

The fractures in the bedrock are characterized by the fact that the fracture faces are altered and usually also coated with fracture-filling minerals. With the exception of calcite, most of the investigated fracture-filling minerals were deposited under hydrothermal pressure and temperature conditions (Larsson et al 1981). They were thus deposited during early periods of hydrothermal activity or formed at great depths where pressure and temperature have been higher than at present-day erosion surfaces in the bedrock. Owing to the fact that the Swedish crystalline basement consists of very old rock types that have been exposed to erosion for a very long period of time, present-day erosion surfaces were originally situated at much greater depth.

The formation of fracture-filling minerals leads to varying degrees of sealing or "healing" of the fractures. The "healed" fractures thus constitute "scars" in the bedrock. Changes in the state of stress in the bedrock caused by tectonic events, or by uplift of the bedrock due to e.g. erosion or deglaciation, bring about a new fracturing of the bedrock. This uplift of the bedrock gives rise to an unloading of the upper parts of the bedrock, which causes fracturing in these upper parts. This fracturing follows to a large extent the previously formed "scars" in the bedrock (Thorpe et al 1980). This leads to a situation where most of the bedrock's open and water-filled fractures usually have an older mineral coating. If fractures are generated through fresh rock, chemical reactions between the pore water and the fracture face will cause the formation of an alteration skin or a calcite coating. It is thus the mapped fractures with alteration skin or mineral coating that constitute possible transport pathways for the groundwater or electric currents, thereby influencing the resistivity measurements and the water injection tests. On the other hand, sealed or "healed" fractures that have resisted these stresses do not serve as transport pathways.

The results show that injected water is primarily channelled in a few discrete fractures, while most of the mapped coated fractures have non-measurable or very low permeabilities. The microfissures in the matrix also have unmeasurable permeabilities. In fracture or crushed zones, the water is therefore injected primarily into a few large fractures, while only an insignificant portion of the water is injected through the other fractures in the measurement section. On the other hand, current transport through the microfissures in the matrix gives rise to measurable resistivity values. Many of the impermeable fractures in a fracture system can constitute good transport pathways for electrical current, i.e. the fractures have sufficient pore water content and electrical connection with each other to constitute good transport pathways. Also, alteration products such as clays may contribute to current propagation in these fractures. Despite the fact that both water and current transport take place through the fractures and microfissures in the rock, the results show large differences between current transport on the one hand and water transport on the other. This may be due to the properties of the unsealed fractures described in the following.

Because the fractures have uneven fracture faces with some roughness, only the projecting parts of the fracture faces come into contact with each other. The groundwater is therefore transported through interconnected cavities between the projecting parts (Greenwood & Williamson 1966, Walsh & Rosenbaugh 1979). This model is in agreement with Maini's (1971) results, which show that the water flow in fractures is primarily limited to channels that are made up of the large, well-interconnected cavities, while large portions of the pore volume contain virtually stationary groundwater (i.e. extremely slow water movements). The water is therefore probably injected only in a few fractures that have a flow channel in contact with the borehole, while most of the mapped fractures do not have any flow channel in contact with the borehole, i.e. at the point where the fracture is intersected by the borehole, the fracture faces have good contact with each other. On the other hand, Brace et al (1965) have shown that electric currents can be conducted relatively easily through thin water films in compressed fractures (this property is called surface conduction). The current may also be transported through interconnected skins of alteration products. Thus, electric current can be transported in many fractures that do not have hydraulic conductivities measurable by the water injection tests. But in these fractures, chemical diffusion can constitute an important mechanism for the transport of substances dissolved in the water. Despite the fact that only a few of the fractures have permeable channels, the water injection tests provide a good statistical picture of the average hydraulic conductivity of the channels and their variation in conductivity. This is because the 500 m deep boreholes intersect many fractures, usually more than a thousand.

Because the water injection tests are controlled by individual fractures that have permeable channels in contact with the borehole, the water injection tests exhibit a poor correlation with fracture frequency. But because the probability of drilling through a water-bearing channel increases with the number of fractures within the measurement section, the water injection tests nevertheless show some tendency to occur in the fractured borehole sections. On the other hand, the value of hydraulic conductivity does not show any correlation to the number of fractures in the measurement section. Nor do the water injection tests exhibit any correlation to observed fracture widths in the borehole wall. But thick fractures, which in general also constitute a diametral recession in the borehole wall (differential point resistance), normally have measurable hydraulic conductivities, although even these fractures can have unmeasurable hydraulic conductivities in some cases. Very thin fractures (<1 mm) that do not have any detectable widening in the borehole wall can in some cases also have high hydraulic conductivities, comparable to those of fractured sections with thick fractures. The fracture widths calculated from the injection tests are normally several times thinner (usually only 10 μm to 1000 μm) than observed fracture widths in the borehole wall (Davidsson 1980). This shows that the fracture width in the borehole wall does not reflect the thickness of the permeable channel-shaped cavities in the intersected fracture planes that are in contact with the borehole. In addition, the fractures can often be apparantly thicker in the borehole wall due to the fact that small chips have been broken loose from the fracture edges. Through electrical surface conduction, current transport is distributed over numerous fractures. Resistivity therefore exhibits a better correlation with fracture frequency along the borehole. Current propagation thereby exhibits a more homogeneous pattern. This is in agreement with Brace et al (1965), who showed that electrical conductivity is approximately proportional to the square of porosity. Because thick fractures have a higher pore water content than thin ones, resistivity therefore exhibits a better correlation with the total fracture width of the fracture zones than with fracture frequency.

Brace (1977) has shown that it is possible to obtain a very good correlation between measured resistivity and hydraulic conductivity on crystalline rock samples. Because Brace used a very saline pore water, the contribution from surface conduction was negligible compared to volume conduction through the large cavities in the rock samples. Consequently, both water and current transport take place primarily through the same cavities, which means that a good correlation is obtained between hydraulic conductivity and resistivity.

With increasing depth, the state of stress in the bedrock leads to increased compression (closure) of the fractures. As compression of the fractures increases, more and more of the asperities on the fracture surfaces are brought into contact with each other. This causes more and more of the flow channels to be cut off, which in turn leads to poorer hydraulic communication between the flow channels of intersecting fractures (Greenwood & Williamson 1966, Walsh & Grossenbaugh 1979). As a result, fewer and fewer of the measurement sections have measurable permabilities with increasing depth. There are therefore very few permeable measurement sections at great depth in the boreholes. In Finnsjön, a decrease in the value of hydraulic conductivity was recorded with increasing depth. In other words, the hydraulic conductivity of the rock mass declines with increasing depth. This is due to the fact that the flow channels in the fractures become narrower and that some of the flow channels are cut off (Witherspoon et al 1980). Walsh

(1981) has shown that the permeability of the fracture is proportional to the cube of the fracture aperture, while increasing complexity (tortuosity, i.e. more winding and longer transport pathways for the water) is only inversely proportional to permeability.

Increased compression of the fractures also leads to higher resistivity due to both the fact that volume conduction through large flow channels decreases and that surface conduction also decreases, since some surface conduction pathways are also cut off. But due to surface conduction, electrical conductivity is affected to a much lesser degree than the water injection tests by compression of the fractures. It is mainly the contact points that increase with the load, while the average distance between the fracture surfaces is affected to a lesser degree (Walsh & Grossenbaugh 1979). Thus, the pore water volume is affected to a lesser degree and the fractures therefore contain water available for diffusion. The resistivity measurements therefore do not in general exhibit any tendency towards higher resistivity with increasing depth.

At great depth, it is therefore common that many highly fractured borehole sections with high electrical conductivity do not have measurable permeabilities. The fractures in these zones do not have any permeable channel in contact with the borehole. Since these fractures have relatively good electrical contact and relatively high pore water content (note: no mapped minerals with good electrical conductivity), it is possible in some cases that the fractures may have permeable channels that have not been intersected by the borehole, i.e. if the fracture zone is drilled through at another point, the section may have high permeabilities. On the other hand, in the more superficial parts of the borehole, compact rock with very high resistivity (i.e. very low pore water content) and extremely fracture-poor sections with large fracture spacing up to tens of metres may have measurement sections with high permeabilities comparable to fractured sections. However, from the viewpoint of water transport, these sections should not be comparable to the fractured sections. It can therefore be justified in detailed studies to use the classification of the bedrock that has been proposed in chapter 4.3.3, where the bedrock along the borehole has been characterized by weighing together fracture frequency, resistivity and hydraulic conductivity. This can serve as a complement to the information obtained from the water injection tests.

The two investigated areas (Kråkemåla and Finnsjön) exhibit very different physical conditions. Finnsjön has a much denser fracture mosaic and a higher frequency of microfissures in the matrix than Kråkemåla. Finnsjön's boreholes exhibit large differences among themselves. Fi 1, which has been drilled through more compact rock with a lower fracture frequency, has a character that more resembles Kråkemåla than the other boreholes (Fi 7 and Fi 8). Despite the fact that Kråkemåla has a sparser fracture mosaic, the fracture zones and the borehole-penetrated fracture systems often have high permeabilities compared to Finnsjön. This indicates that the high frequency of microfissures and the denser network of fractures has made it easier for the Finnsjö area to absorb more recent changes in the state of stress. Due to the very sparse and essentially primary fracture network in Kråkemåla, more recent changes in the state of stress have probably given rise to large and persistent fractures along these older primary fractures with different degrees of sealing. This is because there are fewer weaknesses in the bedrock to absorb the stress. Under the very long period of time that has passed since the formation of the rock, the state of stress may have undergone change in different stages.

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APPENDIX

A DESCRIPTION OF THE BOREHOLE METHODS

A.1 Core examination and TV inspection

Core examination and TV inspection are two methods for visually studying the borehole-penetrated bedrock. Knowledge of the fractures' appearance in the borehole wall and in the drill core provides valuable background information for interpreting the hydrological and geophysical borehole measurements. It is therefore important to compare the appearance of the fractures in the core to their appearance in the borehole wall. A comparative study of core and TV inspection is described in PRAV 4:14 (Brotzen et al 1980). The drill cores from two TV - inspected boreholes (K1, K2) have also been re-examined in order to determine the cause of the deviations noted in the comparison between the methods.

A.1.1 Core mapping

The fractures that have been mapped in connection with core examination constitute breaks of the core. They have been classified with respect to the character of the fracture surfaces.

A Fractures with mineral-coated or altered fracture surfaces = Coated fractures

B Fractures with fresh fracture surfaces without visible mineral coating or alteration skin = Fresh fractures

Fracture systems that consist of at least two fractures and where the spacing between the fractures is less than 10 cm were mapped as fracture zones. In order to be able to estimate the fracture frequency along the boreholes, it was assumed that one fracture occurs every dm in the fracture zones. In mappings carried out since 1977, the number of fractures in each fracture zone has also been noted, for example in the mapping of borehole

Fi 8. During drilling, it sometimes happens that two core pieces are rotated against each other, causing the contact surfaces to be polished (polished fractures). In such cases, it is difficult to determine whether the surfaces have been mineral-coated. In cases where it is not possible to determine whether the fractures have been mineral-coated, they are mapped as fresh fracture.

The core also contains fractures without any accompanying break of the drill core. If these fractures are healed or partially healed with fracture-filling materials, they will henceforth be called healed fractures. If there is no visible fracture-filling material, the discontinuities will be called fracture indications, i.e. fractures without actual break of the core and with no visible fracture-filling material.

Fracture indications and healed fractures were not mapped due to the fact that they were assumed to be of less importance for groundwater transport. In interpreting the core mapping, it was assumed that fresh fractures have mainly arisen in connection with drilling and subsequent core handling and are thereby also of less importance for groundwater transport. In some cases, coated fractures with a very thin alteration skin may have been mapped as fresh fractures. In the core mapping carried out after 1977, fracture indications and healed fractures were also noted. In one of the investigated boreholes (Fig. 8), these fractures have therefore also been studied. Some breaks in the core have probably been induced in connection with drilling and handling of the core. The most probable location of an induced break of the core is in zones of weakness, for example at healed fractures and fracture indications. We can therefore assume that some mapped coated fractures may have arisen through induced break in a healed fracture and that some fresh fractures are induced breaks at fracture indications. Evidence of this is the fact that fresh fractures often occur together with fracture indications.

Comparative studies of TV inspection and cores from 12 m deep boreholes in a drift at a depth of 360 m in the Stripa test station show that fewer than 10% of the open fractures in the core were open in situ (Paulsson et al 1981). It is therefore probable that many mapped coated fractures were originally healed fractures. But coated fractures with very thin alteration skins can also be mistaken for fresh fractures in core mapping.

A.1.2 TV inspection of boreholes

The borehole wall has been inspected with the aid of a TV camera. In order to be able to observe the entire borehole wall around the camera, a conical prism head has been mounted in front of the camera. A compass has been mounted in the centre of the prism, enabling the fracture planes to be oriented. The camera reproduces 2.5 cm of the borehole's length. The fractures observed in the Kråkemåla boreholes (K1 and K2) in connection with TV inspection have been classified into groups with respect to their observed apparent fracture width in the borehole wall (<1 mm, 1-5 mm and >5 mm). In the TV-inspected percussion boreholes in Finnsjön, the fractures have been subdivided into fractures that can be followed around the entire circumference of the borehole wall and fractures that can only be followed part way. Only the former kind can be oriented with respect to strike and dip of the fracture. This method permits an estimate of the relative breadth of the fractures, but it is difficult to determine the degree to which the fractures are filled with fracture-filling material.

A.2 Resistivity measurements

Resistivity measurements provide a picture of the bedrock's content of mobile and diffusion-available groundwater. The measurements are mainly carried out with two different electrode configurations, normal 1.6 m and lateral 1.65 m. The apparent resistivity of the normal measurements is determined by measuring the potential at a given distance (1.6 m) from a current electrode lowered into the borehole.

In the lateral measurements, the potential difference is measured between two potential electrodes in the borehole at a short distance from each other (0.1 m). The distance to the current electrode is considerably greater, 1.6 m. In both cases, a current electrode is placed on the ground surface at a large distance from the borehole. Normal configurations usually give symmetric readings around the fracture zone. After correction for the influence of the conductivity of the borehole fluid, the borehole diameter and the width of the fracture zones (thin fracture zones), the normal configuration is suitable for a quantitative estimate of the actual resistivity of the bedrock. A large body of background material is available for such calculations in the form of theory and laboratory measurements (Dakhnov 1959, 1962).

Since the resistivity of the rock is often 100-1 000 times greater than the resistivity of the borehole fluid, some of the current will be conducted along the borehole. This gives rise to an apparent resistivity that differs from the actual resistivity of the rock. Since measurements are made with a probe whose diameter is almost equal to the borehole diameter, and the probe's electrode distance is about 30 times the borehole diameter, the influence of the borehole fluid is assumed to be small.

In order to obtain a representative value of the resistivity of a zone by resistivity measurements, zones with deviant resistivity must be larger than the configuration distance (1.6 m). This means that at, for example, thin low-resistivity zones, the measured resistivity is too high. The network of microfissures in the matrix that is normally found in connection with isolated large fractures and fracture zones gives rise to an increase in the electrical conductivity of the fractures. As a result, even small thin fractures can be detected in the resistivity loggings.

In order to permit comparison of the resistivity measurements with the water injections, the bedrock along the borehole has been divided into borehole sections with different average resistivities.

A theoretical estimate of the length of the borehole system that affects a resistivity measurement can be obtained from Dakhnov (1962).

Owing to the complex fracture tectonics of the bedrock, the fractures often intersect the borehole in a complex pattern and at different angles. The dip of the fractures in relation to the borehole axis influences the resistivity measurements. This influence is dependent on the intersection between the fractures and the borehole wall. See illustration in Fig. A.1.

An estimate of the width of the zone h_r and the dip of the fractures can be obtained from core mapping or TV inspection. Determining the inclination of the fractures towards the borehole axis by means of resistivity measurements is, on the other hand, difficult and the risk of misjudging is great. h_s is the apparent width of the fracture planes or the fracture zone that can be determined from core mapping or TV inspection, while h_g is the width of the fracture estimated from the resistivity measurements (Fig. A.1). This shows that the resistivity measurements can often give an apparently wider fracture zone.

An example from three shallow boreholes (about 100 m deep) at Finnsjön (G1, G2 and G0), where well-defined fracture zones with comparable fracture frequency and uniform dip (estimated from TV inspection) have been correlated to resistivity, shows that flatter fractures give higher resistivity, see Fig. A.2.

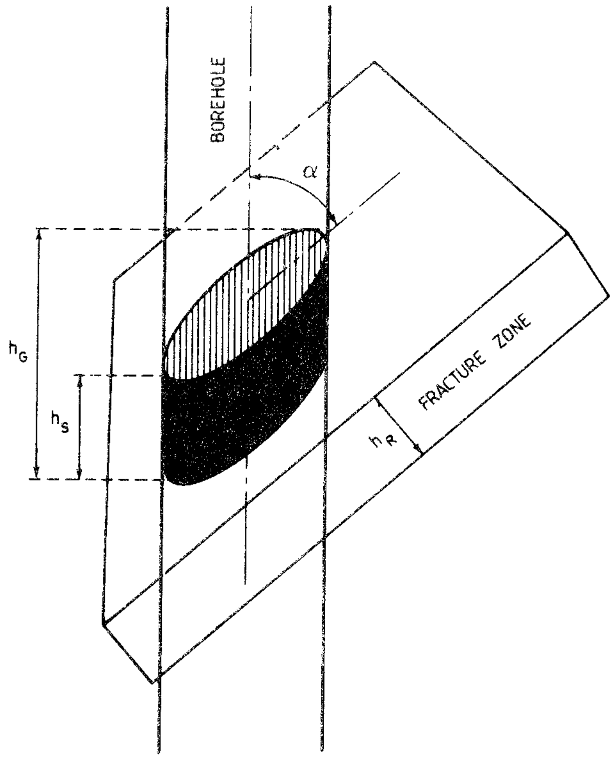

Fig A:1. Intersection between the borehole and the fracture zone. h_s = apparent width at the intersection. h_r = width of the fracture zone. h_g = apparent width estimated from resistivity measurements.

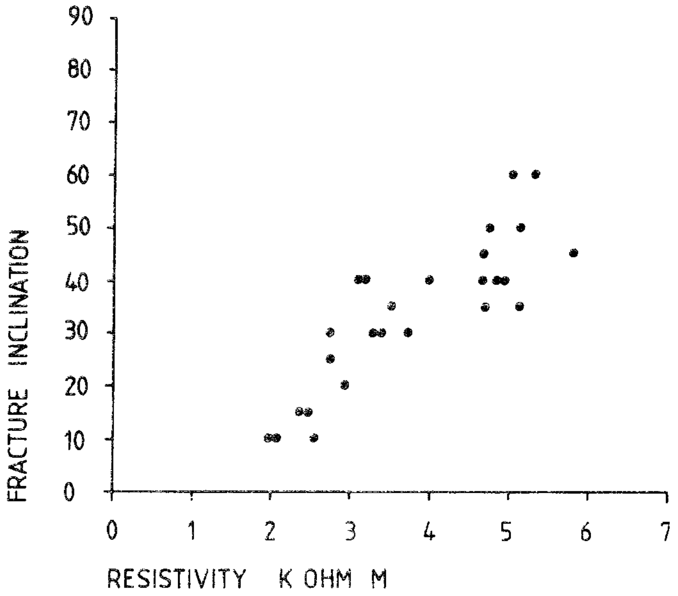

Fig A:2. Resistivity versus the inclination of the fractures i.e. the angle between the fracture and the borehole axis.

A.3 Differential resistance

Variations in the borehole's diameter are normally measured with a caliper log. Another common method that is sensitive mainly to variations in the borehole's diameter is differential resistance measurement. Only differential resistance has been carried out in the logged boreholes. The caliper is a mechanical probe with three arms that sense the diameter of the borehole, while differential resistance can be said to work like an electrical caliper probe that gives qualitative to semiqualitative data on borehole diameter (Brotzen et al 1980).

The differential resistance probe consists of two electrodes that function as both current and potential electrodes. The two electrodes are separated from each other by a 12 mm thick insulator of plastic. The negative electrode (140 mm long) is situated above the shorter (10 mm long) positive electrode. Owing to the fact that the resistivity of the borehole fluid (20 to 300 ohm-m, Duran and Magnusson 1980) is much lower than that of the crystalline bedrock (1 000 to 100 000 ohm-m), the electric current tends to flow in the borehole fluid. Because the insulator has a diameter that is very close to the diameter of the borehole (1 mm smaller than the borehole's diameter), the current between the electrodes is forced to travel between the insulator and the borehole wall. As a result, the method is very sensitive to variations in borehole diameter. More detailed descriptions of this measurement method are provided in other reports (Magnusson and Duran 1978; Nelson et al 1979). Laboratory tests have shown that the differential resistance probe can detect fractures with a width of 1 mm and a diametral recession of 1 mm (Nelson et al 1979). Comparisons between different resistance and the caliper method show that the methods give very similar results (Nelson et al 1982). Electrically conductive veins such as pyrite can also give marked indications on the differential resistance log. With supplementary logs, these veins can be distinguished from deviations caused by variations in borehole diameter (Brotzen et al 1980).

Widenings in the borehole's diameter can be caused by the fact that fractures that are open in the borehole wall constitute a recess in the borehole wall. An increase in the borehole's diameter may also have arisen from various other causes:

In highly crushed formations with unsealed fractures, the fractures divide the rock into a network with only small pieces of intact rock. These pieces can come loose from the borehole wall and cause an increase in the borehole diameter.

Zones of weathering, gangue-filled discontinuities and breccia, which can have considerably lower strength than normal rock, can be scooped-out during the drilling procedure.

Groups of fractures where the fractures are situated only a few mm from each other can together cause the borehole to be widened during drilling.

Open fractures constitute a recess in the borehole wall. The fracture can be further widened by chips detaching from the fracture edges, which gives rise to an apparently wider fracture aperture.

An increase in the diameter of the borehole does therefore not necessarily have to be caused by fractures with large fracture apertures. But besides the fact that borehole sections with widened borehole diameter can contain fractures with large fracture apertures, these sections can also cause difficulties in sealing hydraulically-tested measurement sections. Information on widened borehole diameter therefore provides valuable background information for the hydraulic tests.

The differential resistance method has a small depth penetration, which means that the method is only sensitive to fracture apertures in the immediate vicinity of the borehole wall. Therefore, fractures that are only open in the borehole wall (due to the fact that fracture-filling material has been flushed out or that chips have detached from a fracture (where the fracture surfaces are in good contact with each other) cannot be distinguished from more continuous open fractures.

A.4 Water injection tests

With water injection tests, the hydraulic conductivity of the bedrock in the vicinity of a borehole can be calculated. Both double and single packer measurements have been carried out in a number of boreholes. In the double packer measurements, the measurement sections are sealed off by 0.3 m long rubber packers, which seal against the borehole wall hydromechanically. Water is forced out into the bedrock under constant pressure between the two sealing packers. The flow of the injection water is recorded during the measurement. When only insignificant changes are obtained, equilibrium is assumed to prevail. In calculating the hydraulic conductivity, it is therefore assumed that steady-state flow conditions prevail. But in the measurements performed by SGU (The Geological Survey of Sweden) prior to 1980, the measurement times were probably somewhat too short for a steady state to develop. If so, this leads to slightly too high permeability values in general.

For measurement of the applied injection pressure (differential pressure), pressure sensors are positioned above the upper packer, but in hydraulic connection with the measurement section. The pressure is thus measured directly at the level of the measurement section, so pressure losses in the water injection pipe do not have to be taken into consideration, as they do if the pressure is measured at the ground surface.

In single packer measurements, the injection water is forced out below the rubber packers instead of between them. The measurement section is therefore the section between the lower packer and the bottom of the borehole. The long measurement sections make it theoretically possible to achieve a lower measuring limit for permeability, as calculated over the entire measurement section, than in double packer measurement. Furthermore, any leakage is distributed over a larger section length, reducing the influence of this source of error. Moreover, there should be less risk of leakage in single packer measurements.

Double packer measurements have been used to compare with other borehole methods, because these measurements have been carried out in all boreholes and this method has a greater vertical resolution along the borehole than single packer measurements. In the double packer measurements, differential pressures of 0.2 and 0.4 MPa have been used in most sections. Measurements at 0.6 and 0.8 MPa have also been carried out in certain measurement sections in all boreholes. In presenting the results of the double packer measurements and comparing them with other measurement methods, differential pressures of 0.2 and 0.4 MPa have been chosen, since low pressures are considered to give more realistic results than high pressures, owing to the fact that the stress conditions in the bedrock are affected more at high pressures. Comparison of double packer measurements at 0.2 MPa and 0.4 MPa differential pressure shows that, in general, higher conductivity values are obtained at the lower pressure when the conductivity is greater than 1.0×10^{-9} m/s. When the conductivity is less than 1.0×10^{-9} m/s, however, higher hydraulic conductivity is generally obtained with 0.4 MPa. The differences are small, however (Carlsson et al 1980; Ekman and Gentzschein 1980).

Calculating the hydraulic conductivity in accordance with Bank's equation (1972) assumes both a homogeneous porous medium and steady-state flow conditions:

$$K = \frac{Q}{C\,LH}$$

Where	K =	hydraulic conductivity	m/s
	C =	borehole constant	dimensionless
	Q =	water flow	m^3/s
	L =	length of measurement section	m
	H =	differential pressure head	m H_2O

The constant C has been determined by Moye (1967) to be

$$C = \frac{1+\ln(L/d)}{2\,\Pi}$$

where d is the diameter of the borehole and L is the distance between the packers.

A prerequisite in order for this value of C to be reasonable is that L > d. This condition has been considered to be fulfilled in the double packer measurements, where L = 3 m and d = 0.056 mm. In the single packer measurements, however, L > 50 m, it has been assumed that C = 1.

In calculating hydraulic conductivity, it is assumed that the water flow is distributed evenly over the entire measurement section. But in a fractured medium such as crystalline rocks, the water flow through the rock matrix is neglible. The water flow therefore takes place through a very limited part of the measurement interval, i.e. in fractures that occupy a very small portion of the measurement section. This means that the hydraulic conductivity in the fractures is much greater than the value calculated under the assumption that water propagation is homogeneous. Another calculation method for determining the hydraulic conductivity of the measurement section is to distribute the water flow over the observed fractures in the measurement section. If a fracture model is applied where the fracture comprises a plane-parallel joint of infinite extent, the flow of water in the fracture can be calculated in accordance with the equation in chapter 2.3. Since it is virtually impossible to make a good estimate of the actual fracture apertures of the observed fractures in the measurement section, it is difficult to estimate the hydraulic conductivity of the individual fractures. In other investigations, a model is used where the water flow is assumed to take place through a single open fracture in the measurement section. From this model, an equivalent fracture aperture can be calculated for each measurement section. Both of these models give a generalized picture of the permeability of the bedrock.

Besides the approximations that are made using the different calculation methods for the permeability of the bedrock, there are also practical/technical sources of error. Practical/ technical sources of error tend to overestimate the permeability of the rock mass, above all due to leakage in the equipment or leakage past the packers. This applies to a higher degree to double rather than single packer measurements. Theoretical sources of error give too high permeability values when $K > 10^{-8}$ and too low values when $K < 10^{-8}$ m/s.

In connection with permeability measurement, a hydrostatic pressure is applied that can alter the natural conditions in the rock mass (Carlsson and Olsson 1979, page 15). This leads to effects that are generally of two different types: widening of fractures within the measurement section and flushing-out and redeposition of errodable fracture fillings.

If water with a significantly different salinity or temperature than the natural groundwater, is used, permeability values that deviate from the actual permeability of the rock mass to natural groundwater can be obtained.

Water injection tests can be considered to give permeability values that conform closely to the actual permeability of the rock mass. The influence of various disturbing effects on the representativeness of the measured value should normally be of the same order of magnitude as the naturally occurring variation in the rock mass (Carlsson et al 1980).

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