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by

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SUMMARY

The Kamlunge study site constitutes a 16 km^2 mountain plateau. The topography of the plateau is flat, the soil cover is thin, and in the western part, there is a high percentage of outcrops. The most commonly occurring rock types are gneisses and red granite (Lina granite). A rock type with granodioritic to dioritic composition also occurs. Concentrations of economically valuable minerals are so small that mining operations are not feasible in the area.

The rock mass exhibits a fracture frequency of more than 4.0 fractures per metre down to a depth of 200 metres. Below 300 metres, the fracture frequency is approximately 2.0 fractures per metre.

The Kamlunge study site is surrounded by regional fracture zones to the north, east and west delimiting a 16 km^2 triangular block. The regional zone to the west of the study site has a width of about 550 m.

Only local fracture zones spaced 500-1 500 m apart occur within the study site. The local fracture zones are generally steeply inclined and strike to the north-west and the north-east. At a depth of 555 m below Kamlungekölen, a horizontal fracture zone has been encountered in 4 of the deep drill holes. This fracture zone is permeable to water but less crushed and weathered than the steeply inclined fracture zones. Moreover, horizontal fractures of large lateral extent can occur in the upper 100-200 metres. Common fracture minerals in the fracture zones are calcite, chlorite, laumontite, smectite and various types of iron oxides.

The hydraulic conductivity of the rock mass decreases markedly with depth. It decreases from about 2×10^{-9} m/s at a depth of 100 metres to about 10^{-11} m/s at a depth of 500 metres.

The hydraulic conductivity of the local fracture zones at Kamlunge is 7×10^{-10} m/s at a depth of 500 m. The hydraulic conductivity decreases with depth more slowly in the fracture zones than in the rock mass. The large hydraulic gradients found on the margins of the Kamlungekölen do not affect the groundwater flows at a depth of 500 m within the study site.

1. INTRODUCTION

1.1 Background

Within the scope of the long-range program for final disposal of spent nuclear fuel, investigations will be performed in a number of study sites (SKBF/KBS, 1982). These investigations, performed for the purpose of characterizing different sites, are pursued in accordance with a general work program, known as the Standard Program (Brotzen, 1981; Thoregren, 1982).

Kamlunge is one of the study sites that has been investigated with deep drill holes in order to obtain further knowledge of the geological, hydrogeological and geochemical conditions at great depth in Swedish crystalline rock. The purpose of the investigation has been to bring forth the site-specific data required for a safety analysis of a repository for spent nuclear fuel. The investigations started at Kamlunge with the first drill hole in August 1981, continued with additional drilling in June 1982 and were essentially completed in May 1983.

1.2 Reporting of results

This report constitutes a summary and evaluation of data from the Kamlunge study site. A detailed account of the results obtained from the site is given in the following reports:

Albino, Nilsson, Sehlstedt, Stejskal & Stenberg, 1982:

"Geological, tectonic and geophysical investigations at the Kamlunge study site."

The report accounts for the results of the geological and tectonic mapping, the results of core mapping and percussion drill holes as well as the results of geophysical surface investigations.

Albino, Nilsson & Stejskal 1983:

Compilation of technical data from the different drill holes as well as fracture and rock type logs, Kamlunge study site.

The report deals with drill core mapping and technical data from the drilling work.

Lindholm, Sehlstedt & Stenberg 1983:

Geophysical borehole investigations at the Kamlunge study site.

Danielsson 1983:

Hydrogeological investigations at the Kamlunge study site.

The report accounts for the hydrological conditions at the site, including groundwater level maps and the results of water injection tests in the deep drill holes.

The extent of the main elements of the site investigations at Kamlunge are described in the Appendix. The various investigation procedures are described by Ahlbom, Carlsson & Olsson (1983) and Almén, Hansson, Johansson, Nilsson, Andersson, Wikberg & Åhagen (1983).

2. THE SELECTION OF STUDY SITE KAMLUNGE

As a result of reconnaissance work in 1981, Kamlunge was selected as one of the most interesting sites. The choice of the Kamlunge site was primarily due to the following factors:

- Regional fracture zones delimit an approx. 16 km^2 plateau.
- The plateau has a flat topography.
- The study site has a low frequency of air-photo-interpreted fracture zones.

- Low fracture frequency in rock outcrops.

- One landowner.

The proportion of outcrops is large, about 30% within the site's western and central parts, while the eastern part has a few scattered rock outcrops. The high degree of exposure facilitates the geological and tectonic interpretation of the site.

Geological field reconnaissance and geophysical profile measurements were carried out during the spring of 1981. The latter indicated large areas with few indications of fracture zones. After these introductory geological and geophysical investigations, the site was judged to be promising, and a 700 m deep drill hole was drilled in order to study the characteristics of the bedrock at depth.

The results from this drill hole indicated that the bedrock is of low fracture frequency even at depth. A decision was taken in the spring of 1982 to commence complete investigations.

3. LOCATION AND TOPOGRAPHY

The Kamlunge study site is situated in Norrbotten County, about 65 km north-east of Luleå, see locality map figure 3.1. The site is situated in the municipality of Kalix and is reproduced on the topographical map-sheet 25 M Kalix NV.

The coastland of Norrbotten County is permeated by rivers and water courses that discharge into the Gulf of Bothnia. These river valleys run primarily in a north by northwesterly direction. This direction coincides with the glacial striae. The Kamlunge study site is located 5 km east of the Kalixälven River. The ground level within the site varies between 40 and 170 metres above sea level. A topographical profile over the site is shown in figure 3.3.

The Kamlunge study site is forested, alternating with elongated bogs with a northwesterly orientation. The Quaternary deposits consist of

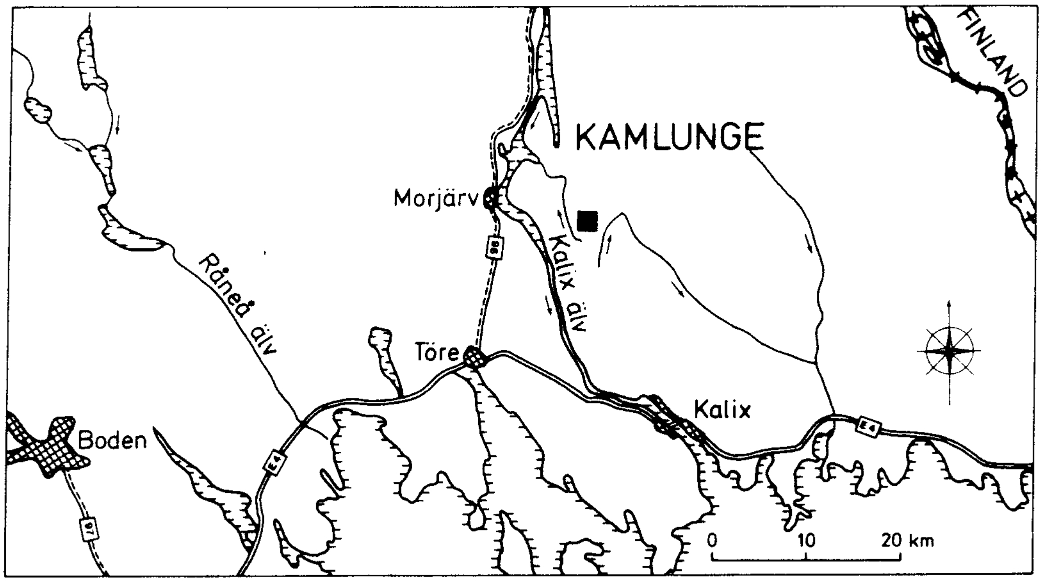


Figure 3.1 Locality map for site Kamlunge.

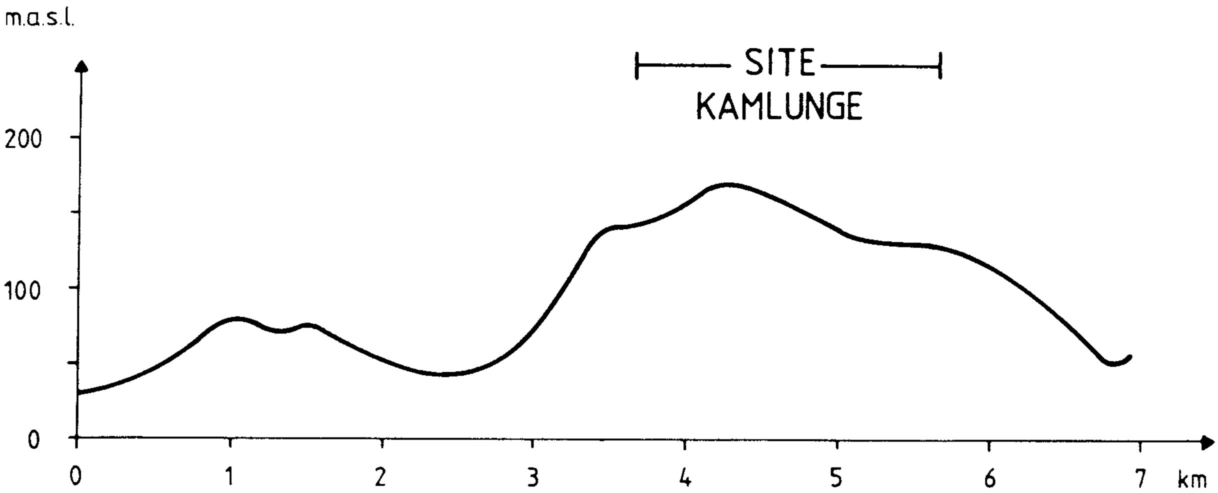


Figure 3.2 Topographical profile across site Kamlunge, location shown in fig. 5.1.

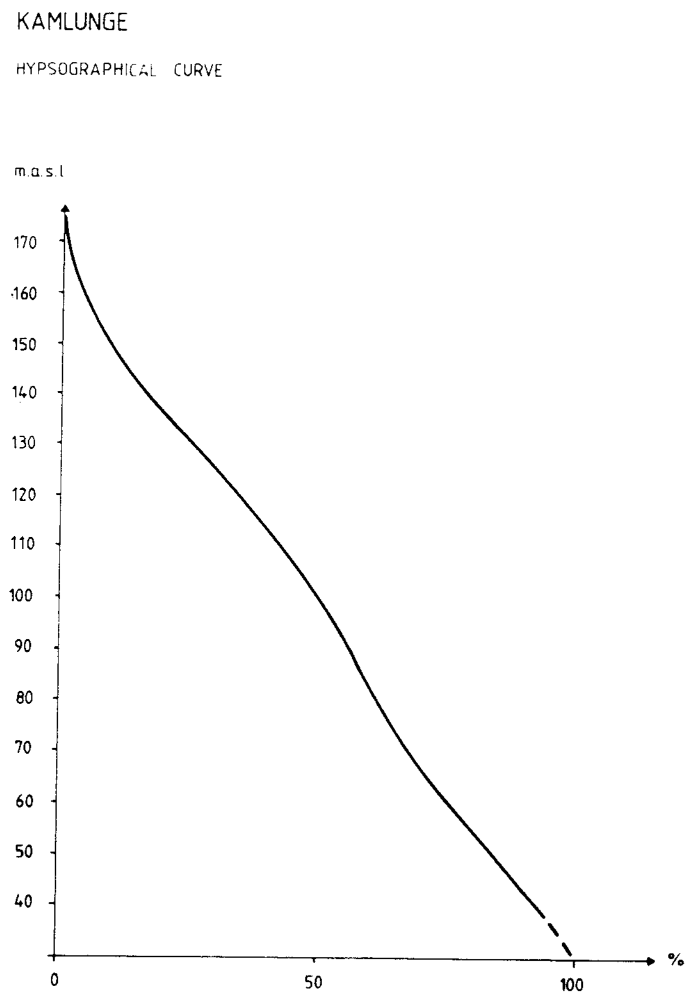


Figure 3.3 Hypsographical curve showing height relationship at site Kamlunge.

boulder-poor moraine and there are areas with "shingle pavement". The soil cover in the eastern and southern part of the site is about 25 m thick. The investigated area is about 2.5 x 3 km.

4. BEDROCK GEOLOGY

4.1 Regional geology

The bedrock in the southeastern part of Norrbotten County consists primarily of rock types involved in the approx. 1800-2000 mill. years old Sweco-Karelian mountain chain formation. These rock types constitute metasediments and metavulcanites. After the mountain chain formation, granites intruded into the older bedrock. These granites are relatively undeformed and are generally referred to as "younger granites" (type Lina granite). The youngest rock types are ultrabasic dikes with a probable age of 1140 mill. years (Kresten et al, 1977). Descriptions of rock types and geological evolution in Norrbotten County have been published by Ödman, 1957.

The Kalix NV map-sheet, within which the Kamlunge site is situated, has not been geologically mapped in modern time. However, a regional geologic map of the northern Gulf of Bothnia region is presented in figure 4.1. The map shows that the bedrock in the east consists of basement, which constitutes the foundation for the Sweco-Karelian rocks. On this basement, which consists of granite gneiss, sedimentary and volcanic strata of varying composition were deposited. These strata have been heavily affected and altered through the acts of folding and metamorphosis so that their original constituents have recrystallised into new mineral combinations. The metasediments have then been intruded by different plutonic rock types of granitic and granodioritic-dioritic composition.

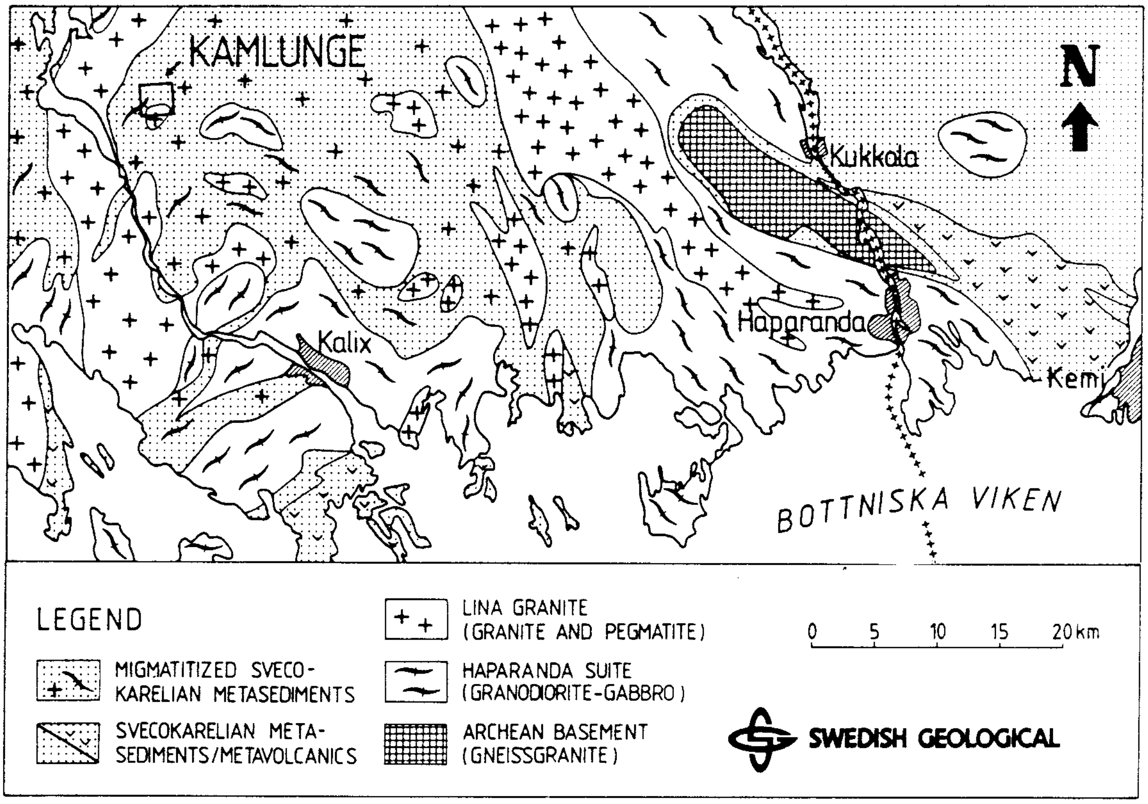


Figure 4.1 Regional geological map including site Kamlunge.

4.2 Bedrock at the study site

The Kamlunge study site consists in part of older sedimentary rocks and in part of granodiorite-diorite as well as red granite. Red granite is the dominating rock type, see figure 4.2. The metasediments are the oldest rock types within the study site, about 1900-2500 mill. years old (Perttunen, 1980) and have been subclassified into quartzitic gneiss and biotite gneiss according to their composition.

The biotite gneiss is usually greyish-black and fine to medium-grained. The main minerals are quartz, biotite and plagioclase. Thin bands of skarn are often found in the biotite gneiss. The rock has a distinct schistosity, which consist of parallel-orientated mica flakes. Bands rich in quartz and feldspar alternating with mica-rich bands also occur. Sulphides occur sparsely primarily as pyrite in the form of small mineral enrichments or fracture fillings.

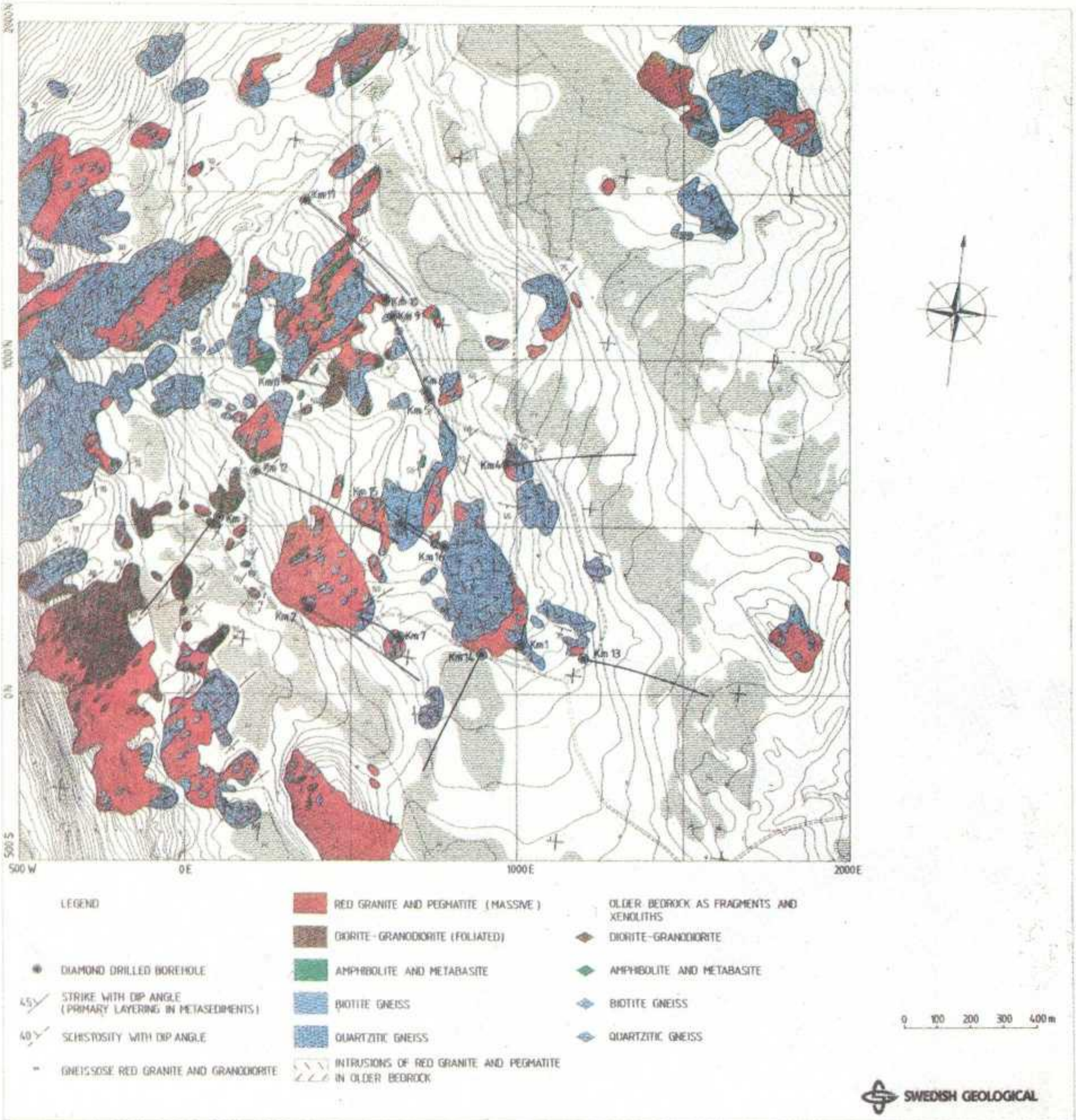


Figure 4.2 Geological map for site Kamlunge.

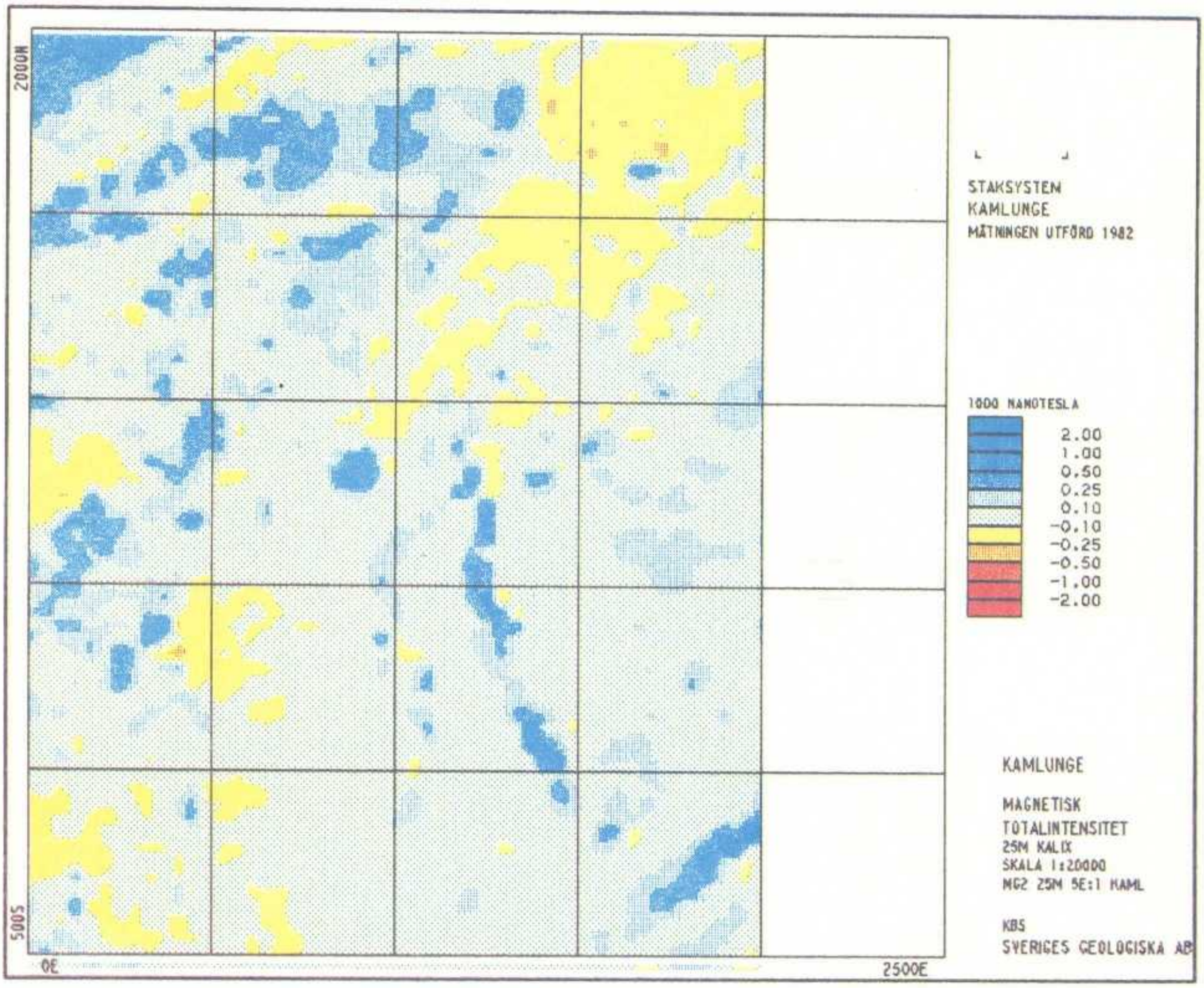


Figure 4.3 Measurement of magnetic field in Kamlunge, showing areas with increased susceptibility due mainly to magnetite.

The quartzitic gneiss is grey and fine-grained. The colour varies with the biotite content. The main minerals are quartz, potash feldspar, plagioclase and biotite. The rock type occurs in several 100 m wide belts and is usually unevenly grained, banded or massive with irregular course-grained quartz-feldspar streaks.

Granodiorite to diorite series constitute a series of intermediary and basic rock types belonging to the Haparanda series. The granodiorite is light brown with 2-5 cm large plagioclase grains in a matrix rich in biotite. This gives the rock type a porphyric appearance. The main minerals are biotite, plagioclase and amphibole. Magnetite is an accessory mineral, its presence revealed by measurements of magnetic parameters. The rock type is therefore outlined in part on the magnetic map. Granodiorite-diorite is often schistose and has been folded in places.

Diorite is subordinated in terms of volume and occurs as isolated lenses. The rock type consists mainly of amphibole and plagioclase, often with grains of magnetite.

Amphibolite occurs in the form of small bodies in the gneisses. The rock type is dark grey and the main minerals are amphibole, biotite and plagioclase. The schistosity increases with increasing biotite content.

The granite is a greyish red and fine to medium-grained rock type. Transitions to pegmatite and thereby coarser grain size take place gradually. The granite is 1560-1800 mill. years old (Welin et al, 1971) and dominates in the southern parts of the site. The main minerals are quartz, postash-feldspar, plagioclase and biotite.

On the magnetic field map, figure 4.3, rocks with high contents of magnetic minerals, usually magnetite, are indicated in blue. Geological structures that are difficult to outline in the field are clearly evident on the magnetic field map. A flexure fold consisting of granodiorite/ diorite and possibly amphibolite appears in blue in the northern part of the site. In the central part of the site there is a magnetic north-south oriented anomaly. Drilling has revealed this to be an ultrabasic rock consisting essentially of hornblende and pyroxene.

4.3 Physical properties of the bedrock

Porosity and a number of other physical parameters have been measured on drill core samples. The results obtained and the variations between different rock types are presented in table 4.1.

Table 4.1 Physical parameters measured on drill core samples from Kamlunge (average values).

Rock type	No. of samples	Density kg/m^3	Porosity %	Resistivity kohmm	IP effect %
Granite	59 (27)	2632	0.22	17 900	1.0
Granodiorite	7 (3)	2742	0.13	14 400	1.9
Biotite gneiss	27 (13)	2722	0.22	6 960	1.6
Quartzitic gneiss	5 (4)	2666	0.17	16 330	1.1
Amphibolite	15 (7)	2867	0.25	10 340	2.0

( ) porosity measurement

The measurements show that all rock types have a low IP effect, between 1 and 2%. This indicates the absence of, or low levels of, sulphides.

The biotite gneiss exhibits lower resistivity than the other rock types. This is probably due to the fact that a higher fraction of the pores are in contact with each other in the biotite gneiss than in the other rock types.

Porosity is low in all rock types, with a mean porosity of 0.22%.

The average temperature gradient for the site has been calculated from temperature measurements in all drill holes to be $10.1^{o}C/km$. The temperature gradient is calculated between the 400 and 600 m levels, where the influence of climatological effects and the drilling procedure are insignificant.

5. FRACTURE ZONES

5.1 Regional fracture zones

Kamlungekölen is bounded by regional fracture zones to the north, east and west. The site can therefore be regarded as a 16 km^2 triangular block, see figure 5.1 The predominant orientation of lineaments is northwesterly, coinciding with the direction of the glacial striae. Lakes and rivers largely follow this lineament direction . The distance between the lineaments on a regional scale is generally one to two kilometres, except at Kamlungekölen, where the distance is approximately 4 km.

The regional fracture zone on the west has been investigated by percussion drilling and refraction seismics in order to investigate a hydrological discharge area. The soil depth is 72 metres at the percussion drill hole and underlying bedrock is fractured and highly permeable to water. Seismics have revealed a low-velocity formation with a width of 550 m, which can be regarded as representing the width of the zone. The dip of the zone is probably steep.

The western and northern regional fracture zones are also assumed to dip steeply.

5.2 Fracture zones within the study site.

The occurrence of local fracture zones on the ground surface has been investigated by means of aerial photo interpretation, geological mapping and surface geophysical measurements. The properties of the fracture zones at depth have been investigated by means of 16 core drill holes and 21 percussion drill holes and geophysical and hydrological measurements in these drill holes. The location and length of the drill holes as well as the total extent of the investigations are reported in the Appendix. The location of the core drill holes is indicated in figure 5.3.

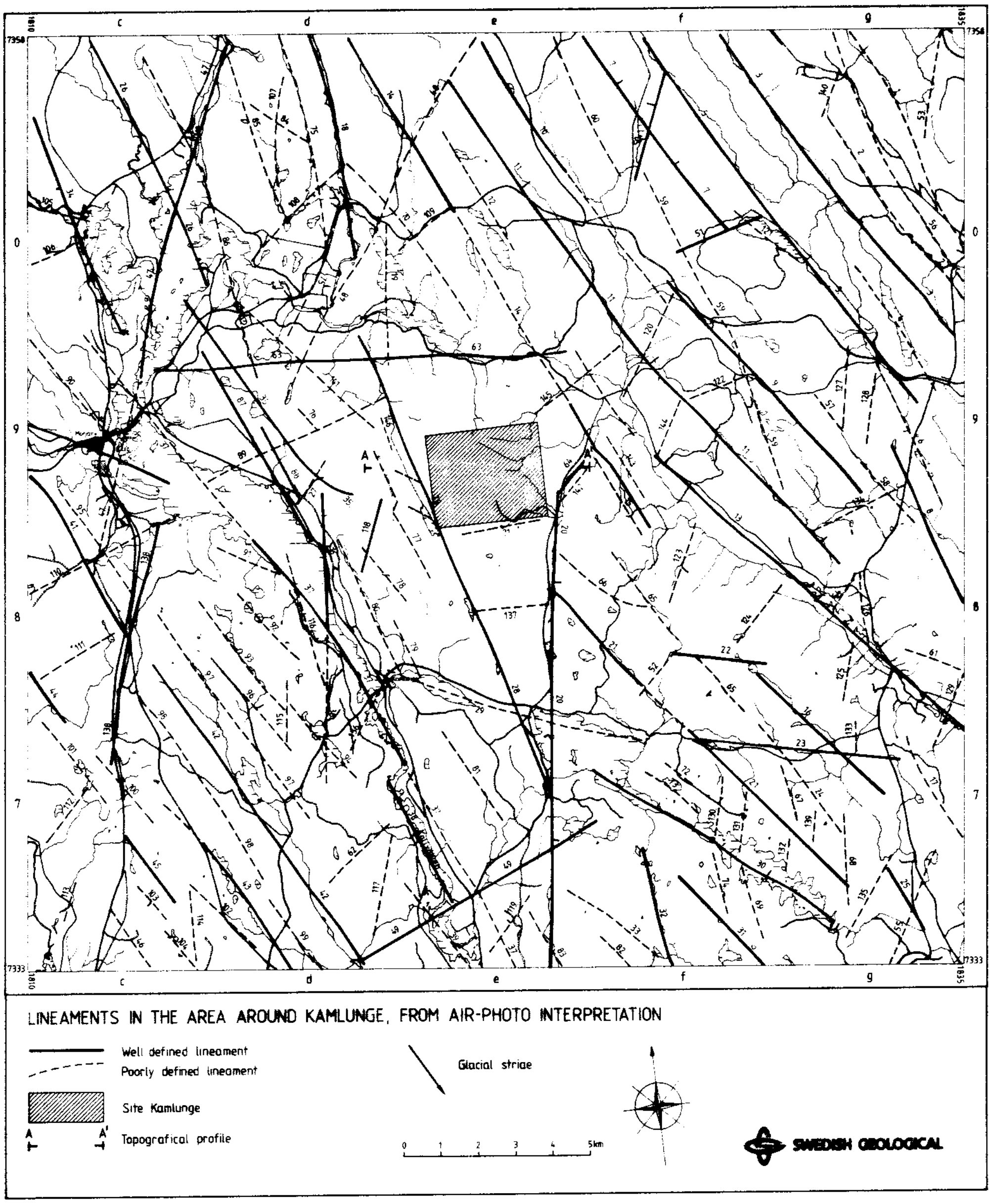


Figure 5.1 Interpreted lineaments around site Kamlunge.

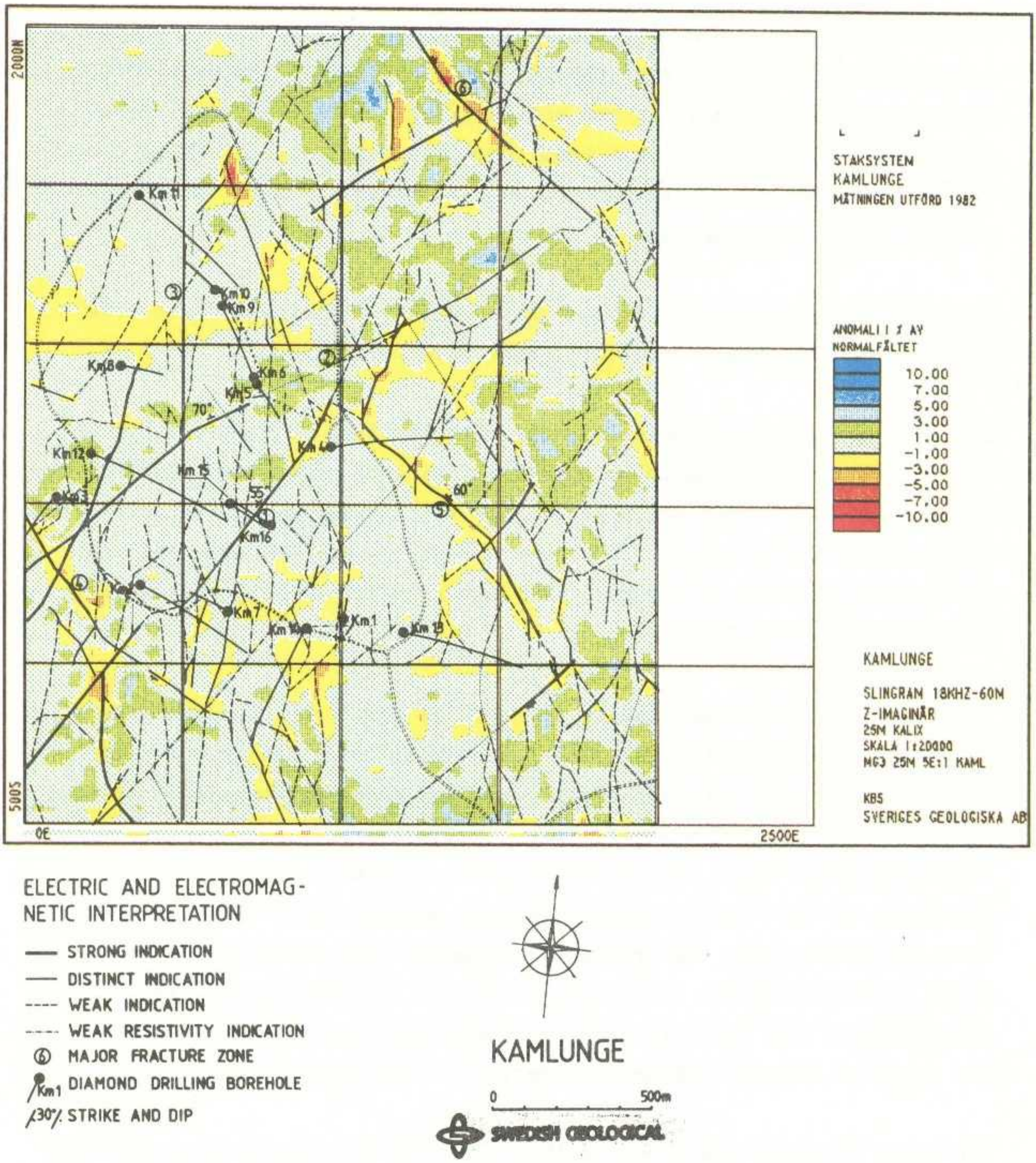


Figure 5.2 Slingram measurement showing areas with increased electrical conductivity in Kamlunge due mainly to fracture zones.

Figure 5.2 presents the slingram imaginary map (horizontal loop EM) plus a combined interpretation of the slingram and resistivity measurements. Zones of weakness appear in red on the slingram map. Peat bogs also appear in red, since the peat bogs sometimes overlay clay, which constitutes a good electrical conductor. This is clearly evident in the southwestern portion of the site.

The anomalies (2) and (3) marked on the interpretation map have been found to be the largest fracture zones within the site.

Indications of local fracture zones, obtained from surface geophysical investigations and from topographical conditions, have been investigated by means of percussion drill holes. The water capacity in the percussion drill holes varies widely. The highest capacity is 9000 l/h, but many drill holes are completely dry. The mean capacity is 1935 l/h and the median capacity is 780 l/h.

The local fracture zones within the central portion of the Kamlunge site have been penetrated by drill holes at a total of 14 different places, see table 5.1. The location of the fracture zones at the ground surface and at a depth of 450 m is indicated in figures 5.3. and 5.4. The width of the fracture zones varies from 1 to 14 m, with a mean width of 6 m. The width of the fracture zones has been determined in the drill holes from the point where the fracture frequency increases markedly to the point where it returns to its normal value. In order to calculate the true width of the fracture zones, a correction has then been made for the angle of the drill hole in relation to the fracture zone.

The local fracture zones are steeply inclined and spaced about 500-1500 metres apart. In addition, a horizontal fracture zone was penetrated at a depth of 550 metres below Kamlungekölen, see figure 5.5. The zone is permeable to water and its width varies between 4 and 14 m. It is also less crushed and weathered than the steeply inclined fracture zones. It has been observed in four core drill holes. In two of these, Km 1 and Km 13, the zone is fractured and reddened through alteration and precipitation of the iron mineral haematite. Chlorite formed after haematite is also present. The other two drill holes, Km 2 and Km 14, show only an increased fracture frequency at this level. The lateral extent of this zone has not been established, but it is not found in Km 12, for example.

Table 5.1 Summary of fracture zones in site Kamlunge.

Fracture	Position in drill hole (m)	Dip (degrees)	True width	K value (m/s)
1	-	90 1)	3 1)	-
2	Km 3 (313-317)	70 NW	4	7 x E-11
	Km 12 (195-210)	70 NW	12	2 x E-7
	Km 9 (414-425)	70 NW	9	2 X E-9
	Km 5 (47- 53)	70 NW	5	not measured
	Km 6 (86- 94)	70 NW	6	not measured
3	Km 12 (52- 60)	70 NW	7	4 x E-9
	Km 8 (63- 69)	70 NW	4	not measured
	Km 11 (324-335)	70 NW	10	not measured
	Km 3 (441-450)	70 NW	1	3 x E-8
4	Km 3 (504-517)	80 SW	4	4 x E-11
5	-	60 NE 1)	4 1)	-
6	-	85 NE 1)	3 1)	-
7	-	75 NW 1)	3 1)	-
H1	Km 1 (544-560)	horizontal	14	not measured
	Km 2 (676-684)	horizontal	7	4 x E-9
	Km 13 (669-674)	horizontal	4	1 x E-8
	Km 14 (667-673)	horizontal	5	6 x E-9

1) Calculated from geophysical observations.

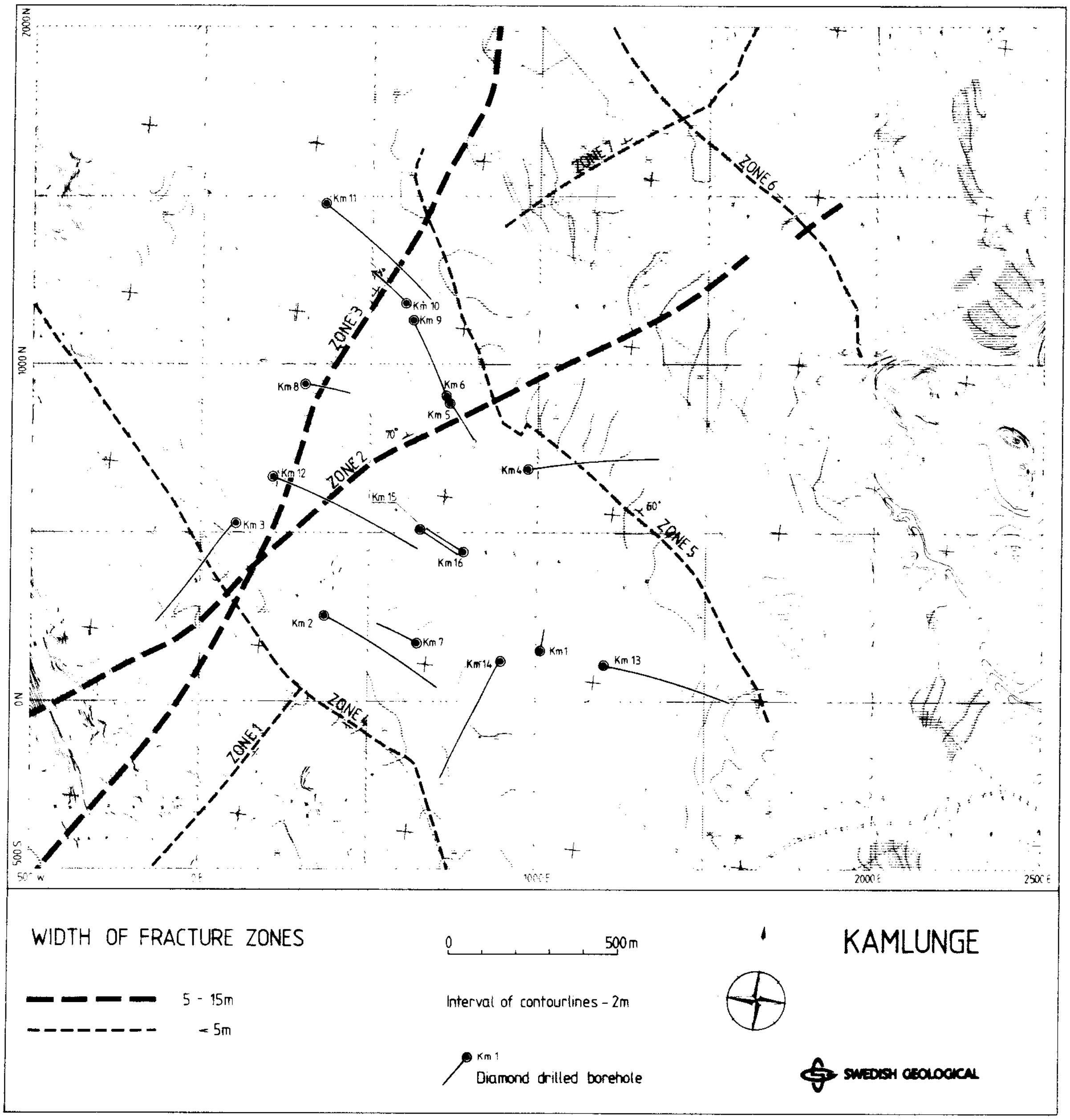


Figure 5.3 Fracture zones at the surface on site Kamlunge.

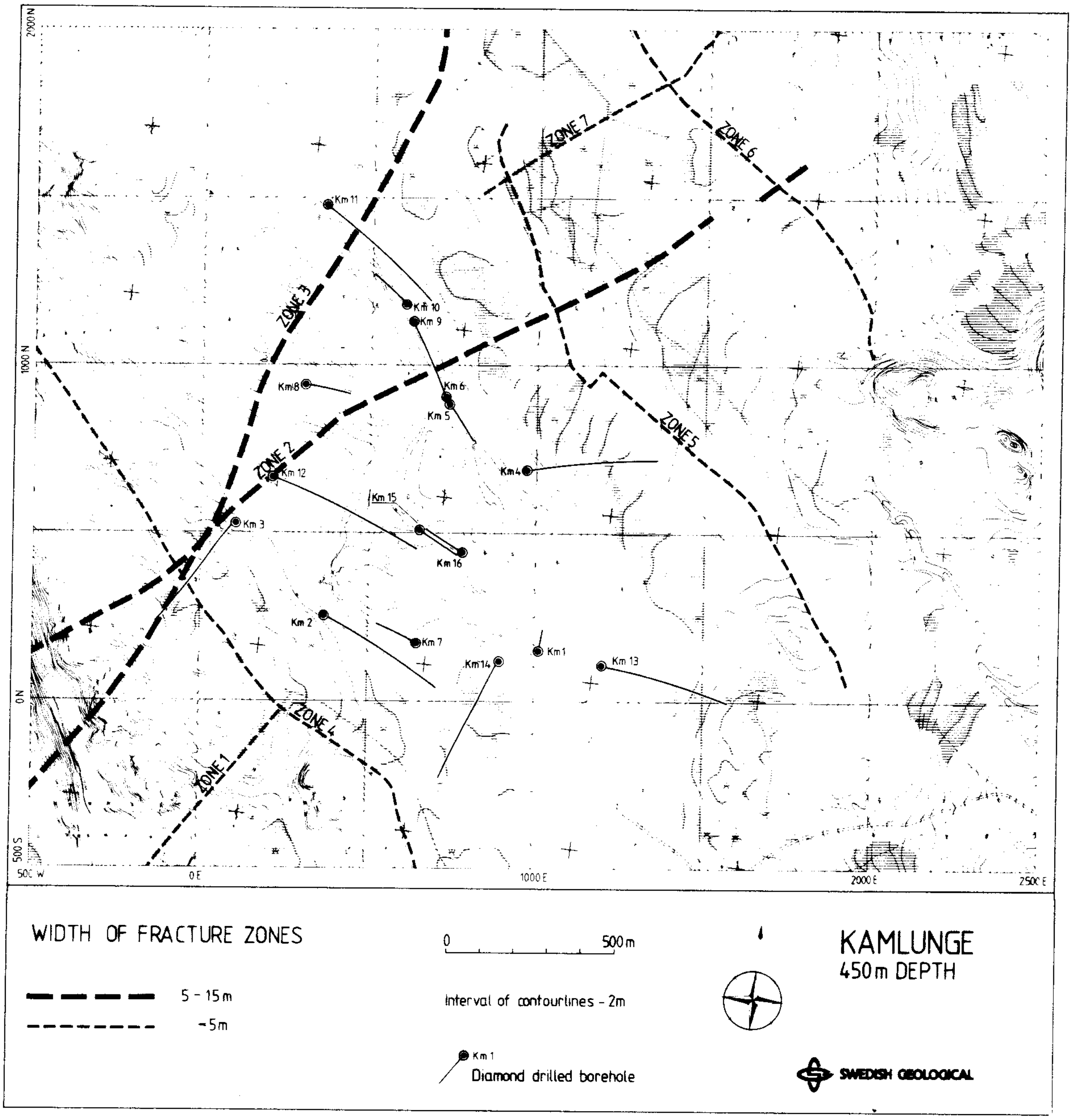


Figure 5.4 Fracture zones at 450 m depth on site Kamlunge.

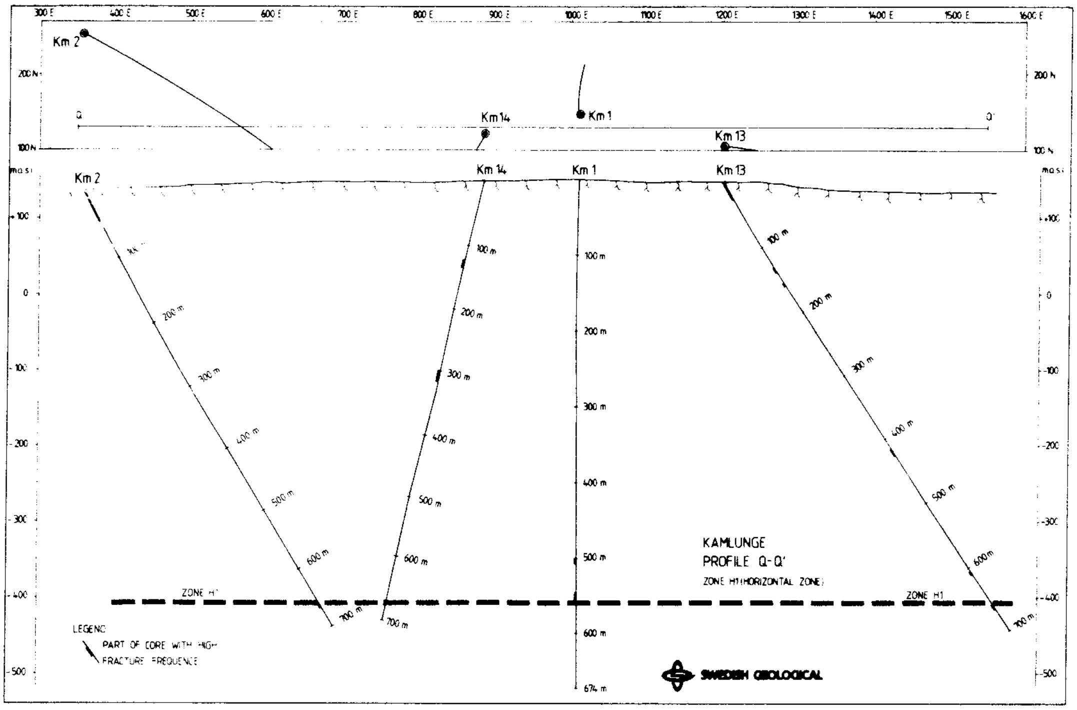


Figure 5.5 Horizontal fracture zone.

The results of the geophysical drill hole logging in Km 12 are indicated in figure 5.8. Below a depth of 400 m, the point resistance measurement indicates homogeneous rock, and there are no indications that the horizontal zone intersects the drill hole. On the other hand, the drill hole does intersect zones 2 and 3 relatively close to the ground surface, which is indicated by marked reductions of the point resistance. The high hydraulic conductivity in zone 3 also gives rise to an anomaly in the temperature gradient.

One or more crushed rock zones normally appear within the fracture zones, usually a decimetre or two in width. The fracture zones also contain sections with low fracture frequency. Figure 5.6 presents the proportion of crushed and fractured rock in the fracture zones as well as rock with a low fracture frequency. Crushed rock is defined in the drill core as rock fragments which cannot be combined into a complete drill core; fractured rock in the drill core has a fracture frequency in excess of 10 fractures per metre; low fracture frequency corresponds to the normal fracture frequency at the level in question. Any core losses are defined in the figure as crushed rock. More detailed definitions of these terms are provided by Ahlbom et al, 1983.

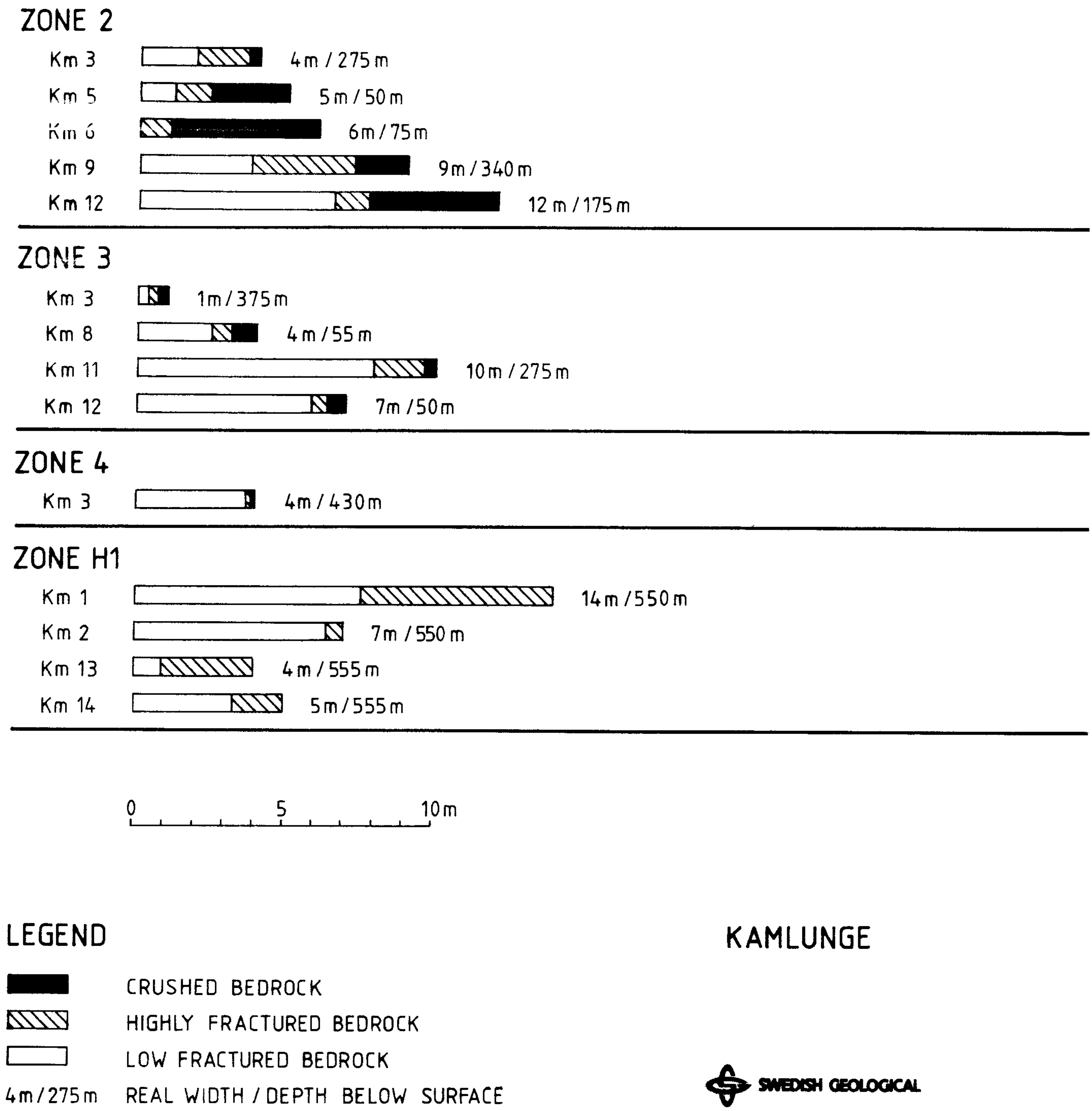


Figure 5.6 Percentage of crushed, highly fractured and low fractured bedrock in the fracture zones at Kamlunge. Fracture zone width and the depth where it is located in the drill hole are given after each bar.

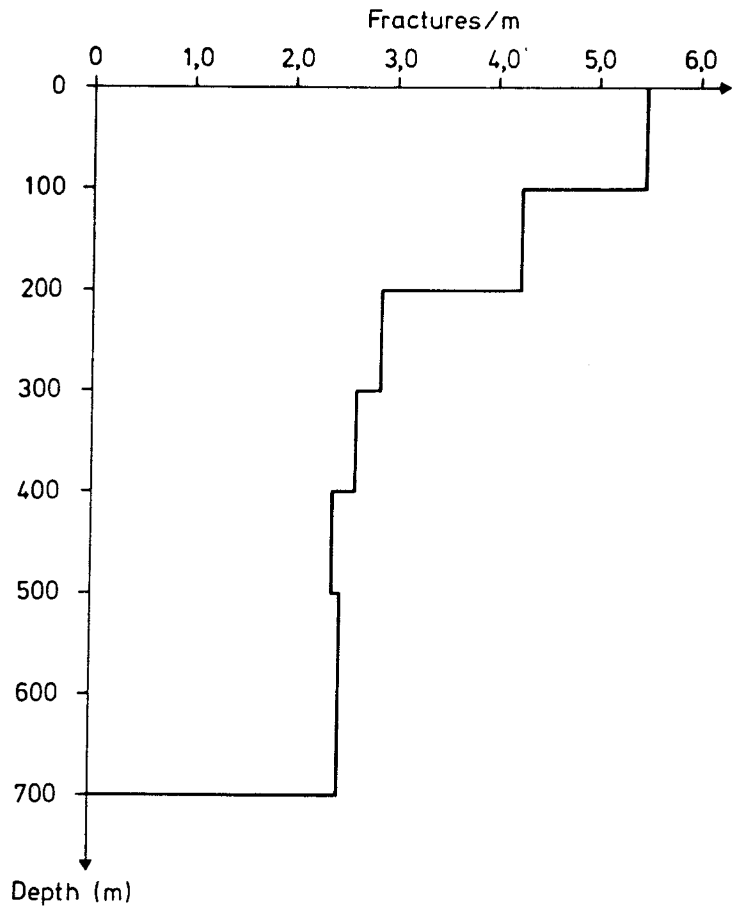


Figure 5.7 Fracture frequency in rock mass within site Kamlunge.

The steeply inclinded zones are often weathered, brecciated and crushed. Core losses when drilling through the zones are common. Commonly occurring fracture minerals are chlorite, calcite, laumontite, smectite and various iron oxides.

5.3 Rock mass fracturing

The fracturing of the rock mass has been mapped on outcrops and on drill cores. The fractures observed on the surface have a dominant west by northwesterly orientation. This direction is largely perpendicular to the direction of foliation. In the gneisses, the fracture frequency on

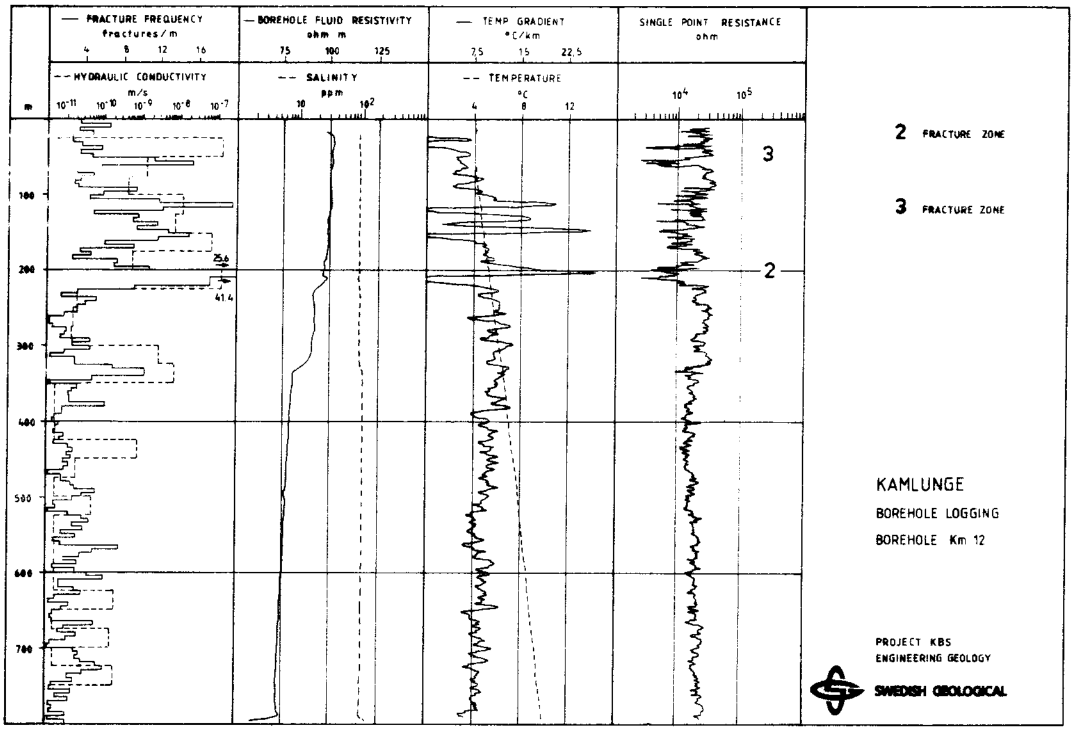


Figure 5.8 Results from logging of drill hole Km 12.

outcrops is 1.3 fractures/m, while the dioritic, granodioritic and granitic rock types have a fracture frequency of 1.1 fractures/m.

The variation of the fracture frequency with depth of the rock mass between the fracture zones is indicated in figure 5.7. The fracture frequency is greatest in the uppermost 200 m, with more than 4 fractures per metre. Deeper down, the fracture frequency is 2.5 fractures/m. The higher fracture frequency of the drill cores when compared with the outcrop measurements is due to the fact that the frequency of horizontal fractures is underestimated in the outcrop mapping. Moreover, the fracture frequency of the drill core includes all fractures regardless of length, whereas the outcrop mapping does not include fractures shorter then 0.5 m.

The total fracture frequency for the different rock types regardless of depth is lowest in the biotite gneiss at 3.6 fractures/m. Biotite gneiss is followed by the granite with 3.9 fractures/m, quartzitic gneiss with 4.0 fractures/m, granodiorite with 4.1 fractures/m and amphibolite with 4.7 fractures/m. The highest fracture frequency has been recorded for an ultrabasic rock type at 10.0 fractures/m. This rock type is primarily found in drill hole Km 9.

The fracture minerals that occur commonly in the drill cores are chlorite, calcite and zeolite minerals. Iron oxides are also present in the form of haematite and goethite. The occurrence of sulphide minerals is sparse.

6. HYDROLOGICAL AND METEOROLOGICAL CONDITIONS

6.1 General

The description of the hydrological and meteorological conditions at the Kamlunge site is based on statistical data obtained from SMHI (The Swedish Meteorological and Hydrological Institute). Data from a number of precipitation stations in the vicinity of the study site have been taken into consideration in assessing the hydrology of the Kamlunge site.

The Kamlunge study site is located on a ridge that constitutes the water divide between the drainage area of the Kalixälven River to the west and that of the Sangisälven River to the east. These rivers flow into the Gulf of Bothnia after 30 and 35 km, respectively. The major part of the investigated area is drained via the Korpikån stream into the Sangisälven River. There are only a few small lakes on Kamlungekölen. Larger lakes are located in connection to the site, such as the lakes Stora Lappträsket (4.2 km^2), Byträsket, Idträsket and Granträsket.

Since the study site constitutes a ridge, the site as a whole can be regarded as a recharge area. Minor local discharge areas occur in low-lying parts of the area, usually in the form of peat-bogs, and on the steep western slope.

6.2 Precipitation and temperature

There are no precipitation stations within the study site itself. Instead, data from nearby stations with long observation periods has been used. Mean monthly and annual precipitation at the site has been calculated on the basis of data from Morjärv ($66^{o}04'$, $22^{o}45'$, 40 m above sea level, observations from 1949). These data have been adjusted to correct for the elevation of the study site in such a manner that the liquid part of the precipitation has been increased by 7% per 100 m, while the solid part (in the form of snow) has been increased by 15%.

Table 6.1 Calculated precipitation at Morjärv and Kamlunge

Place	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Morjärv (unadj.) mm	35	33	26	30	29	36	52	63	62	47	54	52	519
Morjärv (adj.) mm	46	44	35	39	36	44	62	74	72	56	69	67	644
Kamlunge (adj.)mm	52	50	35	44	38	47	66	79	77	51	75	76	690
% snö	97	98	94	60	5					28	70	85	

Table 6.2 Monthly mean temperature at Björkfors

Place	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Björkfors	-13.3	-13.1	-7.5	-1.0	6.0	12.6	14.9	13.0	7.5	1.2	-5.4	-10.1	+0.5

The ground is frozen for an average of 179 days per year. The snow cover duration is on the average 178 days, varying between a maximum of 219 days and a minimum of 169 days.

The values from the Björkfors station have been used in order to reflect the temperature conditions at the Kamlunge site. This also applies with respect to ground frost conditions. Snow conditions should agree rather well with data from Naishedens (95 m above sea level). Precipitation and temperature data are presented in tables 6.1 and 6.2.

6.3 Evaporation

The values for potential evaporation were obtained from the precipitation station at Överkalix. The values of actual evaporation at the Kamlunge site are based on data from Eriksson (1980), with a monthly division based on calculated values of potential evaporation.

Table 6.3 Potential evaporation at the precipitation station at Överkalix and actual evaporation at the Kamlunge study site.

Place	Evaporation (mm)												
	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Överkalix (potentiell)	-1	0	3	13	66	115	106	66	26	3	-1	-1	395
Kamlunge (actual)	0	0	2	5	55	108	100	60	20	0	0	0	350

6.4 Run-off

The run-off from the study site has been calculated on the basis of observation data from other water courses with similar hydrological conditions and pertains to natural run-off conditions during a period of approximately 50 years. The values given in table 6.4 must thus be regarded as approximate.

Table 6.4 Characteristic values of run-off for the Kamlunge study site.

Maximum flood run-off	400	$l/s\ km^2$
Medium flood run-off	150	"
Maximum medium run-off	16	"
Medium run-off	10.5	"
Lowest medium run-off	6	"
Medium low-time run-off	1.5	"
Lowest Low-time run-off	0.5	"
Drainage area	approx.40	km^2
Proportion of lakes	0	%

Table 6.5 Monthly mean run-off, Kamlunge

Place	Monthly mean run-off ($l/s \times km^2$)												
	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Kamlunge	3	2.5	2.5	5	58	15	8	5	11	7	5	4	10.5

Table 6.6 Mean duration of run-off as % of time

$l/s \times km^2$	1	2	3	4	5	6	8	10	15	20	30	50	75	100	150
% of time	99	79	56	44	37	32	26	21	15	11	7	4	3	2	1

The distribution of the run-off during the year is presented in table 6.6 and its distribution in time is presented in the form of a duration curve, figure 6.1. The duration of a given flow is given in % of time

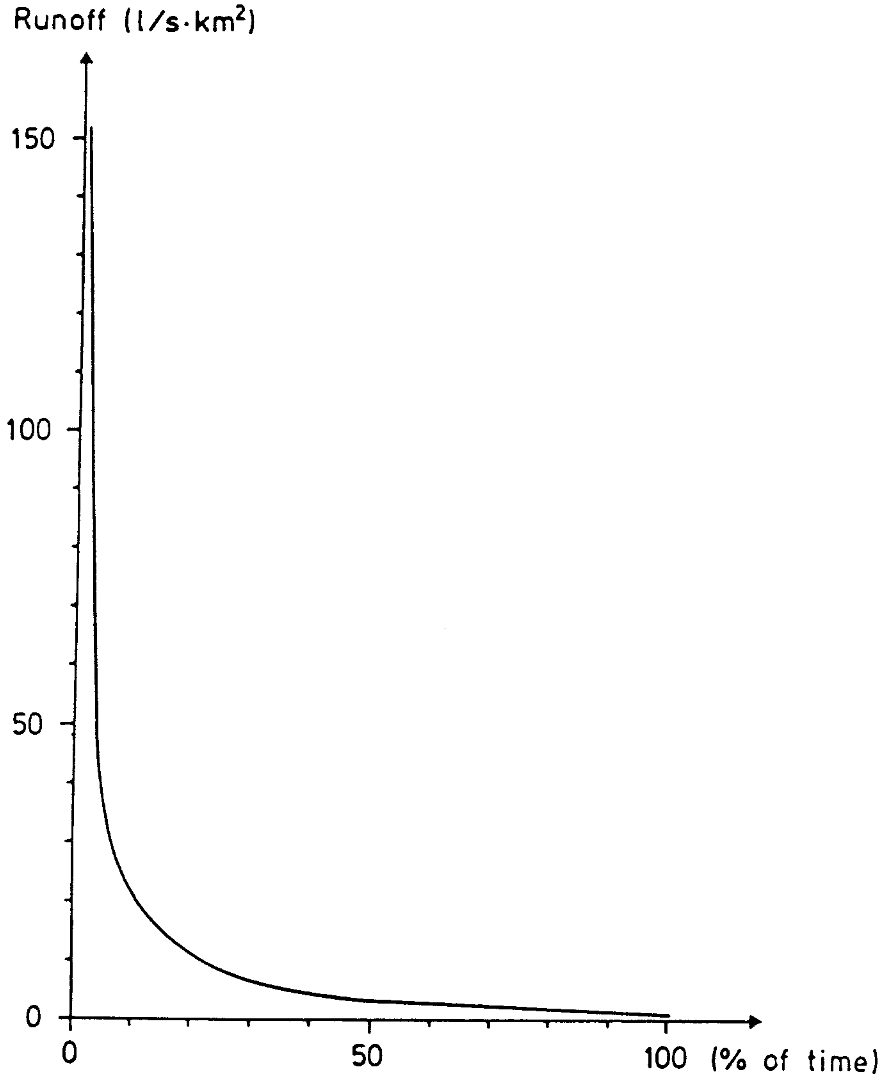


Figure 6.1 Mean duration of runoff at site Kamlunge.

(year/period). The curve shows that the run-off is greater than the mean run-off for an individual year, 10.5 l/s km^2, during 20% of the year.

6.5 Water balance

The water balance on the study site is determined by the following factors: precipitation, evaporation, run-off and groundwater flow through the boundaries of the site. The precipitation is the sum of the other factors.

The mean run-off during the year amounts to 10.5 l/s x km^2 (330 mm). The fact that the difference between adjusted annual precipitation and annual evaporation (690-350 = 340 mm) differs from the calculated annual run-off can be explained by the uncertainty in the values of adjusted precipitation and evaporation. The groundwater run-off through the boundaries of the area or via the bedrock is negligible.

7. HYDRAULIC PROPERTIES OF THE BEDROCK

7.1 Hydraulic tests

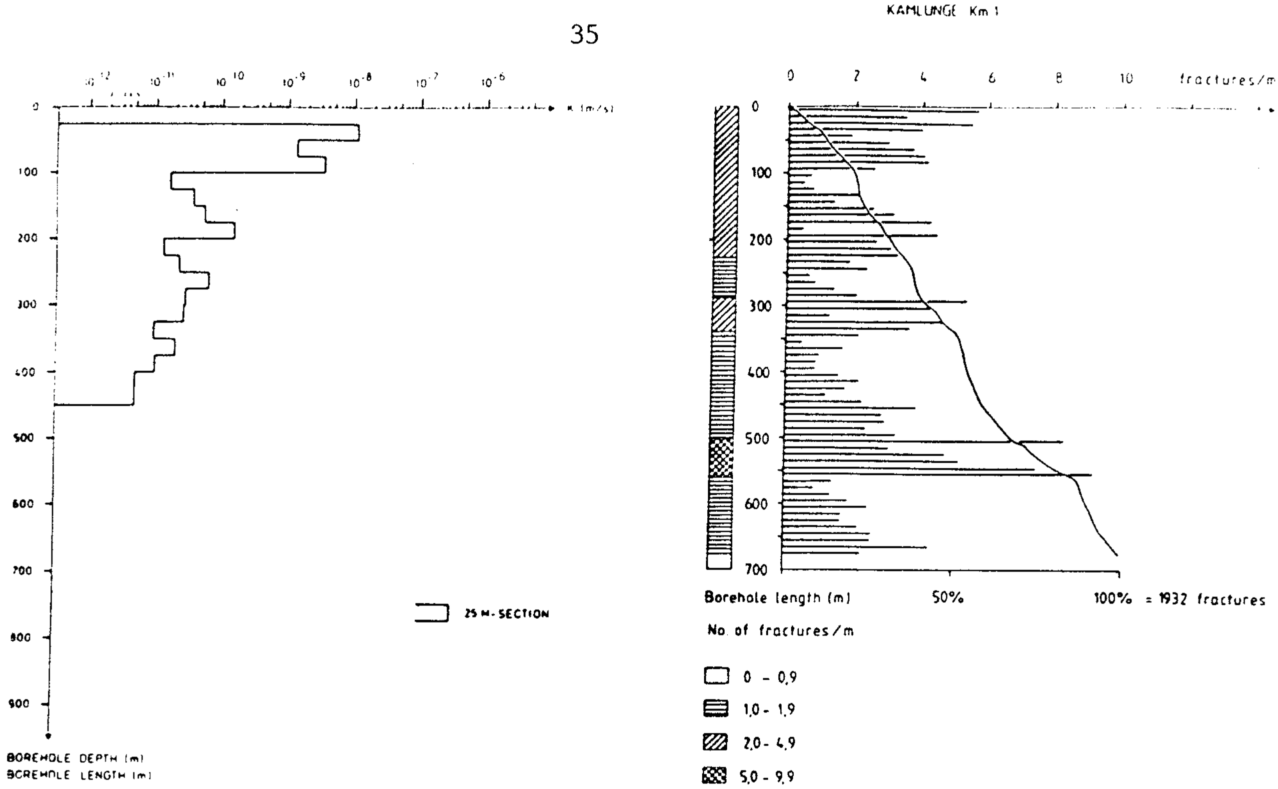
Hydraulic conductivity (K) has been calculated from the results of water injection tests in core drill holes Km 1-6 and Km 9-14. Tests have been carried out in 230 25-m sections. Measurement and evaluation have been carried out in accordance with theories for transient injection tests with constant pressure (Almén et al, 1982). The hydraulic conductivity calculated in this manner constitutes a mean value for the particular 25-m section. Individual fractures within the section may have a high K value, while other fractures may have lower values. Hydraulic conductivity is given together with fracture frequency for the different drill holes in figs. 7.1-7.7.

In the majority of drill holes, the injection tests have been supplemented with measurements where the section length has been 5 m or 10 m. Such measurements have been made in 97 sections. These detailed measurements have mainly been made in sections with high hydraulic conductivity. The purpose has been to delimit the conductive portions of the different 25 m sections. The detailed measurements simultaneously constitute a means of checking the results from the 25 m sections. By comparing the transmissivity (T) obtained from measurements of different section lengths, a rough idea is obtained of the reliability of the results. The transmissivity for 25 m sections has been divided by the transmissivity for 5 and 10 m in the sections in such a manner that the result is always ≥ 1. In most sections, the agreement has been very good. Only in a few cases has the T quotient been > 2. In these cases, the agreement is less good, which may indicate leakage at the packers. The results for all check-measured sections are presented in table 7.1.

Table 7.1 Comparison of transmissivity between 25 m and 5/10 m sections in core drill holes at Kamlunge

Drill hole	Section (m)	T quotient	Drill hole	Section (m)	T ratio
Km 2	200-225	3.44	Km 12	175-200	5.44
	250-275	1.07		200-225	1.03
	275-300	8.24		300-325	1.51
	350-375	18.81		325-350	1.39
	375-400	68.73		425-450	2.53
Km 3	110-135	1.55	Km 13	225-250	4.70
	235-260	5.80		350-375	3.91
	310-335	1.57		475-500	1.08
	335-360			500-525	5.10
	410-435	2.39			
	435-460	3.21	Km 14	300-325	1.82
	460-485	1.00		325-350	1.89
	510-535	1.09		650-700	1.37
	610-635	1.00			
Km 4	275-300	1.47			
	475-500	9.15			
	575-600	1.42			
Km 5	30- 55	1.55			
	80-105	2.55			
	105-130	12.42			
	130-155	4.54			
Km 9	360-385	2.35			
Km 10	75-100				
	100-125				
Km 11	200-225	2.47			
	300-325	3.92			
	325-350	2.62			
	425-450	1.93			

KAMLUNGE Km 1



KAMLUNGE Km 2

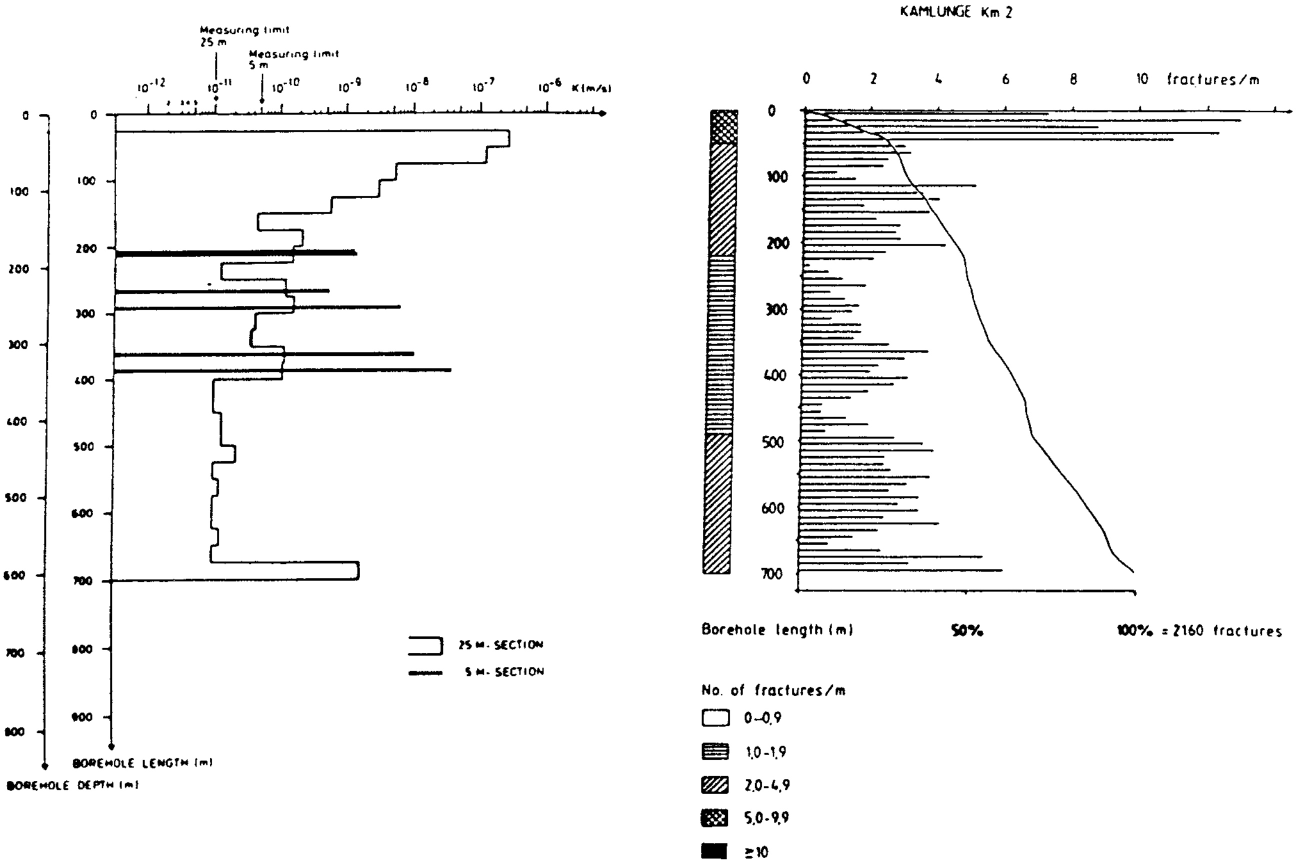
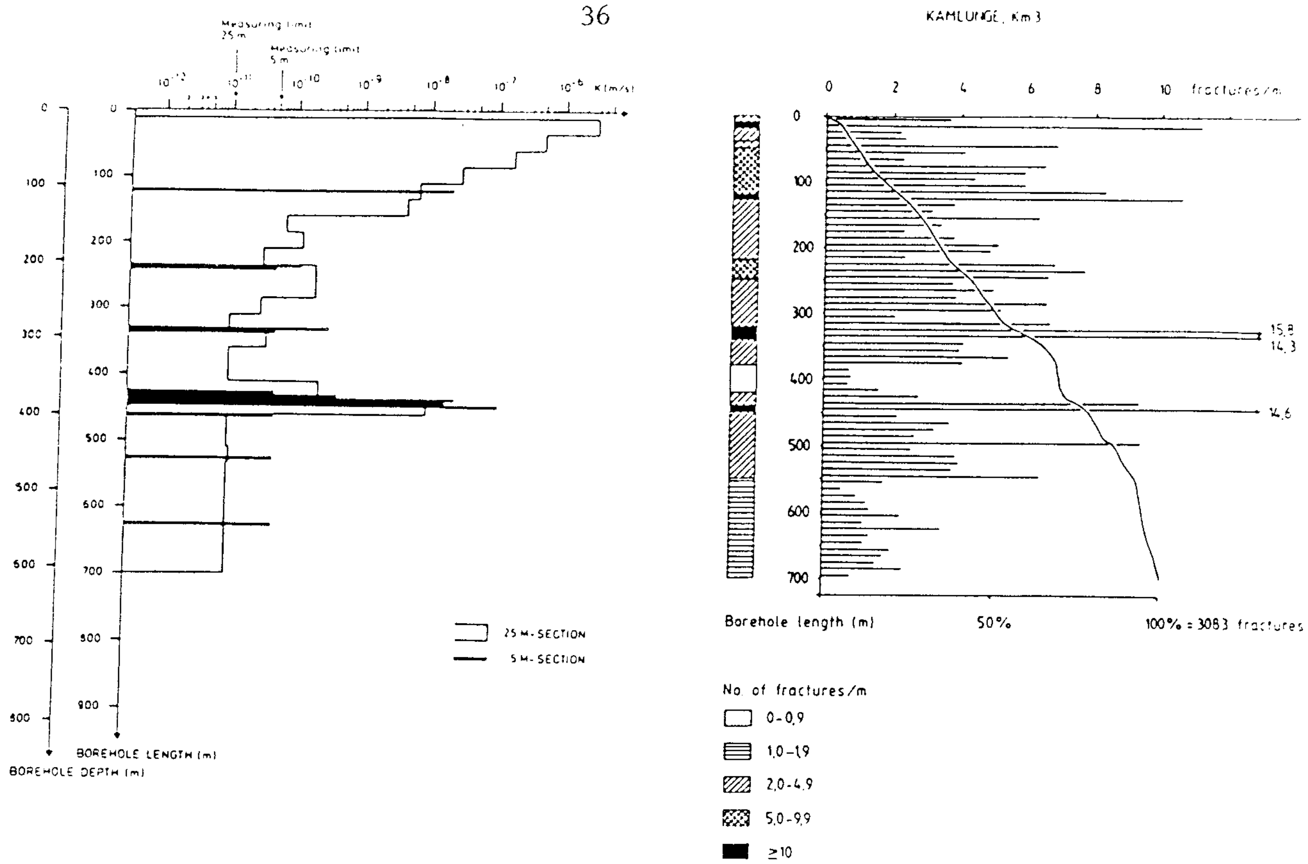


Figure 7.1 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 1 and Km 2.

KAMLUNGE Km 3



KAMLUNGE Km 4

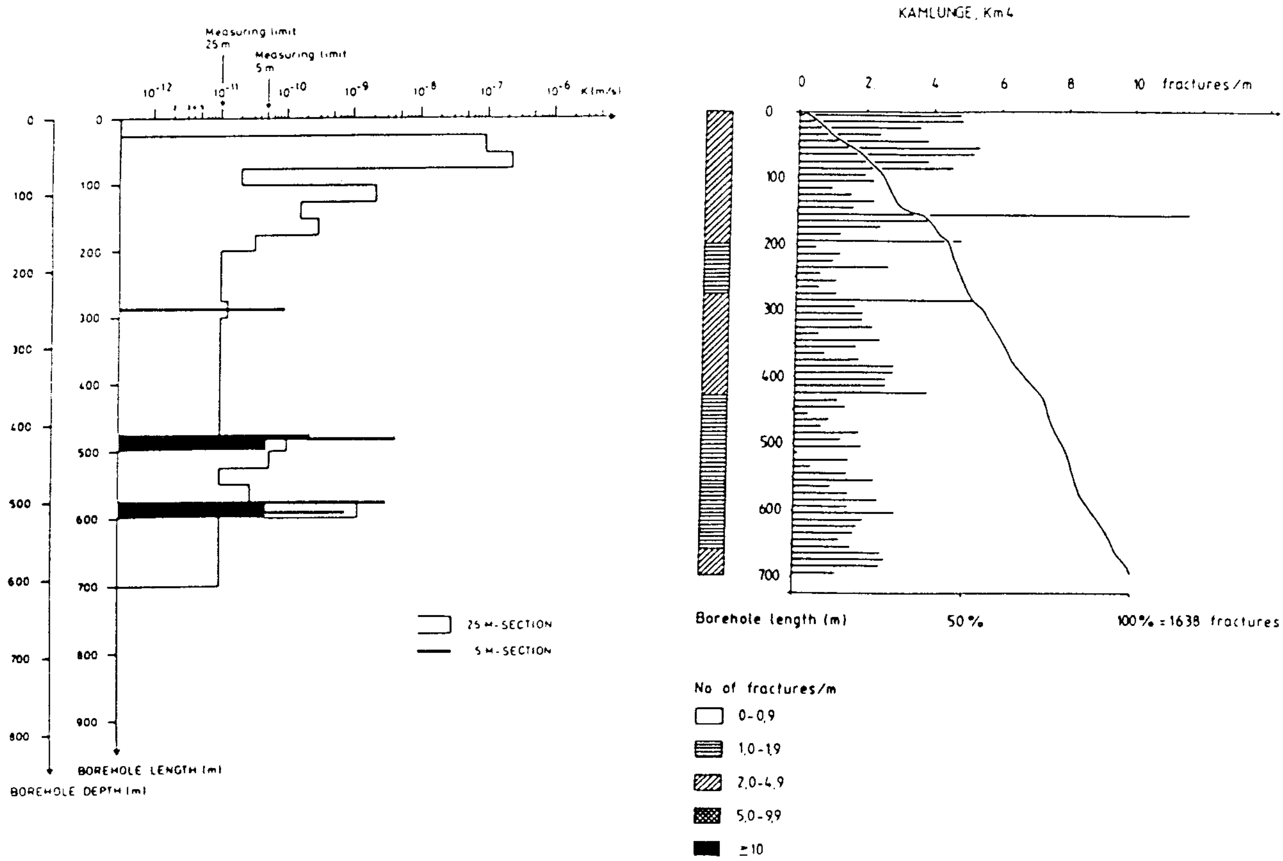
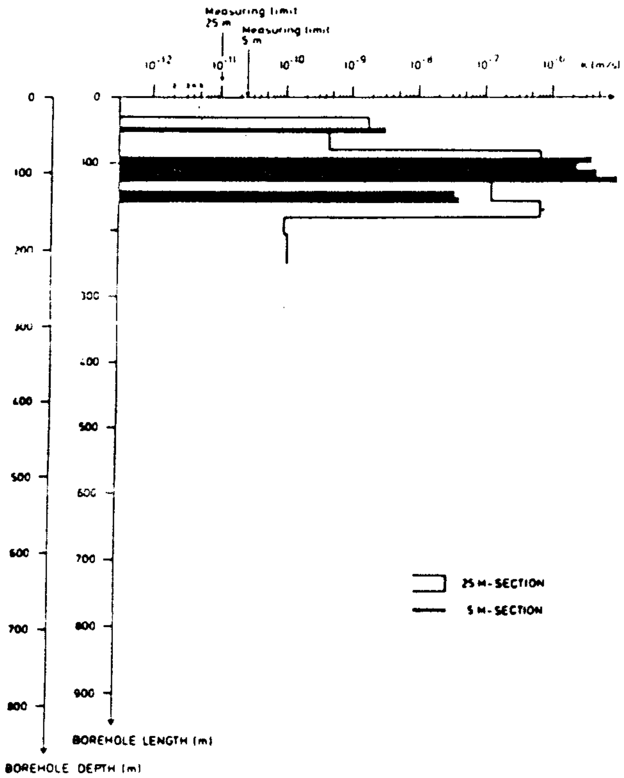
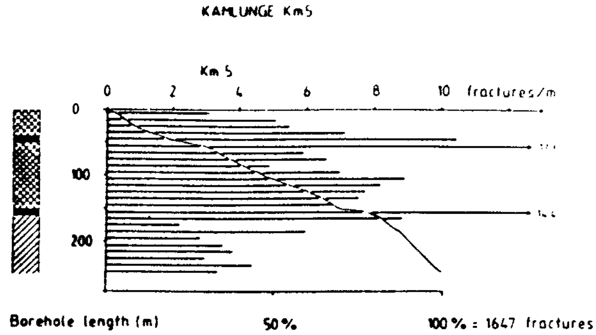


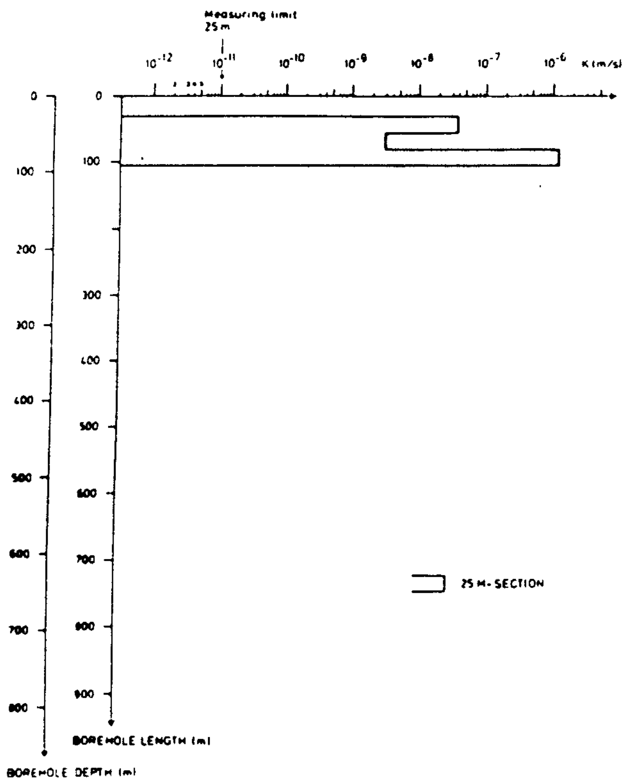
Figure 7.2 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 3 and Km 4.

KAMLUNGE Km 5





KAMLUNGE Km 6



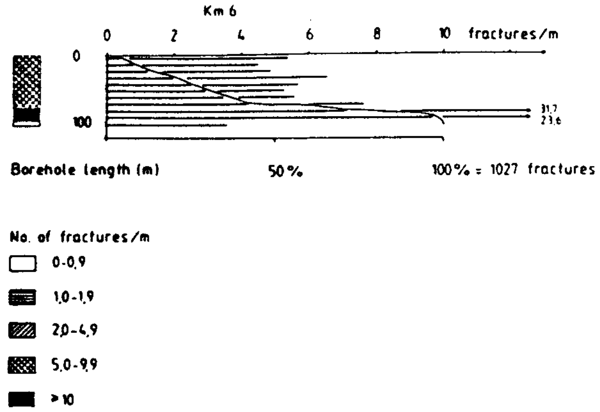
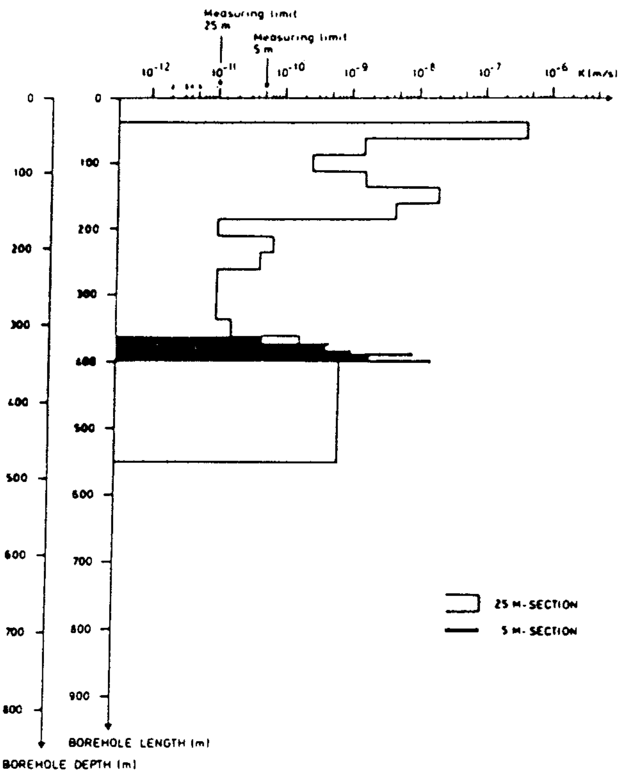
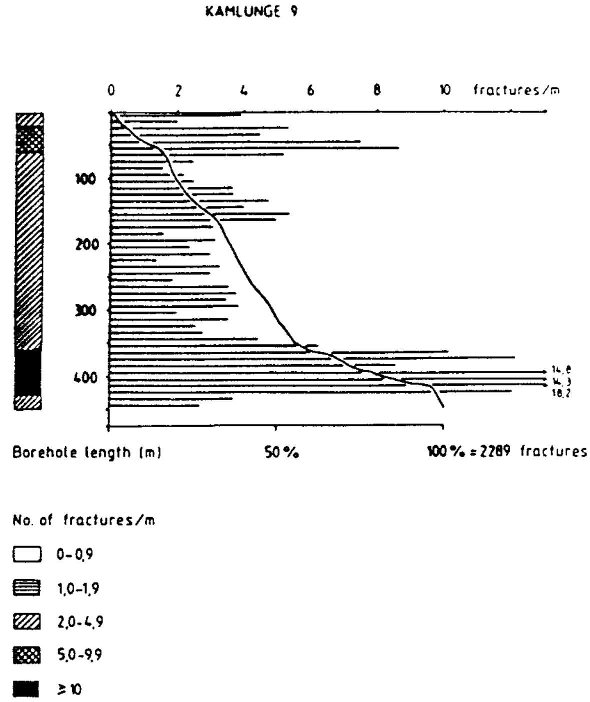


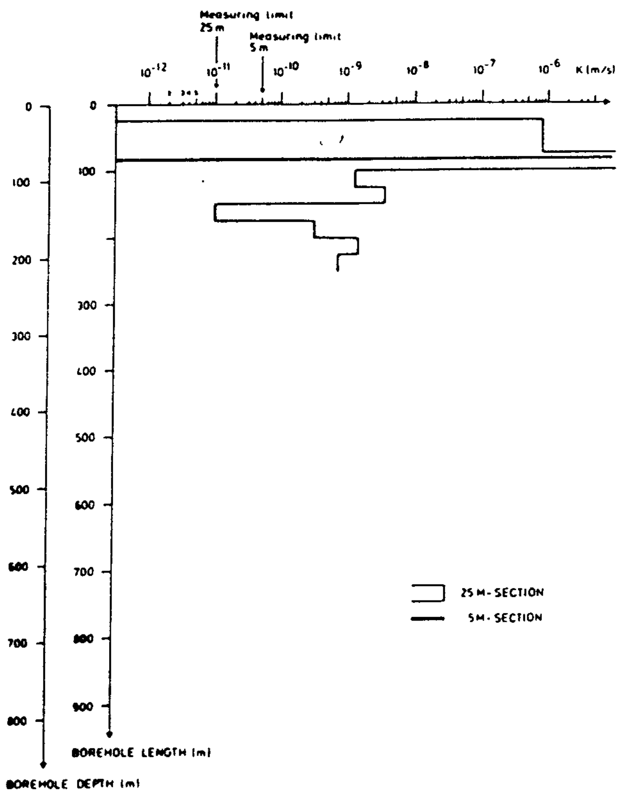
Figure 7.3 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 5 and Km 6.

KAMLUNGE Km 9





KAMLUNGE Km 10



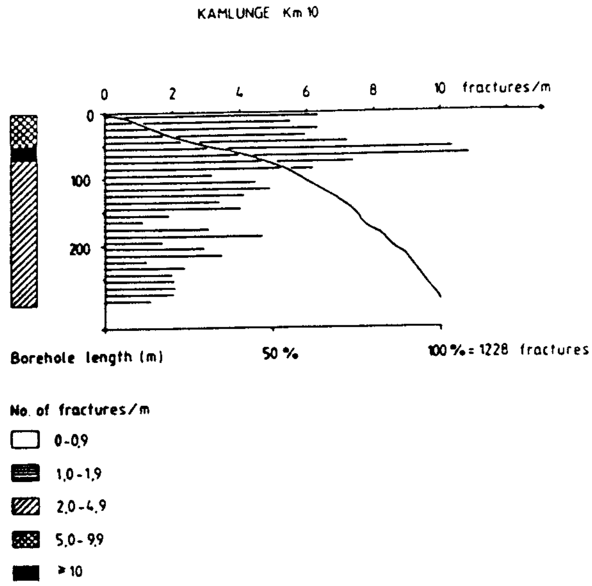
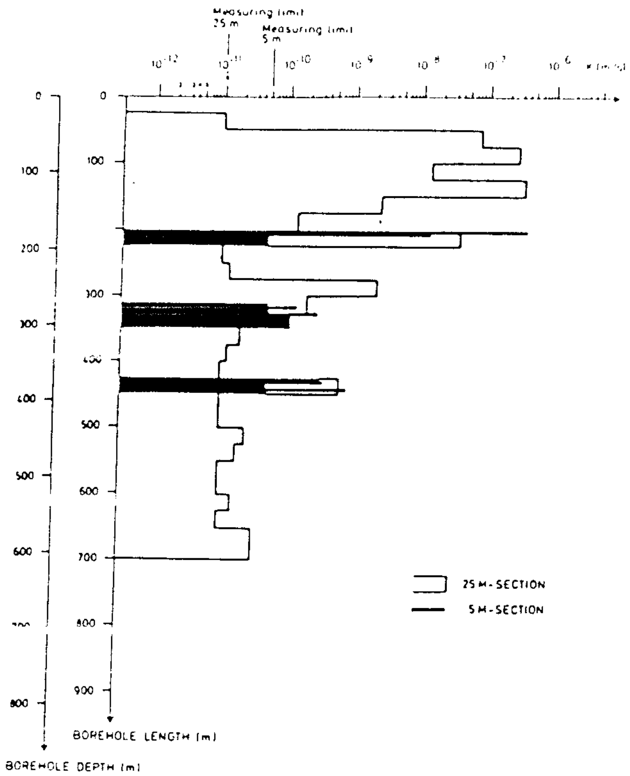
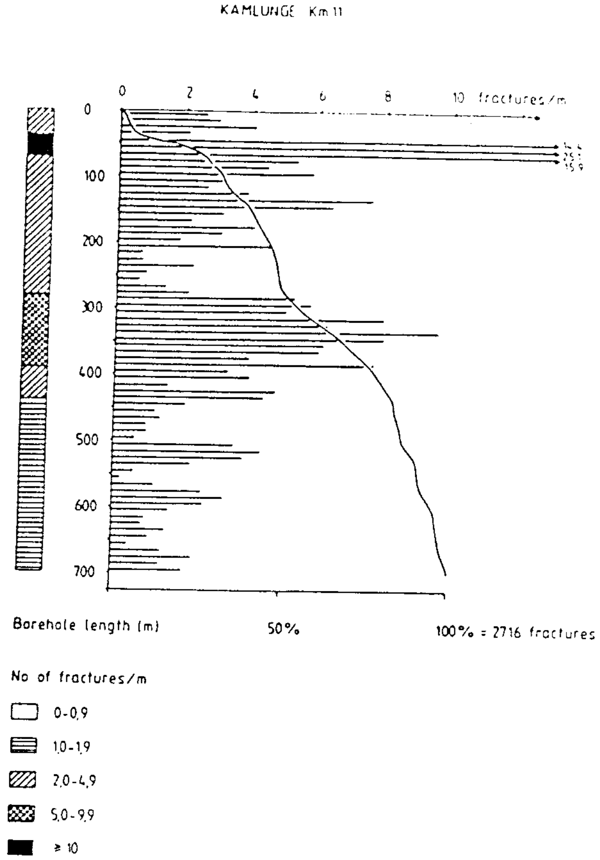


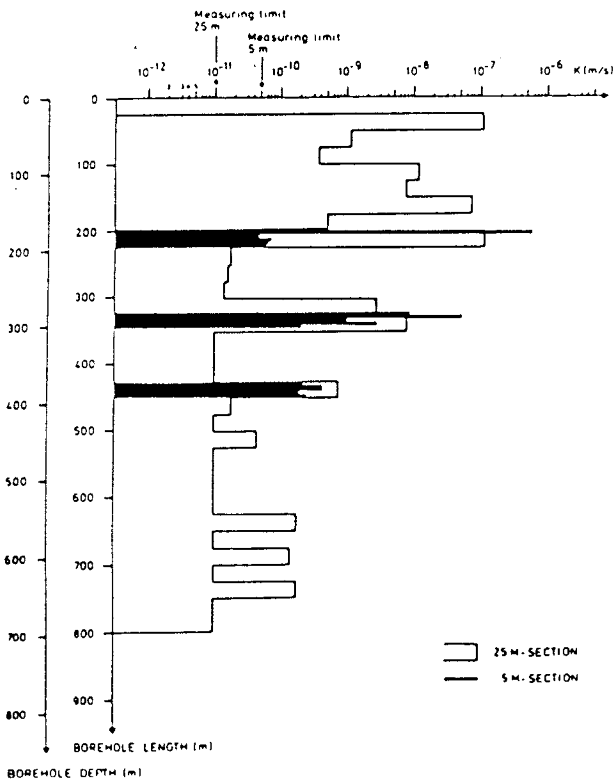
Figure 7.4 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 9 and Km 10.

KAMLUNGE Km 11





KAMLUNGE Km 12



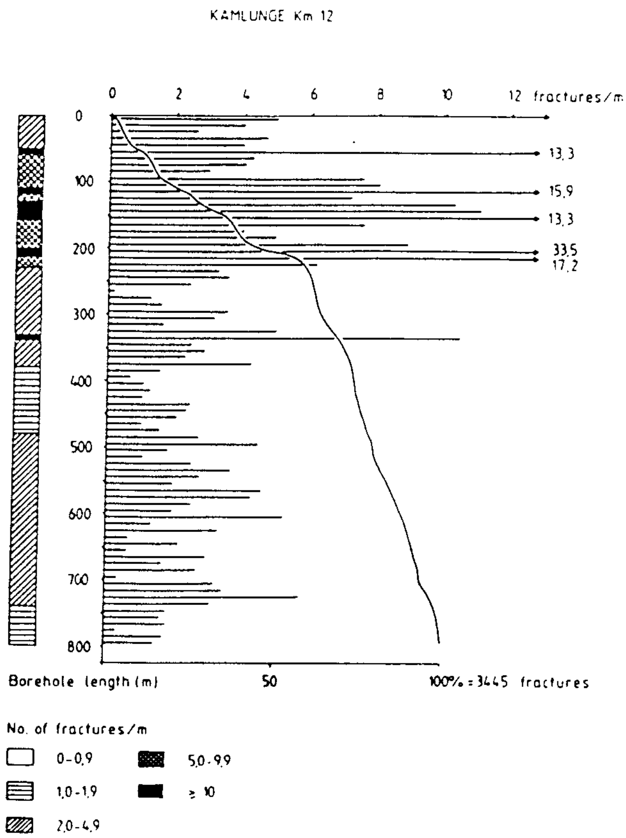
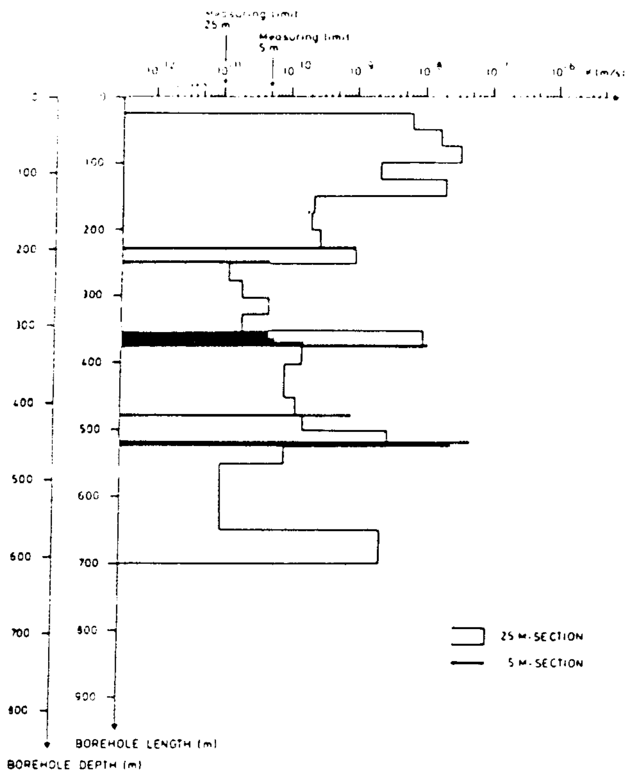
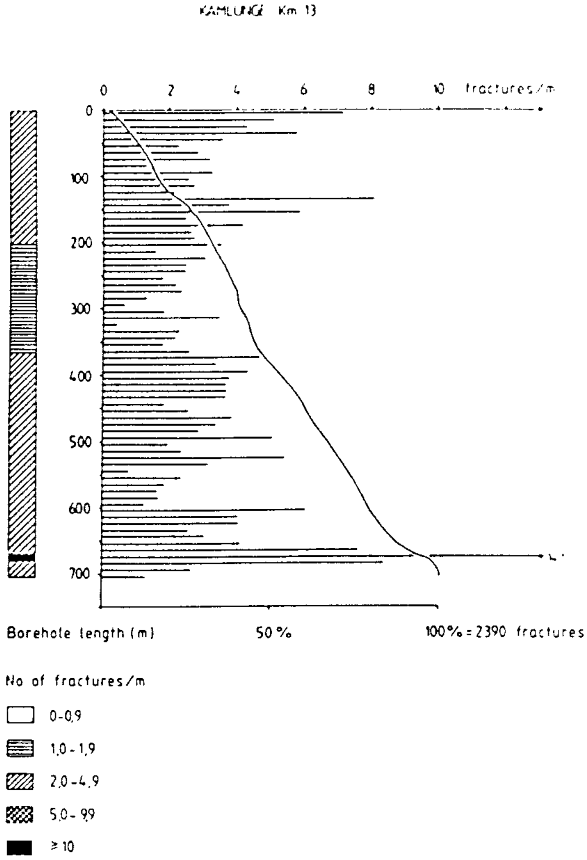


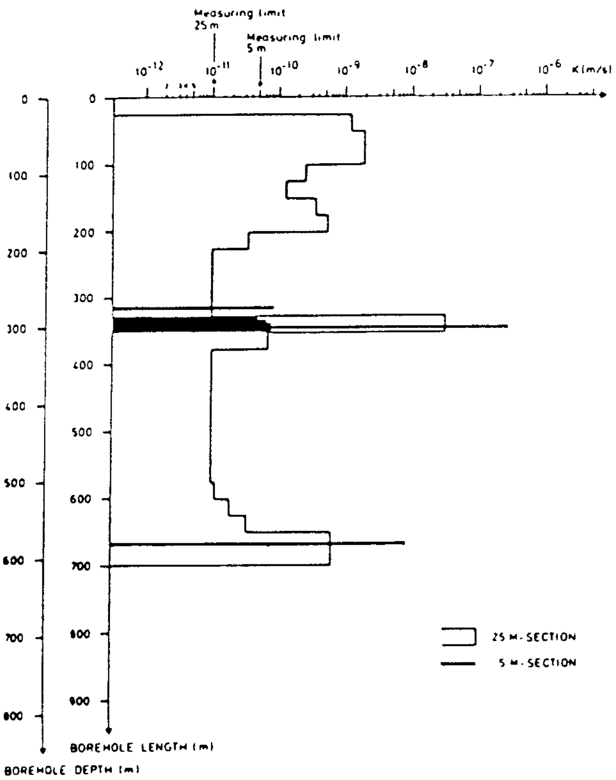
Figure 7.5 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 11 and Km 12.

KAMLUNGE Km 13





KAMLUNGE Km 14



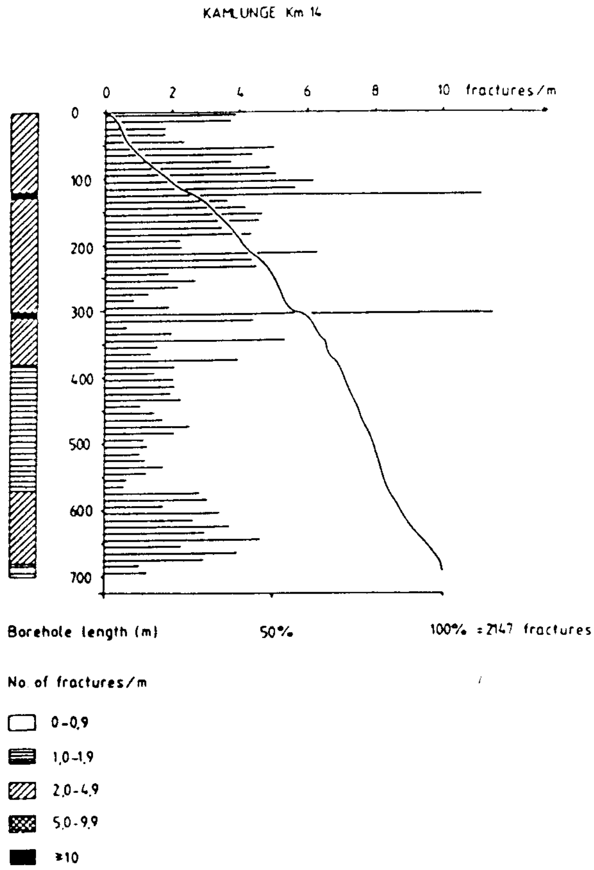


Figure 7.6 Fracture frequency in 10 m sections, cumulative number of fractures and hydraulic conductivity, drill holes Km 13 and Km 14.

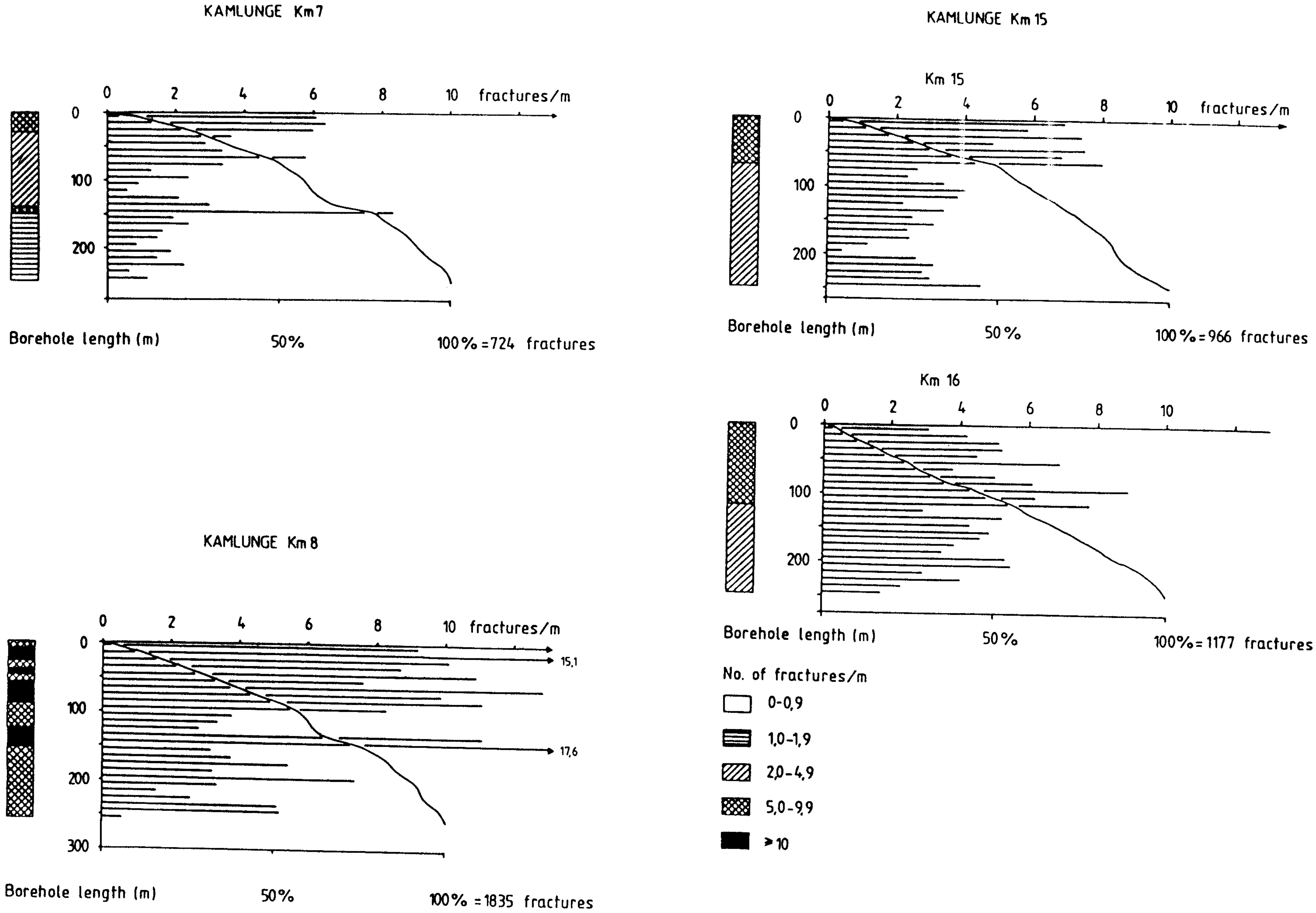


Figure 7.7 Fracture frequency in 10 m sections, cumulative number of fractures, drill holes Km 7-8 and Km 15-16.

7.2 Results

7.2.1 Hydraulic units

The rock volume has been divided into different units with respect to their hydraulic properties. The following units have been identified:

- Local fracture zones
- Horizontal fracture zone
- Rock mass

This division has been based on results of the geological and tectonic investigations that indicate the location and extent of local fracture zones. The indicated horizontal fracture zone has been allowed to constitute a special hydraulic unit in the analysis. Regional fracture zones affect neither the study site nor its immediate vicinity.

The width of the fracture zones in the drill holes has been able to be determined by the drill core mapping. The hydraulically tested 25-m sections that are not affected by the zones represent the rock mass. The K values from all sections that belong to the rock mass have been compiled in figure 7.8.

The rock mass has been divided into three intervals with respect to hydraulic conductivity. High values have been obtained above a vertical depth of 100 m. These values are usually greater than 10^{-9} m/s. In the interval 100-200 m, the hydraulic conductivity varies between 10^{-11} m/s and 10^{-6} m/s. Around 2/3 of the conductivity values are lower than 10^{-9} m/s. Below the 200 m level, the hydraulic conductivity is low. It is normally lower than 10^{-10} m/s (81% of the K values). Seven K values in this interval are higher than 10^{-9} m/s. Of these, two are from depths below 315 m.

The high K values in the uppermost sector are probably due to the fact that the bedrock here is more highly fractured than at greater depth. Data from the drill core mapping show that fracture frequency diminishes with depth. The proportion of open fractures is probably also higher in the surface rock due to relatively small vertical rock stresses on account of the small load exerted by overlying rock. Below a depth of about 200 m, the rock load generates greater vertical stress. Below this level, the proportion of open fractures decreases and the fracture frequency is low. The low hydraulic conductivities below a depth of 200 m may also be due to the fact that the continuity of the fractures is less at greater depth. The 100-200 m sector may be regarded as constituting a transitional zone between the surface rock and the deeper rock.

When the hydraulic conductivity of different rock types is compared, no difference is obtained. The different rock types can be found in both low- and high-permeable parts of the rock mass.

For the local fracture zones, the K values from 25 m, 10 m and 5 m sections have been weighed together with the aid of the drill core mapping. Each fracture zone has been assigned a uniform K-value in each drill hole where it has been encountered. The K-values for the fracture zones are presented in figure 7.9 and table 7.2. Zones that occur in several drill holes have been interconnected. Fracture zones 2 and 3 have been observed in several core drill holes of varying conductivity,

Table 7.2 Hydraulic conductivity (K) values for fracture zones at the Kamlunge study site.

Zone	Zone width (m)	Length in drill hole (m)	K (m/s)	Observed in drill hole
II	8	313-337	6.8 E-11	Km 3
	8	414-425	2.4 E-9	Km 9
	8	195-210	2.1 E-7	Km 12
	8	47- 53	5.0 E-9	Km 5
	8	86- 94	1.0 E-6	Km 6
III	5	441-450	2.5 E-8	Km 3
	5	52- 60	3.5 E-9	Km 12
	5	63- 69	4.0 E-9	Km 8
	5	324-335	2.0 E-10	Km 11
IV	4	504-517	4.0 E-11	Km 3
H 1	10	676-684	4.2 E-9	Km 2
	10	544-560	-	Km 1
	10	669-674	1.0 E-8	Km 13
	10	667-673	5.7 E-9	Km 14

and the hydraulic conductivity varies a great deal. The horizontal zone H1, which is located at a depth of about 570 m, has been detected in four drill holes. The K-value for this zone is 1×10^{-8} m/s.

7.2.2 Depth dependence of hydraulic conductivity

The depth dependence of the hydraulic conductivity in the rock mass and in the local fracture zones has been calculated by means of the following power function:

$$K(z) = a \times z^{b}$$

where

a = constant
b = constant
z = depth

The results of the regression analysis are presented in figures 7.10 and 7.11. A 95% confidence interval has also been indicated in the figures. This means that there is a 95% probability that the power curve is within the confidence limits. The regressional relationships are compiled in table 7.3.

Table 7.3 Depth dependence of hydraulic conductivity for the hydraulic units in the rock mass

Hydraulic unit	Regressional relationship	r^2	n
Local fracture zones	$k = 3.96 \times 10^{-7} z^{-1.02}$	0.10	8
Rock mass	$k = 4.34 \times 10^{-3} z^{-3.17}$	0.54	227

r^2 = regression coefficient
n = no. of k-values

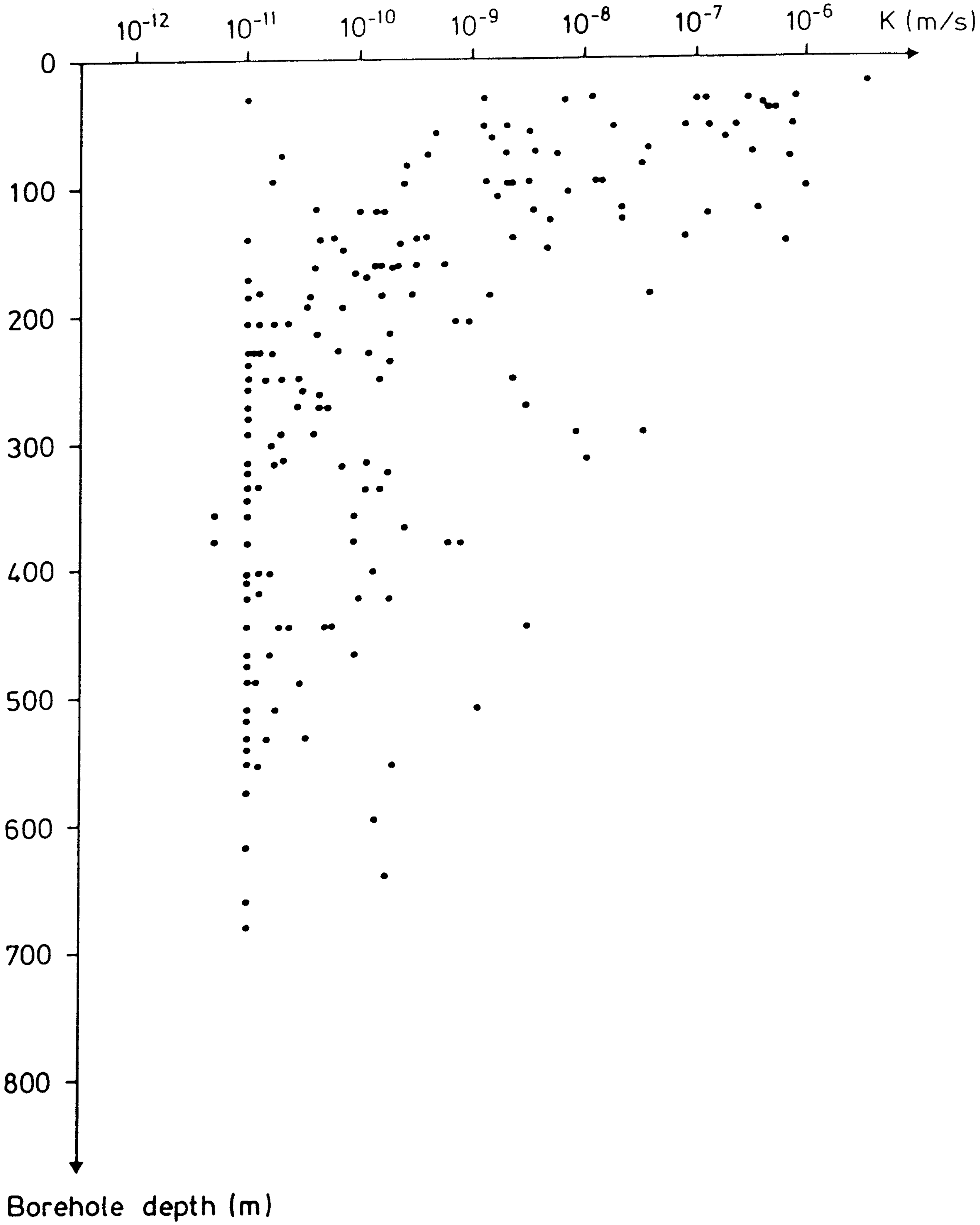


Figure 7.8 Hydraulic conductivity in rock mass, 25 m sections, in drill holes Km 1-6 and Km 9-14.

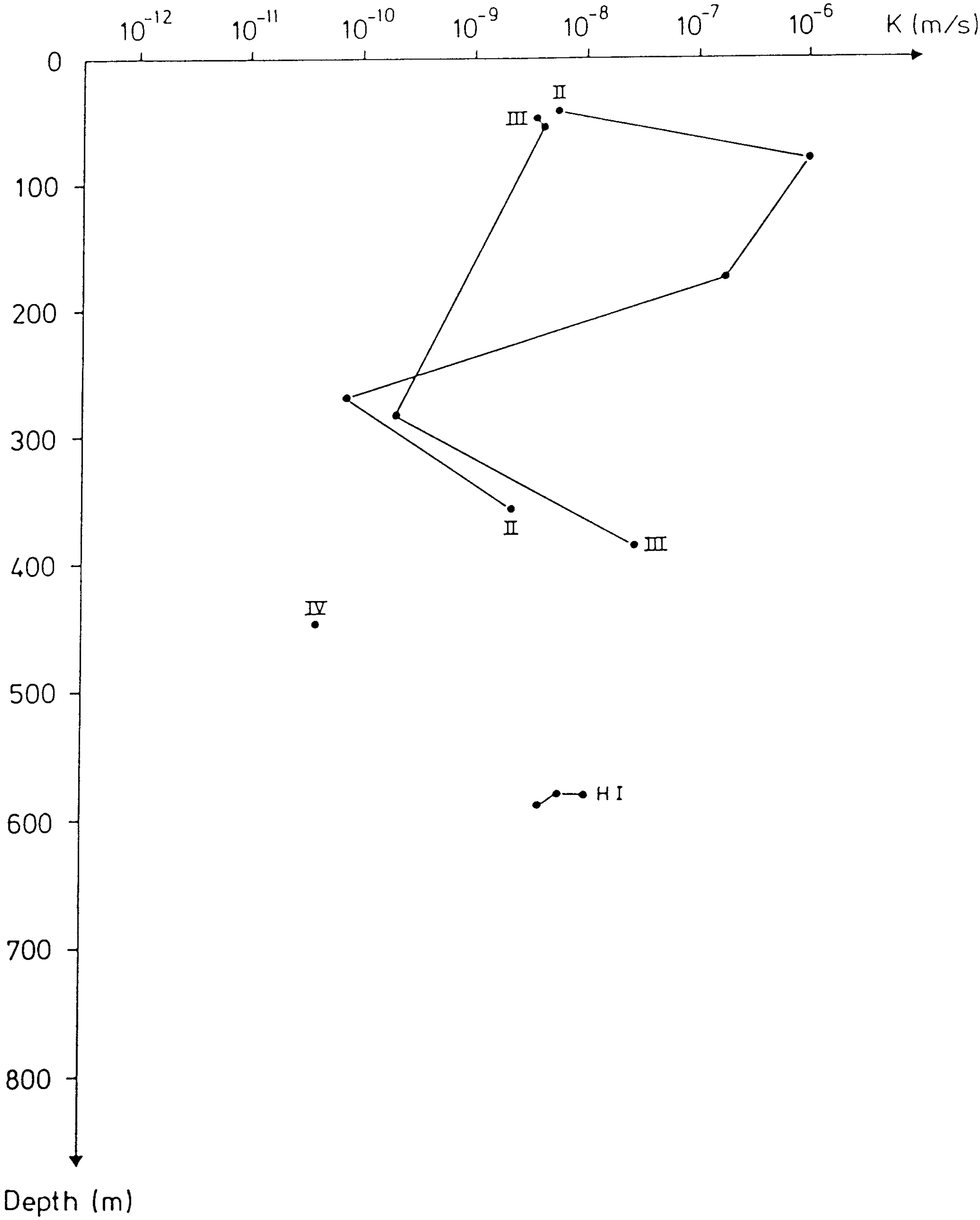


Figure 7.9 Hydraulic conductivity in local fracture zones penetrated by drill holes Km 1-6 and Km 9-14.

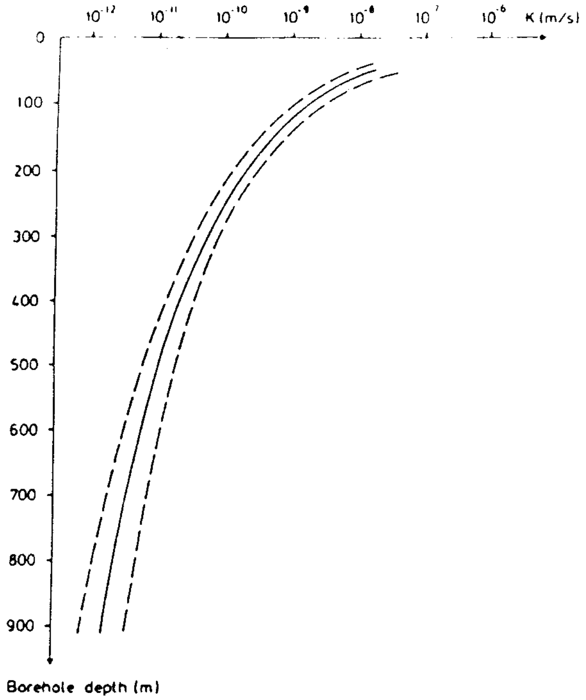


Figure 7.10 Relationship between hydraulic conductivity and depth in the rock mass.

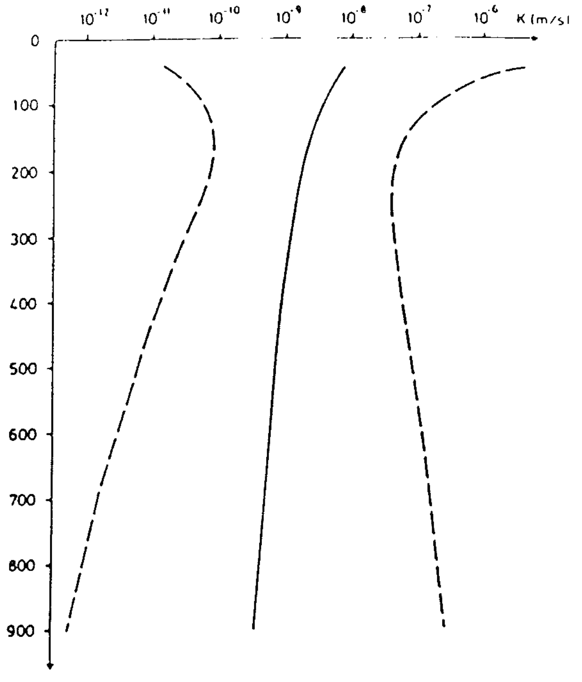


Figure 7.11 Relationship between hydraulic conductivity and depth in the local fracture zones.

The regression analysis shows that the hydraulic conductivity in the local fracture zones is between one and two orders of magnitude higher than in the rock mass. The difference is greatest in the uppermost parts and decreases with increasing depth.

8. GROUNDWATER CONDITIONS

8.1 General

The groundwater conditions within an area are characterized by its topographical, geological and climatological conditions. The geological conditions determine the magnitude and variation of water-transmitting and water-storaging properties. Geology and topography determine how much water the bedrock can transport. Climatological conditions are decisive in determining how much water is available for transport.

The location of the groundwater table has been recorded on the study site in 19 percussion drill holes and in 16 core drill holes. The locations of the drill holes are shown in figure 8.1. The measurements were made during the period November 82 - April 83.

In order to section off the groundwater table in the upper part of the bedrock from the deep-seated groundwater, the upper part of 8 percussion drill holes was sealed off by means of rubber packers. The packers were placed about 10 m below the groundwater level in each case.

Two percussion drill holes were equipped with recording water-level gauges for continuous monitoring of the groundwater table. However, due to defects in the mechanics of the water-level gauges, the recorded values were incorrect, and the measurement results from these percussion drill holes have been omitted.

Manual readings of the level of the groundwater table have been made in those drill holes that have been available for measurement. When the drill holes have been used for other activities, long interruptions in the readings have been necessary.

8.2 Location and level variation of the groundwater table

During the period November 82 to April 83, the groundwater table in the bedrock at Kamlunge has been located at a level of between 135 and 163 m above sea level. The groundwater levels in individual drill holes have varied by between 1 and 8 m. It should be noted that the observation period for all drill holes is very short. As a result, it has not been possible to establish the amplitude of annual variation. In the coastland of Norrland County, the principal groundwater level rise is associated with the intensive snowmelting in the late spring. A secondary period of groundwater recharge occurs during the autumn, when evaporation is low and precipitation falls as rain on unfrozen ground. The highest groundwater level is reached in connection with the snowmelting and the lowest during the late winter.

The greatest variations in groundwater level are noted in those drill holes that have a high topographical location or are situated on steep slopes. The depth from the ground surface to the groundwater table also varies with topographical location. In general, the water table is located 1-3 m below the ground surface. Under small hills and on slopes, the depth to the groundwater can be more than 10 m. Areas of groundwater discharge tend to be located in topographic low points, and the level differences in the location of the groundwater table at those points are relatively small. In recharge areas, the variation in the level of the groundwater table is considerably greater. The groundwater levels in the drill holes on the Kamlunge site are given in table 8.1.

Table 8.1 Groundwater levels in drill holes at Kamlunge during the period November 82 - April 83

Drill hole	Groundwater level (metres above sea level) Highest	Lowest	Range of variation (m)	Remarks
Km 1	151.19	149.00	2.19	
Km 2	139.74	136.94	2.80	Artesian during certain periods
Km 3	136.95	136.13	0.82	Only 3 observations
Km 4	150.71	143.94	6.77	
Km 5	149.51	144.75	4.76	Uncertain observations
Km 6	151.14	146.10	5.04	"
Km 7	151.51	148.87	2.64	
Km 8	160.21	155.59	4.62	
Km 10	155.82	152.61	3.21	
Km 11	158.32	151.10	7.22	
Km 12	140.36	137.92	2.44	
Km 13	143.34	143.34	0.00	Only 1 observation
Km 14	149.33	148.05	1.28	

Km 15	163.43	158.99	4.44	Artesian during certain periods
Km 16	161.82	158.70	3.12	
H 1	146.97	145.34	1.63	
H 2	146.89	145.35	1.54	
H 3	146.04	145.26	0.78	
H 4	144.25	143.91	0.34	
H 5	154.49	146.25	8.24	
H 7	136.91	136.02	0.89	Packer
H 8	135.71	134.78	0.93	
H 9	146.89	142.51	4.38	Packer
H 10	-	-	-	Pumphole, uncertain information
H 11	147.60	140.48	7.12	Packer
H 12	137.66	135.16	2.50	
H 13	160.58	153.19	7.39	Packer
H 14	151.49	145.94	5.55	Packer
H 15	-	-	-	Packer failure
H 16	-	-	-	Instrument failure
H 17	150.78	148.56	2.22	Packer
H 18	-	-	-	Instrument failure
H 19	-	-	-	Packer failure

8.3 Groundwater level map

A groundwater level map has been devised for the Kamlunge site showing the groundwater levels in the bedrock. The scale is 1:10 000. The map is presented in reduced size in figure 8.2.

In producing the map, it has been assumed that the groundwater table follows the topography. On the basis of level observations made on the site, the groundwater table has been assumed to lie 5-10 m below the ground surface on hills and on slopes and 1-3 m below the ground surface in other parts of the area. A morphological adaptation has also been carried out so that the groundwater level at minor topographical deviations has been adapted to the surroundings. For example, the distance to the groundwater table is assumed to be greater on small (isolated) hills than on large ones. Furthermore, the groundwater table is located at a higher level in narrow valleys than in wide ones. Lakes, water courses and peat bogs indicate a near-surface groundwater level and are assumed to be discharge areas for groundwater.

The study site constitutes for the most part a recharge area for groundwater. Small local discharge areas are, however, found in low-lying parts within the site. Larger discharge areas are located around all of Kamlungekölen, where there are large lakes and water courses.

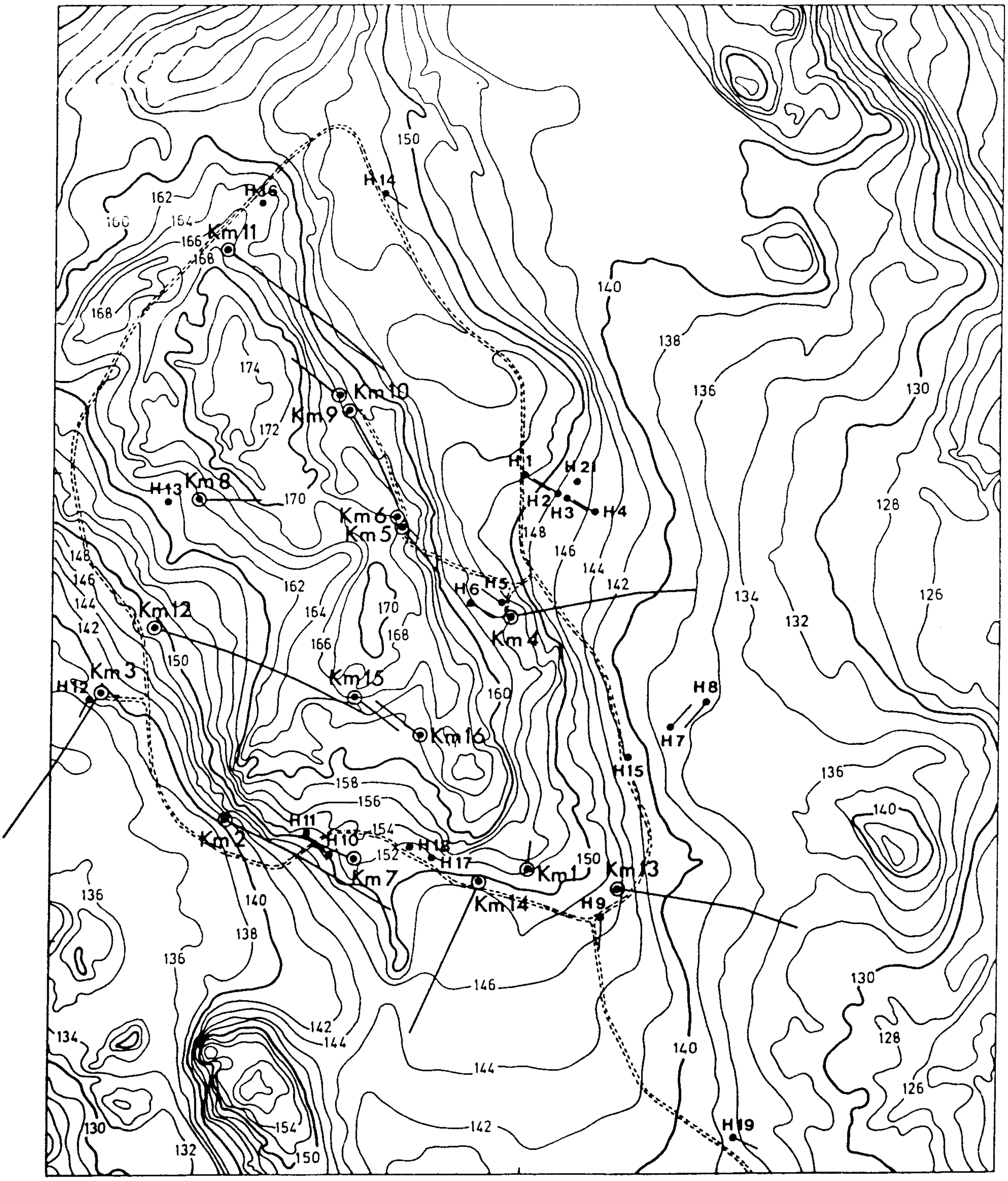


Figure 8.1 Drill holes for observation of groundwater levels at site Kamlunge.

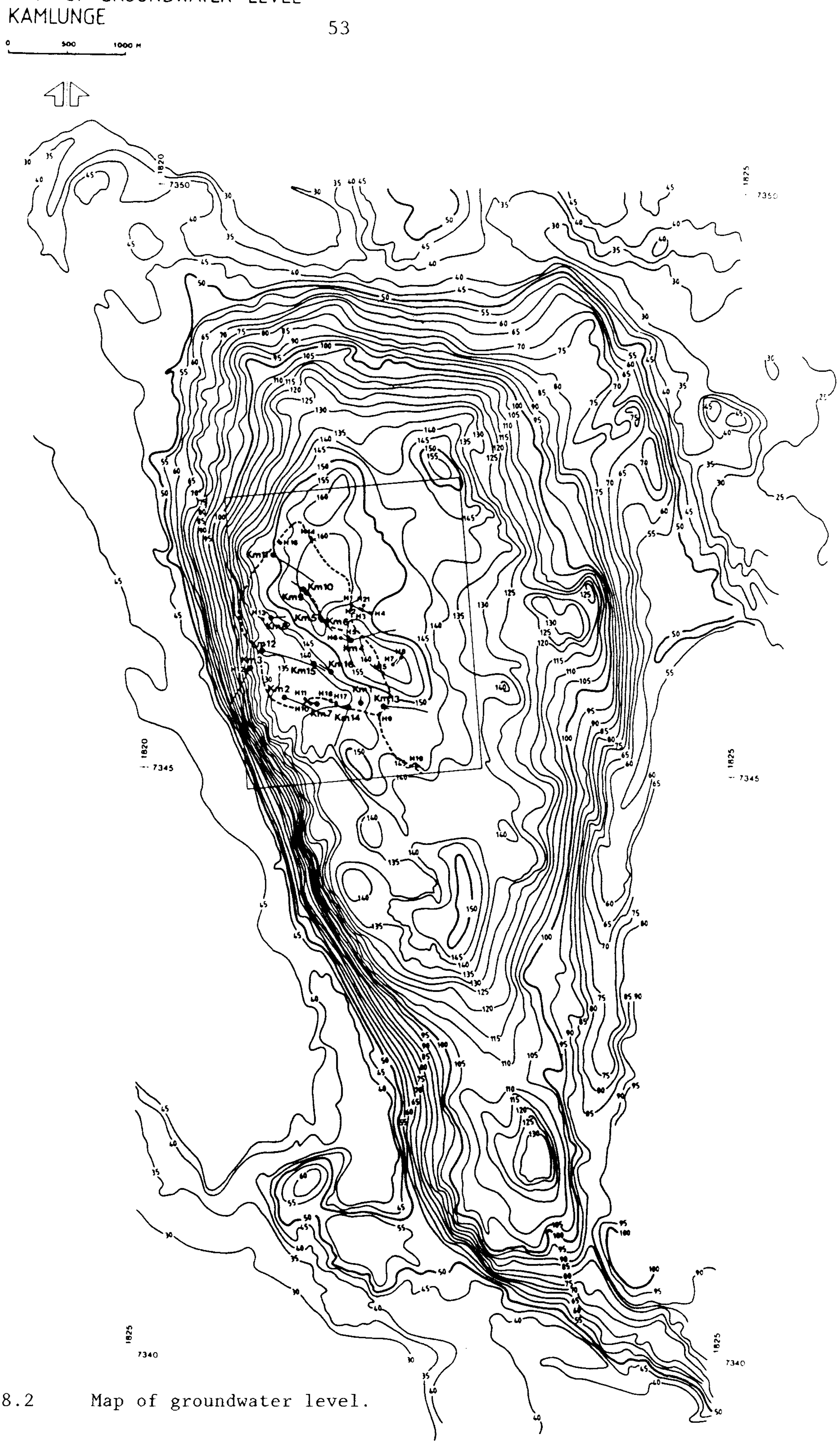


Figure 8.2 Map of groundwater level.

8.4 Groundwater head at various depths in the bedrock

The groundwater head (pressure) in the bedrock varies both laterally and vertically. The groundwater moves from levels of high pressure to levels of low pressure. In drill holes where the groundwater head increases with depth more than the hydrostatic pressure, discharge conditions are said to prevail. Conversely, recharge conditions prevail when the groundwater has a higher pressure in the upper parts of the drill holes compared to the lower parts.

The groundwater head at various levels in the bedrock has been determined by means of the following two methods:

- Calculation based on results of water injection tests with subsequent pressure fall-off phase (Almén et al., 1982).

- Continuous recording by means of pressure gauges in sealed-off sections of the drill holes.

The water injection tests are carried out in two phases. During the first phase a constant injection pressure is maintained and the injected flow volume is recorded. In the subsequent phase, the flow is stopped and the pressure fall-off with time is recorded. The original water pressure in the tested section is calculated on the basis of the results of the two phases, producing so-called Horner plot (Carlsson et al 1983). The groundwater head is indicated as over- or under-pressure, respectively, in relation to the hydrostatic pressure in the drill hole at the corresponding level.

The groundwater head in the measured section deviates in most cases relatively little from the hydrostatic head in the drill holes at corresponding levels. The highest measured positive pressure was obtained in Km 12, + 15.8 m w.c. (water column), and the lowest in Km 13, - 19.5 m w.c. Many drill holes exhibit a clear recharge character with declining pressure with increasing depth. Positive groundwater pressures are found in the upper parts of the bedrock. The groundwater head in the measured drill holes is reported in figures 8.3 and 8.4.

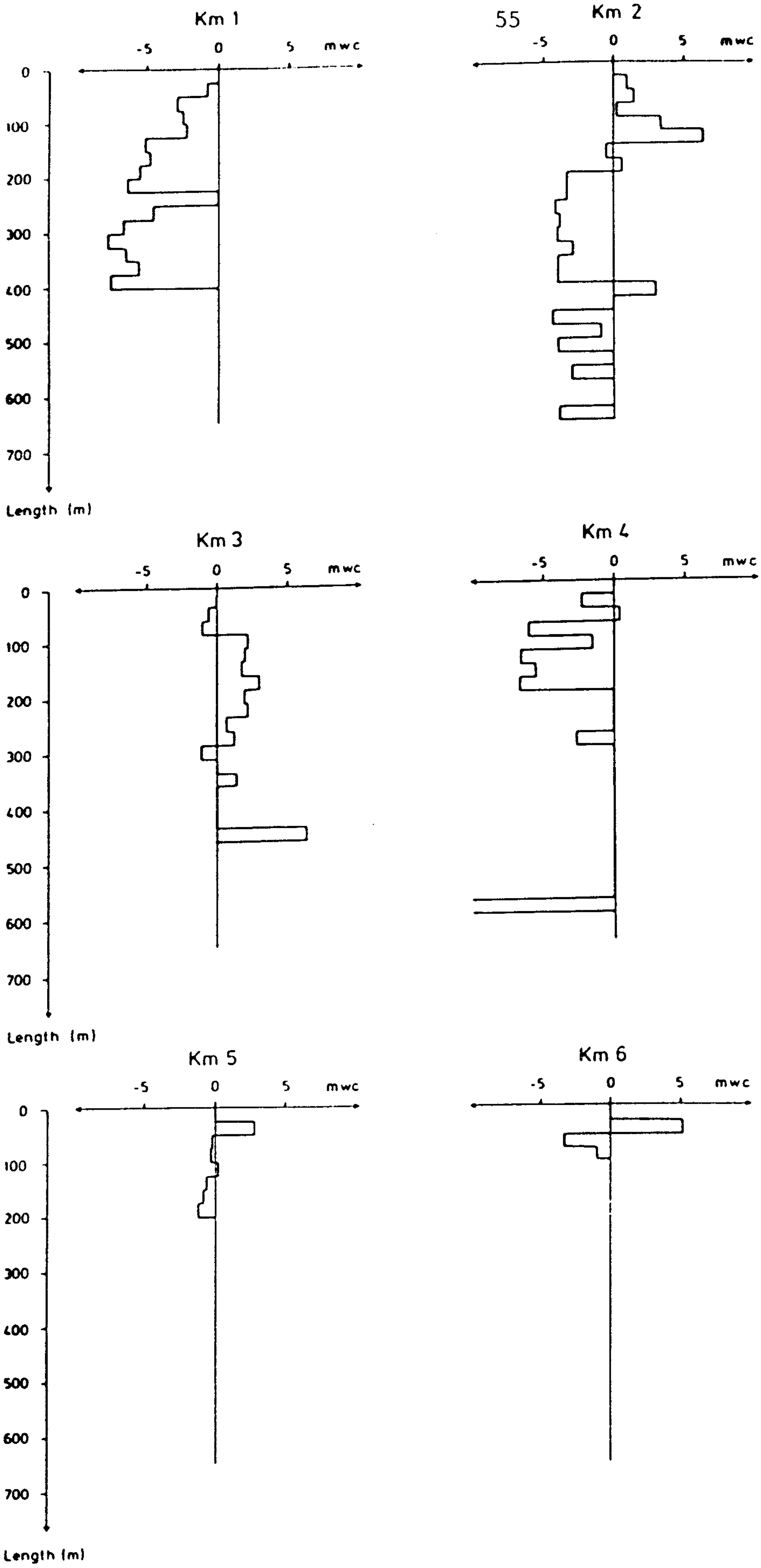


Figure 8.3 Pressure distribution in test sections of drill holes Km 1-6.

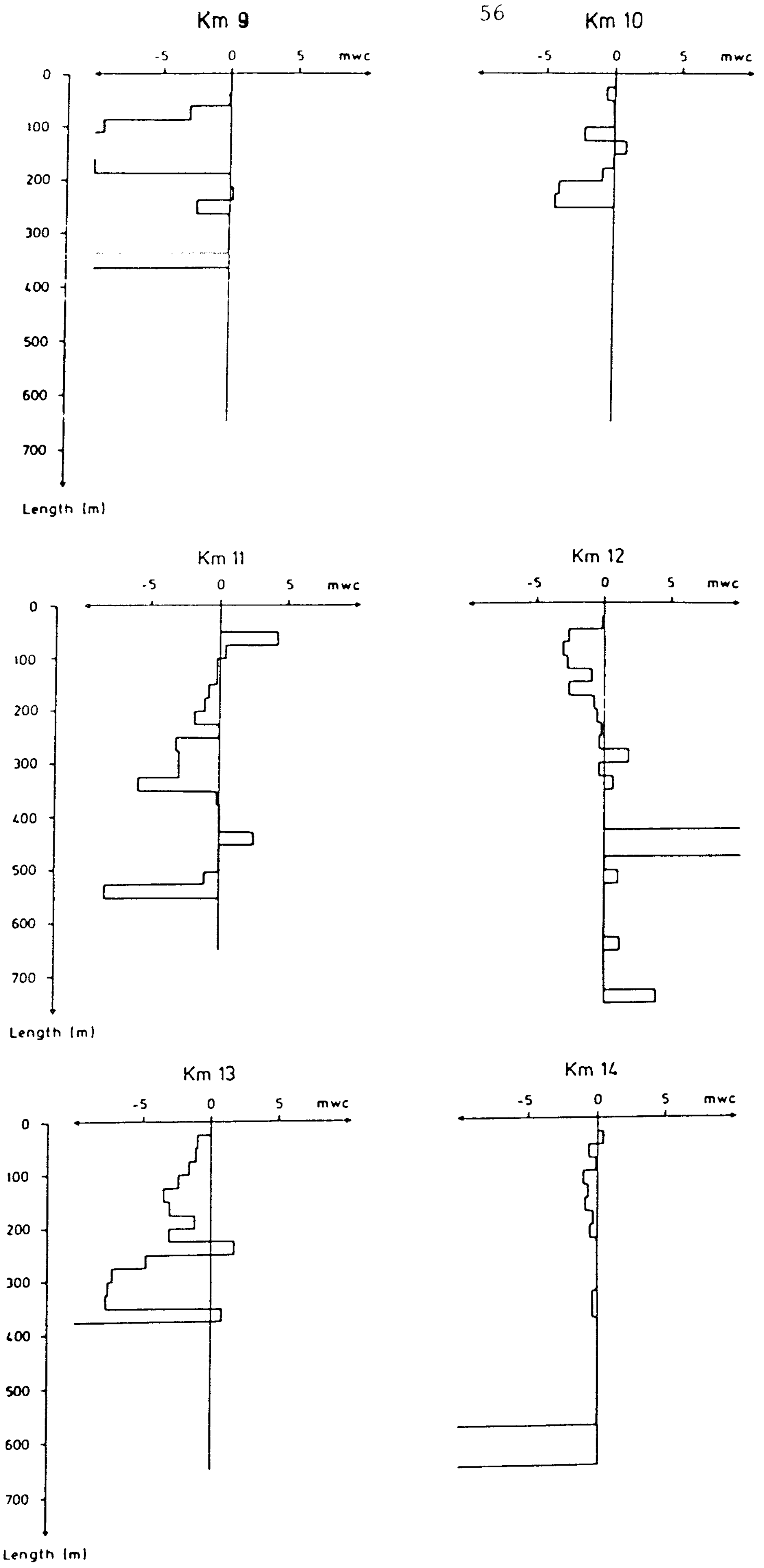


Figure 8.4 Pressure distribution in test sections of drill holes Km 9-14.

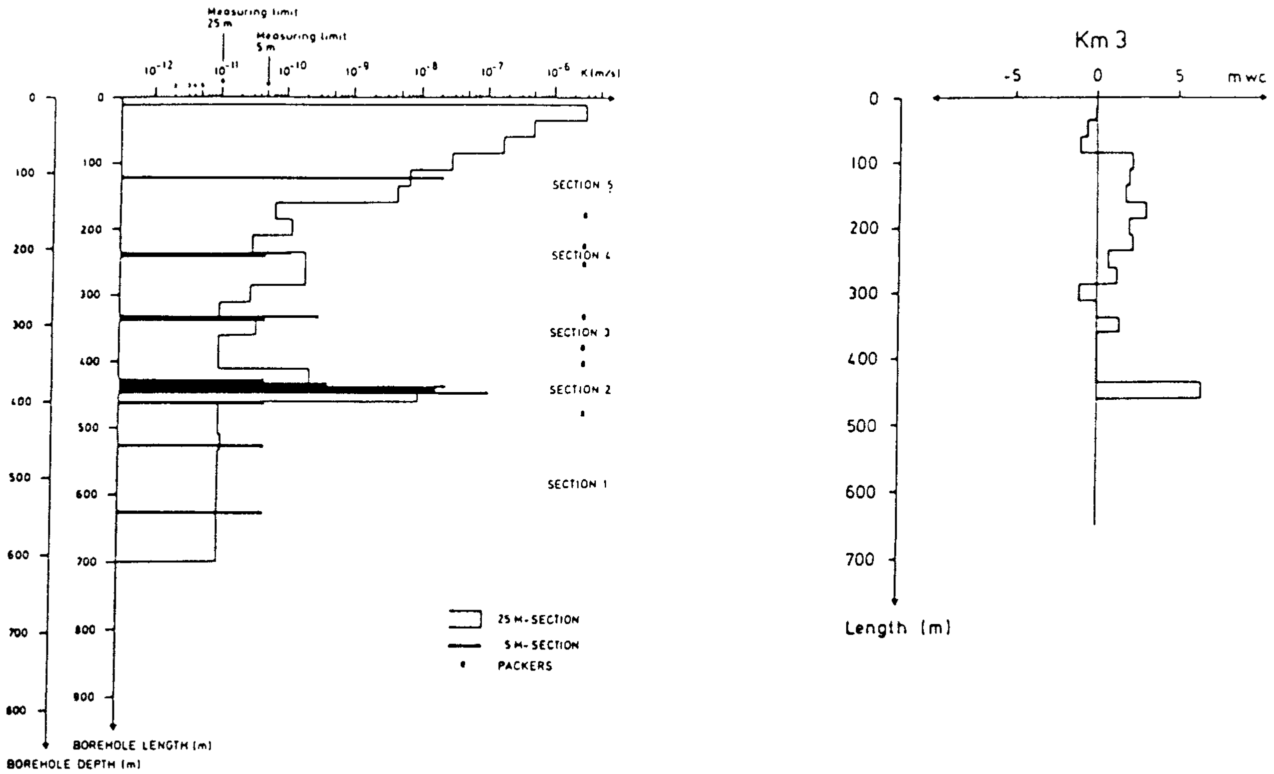
ferent levels. Fracture zones separated by less permeable rock are suddenly interconnected by the act of drilling. Water from one level is then conducted via the drill hole to levels of lower pressure. The natural pressure distribution of the groundwater is thus altered by the existence of the drill hole.

One way to circumvent this problem has been to position packers at several levels in a drill hole simultaneously and thereby reconstruct on a large scale the structure of the rock. Up to seven packers have been used in these so-called piezometric measurements. The groundwater head has been registered in five different sections, one of which constitutes the free groundwater table. The groundwater head is given as positive or negative pressure in relation to the hydrostatic head in the open drill hole at the corresponding level. Piezometric measurements have been carried out in drill holes Km 3 and Km 12. Packer placement is shown in fig. 8.5.

Negative pressures prevail in the lowermost three sections in drill hole Km 3, while positive pressures prevail in the uppermost two. The deviation of the groundwater head from the hydrostatic head of the section in question is small. The deviation is greatest in section 1: about -1.5 m w.c.

Negative pressure prevails in the lowermost section in drill hole Km 12. Positive pressures prevail in the other sections. The deviation of the groundwater head from the hydrostatic head is small in the 4 uppermost sections. The deviation is greatest in the lowermost section: about -10 m w.c.

KAMLUNGE Km 3



KAMLUNGE Km 12

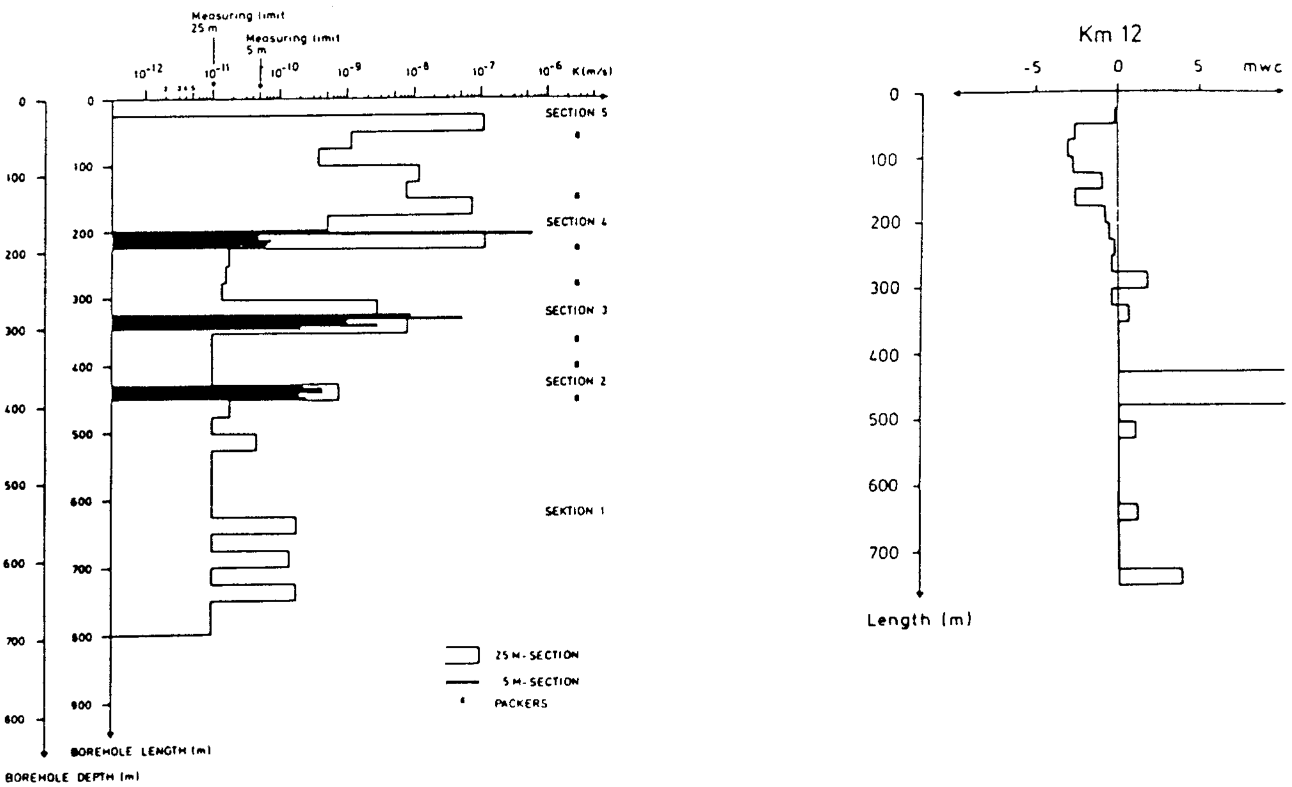
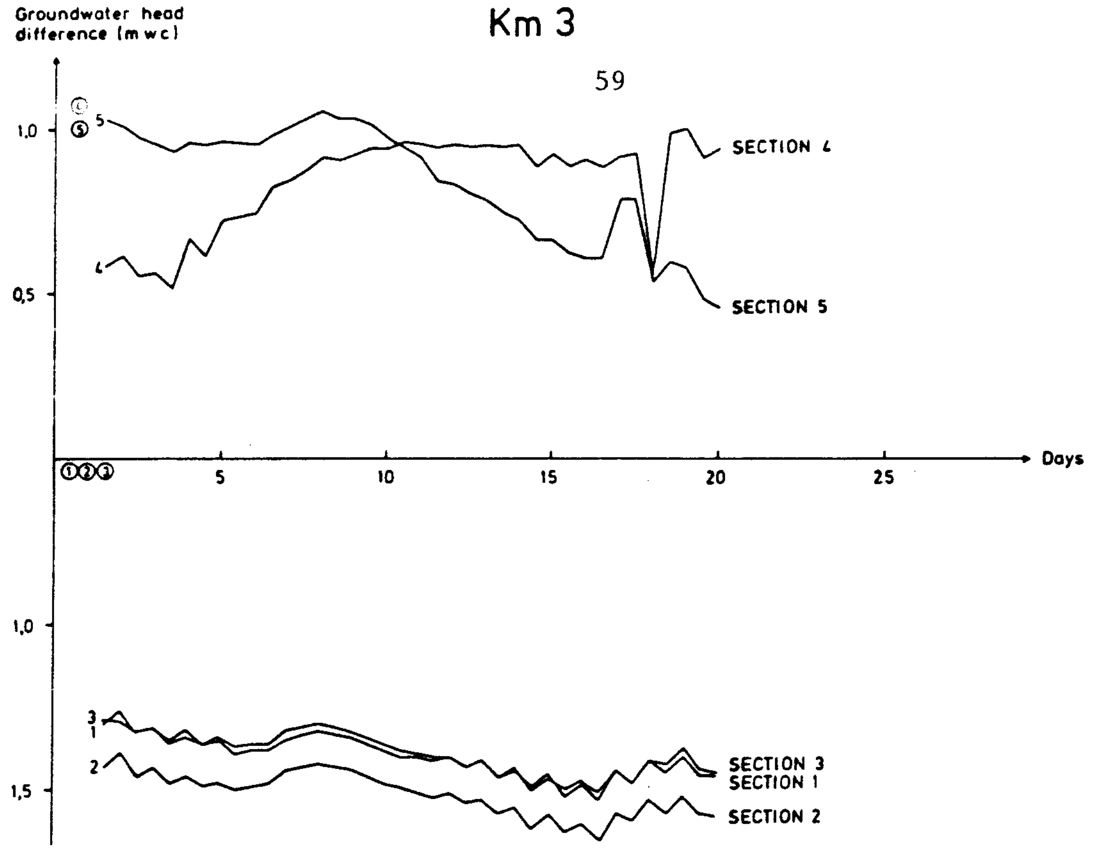


Figure 8.5 Positions of packers and piezometric sections in drill holes Km 3 and Km 12.



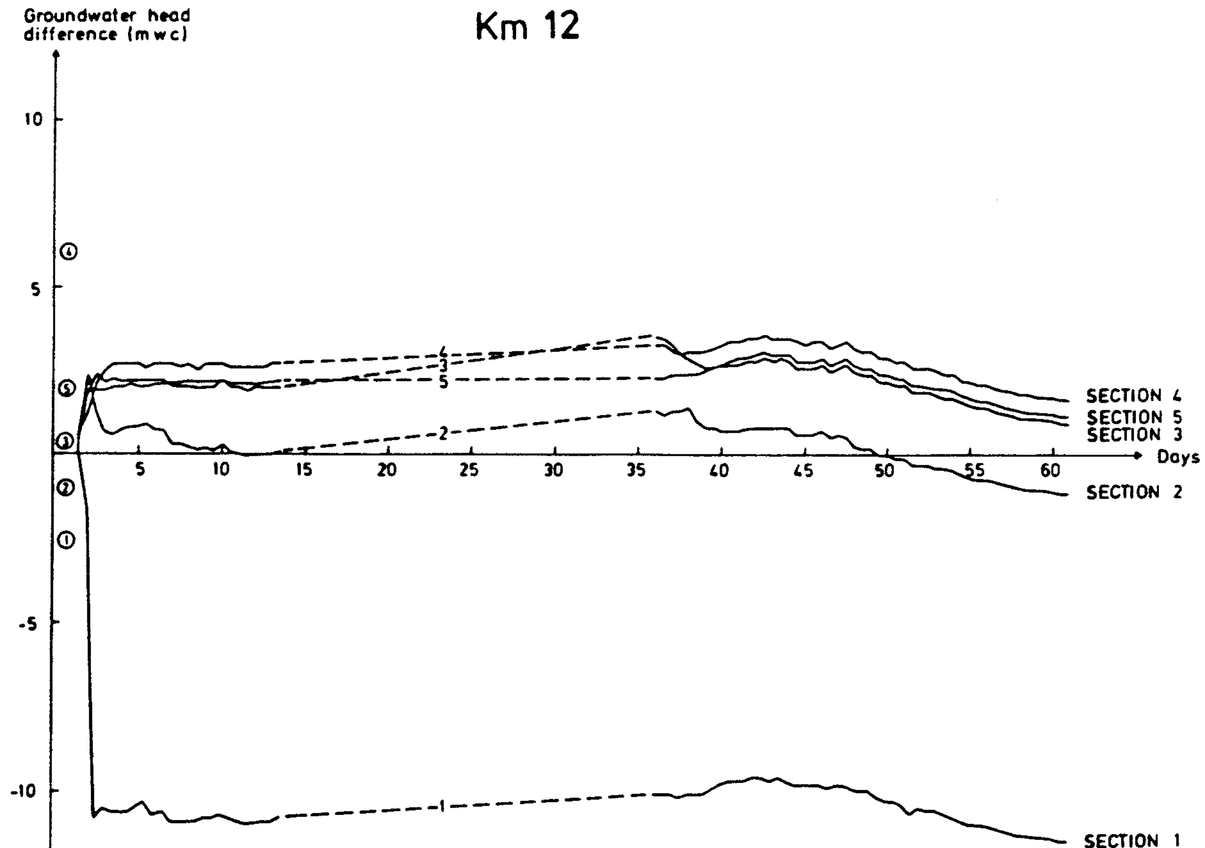


Figure 8.6 Piezometry. Groundwater in sections under simultaneous packer sealing in drill holes Km 3 and Km 12. Groundwater head refers to hydrostatic pressure in the drill hole at respective levels.

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APPENDIX: EXTENT OF SITE INVESTIGATIONS AT KAMLUNGE

Surface investigations:

Geological surface mapping

Detailed mapping — 6.25 km^2

Geophysical surface mapping

Detailed surface mapping (40x20m grid) — 5 km^2

- Magnetic total intensity
- Slingram (horizontal loop EM)
- Resistivity
- Induced polarization (IP)

Refraction seismic profiles — 4 km

Depth investigations

Percussion drill holes

No.	Coordinates	Altitude m	Dir./Incl. degrees	Length m	Vert. depth m	Water capacity l/h
1	994N/1004E	152.7	S60E/55	100	81.9	6000
2	960N/1068E	148.4	N60W/55	107	87.7	1200
3	951N/1089E	148.4	S60E/55	100	81.9	3000
4	920N/1349E	145.6	N60E/55	100	81.9	1800
5	722N/ 949E	154.3	N65W/55	106	86.8	0
6	720N/ 884E	156.4	S65E/55	115	94.2	3000
7	453N/1334E	137.1	N50E/55	115	94.2	300
8	510N/1379E	135.8	S50W/55	120	98.3	0
9	50N/1159E	147.7	N- S/55	120	98.3	0
10	187N/ 592E	151.4	N45W/55	100	81.9	9000
11	226N/ 539E	151.2	S45E/55	120	98.3	0
12	510N/ 80E	138.5	S30W/55	100	81.9	900
13	942N/ 244E	161.3	90	100	100.0	720
14	1594N/ 696E	153.8	S55E/55	100	81.9	1500

No.	Coordinates	Altitude m	Dir./Incl. degrees	Length m	Vert. depth m	Water capacity l/h
15	394N/1217E	142.3	90	50	50	60
16	1580N/ 435E	165.6	90	50	50	600
17	172N/ 804E	151.8	90	50	50	0
18	192N/ 758E	151.9	90	100	100	120
19	422N/1450E	136.9	S65E/55	100	81.9	180
20	*		90	182	182	30000
21			90	100	100	780
22			90	60	60	1800

*) Percussion drill hole in the regional fracture zone to the west.

Core drill holes

No.	Coordinate	Altitude m	Dir./Incl. degrees	Length m	Vert. m	Depth
1	147N/1010E	152.5	N -S/85	674.0	670	
3	252N/ 358E	139.7	S65E/60	701.3	566	
4	518N/ 95E	138.7	S28N/60	700.1	583	
5	881N/ 736E	167.4	S30E/60	251.4	210	
6	904N/ 725E	167.3	S30E/60	104.5	89	
7	173N/ 646E	153.5	N65W/60	249.0	208	
8	938N/ 307E	163.3	N90E/60	251.3	208	
9	1132N/ 626E	164.1	S30E/60	449.3	366	
10	1176N/ 604E	163.8	N50W/60	287.0	205	
11	1475N/ 356E	167.9	S60W/60	700.4	546	
12	663N/ 207E	148.8	S70E/60	801.9	636	
13	105N/1200E	147.0	S70E/60	703.1	582	
14	120N/ 885E	149.6	S20W/60	700.2	579	
15	506N/ 652E	163.4	S60E/60	251.2	210	
16	440N/ 780E	164.6	N60W/60	252.6	211	

Investigations on drill cores

Total core length	approx. 7750 m
Chemical analyses (number)	10
Petrophysical samples (number) 1)	133

1) Evenly distributed among all core drill holes and depths.

Geophysical logging

Methods:	drill hole deviation	1)	2)
	natural gamma radiation	1)	2)
	single point resistance	1)	2)
	resistivity normal 1.6 m		2)
	resistivity lateral 1.65 m		2)
	self potential		2)
	temperature		2)
	salinity		2)
	induced polarisation		3)

1) Measurements in percussion drill holes 1-14, 16, and 18.
2) Measurements in all core drill holes.
3) Measurements in core drill holes Km2 and Km9.

Hydrological investigations

Water injection tests	Number of tests
25 m sections	230
10 m	7
5 m	91
2 m	176

Piezometric measurements		Number of sections
Drill hole	Km 3	5
	Km 12	5

Interference tests

Pump hole	H Km 21
Observation holes	H Km 1, 2, 3, 4

Groundwater level observations

Percussion drill holes	H Km 1-19
Core drill holes	Km 1-16

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