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Evaluation of the hydrogeological conditions at Finnsjön

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Supplementary geophysical investigations of the Stärnö peninsula

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Swedish Geological, May 1983

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Part I

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Part II

SUPPLEMENTARY GEOPHYSICAL INVESTIGATIONS OF THE STÄRNÖ PENINSULA

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SUMMARY

Within the study area Finnsjön in northern Uppland, hydrogeological and geological investigations were carried out during 1977 - 1982. The object of the investigations was to obtain a better knowledge of the groundwater occurrences and movement in crystalline bedrock and to test different investigation methods.

The study area is about 25 km^2 and has a flat topography due to the Sub-Cambrian peneplain. The differences in altitude are in general less than 15 m. The bedrock is composed of metamorphic sediments and vulcanites of Sweco-Karelian age. The dominating rock type is granite gneiss. The area is covered to 85% by Quaternary deposits, mainly till. Eight core drill holes and seventeen percussion drill holes were made in the area. The cores were mapped regarding rock type, fracture fillings and fracture frequency. In the core drill holes water injection tests were performed in sealed-off two- or three-meter sections. The groundwater head was measured in open boreholes and the sealed-off sections in the drill holes.

The tectonics in the area were studied from satellite and aerial photographs. The fracture frequency measured on drill cores is an average 2.5 fractures per meter. No tendency of decreasing frequency with depth was obtained.

The hydrometeorological conditions of the area were obtained by measurements of i.a. precipitation and run-off. Calculations and field-mapping showed that about 30% of the study area consists of areas for groundwater discharge. The precipitation is on the average 670 mm per year and the run-off about 240 mm per year.

The bedrock was divided into different hydraulic units with different hydraulic properties. The division was based on tectonic considerations and results from drillings and hydraulic tests. Depending on the scale used, a different degree of accuracy was applied in the division of the units. In principle the bedrock was subdivided in fracture zones and rock mass.

The hydraulic conductivity within each unit was calculated from the statistical frequency distribution of the values obtained from the field tests. A decrease of conductivity versus depth was observed. However, this decrease was strongly influenced by the measurement limit.

1. BACKGROUND

1.1 The object of the report

The geology and hydrogeology of the bedrock in an area east of Lake Finnsjön in northern Uppland was investigated during the years 1977 and 1978 in connection with the studies for final disposal of radioactive waste. The area was subsequently developed into a study and research site where extensive field studies within the spheres of geology and bedrock hydrogeology were carried out during 1979-1982. The aim of the investigations was to obtain additional knowledge about the presence of groundwater and its behaviour in crystalline bedrock and to find suitable methods and techniques for such investigations.

The object of the present report is to constitute a compilation of the geology and hydrogeology of the Finnsjön study area. The intention is not to provide a comprehensive survey and evaluation of all studies performed in the area but rather to present the geology and hydrology of the area and the surrounding region.

1.2 The disposition of the report

The present report describes the groundwater conditions in crystalline bedrock based on knowledge about:

- the occurrence and extension of various hydraulic units
- the locations of the groundwater tables
- hydraulic parameters in the different hydraulic units.

No investigation method will by itself provide answers to the above mentioned topics, and data from a number of different studies must consequently be compiled in order to obtain a descriptive model of the groundwater condition in a certain area.

For the description of the hydraulic units data are required about the geology and the tectonics of the area concerned. In addition, data from core drillings are necessary in order to determine the geometry of occurring fracture zones.

The hydraulic conductivity of the different hydraulic units is obtained by water injection tests in different sections of the drill holes whereas tests between different drill holes, so-called interference tests, are carried out in order to obtain knowledge about the rock between the drill holes. Groundwater level maps are constructed by the aid of groundwater level observations and the topography of the area.

The description of the groundwater conditions in the area includes the following elements:

- a descriptive hydraulic model

- a quantitative estimate of the groundwater flow and the groundwater head within the site.

The descriptive hydraulic model forms the basis for numerical calculations of the groundwater conditions in the area. The collected data constitute input data for these calculations.

Hydrochemical data provide information on the formation, ages and turnover times for groundwater. These data constitute valuable information for comparison between different descriptive models.

The present report presents in Chapters 2, 4 and 5 basic data on geographical location, area descriptions, topography and geology. In the geology chapter the emphasis is placed on the part concerning tectonics, while the movement of groundwater to a high extent is governed by the fractures and fracture zones in the rock.

Chapter 3 contains a brief presentation of the various studies carried out in the area.

Chapter 6 deals with hydrometeorological data and two different calculations of the water balance of the area. The water balance calculations are based on measured as well as on calculated values.

Chapter 7 indicates the surface hydrological situation in the area. All streams, lakes and mires within the area are dealt with together with descriptions of major drainage constructions carried out as well as lowering of lake surfaces.

The results of the measurements and calculations of the hydraulic conductivity of the bedrock and the groundwater head are summed up in Chapter 8, which also contains a descriptive model of the groundwater conditions at Finnsjön.

2. GEOGRAPHICAL ORIENTATION

2.1 The location of the area

The Finnsjön study area consists of a 25 km^2 area east of Lake Finnsjön in northern Uppland (latitude 60° 20'N longitude 17° 55'E), approx 100 km north of Stockholm (see Fig 2.a).

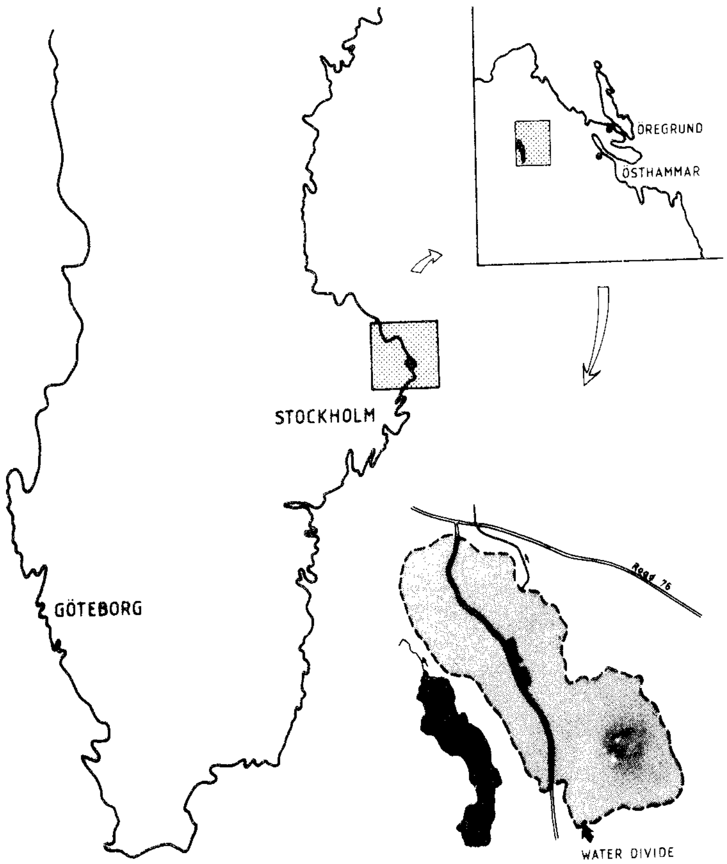


Figure 2.a. Location of the Finnsjön study area

2.2 Different defined areas

2.2.1 Areas for model studies

Two different areas have been defined for the numeric groundwater calculations. Of these one constitutes a regional area with an acreage of 110 km^2. This area is bounded off by lakes and waterways usually connecting on to tectonic lines surrounding the Finnsjön study area. The extent of the regional area is indicated in Appendix 1.

A local site covering a limited part of the regional area was selected for the detailed calculations. The size of this site is approx 2 km^2 and its areal extent is indicated in Appendix 7.

2.2.2. The Finnsjön study area

The run-off area delimiting the Finnsjön study area has been determined by means of topographical maps and field studies. The area is delimited by the surface water divides setting out from the outflow point of the Tannsjöbäcken stream approx 2 km south of the point where the stream is crossing Road 76, see Fig 2.a. The area has also been divided into a number of small subsidiary run-off areas.

3. STUDIES PERFORMED

3.1 Activities

Different investigations in the Finnsjön study area have been carried out relating to geology, hydrology, hydrogeology and hydrochemistry. The different activities may be divided into the following topics:

- preparation of topographical maps
- mapping of the bedrock geology, tectonics and Quaternary deposits in the area
- core and percussion drillings and drill core logging
- hydrological mapping and compilation of hydrological data
- hydraulic conductivity measurements
- tracer tests
- piezometric measurements
- hydrochemical investigations.

3.2 Preparation of topographical maps

Topographical maps of the study area in scale 1:10,000 have been prepared. The equidistance of the maps is one meter. Maps have been prepared of northern Uppland which indicate the general morphology and topography. These maps are based on existing topographical maps of Sweden. The specifically prepared maps are listed in Table 3.a.

Table 3.a. Topographical maps compiled and devised for completed and on-going studies in the Finnsjön test area.

Size of area	Scale	Cartographic material
Finnsjön study area (25 km^2)	1:10,000	Aerial photographs, economic and topographical maps
Local site (2 km^2)	1:10,000	Aerial photographs, economic and topographical maps
Regional area (110 km^2)	1:50,000	Aerial photographs, economic and topographical maps
Northern Uppland (10,000 km^2)	1:250,000	Satellite photographs, aerial photographs and topographical maps

3.3 Geological mapping

3.3.1 Bedrock geology

A bedrock geology map, scale 1:10,000, based on outcrops and core-mappings of the study area has been compiled. The bedrock geology outside the study area has been compiled from the general geological maps of Sweden.

The bedrock geology of and around the Finnsjön study area have been accounted for in the following reports:

- Scherman, S. 1978: Preparatory work on the selection of locations for bedrock investigations. (In Swedish). KBS technical report no. 60.

- Almen, K.E., Ekman, L., Olkiewicz, A. 1978: The Finnsjön test area. Description of the bedrock and Quaternary deposits. (In Swedish). KBS technical report 79-02.

- Kornfält, K-A., Olkiewicz, A., Scherman, S. 1979: Supplementary bedrock investigations in the Finnsjön and Karlshamn area. (In Swedish). KBS technical report 79-05.

o Anefors, J., Olkiewizc, A. 1982: Bedrock description of the Finnsjön study area in northern Uppland.

3.3.2 Tectonics

The bedrock mapping also includes studies of the tectonic conditions. For the purpose of the tectonic mapping, satellite photographs, aerial photographs, and aerial and ground geophysical studies have been utilized. As far as the Finnsjön study area and the local site are concerned, minor lineaments have been mapped out in more detail than in the regional area where only regional lineaments are included. These lineaments have been interpreted as being tectonic zones.

The tectonics of the different study areas are accounted for in the report:

o Olkiewicz, A. 1982: Lineaments, fracture zones and fractures in northern Uppland with special emphasis on the Finnsjön study area. (In Swedish).

3.3.3 Quaternary geology

A detailed Quaternary mapping of the study area has been performed. The result is presented in the form of a map in scale 1:10,000. To the map belongs a description of the Quaternary development during the last ten thousand years.

The material is published in the report

o Almen, K-E., Ekman, L., Olkiewicz, A. 1978: The Finnsjön test area. Description of bedrock and Quaternary deposits. (In Swedish). KBS technical report 79-02.

3.4 Drilling and core loggings

Eight core drill holes and seventeen percussion drill holes have been made in the study area. The cores from the core drill holes have been investigated with respect to rock types, fractures and fracture fillings. The results are presented in the form of core diagrams describing existing fractures, occurring rock types and fracture minerals. The results are part of the above mentioned bedrock-geological report. Core drill hole data are presented in Table 3.b. The diametre of all core drill holes is 56 mm.

Table 3.b. Data on core drilled holes in the Finnsjön study area

Drill hole	Drilled length (m)	Inclination	Vertical depth (m)
Fi 1	494	90^o	494
Fi 2	673	50^o	514
Fi 3	676.5	50^o	518
Fi 4	602.90	80^o	593.3
Fi 5	750.5	50^o	583.2
Fi 6	695.35	90^o	691.35
Fi 7	552.71	85^o	550.6
Fi 8	464.25	60^o	402

3.5 Hydrological mapping and data collection

All superficial water courses in the study area have been mapped and numbered. Measurement stations for run-off from and within the area have been set up on five locations. The groundwater discharge areas have been mapped by means of vegetation indicators (hydrobotanics). Twelve precipitation stations within the study area have been positioned.

The material is compiled in four internal reports:

- o Jacobsson, J-Å., Larsson, N-Å. 1980: Hydrological surface mapping of the Finnsjön study area. (In Swedish). KBS internal report.
- o Svenson, T. 1980: Results of hydrobotanical mapping of the Finnsjön study area in 1979. (In Swedish). KBS internal report.
- o Svenson, T. 1981: Hydrobotanical mapping of the Finnsjön study area. Comparison between aerial photograph and field-mapped vegetation. (In Swedish). KBS internal report.
- o Larsson, N-Å., Svenson, T. 1980: Precipitation data from the Finnsjön study area, February-September 1979. (In Swedish). KBS internal report.

3.6 Hydraulic conductivity measurements

All drill holes, both core and percussion drill holes in the study area have been utilized for determining the hydraulic conductivity of the bedrock. The measurements have been performed by means of water injection tests at constant head. Calculations were made presuming stationary conditions. Also a number of interference tests in the form of test pumping have been performed.

Hydraulic conductivity measurements carried out in the area are accounted for in the following reports:

- o Hult, A., Gidlund, G., Thoregren, U. 1978: Permeability determinations. (In Swedish). KBS technical report no. 61.
- o Carlsson, L., Gentzchein, B., Gidlund, G., Hansson, K., Svenson, T., Thoregren, U. 1980: Supplementary permeability measurements in the Finnsjön area. (In Swedish). KBS technical report 80-10.

3.7 Tracer tests

Tracer tests have been carried out between two or several drill holes under controlled conditions. The aim of the tests has been to test different tracers and to obtain knowledge about the hydraulic properties of the rock.

The results are accounted for in the following reports:

- o Klockars, C-E., Persson, O. 1978: Bedrock groundwater conditions in the north-eastern part of the Finnsjön area. (In Swedish). KBS technical report no. 60.

- o Klockars, C-E., Gustafsson, E. 1981: Studies on groundwater transport in fractured crystalline rock under controlled conditions using nonradioactive tracers. KBS technical report no. 81-07.

3.8 Piezometric measurements

The groundwater head in the Quaternary deposits within the study area has been measured in six drill holes. In two of the drill holes the level has been monitored continuously, the remaining four drill holes having been measured once every week.

The groundwater table in the bedrock as well as the groundwater head in different sections have been continuously registered in two percussion drilled holes.

3.9 Hydrochemical investigations and age determinations

Samples of surface water have been taken in the area in order to document the water status, but also in order to study possible seasonal variations. The samples have been extracted from ten fixed locations in the area.

The chemical composition of the groundwater has also been investigated in conjunction with pumpings in drill holes within and in the vicinity of the study area at Finnsjön. Groundwater from springs and dug and drilled wells in the area has moreover been sampled and analyzed.

Determination of the age of the groundwater has been made by means of three methods, Carbon-14, tritium and $^{18}O/^{16}O$. C-14 and the $^{18}O/^{16}O$ methods are the methods used for determining the age of the old groundwater, whereas the tritium method is used in parallel with the other two, in order to determine any possible mixing of the surface water utilized as cooling water during drilling.

The reports listed below accounts for the chemical composition and age-determinations of the surface and groundwater in the study area:

- Rennerfelt, J. 1977: The composition of groundwater at major depths in granitic bedrock. (In Swedish). KBS technical report no. 36.

- Gidlund, G. 1978: Analyses and age determinations of groundwater at great depth. (In Swedish). KBS technical report no. 62.

- Jacks, G. 1978: Groundwater chemistry at depths in granite and gneisses. KBS technical report no. 88.

- Jcobsson, J-Å. 1979: Results of well inventory in the Finnsjön study area 1979. (In Swedish). KBS internal report.

- Johansson, B. 1980: Groundwater dating by means of isotopes. KBS technical report 80-08.

- Hultberg, B., Larsson, S-Å., Tullborg, E-L. 1981: Groundwater in crystalline bedrock. KBS technical report (in preparation).

4. TOPOGRAPHY AND QUATERNARY GEOLOGY

4.1 Northern Uppland

4.1.1 Topography

Uppland and major parts of the Västmanland and Gästrikland provinces form an area of low relief. More than 50% consists of plains of less than 25 m brokenness, i.e. differences in altitude between the highest and lowest points within a frame of 1 km side. In northern Uppland there are large areas with altitude differences less than 10 m. This very even bedrock surface is part of the Sub-Cambrian peneplain. Appendix 2 specifies the altitude characteristics of northern Uppland with surrounding regions.

4.1.2 Quaternary geology

The dominating Quaternary deposit in northern Uppland is till (45%) which is deposited on the flat bedrock surface. Northern Uppland has a large proportion of mires (35%) and a low proportion of bedrock outcrops (5%) compared to the surrounding regions.

4.1.3 Post-glacial development

The ice movement during the latest inland ice period was approx N25^{o} - 30^{o}E (Lundqvist 1961, Hoppe 1966 and Järnefors 1963). The majority of the glacial striae observed in the study area have, however, a more northerly orientation.

During and after the melting of the inland ice the Baltic depression has undergone several stages of development. More or less saline inland seas have interchanged with stages of fresh water.

When the ice had left the region approx 8000 B.C. this flat region was covered by the Yoldia Sea, the level of which was (to begin with) approx 180-185 m above the present sea level. The deeper parts of the Yoldia Sea probably had a considerably higher salinity than the Baltic of today, whereas the surface layers probably were mixed with fresh water in the form of melting water from the inland ice.

After a comparatively short time, approx 7500 B.C., the Yoldia Sea was sectioned off from the oceans. There are certain indications that the deeper parts of the Ancyluss Sea developed, contained saline water, probably during its entire history (Eriksson 1973).

Via a transitory stage (the Mastogloia Sea, c. 6500-5500 B.C.) the Ancyluss Sea transformed into a new inland sea, the Litorina Sea. The level was at the most about 90-95 m above sea level, northern Uppland still being under water. When the Litorina Sea was at its highest, the straits in the southern Baltic were much wider and deeper than today. The salinity was as a result higher than in the present Baltic.

The present opinion is that around 2000 B.C. the Litorina Sea developed into a brackish sea, the Limnea Sea, which later successively transformed into the present Baltic. It was during the Limnea Sea period that northern Uppland was elevated above sea level. The countryside was then altered by the eroding effect of the waves (abrasion).

The isostatic land uplift, rebound, in northern Uppland today amounts to 5.5 mm/year.

4.2 Description of the study area

4.2.1 Topography

The denomination "Finnsjön area" is slightly incorrect since Lake Finnsjön as such is situated outside the water divide. Topographically, the Finnsjön area is flat (Appendix 3). The western parts are situated at levels higher than 25 m above sea level. The highest parts in the southwest are slightly over 40 m above sea level. The eastern part is mainly situated between 20 and 25 m above sea level. Farthest to the east, the topography is more broken, with a highest point at 36 m above sea level in the northeastern corner.

The run-off area which is of marked northwesterly extension is located on a slope dipping slightly towards the northeast. The low-lying parts of the area are located around its eastern water divide.

4.2.2 Quaternary deposits

The distribution of the different Quaternary deposits within the study area is specified in Appendix 4 and Table 4.2.a.

Table 4.2.a. Estimated areal distribution of different Quaternary deposits in the Finnsjön study area

Deposit	% of the test area
Till	57
Glacifluvial deposits	0,5
Gravel and sand	4
Clay	4,5
Organic deposits	20
(Exposed rock)	(14)

The western part of the area is dominated by exposed rock. Between the outcrops the soil is primarily till and peat. The proportion of till increases in the northern and southern parts of the study area. There are two large peat bogs to the northwest. Under the peat there is generally a thin layer of outwashed material resting on clay. There are only minor areas of the previous deposit without a peat layer on top.

The central part of th study area with its north-northwest oriented valleys is dominated by peat, including the today-drained Lake Tannsjön. Otherwise till and outcrops are of approximately equivalent acreage.

The eastern part of the area is dominated by till. There is also outwashed material to a comparatively great extent, particularly in the eastern parts, where outwashed sand of a thickness of about 2 m covers fairly large areas.

Most of the higher situated parts of the region are constituted of bedrock outcrops. The till in the area is not very thick and generally does not form any independent topographical features.

The till in the Finnsjön area is largely of a sandy-silty type. The clay content is between 1 and 4%. The till has usually a normal boulder content.

Since the entire area is situated below the highest coastline the till is more or less influenced by abrasion. In some places, the till has been abrased to an extent where the surface layers have been transformed into a cobbles.

In the central parts of the area there are some minor deposits of a glacifluvial material.

In major, as well as minor valleys and depressions there is clay, as a rule covered by outwashed sand or organic soils.

Among the clays, the glacial clay is completely dominating. There are distinct annual layers, the clay being calciferous and deposited during the period when the Yoldia Sea covered northern Uppland, i.e. the clay was deposited in salt water.

The thickness of the clay layers is varying. In the minor clay deposits the thickness is in general less than 1-1,5 m, whereas the thickness of the clay in major basins is usually several meters, which is confirmed by soil depth soundings.

4.2.3 Land-use

The Finnsjön area is largely wooded. Earlier, part of the clay acreage and mines were cultivated. On till-covered land the woods are dominated by pine and fir. In the depressions there are usually swampy forests, densely intermixed with deciduous trees. The more elevated parts of the area usually consist of bedrock outcrops where the ground is dry and pine is dominating. Flat lands, even at high altitudes, are water-logged due to insufficient drainage, and consequently swamps or peat bog vegetation is to be found here.

5. GEOLOGY AND TECTONICS

5.1 The geology of northern Uppland

The rock types of northern Uppland are of Sweco-Karelian age and belong to the oldest rock types in Fennoskandia. A majority of the different Sweco-Karelian rock types are represented in northern Uppland. These rock types were formed 1800-2100 million years ago. The oldest parts of these rock types constitute sedimentary and volcanic surface rocks. The dominating rock type is granite gneiss.

The volcanites, which appear as acid as well as intermediary and basic, are inter-stratified with crystalline limestone and weathering sediments.

During the Sweco-Karelian mountain-range folding the oldest sedimentary and volcanic rock types became strongly folded and were at the same time intruded by a series of deep-seated rock including granite as well as gabbro. During a subsequent stage, the above mentioned surface and deep-seated rock types were intruded by a large number of diabase dikes which were later transformed into amphibolites.

During the last phase of the Sweco-Karelian period, the youngest rock types intruded, partly in the form of less coherent granite massifs, partly as pegmatites which penetrate the older bedrock (Anefors and Olkiewicz 1982).

5.2 The tectonics of northern Uppland

5.2.1 General

In the area, a number of large lineaments of regional extent has been identified (see Appendix 5). The lineaments shown on the tectonic map have been identified as tectonic zones. These zones form a backup for a descriptive model used for model calculations of groundwater conditions (Carlson, Winberg and Grudfelt 1983).

The prevailing lineaments have been interpreted from satellite photographs (Landsat) as well as from aerial photographs and topograpical maps. The criteria primarily used in the interpretation are:

- o Topographical altitude differences
- o Rock type differences
- o Soil type differences
- o Biotop differences.

In addition, results of aerial-geophysical investigations earlier performed in parts of northern Uppland have been used. This material has been used as a basis for estimating the length and width of the different lineaments and also the possible water transmitting properties of the zones. Other information on the properties of the lineaments has been collected from rock constructions and mining operations carried out in the region. Supplementary geological information and data on prevailing rock stress conditions have been obtained from investigations made at the Forsmark nuclear power station (Carlsson and Olsson 1977, Carlsson 1979, Stephansson and Carlsson 1976).

5.2.2 Definitions of different tectonic concepts

In the following section, different tectonic concepts are used, which are defined as follows:

- o A fracture is every mechanical discontinuity in the bedrock which can be measured when mapping.

- o A fracture zone is a zone with densely packed parallel or subparallel fractures.

- o A crushed zone is a zone mainly consisting of crushed rock.

- o By a fault is to be understood a fracture or fractured zone where two adjacent parts are dislocated in relation to each other.

- The lineament concept is used according to the interpretation by O'Leary, Friedman and Pohn (1976): "a lineament is a chartable, simple or composite linear formation in a surface. Its parts are oriented in a rectilinear or faintly curved-line relation which deviates markedly from the pattern of surrounding formations and probably reflects a subterranean condition."

5.2.3 Lineaments

The largest lineaments, which are letter-coded in Appendix 5, are, in the interior parts of northern Uppland, mainly of a northerly orientation, whereas the lineaments closer to the Baltic turn somewhat westwards in order to finally run in parallel with the coastline.

Among the largest lineaments of mainly northerly orientation may be mentioned the Tämnarån valley (A), the Dannemora line (B), the Olandsån valley(C), the Edeboviken bay towards Lake Närdingen (D), and the strait between the island of Väddö and the mainland (E).

A number of large lineaments of a westerly orientation are also to be found. These lineaments largely intersect the northerly lineaments at right angles. Among the largest westerly lineaments may be mentioned the lineament beginning in the east at the Norrtälje bay and extending westwards to Rimbo and Östuna (F). At Östuna the lineament is split in two parts of which one leg continues in the original direction towards lake Ekoln and Örsundsbro. The other leg extends from the intersection point at Östuna in a northwesterly direction past Uppsala and thereafter along the Jumkilsån valley.

The next major westerly lineament has its extension between the location of Älmsta and Knutby and there follows lakes Ströjan, Närdingen and Sottern (G).

From Grisslehamn towards Hargshamn and further on towards lake Älgsjön southeast of the Finnsjön study area, there is additionally one major westerly lineament (H).

The most northerly of the major westerly lineaments extends along the Forsmarksån valley (I). The rock inbetween the large system of lineaments is intersected by lineaments of minor magnitude as shown in Appendix 5.

5.2.4 The width of lineaments

The width of the lineaments may vary considerably over comparatively short distances. The lineaments may moreover consist of parallel structures, fracture zones, comprising parts of more competent bedrock as illustrated in Fig 5.2.a. The structures may also be mutually dislocated although the lineaments interpreted as tectonic zones are assumed to be in good hydraulic contact along their extension. The widths of lineaments specified in Appendix 5 indicate a mean width within which a significant increase (more than 100 times) of the hydraulic conductivity in relation to the surrounding rock is presumed.

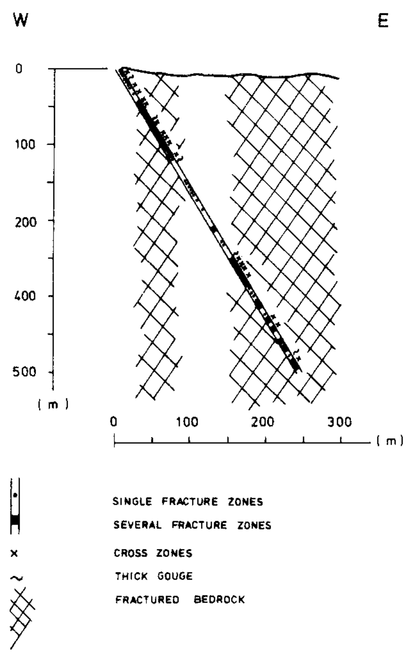


Figure 5.2.a. Core drill hole Fi 8 penetrating two major fracture zones and between these zones a section with a more competent bedrock.

The lineaments in northern Uppland interpreted as tectonic zones have been divided into five classes (I - V) according to magnitude.

- Class I consists of lineaments where the width may vary between 30-300 m, assuming a mean width of some 150 m.
- In Class II the width varies between 20-200 m, the mean width being 100 m.
- Class III varies between 10-100 m and the mean width is specified to be 50 m.
- Class IV varies between 5-50 m, the mean width being 25 m.
- Class V varies between 3-30 m with a mean width of 15 m.

Studies of drill holes penetrating major lineaments and experiences from mines in the region indicate that the major lineaments as a rule are of steep inclination.

The movement direction of the latest inland ice seems to largely have been north to south, judging from the studies carried out in the area. The glacial striae in the area are as a rule oriented N25 - 30E.

Lineaments in parallel with the ice movement direction (north-to-south) have probably been exposed to a more extensive depletion of soil layers as well as crushed materials than in the case of lineaments of an extension perpendicular to the ice movement direction (east-to-west). This means that the northerly lineaments in the region are more topographically distinct than the westerly ones of the same magnitude. This circumstance is, however, included in the determining of classification of different lineaments.

In a flat area such as the northern Uppland peneplain, the extension of the surface water courses is to a high degree influenced by the effects of the latest inland ice. This includes the depletion effect as well as the deposition of loose soil layers. This has entailed a largely north-to-south extension of the water courses in the area which is evident from Appendix 1.

5.3 The geology of the study area

5.3.1 Bedrock mapping

The degree of exposure of the bedrock varies within different parts of the area as indicated by the outcrop markings on the bedrock map. The degree of exposure is throughout comparatively high, primarily in the more elevated parts along the surface water divides.

As a basis for the bedrock geology mapping an outcrop map has been used in scale 1:10,000. The field mapping has constituted notation of rock types, contact conditions, conversion zones, magnetic properties and surface structures. Measurements of foliation and folding axes have also been performed in conjunction with the field study.

For geological testing in laboratory (analyses, thin sections) 50 rock-type samples have been collected. Thin sections have been made of all chemically analysed samples. For quantitative determination of mineral composition, point-counting analyses have been performed.

5.3.2 Rock types

The study area contains most of the rock types represented in the previously described region.

The oldest rock types, which in the area are constituted of volcanic surface rocks dominated by leptite, are to be found in the north and south of the area (see Appendix 6).

Greenstones are found in the northern part of the area, south of the leptite series. Between the greenstones in the north and the leptites in the south the bedrock is made up of granite gneiss. The western parts of the study area exclusively consist of greenstones and granite gneiss. These rock types are of approximately the same age.

In the south, the granite gneiss is bounded off by the leptite whereas its west boundary extends out into Lake Finnsjön. The youngest rock type in the area is the younger granite which is to be found in the central and the eastern parts of the area.

The younger granite which intruded during the late Sweco-Karelian period (1800-2100 mill. years) extends outside the eastern boundaries of the study area. Its western boundary is, as already mentioned, made up of granite gneiss of a higher age.

All core drill holes in the area are drilled in the granite gneiss (Fi 1 - Fi 8). Some of the drill holes (Fi 3, Fi 5 and Fi 8) penetrate younger granite at depth.

5.3.3 Fracture frequency in the bedrocks

The fracture frequency in the study area as determined on exposed bedrock is on the average 3.0 fractures per meter. In Table 5.3.a the fracture frequency is indicated for existing rock types in the study area, as well as for other study areas in Sweden.

The core drill holes (Fi 1-8) have been made in order to provide information on tectonic zones as well as on the rock mass in between. The results relating to fracture frequency, proportion of crushed zones, etc. are presented in Table 5.3.b. The fracture frequency distribution is detailed in Fig. 5.3.a and b.

Table 5.3.a. Fracture frequency in different rock types in four investigated areas in Sweden measured on outcrops (after Ahlbom 1980)

Area	Rock type	Fracture frequency fractures/m		Standard deviation	Number of localities
Finnsjön	granite gneiss	2.9		1.1	45
	younger granite	2.7		1.0	14
	greenstones	4.0		1.7	9
Average			3.0	1.2	68
Sternö	gneisses	1.1		0.4	7
	granite gneiss	0.8		0.4	13
	granite	0.9		0.2	5
Average			0.9	0.4	25
Kråkemåla	granite		1.4	0.9	43
Kynnefjäll	veined gneiss	1.5		0.6	25
	granite gneiss	1.2		0.6	12
Average			1.4	0.6	38

Table 5.3.b. Data on fracture frequency (fractures/m), proportion of crushed and fractured zones in the cores drill holes in the Finnsjön study area.

	Fi 1	Fi 2	Fi 3	Fi 4	Fi 5	Fi 6	Fi 7	Fi 8
Borehole angle	90	50	50	80	50	90	85	60
% crushed zones	4.5	5.0	1.2	2.0	5.2	1.1	1.5	5.3
% fractured zones	3.2	4.2	20.0	9.9	8.4	5.7	2.6	17.0
fracture frequency	2.0	2.7	4.4	2.7	3.3	2.5	1.5	5.1

Fig. 5.3. a

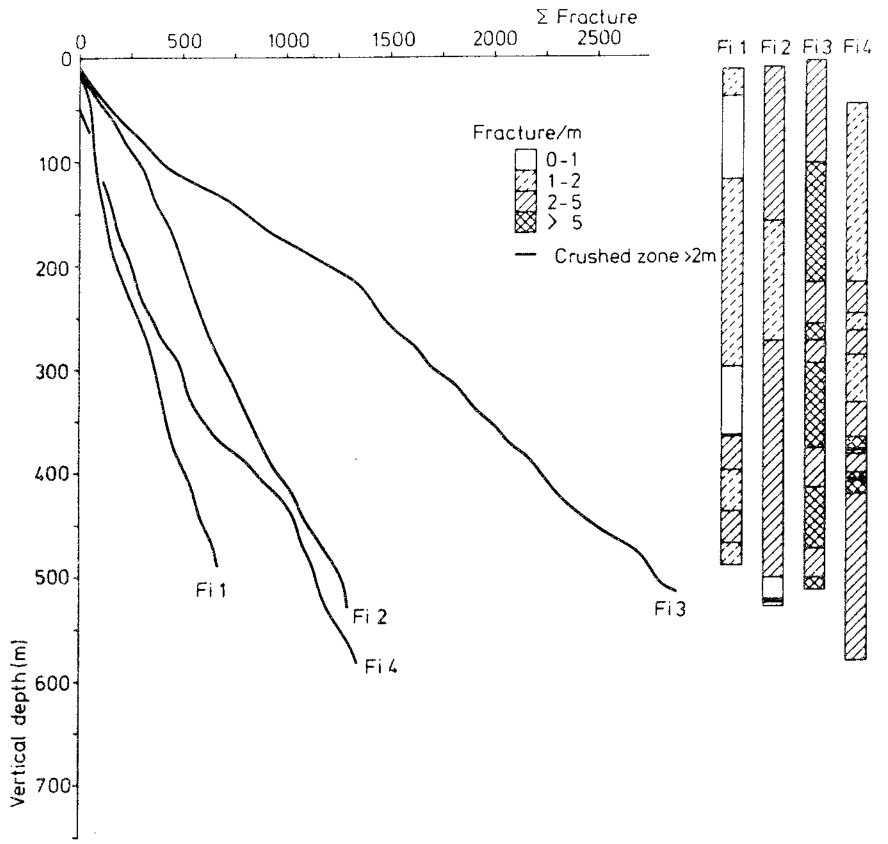
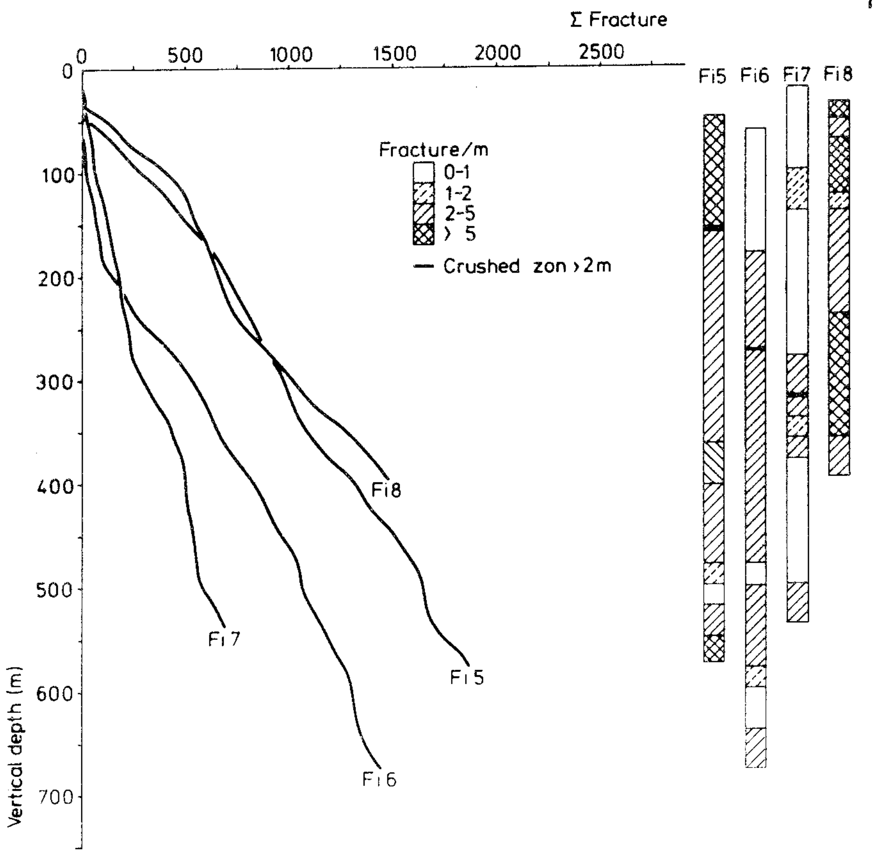


Fig. 5.3. b



Figures 5.3.a and 5.3.b. Fracture frequency versus depth for drill hole Fi 1, Fi 2, Fi 3 and Fi 4 (Fig 5.3.a) and for drill hole Fi 5, Fi 6, Fi 7 and Fi 8 (Fig 5.3.b).

The eight core drill holes in the study area have an average fracture frequency of 2.9 fractures/m (including fracture zones). The variation in the fracture frequency of the rock mass (excluding fracture zones) with depth is illustrated in Fig 5.3.c. On the average, the fracture frequency excluding fracture zones is 2.5 fractures/m. No decrease in the fracture frequency with depth (0-600 m) has been observed.

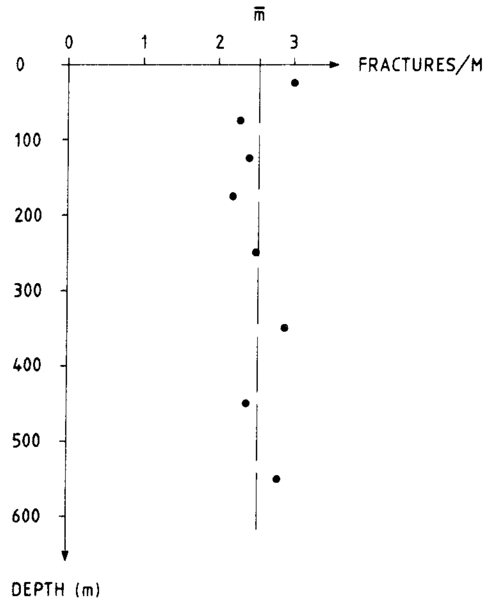


Figure 5.3.c. The average fracture frequency versus depth for all drill holes in the Finnsjön study area when fracture zones are excluded ($\bar{m}$=2.5 fractures/meter).

5.4 Tectonics in the region

5.4.1 General

The areal extension of the regional area is shown in Appendix 1 and 3.

The major regional lineaments have been identified and delimited from satellite and aerial photographs. The minor zones in the area have been mapped from the aerial photographs, the special topographical map constructed, the Quaternary map, the geophysical ground measurements and observations in the field. Data have, moreover, been obtained from the core mapping as well as from the drill hole geophysics and the hydraulic tests of two of the core drill holes (Fi 5, Fi 8) both of which penetrate two medium-sized local lineaments.

5.4.2 Lineaments

Lineaments in the regional area are indicated in Appendix 7.

The overall pattern of the tectonic zones in northern Uppland is recurrent also in the regional area. The majority of the lineaments extend north to south. However, in the western parts of the area, the lineaments are transitioned towards a more northwesterly orientation.

The eastern boundary of the area follows the major regional lineament along its extension from Uppsala to lake Södra Åsjön in the northeastern corner of the area (marked B in Appendix 7).

Another major lineament in the area is the lineament transversing the lake system Ensjön, Åkerbysjön, Lissvass and Finnsjön. The lineament leaves the Finnsjön basin at Källviken bay and extends from there in an east to southeasterly direction on towards lake Älgsjön (a).

A lineament extends, moreover, from lake Älgsjön in the south towards lake Tannsjön and on in a northwesterly orientation along the extension of the Tannsjöbäcken stream in the Gåvastbomossen valley (b). To the west of this zone runs the Gåvastbo fault (c). The Brändan zone which intersects the Gåvastbo fault immediately northeast of drill holes Fi 5 and Fi 6 has a south to southwest extension down towards Lake Finnsjön where the lineament is transitioned towards a north-to-south extension (d). In the northern part of the area a westerly lineament runs from lake Södra Åsjön through the Frebbenbo bog towards Giboda, there transitioned towards a more northwesterly extension north of Road 76 (e).

5.4.3 The width of lineaments

The width of the lineaments has been appraised setting out from the same background information as applied to northern Uppland (see section 5.2.4). All lineaments are of such magnitude that they can be observed in the field.

Lineament classification is specified in Appendix 7.

6. HYDROMETEOROLOGY - WATER BALANCE

6.1 General

Within a specific area two main types of water balances may in principle be studied:

- o general water balance
- o groundwater balance.

The first of the above mentioned types generally relates to water above the ground surface, i.e. surface water conditions. The most important hydrometeorological parameters are in this context:

- o precipitation
- o evaporation
- o run-off
- o change in water storage

In groundwater balance studies, the water conditions in the groundwater system are taken into account. The most important parameters in this context are

- o groundwater recharge
- o groundwater discharge
- o groundwater flow

The two types of water balance may be treated separately, or jointly. Studies of general water balance in an area are based on data from long measurement series, as a rule longer than ten years. During such a long period of time, changes in water storage are assumed to be negligible.

Studies of groundwater balance comprising the above mentioned parameters require access to more or less detailed data on groundwater level changes, run-off and the variations in precipitation and evaporation during the period of time concerned. Basic data required is also information on different hydraulic units in the groundwater system and the hydraulic properties of the units. Appraisals and calculations of groundwater balance should preferably be performed using numeric model techniques.

6.2 Precipitation

The precipitation in northern Uppland has been measured at 17 stations located within a radius of 80 km from the Finnsjön area. Within this area the precipitation is measured on a weekly basis at eleven stations since 1979. The precipitation measurements are accumulating, and the spread of measurement points corresponds to one point per 2.5 km^2. Fig 6.2.a shows the distribution of the stations in relation to the hypsographical curve of the area.

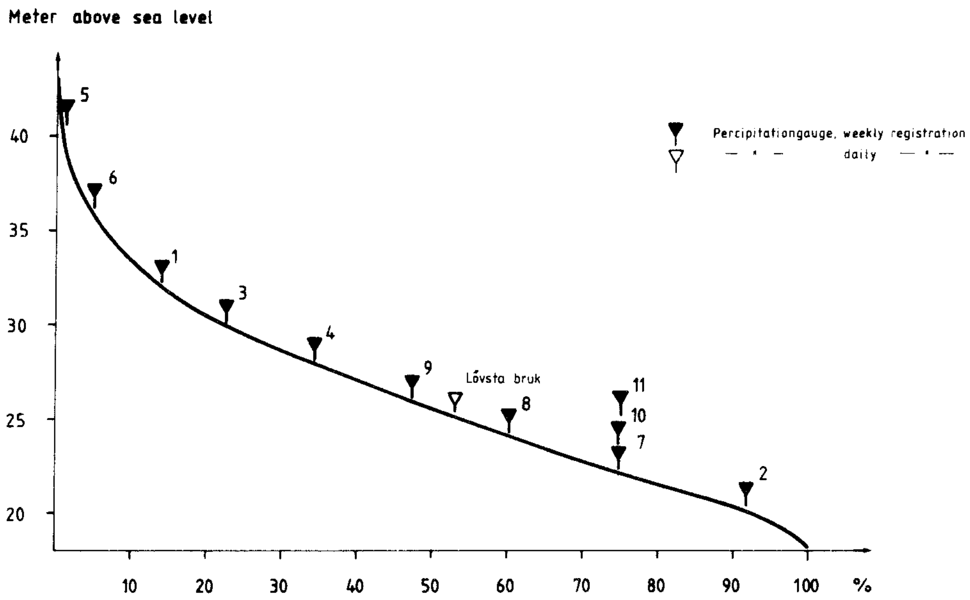


Figure 6.2.a. The distribution of the precipitation stations in relation to the hypsographical curve in the Finnsjön area.

The precipitation values measured have been corrected for i.a. evaporation, wind and wetting of the precipitation instrument (Eriksson 1980 a and b). The mean precipitation in the Finnsjön area is 670 mm/year.

The distribution in space of the annual precipitation varies from 640 mm in the eastern part to 760 mm in the northwestern part of the area (adjusted precipitation).

The precipitation generally falls in the form of snow in northern Uppland from the middle of November to the middle of April. The percentage of snow is about 35% of the annual mean precipitation.

The durability of the snow cover varies considerably between different years. In general, the durability of the snow cover is about 110 days.

6.3 Evaporation

The annual mean temperature in northern Uppland is about +5.5°C. The temperature is below 0°C for almost five months of the year. Both the potential and the actual evaporation vary substantially during the year. In Table 6.3.a values are specified for the evaporation in northern Uppland.

Table 6.3.a Annual potential and actual evaporation in northern Uppland

Evaporation from	Evaporation mm/year
Water surface	755
Vegetative surface, potential	540
Vegetative surface, actual (recharge area)	380

By the potential evaporation is to be understood the volume of water consumed in plant transpiration and evaporation from the plant community under ample growth and under conditions of optimum access to water in the root zone.

By actual evaporation is to be understood the volume of water consumed in plant transpiration and evaporation from an actual plant community with actual access to water in the root zone.

6.4 Run-off

The run-off from northern Uppland has been measured at three stations. At one of these, the river Tämnarån, the annual mean discharge measured was 240 mm. The duration of the discharge measured was 240 mm. The duration of the discharge in Tämnarån is indicated in Fig 6.4.a and Table 6.4.a. In the study area, water discharge measurements have been made in the two main streams, referred to as Ao and Bo, at the confluence point at the boundary of the run-off area.

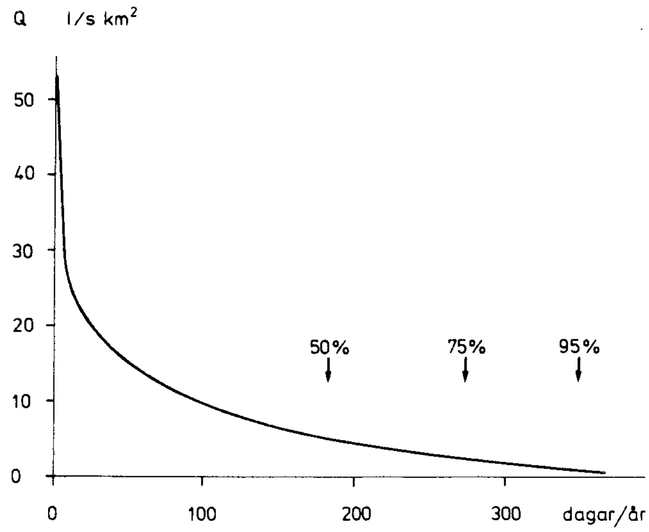


Figure 6.4.a. Duration curve for the discharge of the river Tämnarån in northern Uppland.

Water discharge measurements have also been carried out in a small stream in a subsidiary run-off area named Kvarnbo. Table 6.4.b specifies data for some of the run-off stations in the region and in the study area. In Table 6.4.c run-off data are specified for the Finnsjön area during 1981.

Table 6.4.a Water discharge data and duration for the river Tämnarån at the Näs run-off station (16 m.a.s.l.) 1925 - 1970

	maximum		mean		minimum			duration			
	high	mean	high	mean	low	mean	low	1%	50%	75%	95%
m^3/s	103	46	17.4	9.0	3.6	1.4	0.12	43	5.8	2.8	1.2
$l/s.km^2$	88	39	14.8	7.6	3.1	1.2	0.10	37	4.9	2.4	1.0
mm/yr	2772	1229	466	239	98	38	3	1166	154	76	32

Table 6.4.b Stations and areas of run-off measurements in northern Uppland

River	Station	Run-off area (km^2)	% Lakes	Measured period
Tämnarån	Näs	2276	4.2	1925-1970
Forsmarksån	Bruksdammen	302	6.9	1973-1979
Tannsjöbäcken	Ao	16.7	5	1979-
Kvarnbobäcken	Kvarnbo	3.6	0	1981-

Table 6.4.c. Monthly water run-off during 1981 from two stations in the Finnsjö study area

Station	Run-off area km^2	Run-off in mm J	F	M	A	M	J	J	A	S	O
Ao	16.7			22	125	34	30	10	74	33	30
Kvarnbo	3.6	37	25	4	118	33	37	5	88	17	33

6.5 Water balance

The following data and estimates have been used in an overall water balance for northern Uppland.

- o Precipitation data from Lövsta, adjusted for evaporation, wetting and wind losses according to Eriksson (1980).
- o Potential evaporation from Uppsala aaccording to Eriksson (1980).
- o Actual evaporation estimated according to modified Budykov method.
- o Run-off data from Tämnarån.

The adjusted mean precipitation is 670 mm, corresponding to an actual evporation of 380 mm per annum.

Long-term mean values on precipitation, evaporation and run-off enable the computation of the proportion of groundwater discharge areas in the region concerned. Within the discharge areas, which as a rule are continually supplied with water, the evaporation may be assumed to be potential evaporation. Utilizing the data given in Table 6.5.a the areal proportion of discharge areas can be estimated at about 30%.

Table 6.5.a. Gross water budget for northern Uppland in mm water per year (long-term).

Precipitation	670
Potential evaporation	540
Actual evaporation	380
Run-off	240

6.6 Groundwater recharge

The groundwater recharge in an area can generally be determined on the basis of

- o data on the groundwater level variation
- o hydrometeorological data
- o hydraulic model calculations
- o chemistry and isotope investigations
- o tracer tests
- o direct measurement of percolating water.

Observations of the groundwater level variations in the Quaternary deposits have been used for calculating the groundwater recharge. This requires a knowledge of the effective porosity of the soil concerned.

By studying the water balance during short periods of time, i.e. in connection with major rainfalls or dry periods of longer duration, the effective porosity has been determined. For this purpose data have been used from the Finnsjön area for 1979-80, the result indicating an effective porosity of 0.04. This value corresponds to a mean groundwater recharge of c. 180 mm annually to the soil layers. The portion of this water volume which penetrates farther down into the bedrock remains to be studied, e.g. by comparison of groundwater level variations in soil and rock.

6.7 Estimated groundwater balance

The precipitation during the period November 15th to April 15th is assumed to come down as snow or to be accumulated in snow cover. A portion of this accumulated snow probably runs off directly as surface water in conjunction with the snow melting. This volume may roughly be estimated as follows:

$$R = i \times (G + S) + u\ (P_k - E_p)$$

where R = run-off
G = groundwater recharge within the recharge areas
S = run-off in connection with snow melting
P_k = adjusted annual mean precipitation
E_p = potential evaporation
i = percentage recharge areas
u = percentage discharge areas

The estimates are based on data in Table 6.5.a and the above specified data indicate that about 105 mm of the snow runs off directly as surface water in conjunction with the snow melting, i.e., c. 45% of the snow. This is valid within the recharge areas. Within the discharge areas the presumption is that all the melted snow runs off as surface water. Table 6.7.a summarizes the results with regards to water balance and groundwater recharge.

Table 6.7.a Summary of water balance and estimated groundwater recharge in mm of water per year (long-term)

Precipitation	P	670
Run-off	R	240
In discharge areas (30%)		
Evaporation	E_D	540
Groundwater recharge		-
Groundwater discharge	G_P	420
Available run-off precipitation	R_P	130
In recharge areas (70%)		
Evaporation	E_R	380
Groundwater recharge	G_R	180
Groundwater discharge		-
Snowmelting run-off water	R_S	105

It should be emphasized that the calculated groundwater balance illustrates the conditions within the upper part of the groundwater system of a certain area. The estimated values are moreover based on soil layer data and the conditions in the upper parts of the bedrock may be deviating. Fig 6.7.a specifies the estimated water balance values.

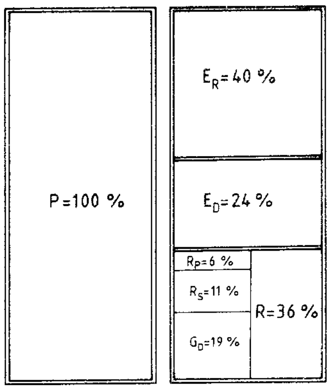


Figure 6.7.a. Illustration of the calculated groundwater balance in the Finnsjön test area (Legend as in Table 6.7.a).

7. HYDROLOGY

7.1 Water courses

7.1.1 The water courses of northern Uppland

Northern Uppland with surrounding areas is drained into the Bottenhavet, part of the Baltic, primarily by the rivers Dalälven, Tämnarån, Forsmarksån and Olandsån. Towards the south the area is drained into the lake Mälaren system via the river Örsundaån and Fyrisån, see Appendix 1.

The river Tämnarån, Forsmarksån and Olandsån all follow northerly lineaments in their main extension. This direction of flow transverses the overall inclination of the land surface in the area. The river Forsmarksån, however, changes its flow in its lower parts towards an east-westerly direction following a large, intersecting lineament, the so-called Forsmark-Granö line.

Since the topography is very flat, the depletion effect of the last inland ice on lineaments in the directional movement of the ice seems to have formed today's flow routes for the above mentioned water courses. This effect is also obvious when considering the form and extension of the lakes in northern Uppland, examples of which are lakes Strömmaren, Finnsjön, Dannemorasjön, Vällen, and Gisslaren (see Appendix 1).

7.1.2 The water courses in the Finnsjön study area

The Finnsjön area is drained via two separate water course systems which flow together northeast at the point from where the surface water divide of the run-off area sets out, see Fig 2.a.

One of the drainage systems, referred to as the A system, drains the central and southern parts of the area and constitutes about 2/3 of the area (16.7 km^2). The water courses in this area are in their major part constituted of dug and open drainage trenches. In the southwestern part, where the terrain is most hilly and the channels of the water courses are badly developed, there is an abundance of more or less coherent water-logged areas in local low-level points in the terrain. The only free water surface in the Finnsjön area is located in this drainage area, viz. the choked-up and subsequently ditched-out lake Tannsjön.

The second drainage system, the B system, drains the north-western parts of the study area and comprises 8.6 km^2 (1/3 of the area). The water courses of the B system mainly consists of dug trenches. The area is much flatter than the A area, the soil cover thinner and outcrops are more prevalent. To the west the area has a plateau character with a mosaic-type surface of exposed bedrock, bogs and till-filled depressions. In this part of the area, the water course network is very diffuse.

7.2 Water-logged grounds

Northern Uppland belongs, with regard to soil types, to a till area characterized in its northwestern part of about 35% mire and 45% till (Lundqvist 1958). The proportion of mires decreases towards the south and east. To the west of Lake Finnsjön, there is the mire complex Frororna of an approx 50 km^2 acreage. The mires are of choked-up type, i.e. they have developed from lakes.

Within the Finnsjön study area, 20% is mires (5 km^2). Of this approx 3 km^2 is swamp and 2 km^2 bog. In the northern and western parts there are mainly bogs whereas the swamps are most prevalent in the southern and eastern parts. Bogs are primarily to be found in recharge areas whereas the swamps mostly are located in low-lying parts of the area where the more nutritious groundwater is flowing out.

With the exception of a couple of large bog systems the bogs are uniformly distributed. The swampland is on the other hand dominated by two major units, the drained lake Tannsjön and the similarly drained, elongated Gåvastbo bog.

7.3 Lakes

The major lakes in the northern part of Uppland are given in Table 7.3.a. The location of the lakes is indicated in Appendix 1.

Within the Finnsjön study area there is a (nowadays) drained lake, Tannsjön. Its area is, as a free water surface, 0.01 km^2. Before being lowered, its surface was about 0.4 km^2.

To the west of the study area is Lake Finnsjön which has given the name to the district. The lake belongs to the run-off area of the river Forsmarksån. The surface area of lake Finnsjön is 4.3 km^2, and the size of the catchment area is 93 km^2 at the inlet and 117 km^2 at the outlet. Lake Finnsjön is long and narrow with a north-south extension, its length 6.5 km and the width 1 km. The maximum depth is 4.1 meter (see Fig 7.3.a) and the faintly indicated elongated bottom depression is displaced towards the western shore of the lake's northern part and towards its eastern shore in the south part.

The water in the lake is brownish in colour due to dissolved iron and humus substances. The pH-value of the lake's water varies between 6.95 - 7.10 and the content of organic substances is high which is in accordance with the high consumption of potassium permanganate (100 mg/l). The concentration of other dissolved substances is comparatively low which is indicated by the low specific conductance (85 uS/cm).

Table 7.3.a Major lakes in the northern part of Uppland

Name	Lake surface area (km^2)
Tömnarån + Storsjön	39.4
Erken	24.9
Vällen	10.9
Vendelsjön	5.6
Giningen	6.1
Närdingen	5.6
Strömaren	4.8
Finnsjön	4.3

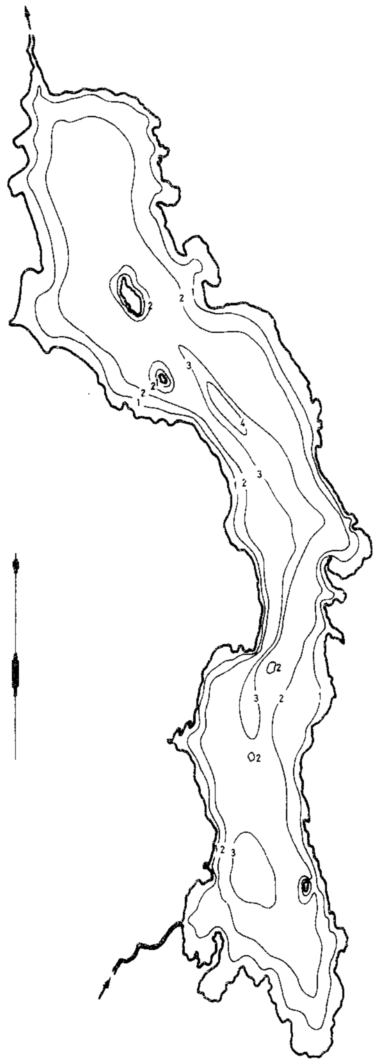


Figure 7.3.a Depths of the lake Finnsjön (meter).

7.4 Drainage and lake conservance projects

Two major drainage projects have been carried out in the study area. One is the draining of the Gåvastbo bog, see Appendix 4, which was, according to information, carried out in the middle of the 19th century. This ditch system is probably the same which still today is draining the Gåvastbo bog.

The second drainage project is the lake Tannsjön lowering project of 1938. The purpose of the project was to drain the land areas around the increasingly more choked-up Tannsjön lake in the central part of the study area. When the lake lowering project was carried out in 1941, the draining of lake Tannsjön was connected to the draining ditch across the Gåvastbo bog. This meant that the Tannsjön lake had its drainage changed from an easterly to a northerly direction.

8. GROUNDWATER CONDITIONS

8.1 Groundwater head and piezometry

8.1.1 General

The Finnsjön study area is like the surrounding region very flat. This, in combination with a humid climate which entails ample access to groundwater recharging precipitation, implies that the depth down to the groundwater table in the area is small. This also means that the hydraulic gradient in the area generally is small.

The general rule apples that the groundwater table largely is conformal with the ground surface. In the low-lying parts of the study area, the groundwater head is in general at, or slightly above, the ground surface. These parts constitute discharge areas for groundwater and as a rule coincide with tectonic lineaments in the underlying bedrock.

The more elevated parts of the area usually constitute recharge areas for groundwater and the general depth down to the groundwater table is greater here than in the case of the discharge areas.

In the recharge areas there is a downward oriented gradient for the groundwater, whereas an upward oriented gradient characterizes the discharge areas.

8.1.2 Groundwater head

A map indicating the head of the groundwater in the regional area (110 km^2) has been made, based on groundwater level observations in springs, lakes, streams, water-logged grounds, percussion drill holes and core drill holes.

Fig 8.1.a indicates the levels of the groundwater table in the upper part of the bedrock, presuming that the lowest parts of the area are discharge areas for groundwater, i.e. the head of the groundwater coincides with the ground surface.

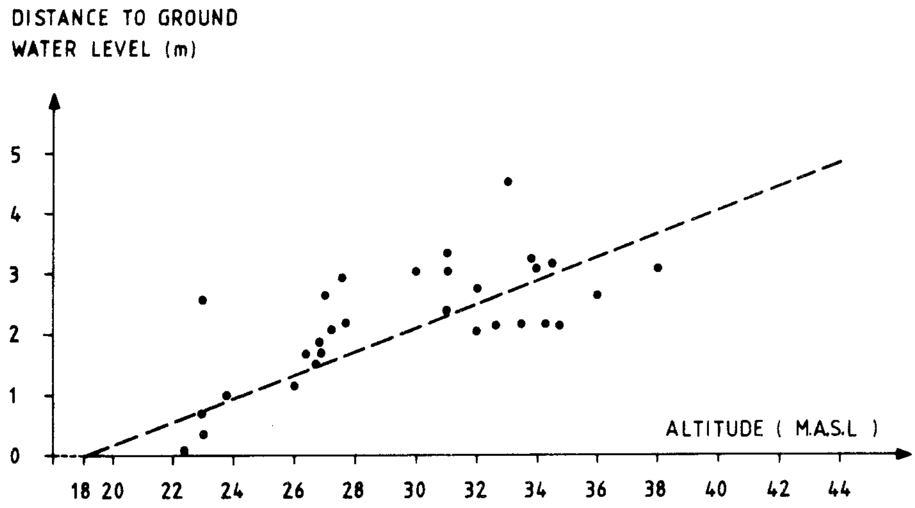


Figure 8.1.a. Relation between altitude and observed depths to the groundwater table in the bedrock within the Finnsjön test area

From Fig 8.1.a it is evident that the depth to the groundwater table is about 2 meters in the altitude interval around 30 meters, whereas the depth to the groundwater table in areas at altitudes of 40 meters above sea level should be approx 4 meters. This is assumed to apply to an ideal profile through the study area. Basic to Fig 8.1.a is in this case data from 36 groundwater level observation points within the area.

In reality, local depressions in the terrain may constitute local discharge areas. The groundwater level coincides with the levels of lakes, water-logged grounds, streams and springs. These parts have been regarded as discharge areas only on the precondition that they have levels 28 m above sea level or less. Higher levels in the water-logged grounds, etc., have been regarded as reflecting local groundwater or surface water occurrences separated from the large-scale circulating groundwater, e.g. by sealing sediments. By means of efficient drainage, however, the groundwater head can be kept down over extensive areas also in natural discharge areas.

Appendix 8 shows a map of the groundwater levels. The map is characterized by profiles being drawn between distinct high points in the area. Along the profiles the above mentioned information on natural discharge areas has been noted, while the conditions in the recharge areas, being based on the groundwater level observations, are illustrated in Fig 8.1.a.

The information utilized for the construction of the groundwater level map, Appendix 8, over the regional sector, is not distributed over the entire area in a representative way.

Data from the central parts of the 110 km^2 area mapped have been used as basic information also for determining the conditions in the more peripheral parts of the area. The fact that the regional area borders in all directions to constant groundwater levels (lakes and streams) means that the groundwater level data along the boundaries of the area can be regarded as correct. The groundwater levels are to be regarded as normal annual mean values.

The variations in groundwater head with depth and time have been continuously monitored in areas regarded as recharge and discharge areas, respectively. These recordings have been made simultaneously at different depths below the groundwater table.

The results indicate that the above presumed gradient conditions in the recharge and discharge areas, respectively, apply. Furthermore, the results indicate distinct reactions to individual precipitation occasions and differences in atmospheric pressure in the various hydraulic zones down to a depth of 100 m (max. depth for measurement).

8.2 Hydraulic conductivity

8.2.1 Measurement method

The hydraulic conductivity of the bedrock has been determined by means of water injection tests. These have comprised both double and single packer tests. In the latter tests the tested section is made up of the drill hole between the bottom and the packer. The measurements made are described by Hult et al. (1978) and Carsson et al. (1980).

The hydraulic conductivity has been caluclated from the obtained measurement data under assumed stationary conditions. The so-called Banks formula has been utilized in this context.

8.2.2 Results

The results of the hydraulic tests performed have been presented by Hult et al. (1978) and Carlsson et al. (1980). The values obtained are discussed and compared with the corresponding values from Sternö by Almén et al. (1980).

Fig 8.2.a shows hydraulic conductivity values measured in drill holes Fi 1-6.

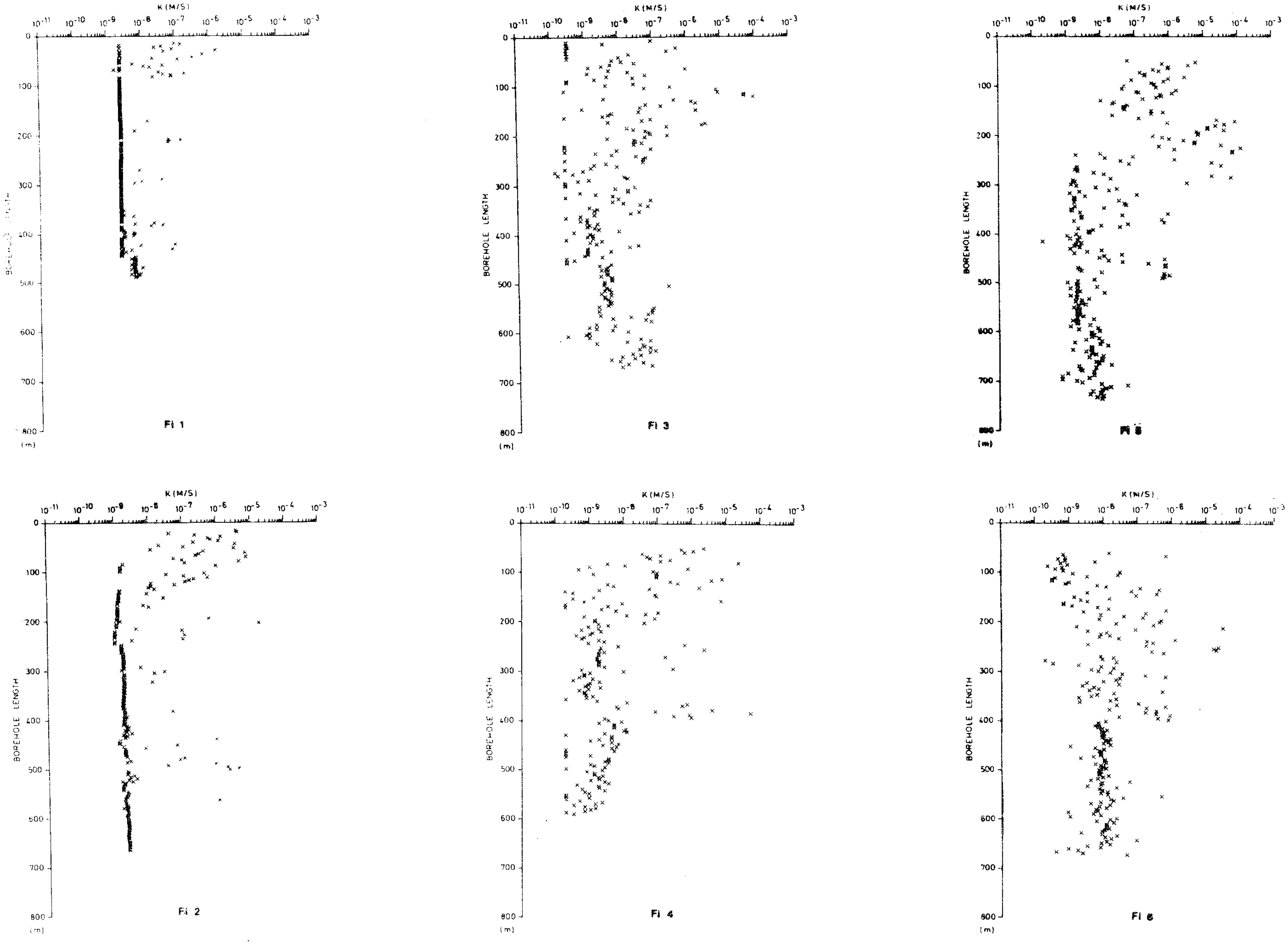


Figure 8.2.a Hydraulic conductivity versus depth in the drill holes Fi 1, Fi 2, Fi 3, Fi 4, Fi 5 and Fi 6.

8.2.3 Data processing

The ability of crystalline bedrock to conduct water depends on its fracture frequency and the fracture apertures. The hydraulic conductivity of individual fractures is generally described using Navier-Stokes equation for flow between parallel plates, referred to as Poiseuille flow. Fractures in rock, however, have uneven surfaces and varying apertures. The fact that fractures in bedrock under pressure are permeable means that the fracture surfaces are in contact at several points.

Bedrock, being such a heterogenous hydraulic medium, exhibits variations in porosity, hydraulic conductivity and specific storage coefficient (Dagan 1979). The detailed spatial distribution of these properties cannot be unambiguously defined. Instead, the bedrock is subdivided into different hydraulic units attributed the above mentioned properties in the form of stochastic variables with a frequency function given by measurement data. This means that defined hydraulic units are regarded as statistically homogenous.

The measurement values of hydraulic conductivity have been divided into two different groups according to the results of the core mapping, viz.:

1. Rock mass without fracture zones of well-defined extension.

2. Fracture zones of well-defined extension.

The hydraulic conductivity in major, statistically homogenous porous formations indicates logarithmic normal distribution (Freeze 1975). The different hydraulic units may be characterized by an effective hydraulic conductivity based on the obtained measurement values and their frequency function (Warren and Root 1961). Dagan (1979) has demonstrated that the effective hydraulic conductivity K(e) of a logarithmic normal distribution can be expressed as:

$$K(e) = K(g)\ (1 + (0.5 - 1/p)\ s^2) \qquad (8.2)$$

where K(g) = geometric mean value

p = 1, 2 or 3 depending if the flow conditions are 1-, 2- or 3-dimensional

s = the standard deviation of ln (K)

Drill holes Fi 1, 2, 4, 6, and 7 are judged as best representing the rock mass and existing fracture zones in the Finnsjön area. Data from these drill holes are thus basic to all computed results relating to effective hydraulic conductivity or mean values in the Finnsjön area.

The hydraulic conductivity within the individual hydraulic units has been assumed to be of statistical logarithmic normal distribution. In order to test this, the measurement values obtained in the rock mass have been divided into 100 m intervals with regard to vertical depth, the frequency distribution of the measurement values having been drawn in a logarithmic normal diagram as in Fig 8.2.b. In the figure, the calculated geometric and arithmetic mean values are specified. Table 8.2.a gives the calculated hydraulic conductivities within 100 m vertical intervals in the rock mass at Finnsjön.

The hydraulic conductivity is i.a. depending on the rock stress conditions in the bedrock. A decreasing conductivity with the depth may thus generally be expected. The histogram in Fig 8.2.c indicates the frequency of different K-values within calculated 100 m intervals. This figure like Fig 8.2.b indicates that there is a general decrease in hydraulic conductivity with depth.

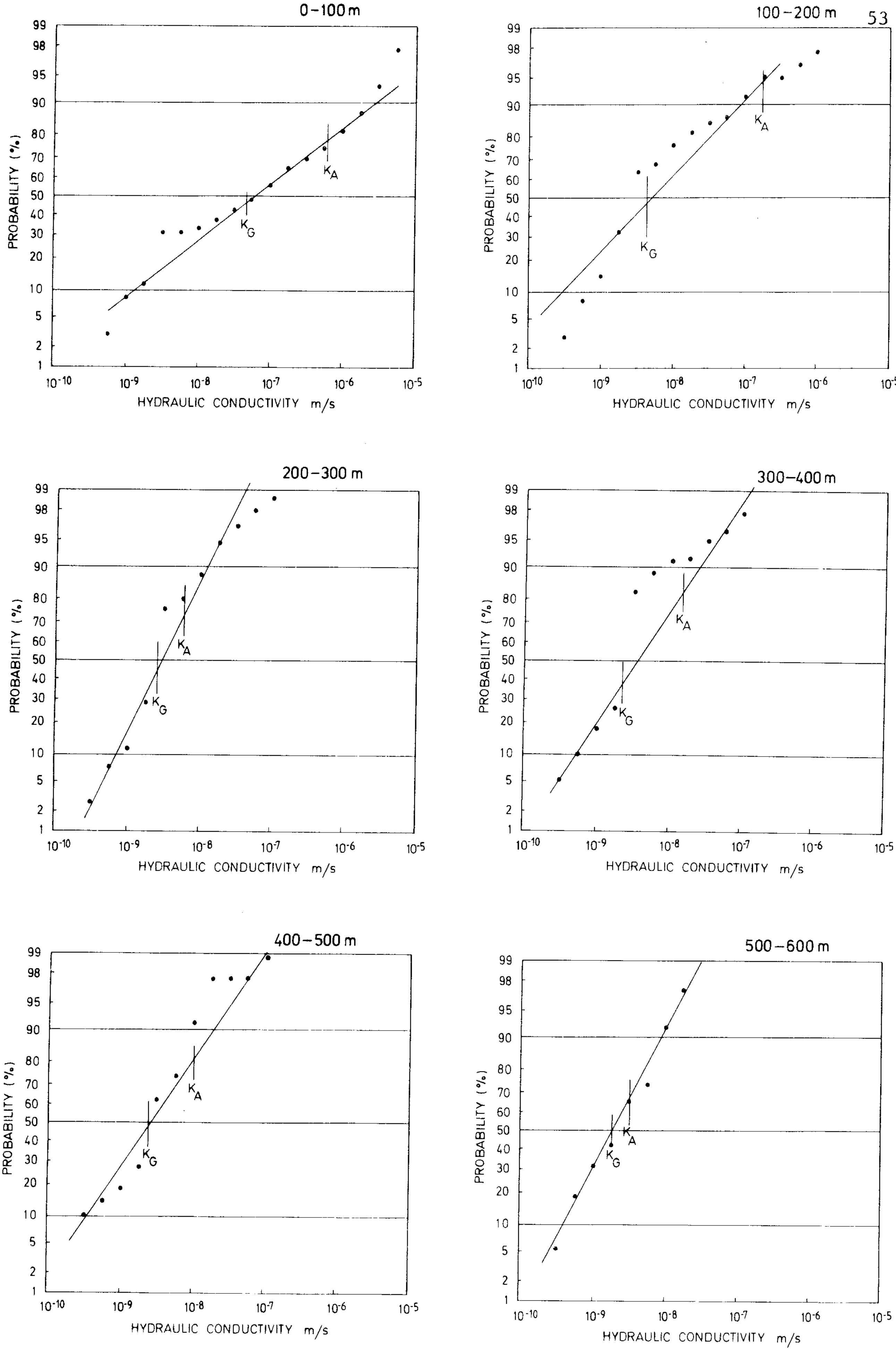


Figure 8.2.b. Frequency distribution of hydraulic conductivity in lognormal diagrams. Values within different 100 m sections from the drill holes Fi 1, 2, 4, 6, and 7.

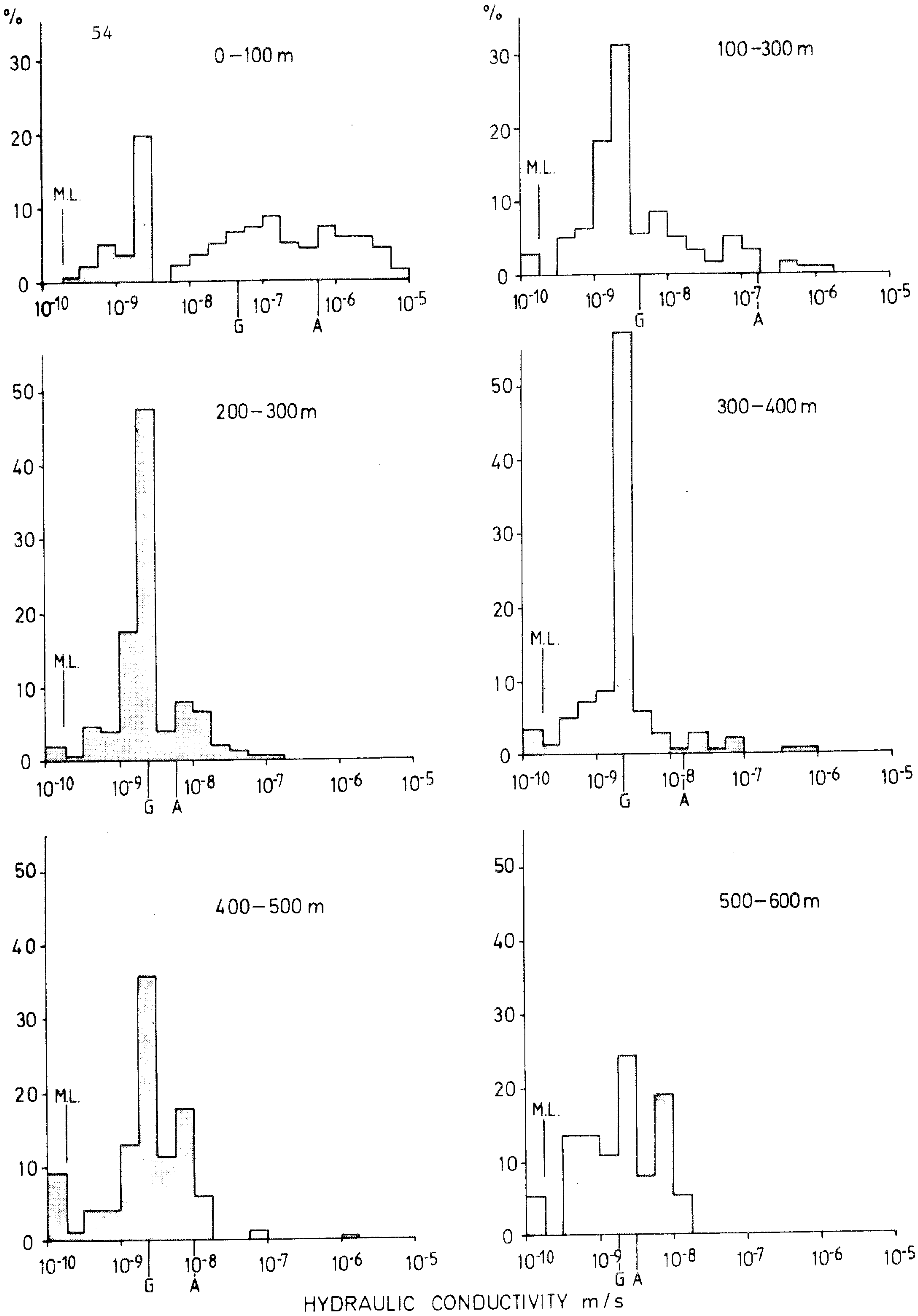


Figure 8.2.c. Frequency distribution of hydraulic conductivity. Values within different 100 m sections from drill holes Fi 1, 2, 4, 6, and 7.

Based on all data obtained from the drill holes referred to, a regression relationship between depth and K-value has been obtained for the rock mass K(b) and fracture zones K(s), respectively, according to:

$$K(b) = c\ 4.90\ 10^{-6}\ z^{-1.30} \qquad (8.3)$$

$$K(s) = c\ 5.06\ 10^{-3}\ z^{-2.15} \qquad (8.4)$$

where c is a correlation factor depending on the assumed flow conditions, c = 1 for 2-dimensional flow in fracture zones and c = 1.52 for 3-dimensional flow in the rock mass, and z = vertical depth. Table 8.2.b contains additional statistical data obtained from the regression analysis. Fig 8.2.d presents the obtained relationships and also specifies a 95% confidence interval for the curves.

Table 8.2.a. Calculated arithmetic, geometric and harmonic means of the hydraulic conductivity of the rock mass at Finnsjön. Data from drill holes Fi 1, 2, 4, 6, and 7.

Depth interval	Harmonic mean m/s	Geometric mean m/s	Arithmetic mean m/s	No. of data
0-100	$3.6\ 10^{-9}$	$4.6\ 10^{-8}$	$6.1\ 10^{-7}$	136
100-200	$1.5\ 10^{-9}$	$4.3\ 10^{-9}$	$1.7\ 10^{-7}$	176
200-300	$1.5\ 10^{-9}$	$2.5\ 10^{-9}$	$5.8\ 10^{-6}$	149
300-400	$1.2\ 10^{-9}$	$2.2\ 10^{-9}$	$1.5\ 10^{-8}$	138
400-500	$1.0\ 10^{-9}$	$2.3\ 10^{-9}$	$1.0\ 10^{-8}$	168
500-600	$9.4\ 10^{-10}$	$1.8\ 10^{-9}$	$3.2\ 10^{-9}$	37

Table 8.2.b. Statistical data from regression analysis of hydraulic conductivity versus depth (drill holes Fi 1, 2, 4, 6, and 7).

Hydraulic unit	Amount of data	Standard deviation	Regression r^2 coefficient
Rock mass	817	1.77	0.25
Fracture zones	206	2.67	0.13

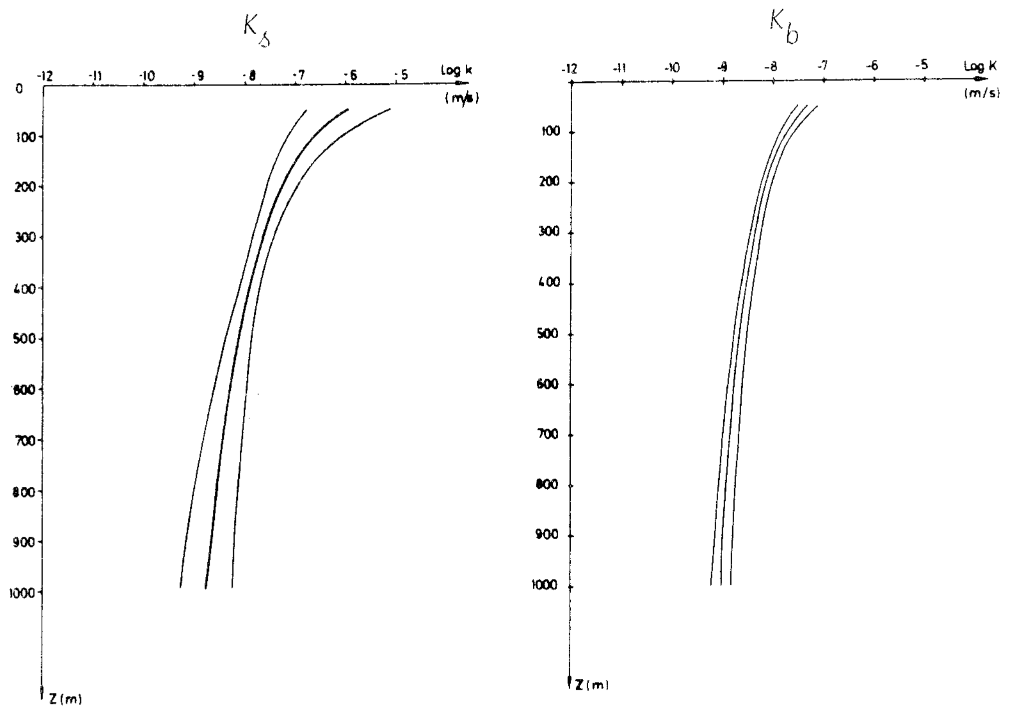


Figure 8.2.d. Hydraulic conductivity versus depth from regression analysis for different hydraulic units.
K_b = Hydraulic conductivity in the rock mass
K_s = Hydraulic conductivity in the fracture zones

8.3 Porosity and dispersivity

The porosity of the bedrock has been studied in connection with resistivity measurements on drill core samples and in drill holes. Data on porosity and dispersivity have moreover been obtained from tracer tests performed in the Finnsjön area.

The kinematic porosity, calculated on the basis of results from the tracer tests, is 8-9 x 10^{-4} in the upper parts of the bedrock. The dispersivity has, on the basis of the tracer tests, been estimated at 0.9 - 1.2 m. along a selected fracture. Along a fracture zone, the corresponding value has been calculated to be ten times higher. The transportation distance during the investigation was 30 m (Gustafsson and Klockars 1981).

8.4 Descriptive model of the groundwater conditions

8.4.1 General

Data on geology, tectonics, hydrology and topography constitute the basis for the descriptive model of the groundwater conditions in the Finnsjön area. Such a model must necessarily be comparatively rough and primarily take into account factors and properties which are of importance on a major scale to the groundwater conditions. This means that the individual fractures of minor size cannot be included. Certain other simplifications are also necessary in an initial descriptive model of the groundwater conditions in northern Uppland, which may be summarized as follows:

- Different areas or hydraulic units are geometrically delimited. Thus, a highly permeable fracture zone is bounded off against the surrounding rock mass by a surface over which a difference exists in hydraulic conductivity corresponding to a difference bewteen that of the fracture zone and the rock mass, respectively. This, despite the fact that a fracture zone frequently indicates a gradual transition to the fracturing of the rock mass.

- For individual hydraulic units constant hydraulic conductivity values have been specified. This is an effective value calculated on the basis of the frequency distribution of the hydraulic conductivity in the unit concerned. This means that higher and lower values, respectively, may be found within the individual units.

- The hydraulic conductivity as well as the kinematic porosity has been assumed to decrease with depth. The decrease is presumed to be different mathematically in different hydraulic units.

- The groundwater recharge to the bedrock has been assumed to take place in the topographically most elevated parts, and particularly extensive groundwater recharge is estimated where these more elevated parts are also covered by Quaternary deposits.

- o The groundwater head in the upper parts of the bedrock is assumed to largely follow the topography. The groundwater table, however, is lower than the ground surface in topographically more elevated parts, whereas the table in lower parts follows the ground surface.

- o The groundwater head is assumed to be equalized with depth under the ground surface, i.e. the hydraulic gradient decreases with depth.

It should be emphasized that the descriptive model primarily is to be regarded as backup material for numeric model calculations, and that these in their turn may be pursued on different scales. The accuracy in detail of the descriptive model may be increased but has, in this case, to be adapted to the estimated abilities available in the present numeric model, and the accuracy and amount of field-data available.

8.4.2 Hydraulic units

The units of interest in determining groundwater conditions are the major hydraulically conductive zones and the surrounding rock mass.

Hydraulically conductive zones may be divided into regional fracture zones and local fracture zones. These zones all have an increased conductivity in relation to the surrounding rock mass.

On a regional scale, certain minor fracture zones cannot be attended to in detail. Consequently, they are included in the rock mass and entail a higher hydraulic conductivity in the scale applied. The lateral extension and width of the different hydraulic units are indicated by the lineament map in Appendix 5 and 7 (also see section 5).

The conductive fracture zones defined are of such extension that they can be followed in the terrain. The lineaments mapped are assumed to be vertical or subvertical in all scales considered. Larger zones have been assumed to have the same configuration as small fractures, that is the form of a cut ellipsoid. Thus the relation between length, l, and depth, d, of the zones is assumed to be:

$$l/d = 3$$

This means that most of the identified lineaments reach interesting circulation depths for groundwater (max depth 1500 m).

8.4.3 Hydraulic properties of the units

A prerequisite condition for the numeric calculations of the groundwater flow is the assumption that flowing groundwater at depths greater than 1500 m in the rock mass as well as in the zones may be disregarded. This assumption means that a tight bottom has been set at 1500 m depth in the descriptive model.

The hydraulic properties of the hydraulically conductive zones and the rock mass are outlined in equations 8.3 and 8.4. Table 8.4.a indicates the calculated effective hydraulic conductivity in regional and local fracture zones and in the rock mass at different levels in a local scale. The regional fracture zones have been assumed to have a hydraulic conductivity ten times that of the local fracture zones.

Table 8.4.a. Effective hydraulic conductivity versus depth in different hydraulic units in the bedrock on local scale in the Finnsjön study area.

Vertical depth (m)	Rock mass	Hydraulic conductivity in m/s Reg. fracture	Loc. fracture
100	1.8 E-8	2.5 E-6	2.5 E-7
200	7.1 E-9	5.7 E-7	5.7 E-8
300	4.2 E-9	2.4 E-7	2.4 E-8
400	2.9 E-9	1.3 E-7	1.3 E-8
500	2.2 E-9	8.0 E-8	8.0 E-9
1000	8.8 E-10	1.8 E-8	1.8 E-9
1500	5.2 E-10	7.5 E-9	7.5 E-10

8.4.4 Groundwater head

The groundwater head measured and calculated in the Finnsjön area is presented in section 8.1. The methods used when constructing the map of the groundwater table in Appendix 8 which indicates the groundwater head in the upper parts of the bedrock, are also described in section 8.1. It may be generally stated that the altitude of the ground surface above sea level as well as the magnitude of topographic units and heights, slopes and lowly situated parts have been decisive in devising the map.

Within the higher situated parts of the terrain the groundwater table in the bedrock has been assumed to be located 2-4 m under the ground surface. In certain limited areas, the depth is greater than 4 m. The lower parts of the terrain are assumed to be discharge areas for the groundwater with a groundwater head in the upper part of the bedrock in correspondence with, or usually assumed to have commenced in, the lower parts of the included zones.

The variation in groundwater head with depth has been illustrated by a number of piezometric profiles (see section 8.1). It may be stated in principle that the groundwater head in the discharge areas increases with depth under the ground surface and that the reverse condition applies in the recharge areas.

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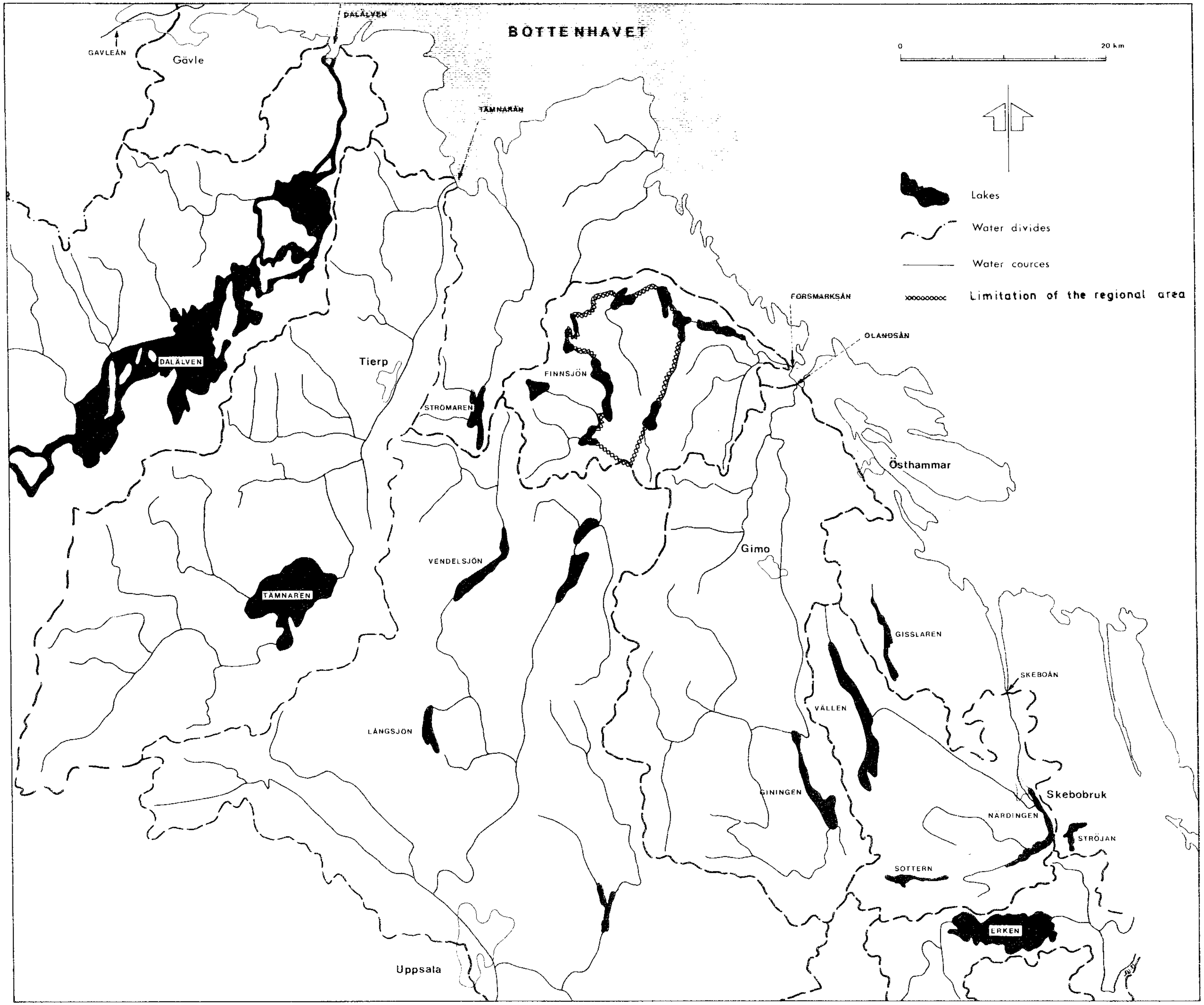
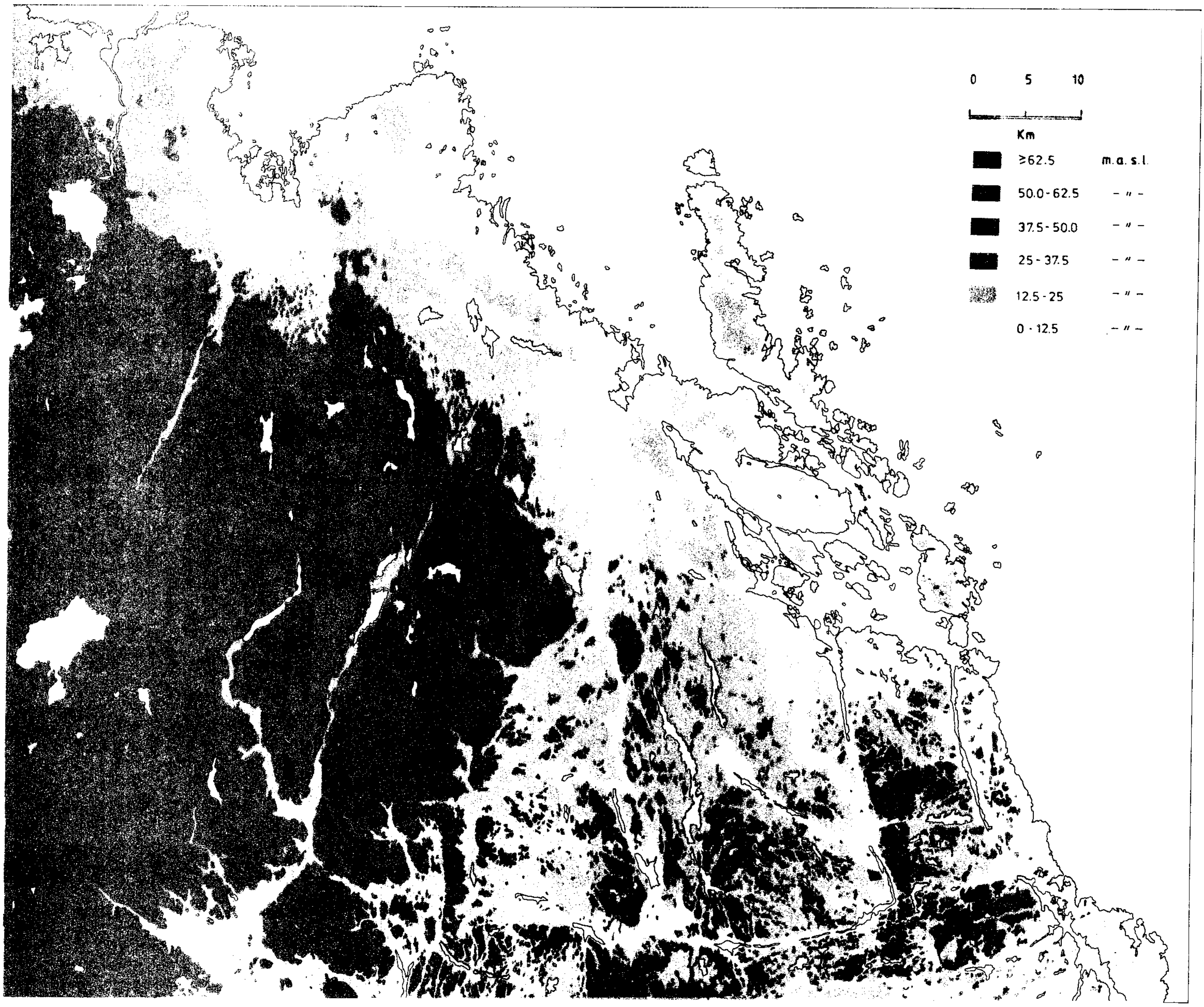
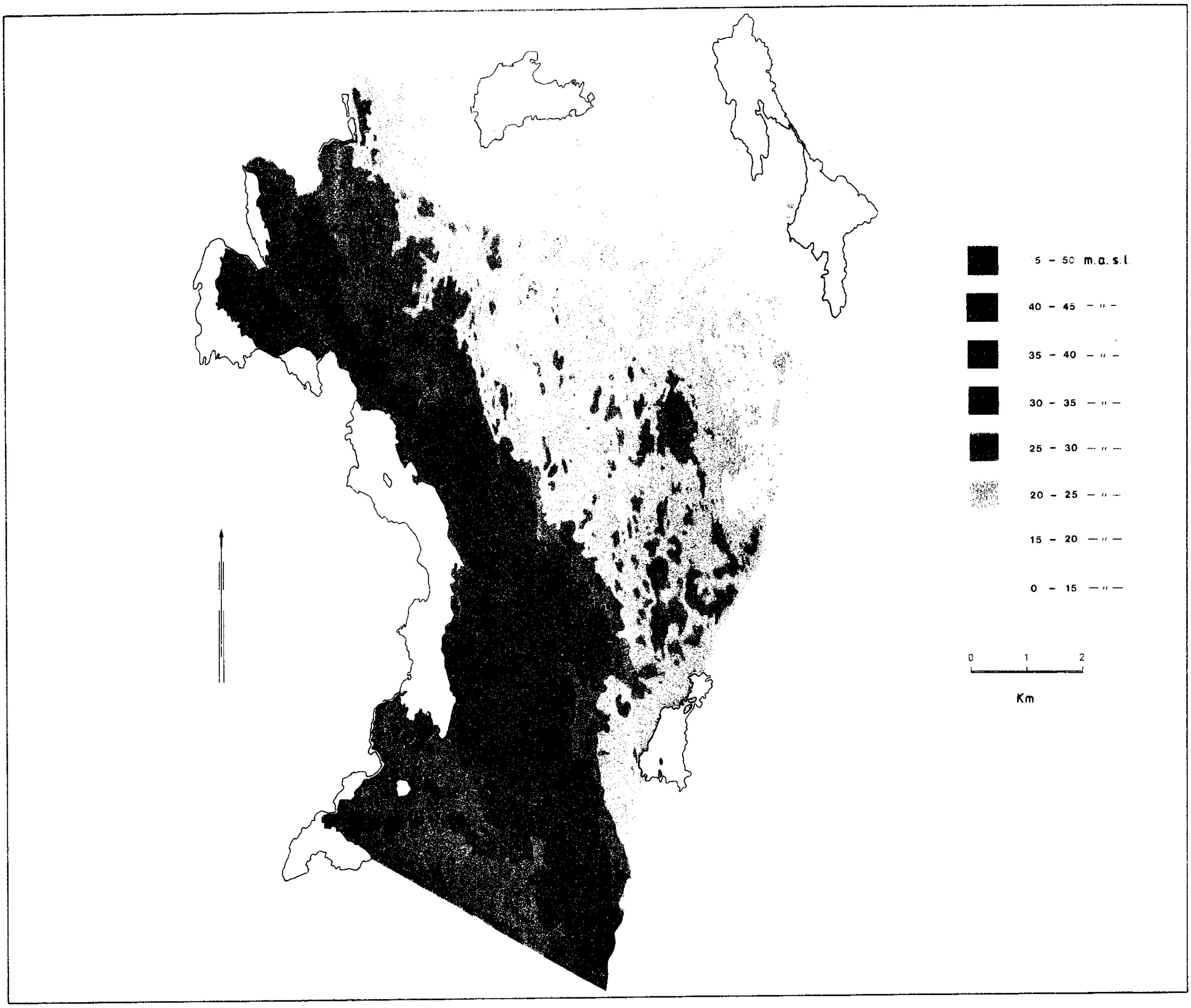


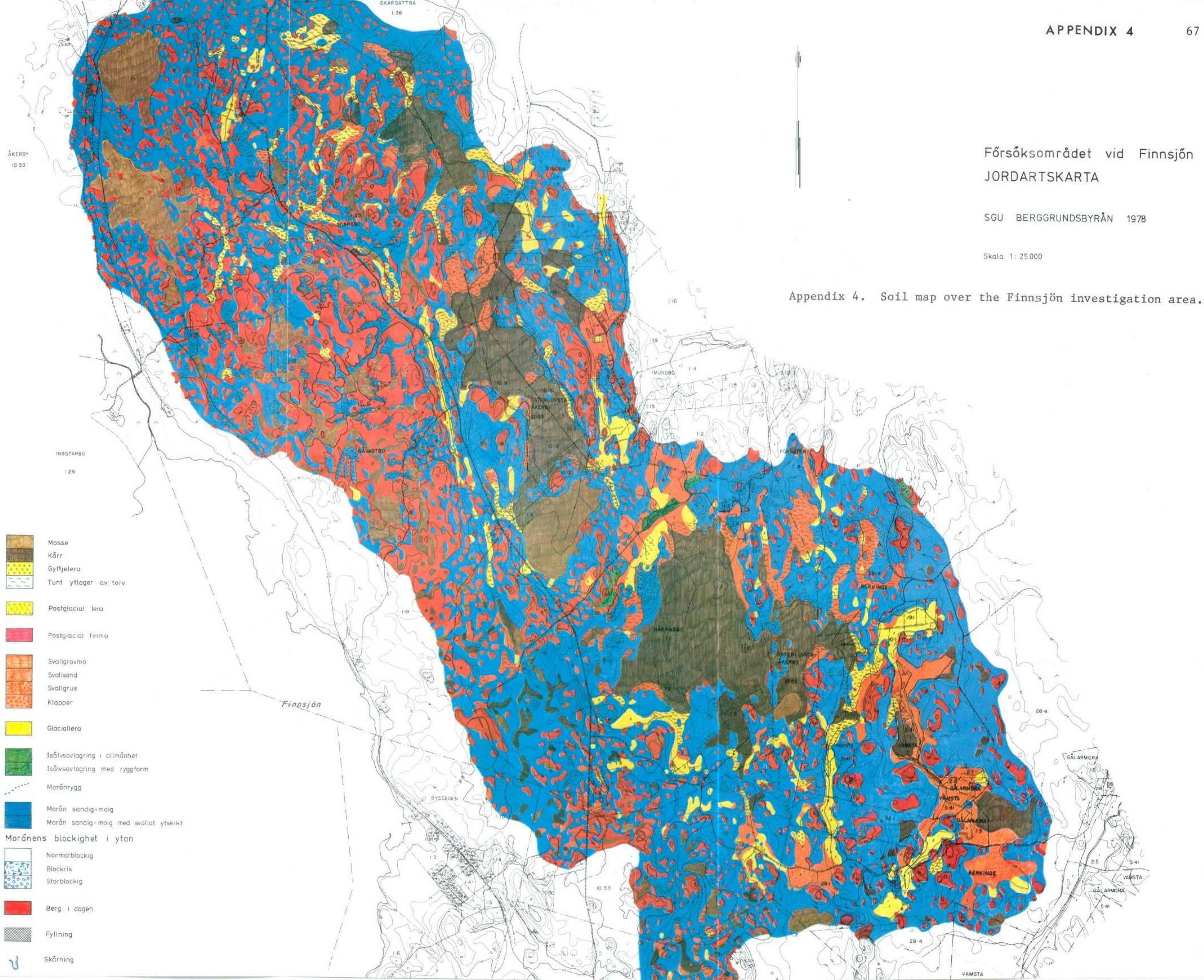
Appendix 1. Drainage basins and larger lakes in Northern Uppland.



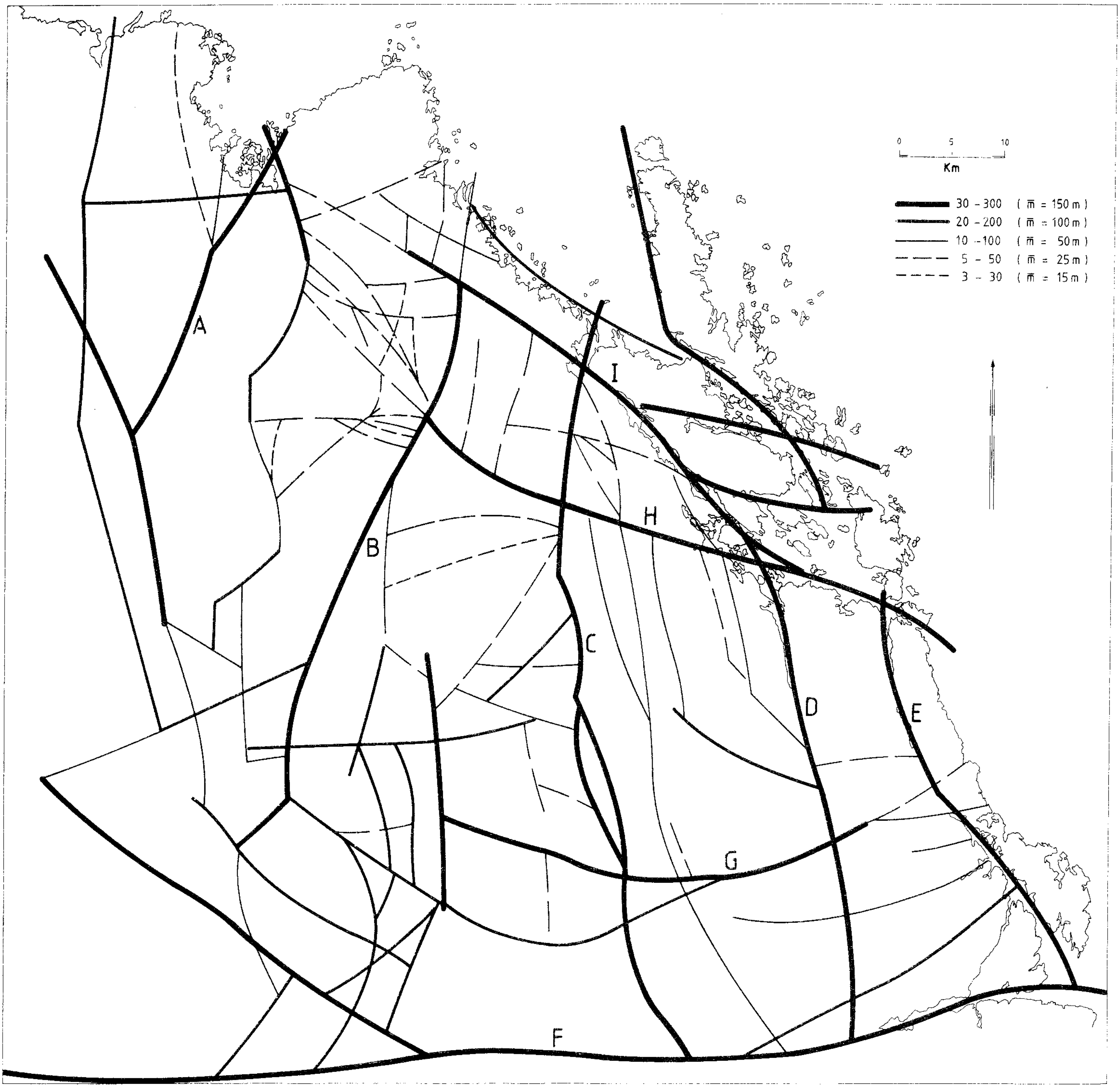
Appendix 2. The topography of Northern Uppland shown with the equidistance of 12,5 meters.



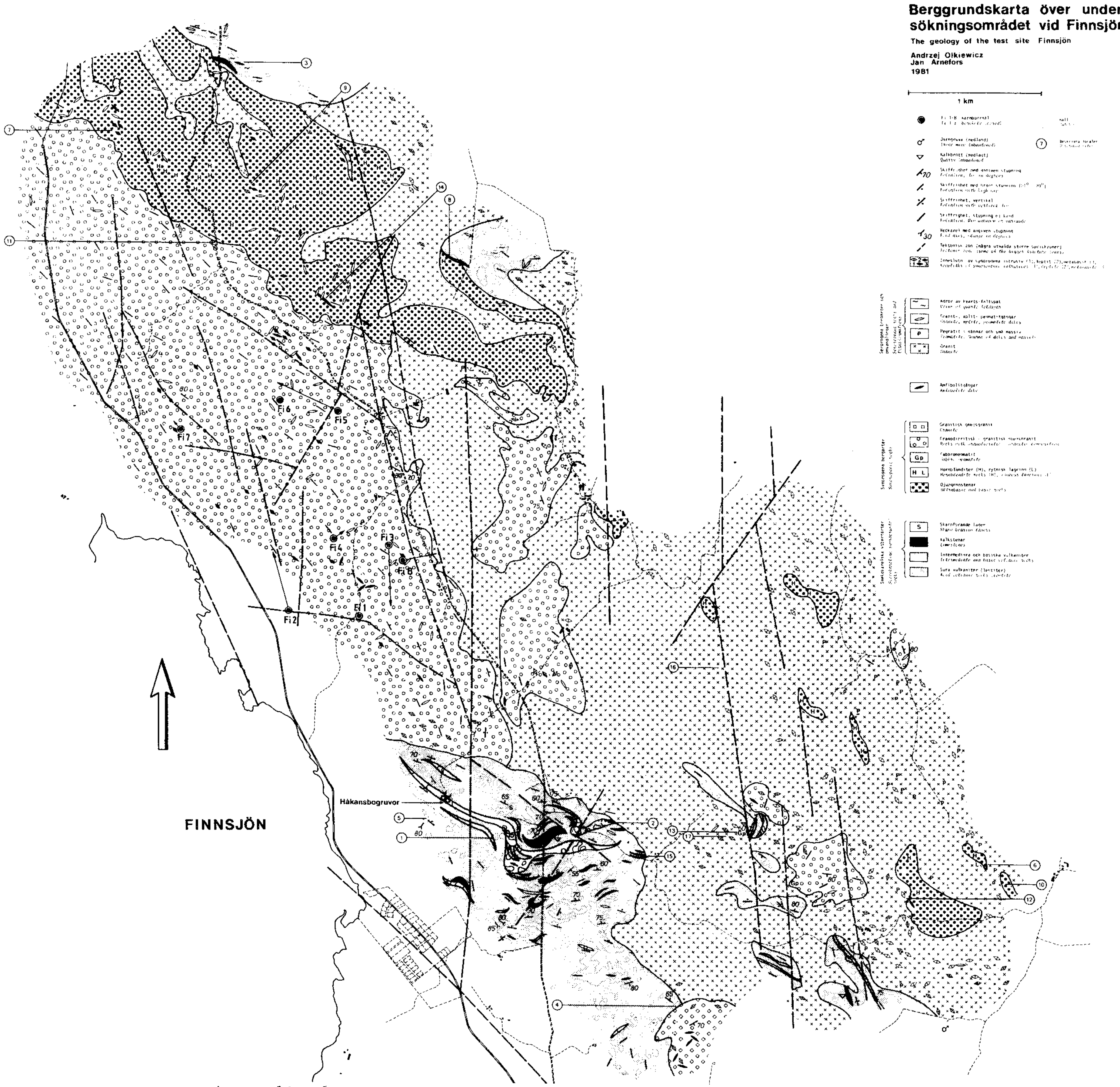
Appendix 3. The topography of the regional area around the investigation area. Shown with the equidistance of 5 meters.



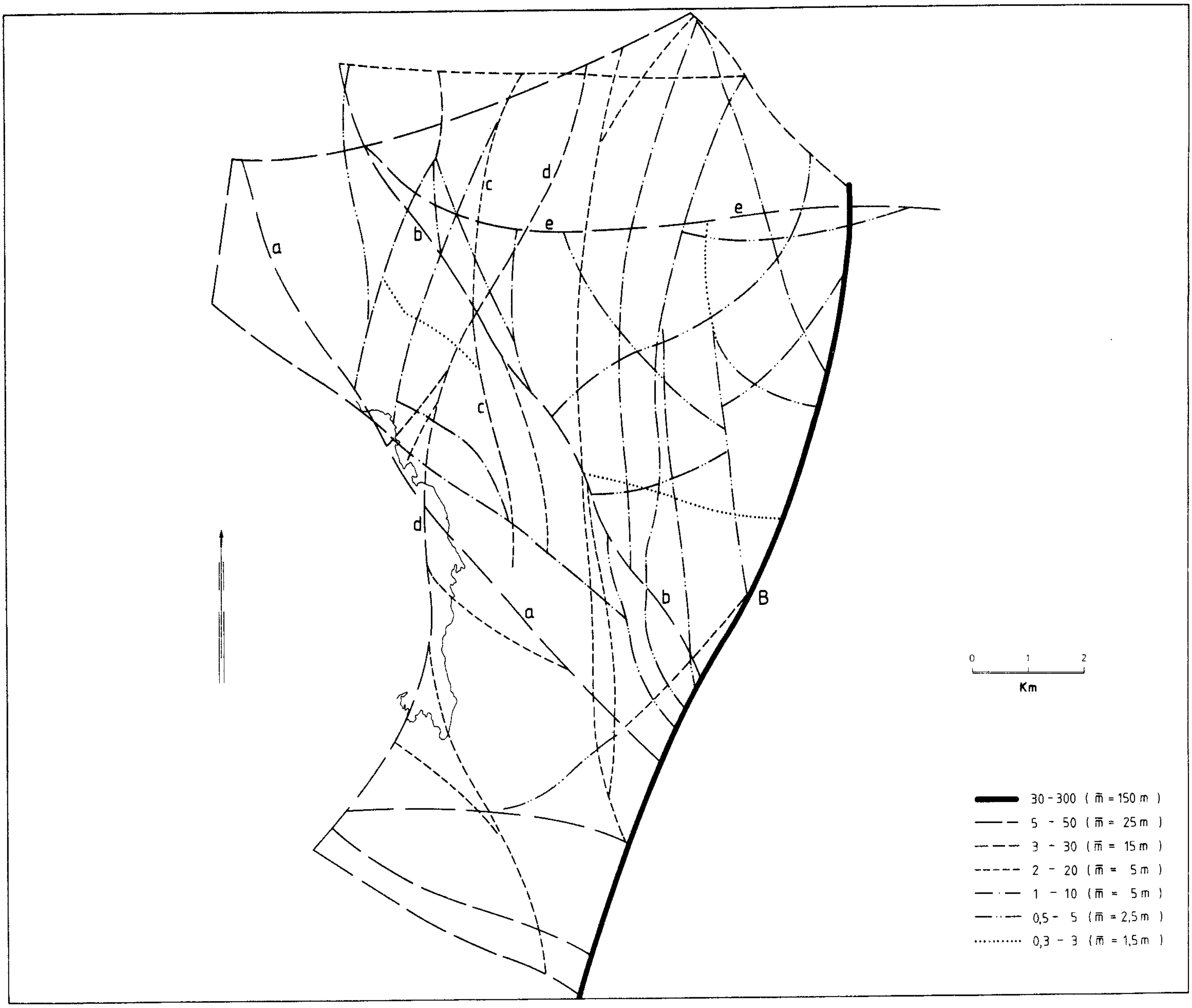
Appendix 4. Soil map over the Finnsjön investigation area.



Appendix 5. Lineaments and their widths in Northern Uppland. (Estimated variations and average widths in meters).



Appendix 6. Bedrock map over the Finnsjön test area.



Appendix 7. Lineaments and their widths in the regional area.

Appendix 8. The topography of the groundwater table in the regional area in meters above sea level. (Estimated variations and average widths).

Part II

SUPPLEMENTARY GEOPHYSICAL INVESTIGATIONS OF THE STÄRNÖ PENINSULA

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Uppsala, May 1983

SUMMARY

The dip of the Stärnö dolerite dike has been determined by fitting computed anomalies from assumed dike orientations to measured magnetic data. One ground and one aeromagnetic profile were used in the interpretation, along with in-situ susceptibility measurements from the dike and the surrounding rock. The remanence of the dolerite was determined from orientated samples. The best fit between measured and calculated data was obtained for a dike, dipping 80 degrees towards the southeast.

1. INTRODUCTION

One of the sites being investigated for the final disposal of radioactive waste is located on the Stärnö peninsula in Blekinge, southern Sweden, see Fig 1. About one km to the east of the site is a dolerite dike, over 100 m wide and striking north by northeast. As the dolerite is highly fractured, and thus potentially permeable to water, it proved necessary to gain knowledge of the dip angle of the dike in order to facilitate numeric modeling of the ground-water conditions at the site, with surroundings.

The dip of a dolerite dike can often be estimated from magnetic measurements, as these dikes generally are fairly high magnetic, and in low magnetic surroundings give rise to typical "sheet-like" positive magnetic anomalies. From the anomaly, the dip of the dike is estimated by fitting calculated anomalies from theoretical models to the measured anomaly.

However, the Stärnö dolerite appears on the aeromagnetic map of the area as a negative anomaly of about 1400 nT amplitude. This may be due either to the fact that it is less magnetic than the surrounding rock, or that it has a strong remanent magnetization in a direction opposite to the direction of the earth's magnetic field.

Especially in the latter case, one has to know the magnetic properties of the dike and of the surrounding rock in order to be able to make any reliable model calculations. In this case also ground magnetic measurements were needed to augment the resolution.

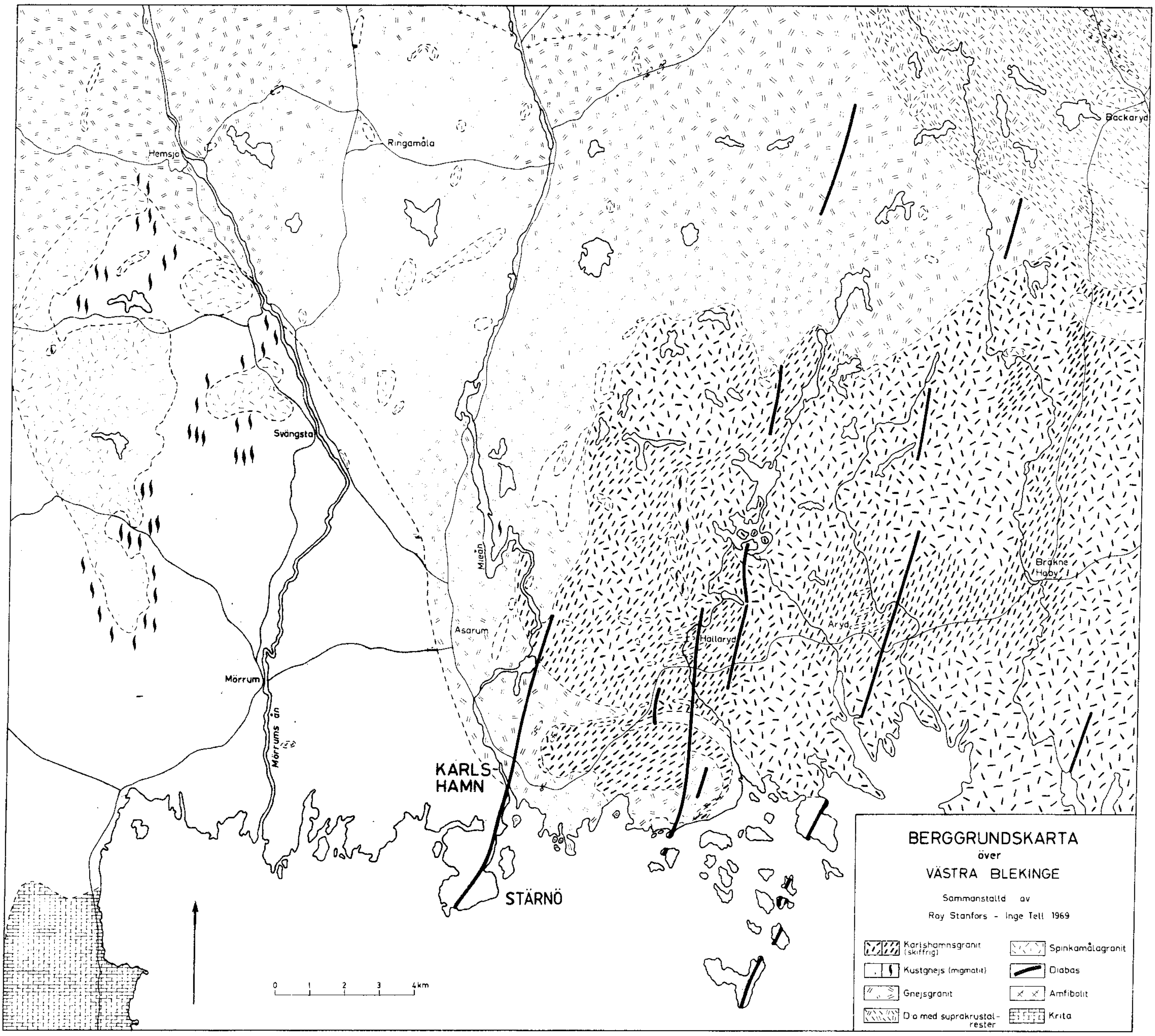

Figure 1. Geological map of the Blekinge region.

2. FIELD WORK

During a two-day field excursion, magnetic total field measurements were made along a profile, 1680 m long in a NW - SE direction across the dike, see Fig 2. The distance between measured points was 10 m. Fourteen sun-orientated samples of the dolerite were taken. Thirteen of these were collected in a dolerite quarry in the southern part of the peninsula.

In-situ susceptibility measurements, 110-146 readings for each type of rock, were made for the dolerite and the surrounding rock. Fig 2 shows the locations of the ground magnetic profile (A-B), and of the observation points. An earlier aeromagnetic survey, the profile C-D, has also been used for the model computations.

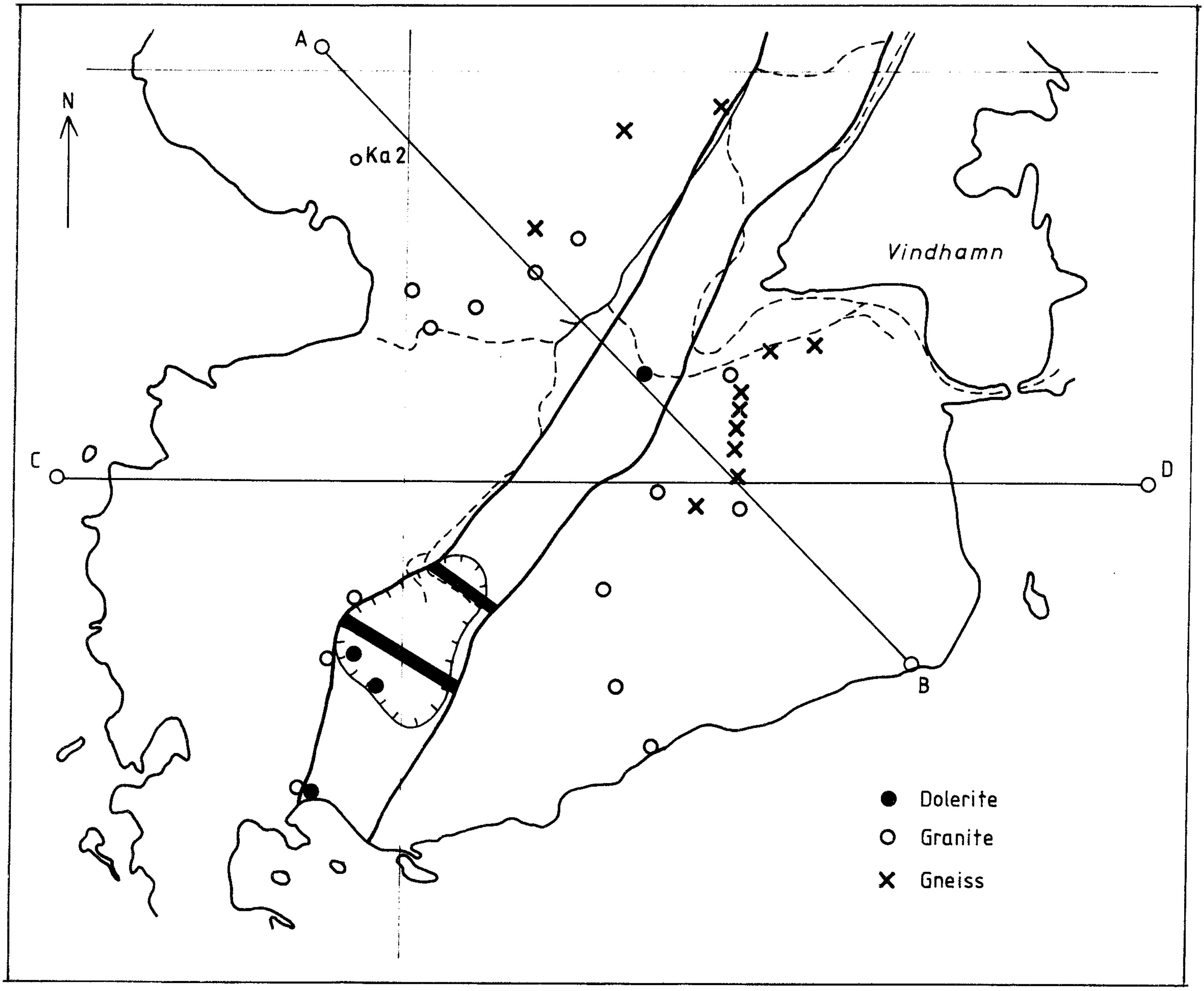

Figure 2. The southern part of the Stärnö peninsula. The figure shows the location of the dolerite dike and the observation points. A–B = ground magnetic profile, C–D = aeromagnetic profile.

3. MAGNETIC PROPERTIES OF THE ROCKS

The remanence direction is quite constant in all but one of the collected dolerite samples. The remaining sample has been discarded, as its deviating remanence direction and high Q-value may be due to re-magnetization by lightning. The distribution of the remanence directions of the other 13 samples is shown in Fig 3. The vectorial average of the remanence inclination is 83 degrees and the declination 88 degrees clockwise from the magnetic north. The Q-value, that is the ratio of the remanent to the induced magnetization, varies from 1.38 to 3.54, and is on the average about 2.1.

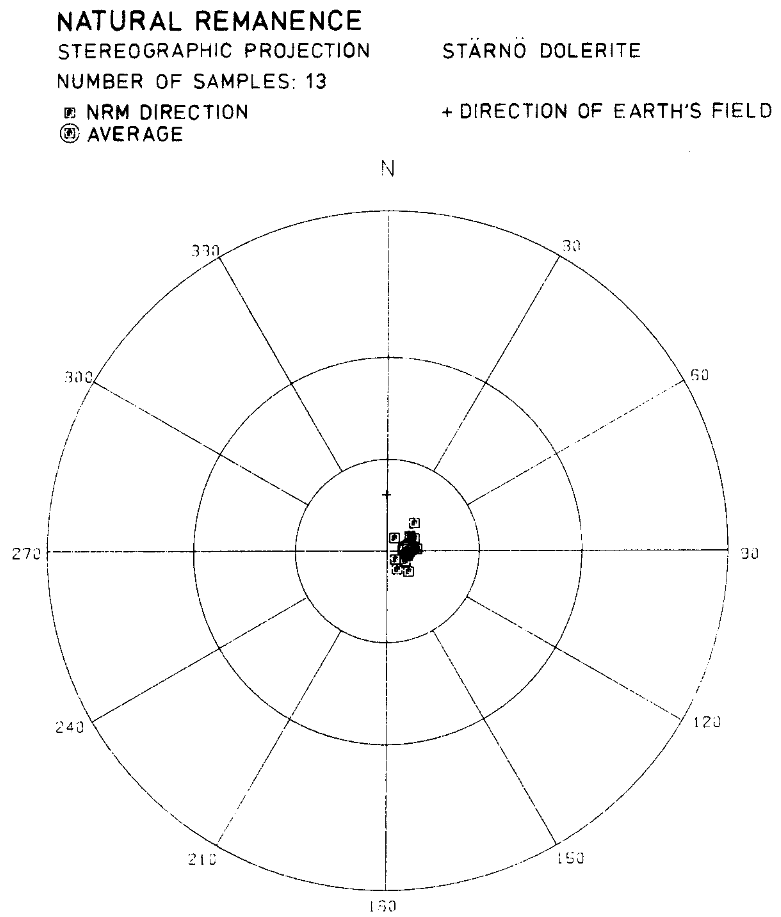

Figure 3. The diagram shows the directional distribution of the natural remanent magnetization of 13 of the samples taken of the Stärnö dolerite.

The in-site susceptibility measurements of the dolerite (146 readings, mainly from the quarry) indicate a log-normal distribution of the susceptibility around 0.010 SI units, see Fig 4. The readings from the outer parts of the dike show a slightly higher susceptibility than those from the central part. This is shown in Figs 5, 6 and 7. However, a corresponding variation of Q-value cannot be traced, due to the small number of samples taken.

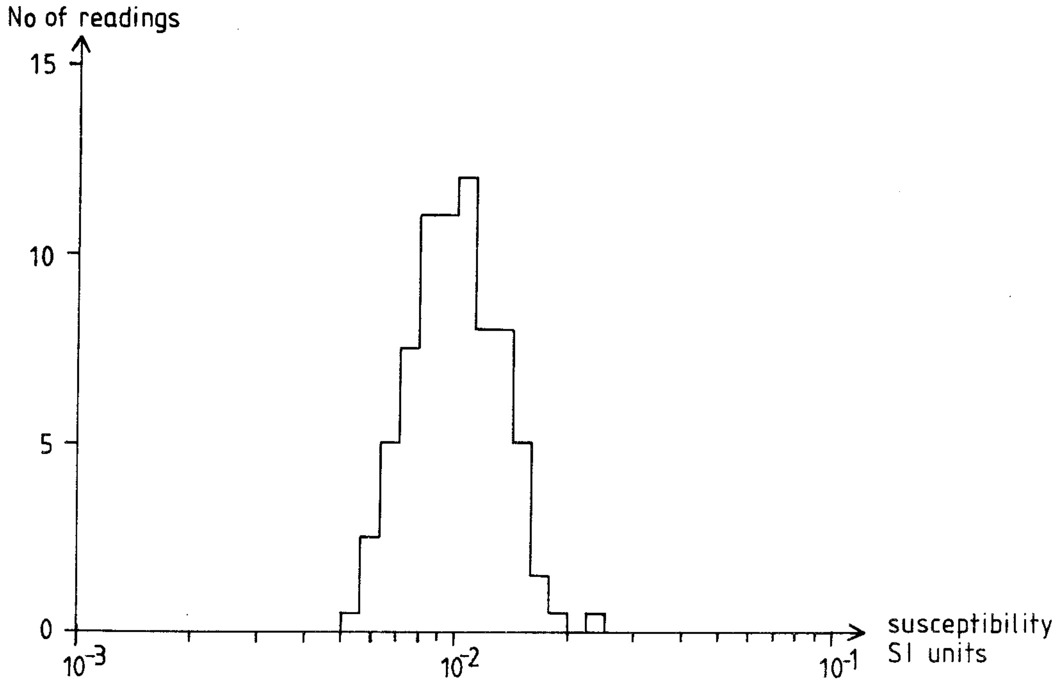

Figure 4. In-situ susceptibility measurements of the Stärnö dolerite. 146 readings.

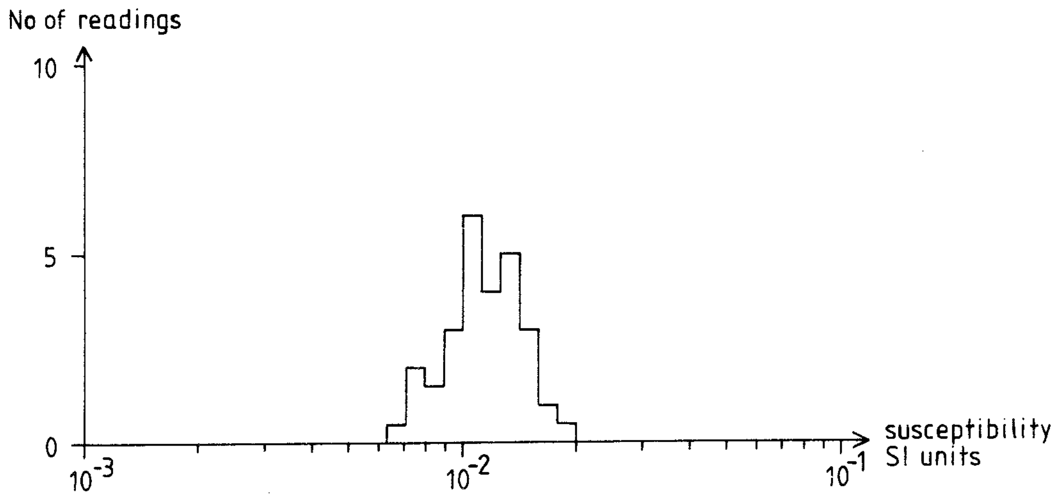

Figure 5. In-situ susceptibility measurements from the western part of the Stärnö dolerite. 53 readings.

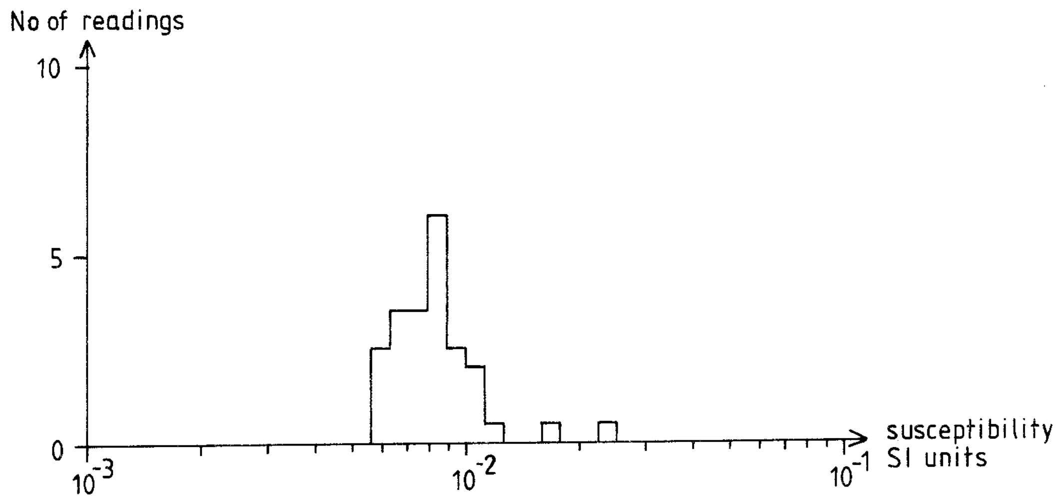

Figure 6. In-situ susceptibility measurements from the central part of the Stärnö dolerite. 43 readings.

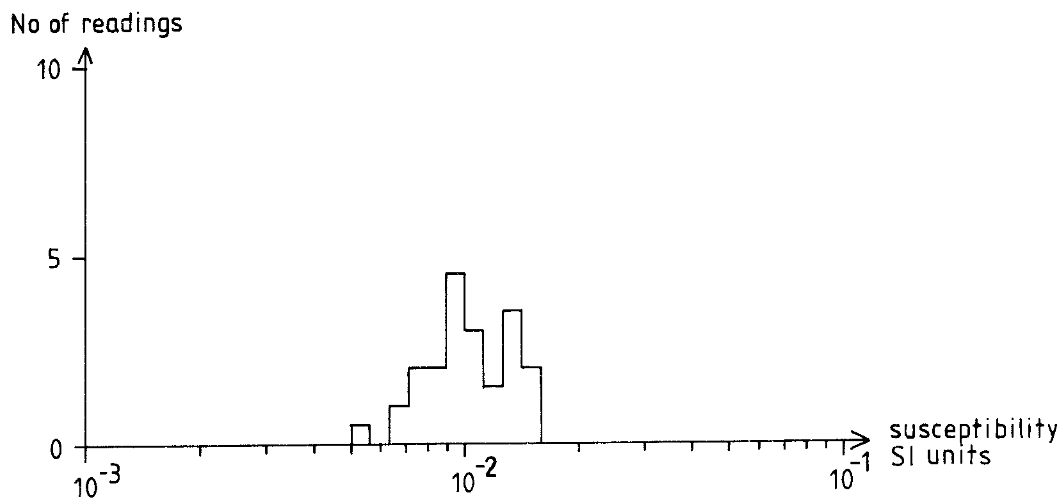

Figure 7. In-situ susceptibility measurements from the eastern part of the Stärnö dolerite. 40 readings.

The surrounding rock is mainly of two types, with clearly different magnetic susceptibility. The first type, a grey gneiss, has a fairly narrow susceptibility spectrum, with the peak at about 0.025 SI units (Fig 8). The other, a red coarse-grained granite, has a wider distribution around 0.06 - 0.07 SI units (Fig 9). The slope of the lower flank of the distribution is probably due to some pegmatite in the rock and to surface weathering. The latter phenomenon in this case tends to decrease the magnetite content. In computer modeling it should be borne in mind that the lower values from weathered material do not represent the properties of the underlying rock. Hence, the value of the higher peak is chosen rather than the average.

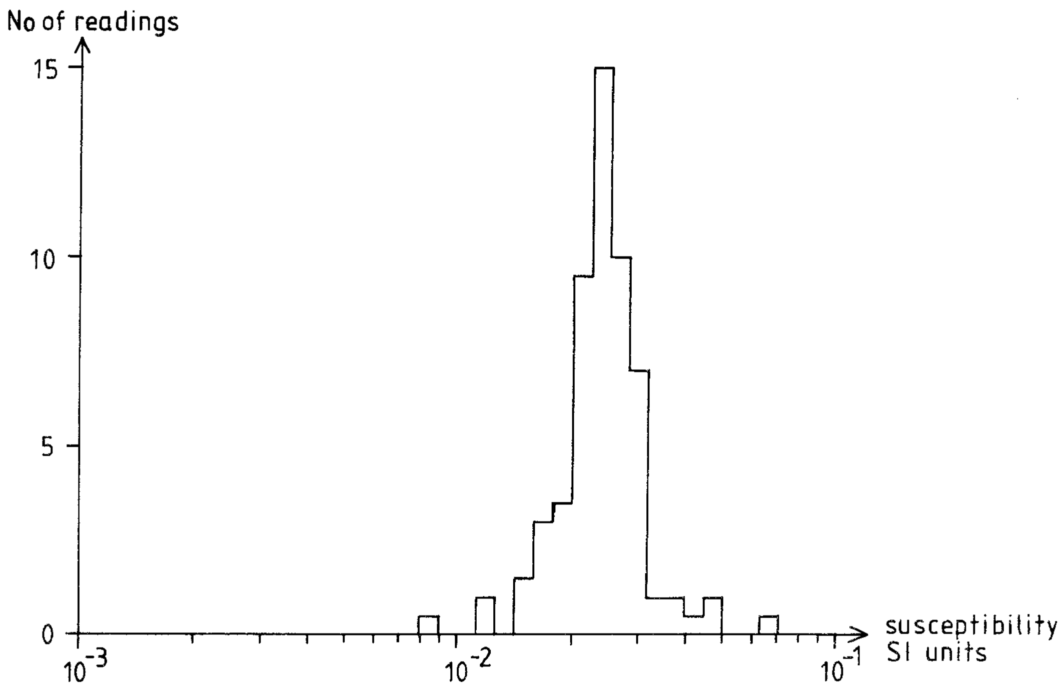

Figure 8. In-situ susceptibility measurements of gneiss on the Stärnö peninsula. 110 readings.

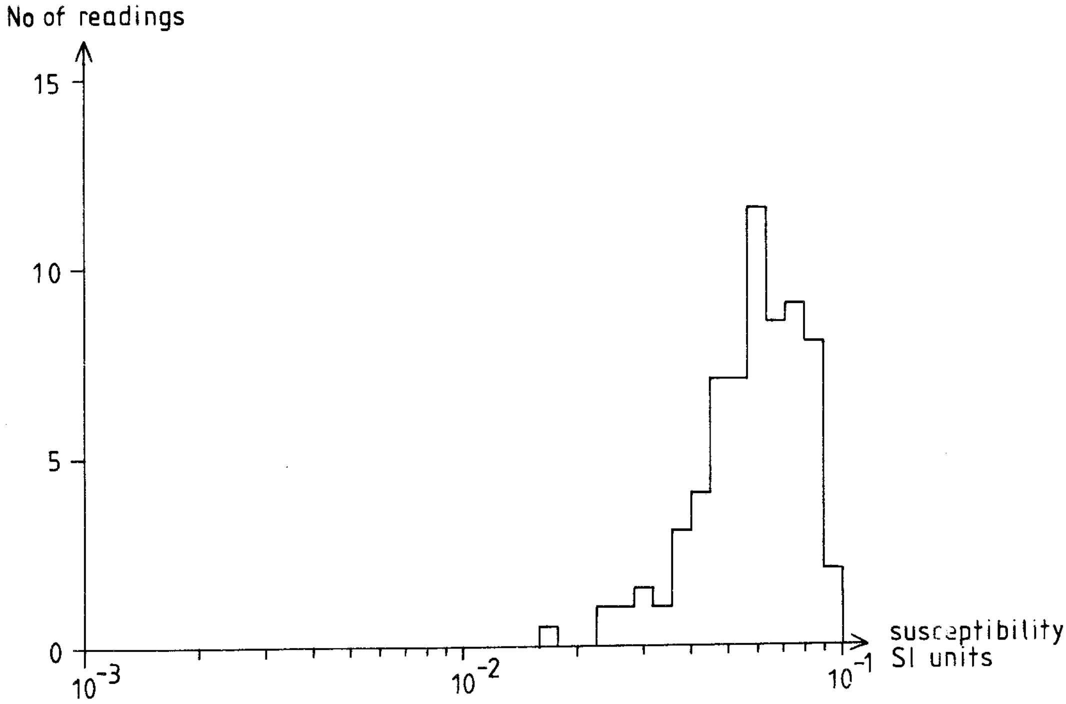

Figure 9. In-situ susceptibility measurements of granite on the Stärnö peninsula. 130 readings.

The Q-value of the few samples taken of the gneiss and granite varies from 0.1 to 0.3 (although one sample of weathered gneiss had a Q-value of 1.0). These samples were not orientated, but as a rule, the remanent magnetization of these rocks is viscous, i.e. has the same direction as the earth's magnetic field.

4. PREMISES FOR THE COMPUTER MODELING

The modeling was made by means of a computer program that allows computation of the magnetic effects of 2½-D models, that is, models consisting of horizontal finite length prisms. The program uses algorithms developed by Rasmussen and Pedersen (1979), and is written by Dr. Thomas Enmark of the University of Luleå. One convenient feature of the program, that has been useful in this study, is that it allows computation along profiles that are oblique to the strike of the bodies.

The following simplified conditions were stated:
The dike is 5 km deep, 10 km long and situated in a prism of rock, 5 km deep, 10 km wide and 10 km long. The strike of the

dolerite is N30E at the crossing of the profles. (With the profile length chosen, this case is roughly a half-infinite one, in that the outer edges of the model will not affect the dip estimations.)

For the dolerite, the remanence inclination is taken to be 83 degrees, and the declination 90 degrees clockwise from the magnetic north. The susceptibility of the dolerite is taken to be 0.010 SI units, and the Q-value 2.1.

The following parameters were used for the high magnetic granite: Susceptibility 0.075 SI units, Q-value 0.25 and viscous remanence.

For the gneiss, a susceptibility of 0.025 SI units, a Q-value of 0.25 and viscous remanence were assumed.

The earth's magnetic field at the locality is about 49200 nT, the inclination 71.3 degrees and the declination 0.9 degrees to the west.

5. DISTRIBUTION OF THE SURROUNDING ROCK TYPES

From Fig 2, no obvious conclusions regarding the boundaries of the two surrounding rock types, gneiss and granite, can be drawn. However, as is shown in Fig 10, the assumption that the dolerite is surrounded mainly by the high magnetic granite leads to a fairly good fit of the calculated anomaly to the observed aeromagnetic data. (Note that if the remanent magnetization of the dolerite was not known, this conclusion could not have been drawn.)

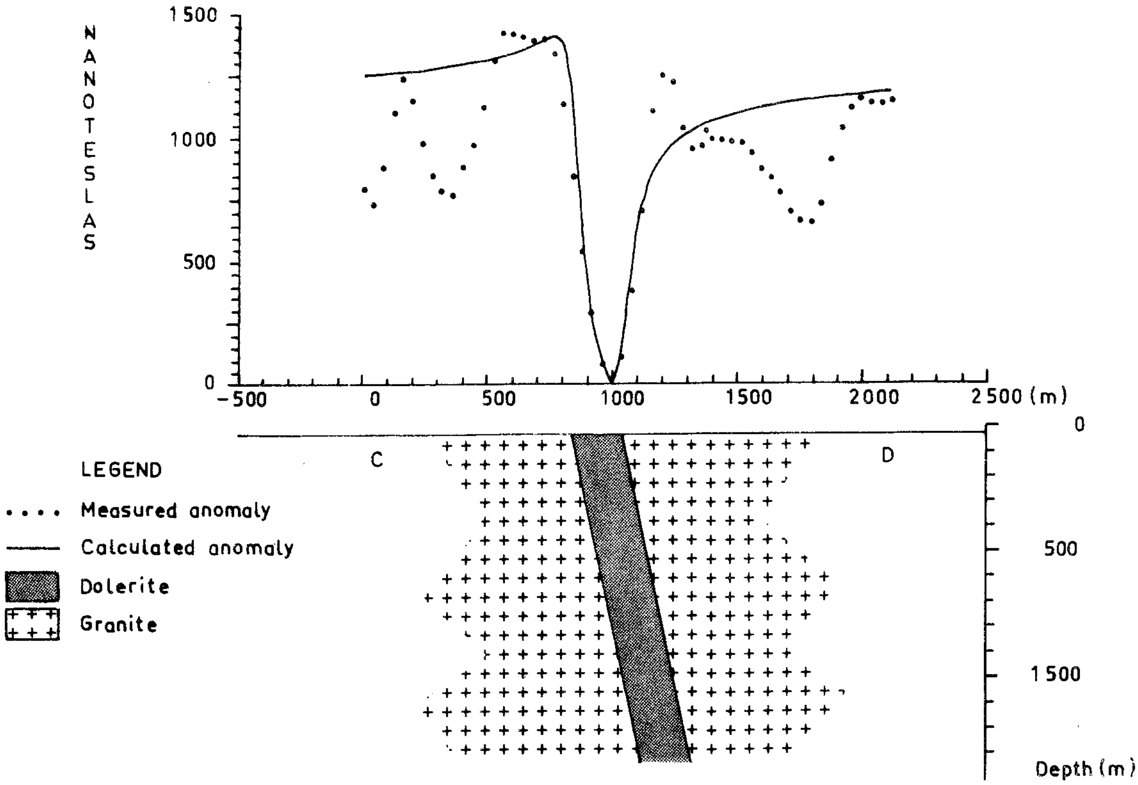

Figure 10. Model computations along the aeromagnetic profile C-D. Flight altitude was 30 m. Here, the dike dips 80 degrees to the SE.

6. MODEL CALCULATIONS, AEROMAGNETIC DATA

As is shown in Fig 10, a fairly good fit of the calculated to the measured anomaly is obtained with the assumption that the dolerite dips steeply to the east (80 degrees) and is surrounded by high magnetic granite. However, as is shown in Fig 11, a westerly dip cannot be precluded, since the ratio of gneiss to granite in the vicinity of the dike is unknown. (The negative anomalies on the sides of the dike are probably caused by superficial bodies of gneiss, see Fig 12.)

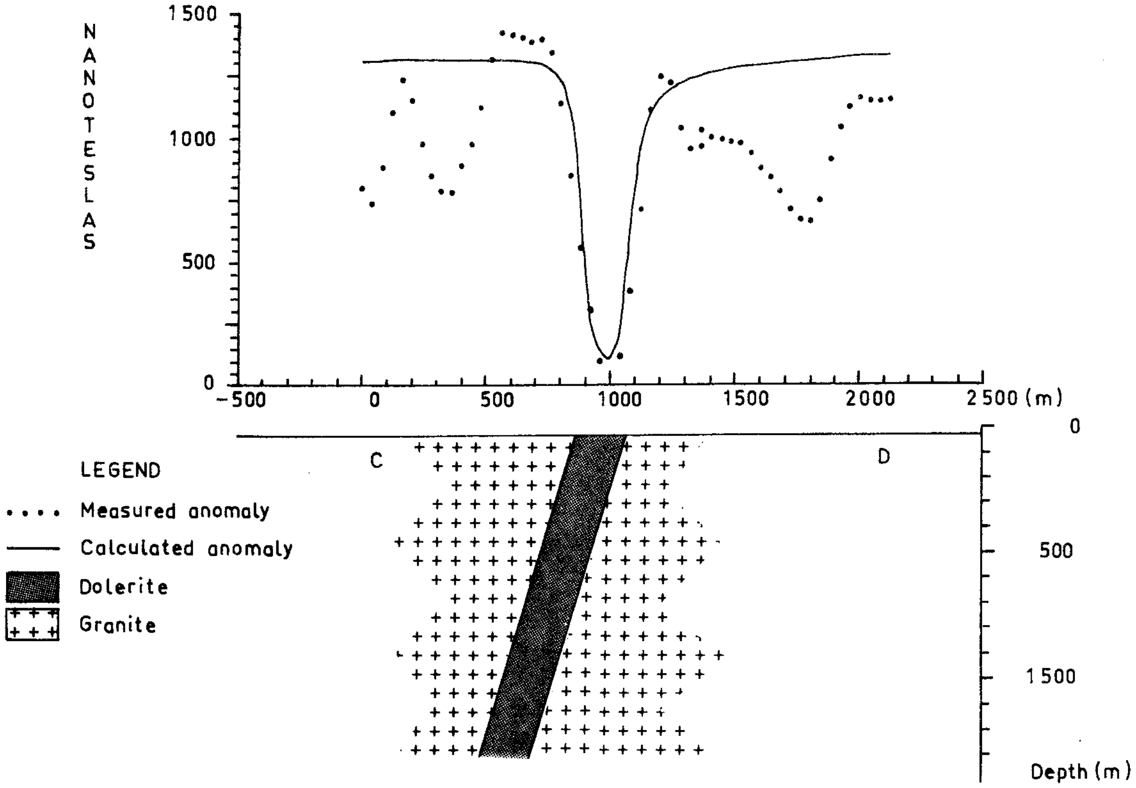

Figure 11. Model computations along the aeromagnetic profile C-D. Here, the dip of the dike is 75 degrees to the NW. Although the agreement of the calculated to the measured anomaly is less good than is shown in Fig 10, it is evident that unambiguous dip determination hardly can be made from the aeromagnetic data alone.

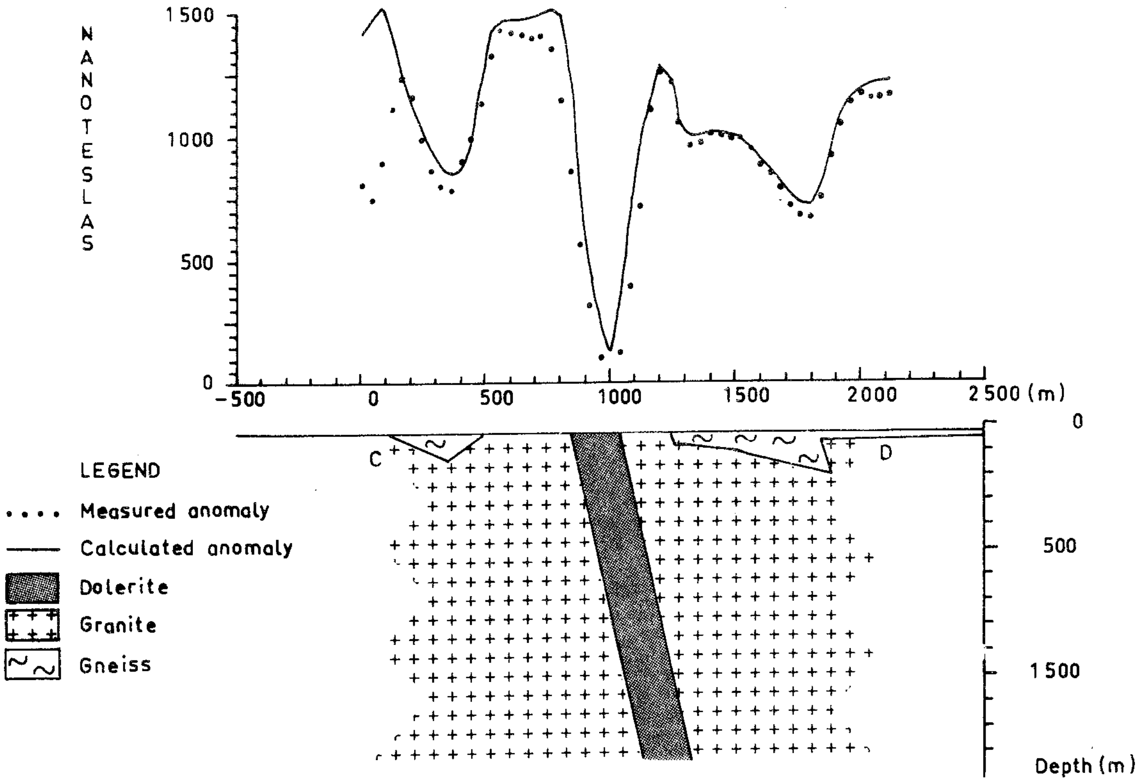

Figure 12. This is the same model as shown in Fig 10, with the addition of two bodies of the less magnetic gneiss. As can be seen, superficial bodies of less magnetic material have a great influence on the anomaly. The fact that these bodies are unknown increases the ambiguity of the dip determination.

7. MODEL CALCULATIONS, GROUND MAGNETIC PROFILE

These calculations offer possibilities to attain a more reliable dip estimation, due to the improved resolution in the ground magnetic data. However, here another problem arises, namely the "noise" caused by varying magnetization in the granite in combination with the low altitude of measurement. This makes exact fitting of theoretical anomalies to the flanks of the measured anomaly impracticable. However, due to the fairly constant magnetization of the dolerite, the measured anomaly curve is smoother here, and this is where we have the best opportunity to estimate the dip.

As can be seen from Fig 13, a westerly dipping dolerite dike does not give any correspondence with the measured anomaly. On the other hand, an easterly dipping dike makes a fair fit (Fig 14). An elaborate example is shown in Fig 15. Here, the outer parts of the dolerite are slightly more magnetic, nonmagnetic soil covers the dike, and a body of gneiss to the east of the dike is added. This model has provided the best fit of the ones tried. In this case, the dip angle is 80 degrees to the southeast.

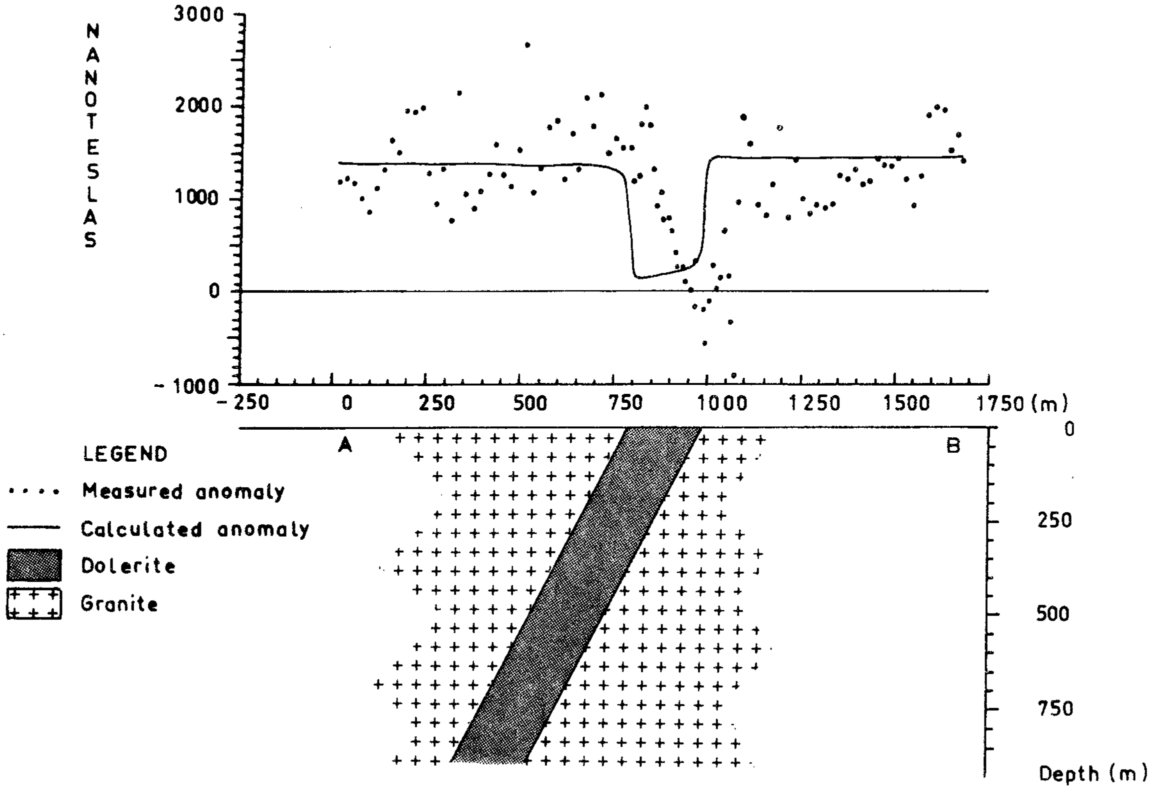

Figure 13. Model computations along the ground magnetic profile A-B. Altitude of measurement is 2 m. In this case, where the dike dips 64 degrees to the NW, the shape and the location of the calculated anomaly do not fit the observed data.

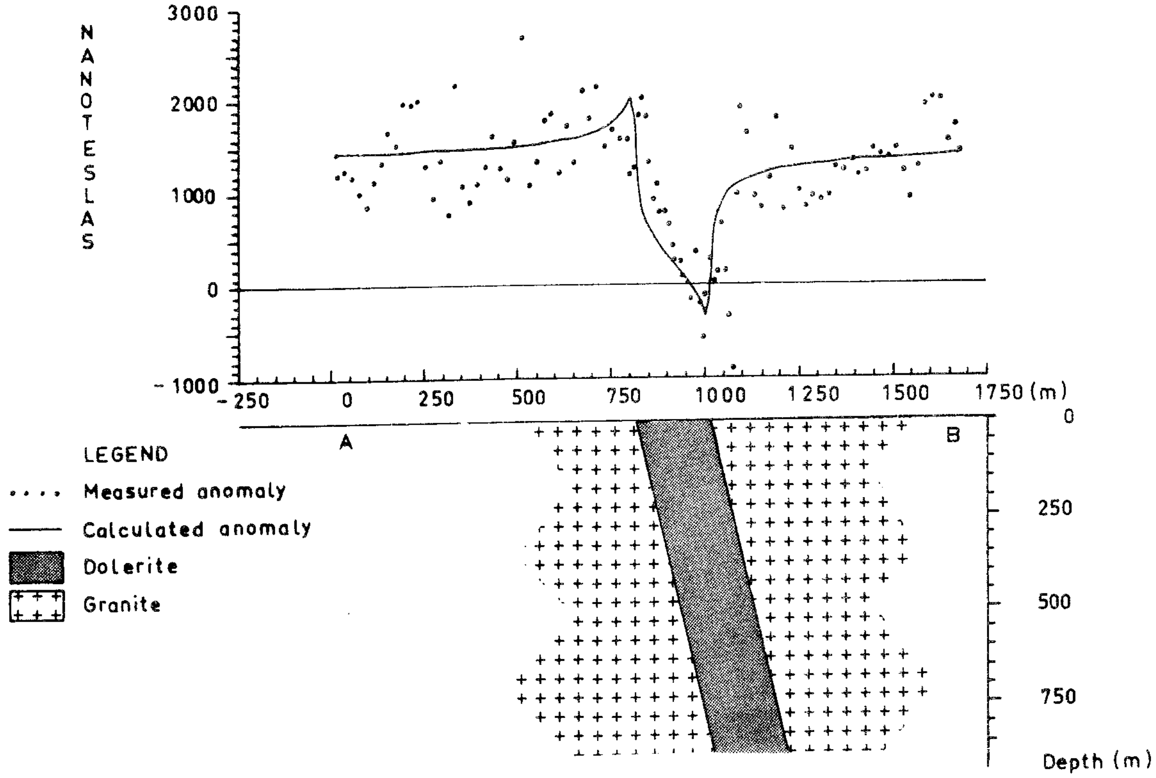

Figure 14. The same case as in Fig 13, but here the dike dips 79 degrees to the SE. This model makes a better fit, especially immediately over the contacts of the dike.

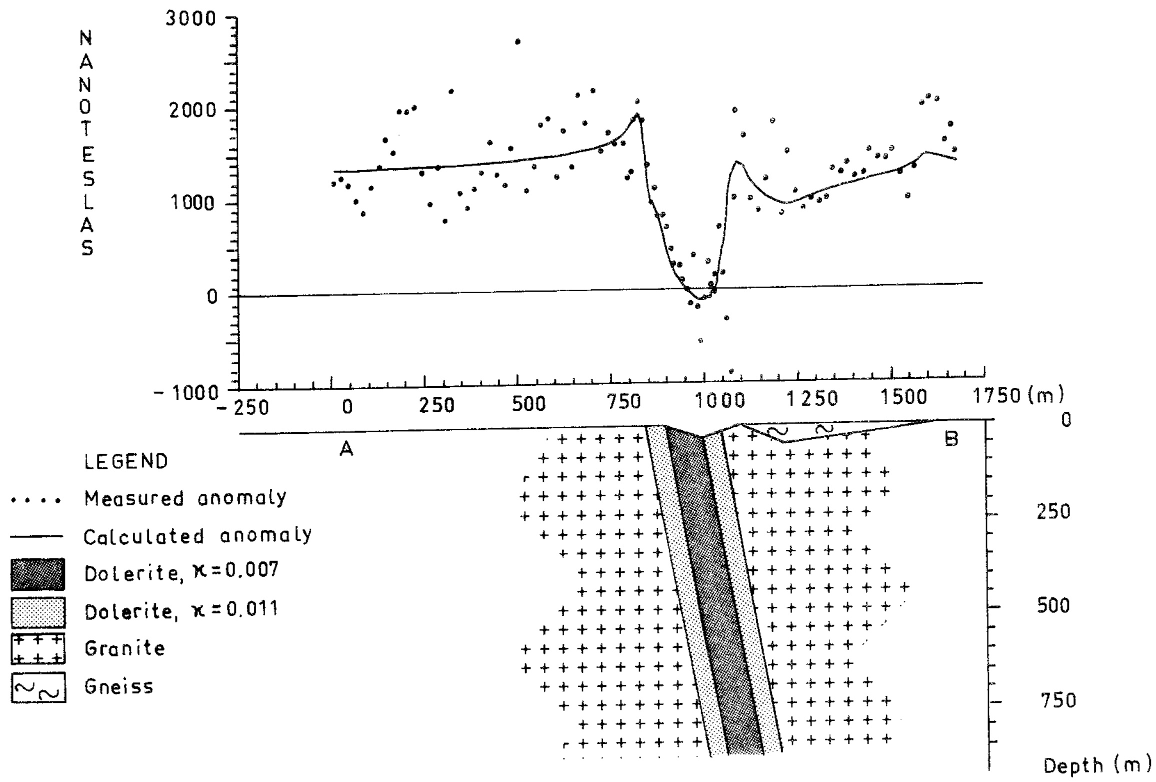

Figure 15. Here, the dike is divided into 3 layers, a central, less magnetic one, and two outer ones with higher magnetic susceptibility. Also, a superficial body of gneiss to the SE of the dike, and a thick layer of nonmagnetic soil over the dike are added. It would, however, be quite impractical to make a model that accounted for all the short-wavelength anomalies on the sides of the dolerite dike. In this model, the dike dips 80 degrees to the SE.

8. CONCLUSION

The case is complicated by the high and varying magnetization of the rocks surrounding the Stärnö dolerite. The measured magnetic data do, however, imply that at the surveyed locality, the dike dips steeply to the east. With reservation for unexpected complications, as for example a too irregular shape of the dike, the dip of the dike is estimated to be 80 degrees towards the southeast. A flatter easterly dip may be possible, whereas the observations made apparently preclude a westerly dipping dike.

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