CHALMERS TEKNISKA HÖGSKOLA

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PREFACE

This report deals with sediment structures in glacial till and their influence on the hydraulic conductivity.

For a long time it has been a general opinion among hydrogeologists that, besides grain-size distribution, the sediment structure has a significant influence on the hydraulic conductivity in till. However, the sediment structure is built up of many separate factors and the quantitative importance of these factors is very little known. Studies of small structures in till and their influence on the hydraulic conductivity properties are a quite new field within the hydrogeological science.

The investigations presented in this report started in 1984 as a 3-year project which ended 1987. The research project has been carried out at the Department of Geology, Chalmers University of Technology and University of Gothenburg, and is a part of a major research effort by the Urban Geohydrology Research Group.

The research has been financially supported by the Swedish Council for Building Research (BFR).

A great number of persons have been involved in discussions and have given valuable contributions to the project. Besides our colleagues at the university we wish to express our gratitude to following persons:

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Bo Lind Mats Nyborg

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BACKGROUND

The paucity of knowledge about the sediment properties of geological formations is often the weakest link of the data input for hydrogeological calculations. Rough, generalised pictures of different geological layers, based on information on thickness, extension and orientation, are used as geological basic data. More seldom is there information about inhomogeneities and other structural characteristics.

From a hydrological point of view, till is one of the most poorly known sediments. At the same time, it is clear that there is, in many situations, increasing interest in till - as ground material as well as construction material. Waste disposal leakage, ground-water findings in wells, acidification of ground-water, waste-covering, infiltration, drainage, and substitutes for gravel and sand are some of the fields where more knowledge about the properties of tills would be welcomed.

It has been a general opinion among hydrogeologists for a long time that, besides the texture, the structure has an influence on the soil moisture conditions, as well as hydraulic conductivity in soft sediments (cf. Fair & Hatch, 1933; Fraser, 1935; Knutsson, 1971; New York DOT, 1973; Currie, 1979; Dahl et al, 1981; Prudic, 1982; Lundin, 1982; Williams et al, 1983; Haldorsen et al, 1983). The problem of structure and hydraulic conductivity is also touched upon in engineering geology concerning dams of well graded sediments (of Bernell, 1976; Kjellberg et al, 1985). However, the sediment structure is built up of many separate factors and the quantitative importance of these factors is very little known.

INTRODUCTION

The hydraulic conductivity of a porous media has the dimension distance divided by time (L/T), that is velocity, and can be seen as an expression of the ease with which a fluid can pass through the media. Besides the fluid itself, the flow velocity is dependent on the route it has to go and the inner friction that the flow causes at the borderline between the fluid and the pore-walls.

According to Poiseulle's law, it can be shown that the hydraulic conductivity is dependent on the porosity and the inner specific surface of the porous media. Increasing inner surface means decreasing conductivity and equivalent results are obtained with decreasing porosity values. Kozeny (1927) has derived the following relationship between porosity, specific surface and intrinsic permeability (without consideration of the fluid properties):

$$k = c_3 \cdot \frac{n^3}{(1-n)^2} \cdot \frac{1}{s^2} \qquad (1)$$

where k = intrinsic permeability
n = porosity
s = specific surface
c = constant

The specific surface was used as a basis for calculation of intrinsic permeability and later on by Fair & Hatch (1933), DeRidder & Wit (1963), and Ernst (Kessler & Oosterbaan, 1974).

Gustafsson (1983), among others, has shown how the specific surface is correlated to the grain-size. According to Beard & Weyl (1973), the total porosity is independent on the grain-size in natural sand; it is, however, correlated to sorting, or dispersion.

Besides grain-size, the specific surface value is influenced by the grain-shape, a factor that Fair & Hatch (1933), among others, have taken into account. They defined a special form factor, θ, for the grain shape, which was 6.0 for spherical grains and 7.7 for elongated grains. New York DOT (1973) specified the form factor to 6.0 for glass pearls and 10.8 for shattered glass.

Although the hydraulic conductivity is primarily dependent on specific surface and porosity, it is also dependent upon the flow pattern and the flow route. Furthermore, Gustafsson (1983) has shown that within certain grain-size intervals there is a direct correlation between pore-size and grain-size. This means that, instead of pore-size, the grain-size could be used. This is, for instance, the case in the well-known Hazen's formula:

$$K = 1.157 \cdot 10^{-4} \cdot d_{10}^{2} \qquad (2)$$

if

$$d_{60}/d_{10} < 5$$

where

K = hydraulic conductivity (m/s)

d_{10} = the grain-size for 10 weight-% passing quantity according to grain-size analysis (mm)

d^{60} = the grain-size for 60 weight-% passing material (mm)

In general form and irrespective of the fluid properties the intrinsic permeability, k, can be expressed as:

$$k = c \cdot d^{2} \qquad (3)$$

If d in this equation is a measure of the representative grain-diameter, then the constant c is related to all other factors that influence the degree of flow through the media; these are:

- grain shape (sphericity)
- grain roundness
- grain surface structure
- porosity - pore orientation - spatial pore-size variations
- fabric
- mineralogy

The structural factors listed above are closely interrelated in such a way that their influence on the hydraulic conductivity cannot be added. Most of the empirical equations for hydraulic conductivity calculations do not separate and take into consideration the influence of assymmetry in the factors above. Instead, the empirical methods are defined and valid for wellsorted and isotropic porous media.

It is well known that till often has a well-developed structure as regards foliation, bedding and fabric. Besides this, asymmetry also commonly occurs in the other structure factors. In an important work from 1971, Knutsson presented an investigation of well capacity in dug wells in different types of tills. The results showed that wells in drumlins had, on average, a higher, and more equal, capacity than wells in hummocky till. The dependence of hydraulic conductivity on the till genetics has also been touched upon by Haldorsen et al (1983). In a study on hydraulic conductivity with calculations from 42 infiltrometer tests in till with genetic variations, it was found that lodgement till in Norway had a lower hydraulic conductivity than melt-out till (Haldorsen et al, 1983).

In agricultural science, the influence of soil structure on the water retention characteristics has been dealt with for a considerable number of years. The relationship between water characteristics and soil structure has been stated by, for instance, Williams et al (1983).

Accordingly, it is a well-established fact that the hydraulic conductivity in till is directed by the sediment structure. To what extent the hydraulic conductivity is dependent on the structure or the texture is, however, very little known, and our knowledge about the magnitude of the influence from the individual structure factors is limited. An attempt to make a rough estimate of the influence of sediment structure factors on the hydraulic conductivity has earlier been made by Lind & Nyborg (1986).

As we have seen, the hydraulic conductivity is dependent on the specific surface and the flow route. There is also a correlation between the specific surface and the characteristic grain-size, as well as between the specific surface and grain-shape, surface structure and roundness. The route of flow of a water-particle is in turn dependent on the grain-orientation. The flow route perpendicular to the grain orientation is longer than the flow route parallel to the grain-orientation (Jensen et al, 1985).

The work in our project has aimed at describing the influence of sediment structure on the hydraulic conductivity in till. The structure factors studied are related to the specific surface and to the route of flow. The hydraulic conductivity is also influenced by the varying hydrofilous properties of different minerals. This factor is not insignificant with regard to water accessibility of plants. In practical hydrogeology, however, this aspect can be excluded and it has not been further discussed in this project.

INVESTIGATION STAGES

The investigations of till-structures and hydraulic conductivity can be summarised in the following stages:

- sampling in the field
- bulk and compact-density measurements
- permeameter tests
- chemical analyses on inflowing and outflowing water
- water-retention analyses and pore-distribution calculations
- grain-size analyses
- clay-mineral analyses
- epoxy-resin impregnation
- preparation of thin sections
- structure analyses

Sampling sites

The sampling sites were selected with the ambition of studying different types of tills but the need for suitable soil conditions was also considered. Because our main aim was to study hydraulic conductivity in the C-horizon, it was necessary to have a thickness of the till of at least 2 m. Till studies made by Lundin (1982) have shown that great variations can be found in porosity and permeability in the uppermost 0-50 cm of the soil profile, a factor that Haldorsen (1983) has also taken into consideration. We have chosen to study the conditions at considerably greater depths in order to avoid variations caused by influences within the A and B-horizons.

Furthermore, it was necessary to find a till with an appropriate consolidation, that is with a certain clay content, to allow sampling with our method. The till should also be uniform within a certain area and have a clearly visible structure. Finally, the choice of sampling sites was also directed by practical considerations such as accessibility (distance from the laboratory, for instance).

The locations of the sampling sites are shown in Figure 1. The main series of analyses was taken at Tahult and the series was supplemented with samples from two differing tills at Ödenäs and Lekeryd. The till accumulations at Tahult and Ödenäs are in the form of drumlins whereas the landscape at Lekeryd consists of relatively flat till areas.

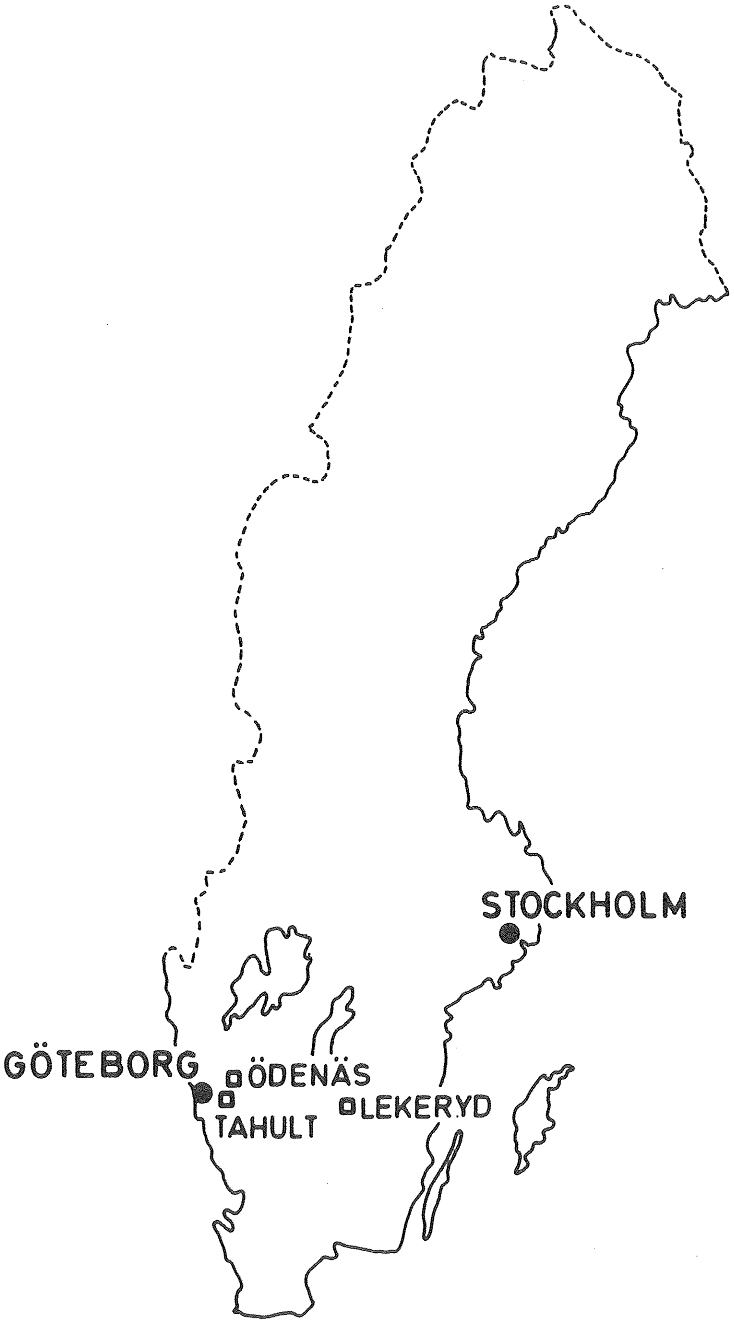


Figure 1. Locations of sampling sites at Tahult, Ödenäs and Lekeryd.

Tahult

The Tahult sampling site is situated close to the crest of a drumlin ridge, approximately 2 km long. The highest point of the Tahult drumlin reaches up to 155 m a.s.l. and the relative height over the surrounding terrain is about 50 m. The accumulation is situated above the highest shoreline and has not been wave-washed.

The till is in general silty with sandy parts. A detailed description of the till has been given earlier (Lind & Nyborg, 1986). The investigations and the samplings have been made in two shafts, 5 m long and 3 m deep, on top of the drumlin. The shafts were excavated approximately parallel and perpendicular to the drumlin orientation.

Ödenäs

Like the Tahult site, the Ödenäs site is located on a drumlin accumulation oriented in the northeast-southwest direction. The Ödenäs till has in several respects another structure than the Tahult till, however.

The Ödenäs drumlin is about 2.5 km long and reaches at its highest parts 215 m a.s.l., which is about 115 m above the highest shoreline in the area. The drumlin is situated high up in a broken landscape, rising about 30 m above the surroundings.

The investigations were made and the samples taken in a 6 m long and 3.5 m deep shaft situated near the drumlin crest and oriented approximately perpendicular to the drumlin orientation.

The Ödenäs till is sandy-silty with normal contents of stones and blocks. The till is very firmly and compactly stratified and difficult to dig out even for a big excavator. Especially when the shaft had been standing open for some days, a clear fissure pattern appeared in the walls. When the samples were excavated, there was an almost instantaneous tension-unload, resulting in horizontal cracking of the samples, causing them to collapse completely. Only with rigorous caution and many attempts was it possible to get 12 intact permeameter samples. Some of these samples were used to study the influence of tension-unload in till-samples taken at depths of 2-3 m.

Lekeryd

The Lekeryd sampling site is situated south of Lekeryd, about 500 m north of the Klackarps farm. The whole area around Lekeryd is characterised by a hilly terrain with till deposits, here and there broken by small bedrock outcrops. The height of the landscape is about 250 m a.s.l., which is well above the highest shoreline. The main ice movement during the deglaciation was from NNW.

The sample site is situated in an undulating till terrain. The thickness of the deposits is not known but through information from the surroundings it can be estimated to be 3-4 m. The samples were taken at the edge of a ditch, in the C-horizon about 1.2-1.5 m below the ground surface. The till in this area varies between silty and clayey. At the sample site, the clay content is about 15-18%. The till is relatively loose and the consolidation is only moderate, in spite of the high clay content.

METHODS AND ANALYSES

Sampling method

All samples were taken at the C-horizon; at Tahult and Ödenäs about 2-3 m below ground surface, and at Lekeryd about 1.5 m below ground surface. The samples were in the form of excavated lumps of till of about 20 x 15 cm in size. By careful scraping, the samples were trimmed to a cylindrical shape with a diameter of 70 mm and a height of 80 mm and placed in PVC-cylinders with a diameter of 93 mm and a height of 87 mm. The size of the representative element volume, REV, corresponds to the hydraulic properties, such as sparse fractures, solution channels or coarse material. A sample size of about 250-300 cm^3 was chosen and anisotropy in any degree in these samples was believed to be shown in the values of hydraulic conductivity. Theoretically, the REV is correlated with fluctuations in hydraulic conductivity, as illustrated in Figure 2. In our case, this means that extrapolations from our small samples to the field macro-scale are doubtful. All measured values are to be regarded as bound to the specific sample itself.

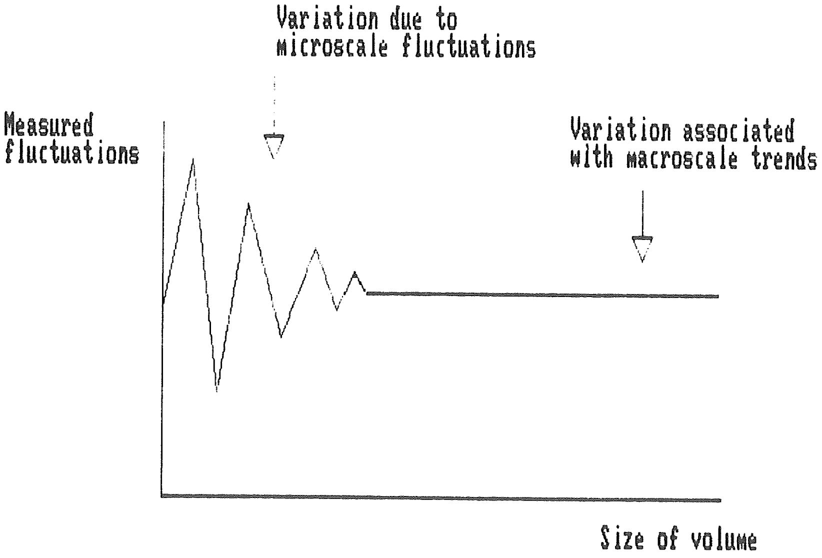


Figure 2. Hypothetical relationship between measured fluctuations and the size of the REV.

The PVC-cylinders with the till-samples were put into shock-absorbing cooling-boxes for transport to the laboratory. The air in the cooling-boxes was water-saturated by spraying water on the walls and inserting wet cloths. No dry-fissures or other damage has been observed in the transported samples.

The sampling method required a certain consolidation of the till. The clay content in the till must not be too low. Experience has shown that the clay content should be at least 3% at a water content of between 5-10% to get well-combined samples. Our sampling method offered an opportunity to get undisturbed till samples, as far as possible.

In the laboratory, the water content and the bulk density of special samples were measured, as well as the weight of the trimmed permeameter samples. The bulk volume of the permeameter samples was calculated from the bulk density and the weight. The volume values were later checked by the amount of epoxy used in the preparation of the permeameters.

Permeameter tests

The hydraulic conductivity of soft sediments can be measured with different types of permeameters. Methods that have been more or less standardised were described by Akroyd (1957). The sample-size and the permeameter method in this project emanate from the constant head permeameter but have been developed and adjusted to our special requirements.

Nipple permeameters were made for each sample by pouring epoxy-resin (Araldite M and Hardener HY 956) over the till lumps in the PVC-cylinders (Lind & Nyborg, 1986). The natural moisture content of about 5-10% was retained in the samples, which effectively prevented the resin from penetrating the samples.

After the hardening process, an opening with a diameter of 70 mm was made at top and bottom by boring with a slow-turning lathe and the permeameters were preparated as shown in Figure 3.

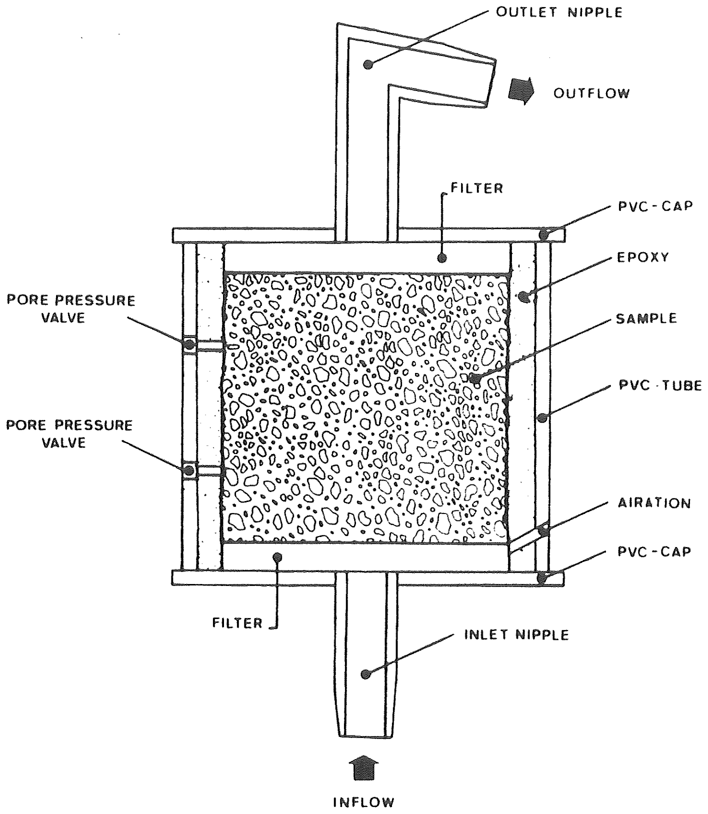


Figure 3. Permeameter.

The hydraulic conductivity was measured in a special constant head permeameter in which a steady upward flow through the sample was established, Figure 4. To prevent air becoming trapped, the saturation process was accomplished gradually to ease capillary rise in the finer part of the pore system. The inflow water was de-aired by heating and during the tests the inflow water was warmed up to 25 degrees centigrade, which is about 5 degrees warmer than the till samples.

The pore pressure nipples had an inner-diameter of 3 mm to prevent capillary effects. The permeameter measurements were made at a low inflow head pressure to prevent disturbance of the sample fabric due to lack of backpressure. The established gradient was about 2. The hydraulic conductivity was calculated both from the pore pressure difference and from the gradient over the sample height. In practice, the reliability of the calculated hydraulic conductivity is dependent on the moisture-saturation and the hydraulic gradient. Too low gradient during insufficient moisture-saturation will give an invalid value of hydraulic conductivity.

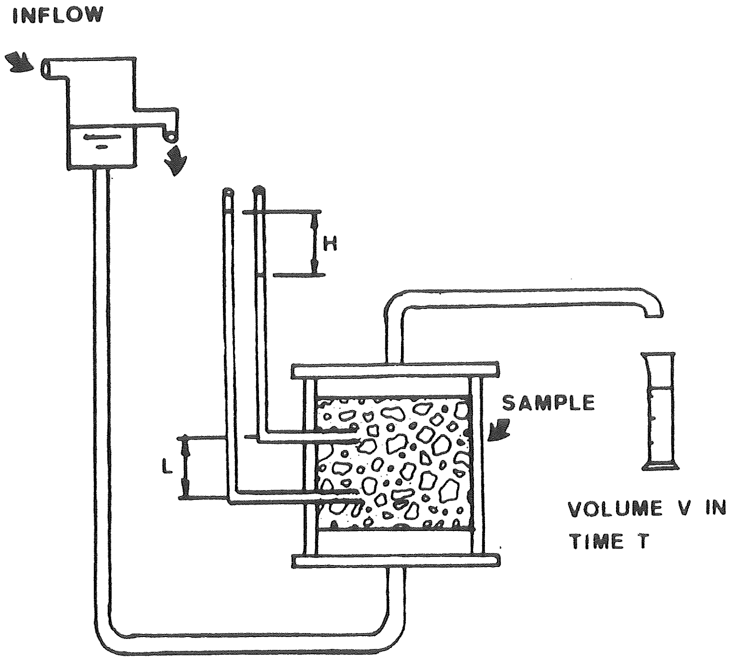


Figure 4. Constant head permeameter.

However, provided there is total moisture-saturation during measurements, all negative effects of the low gradient are negligible. All tests during our measurements have shown an almost total saturation during the experiments.

The hydraulic conductivity was calculated by means of Darcy's law. The hydraulic conductivity varies with the temperature and the K-value was specified for 15.6 degrees centigrade (60 degrees Fahrenheit) according to the definition given by Wenzel (1942).

Water retention analyses

After the hydraulic conductivity measurements, the top and bottom parts of the permeameters were removed and the samples were then placed in a device for water-retention analysis (Holm, 1981).

The pore-size distribution was calculated to define the active part of the pore-system (the effective pore-volume) during the saturated water-flow test. Pore-size distribution curves were obtained by means of standard suction moisture content measurements, from which the effective porosity was calculated.

Grain-size statistics

After the water retention analyses, grain-size distribution and sorting were obtained by sieving and pipette-analyses on a quarter of the samples. Grains for roundness and sphericity analysis were separated. The spatial relationship was also studied since tills of different origin have different frequencies of beds and bands of coarse-sorted material. Samples containing clasts larger than one-fifth of the sample diameter were excluded from the hydraulic conductivity calculations. After the grain-size distribution, the rest of the samples were impregnated with an epoxy-resin mixture to make the thin-sectioning procedure possible.

Impregnation

Through impregnation of fluid-sensitive, friable, uncemented and naturally moistured till is difficult using standard techniques. An impregnation method was therefore developed to make impregnation into naturally moistured till possible without macro, or micro, texture disruption (Lind & Nyborg, 1986). The method is divided into two stages. First (Figure 5) the pore water is successively replaced with an increasing amount of acetone, starting

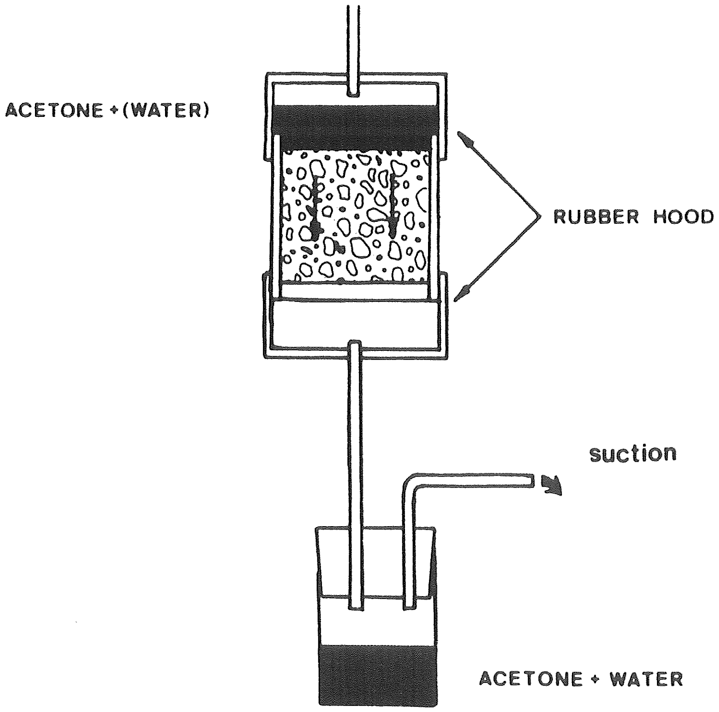


Figure 5. Replacement of pore water with increasing concentrations of acetone in water.

with a 5% mixture. This successive penetration by acetone takes about 48 hours. That no water is left in the sample is tested by shaking the outcoming fluid with ligroin. Remaining water would then cause an emulsion. After replacement of the pore water, an epoxy-resin mixture is allowed to penetrate the samples (Figure 6), partly by suction and partly by a slight positive pressure (0.04 bars) in the upper chamber (Z). The positive pressure is built up by creating an acetone-vapour (W). The epoxy-resin is injected into the upper chamber and is allowed to penetrate for 12 hours. Afterwards, the rubber caps are removed and the resin is allowed to cure. After several experiments with different conventional resins, Epofix was selected for its excellent impregnant properties. Epofix is a two-component, cold-setting epoxy-resin. When diluted with acetone, its low viscosity permits effective penetration of the till. The cured epoxy has high strength and medium hardness, withstanding routine thin-sectioning procedures.

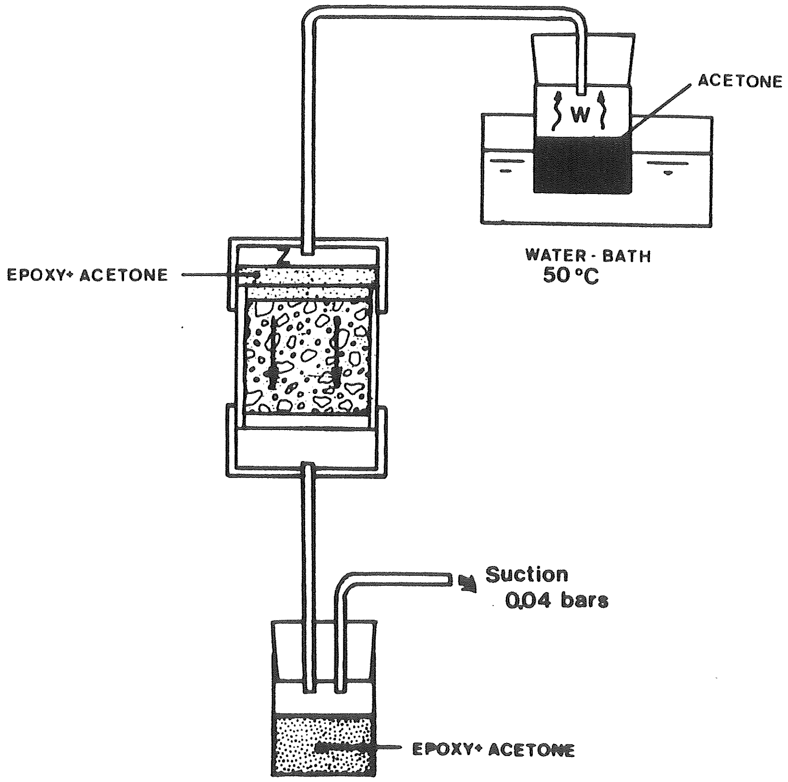


Figure 6. Impregnation of samples containing acetone with an epoxy-resin mixture.

Thin-sectioning procedure

The thin section, an 0.03 mm thick slice of till, is the standard type for all structural microscopy and image analysis. The samples are cut according to Evensson (1970), Figure 7, to an appropriate size and cast in a mounting medium ready for grinding and polishing. The purpose of grinding is to remove surface irregularities, remove casting resin that covers the sample, reduce the thickness, prepare a smooth surface for further work and remove any zone of major deformation resulting from initial sample cutting. Important structural information is readily obtained by an image analytical system only in polished sections.

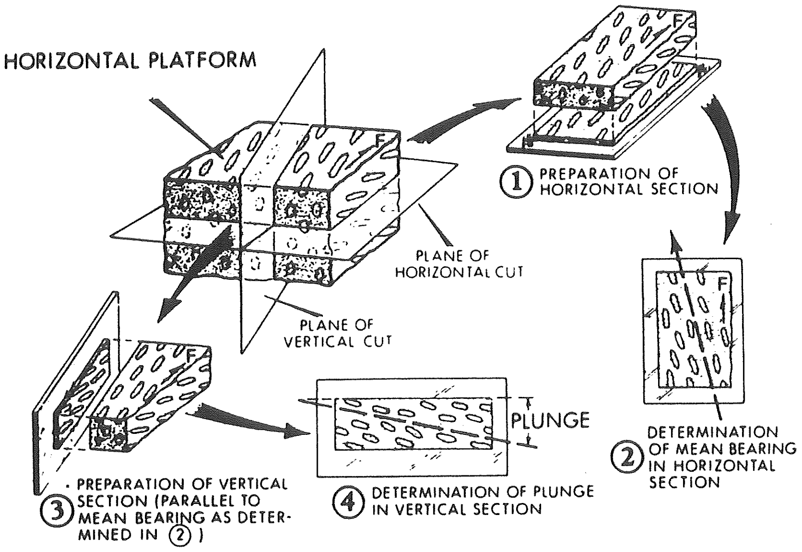


Figure 7. Preparation of thin sections (from Evenson 1970).

Polishing is done using diamond abrasives and is continued until no deep scratches are visible even in the hardest phases. The sample is fixed horizontally on a plate and mounted on a microscope universal stage for grain orientation preference analysis. The water-flow direction was coordinated with the universal stage and with a reference line in the ocular. About 60X magnification was used. Every particle of medium-sand size was investigated. When a particle of a suitable shape had been observed (A/B > 3/2, A=long axis, B=short axis), the strike of the A-axis was measured. The number of grains that did not fulfill the criteria was also counted and the percentage of grains that were elongated was calculated. The same procedure was repeated on the vertical thin-section when the dip was measured. About 200 elongated grains were measured in both the horizontal and vertical sections.

Grain-orientation preference analysis

The results of the grain-orientation preference analyses are in the form of two-dimensional values on each sample - one horizontal (the azimuth direction) and one vertical (the dip direction). The mean direction or preferred orientation was computed in both the horizontal and vertical plane. This was done using the computer program TILSTAT (Nyborg, in press) in order to determine the semi-3-dimensional orientation (3D-angle), Figure 8. Because the elongated grains have two ends that point in opposite directions, it is in this case not appropriate to use the traditional eigenvector analysis to calculate the mean direction. A solution to this problem is to find a function that is periodic in 180 degrees. The cosine-squared distribution then reaches a maximum at either end of the preferred axis.

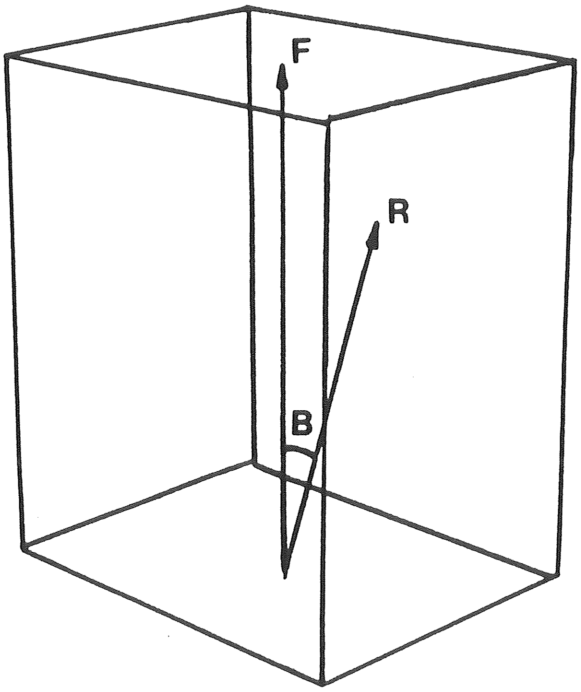


Figure 8. A hypothetical block of soil with the mean 3-dimensional orientation of grains, R, versus the direction of water flow, F, in the permeameter.

Analysis of axial data using this distribution has been discussed by a number of writers, including Mark (1973). If θ is the mean direction and θ_i the direction of the axis of the i^{th} grain, the mean direction will be that direction θ which maximises the function:

$$\sum_{i=1}^{N} \cos^2(\theta-\theta_i) = \max \qquad (4)$$

where

θ = Mean direction

θ_i = Direction of each grain

N = Number of grains

Eigenvectors and normalised eigenvalues are then computed. The eigenvectors refer to the direction of maximum clustering. The eigenvalue method gives better information about the distribution of a set of axes than does the rational vector approach. This will provide a better basis for a physical interpretation of the statistical results. The eigenvalue represents the degree of clustering or orientation strength, S. The higher the value of S, the stronger the orientation. Eigenvalues must be interpreted with caution, when data are bimodal or multimodal because this can result in the eigenvectors falling between modes. The azimuth mean direction (horizontal thin-section) and the dip mean direction (vertical thin-section) of all samples are then plotted on a Schmidt equal-area lower hemisphere projection as linear elements. Three-dimensional analysis is important because presentation such as rose diagrams results in the loss of information concerning clast dip.

For the calculation of the 3D-angle, B, we used spherical trigonometry. In this case, we used a solution for oblique-angled triangles (Higgs & Tunell, 1959). Unlike in plane trigonometry, we were not concerned with the lengths of the sides - the size of the triangle (or radius of the sphere) is immaterial in a Schmidt-net, and the sides are expressed in circular measurement as the angle which they subtend at the centre of the sphere. Labelling the centre of the stereogram O (Figure 9), two sides are given - y(dip) and z(dip) and the included angle X (as with two dips of known azimuths). To calculate the third side, FH (space-angle B), the following formula is used:

$$\cos FH = \cos y * \cos z + \sin y * \sin z * \cos x \qquad (5)$$

since y = 0 degrees (the dip of the applied water flow direction = 0 degrees)

$$\cos FH = \sin z * \cos y \qquad (6)$$

where FH is the semi-3-dimensional angle B.

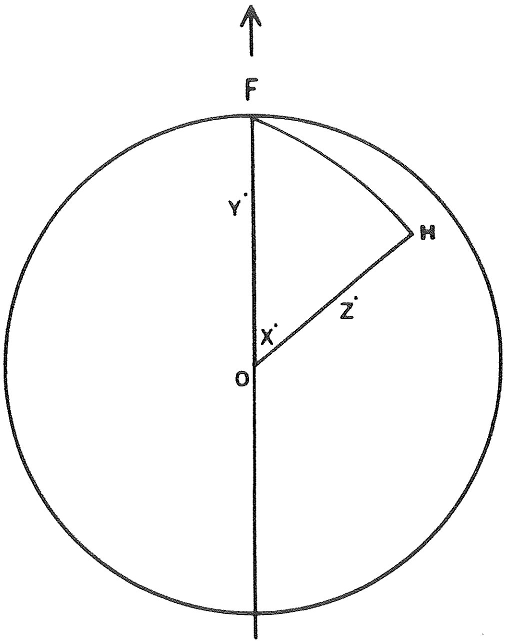


Figure 9. Calculating the semi-3-dimensional space-angle to the direction of water flow in the permeameter.

Image analysis

The saturated water flow through a media is dependent upon the porosity and the inner specific surface of the media. Thus, it is of interest to study the grain shape and the grain surface structure (Lind & Nyborg 1988). The grain shape is defined by the sphericity, S, as a relationship between the perimeter and the area

$$S = \frac{P^2}{4\pi A} \qquad (7)$$

where P = perimeter

The sphericity is a dimensionless expression for grains projected in a two-dimensional plain. S for a circle is 1.00, and for a square 1.27.

The surface structure, roughness, has been discussed by Ehrlich et al. (1969, 1980). They use a method based on Fourier - analysis to describe the surface structure. The roughness coefficient, P, is defined as:

$$P = \sqrt{\tfrac{1}{2} \sum_{n=1}^{\infty} C_n^2} \tag{8}$$

where C = The Fourier coefficient

P is thus the square root of one-half the sum of the squared Fourier coefficients. This is directly proportional to the variance. It is then possible to define another roughness coefficient, F, based on the variance.

$$F = \frac{1}{n} \Sigma\, r_x^2 \tag{9}$$

where r_x = deviation from the mean grain radius

To make the expression dimensionless, we divide by the squared average radius

$$F = \frac{\frac{1}{n} \Sigma\, r_x^2}{\bar{r}^2} = \frac{\frac{1}{n} \sum_{i=1}^{n} (\bar{r} - r_i)^2}{\bar{r}^2} \tag{10}$$

where $\bar{r}$ = average radius

Grains of the size of 1-2 ϕ (0.50-0.25 mm) were separated from the till samples. The grains are mainly separated along mineral boundaries, into uncomminuted separate mineral grains (Haldorsen 1980). This makes it easy to separate quartz-grains from grains of differring composition. The grains were placed under a microscope with a magnification of 40x. A video camera was mounted on the microscope and gave the input signal.

The image analysis system consisted of the following (see Figure 10):

- A personal computer (IBM PC/AT)
- A printer (IBM Proprinter)
- A frame grabber with image memory (Imaging Technology, FG-100-AT)
- A digitiser (Summagraphics, MM1201)
- A video monitor (Digital Equipment, VR 241)
- A TV-camera (Panasonic, CCD WVCD110E)
- A microscope (Olympus BH-2-TR30)

The video signal was captured in real time and the digitised image was presented on a video monitor. The contours of the grains were manually traced with the aid of a digitiser. Contour data were analysed in the personal computer and the results were stored on a hard disc. It was also possible to get a print-out of the results. The software was developed in cooperation with the Department of Applied Electronics, Chalmers University of Technology, Göteborg.

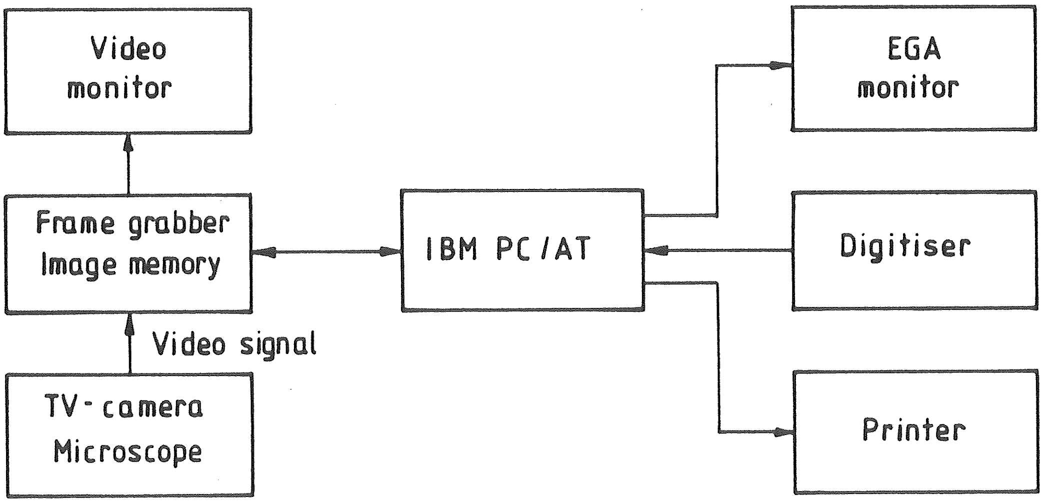


Figure 10. Image analysis system.

RESULTS

Chemical analysis

The permeameter tests have been carried out with relatively oxygen-rich water with another chemical composition than the natural pore water. One purpose of the chemical analysis was initially to study the relationship between the pore-water composition and the content of swelling clay minerals. However, the x-ray diffractograms showed that there were no such clay minerals in the till. Below follows a general interpretation of the change in pore-water chemicals and the effect on the hydraulic conductivity.

Chemical analyses have been carried out on water from 22 permeameters, see table in Appendix. During five of these analyses, outgoing water was continuously sampled during the permeameter tests (0-300 minutes).

The effect of exchangeable cation species on soil permeability is well documented (U.S. Salinity Laboratory Staff, 1954: Quirk and Schofield, 1955; Chen, Banin and Borochovith, 1983), in particular the deleterious effects of Na vs. (Ca+Mg). Soil permeability generally relates to exchangeable cations in the following order: Ca = Mg > K > Na. However, differences in the relative values of permeability have been reported. An example of measurements of hydraulic conductivity as a function of time during a permeameter test is presented in Figure 11. These data show a slight reduction of hydraulic conductivity, suggesting that some short-term clay migration takes place. This could be caused by cation exchange through leaching. The major mechanisms involved in the decreases in permeability due to monovalent exchangeable cations are swelling, dispersion and clay migration, which affect the hydraulic conductivity of the soil. In situ clay particle rearrangement following aggregate destruction and resulting pore-size reduction is considered short-range migration, the downward movement of clay, which often leads to the formation of an impeded layer, being considered long-range migration (Chen, 1975; Chen and Banin, 1975). It is interesting to compare the effect of Na (Chen and Banin, 1975) with that of K. According to Chen and

Banin, 60-75% exchangeable K was required to cause the same reduction of hydraulic conductivity as exchangeable Na, suggesting that the deleterious effect of potassium is less than that of sodium.

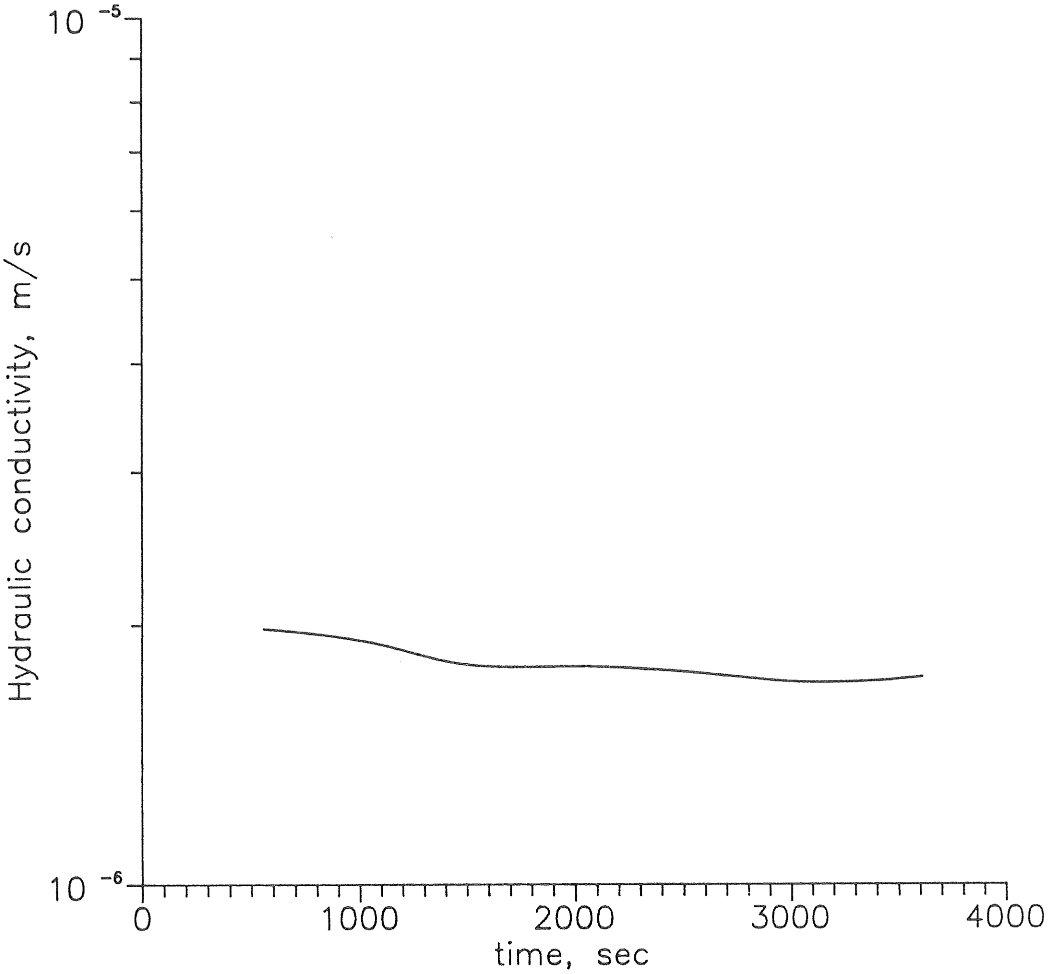


Figure 11. Example, TA 52, of the hydralic conductivity trend during a permeameter test.

The sampling series comprised altogether about 250 cm^3 of water from each permeameter, which is about three times the por volume. The declining cation concentration is explained by the direct correlation between the contact time of the pore water and the ion content. In the tests, the pore water that was held in the samples was successively replaced by input percolating water with short contact time in the samples.

Summary statistics for the chemical parameters are presented in Figures 12-14. A trend analysis has also been performed. It fits a line through the time series data in an exponential power curve.

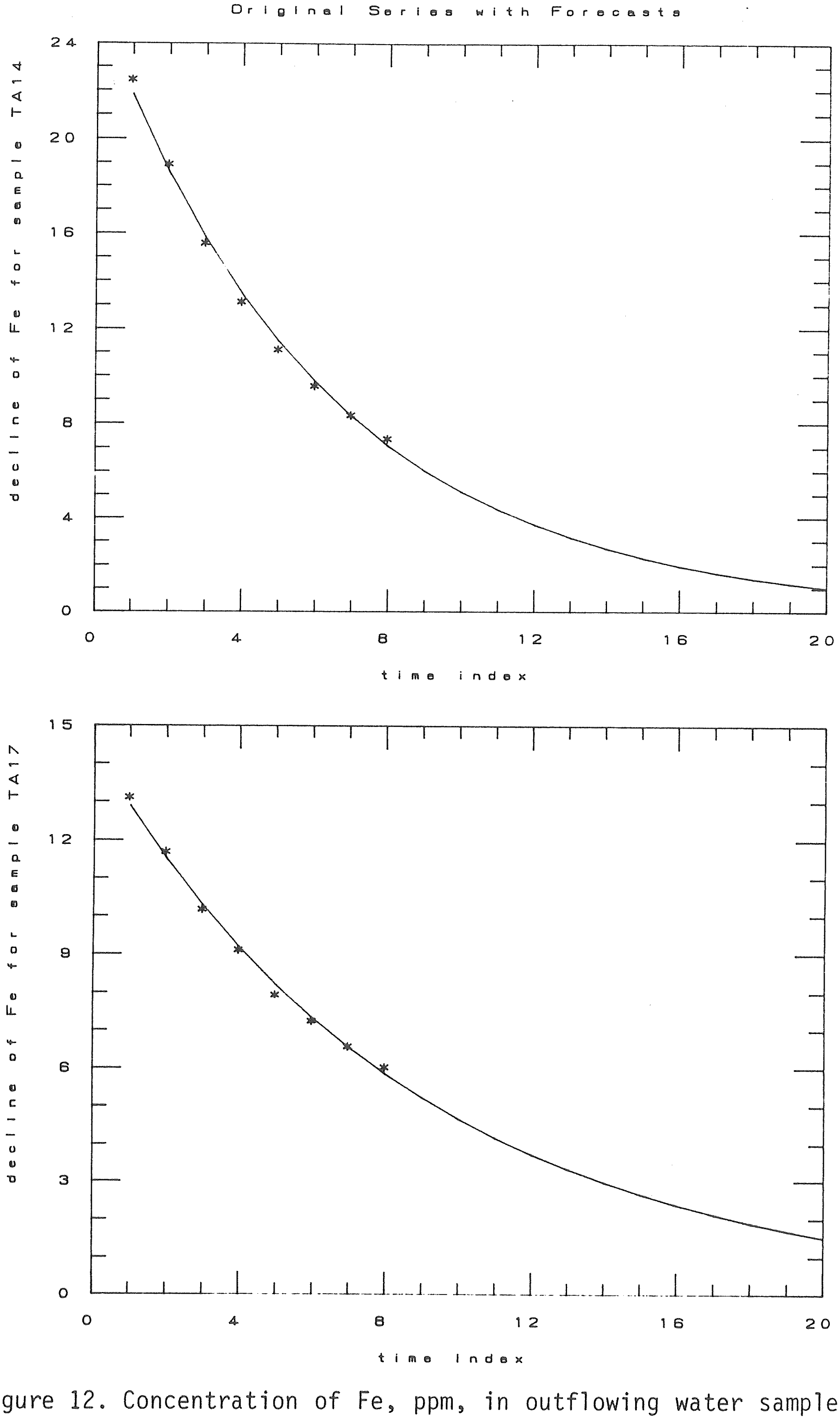


Figure 12. Concentration of Fe, ppm, in outflowing water sampled at intervals of 30-40 min.

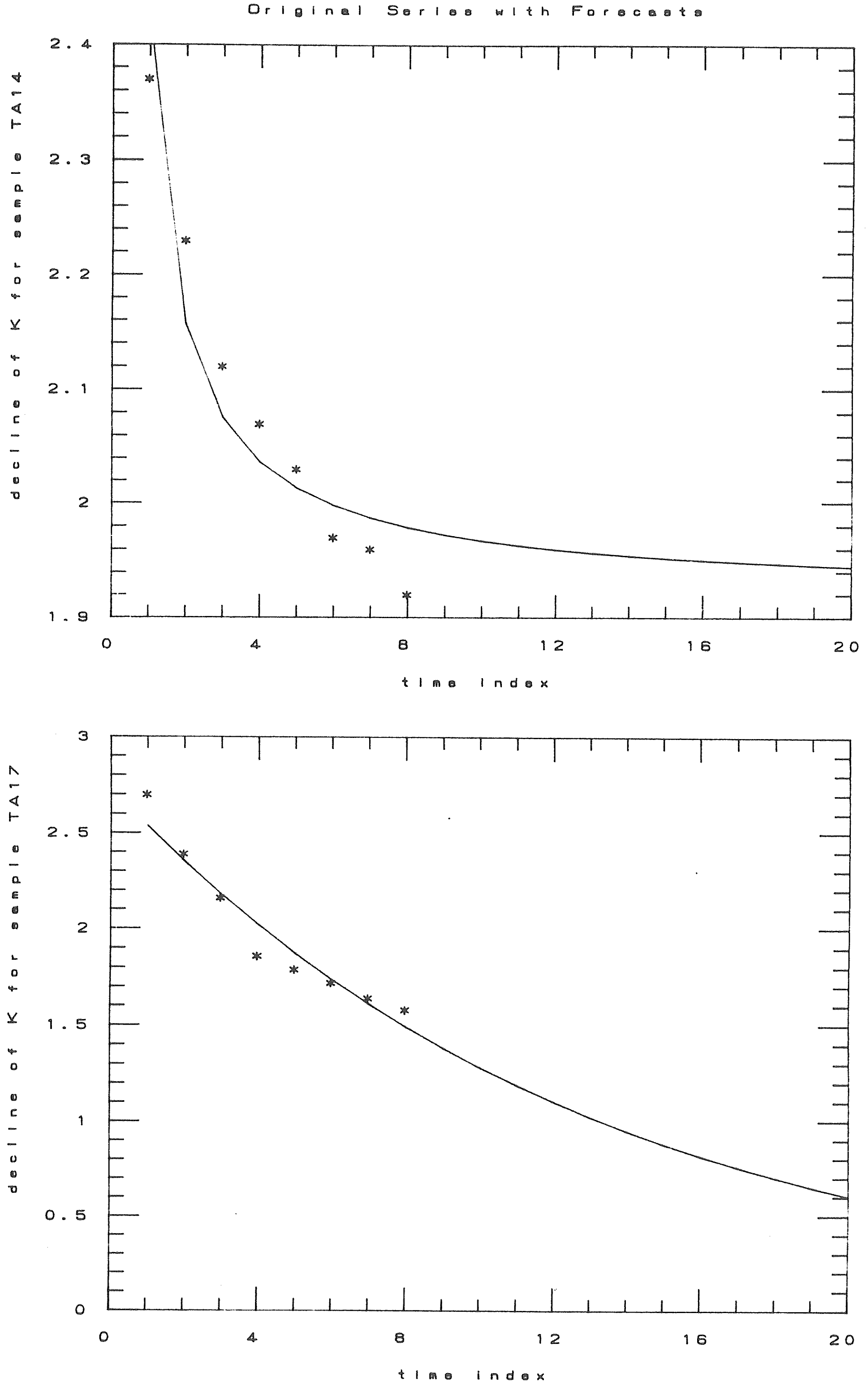


Figure 13. Concentration of K, ppm, in outflowing water sampled at intervals of 30-40 min.

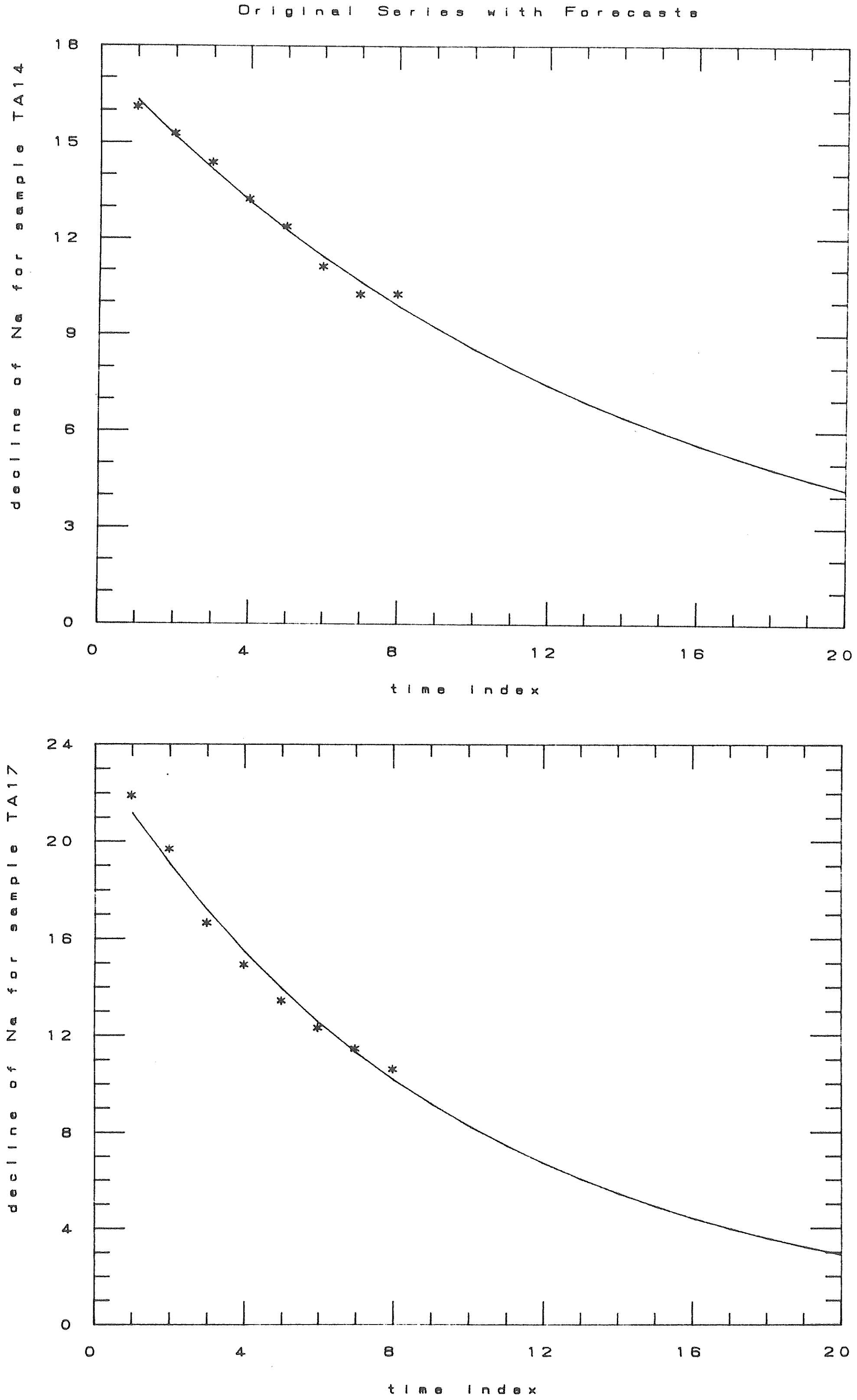


Figure 14. Concentration of Na, ppm, in outflowing water sampled at intervals of 30-40 min.

The exponential curve is based on the function $Z = \exp(a+bt)$ which fits an exponential decline curve through the data. The original observations and the estimated trend line are plotted.

The decrease in the concentrations approaches the chemistry of the ingoing water. The cation concentration declines at various rates in the different samples; the steepness of the concentration curves differs.

It could be assumed that the leaching of ions is dependent on the water velocity. It would then be possible to see a connection between the steepness of the concentration curves and the hydraulic conductivity. From our measurements, however, no such relationship can be established. The leaching seems to be independent of the hydraulic conductivity.

The total exchange of cations varies considerably between the samples. Nothing indicates that there is a connection between the hydraulic conductivity and the total amount of ions. The amount of aluminium oxide (Al_2O_3) and Silica (SiO_2) can be used as an indication of the weathering in the till. In the present investigations, however, there seems to be no connection between these oxides and the hydraulic conductivity.

Chemical composition of ingoing water

pH		6.93
Calcium	mg Ca^{++}/l	16.40
Magnesium	mg Mg^{++}/l	1.80
Iron	mg Fe^{+++}/l	< 0.1
Manganese	mg Mn^{+}/l	0.05
Aluminium	mg Al^{+++}/l	0.05
Sodium	mg Na^{+}/l	8.00
Potassium	mg K^{+}/l	1.28
Silica	mg Si^{++++}/l	1.12

Bicarbonate	mg HCO_3^-/l	18.30
Chloride	mg Cl^-/l	9.30
Sulphate	mg SO_4^{--}/l	37.60

Tension and pressure in glacial till

Within the project there has been discussion on soil pressure in glacial tills and the risk of disturbance and tension unload fissures in samples taken at a depth of 2-3 m. The tills at Tahult and Ödenäs have been interpreted as basal deposits, lodgement tills according to Haldorsen et al. (1983), and a little overconsolidation could be expected. This has, to some extent, been supported by the bulk density measurements, where no significant changes were indicated at 0.5-2.0 m depth. At the sampling and the following analyses of thin sections, there was no trace of disturbance in the samples.

In our investigations, we could not see any visible disturbances either in the Tahult and Lekeryd samples or in the samples from Ödenäs.

We would like to underline in this connection that the whole chain of analyses within this project is based on corresponding samples. Small disruptions that may occur during the sample-excavation are included in the sediment structure and do not disturb the results.

Hydraulic conductivity

The hydraulic conductivity, K, was calculated in two ways; as the hydraulic gradient relative the sample-height, K_{tube}, and as the gradient of pore pressure measurements in pore pressure values, K_{nipple}.

As shown in Figure 15, there is a good correlation between the K_{nipple} and the K_{tube} values. K was expressed as the mean of 3-8 measurements. The variance was generally lower for the K_{tube} values and in the further discussion the hydraulic conductivity is expressed by K_{tube} values.

The hydraulic conductivity varied from about $1 \cdot 10^{-8}$ m/s to $1 \cdot 10^{-5}$ m/s. The sample values from the same locality at Tahult were spread over the whole range and it could be established that the till, at least on a scale of 10 cm, was very anisotropic.

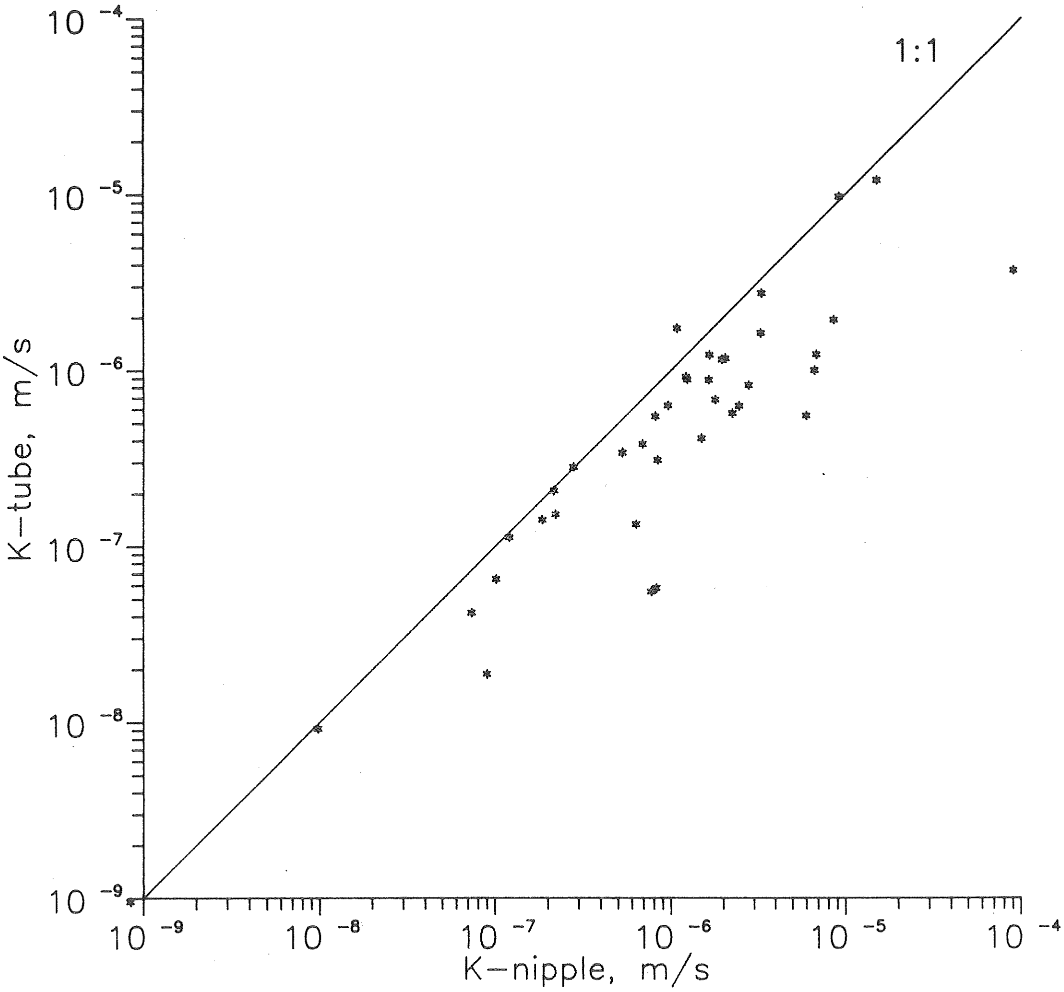


Figure 15. Hydraulic conductivity calculated as K_{tube} and K_{nipple}.

Water-retention characteristics

Water-retention curves have been drawn for the individual samples within the permeameters. The equipment used was described by Holm (1981) and is comparable to that described by Andersson and Wiklert (1972) model. The samples were applied to a porous plate with the aid of a quartz-meal so that an unbroken capillary pore-system was established between the plate and the sample. The permeameters were cut off close to the till surface before application to the plates. In some permeameters, with irregularities in the samples, the surface was adjusted with till material from the same locality. This "pack-till" was excluded from any calculations, however.

A series of pressures (suctions) were applied to the plate and the samples were drained to equilibrium before each pressure session. Tests have shown that at a higher pressure than about 2.5 mwp (pF 2.4) there is a risk of disturbance in the samples and the water retention measurements were therefore made only on coarse to fine pores down to about 15 µm. With the aid of Navier-Stokes' equation (11) for the relationship between the driving forces and the average velocity, v, in a cylindrical tube of small radius, it is possible to estimate the pore size of a corresponding porous isotropic media on the basis of gradient and velocity. Applied to the present permeameter tests, a distribution of pore-size values of the corresponding isotropic media was obtained from about 2 to 500 µm. The lowest values were found in samples with high flow-active porosity and low hydraulic conductivity. However, since the till also contains coarse pores, part of the waterflow is likely to take its way through these, whereas the flow within the fine pores is decreased to the same extent. The ground-water flow in pores finer than 15 µm is in practice of no importance. The chosen pF-series should then give a good picture of the active pore spaces in the permeameter. (The fine-pore system is, however, of great importance for the capillar water transport from the saturated zone to the root zone.)

$$\frac{8\mu}{R^2}\,\bar{v} = -\left(\frac{dp}{dl} + \rho g\frac{dz}{dl}\right) \qquad (11)$$

where

μ = dynamic viscosity
R = radius
$\bar{v}$ = mean velocity
ρ = density
g = gravitation

Pore-size distribution curves based on water-retention measurements are formed under the assumption that the force with which water is retained in a pore depends, among other things, on the pore diameter. These curves will reflect the true pore-size distribution only to the extent that the pores form a continuous system, with numerous broad cylindrical interconnections and few large pores with restricted access to the main system. For this reason, Hall et al (1977), among others, have generally adopted terms such as "air capacity" or "retained water capacity" to designate drained or undrained pores at a particular suction and use "pore diameter" only as a secondary descriptive term. It has been shown that porosity values obtained by image analysis of thin sections are larger than those obtained by water retention measurements (Bullock & Thomasson, 1979). The pore distribution values in this report should therefore be considered more or less as minimum values.

Pore distribution

The total porosity, n, of the samples has been calculated from the water content measured in saturated samples. The porosity values ranged from 17.5% to 47%. Examples of pF-curves can be seen in Figure 16. More than 80% of the samples had a total porosity value of between 20% and 35%, however. Lundin (1982) presented a similar distribution of the total porosity within till-samples taken at depths of 1-1.5 m.

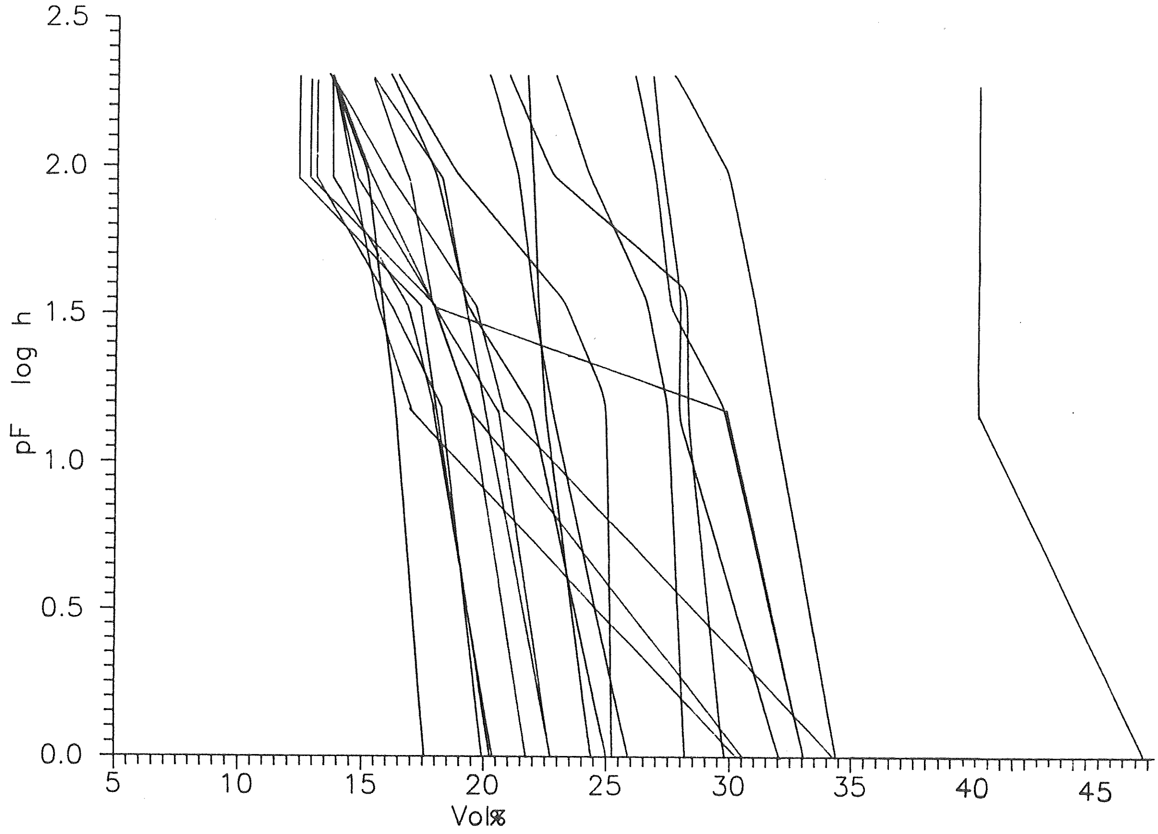


Figure 16. Examples of pF-curves.

From the pF-curves, it can furthermore be seen that most of the samples had quite a uniform pore distribution within the measured interval. Some of the curves deviate at about pF 1-1.5, however, and form either concave curves with over-representation of coarse pores, about 100-2000 µm, or convex curves with corresponding under-representation of coarse pores. The pF-curves are classified as a = straight "curves" (lines); b = concave curves, and c = convex curves. In the next chapter, these curves are compared with the corresponding hydraulic conductivity curves.

Of interest concerning the hydraulic conductivity is the effective porosity, n_e, that is the part of the total soil volume that is occupied by pores which are wide enough to allow water to flow at a certain hydraulic gradient. The effective porosity is usually defined as: "the ratio expressed as a percentage of the volume of material which, after being saturated, can be drained by gravity to its own volume" (Todd, 1959). Drainable water is usually defined as the amount of water that, after saturation, can be drained by a pressure (suction) of pF 2.0.

The effective porosity values varied between 2.5 and 18.0 per cent, but approximately three-quarters of the samples had an n_e value between 3 and 10%, Figure 17. Similar values have been calculated by Lundin (1982) and Nordberg & Modig (1974) on till samples taken at a few meters depth.

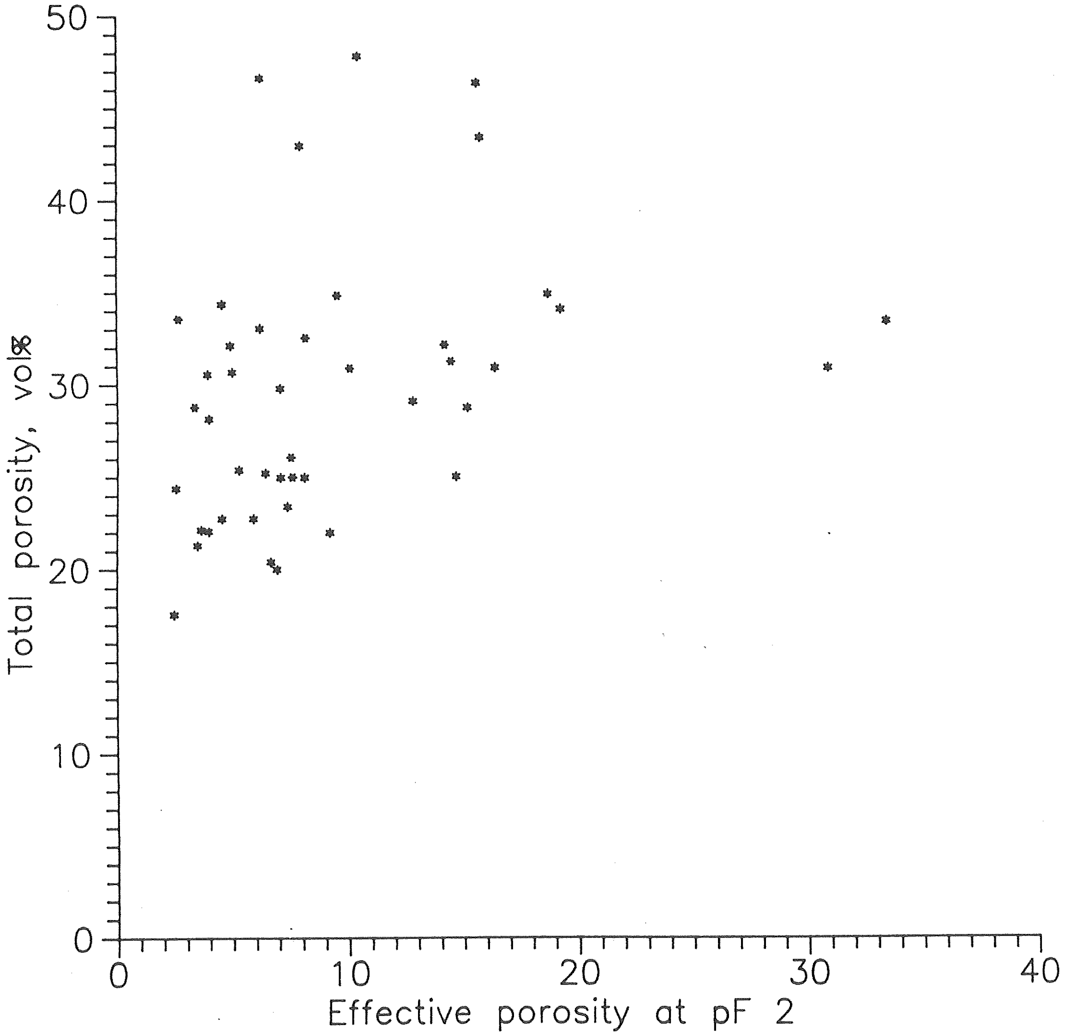


Figure 17. Total versus effective porosity.

There is an obvious positive correlation between the total porosity and the effective porosity. A rough estimate is that the total porosity is about 3 times the effective, and the relationship linear with a gradient of 2:1.

Because of the high gradients used in the permeameter tests compared with natural conditions one would expect an extension of the effective porosity interval. n_e was therefore also calculated for the whole drained interval, pF 0 - pF 2.31. This gave somewhat higher values of n_e. The relationship between n_e at pF 2.31 and n_e at pF 2.0 is shown in Figure 18. Especially for samples with low n_e-values, a certain adjustment is thus of importance in calculations of flow velocity and flow time.

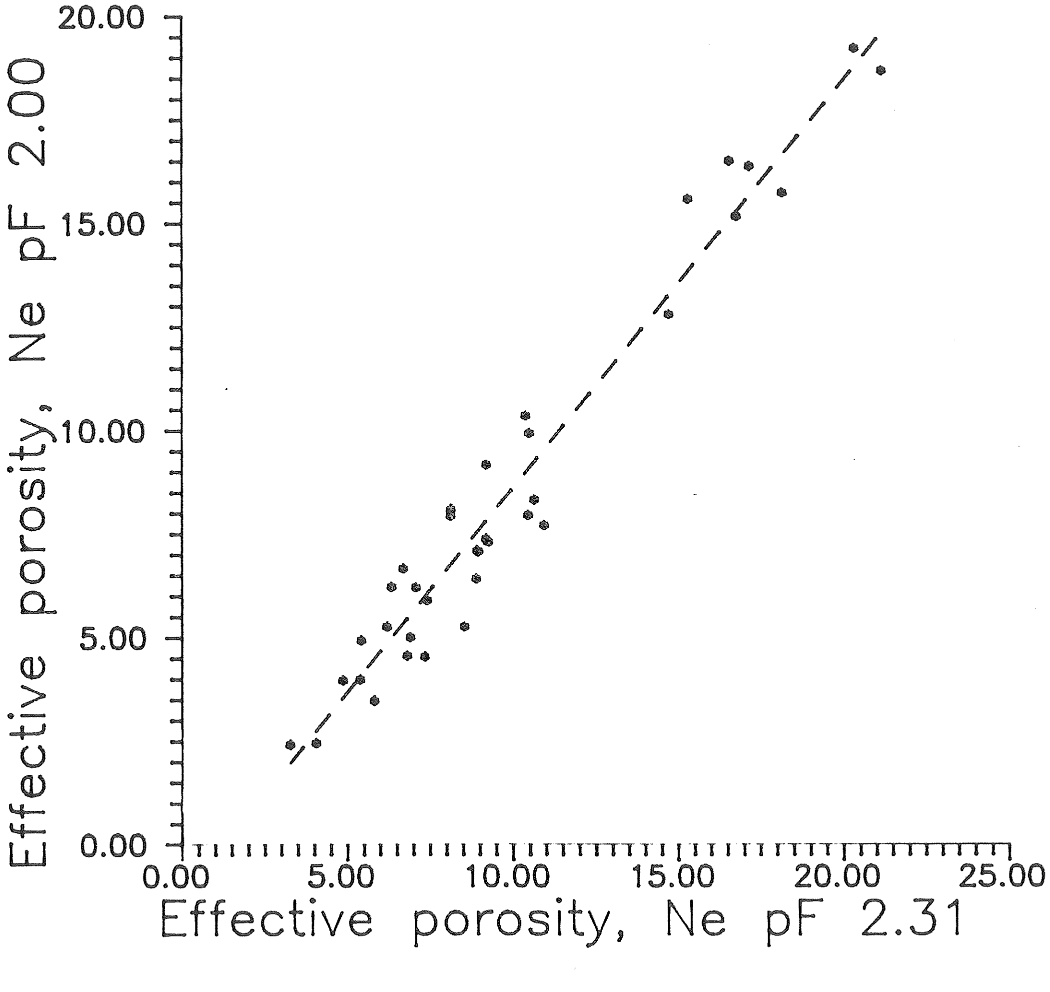


Figure 18. Effective porosity calculated at pF 2.0 and pF 2.31.

Porosity and hydraulic conductivity

Figure 19 shows the relationship between the total porosity and the hydraulic conductivity. The picture shows that there is a surprisingly weak correlation. It was assumed, however, that the highest correlation should be with the effective porosity or with a characteristic pore interval established in one way or the other.

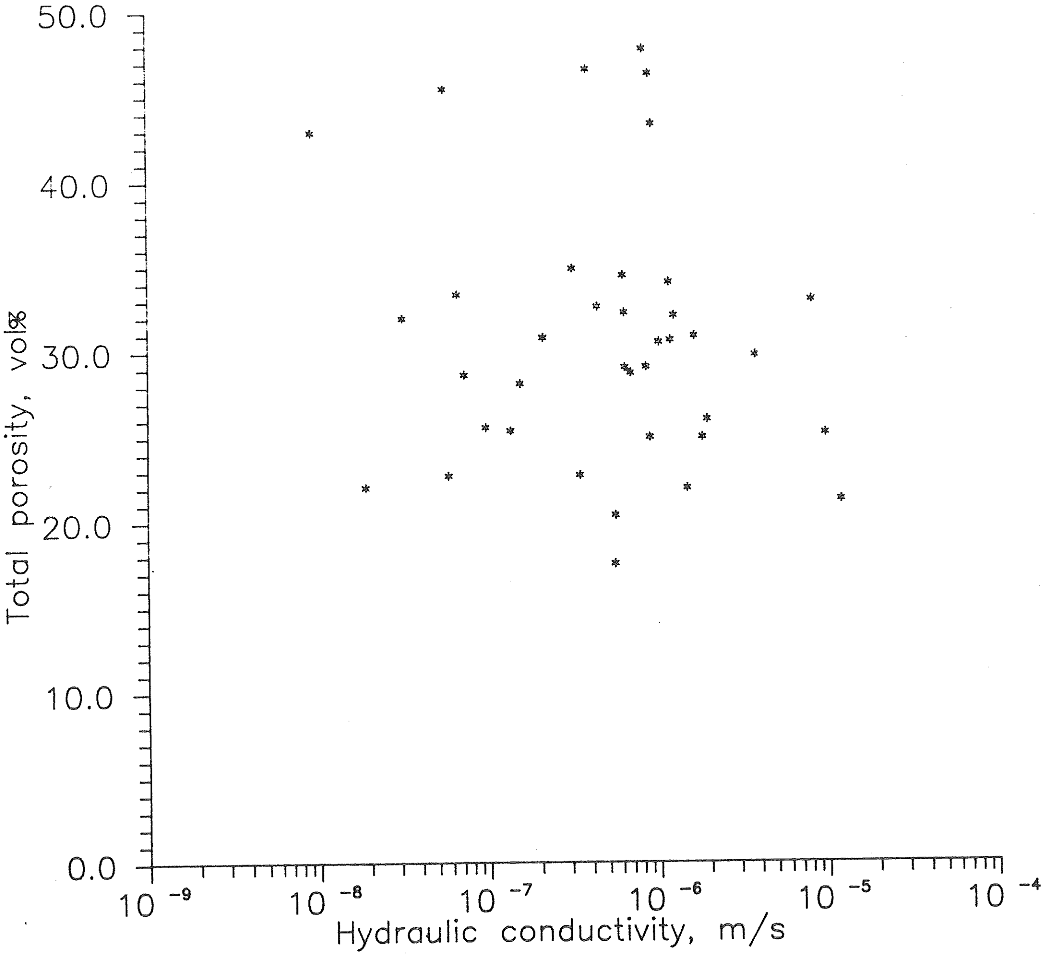


Figure 19. Relationship between the total porosity and the hydraulic conductivity.

The first step was to study the relationship between K and n_e defined at pF 0 to pF 2.31, pF 2.00, and pF 1.54, respectively. This is a way of studying the influence on the hydraulic conductivity of smaller and smaller intervals of the coarsest pores. The results, which are summarised in Figures 20-22, show an increasingly random picture as the pore interval is narrowed. A conclusion that could be drawn from this is that the coarse porosity not alone is the factor determining the hydraulic conductivity of till. This conclusion is supported by findings of Lundin (1982), where it can be seen, by combining water retention curves and hydraulic conductivity data, that the K-values of five different samples were very similar, whereas the effective porosity values varied from 2% to 10%.

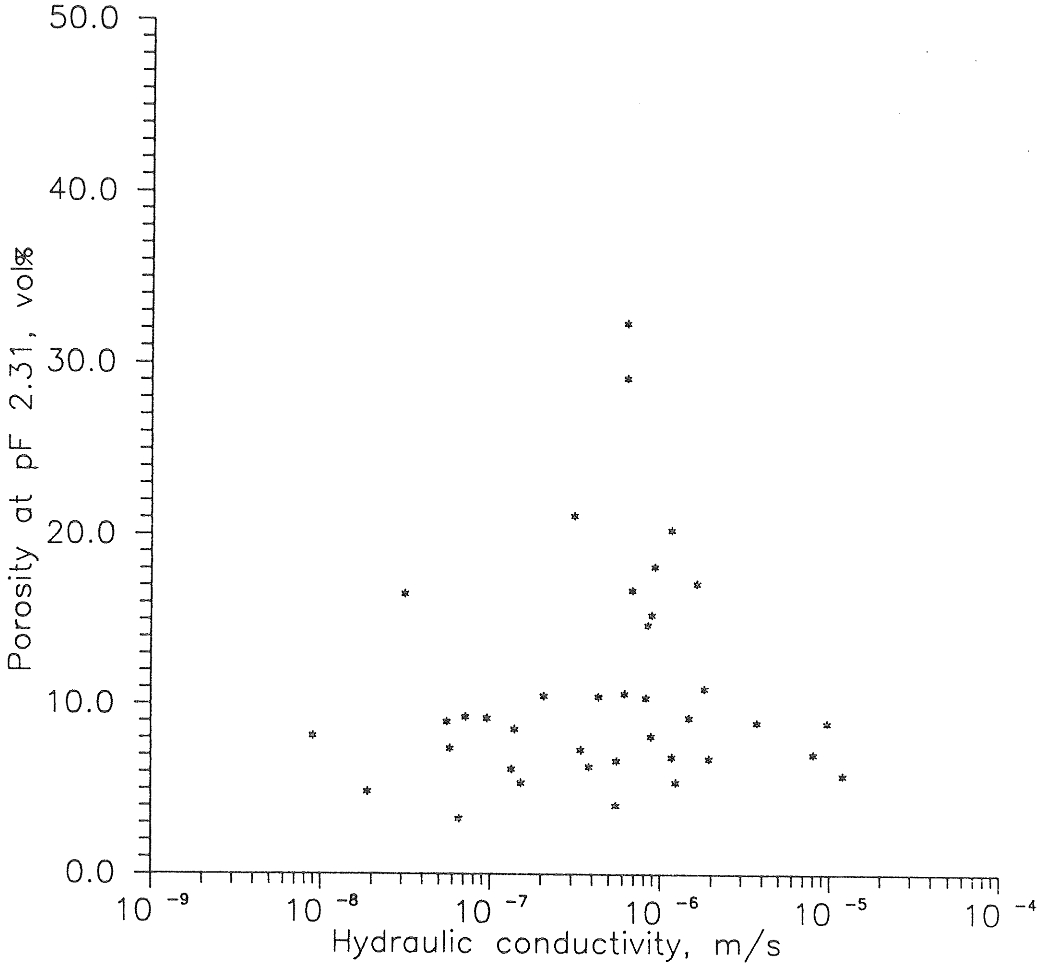


Figure 20. Effective porosity in the interval pF 0 - pF 2.31, versus the hydraulic conductivity.

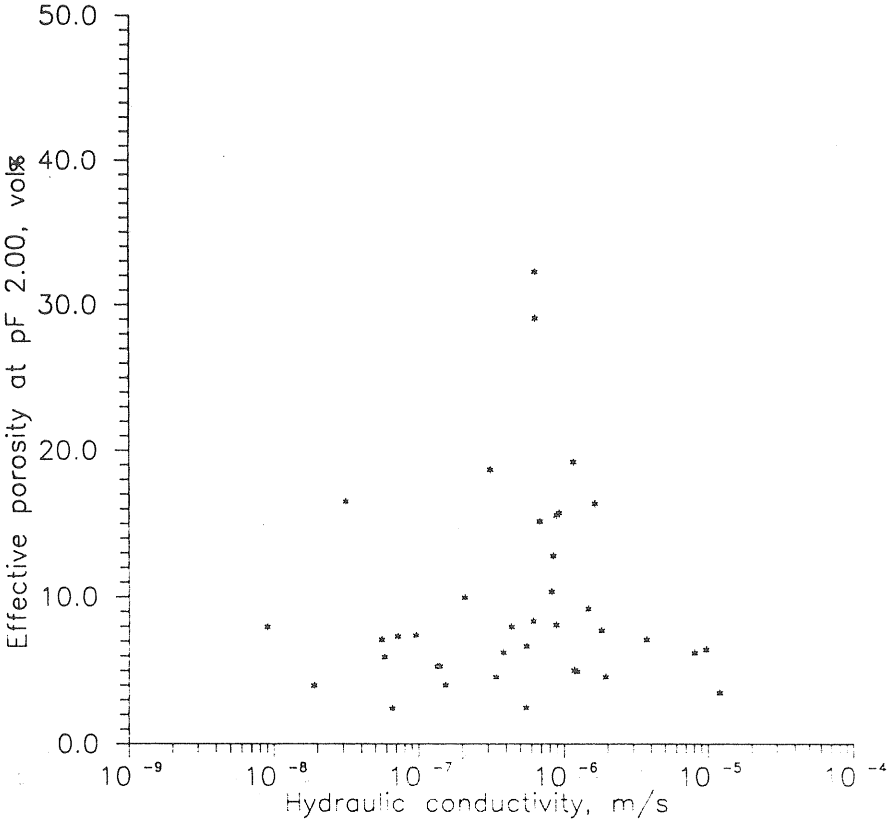


Figure 21. Effective porosity, in the interval pF 0 - pF 2.0, versus the hydraulic conductivity.

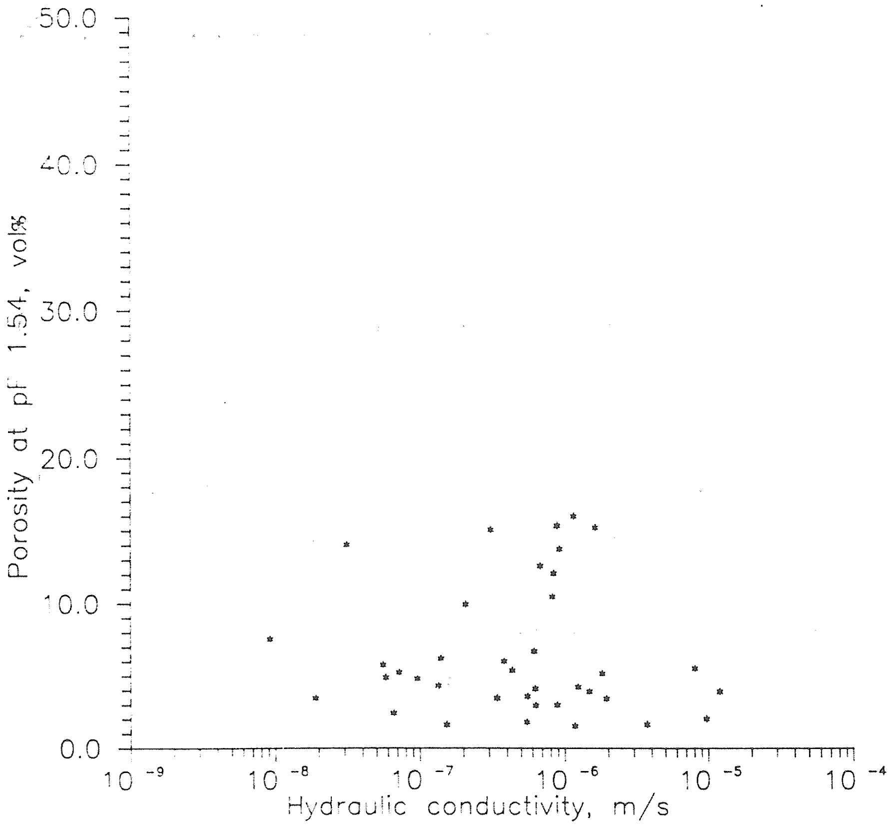


Figure 22. Effective porosity, in the interval pF 0 - pF 1.54, versus the hydraulic conductivity.

One limitation of the above method is that the samples are treated equally, without consideration of the indivudual pore distribution.

The next step was therefore to use the shapes of the water retention curves classified as a: straight, b: concave, and c: convex; (see previous chapter). The result is shown in Figure 23. This result also shows that the hydraulic conductivity is dependent on the pore distribution. Concave curves, that is over-representation of coarse pores, lead to higher hydraulic conductivity, but it is evident that the correlation is quite weak.

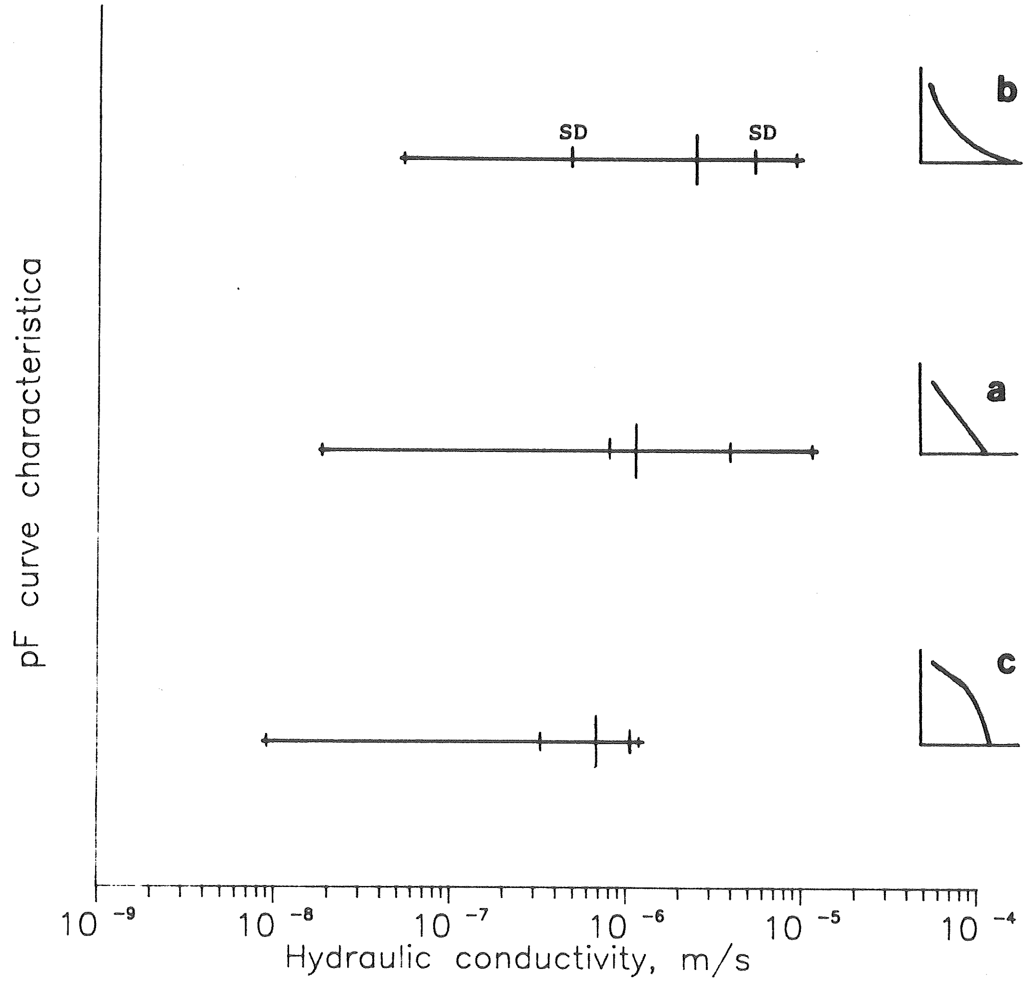


Figure 23. Relationship between the shapes of the pF-curves and the hydraulic conductivity.

Texture and hydraulic conductivity

The grain-size distribution was obtained by sieving and pipette-analysis of a quarter of the till samples, taken from the top and bottom of the permeameters. The dominating texture fraction was coarse silt up to, and including, medium sand. The clay fraction varied between 4% and 7% at Tahult and Ödenäs, and up to 18% at Lekeryd. The grain-size distribution is illustrated in Figure 24.

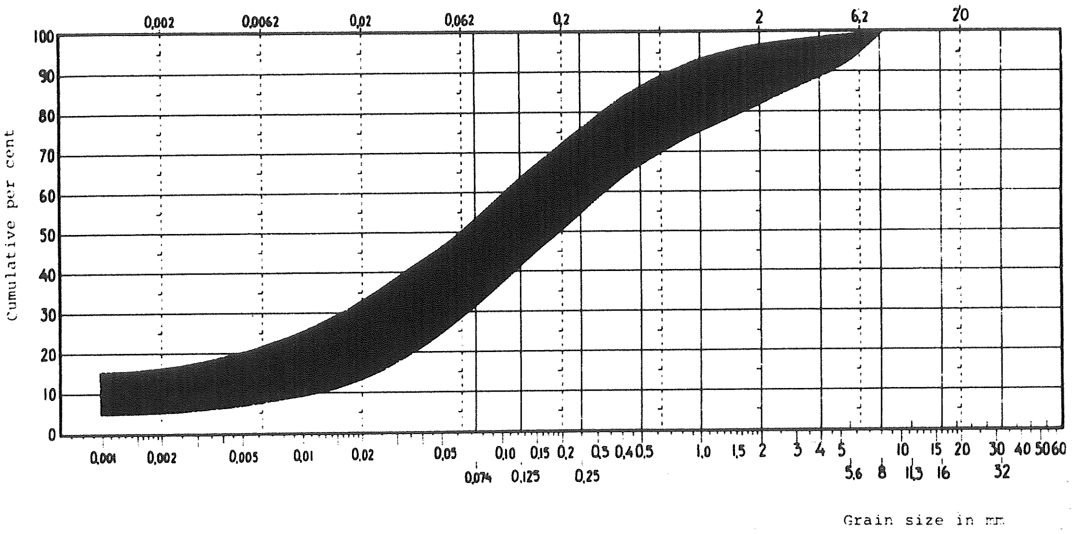


Figure 24. Range in grain-size distribution.

Sorting, σ_1, and mean grain-size, M_z, were calculated according to Folk & Ward (1957) as:

$$\sigma_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6} \qquad (12)$$

$$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \qquad (13)$$

where

ϕ-values = the grain-size for weight-% passing quantity according to grain-size analysis

The sorting, σ_1, varied between 2.5 and 4, which signifies poorly to very poorly sorted sediment according to the relative scale for classifying sediment sorting suggested by Folk & Ward. In Figure 25 σ_1 is plotted against K for each individual permeameter sample. The diagram shows that a lower sorting factor - that is better sorting - corresponds to higher hydraulic conductivity, but that the correlation factor is rather low. At the same time, there is a lack of clear correlation between M_z and K, Figure 26. Similar results with very low correlation between mean grain-size, sorting and hydraulic conductivity (calculated from infiltration tests) have been presented by Haldorsen et al (1983).

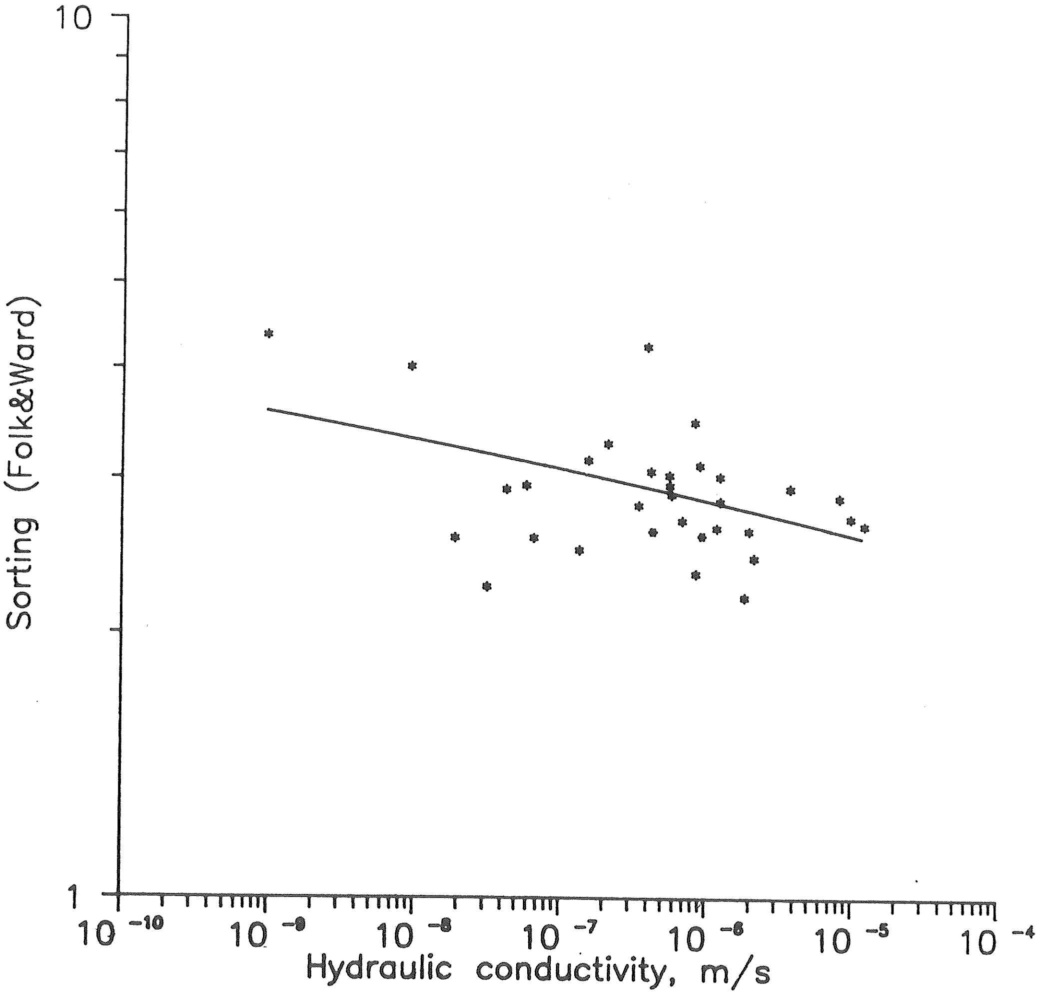


Figure 25. Grain sorting and hydraulic conductivity.

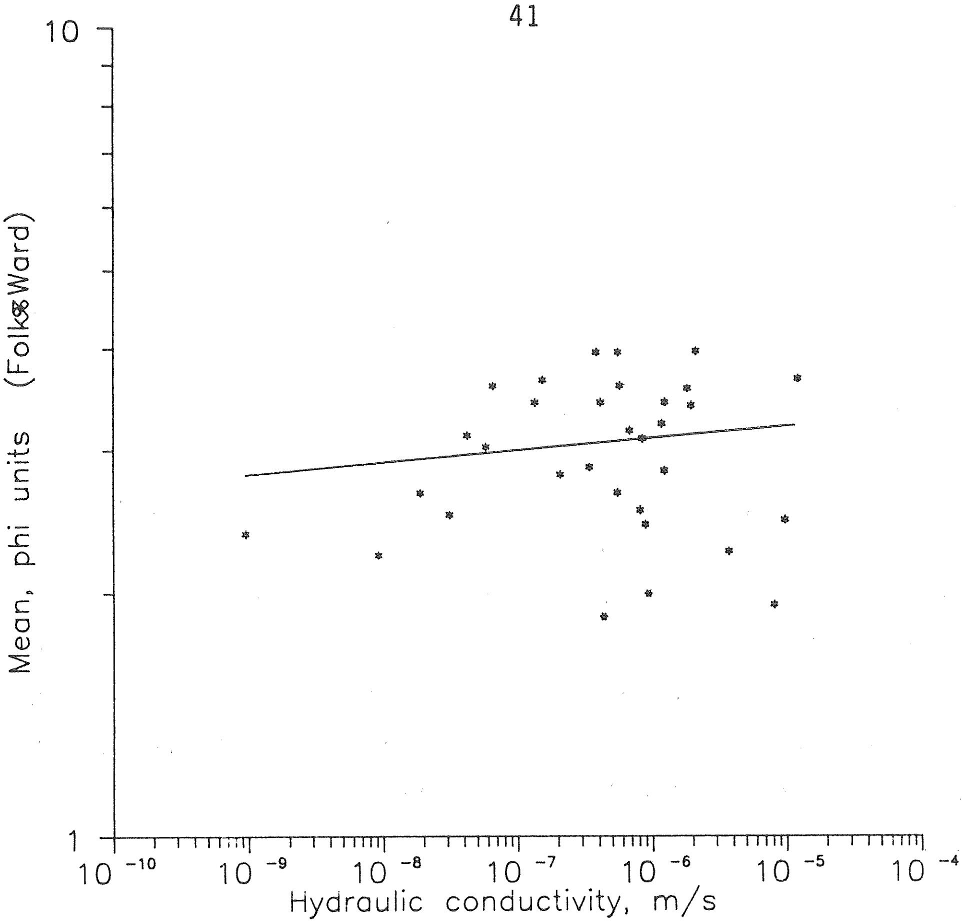


Figure 26. Mean grain-size and hydraulic conductivity.

Our results may be interpreted as showing that the hydraulic conductivity in the till samples is more or less independent of the grain-size, expressed as mean M_z, in the narrow interval that was studied, whereas the sorting, σ_1, is more important and has a detectable affect on the hydraulic conductivity. A change in the sorting value of about 0.5 corresponds roughly to a change in the hydraulic conductivity of about three decades.

Gustafson (1983) has shown that the porosity and the horizontal hydraulic conductivity for glaciofluvial sediments can be derived from the grain-size distribution, approximately expressed as the dispersion d_{60}/d_{10}. From pumping tests, he derives a function E(u), which can be used to calculate the hydraulic conductivity for more poorly sorted sediments. The confidence interval shows that 80% of the K-values calculated from the grain-size distribution, K_r, are within the interval of $\frac{1}{2}K$ calculated from pumping tests, K_p

$$K_p > \tfrac{1}{2}K_{r80}$$

For some of our samples, with a dispersion d_{60}/d_{10} > about 15, the hydraulic conductivity can be approximately calculated with Gustafson's formula. The result, compared with the K-values obtained from the permeameter tests, is shown in Figure 27. The relatively uniform dispersion is reflected by the similarity in K-values calculated with Gustafson's formula. The measured permeameter values from the same samples, however, show a much greater variety. This could partly be a result of the fact that the grain distribution was analysed from only a quarter of the permeameter sample, but it also reflects the fact that the empirical method is independent of the flow direction whereas the permeameter measurements are dependent on the sediment structure and the flow. The reliability of this comparison between the two K-values is questionable and far-reaching conclusions must not be drawn but it is obvious that the hydraulic conductivity of the till is also linked to the till structure.

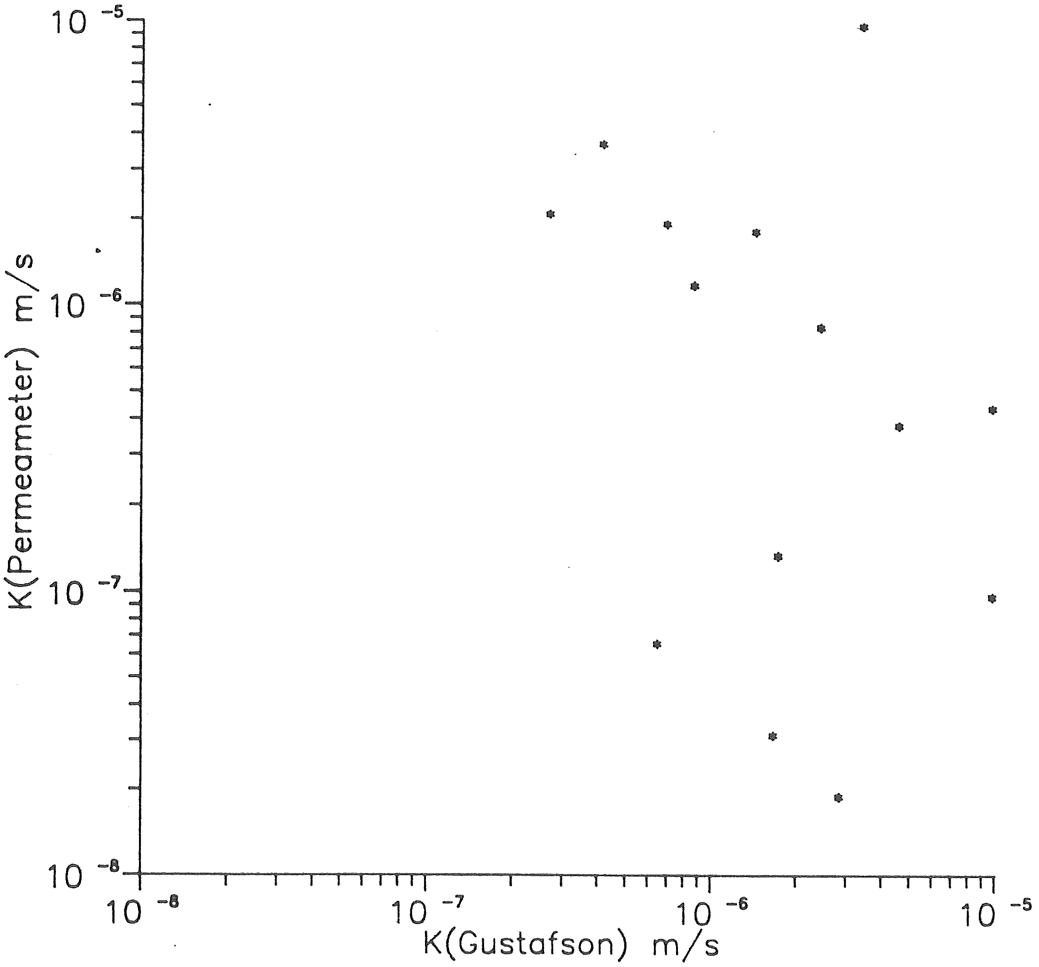


Figure 27. Hydraulic conductivity calculated with Gustafson's (1983) formula and obtained from the permeameter tests.

The hydraulic conductivity of proctor-packed randomly structured till samples from the same sites are about 10^{-8} - 10^{-9} m/s (Annika Lennartsson, in prep.).

It is of interest in this connection to study the relationship between the texture and the porosity. Figures 28 and 29 show the correlation between the total porosity and the mean grain-size, M_z, and sorting, σ_1, respectively. In the same way, M_z and σ_1 are compared with the effective porosity (Ne pF 2.0) in Figures 30 and 31.

From this comparison, it is evident that the porosity of the till is more or less independent of the grain-size, expressed as M_z, but correlated to the grain sorting σ_1, a finding that has earlier been shown for sand by Beard & Weyl (1973).

Grain shape

The sphericity, S, Roughness, F, and Area, A, of separated grains of the size of 1-2 ϕ (0.50 - 0.25 mm) were studied in an image analysis system (IBM PC/AT).

In order to show that both sphericity and roughness, at least within certain limits, are independent of the area, studies were made of these relationships. The results in Figures 32 and 33 indicate that this is the case. It is then possible to compare S and F without consideration of the grain size (A).

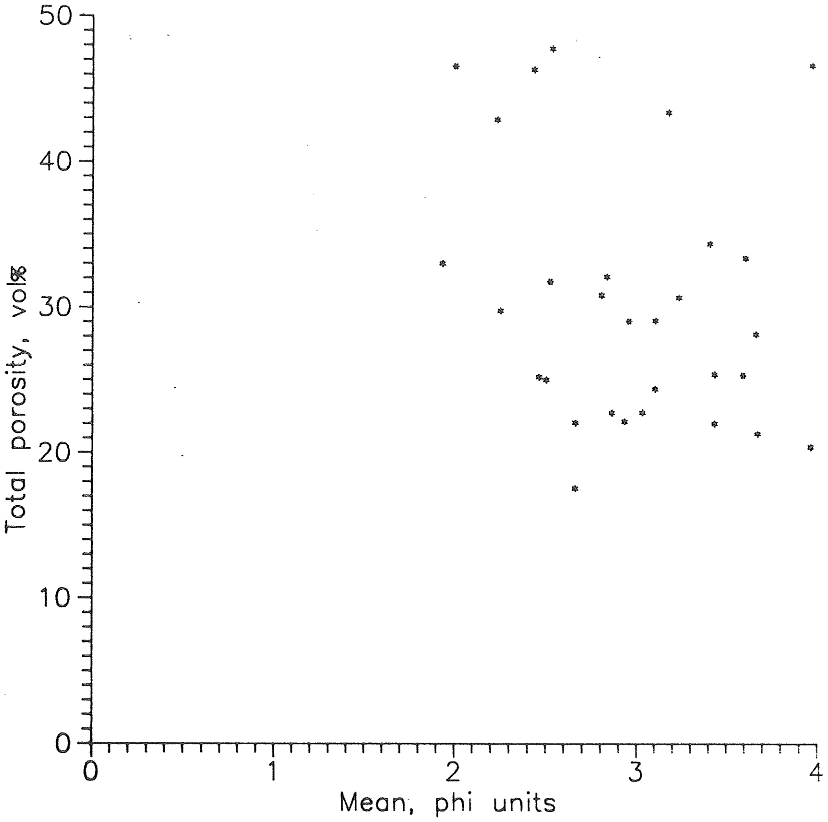


Figure 28. Mean grain-size and total porosity.

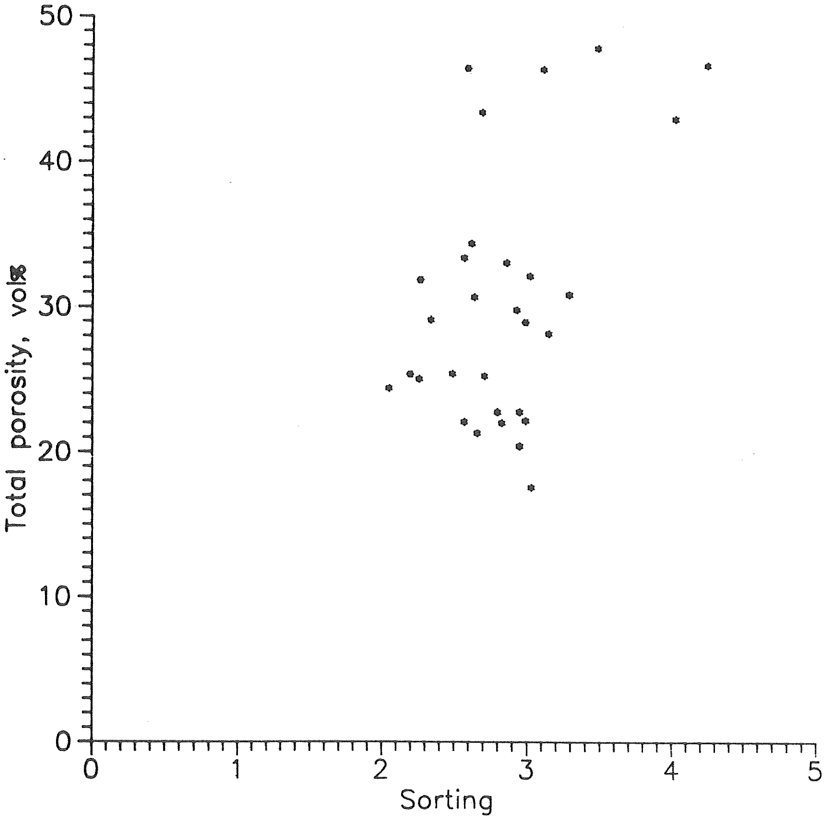


Figure 29. Grain sorting and total porosity.

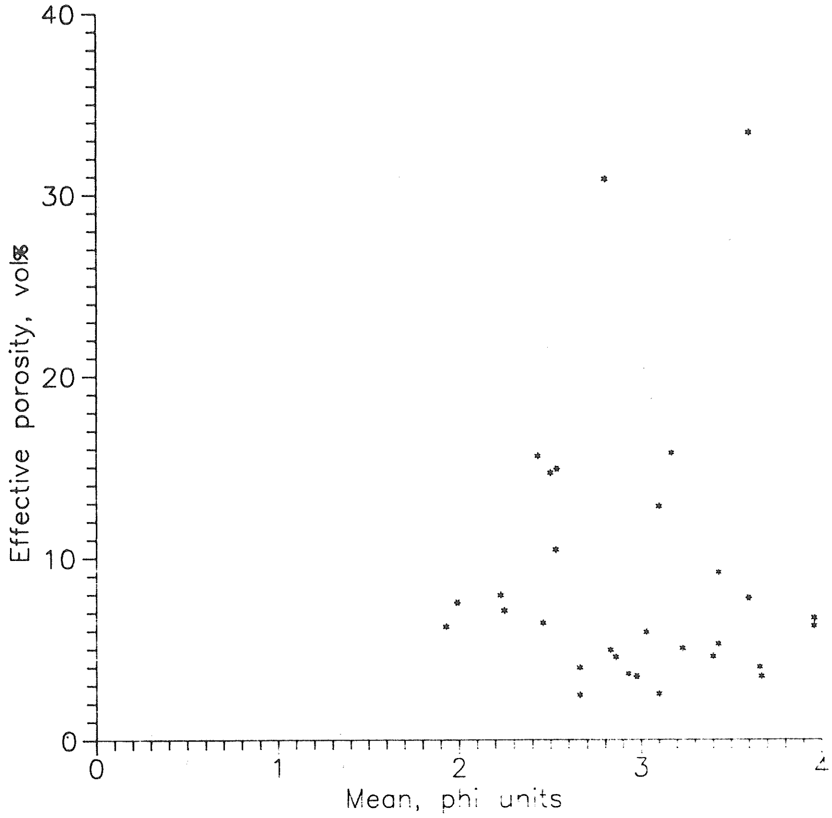


Figure 30. Mean grain-size and effective porosity.

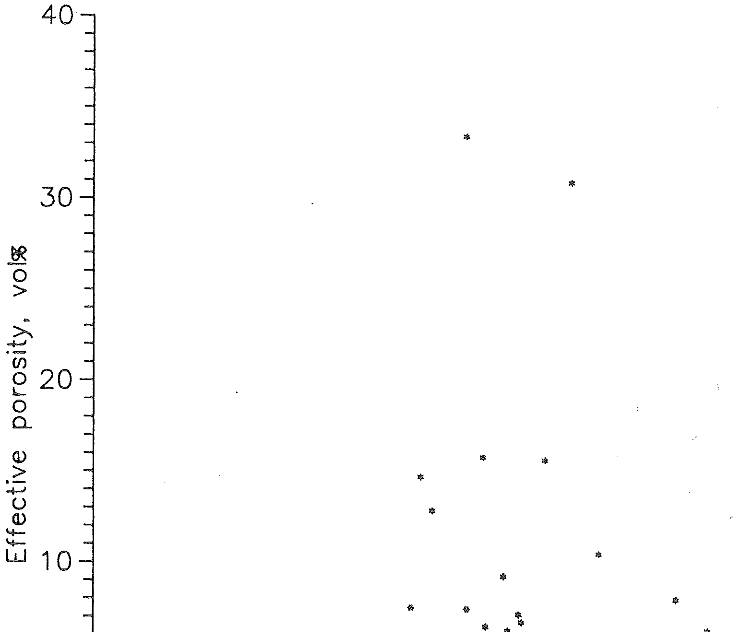


Figure 31. Grain sorting and effective porosity.

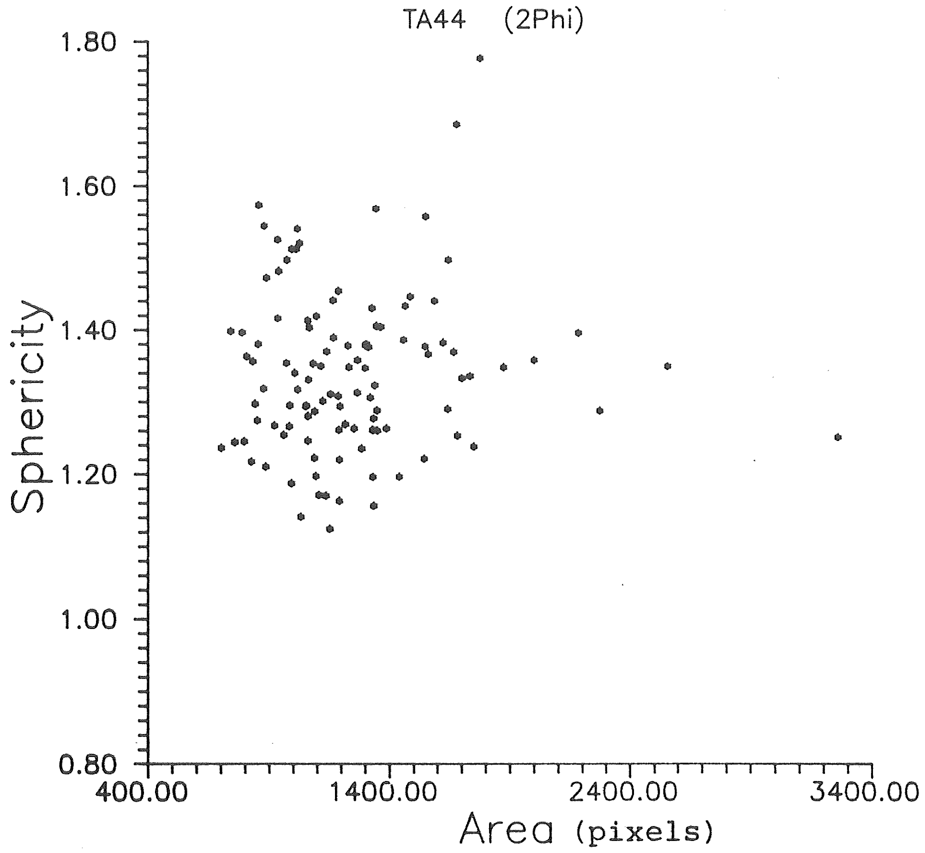


Figure 32. Grain sphericity correlated to grain area.

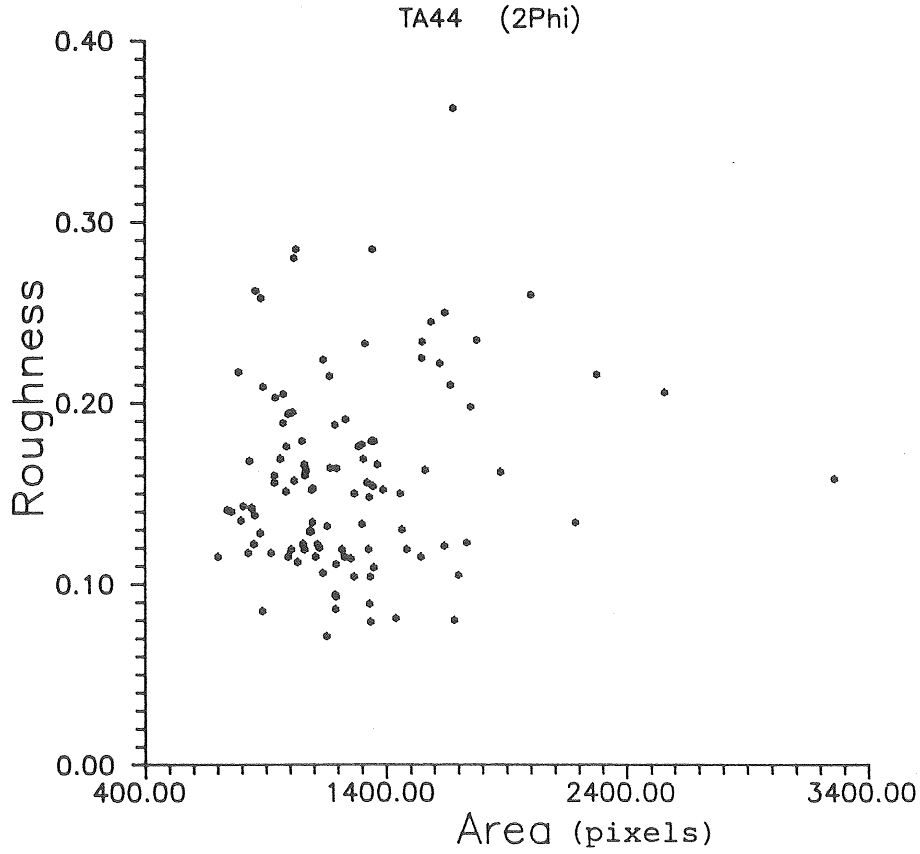


Figure 33. Grain roughness correlated to grain area.

How many grains, n, should be measured? To answer this question, a study was made on changes of the mean with the number of observations, Figure 34. It could be seen, and statistically calculated, that a good mean was established with about 50 observations. The standard deviation for S at 100 observations is about 0.09. With an acceptable change in the average of 5% of the standard deviation from one observation, it is necessary to have 50 observations. To ensure a very good stability of the mean, we have used 100 observations in this study.

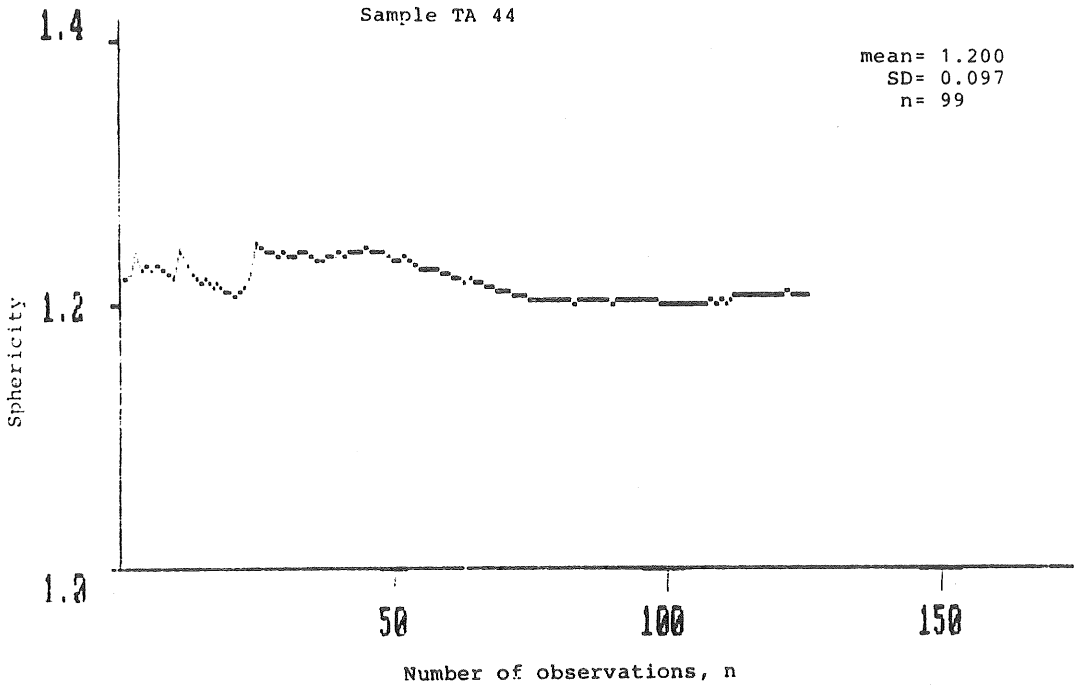


Figure 34. Changes of mean grain sphericity with number of observations.

The results from the sphericity and roughness studies show that there can be a difference in these structure factors especially between samples from the Lekeryd till and samples from Tahult and Ödenäs, as shown in Figure 35. The difference is significant with more than 95% probability, (t - tests). The difference in S and F in permeameter samples from the same locality are too small to account for any differences in hydraulic conductivity. In samples from different localities, there is greater variation of S and F. This could influence the hydraulic conductivity. However, in this study it has not been possible to link variations in sphericity and roughness to corresponding variations in hydraulic conductivity. Studies of till structures with the help of image analysis have just begun and the experience is limited. It is also obvious from our project that this is an important field to develop and that it is a useful tool for studying the influence of grain properties on porosity, hydraulic conductivity and water retention characteristics.

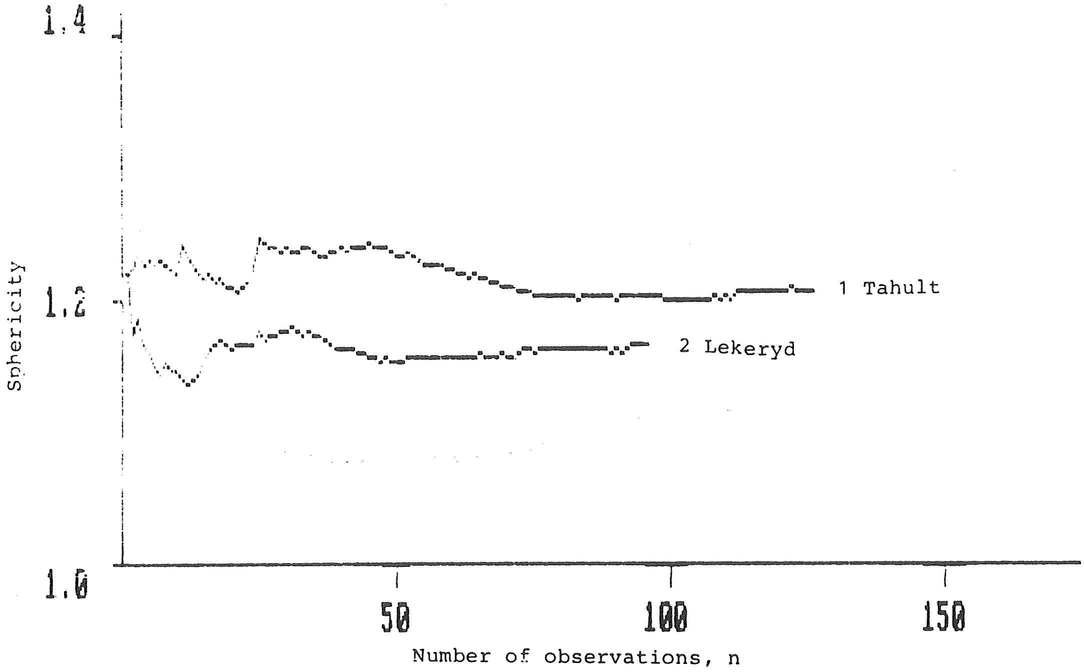


Figure 35. Example of differences in sphericity between samples from Tahult and Lekeryd.

A more accurate way to calculate a characteristic porosity was introduced to us by our colleague Sven Jonasson. This method, described by Thomèer (1960) and refined by Swanson (1981), is based on the observation that the location and shape of a water retention curve reflect characteristics of the pore structure of the sample, Figure 36.

Using this method, we can define a pore geometrical factor, SWA-value, which can be calculated in a way that expresses the *active* porosity that contributes most to the fluid flow at saturation (Jonasson in prep).

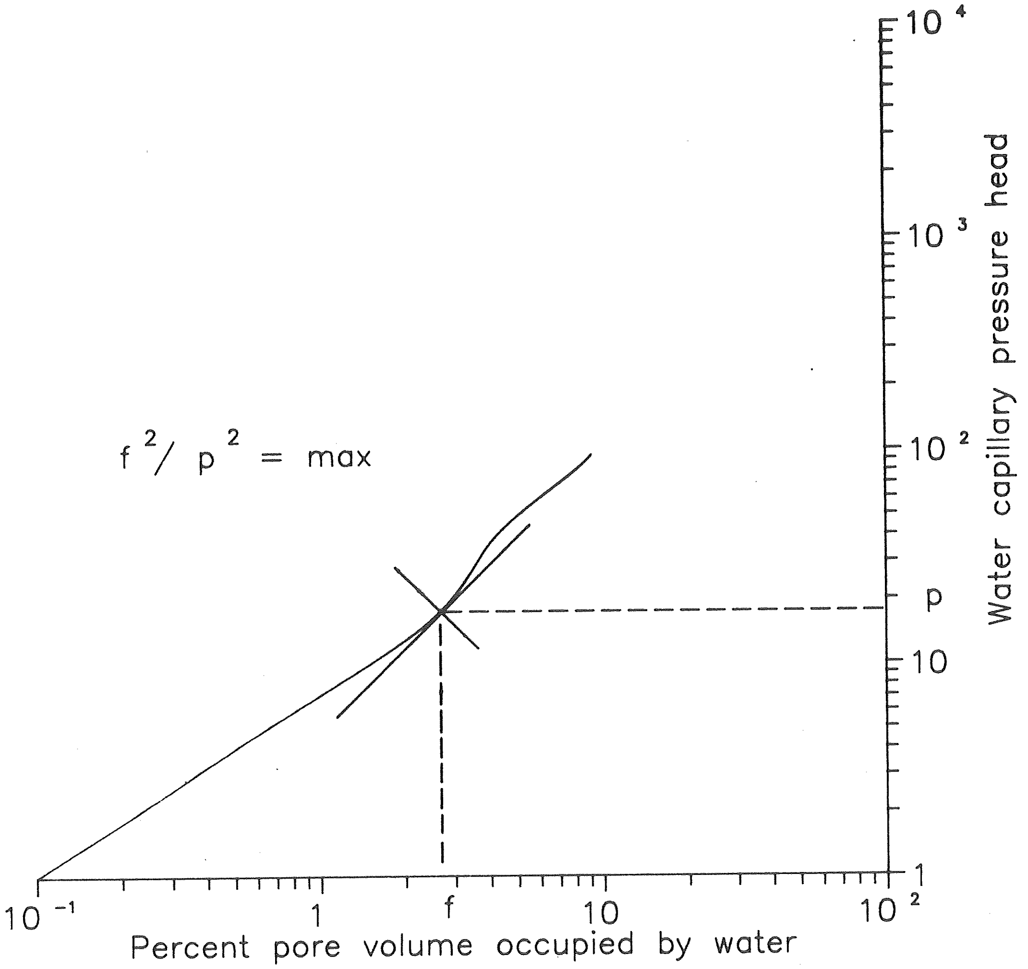


Figure 36. Pore geometrical factor Sb^2/Pc^2, SWA-value, calculated from the pF-curve (after Thomèer, 1960).

In the following chapter, four main tasks are performed and presented:

- Characterisation of fabric analysis together with pore geometry factor.
- Individual fabric and pore geometry.
- Structural parameter paired relations.
- Multiple regression modelling.

The studies concern individual and paired characteristics of two structural variables together with regression and modelling of relations. The population consists of 35 analyses. The data have been transferred to data-files on PC-environment and have mainly been studied by computer interactive work.

Structural parameter paired relations are studied by single regression techniques together with multiple regression modelling for processing information for the conceptual model.

Distribution diagrams and summary statistics

The distribution diagrams for these two structural parameters including hydraulic conductivity are presented in Figure 37. The parameters are presented as the logarithmic value, and as forming a relatively straight line in a normal probability plot. This indicates that the values are approximately log-normally distributed. The shape of the distribution is approximately symmetrical, indicating low skewness. The distribution diagrams are suitable for analysing with which probability a certain value can be encountered when a sample is taken from the population.

Summary statistics have been developed for the structural variables and are presented in the table below. The distribution diagrams and summary statistics together characterise the individual parameters.

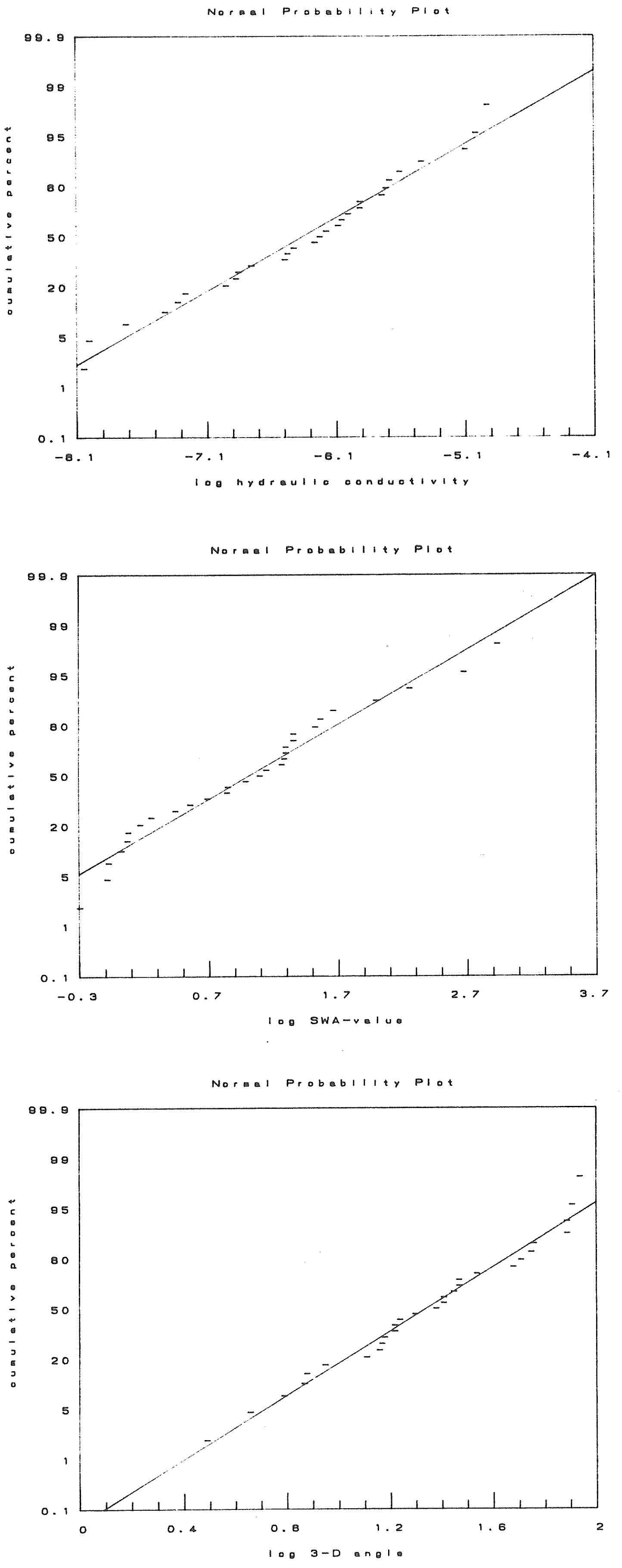


Figure 37. Normal probability plots of log hydraulic conductivity, log SWA-value and log 3D-angle.

Variable:	log 3D-angle	log SWA-value	log conductivity
Sample size	35	35	35
Mean	1.35	0.96	-6.36
Median	1.38	0.99	-6.22
Variance	0.15	0.72	0.72
Standard dev.	0.39	0.85	0.85
Minimum	0.49	-0.29	-8.04
Maximum	1.94	2.94	-4.92
Skewness	-0.27	0.46	-0.33
Kurtosis	-0.52	-0.15	-0.50

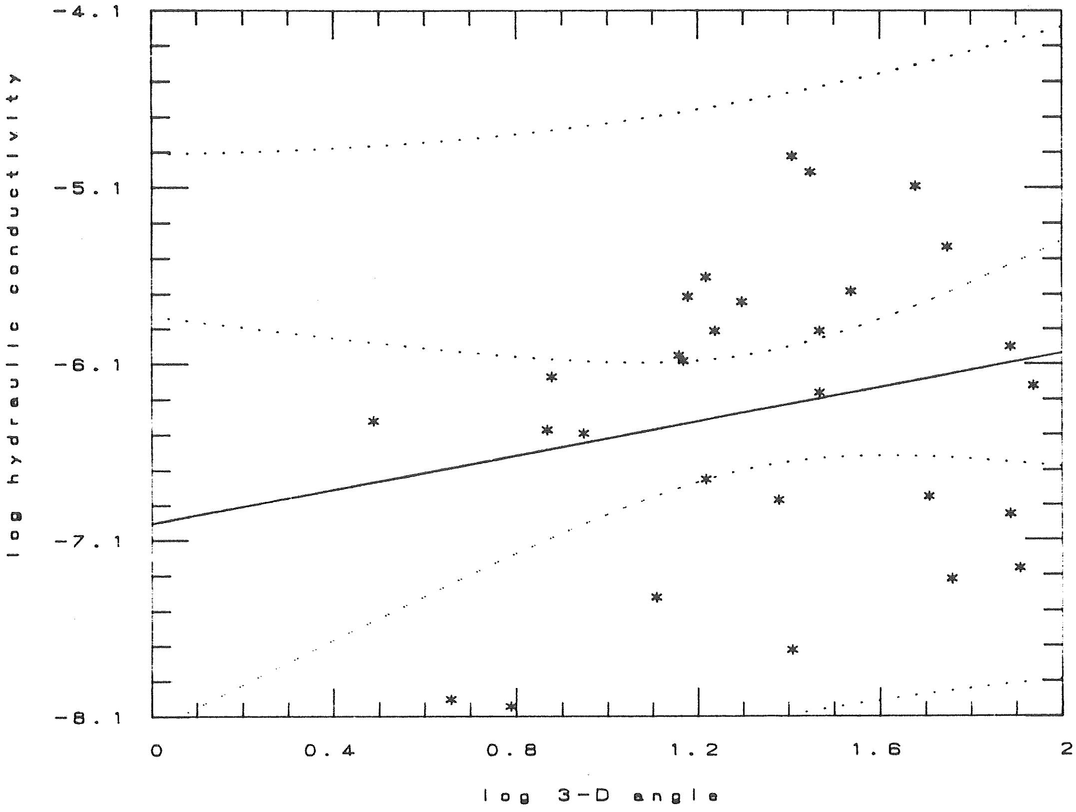
Structural parameter paired relations

In order to understand some of the intricate relationships between these different structural parameters, it is necessary to evaluate the correlations.

A simple regression analysis (Figure 38) has been performed for the possible correlations between the structural parameters. The correlations are here presented and ranked by the R-squared factor as a measure of model goodness of fit. An R-squared factor of 40% means that 40% of the variability in a value is associated with variations in the related variable.

Subsequently, this simple regression analysis shows that only weak, if any, correlations are found between the pair structures. The following table show the relationships according to R-squared factor between the variables:

Dependent var.	Corr. variable	Coefficient
Hydraulic cond.	3D-angle	0.220
Hydraulic cond.	SWA-value	0.027



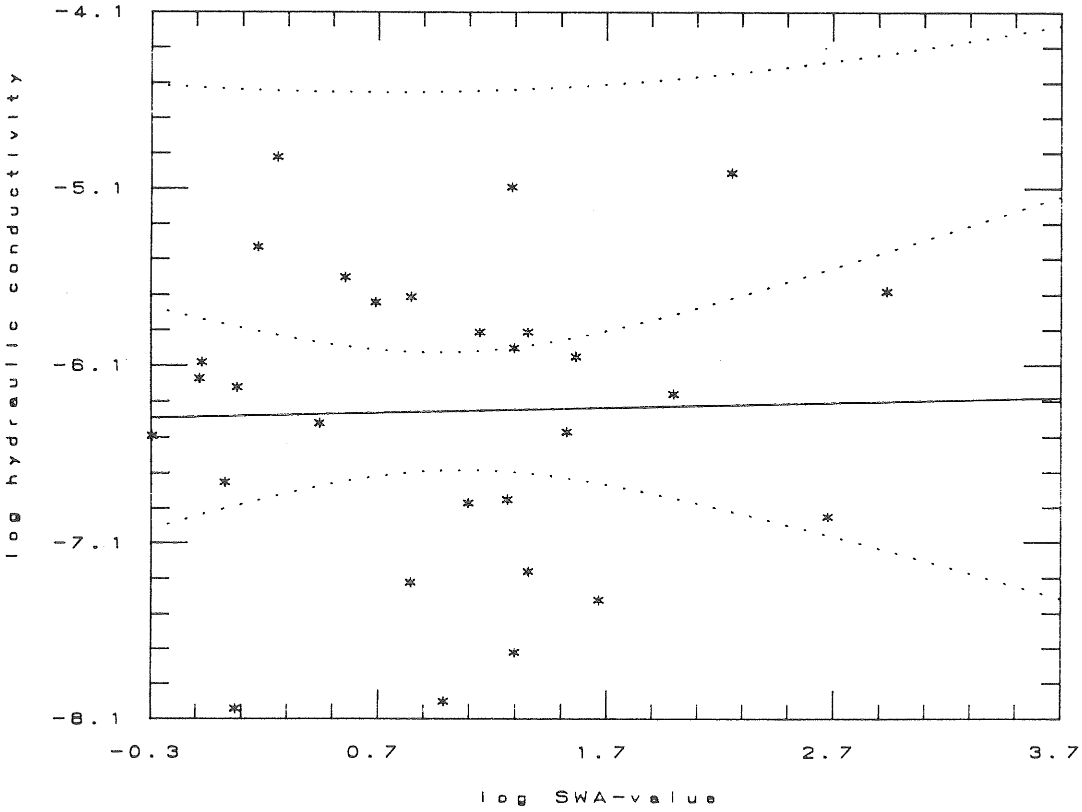


Figure 38. Linear relations between log hydraulic conductivity and log 3D-angle, and log SWA-value respectively.

The table shows what extent and with what level of significance different relationships can be established for modelling purposes. It must be emphasised that no direct correlation needs to exist but the produced formulas give the best fit according to least square procedures.

The simple regression between structural variables exhibited very weak correlations. Our conclusion from the result is that the individual variation in structural values is greater than would be foreseen by simple single models, at least from this level of analysis.

Swanson (1981) presented a figure with a lot of data showing a good correlation between the air permeability in sandstone and carbonates and a pore geometrical factor, but it is evident that greater deviations are found in the low permeability region. Even though our data are quite widely spread in the diagram, they are within the deviation-range of the comprehensive data presented by Swanson (1981).

Multiple regression modelling

Besides single regression modelling between two variables, a multiple regression modelling procedure has been performed. The object was to check the magnitude of the correlation between the hydraulic conductivity and SWA-value and 3D-angle. By this analysis, it would be possible to control whether the hydraulic conductivity could be expressed by porosity and orientation of alignments. Multiple regression uses least squares to estimate the regression model. Modelling is performed to determine whether more complex models can be used with better accuracy than single simple models.

The analyses have been performed using a full multiple linear regression procedure. An arbitrary second order polynom is chosen, without a constant term. The logarithmic hydraulic conductivity was selected as the dependent variable and log SWA-value and log 3D-angle as independent variables. The coefficient of determination (R-squared) was used as a measure of goodness of model fit.

Model fitting results for hydraulic conductivity

Independent variable	Coefficient	t-value	Sig.level
3D-angle	-9.780	-7.64	0.0000
SWA-value	-0.626	-0.45	0.6530
3D-angle (raised to 2)	3.595	4.16	0.0003
3D-angle * SWA-value	0.104	0.09	0.9264
SWA-value (raised to 2)	0.205	0.55	0.5837

R-squared 0.96

Note that neither the SWA-values nor the product of 3D-angle and SWA-value show a significant t-value. This does not mean that it should be dropped since t-statistics measure the marginal contribution of each variable as if it were the last to be entered in the model. An analysis of variance yields a highly significant regression, with an overall F ratio equal to 127.5. The coefficient of determination (R-squared) equals 96.0%.

Analysis of variance for the full regression

Source	Sum of squares	D.F	Mean squares	F-test
Regression	1148.78	5	229.75	127.47
Deviation	43.25	24	1.80	
Total	1192.01	29		

R-squared 0.9637

A component effect plot for squared SWA-value and squared 3D-angle is presented in Figure 39. Note that the points are distributed fairly uniformly about the diagonal line for 3D-angle. This is a sign that the 3D-angle provides useful information for predicting the hydraulic conductivity of these samples.

Compared with the simple regression analysis of variable pairs, the R-squared factor is here very high, which indicates that a more complex model results in better agreement between actual and predicted value than a simple regression model. Compared with single relation modelling, a multiple linear model will provide better opportunities for modelling.

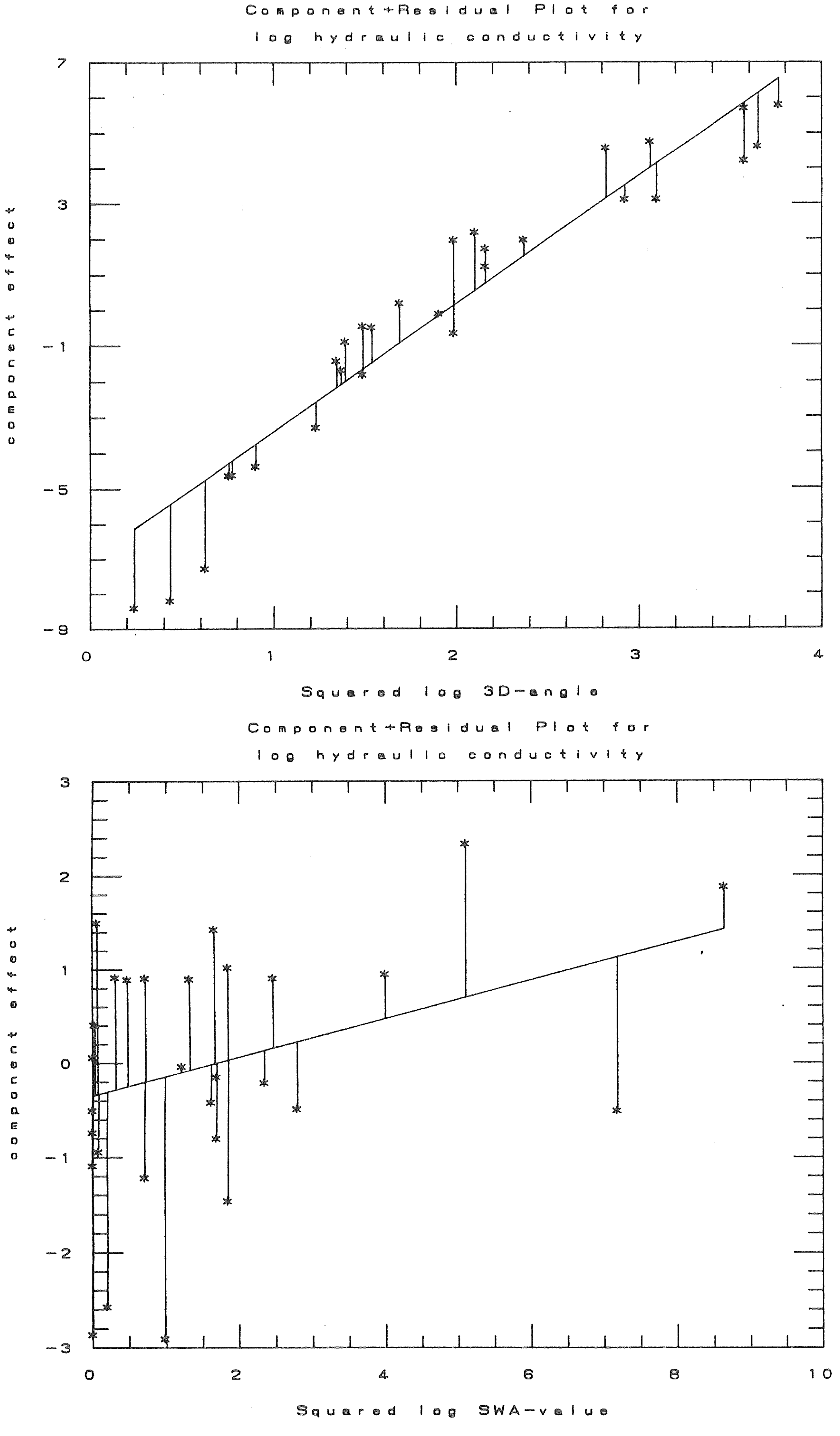


Figure 39. Component plot for squared 3D-angle and SWA-value contribution in the formula.

Multiple variable modelling

In a response surface plot, we can produce a surface for the second-order polynomial function that fits our modelling purposes. Based on our multiple regression analysis, we assume an XY polynomial.

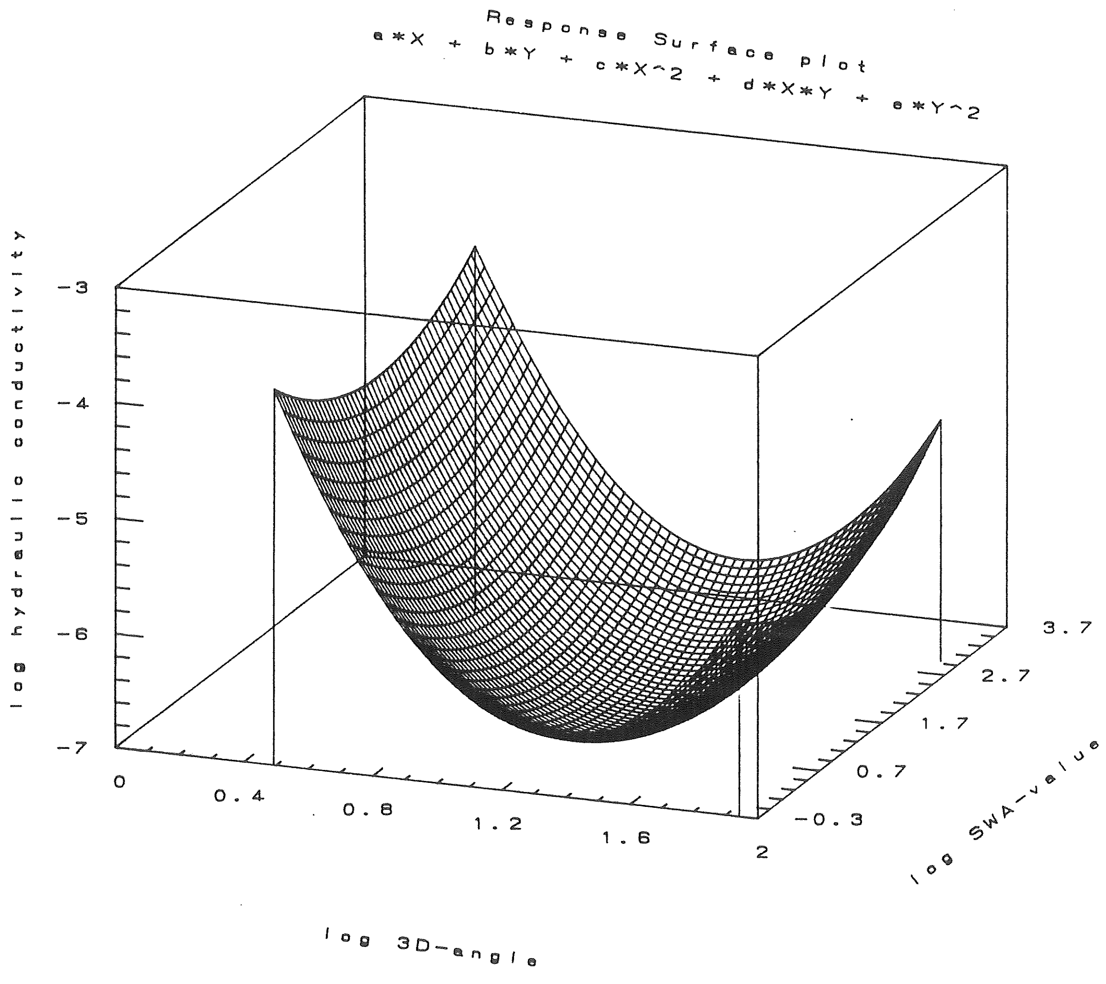


Figure 40. Response surface plot for regression model.

The plot in Figure 40 represents the final model for the relationship between mean orientation of alignments, pore geometry and saturated hydraulic conductivity. This model explains 96% of the variability in the hydraulic conductivity of the samples. The hydraulic conductivity decreases with increasing 3D-angle, and increase slightly with the SWA-value. Overall, the 3D-angle has a significant influence on the saturated hydraulic conductivity in the tested samples.

CONCLUSIONS

The hydraulic conductivity of soft sediments is related to the sediment properties in a very complicated way. The importance of sediment structures such as porosity, grain dispersion, grain orientation, plasmic fabric and grain shape has often been suggested but the documentation on the influence on the hydraulic conductivity is sparse. It appears that the approach used in this study, providing that the hydraulic conductivity is a function of sediment structure and textural factors, can contribute to our knowledge about hydraulic conductivity in tills and improve the input data of hydrological calculations.

The investigated tills have a texture that is well known from Swedish glacial diamicton sediments. The mean grain size and sorting are within the range of deviation of common tills.

In spite of the relatively uniform texture, the hydraulic conductivity varied within wide limits between the samples, from about 10^{-9} m/s up to about 10^{-5} m/s. It is obvious that the structure of the till has a great influence on the hydraulic conductivity.

A number of structural factors have been studied and compared with the hydraulic conductivity. The results show that the variations in hydraulic conductivity are associated with variations in fabric, porosity, pore distribution and grain dispersion. Generally, the correlation between the structural factors and the hydraulic conductivity is notably weak and this should be considered a result of the intricate multivariate relationships between the structural factors and the hydraulic conductivity.

It is very difficult to find correlations between each separate structural factor and the hydraulic conductivity. A more fruitful approach is to study the multiple correlations for preferred alignments, flow-active porosity and hydraulic conductivity. The co-variations of these factors have a decisive influence on the hydraulic conductivity. However, these properties must be considered in conjunction with, in the first place, porosity and grain dispersion.

The hydraulic conductivity of the till matrix is influenced by the micro-structures as well as by the texture. The grain orientation and plasmic fabric structures (Brewer, 1976) are dependent upon the observed direction whereas porosity, pore distribution, grain sorting and grain size are independent on the direction. The orientation structure is also the most important individual factor for the hydraulic conductivity in the studied tills. The hydraulic conductivity in the laboratory tests varies by 10^3 m/s if the mean direction of alignment varies between parallel and perpendicular to the flow direction, provided all other factors are constant.

The determination of hydraulic properties from field investigations of till genetics has proved to be difficult due to spatial variations within each group. A classification scheme of hydrogeological properties of tills should be based on lithostratigraphic facies studies and take into consideration the directional component of the grain orientation and other fabric structures.

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APPENDIX

CHEMICAL ANALYSES

No.	Amount of sediment, g, that has been dispersed in 100 ml distilled water for 2 h in turning apparatus, to get the values in columns 2-7	Fe mg/l	K mg/l	Na mg/l	Ca mg/l	Mg mg/l	Mn mg/l	Al_2O_3 mg/l	SiO_2 mg/l	R_e m_V in +550 m_V	n_e, pF2,31 vol-%	K m/s
13			3.04	20.91		1.813						
14		22.46	2.37	16.11	19.31	1.813						$4.11 \cdot 10^{-7}$
		18.93	2.23	15.29	16.56							
		15.59	2.12	14.38	14.02							
		13.13	2.07	13.24	12.60							
		11.11	2.03	12.39	11.17							
		9.58	1.97	11.12	10.27							
		8.35	1.96	10.25	9.99							
		7.37	1.92	10.26	9.52							
15		65.29	4.15	10.30	3.88	0.119						$6.27 \cdot 10^{-7}$
		53.05	3.38	9.06	2.62	0.080						
		43.33	2.99	9.52	2.12	0.064						
		34.24	2.74	8.95	1.83	0.054						
		28.32	2.55	8.52	1.57	0.051						
		23.26	2.41	7.76	1.47	0.046						
16		42.74	4.18	17.36	12.02	0.504						$8.15 \cdot 10^{-7}$
		34.45	3.95	16.12	9.90	0.432						
		27.26	3.69	13.87	8.23	0.362						
		21.80	3.26	12.41	7.21	0.333						
		17.48	2.79	11.64	6.19	0.286						
		14.54	2.49	10.66	6.14							
		12.12	2.32	10.66	5.85							
		10.48	2.39	10.48	5.74							
		9.25	2.14	9.85	5.68							
17		13.12	2.70	21.92	28.86							$5.69 \cdot 10^{-7}$
		11.70	2.39	19.70	25.04							
		10.18	2.16	16.67	21.88							
		9.12	1.86	14.95	18.28							
		7.95	1.79	13.46	16.29							
		7.26	1.72	12.33	14.69							
		6.58	1.64	11.47	13.68							
		6.03	1.58	10.63	12.77							
18		44.42	5.15	23.35	9.28	2.04						$3.31 \cdot 10^{-7}$
		39.18	4.77	20.95	8.07	1.68						
		33.27	4.42	18.62	6.92	1.44						
		27.36	4.07	16.59	5.98	1.27						
		22.30	3.79	14.59	5.33	1.16						
		18.19	3.56	13.18	4.86	1.06						
		14.89	3.37	12.08	4.40	1.00						

26	16.4684	0.00	0.98	0.88	0.52	0.07	0.01	1.691	2.451		7.39	$5.80\cdot10^{-8}$
28	20.0405	0.04	0.58	0.71	0.38	0.04	0.02	2.181	2.599			$2.10\cdot10^{-6}$
29	19.0446	0.03	0.77	0.54	0.40	0.08	0.00	0.564	2.599		7.06	$8.05\cdot10^{-6}$
31	23.9587	0.01	0.58	0.56	0.41	0.03	0.00	0.539	2.748	+265 260 258 250 250 +390 330 320 310 295	5.39	$1.23\cdot10^{-6}$
33	18.5917	0.04	2.83	2.69	3.86	0.92	0.81	0.171	4.531		6.80	$1.93\cdot10^{-6}$
35	21.2997	0.17	1.80	3.21	0.95	0.06	0.14	0.073	5.570		5.37	$1.53\cdot10^{-7}$
36										440 415 410 420 390 360	6.32	$3.82\cdot10^{-7}$
37	17.4095	0.37	1.38	2.30	1.14	0.03	0.01	0.147	4.382		2.78	
39	20.7997	0.04	4.11	2.30	11.24	2.27	2.97	0.907	4.976		8.91	$3.70\cdot10^{-6}$
42	21.4076	1.29	6.33	3.49	38.43	7.08	3.19	7.301	6.833		3.26	$4.81\cdot10^{-8}$
44	21.0321	2.81	1.57	2.26	0.2	0.10	0.11	0.735	4.902		6.89	$1.17\cdot10^{-6}$
45										360 325 320 312 320	10.37	$8.12\cdot10^{-7}$
46	23.3032	1.07	1.69	1.12	11.73	1.12	0.18	15.37	6.686		4.84	$1.89\cdot10^{-8}$
48	26.8752	0.29	0.83	2.22	0.70	0.01	0.00	0.147	3.119		10.47	$2.08\cdot10^{-7}$
49										290 260 260 255 245	15.28	$8.88\cdot10^{-7}$
50	23.1873	0.09	0.8	1.04	0.50	0.01	0.01	0.122	2.897		6.18	$1.34\cdot10^{-7}$

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