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Analysis of Spatial Correlation of Hydraulic Conductivity Data from the Stripa Mine

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TECHNICAL REPORT

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ANALYSIS OF SPATIAL CORRELATION OF HYDRAULIC CONDUCTIVITY DATA FROM THE STRIPA MINE

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This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

A list of other reports published in this series is attached at the end of the report. Information on previous reports is available through SKB.

Abstract

Hydraulic conductivity data from the Stripa mine were analysed to establish the characteristics of spatial variability. In addition the univariate statistics were calculated. Data on different supports were analysed; 10m data, variable section length data (1-7m), and the latter variable section data deregularised to 1m data. The analyses of data from boreholes with orthogonal orientations indicated an apparent anisotropy in the geometric mean hydraulic conductivity, with a one to two order higher mean conductivity in the east-west direction than that of north-south. The analysis of spatial variability on a 10m support revealed weak spatial correlation, whereas that based on the data deregularised to 1m data showed finite, well developed spatial correlation with practical ranges of c. 10m. The covariance structure of hydraulic conductivity, as opposed to that of the calculated geometric mean hydraulic conductivities, showed an isotropic structure. The established variograms constitute a starting point for further data expansion and estimation by eg. stochastic continuum simulations of groundwater flow and mass transport within the SCV block at Stripa.

Keywords:

Anisotropy, hydraulic conductivity, scale effects, spatial variability, univariate statistics, variogram

Summary

Mass transport in fractured rock is controlled by the spatial variability in the velocity field, which in turn is dependent on the heterogeneity of the hydraulic conductivity. One way to describe the heterogeneity is to establish the covariance structure of the hydraulic conductivity in terms of a variogram.

Hydraulic conductivity data from the Stripa mine on different supports (10m, 1-7m and 1m) were analysed with regard to univariate statistics and variography. The analysis results were discussed eg. in terms of scale effects, geometrical effects, geological and tectonic effects.

Calculated geometric mean hydraulic conductivities (10m) are varying between -12 and -9.5 (logK). Variable section data deregularised to 1m support show geometric mean values between -11 and -10. No variance reduction for the 10m data is observed compared to the 1m data. Analysis of the calculated geometric mean hydraulic conductivities show evidence of an apparent anisotropy in the east-west:north-south:vertical. The noted ratios are 100:1:1 and 10:1:1 for the 10m and 1m data, respectively.

Spatial variability on a 10m support reveals weak signs of finite spatial structure, ie. well developed variograms. Where possible to infer, the practical ranges are on the order of 30-50m. A more stronger pronounced spatial correlation is noted for the variable section length data from the SCV site deregularised to a 1m support. The variograms show that data are correlated within 10m, ie. a factor 3-5 shorter correlation length. In addition, spatial correlation inferred from boreholes of varying orientation indicate an isotropic covariance structure. To add to the knowledge of spatial correlation on a smaller support, 2m data from two vertical holes from the Macro-permeability site were added to the analysis.

Fracture statistics as inferred from logs of boreholes at the SCV site sustain the noted differences in geometric mean hydraulic conductivity established between boreholes trending west and north, respectively. In addition, the appearance of the corresponding variograms correlate well with the variability in fracture frequency in the corresponding boreholes.

The near isotropic covariance structure established for the 1m data from the SCV block constitutes a starting point for further data expansion/estimation (kriging) and/or simulation of groundwater flow and mass transport within the SCV block using stochastic continuum techniques.

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1. INTRODUCTION

Mass transport in fractured rock is controlled by the spatial variability in the velocity field which in turn is dependent of the heterogeneity in hydraulic properties. One way to describe the spatial variability (heterogeneity) is to establish the covariance structure of the material property. The modelled covariance structure in the form of a variogram can be used in eg. stochastic continuum methods (Winberg and Cvetkovic 1990) to address uncertainty in mass transport in fractured rock.

The varied geometry of the holes at Stripa, and particulary the large number of horizontal boreholes will provide a valuable complement to the analysis of spatial variability of data from vertical and subvertical holes at eg. Finnsjön (Winberg 1989).

2. SCOPE OF WORK

The scope of this report is to infer the characteristics of spatial variability of the hydraulic conductivity data available in the database of hydraulic conductivity data from Stripa. These data are presently not available in the SKB database GEOTAB which contains data from most of the SKB test sites.

The main hypothesis to be tested in this study is whether spatial variability has a format which is possible to describe in terms of a variogram, and secondly, if so, is there is any significant difference in spatial structure between data from boreholes with different orientations. If there is a difference, thirdly, discuss differences on the basis of differences in lithology and fracturation.

Jointly with, or rather preceding the variography, conventional summary statistics have been applied to the data sets to supply valuable information for defining the subsets but also to help in the evaluation of differences in the hydraulic characteristics of the analysed boreholes.

The analysis has been performed using the software package GEOSTAT-Toolbox version 1.2 supplied by FSS International (Froidevaux 1988).

3. DATA ANALYSED AND MADE ASSUMPTIONS

The analysed data comprises hydraulic conductivity data in 10m sections from boreholes N1, E1 and V1 (Carlsson and Olsson 1985). In addition 10m data from the F-series boreholes at the "cross-hole site" have been analysed. Further, data from the boreholes at the SCV site; N2-N4, W1 and W2, C1-C3 have been analysed. The latter holes have been tested with a tool that allows variable section length. The section lengths in this case varies from 1 to 10m (Holmes 1989, Holmes et al 1990).

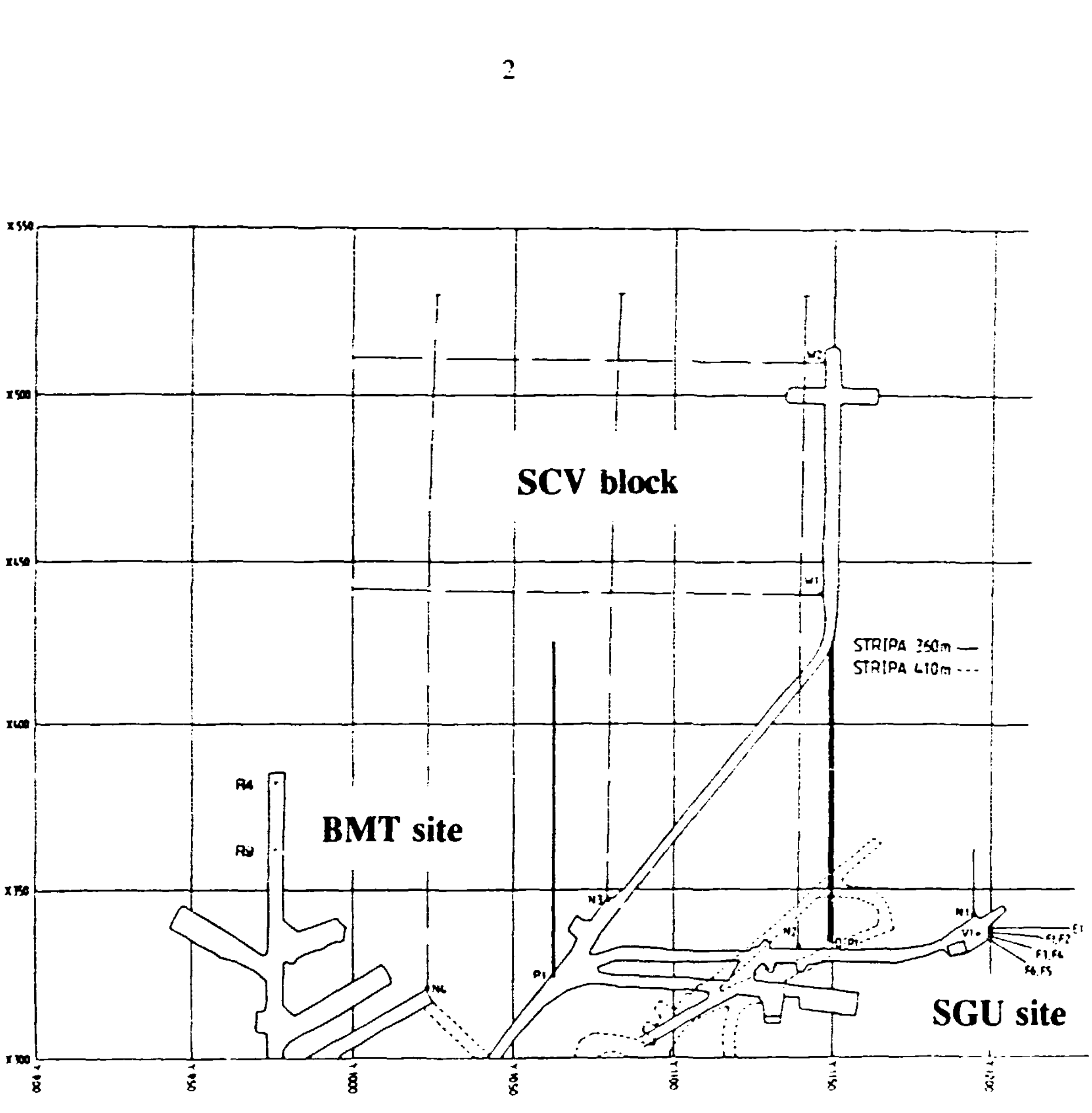


Figure 3.1 **Relative location of boreholes used in the study (from Holmes 1989).**

The available data is compiled in Table 3.1 as distributed between the analysed boreholes and measurement scales (section lengths used). The relative location of the boreholes included in this study is shown in Figure 3.1.

The variable section length data from boreholes W1-W2, N2-N4 and C1-C3 deconvulated (deregularised) to 1m data have also been analysed accordingly. To study the spatial correlation of short section data in vertical holes, data from boreholes R4 and R9 at the Macropermeability test site (BMT) have also been analysed.

In the study, each population, single borehole or pooled population, has been assumed to be statistically homogeneous. No distinction has been made between data from fracture zones or data from the normally fractured rock mass.

4. STATISTICAL AND HYDROLOGICAL CONCEPTS

4.1 General

This chapter describes many of the definitions used in the hydrogeological description of hydrogeological characteristics of the bedrock.

Further a review is made of the summary statistical parameters used in the conventional statistics employed to the data. In addition a brief description is made of the technique used to describe the spatial variability and characteristics of the data (variography).

Table 3.1 Data as distributed on different measurement scales and boreholes.

Borehole	Section length (m)		Number of data	
E1	10		22	
N1	10		9	
V1	10		42	
F1	10		19	
F2	10		23	
F3	13		27	
F4	10		28	
F5	10		28	
F6	10		23	
N2	1-7	1	80	199
N3	1-7	1	46	184
N4	1-7	1	71	212
W1	1-7	1	102	140
W2	1-7	1	93	140
C1	1-7	1	46	143
C2	1-7	1	39	143
C3	1-7	1	29	92
R4	2		10	
R9	2		11	

4.2 Hydraulic definitions

The parameter which is subject to the present study is the *hydraulic conductivity (K)*. The analysed hydraulic conductivity data have been measured either with "long time" (=2 hours) constant rate or constant head injection tests in 1-7m or 10 m test sections evaluated on the basis of steady state theory, or "short time" pulse and slug tests and constant rate and head tests in 1-7m or 10m (F3-F6) section test sections evaluated with transient state theory (Black et al 1987).

Rather than using the absolute value of the hydraulic conductivity in the analysis, a transform of K has been used. Often the logarithm of the parameter studied show a higher degree of spatial structure than the absolute value itself. Common geostatistical practice is to use the natural logarithm (ln K) of the parameter studied (de Marsily 1986) but in order to conform with common hydrogeological practice and also to obtain an improved readability the base 10 logarithm (*log K*) has been used throughout this report. In places also the logarithm of *transmissivity* (*log T* = log K·L), i.e. the logarithm of K multiplied with the section length L, has been used for reasons of easy comparison.

The definition of hydraulic conductivity as inferred from double packer tests in boreholes implies that the measured flow is averaged over the section length used. The downhole tool has a lower physical limit with respect to flow which defines the lower *measurement limit* of the hydraulic conductivity. With given physical characteristics of the used tool this implies that the measurement limit of longer sections is lower than that of shorter section lengths. The measurement limit of 20 or 10m constant head injection tests is typically $1 \cdot 10^{-14}$ m/s (logK=-14), whereas that of the varying section length is $1 \cdot 10^{-13}$ m/s (logK=-13) at the lowest.

In the analysis, no distinction has been made with regard to the hydraulic units often defined for a typical SKB study site.

4.3 Descriptive statistical tools/parameters used

As already stated the conventional statistical methods have been employed to support and supplement the description of the spatial variability. The different measures used may be divided into; (1) measures of *location*, (2) measures of *spread* and (3) measures of *shape* (symmetry). In the analysis use has predominantly been made of the former two types of measures.

Measures of location

The foremost used measure of location used in this study is the (arithmetic) *mean* defined by Equation 4-1. Since the parameter studied is the logarithm of the hydraulic conductivity (log K) what we are in reality observing is the mean of log K. The arithmetic mean of the log is synonymous to the *geometric mean* of the hydraulic conductivity ($\log K_g = E\,[\log K]$). Throughout the report the geometric mean and mean hydraulic conductivity area used with identical meaning.

$$m=\sum_{i=1}^{N} \log K_i \qquad (Eq.\ 4\text{-}1)$$

Further the *quartile* concept is used where the first quartile (Q_1) refers to the cumulative proportion of data and the value at which 25% of the data are below this value. Correspondingly at the third quartile (Q_3), 75% of the data are below this value.

The *median M* consequently refers to the second quartile (Q_2) with an even 50% of the data above and below. If instead 10% increments is used in subdividing the cumulative proportion we obtain the *quantiles* of the distribution

The minimum value (*min*) and maximum value (*max*) of the studied population are also used.

Measures of spread

The classical measure of spread is the *variance* (σ^2) defined by Equation 4-2, which is used throughout this study. The standard deviation (σ) of the parameter studied is obtained by simply taking the square root of σ^2.

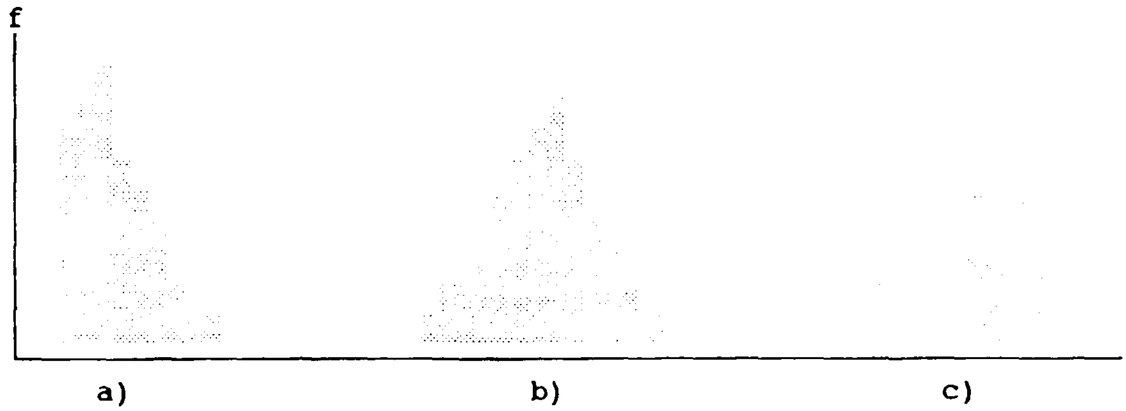


Figure 4.1 **Coefficient of skewness. Examples of histograms of populations with a) positive skewness (S>0), b) symmetry (S≈0) and c) negative skewness (S<0) (from Winberg 1989).**

The second measure used is the *interquartile range (IQR)* which is the difference between Q_3 and Q_1. This latter measure is a good compliment to the variance.

$$\sigma^2 = \sum_{i=1}^{N} (logK_i - m)^2 \qquad (Eq.\ 4\text{-}2)$$

Measure of shape

One measure of shape is the *coefficient of skewness (S)* defined by Equation 4-3. The relevance of S is questionable when the distributions are highly skewed. The concept is visually exemplified in Figure 4.1.

$$S = \left(\frac{1}{N}\sum_{i=1}^{N} (logK_i - m)^3\right)/\sigma^3 \qquad (Eq.\ 4\text{-}3)$$

Another measure of shape maybe more applicable and relevant to the data analysed in this report is the *coefficient of variation (CoV)* which may be a useful measure of asymmetry of positively skewed distributions whose minimum is zero. The coefficient of variation is defined as CoV = σ/m and is in the report, where presented, expressed as a percentage.

The primary advantage with the use of the above described summary statistical parameters are that they constitute very condensed and portable descriptors of the studied population.

The disadvantages may be that the information is too condensed to grasp the essence of the population studied. In these instances some additional graphical description, eg. a *histogram* of the data may provide necessary insight.

Not to be forgotten is also the very strong impact on the some parameters, eg. the mean, variance and coefficient of skewness, by *extreme values* in the data. Again the histogram is an invaluable means to fully appreciate the population studied.

4.6 Spatial variability - the variogram

4.6.1 The random function model

The property x (eg. hydraulic conductivity K) as distributed over a site (area or volume) S, appears as a spatial function x(u) of a set of coordinates u ε S. Each value x(u) is interpreted as a realization of a *random variable (RV)* denoted X(u). The set of values {x(u), u ε S} is then interpreted as a particular realization of dependent RV's:

$$\{X(u), u \in S\}$$

also called a *random function (RF)*, which is a function of the location u (Journel 1987). The study of spatial dependence between any two values x(u) and x(u') then breaks down to the study of the pattern of spatial dependence between two corresponding RV's X(u) and X(u').

4.6.2 Spatial description

The spatial dependence between two RV's with an interdistance defined by the vector h = u'-u may characterized with different measures. These include the covariance and the correlogram (Journel 1987, Isaaks and Srivastava 1989). In this study we use the semivariogram, in the following for convenience, but incorrectly, denoted *variogram*, defined by:

$$2\gamma(h) = E\{[X(u) - X(u+h)]^2\} \qquad (Eq.\ 4\text{-}4)$$

which is estimated by:

$$2\gamma(h) = \frac{1}{n_A} \sum_{\alpha=1}^{n_A} [x(u_\alpha) - x(u_\beta)]^2 \qquad (Eq.\ 4\text{-}5)$$

$$u_\alpha, u_\beta \in A \in S, u_\beta - u_\alpha \approx h$$

The choice of this subarea A of the domain S over which separate statistics or averaging will be performed is governing the *stationarity* of the studied RF. In the *intrinsic case* stationarity implies that within the subarea the spatial correlation is dependent only on the interdistance h between studied points u and u', not on their actual locations. In addition the expected value is constant, independent of location u, i.e. $E\{X(u)\} = m$ (Journel and Huijbregts 1978).

The variogram $\gamma(h)$ which is half the squared difference between the paired data values with interdistance h corresponds to the moment of inertia around the u=u' diagonal in a h-scatter plot of the data pairs (Isaaks and Srivastava 1989). The shape of the h-scatterplot tells us how continuous the data values are over a certain distance in a particular direction. If the data values are very similar they tend to plot close to the diagonal. As the data values become less similar, ie. with increasing distance or *lag* h the cloud of data points on the h-scatter plot becomes more fat and more diffuse and the value of the moment of inertia increases, and so does the variogram.

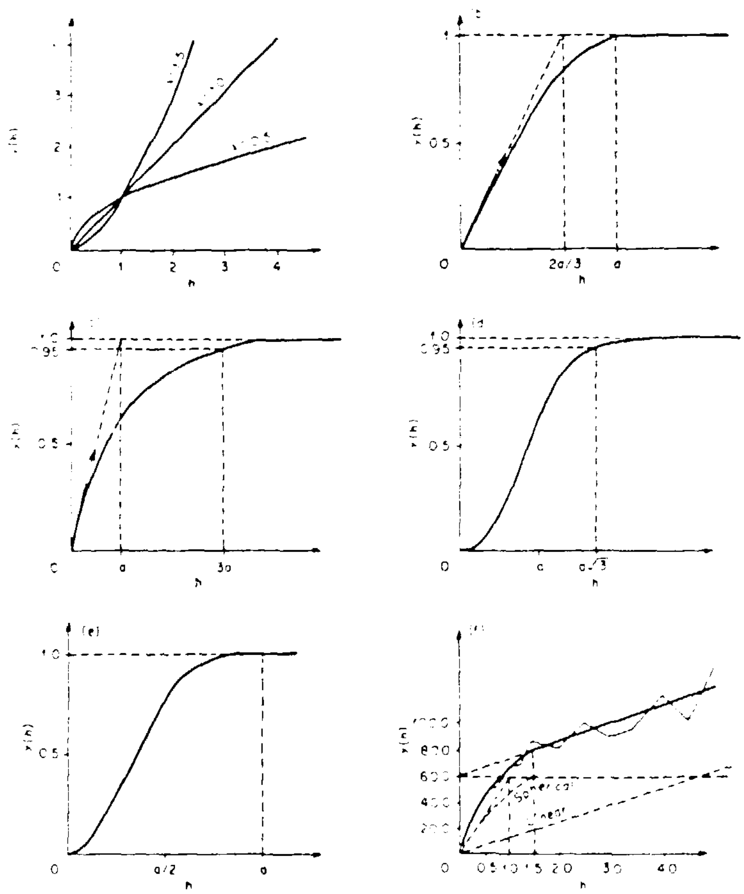


Figure 4.2 **Graph of variogram models most frequently used in geostatistical applications, a) model in h^{τ}, b) spherical, c) exponential, d) gaussian, e) cubic, f) linear with superimposed spherical model (from de Marsily 1986).**

The variogram is consequently a measure of deviation and as already stated an increasing function of the interdistance $|h|$ for a given vector h. The distance $|h|$ where the spatial *(auto-)correlation* ceases to exist, ie. where the variogram reaches a *sill* value **C** is called the ***range*** **(a)** of correlation, cf. Figure 4.3. Ideally, the sill value C equals the population variance σ^2. Beyond $|h| = a$ the RV's X(u) and X(u+h) are uncorrelated, which does not necessary entail that they are independent (Journel 1987). If the spatial correlation is equal in all possible directions the resulting variogram is said to be *isotropic*. If on the other hand the range of correlation varies with orientation the variogram is said to be *anisotropic*. A variogram calculated for a spectra of orientations, eg. data from all available orientations of boreholes in an area is denoted an *omnidirectional variogram* (Isaaks and Srivastava 1989).

A number of different variogram models have been presented over the years in the geostatistical literature. A compilation has been made by de Marsily (1987). A graphical representation of the various variogram models is provided in Figure 4.2.

At any given scale, say that of the range, there may be a discontinuity at the origin of the variogram called the *nugget effect*. The nugget effect composites and quantifies the contribution of all scales of spatial variability smaller than the shortest available experimental interdistance between samples. This component also include possible measurement errors.

If the scale of measurement is confined to an interval within which the variogram is flat the variogram is said to constitute a *pure nugget effect*. Sometimes a pure nugget effect may be difficult to distinguish from a noisy variogram with structure (Journel 1987).

An experimental variogram which at large distances h increases proportionally to $|h|^2$ is not compatible to the intrinsic hypothesis (Journel and Huijbregts 1978). This type of increase in the variogram most often indicates the presence of a *drift*, ie. a non-stationary mathematical expectation; $E[X(u)] = m(x)$. If the drift component is filtered out, the spatial characteristics may be inferred from the residuals.

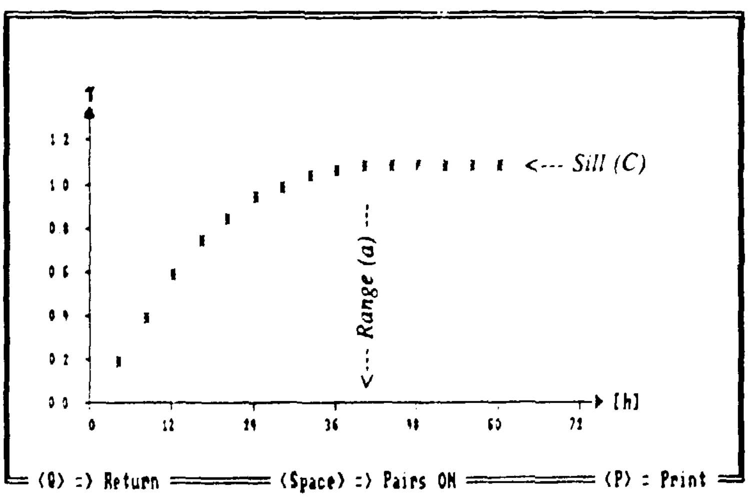


Figure 4.3 Definition of characteristics of a variogram.

Table 5.1 **Summary statistics for boreholes E1, N1, V1 and F1-F6 (10 m sections)**

Borehole	m	σ^2	Q_1	M	Q_3	IQR	CoV	N
E1	-10.15	1.89	-11.15	-10.70	-9.11	2.04	13.5	22
N1	-12.12	0.39	-12.56	-12.13	-11.64	0.92	5.1	9
V1	-12.14	2.57	-13.47	-12.57	-11.52	1.95	13.2	42
F1	-10.41	0.88	-11.04	-10.32	-9.76	1.27	9.0	19
F2	-10.84	1.06	-11.70	-11.13	-10.50	1.20	9.5	23
F3	-9.54	1.33	-10.12	-9.52	-8.95	1.17	12.1	27
F4	-10.11	0.91	-11.00	-10.19	-9.74	1.26	9.4	28
F5	-9.65	1.28	-10.33	-9.46	-8.74	1.58	11.7	28
F6	-9.87	0.96	-10.51	-10.51	-9.36	1.15	10.0	23

m = arithmetic mean of logK = geometric mean, $K_g = 10^m$
Q_n = nth quartile
IQR = interquartile range = $Q_3 - Q_1$
N = number of data
σ^2 = variance of logK (base 10)
M = median of logK
CoV = coefficient of variation = σ/m (%)

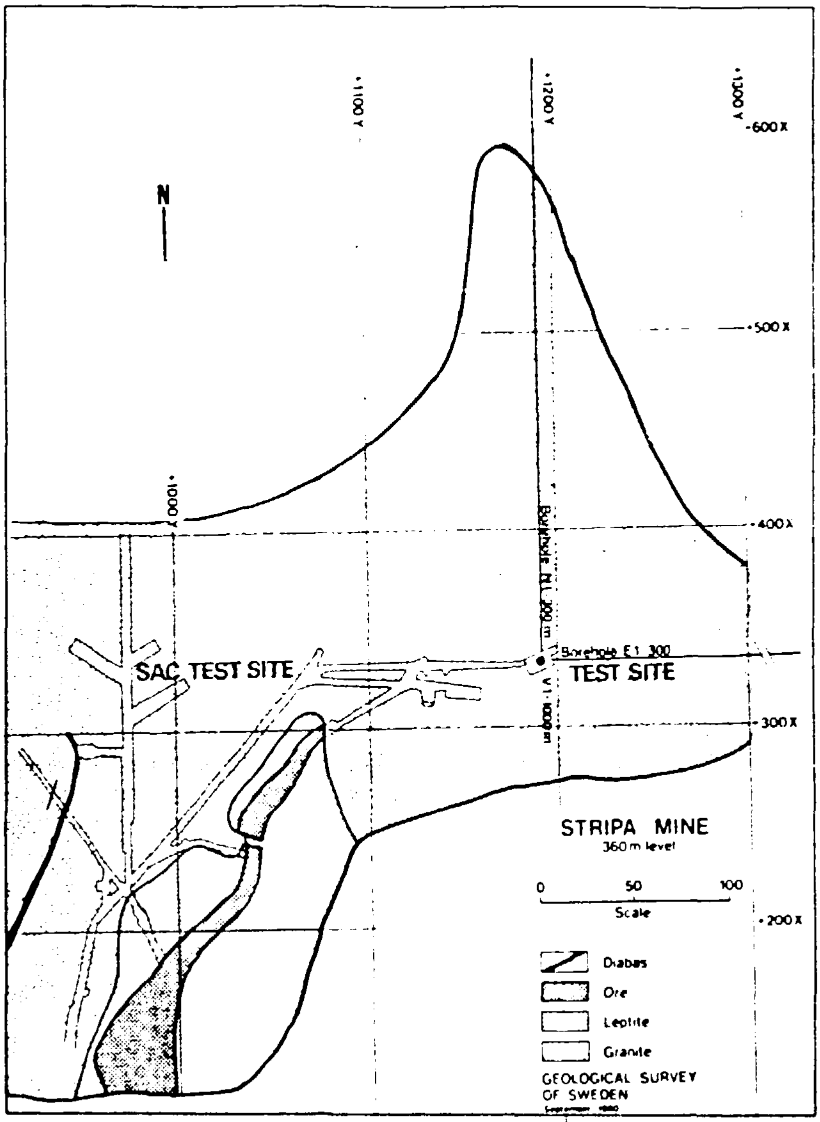


Figure 5.1 Layout of boreholes at the SGU site at the 360 m level and associated geology (from Carlsson et al 1981).

5. ANALYSIS OF DATA

5.1 Analysis of data from the SGU site

5.1.1 General

Three boreholes are located at the so-called SGU site at the 360 m level in th ipa mine. The boreholes constitute one vertical (V1) and two near horizontal (E1 a N1), trending east and north, respectively. The core logging of the boreholes is reported elsewhere (Carlsson et al 1981, Carlsson et al 1982). Data on borehole specifics is provided in Appendix A, and a schematic view of the boreholes is provided in Figure 5.1.

In the reporting of results, Carlsson and Olsson (1985) present three hydraulic conductivities; from the injection phase, from the recovery phase and in the form of a pseudo-stationary value. In the following only the value based on the injection phase is presented. It should however be indicated that the difference between the different values is limited.

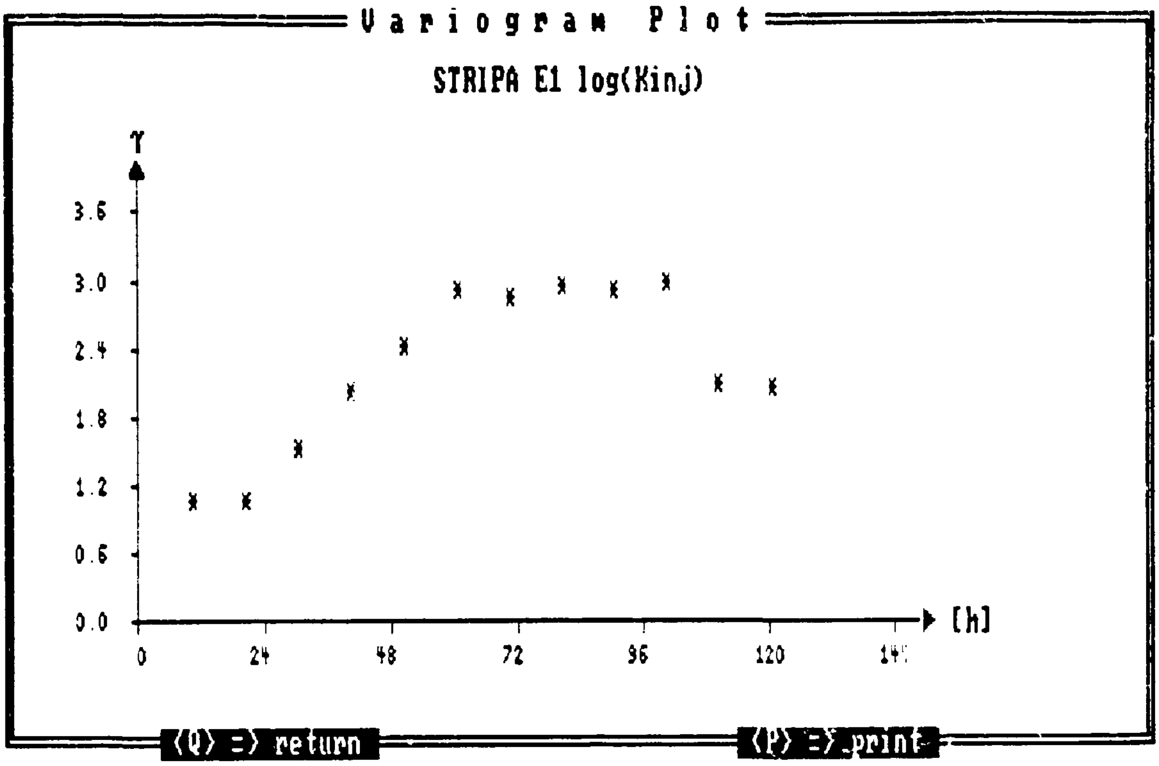
5.1.2 Hydraulic conductivity - summary statistics

The summary statistics for the hydraulic conductivity data in E1, N1 and V1 are given in Table 5.1. The results indicate mean values of log K (geometric means) of -10.15 and -12.14 for E1 and V1, respectively. The mean value for N1 is -12.12 but is based on a limited amount of data (N=9), the variance is in this case very low (0.39). The variances of data in E1 and V1 is 1.89 and 2.57, respectively.

5.1.3 Experimental variography

Experimental variograms have been produced for the injection phase hydraulic conductivities. In the case of borehole N1, the number of data was too limited to produce any meaningful results. In the case of data from E1, cf. Figure 5.2a, a fairly well developed variogram, spherical in shape, is obtained. The nugget effect is insignificant and the sill of c. 3.0 is 60% higher than the population variance. The practical range is on the order of 60 m.

The variogram based on data from V1, cf. Figure 5.2b, has a similar (exponential) appearance to that of E1 with the exception that the nugget effect is higher. As is the case of E1 the sill value is higher (c. 20%) than the population variance. The practical range is on the order of 50-60 m. Before assigning a mathematical model to the variograms a critical scrutiny of anomalous contribution to the variograms at each individual lag should be explored. This has not been performed here because of time constraints.



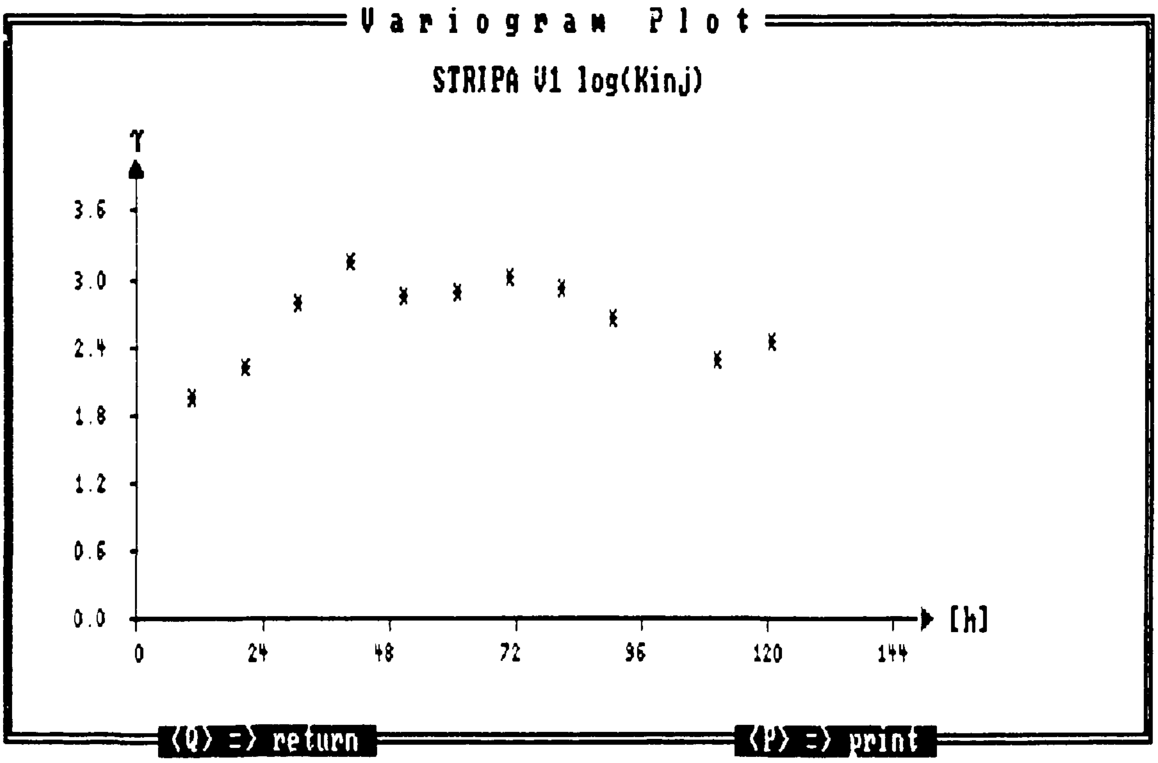


Figure 5.2 **Experimental variograms based on data from boreholes; a) E1 b) V1.**

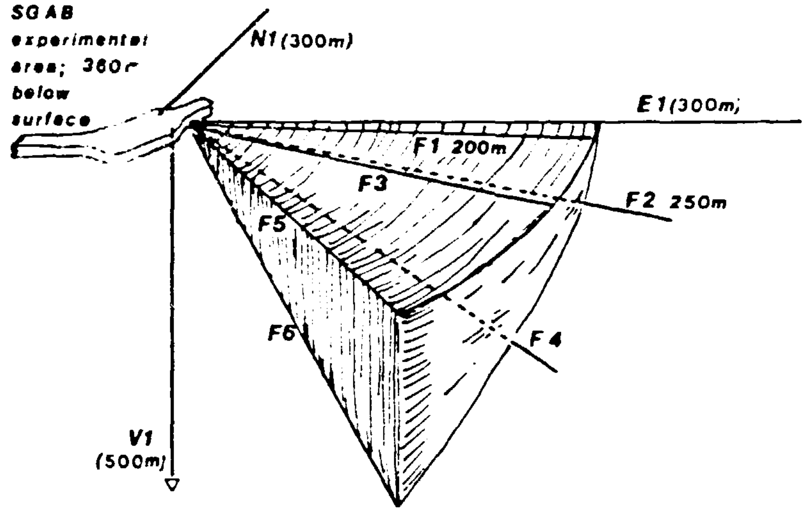


Figure 5.3 **Schematic 3D representation of the fan-like F-hole array at the cross-hole site (from Black et al 1987).**

5.2 Analysis of data from the cross-hole site

5.2.1 General

The six boreholes at the cross-hole site are denoted F1-F6. They constitute a fan-like array of boreholes collared at an extension of the old SGU site, cf. Figure 5.1 and 5.3. The geometrical data associated with the holes are given in Appendix A. F1, F3 and F5 all have an inclination of 10° whereas the remaining holes have inclinations varying between 20° and 40°. The holes were drilled to facilitate geophysical and hydrological cross-hole investigations to test developed methods to obtain a three-dimensional understanding of crystalline rock mass. A description of the hydrogeological work is provided by Black et al (19°7). A description of the core logging of the six holes is presented by Carlsten and Stråhle (1985).

5.2.2 Hydraulic conductivity - summary statistics

The summary statistics of data from the individual F-holes is given in Table 5.1. The mean values of the holes are within a factor 20. There is a weak tendency that the near-horizontal holes have a somewhat increased mean hydraulic conductivity. The variances are generally very low, between 0.88 and 1.33. The higher variances are noted for the holes with high mean conductivities indicating a proportional effect (Isaaks and Srivastava 1989).

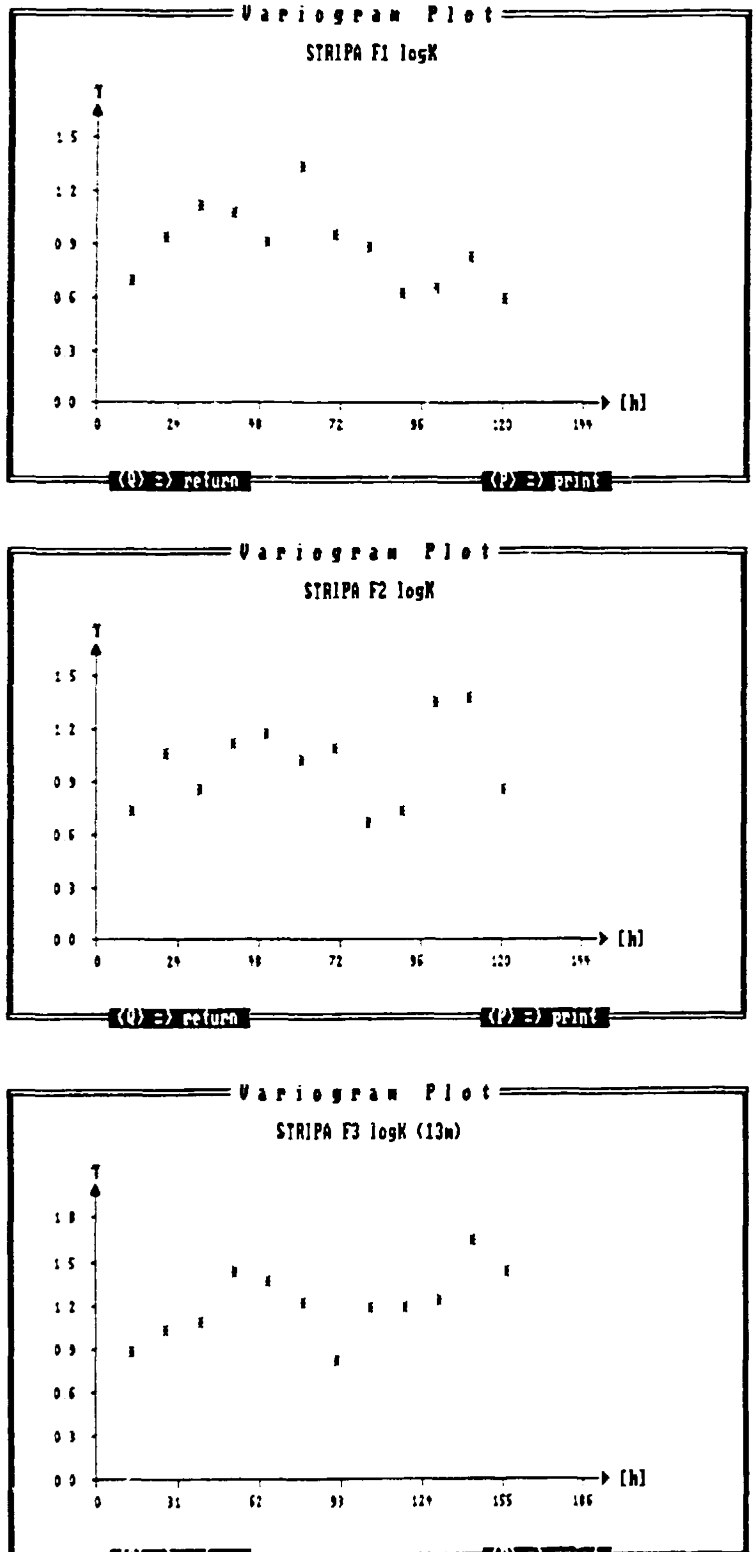


Figure 5.4 Experimental variograms of hydraulic conductivity data (10m) from boreholes; a) F1, b) F2, c) F3.

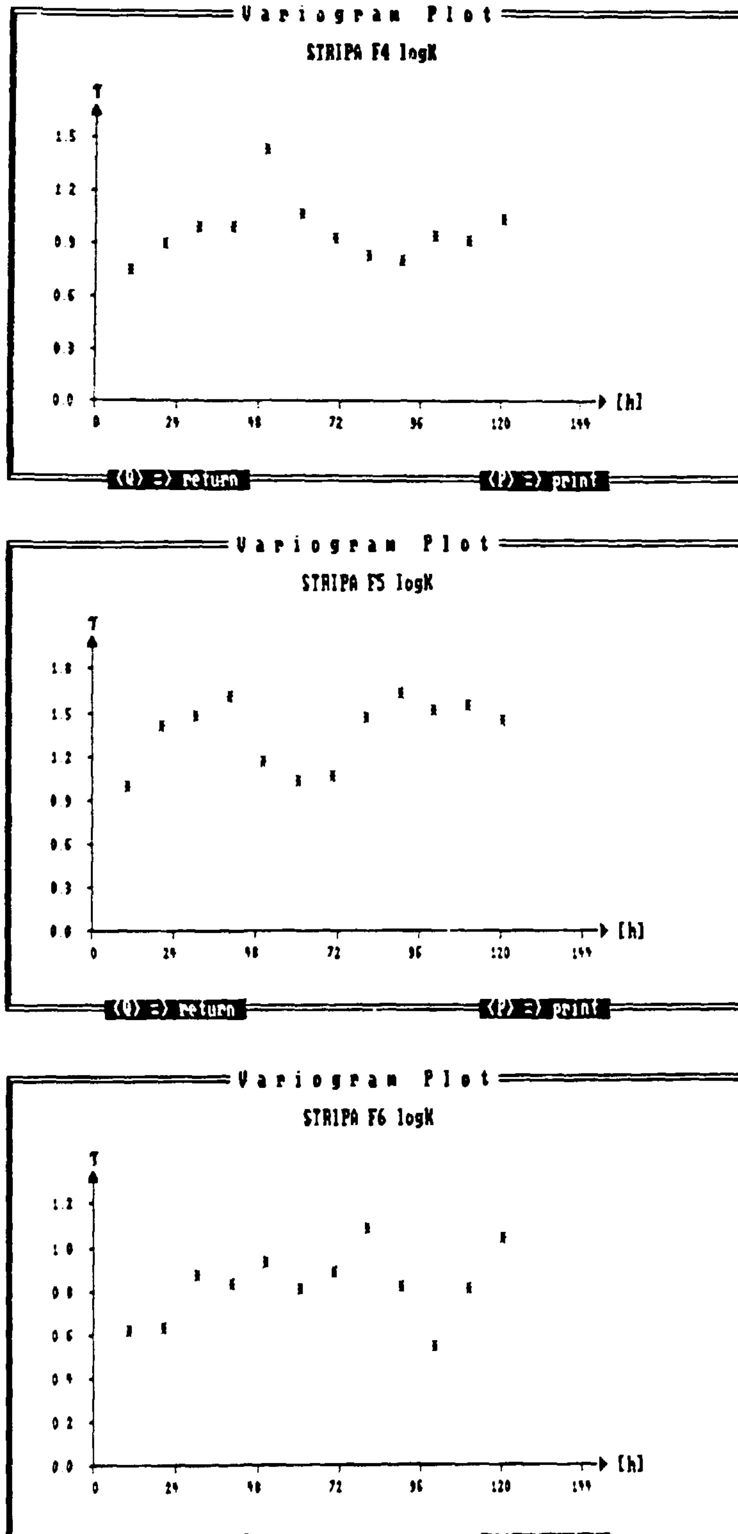


Figure 5.5 **Experimental variograms of hydraulic conductivity data (10m) from boreholes; a) F4, b) F5, c) F6.**

5.2.3 Experimental variography

The variograms calculated from the data in boreholes F1 to F6 are presented in Figures 5.4 and 5.5. Analysis of the variograms, which have not been filtered in any way, reveal weak signs of finite structure. This applies especially for data from boreholes F1, F3 and F5. The latter holes are subhorizontal, fanning out in different directions, essentially sampling subvertical fractures. The observed practical ranges are on the order of 30-50 m. The remaining holes to a larger extent sample also subhorizontal sets, which might explain the appearance of the remainder of variograms which have a more pronounced nugget effect.

In the variogram based on the F5 data there is evidence of a hole effect indicated by the depression at a lag distance of c.60 m. This indicates that data at an interdistance of 60 m are more similar in magnitude.

5.3 Analysis of 1-7m data from the SCV site

5.3.1 General

The data from the SCV site originates from two different phases in the Site Characterization and Validation (SCV) experiment. The layout of the different holes is presented in Figure 5.6. The first phase includes data from the bounding subhorizontal westerly oriented holes (W1 and W2) and northerly oriented boreholes (N2-N4). The analysis of these holes were used to make predictions of the hydrogeological and fracture characteristics of the fan of C-holes (C1-C3) which cross-cut the target volume of rock with different geometries. The geometrical specifics of the different boreholes are presented in Appendix A.

The holes have been hydraulically tested with varying section lengths. The logs of hydraulic conductivity vs. depth are provided in Appendix B. This implies that the data set subject to study is not statistically homogeneous. The longer section lengths should be given more weight than the short (1m) sections in the statistics based on logK. One way to circumvent this problem is to analyse the statistics of the log transmissivity logT, whereby the length of the test section is introduced as a multiplier to the hydraulic conductivity. No other weighting scheme has been applied.

5.3.2 Hydraulic conductivity - summary statistics

The calculated geometric mean transmissivities are all varying between -10.03 and -9.32, ie. within a factor 5, cf. Table 5.2. The variances span between 0.6 and 2.7. There is a tendency that the westerly oriented boreholes show a somewhat increased variability. Considering the varying support of these data, the summary statistics are of limited value.

In order to overcome the problems with varying support, without resorting to weighting, the data were divided in two populations; 1) section length $\leq$ 2m, and 2)

Table 5.2 Summary statistics for boreholes W1-W2, N2-N4 and C1-C3 (variable section length)

Borehole	$\overline{\log T}$	σ^2	Q_1	M	Q_3	IQR	CoV	N
W1	-9.98	1.53	-10.85	-9.96	-9.10	1.75	12.4	102
W2	-9.32	2.66	-10.38	-9.28	-8.23	2.15	17.5	93
N2	-9.92	0.99	-10.62	-9.96	-9.31	1.31	9.9	80
N3	-9.94	0.75	-10.50	-9.91	-9.57	0.94	8.7	46
N4	-9.91	1.95	-10.95	-10.04	-8.96	1.99	14.1	71
C1	-9.78	1.27	-10.51	-10.00	-9.25	1.26	11.5	46
C2	-10.02	1.39	-10.96	-9.95	-9.27	1.69	11.8	39
C3	-10.03	0.56	-10.35	-10.03	-9.51	0.84	7.5	29

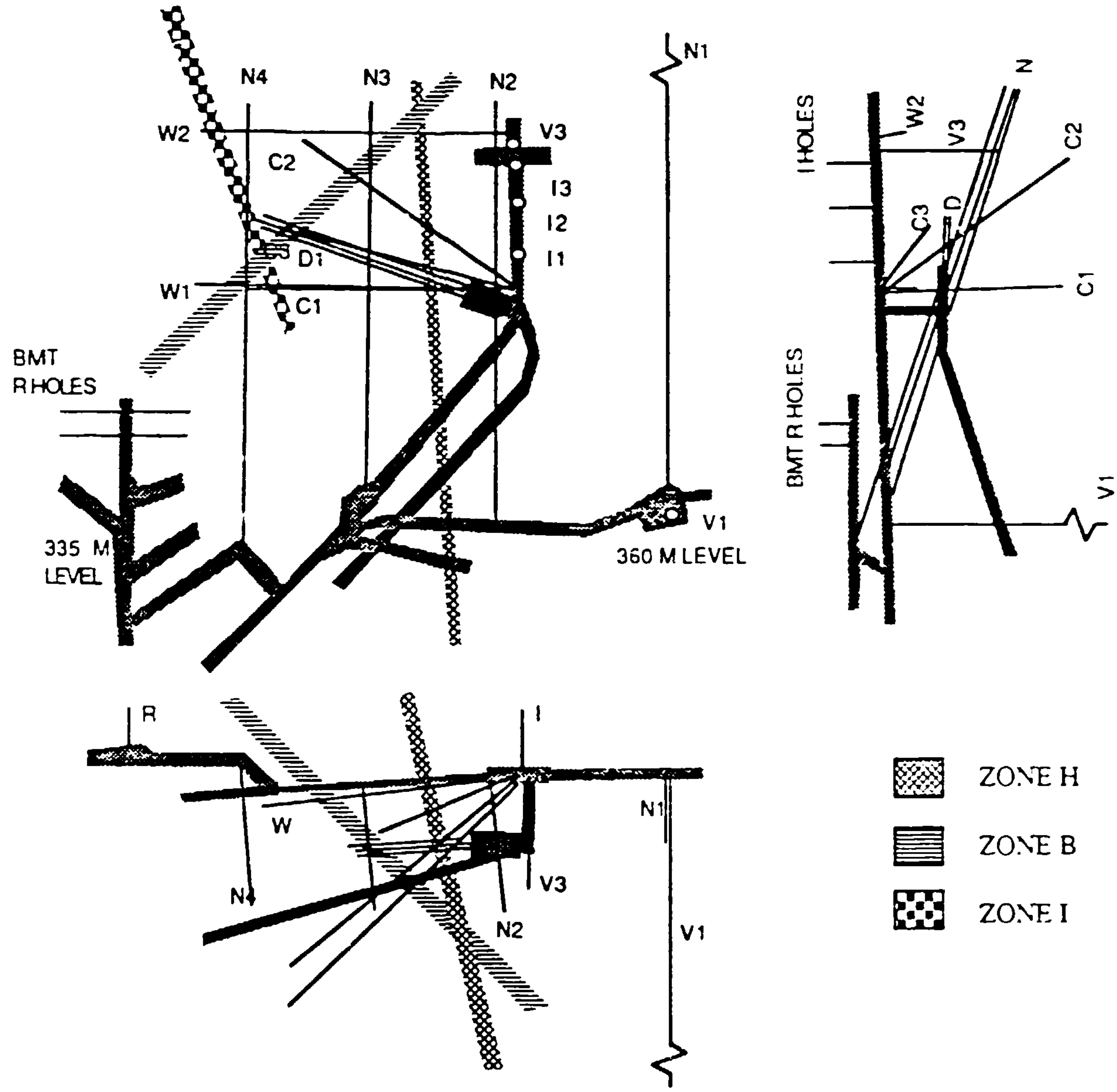


Figure 5.6 Layout of boreholes at the SCV site (from Holmes et al 1990).

section length 3-7m. In the case of data from W1 and W2, no subsetting was done since most of the test sections are c. 1m. The resulting summary statistics for the subsets are presented in Table 5.3. Where the number of data was insignificant in a statistical sense, no calculations were made.

The results in Table 5.3 compared to those in Table 5.2 show the relative weight of data with short section lengths. In Table 5.2 the short section data influence the results with equal weight. In Table 5.3 we see that the longer section length populations tend to have a lower mean value and in most cases also a lower variance.

5.3.3 Experimental variography

The fact that the data to be analysed have varying support imposes a problem. At this stage no deregularisation was performed, instead the transmissivity data were analysed "as is". However, a "mean" support or measurement section was assigned to each borehole population based on the appearance of the logs in Appendix B. The resulting variograms are shown in Appendix C. The variograms are generally distinguished by a tendency towards a "pure" nugget effect, ie. the variogram is horizontal and the data are spatially uncorrelated. The data in boreholes N3, C1 and C3, however, appear to be more spatially correlated. The practical ranges are in this case on the order of 50 m.

In order to suppress the effect of varying support, variograms were also produced for the subsetted data from the N and C holes, ie. 1) data with section lengths ≤ 2m and 2) data with section lengths 3-7m. The resulting variograms for the data sets with a meaningful number of data are reproduced in Appendix D. As can be seen in the case of boreholes N2, N4 (≤ 2m, 3-7m) and C2 (3-7m) the subdivision did not help to improve the spatial correlation. In the case of N3 and C1 (3-7m data) the spatial structure is maintained, whereas it is lost for the subsetted 3-7 m data from C3.

The lack of evident spatial structure was also noted for the 20m hydraulic conductivity data measured in coreholes in the Brändan area, Finnsjön, Sweden (Winberg 1989). This fact was attributed to the fact that the 2m data showed correlation lengths on the order of the larger section length, ie. c. 20m. Thus, any spatial structure beyond 20m was blurred by the choice of larger section length over the scale of measurements, usually 200-300 m.

A hypothesis posed in the context of the SCV data is whether the same conditions applies for the data in the W-, N- and C-series boreholes, ie. that the correlation length of deregularized data over smaller section lengths have a correlation length equal or close to the maximum section lengths used in the hydraulic testing of the holes.

To test this hypothesis, focus was put on the data deregularized to 1m sections, produced for the W-, N- and C-series holes (Holmes 1989, Holmes et al 1990, Black et al 1991). To create this data set, use has been made of overlapping and integral

Table 5.3 Summary statistics for N2-N4, C1-C3 (subsets of data)

Borehole	Subset	$\overline{\log T}$	σ^2	Q_1	M	Q_3	IQR	CoV	N
N2	3-7m	-10.34	0.58	-10.93	-10.35	-9.81	1.12	7.4	32
N2	≤ 2m	-9.65	1.02	-10.35	-9.72	-9.08	1.27	10.5	48
N3	3-7m	-10.26	0.53	-10.64	-10.13	-9.83	0.81	7.1	29
N4	3-7m	-10.67	1.17	-11.64	-10.75	-10.19	1.45	10.1	29
N4	≤ 2m	-9.39	1.82	-10.19	-9.48	-8.31	1.88	14.3	42
C1	3-7m	-10.47	0.36	-11.14	-10.49	-9.98	1.16	5.7	20
C2	3-7m	-10.35	0.71	-11.22	-10.22	-9.73	1.49	8.2	22
C3	3-7m	-10.40	0.68	-11.40	-10.14	-10.00	1.40	8.0	13

part measurement to calculate a continuous log of 1m data in each hole. Naturally this leads to assignment of repetitive low conductivity values over longer section with low hydraulic conductivity. This effect may overemphasise spatial continuity and has to be taken into account. The following chapter will present the results of the analysis of the data deregularised to 1m sections.

5.4 Analysis of 1m data from the SCV site

5.4.1 General

Analysis of SCV hydraulic conductivity data deregularised to 1m sections has been performed on data from individual holes as well as data sets consisting of pooled borehole data sets of similar geometry.

5.4.2 Hydraulic conductivity - summary statistics

The summary statistics of the 1m data from the SCV holes is reproduced in Table 5.4. The calculated mean values span over one order of magnitude. Noteworthy is also the somewhat increased mean conductivities in the westerly boreholes (c. -10) compared to the northerly ones. The mean conductivities in the inclined C-series holes are on the order of that calculated for the northerly holes.

The calculated population variances are somewhat less in the northerly holes when compared with the westerly. The variance of the C-hole data is on the order of that of the data from the northerly holes.

To study directional effects on the basis of larger populations the data from the W-, N- and C-series holes have been pooled together in three populations. The summary statistics based on these populations are presented in Table 5.5. It should be emphasised that the bearings and inclinations of the C-holes are not identical, cf. Figure 5.6. Notwithstanding this fact, the C-hole data have been pooled together since the data represent a more complete sampling of the occurring fracture sets within the SCV block.

The calculated mean hydraulic conductivity of the W-population is a factor 5 higher than the N-population. The C-series population has a somewhat lower mean than the N-population. The calculated population variances show a strong element of correlation between variance and mean value, ie. a *proportional effect.*

The histograms and cumulative distributions of the W-, N- and C-populations are shown in Figures 5.7 and 5.8, respectively. The overall impression of the populations are that they are near lognormal. However, a more detailed scrutiny reveal more of a bimodal distribution of the data in the W- and N-populations, and even three-modal in the case of the C-population.

Table 5.4 SCV site - 1m data - summary statistics (individual boreholes)

Borehole	m	σ^2	Q_1	M	Q_3	IQR	CoV	N
W1	-10.23	1.48	-10.96	-10.35	-9.40	1.56	11.9	140
W2	-10.01	3.30	-11.43	-10.08	-8.80	2.64	18.2	140
N2	-10.60	0.90	-11.25	-10.70	-10.05	1.20	9.0	199
N3	-10.89	0.85	-11.41	-10.85	-10.52	0.89	8.5	184
N4	-10.95	1.84	-11.92	-11.28	-10.15	1.77	12.4	212
C1	-10.84	1.09	-11.43	-10.92	-10.54	0.89	9.7	143
C2	-11.02	1.22	-11.73	-11.00	-10.55	1.18	10.0	143
C3	-10.89	0.96	-11.66	-10.85	-10.15	1.50	9.0	92

Table 5.5 SCV site - 1m data - summary statistics (pooled populations)

Population	m	σ^2	Q_1	M	Q_3	IQR	CoV	N
W1,W2	-10.12	2.40	-11.02	-10.21	-8.96	2.06	15.3	280
N2,N3,N4	-10.82	1.25	-11.51	-10.85	-10.26	1.25	10.3	595
C1,C2,C3	-10.92	1.12	-10.55	-10.90	-10.49	1.07	9.7	378
All	-10.69	1.56	-11.44	-10.80	-10.07	1.37	11.7	1253

Table 5.6 SCV site - 1m data - summary statistics (<u>reduced</u> pooled populations)

Population	m	σ^2	Q_1	M	Q_3	IQR	CoV	N
W1,W2	-9.78	2.36	-10.78	-9.77	-8.70	2.08	15.7	202
N2,N3,N4	-10.31	1.67	-11.26	-10.50	-9.49	1.77	12.5	221

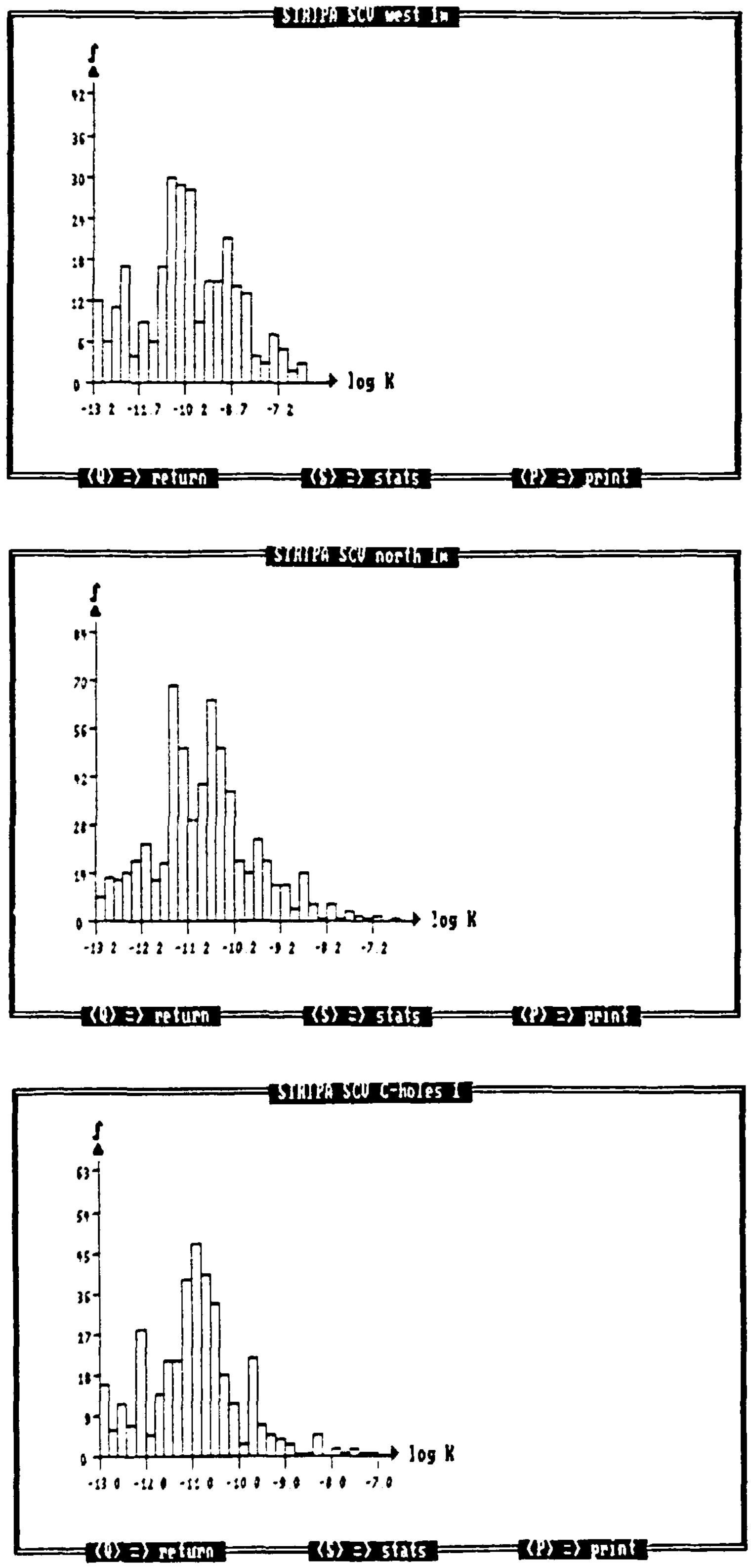


Figure 5.7 **Histogram of logK (1m data) based on pooled populations from the SCV site. a) W-population, b) N-population, c) C-population.**

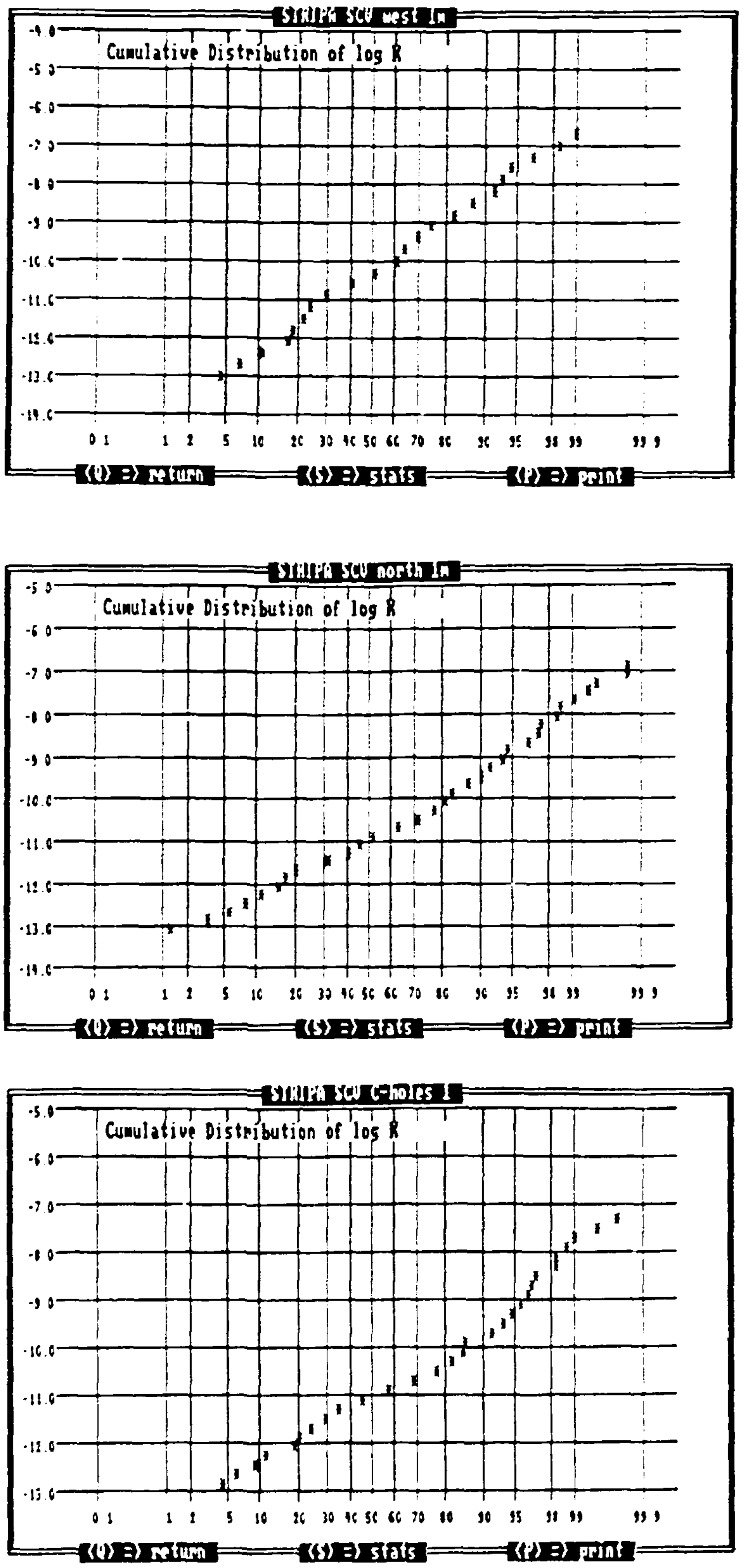


Figure 5.8 Cumulative distribution of logK (1m data) based on pooled populations from the SCV site. a) W-population, b) N-population, c) C-population.

Table 5.6 show the summary statistics of reduced W- and N-populations, cf. Section 5.4.3. The resulting mean values are a factor 2 and 4 higher than for the initial pooled populations, respectively. The calculated variance for the N-population is somewhat increased which is also reflected in the coefficients of variation (CoV).

5.4.3 Experimental variography

Experimental variograms based on data deregularised to 1m sections have initially been produced for the following three types of populations;

1) Individual boreholes
2) Pooled populations
3) Complete SCV pooled population

The experimental variograms for data from individual holes in the W-, N- and C-series are presented in Appendix E.

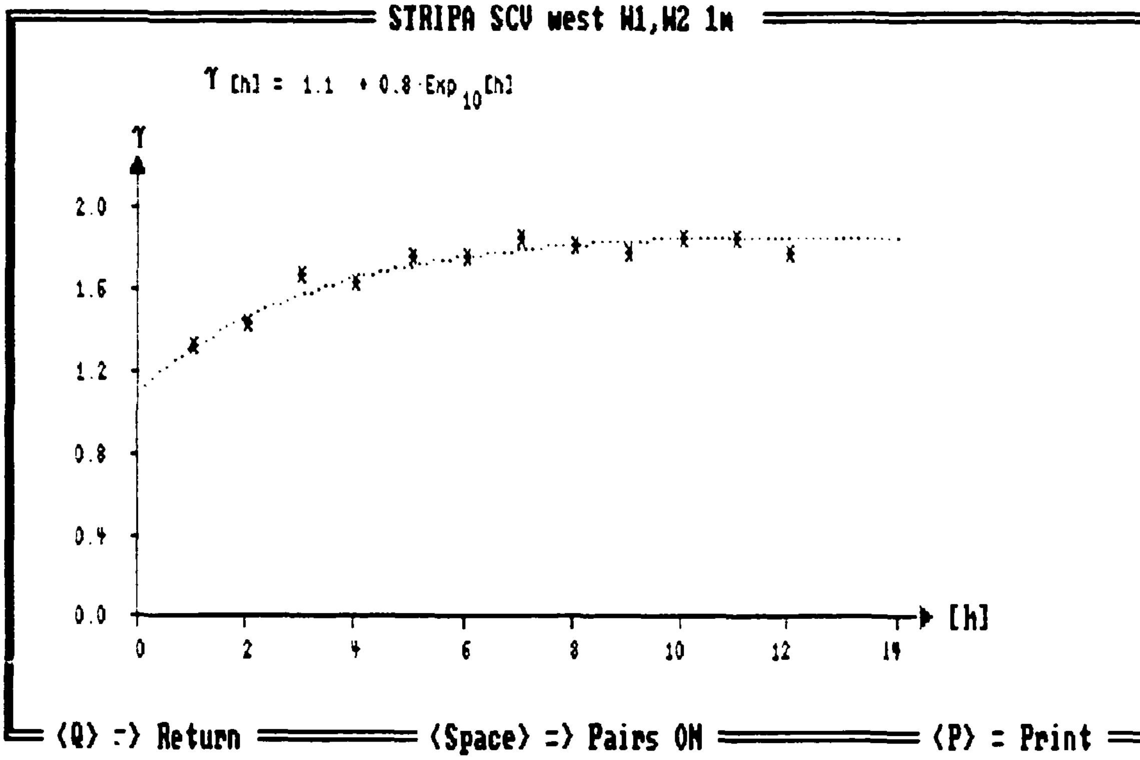
The variograms for the pooled W-, N-, and C-populations and that based on all 1m data from the SCV site are shown in Figures 5.9 and 5.10. There is a tremendous difference between the variogram based on the W- and N-population, cf. Figure 5.9. The data from the W-holes result in a variogram which show a high degree of continuity with an associated high nugget. This could also be interpreted as a *pure nugget effect* since the nugget is 60% of the total sill. The variogram of the N-population on the other hand show a high degree of variability. The nugget is zero and the total sill is 1.0. In both cases the total sill (C_o+C_1) is 80% of the population variance, cf. Section 5.4.2. The inferred practical ranges of the modelled exponential variograms are 10 and 8.5 m, respectively.

The experimental variogram based on the C-population is similar to that of the N-population. The total sill is c. 1 which is 90% of the population variance. The range of the spherical model is 10 m, cf. Figure 5.10a.

The variogram based on all 1253 deregularised data is very similar to that of the N- and C-populations, cf. Figure 5.10b. The total sill of 1.21 is close to 80% of the calculated population variance. The practical range of the exponential variogram is 9 m.

As previously mentioned, the deregularisation scheme and the underlying testing methodology used may overemphasize the continuity of low-permeable sections in the rock. The testing philosophy stated that when a 10 m section had a hydraulic conductivity less than 10^{-11} m/s, it was assumed to have a minimal hydraulic significance, and no further testing was warranted. This means that as long as ten 1m sections of a borehole may have been assigned identical low hydraulic conductivity.

This problem may be treated in different ways. One way would be to randomly distribute the 1m data from a uni-conductive 5 or 10m sections below the cut-off values, ie. 10^{-10} and 10^{-11} m/s, respectively. This calls for a fair understanding of the



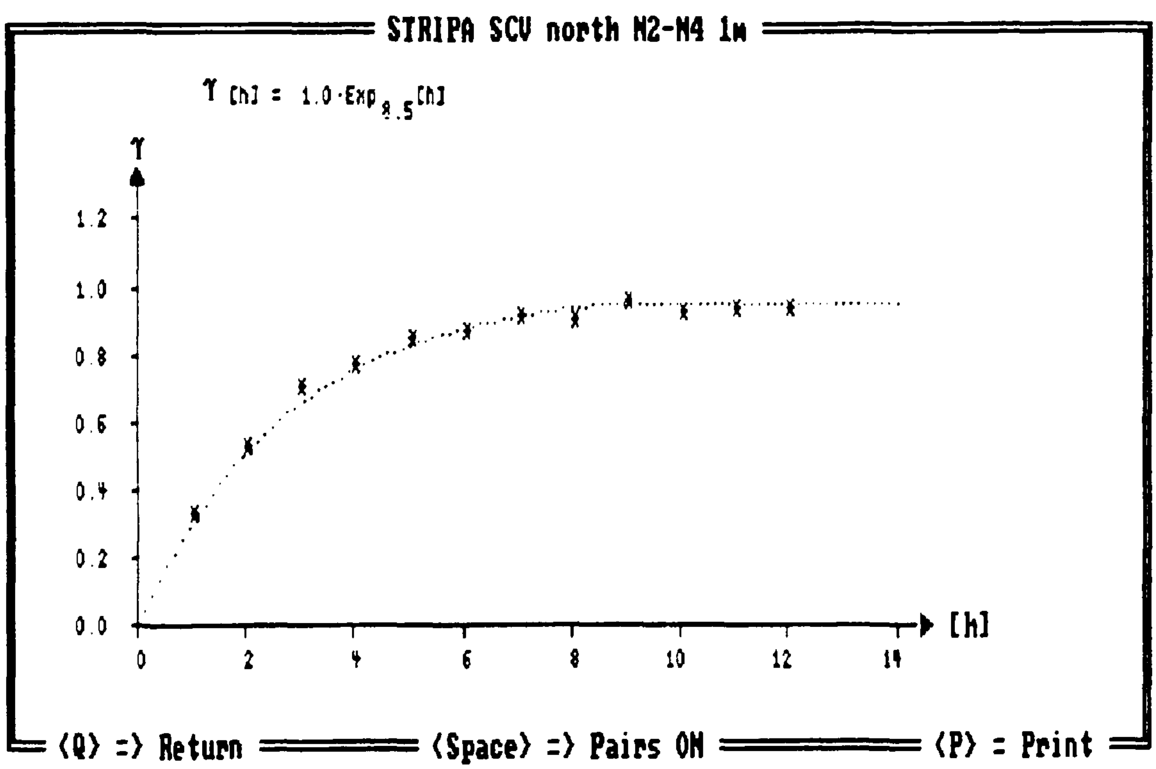
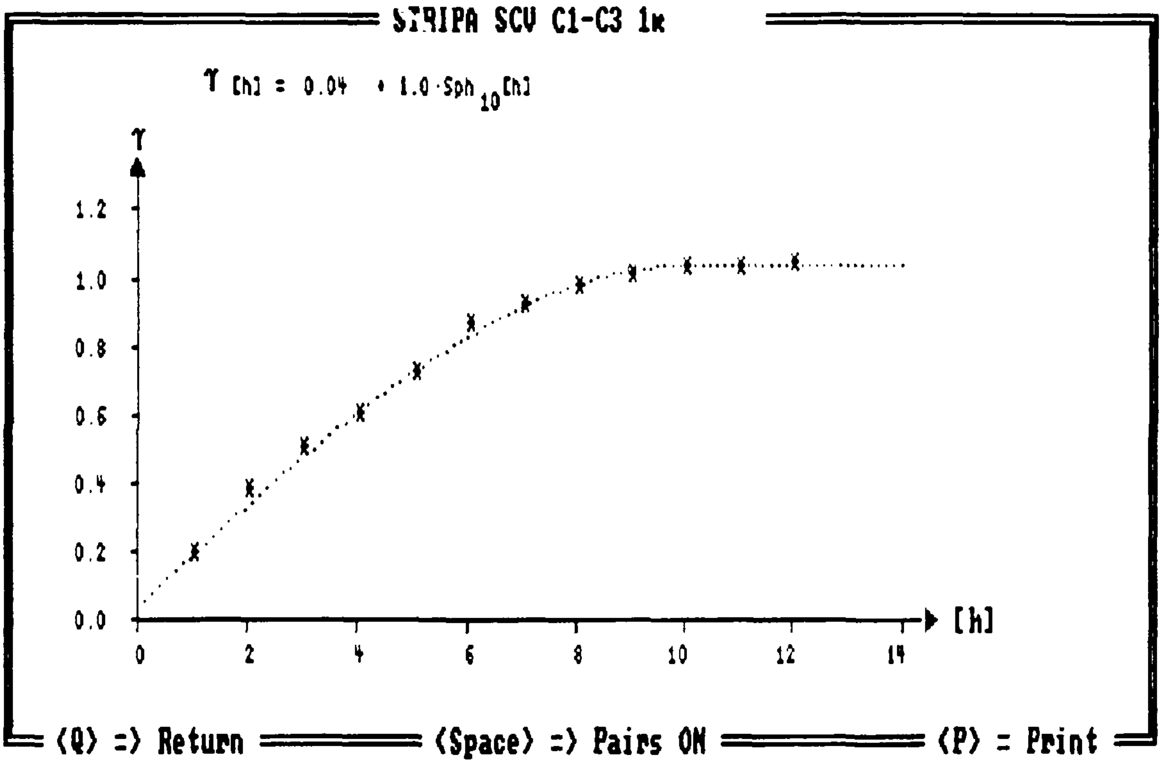


Figure 5.9 **SCV site. Experimental variograms based on data deregularised to 1m sections. a) W-population, b) N-population.**



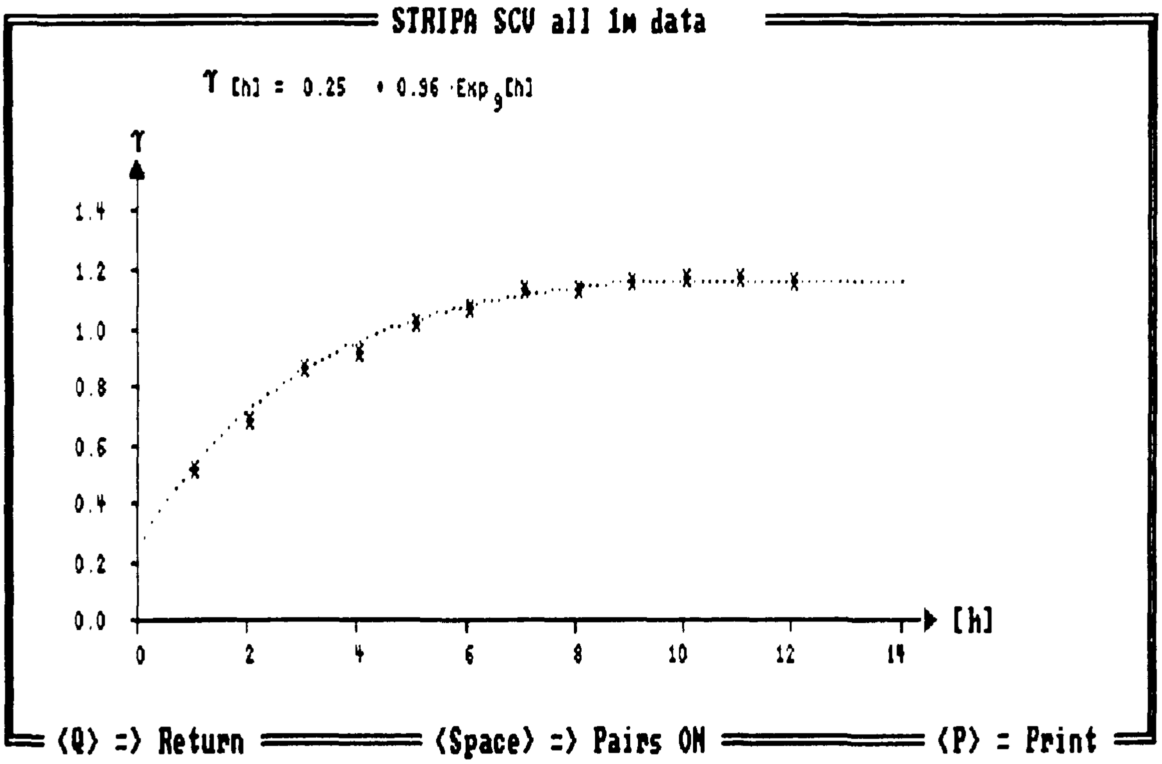
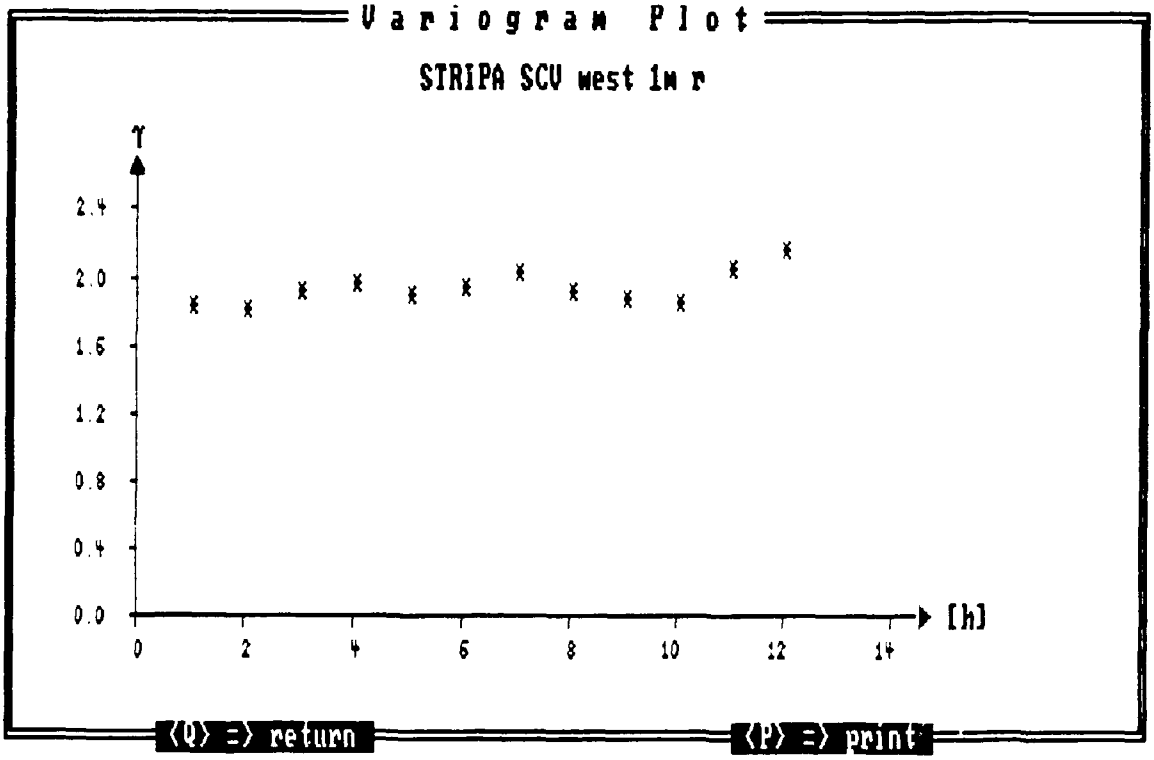


Figure 5.10 SCV site. Experimental variograms based on data deregularised to 1m sections. a) C-population, b) all data (W+N+C)



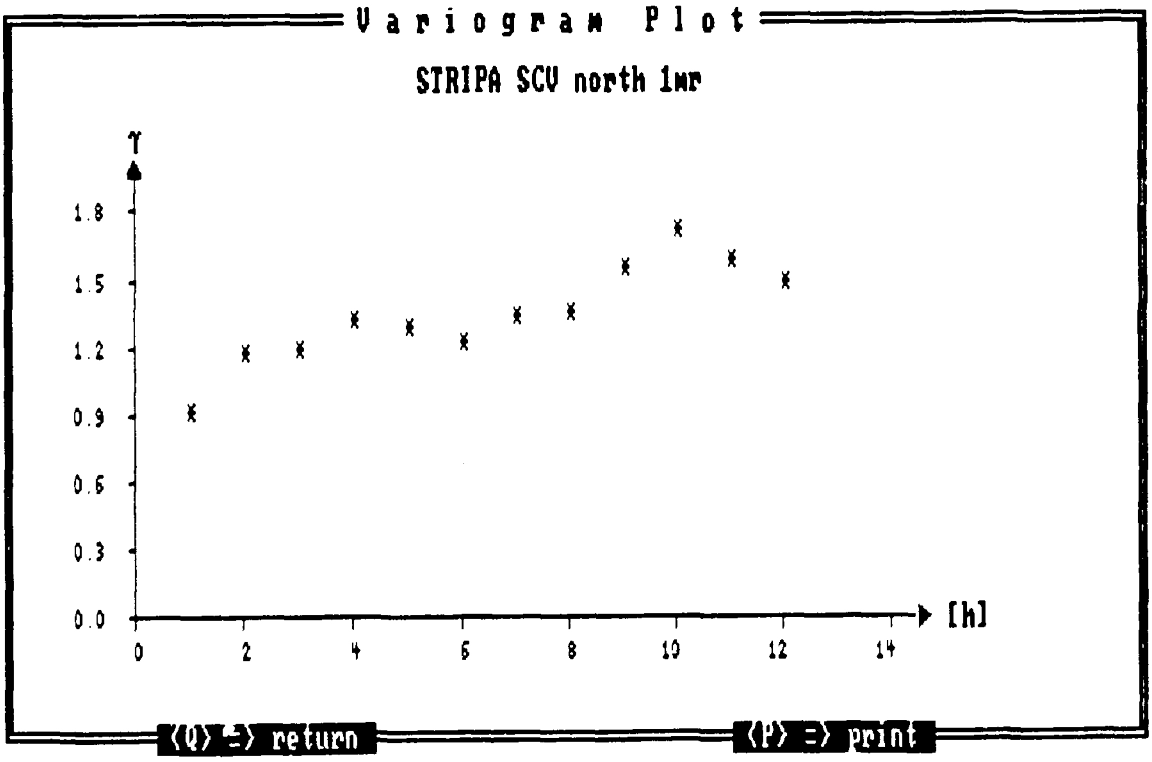


Figure 5.11 **SCV site. Experimental variograms based on reduced populations of data deregularised to 1m sections. a) W-population, b) N-population.**

underlying distribution function. In the case of the SCV data, a lognormal model seems to be a fair assumption. In addition it would call for a large number of simulations with subsequent statistical and geostatistical analysis. A more tractable alternative is to use a scheme where the parameters of the distribution function is updated after each simulation and the simulation is carried out iteratively until some stated convergence criteria in the parameters of the model is met. Then the statistics and geostatistics is carried out on the last realization.

None of the alternatives discussed above have been pursued within this study due to time constraints. Instead the probable extreme towards the other (more variable) end was investigated. The analysis was performed as follows; the data files with data from the W- and N-holes were revisited and all clusters of (identical) data more than *two in a sequence were deleted, leaving only the "top" value.*

The resulting univariate statistics of the two populations which were reduced with 28 and 53%, respectively is discussed in Section 5.4.2. The large reduction in the case of the N-population is compatible with the almost one order of magnitude lower mean and a half an order of magnitude lower first quartile in the case of the N-population.

The resulting experimental variograms are shown in Figure 5.11. Obvious is the complete loss of structure observed for the variogram based on the reduced W-population. The variogram based on the reduced N-population show a still higher degree of variability than the original population. An approximate range in the latter case is on the order of 4-5 m, ie. a reduction with a factor of 2 compared to the initial variogram. The total sill of the N-population variogram is c.1.3 whereas the pure nugget of the reduced W-population is 1.85, in both cases close to 80% of the calculated population variances, cf. Table 5.6.

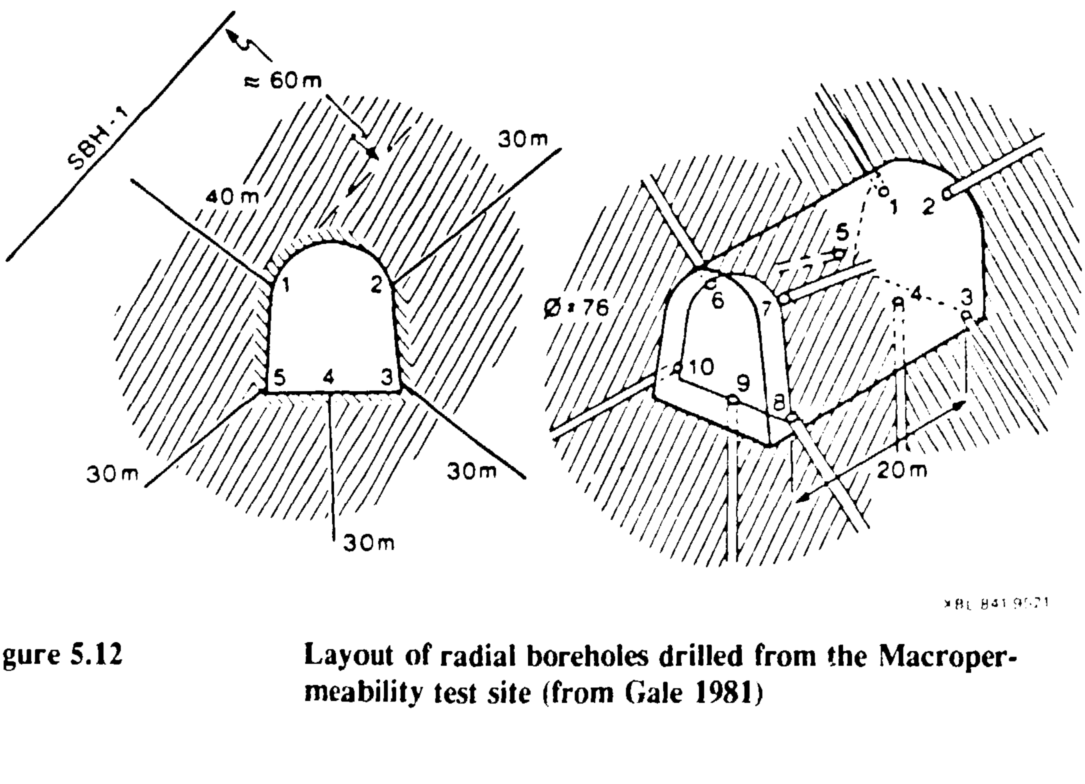


Figure 5.12 **Layout of radial boreholes drilled from the Macropermeability test site (from Gale 1981)**

5.5 Analysis of 2m data from the Macropermeability test site

5.5.1 General

One of the "drawbacks" of the analysis of the hydraulic conductivity data from Brändan presented by Winberg (1989) was the fact that the vertical and subvertical holes only informed about the spatial continuity in the near vertical direction.

That was one reason to pursue a study on Stripa data which offer a larger variability in borehole geometry, and particulary offer a large amount of data from near horizontal boreholes underground. However, a close scrutiny of the Stripa data reveal that no short section data exist from vertical holes. This applies also to the SCV site.

In order to add to the understanding of spatial continuity of short section hydraulic conductivity data at Stripa, it was also decided to analyse data from the two short vertical holes, R4 and R9, drilled vertical down at the Macropermeability drift, cf. Figure 5.12. These holes have been subject to hydraulic testing in 2m sections, in all 21 sections have been tested (Gale 1981).

5.5.2 Hydraulic conductivity - summary statistics

The data from R4 and R9 have been analysed as a pooled population, ie. ali 21 data points. The univariate statistics indicate a geometric mean hydraulic conductivity of -9.82 and a variance of 0.59.

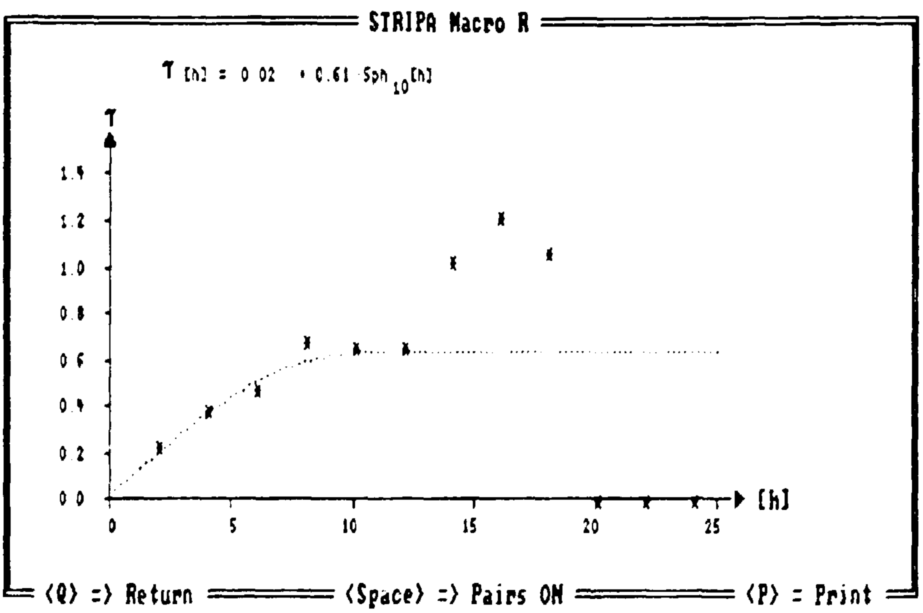


Figure 5.13 **Experimental variogram calculated from pooled 2m data from the vertical holes R4 and R9 at the Macropermeability test site.**

5.5.3 Experimental variography

The experimental variogram calculated is based on two times the support of the 1m SCV data. The variogram, cf. Figure 5.13, has been fitted with a spherical model. The nugget is insignificant and the sill value of 0.63 is compatible with the calculated population variance. The range of the variogram is 10m.

6. DISCUSSION

6.1 General

The discussion of results will cover how the calculated geometric mean hydraulic conductivity and the inferred spatial continuity is affected by; a) *varying measurement scale*, b) *geometry of the boreholes*, c) *geology and tectonics of the site*, and d) the *statistical assumptions* made. Finally, the *potential use of the obtained relationships* is discussed.

6.2 Scale effects

The analysis of 10m hydraulic conductivity data from E1, N1 and V1 show geometric means varying between -12 and -10. The variance of the data varies between 0.4 and 2.6. Correspondingly, the 10m data from the F-series holes at the crosshole site vary between -10.8 and -9.5. The calculated population variances vary between 0.9 and 1.3.

Analysis of data from the SCV site deregularised to 1m show geometric means varying between -11 and -10. The calculated variances span between 0.85 and 3.3.

A comparison between the two scales (supports) show that the increase in geometric mean for the 1m data is nearly inversely proportional to the decrease in support. A similar proportional increase in variance can not be observed.

In a study of the heterogeneous Culebra dolomite at the WIPP site in New Mexico, Beauheim (1988) noted that in a system where fractures have heterogeneous distribution, continuity and connectivity, a change in the test volume will result in different average hydraulic properties over that volume. A representative elementary volume (REV) as defined by Bear (1972) may not be defined. The average properties may either increase or decrease as the scale of testing increases, depending on how fracture geometry, conductivity and connectivity vary within the volume studied.

The correlation lengths of the 10m data in E1 and V1 are on the order of 50m. The F-series borehole data from the cross-hole site indicate practical ranges on the order of 30-50m.

The variograms based on the variable section length (logT) data from the SCV site show very weak signs of spatial correlation. The holes that do show spatial correlation, N3, C1 and C3, are dominated by 3-7m (test section) data. The practical ranges are, where possible to infer, on the order of 50m.

The variograms based on variable section length SCV data deregularised to 1m sections show a much higher degree of spatial continuity with well developed variograms with practical ranges on the order of 10m.

The analysis of spatial continuity thus show weak signs of correlation for the 10m hydraulic conductivity data. The spatial continuity of the data deregularised to 1m sections is more pronounced and well developed with practical ranges on the order of 10m.

6.3 Geometrical effects

Univariate analysis of data from the tri-axial array of boreholes at the SGU site (E1, N1 and V1) show a two orders of magnitude lower geometric mean in the vertical and northerly directions compared to that calculated for the easterly direction. Thus an apparent anisotropy in hydraulic conductivity exists, though inferred from only three boreholes, with a ratio of 100:1:1 (east-west:north-south:vertical). A correspon-ding analysis of the 1m data from the similarly bounded SCV block show a similar pattern but with a lesser degree of anisotropy (10:1:1).

The spatial correlation as obtained from the SCV site and the neighbouring Macro-permeability test site show more of an isotropic (1:1:1) pattern. Thus, a correlation between the noted anisotropy in geometric mean hydraulic conductivity and that of the covariance structure of the rock cannot be observed. A correlation between anisotropy in hydraulic conductivity and anisotropy in correlation structure of hydraulic conductivity is to be expected, and have been used by eg. Neuman and Depner (1988).

The isotropy in spatial correlation between the vertical and the east-west direction is also supported by analysis of the 10m data from E1 and V1. Thus support for isotropy is obtained at two different scales.

6.4 Geological and tectonic aspects

In this section we will try to correlate the observed average hydraulic properties and evidences of spatial correlation with the existing geological and tectonic information.

A first observation is the noted hole effect observed for a lag of c. 60m in the data from borehole F5 at the crosshole site. This hole effect is compatib'e with the inter-distance of fracture zones interpreted at the cross-hole site (Black et al 1991).
This is a sole observation which is not observed in data from other holes. The reason for the lack of geologically interpretative power on these scales is that most of the

boreholes are less than 300 m long, thus providing limited possibility for interpretation of repetitive geological features, eg. fracture zones.

The general geology of the SCV block is described by Gale et al (1990). They state that much of the control of the geological framework within the SCV would be expected to be controlled by the high frequency and long extent of east to northeast trending fracture zones observed outside the block. On the contrary, core data and crosshole geophysics show several north trending fracture zones cutting through the block.

Appendix F (Gale and Stråhle 1988) shows pole plots of the normal of the fracture planes observed in the N- and W-holes. Obvious in these plots is that the westerly boreholes essentially sample a north to north-northeasterly trending fracture set, whereas the N-holes sample more varied geometries of fractures including traces of a subhorizontal set.

Appendix G (Gale and Stråhle 1988) shows logs of the frequency of fractures (sum of open, sealed and induced fractures) and RQD for the N- and W-holes. It can be assessed from the graphs that the fracture frequency of the W-holes is much more erratic than that of the N-holes. The variogram of the W-population which is close to a pure nugget effect could thus, in part, be explained by the appearance of the fracture log. The fracture log of the N-holes still show a fair degree of variability, but superimposed on a more continuous variation which can explain the obtained variogram with definite structure, however still with high variability and consequently a short range.

It is also obvious from the graphs that the average fracture frequency in the W-holes is higher than that of the N-holes. Although a clear correlation between fracture frequency and hydraulic conductivity has not been proven (Neuman 1987), the noted differences in fracture frequency support differences in calculated geometric mean hydraulic conductivities.

6.5 Statistical assumptions

The analysis has been performed on populations of the random function logK, either as single borehole or pooled populations, where the random function has been assumed to be statistically homogeneous, ie. stationary and ergodic (de Marsily 1986).

The assumption may be considered questionable since the borehole data contains both data from the naturally fractured rock mass and data associated with fracture zones transecting the block. It could thus be argued that a subdivision in each borehole should have been made accordingly.

The number of statistical populations, or rather the number of averaging areas, to be considered is closely related to the number of data needed to infer a variogram model. A physicist would argue for "as many" populations "as possible", whereas a statistician probably would respond as "few as possible". The answer to this problem is that most often the demand for physical resolution must find a compromise with the statisticians demand for enough data to facilitate statistical inference with an acceptable spatial resolution to comply with the physicists demands.

A further subdivision into a rock mass and a fracture zone population has not been pursued within the scope of this study. It is however expected that an analysis of a pure rock mass population, data associated with fracture zones (FZI index >2 (Black et al 1991) excluded, would provide essentially unaltered correlation lengths. The population variance and the total sill value of the variograms would decrease somewhat, and so would any noted nugget effect.

A further analysis of subdivided populations should be the focus of any subsequent analysis.

6.6 Use of established relationships

Mass transport in fractured rock is to a large extent controlled by the spatial variability in fluid advection that is due to heterogeneities in the hydraulic properties of the rock formation. The magnitude and directional dependence in this heterogeneity in the Stripa bedrock is mapped by the established variograms presented in this report.

The near isotropic correlation structure on a 1m support for the SCV site could be used, and regularised to a convenient support to facilitate either data expansion/estimation (kriging) or simulation. With the use of stochastic continuum techniques the uncertainty in mass transport could be addressed.

7. CONCLUSIONS

The results of the statistical and geostatistical analysis of hydraulic conductivity data from the Stripa Mine has revealed the following features;

1) Calculated geometric mean hydraulic conductivities on a 10m support are varying between -12 and -9.5 (logK). Variable section data deregularised to 1m sections show geometric mean values varying between -11 and -10. No variance reduction for the 10m section data is observed compared to that calculated for the 1m data.

   The inconsistencies observed in the calculated statistics as a consequence of the averaging process are attributed to the fracture control of the hydraulic conductivity of the Stripa granite, which entails that an REV is difficult to define for the analysed data.

2) The analysis of calculated geometric mean hydraulic conductivities for individual holes and pooled populations show evidence of an apparent anisotropy in the east-west, north-south, vertical direction. The noted ratios are 100:1:1 and 10:1:1 for the 10 and 1m section data, respectively. It should be emphasized that the inference is based on a limited amount of data and that the indicated ratios do not necessarily reflect the major axises of the three-dimensional hydraulic conductivity ellipsoid.

3) The analysis of spatial variability on a 10m scale reveals weak signs of finite spatial structure, ie. a well developed variogram. The noted practical ranges are on the order of 50m, where possible to infer. The analysis of data of variable test section length deregularised to 1m sections, however, show a much stronger element of spatial correlation. The observed practical ranges showed that the 1m data are correlated within 10m, ie. a factor 5 shorter correlation length than that possible to infer for the 10m data.

The assumption that the 1m data may suffer from a overemphasised continuity of low-permeable sections was tested by extracting all but one value in each cluster of identical data of low hydraulic conductivity. The resulting variogram showed a practical range of 4-5 m. Thus it can be assumed that the true correlation length of data deregularised to 1m lies within the interval 5-10m.

The spatial correlation as inferred from boreholes of varying orientation indicates an isotropic covariance structure.

4) The fracture statistics as inferred from the boreholes at the SCV site sustain the noted differences in calculated geometric mean hydraulic conductivities between the W- and N-series borehole data, although a rigorous relationship has not been established in this study. In addition, the appearance of the variograms based on the data in the above mentioned boreholes correlate well with the variability in fracture frequency as inferred from fracture logs.

5) The univariate statistics and modelled experimental variograms on a 1-2m support presented in this study constitute a starting point for further analysis and modelling of particulary the SCV site at Stripa. The relationships obtained may eg. be used in stochastic continuum simulation schemes of groundwater flow and mass transport within the SCV block.

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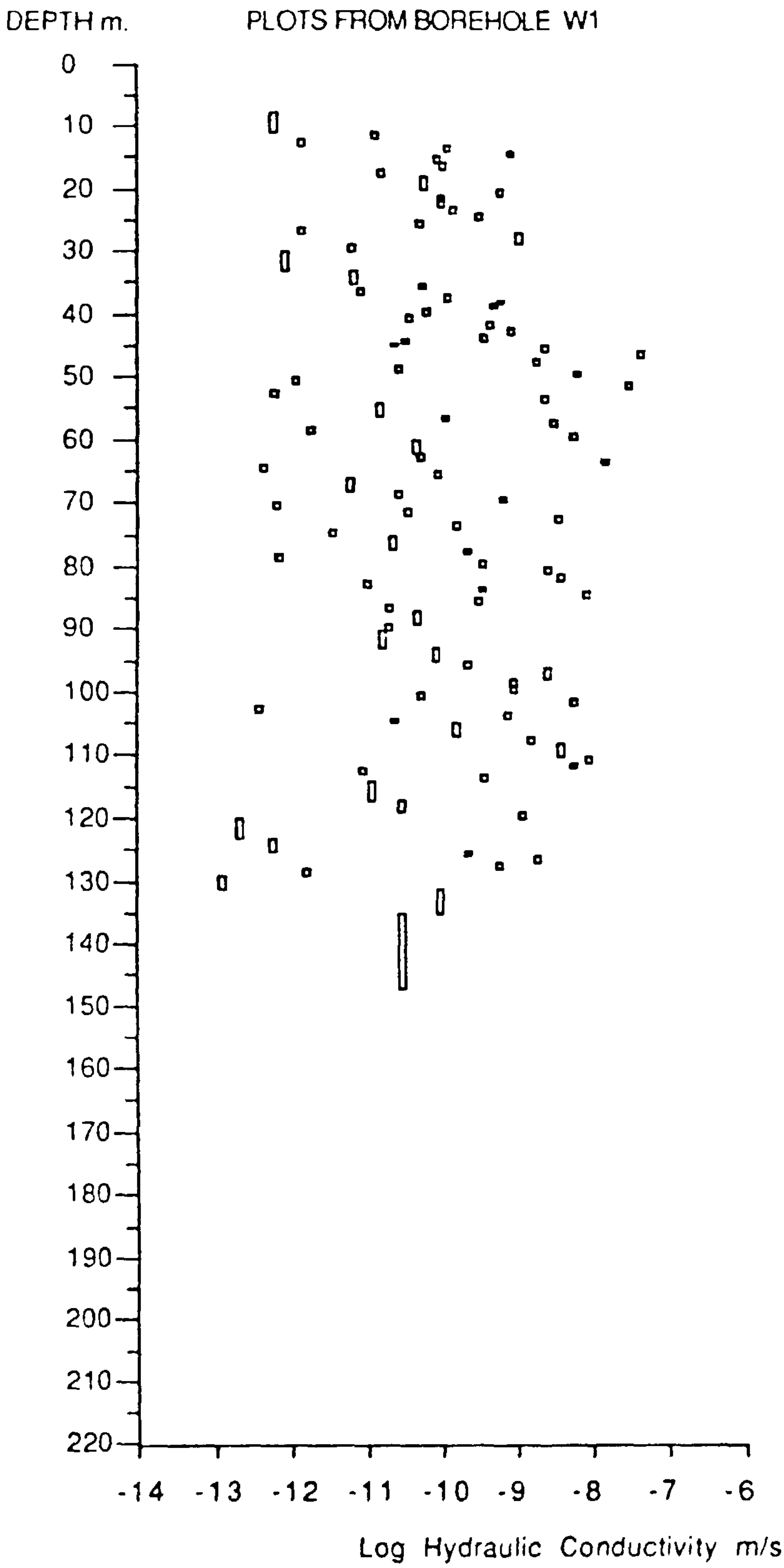
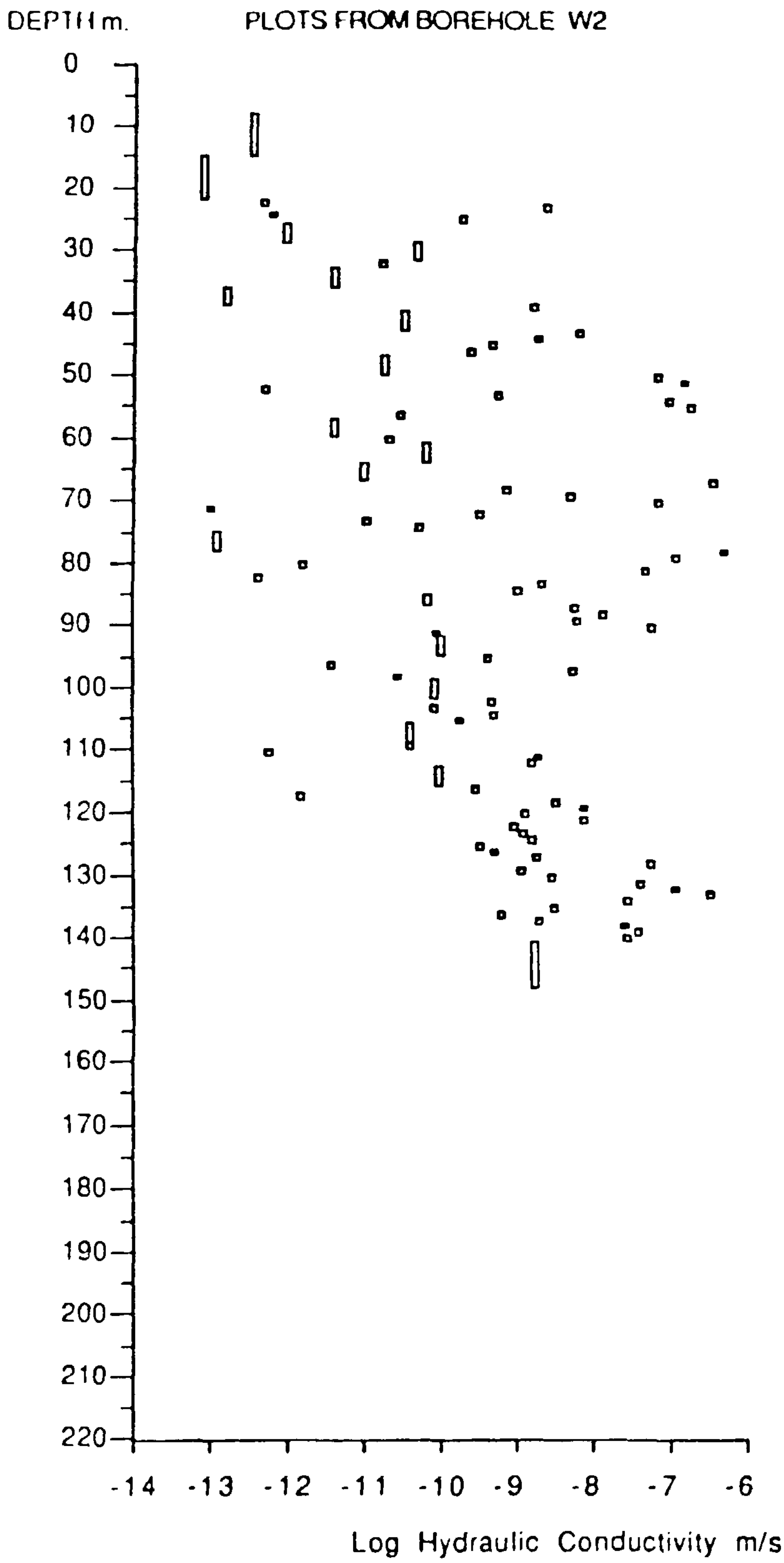
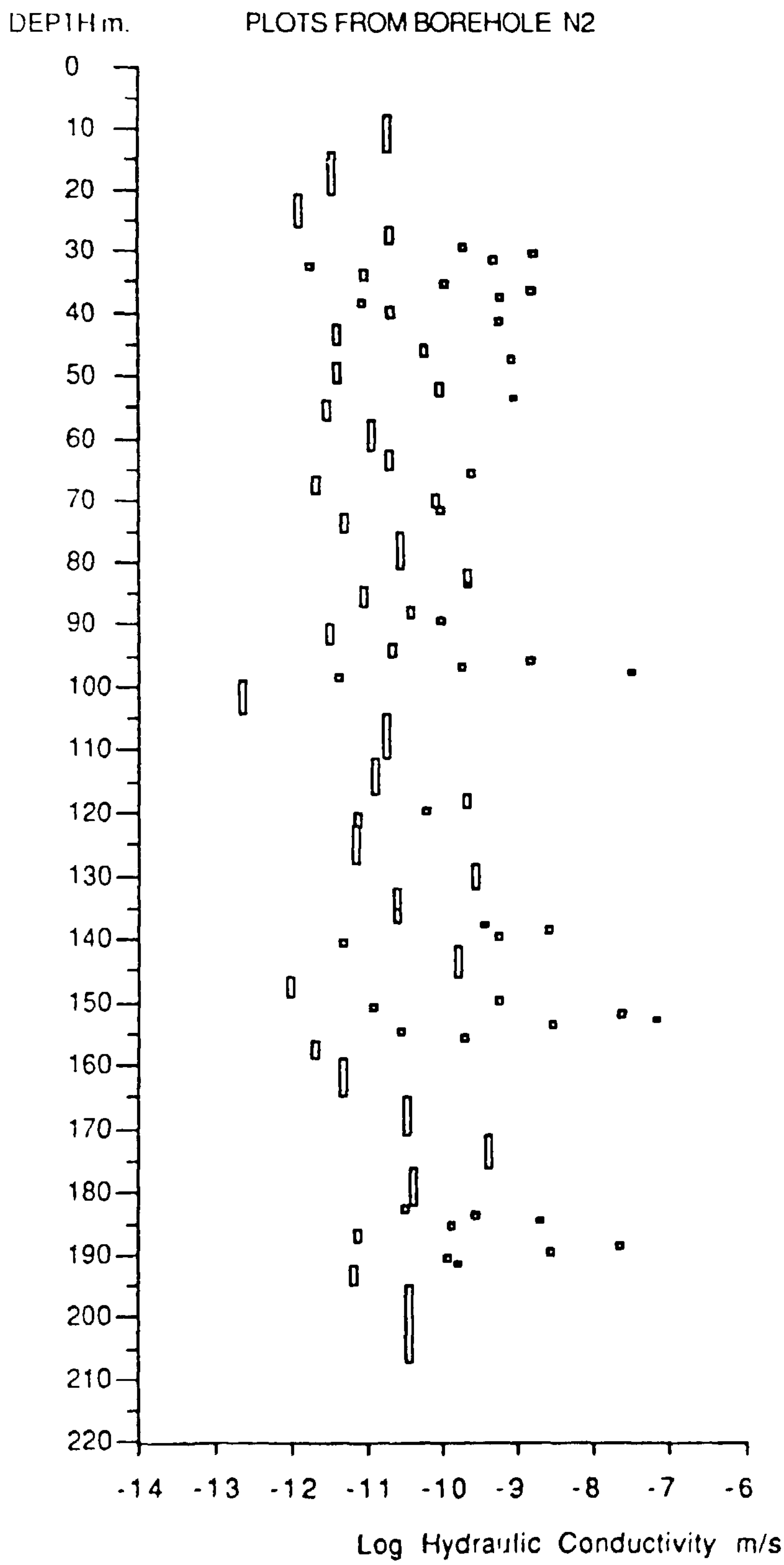
Bore-hole	Length (m)	Collar coordinates			Collar dev.	
		X (m)	Y (m)	Z (m)	D (°)	I (°)
E1	300	338.4	1199.7	355.7	1.0	8.5
N1	300	342.2	1194.6	355.5	91.0	5.5
V1	506	336.8	1195.6	356.7	0.0	90.0
F1	200	337.4	1199.3	355.4	96.2	10.2
F2	250	337.4	1199.2	355.9	95.9	20.6
F3	200	336.5	1199.1	355.4	106.2	10.1
F4	250	336.5	1199.1	356.0	106.2	31.0
F5	200	335.5	1199.1	355.4	122.1	10.1
F6	250	335.6	1199.1	355.7	121.9	40.2
W1	147	440.0	1146.8	356.1	269.9	5.0
W2	147	510.0	1147.4	355.3	269.9	5.0
N2	207	333.3	1139.2	356.7	359.8	18.6
N3	189	347.4	1079.1	356.9	360.0	18.6
N4	219	321.1	1023.1	345.0	359.2	18.8
C1	150	438.5	1147.0	356.2	267.8	39.0
C2	150	422.5	1147.0	356.3	305.4	40.5
C3	100	432.8	1147.6	355.9	287.4	14.7
R4	30	384.1	976.6	336.5	98.0	89.8
R9	30	364.1	976.4	336.7	226.3	89.9


DEPTH m.
PLOTS FROM BOREHOLE W1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-14
-13
-12
-11
-10
-9
-8
-7
-6
Log Hydraulic Conductivity m/s

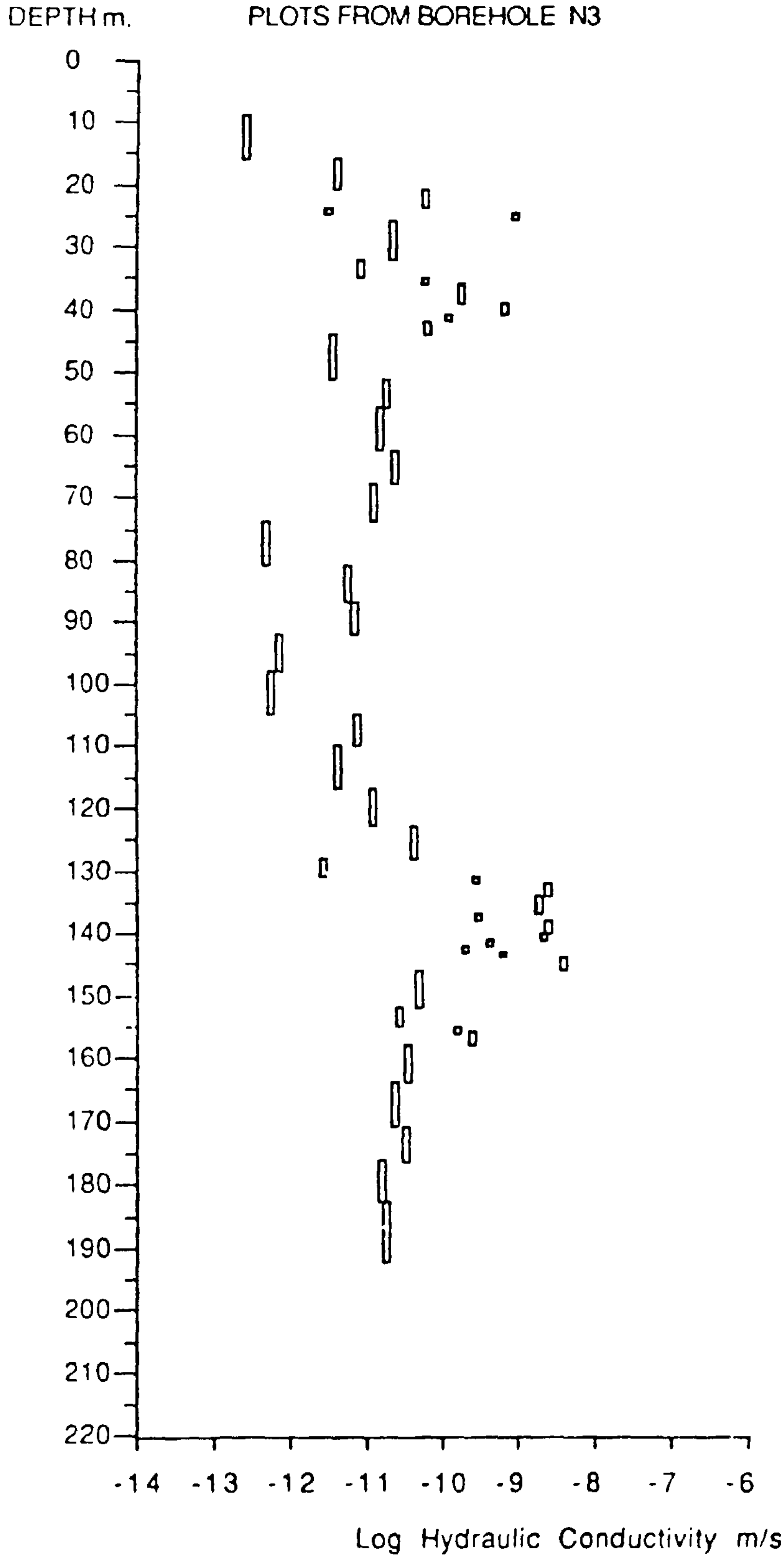
(Holmes 1989)


DEPTH m.
PLOTS FROM BOREHOLE W2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-14
-13
-12
-11
-10
-9
-8
-7
-6
Log Hydraulic Conductivity m/s

(Holmes 1989)


DEPTH m.
PLOTS FROM BOREHOLE N2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-14
-13
-12
-11
-10
-9
-8
-7
-6
Log Hydraulic Conductivity m/s

(Holmes 1989)


DEPTH m.
PLOTS FROM BOREHOLE N3
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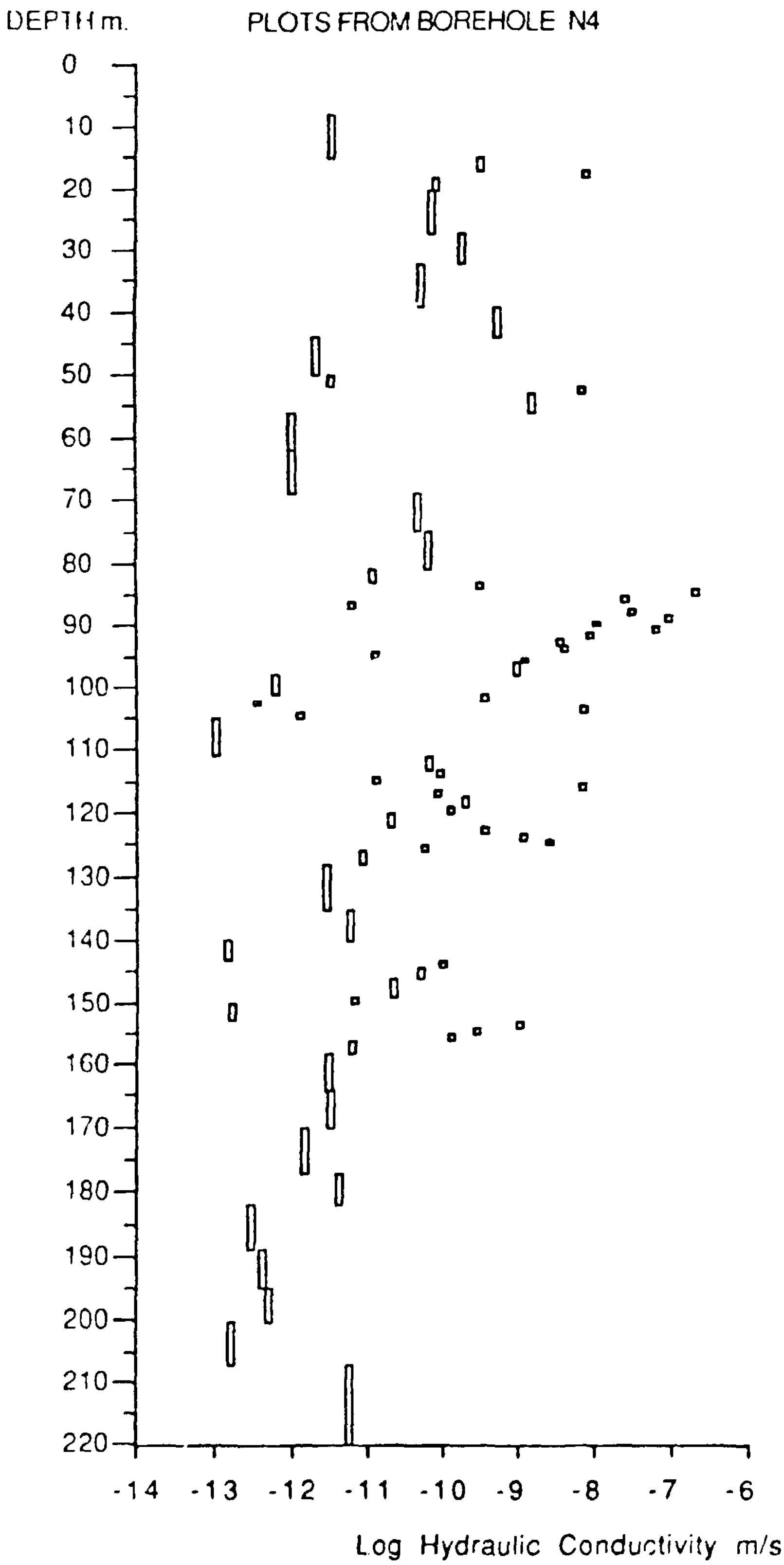
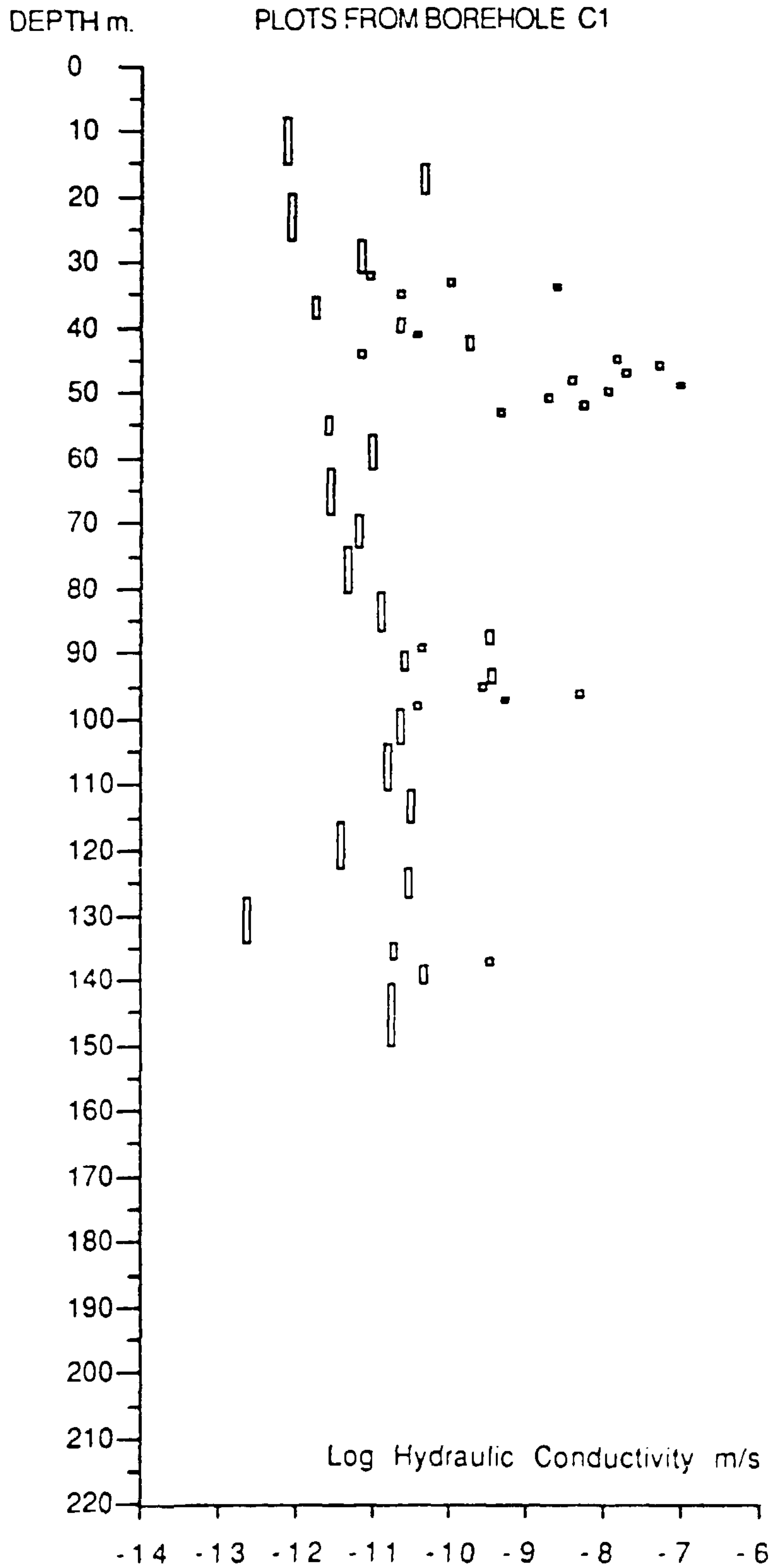
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-14
-13
-12
-11
-10
-9
-8
-7
-6
Log Hydraulic Conductivity m/s

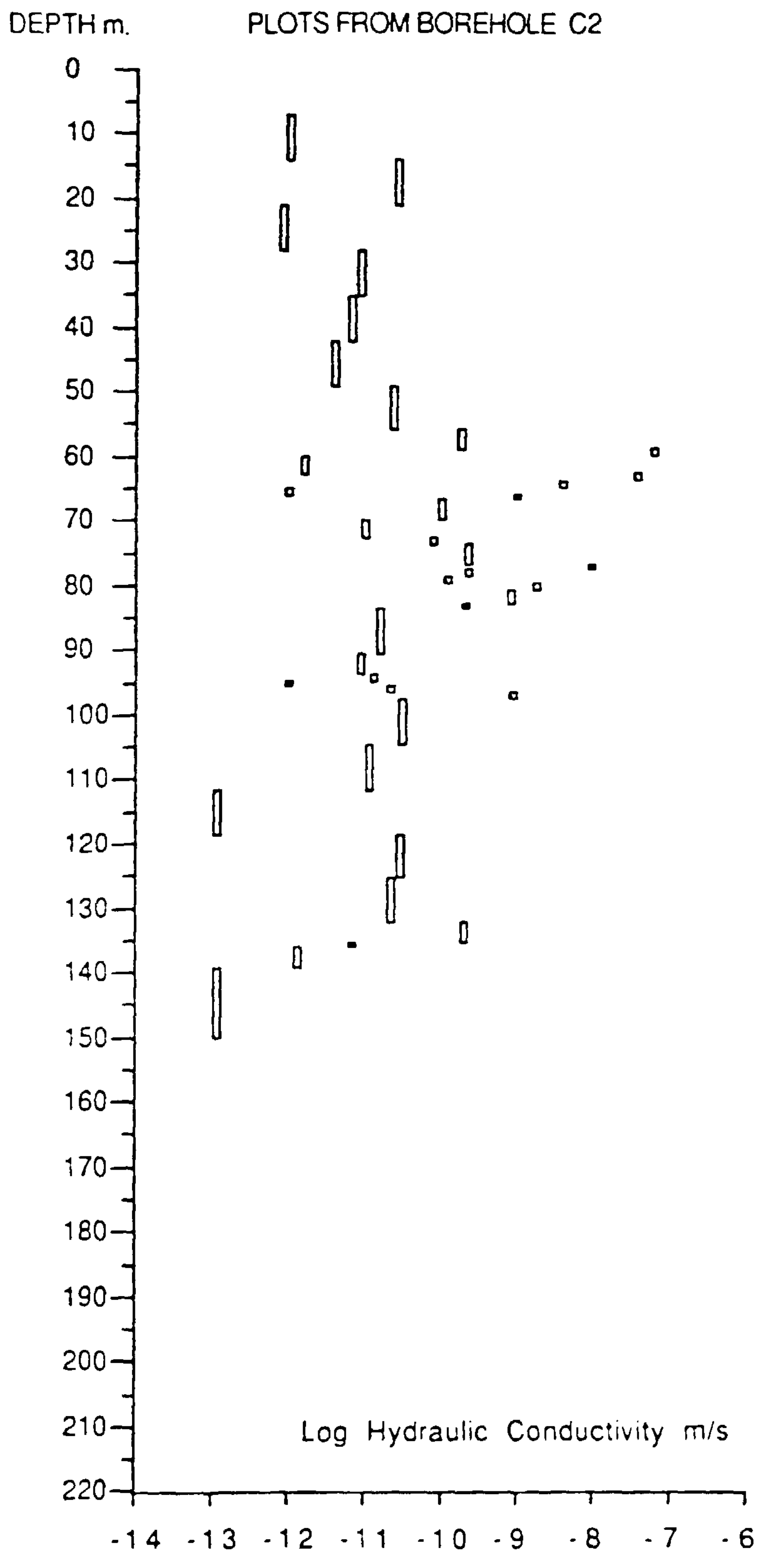
(Holmes 1989)


DEPTH m.
PLOTS FROM BOREHOLE N4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
-14
-13
-12
-11
-10
-9
-8
-7
-6
Log Hydraulic Conductivity m/s

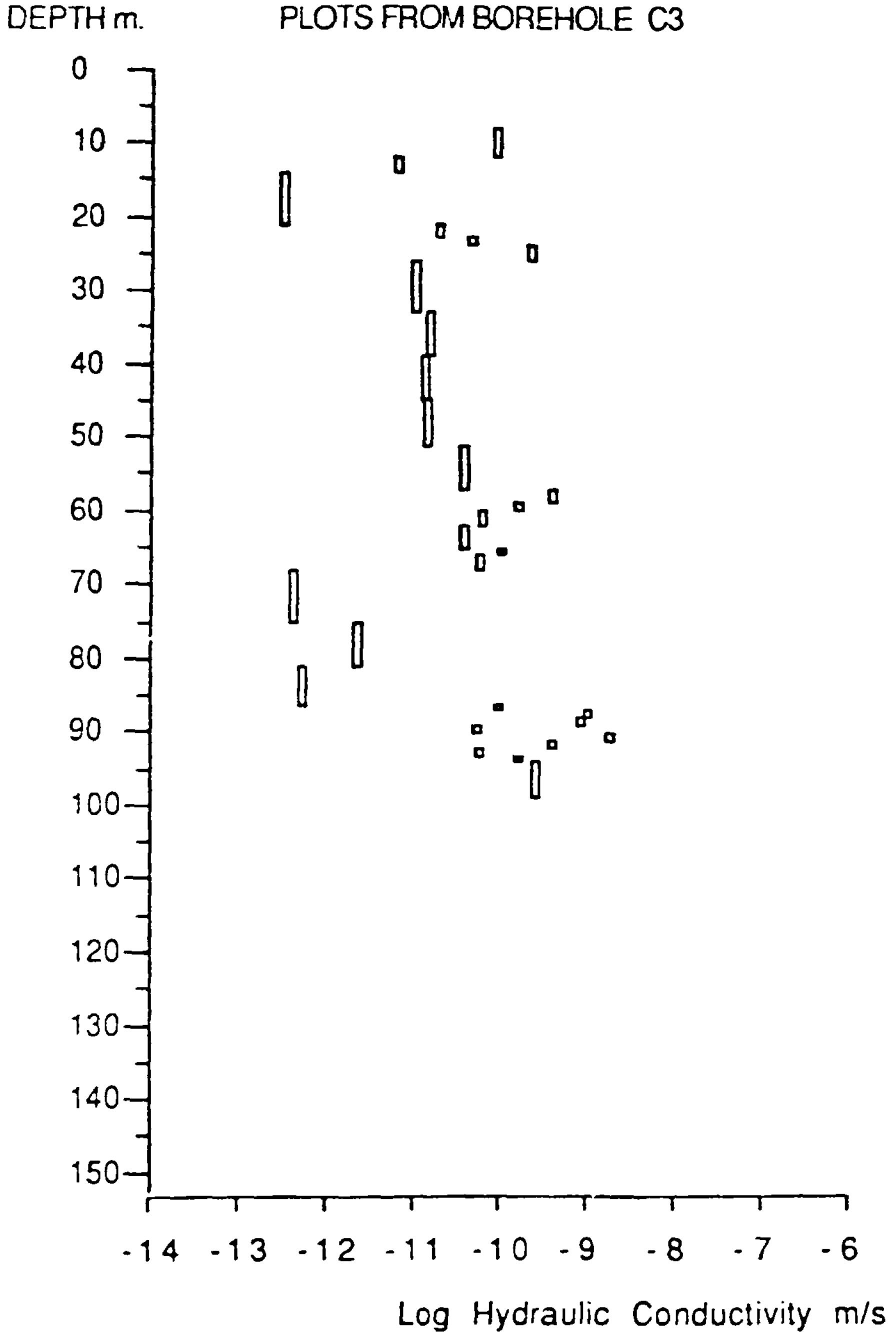
(Holmes 1989)



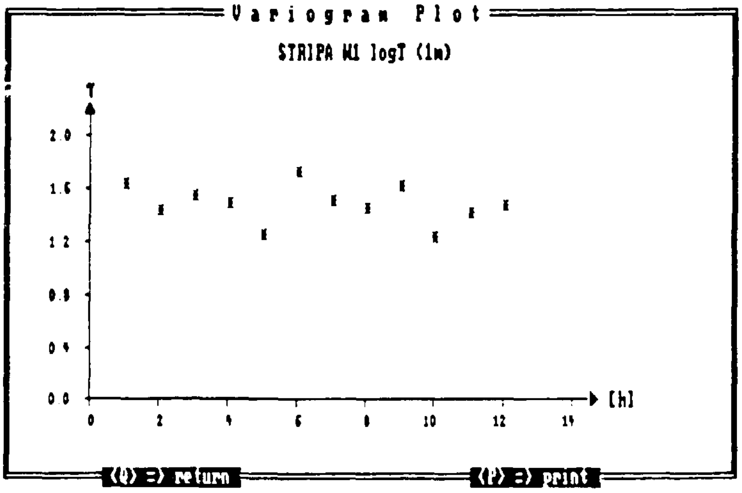
(Holmes et al 1990)

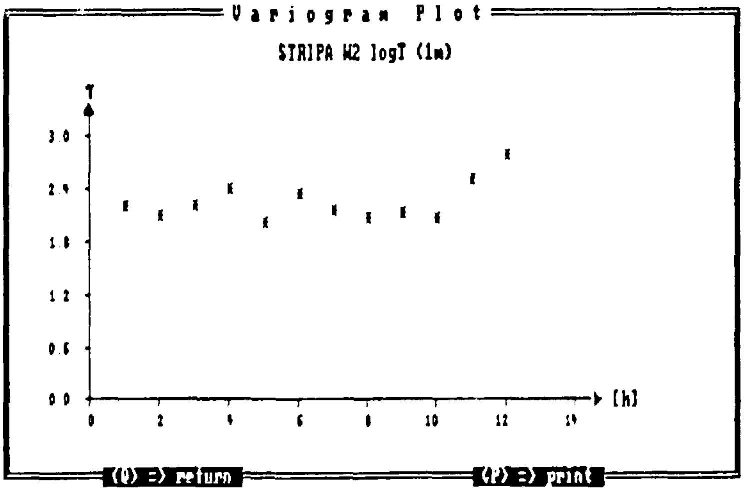


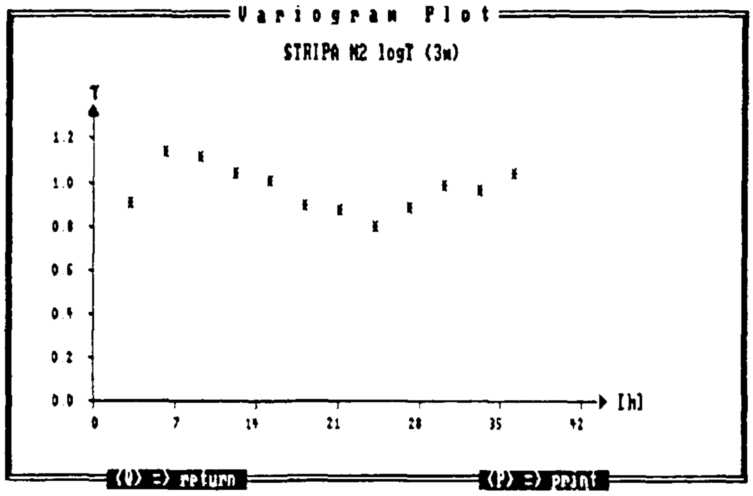
(Holmes et al 1990)

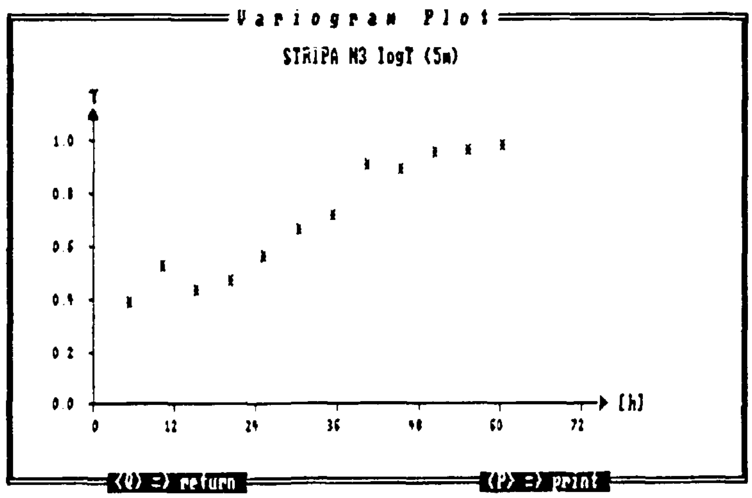


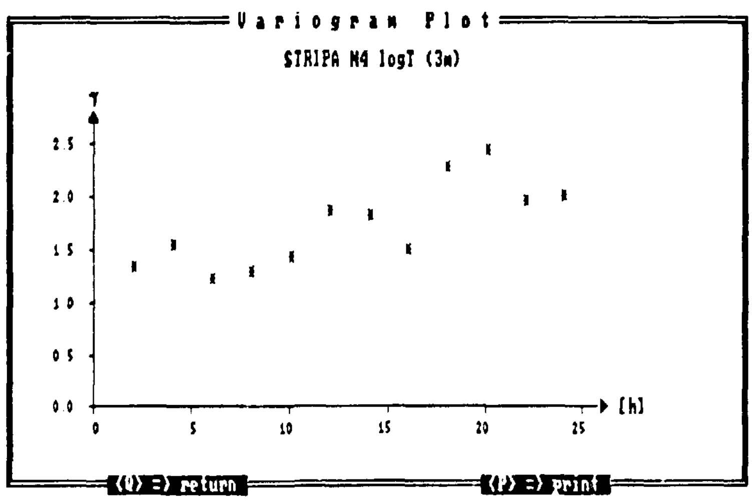
(Homes et al 1990)

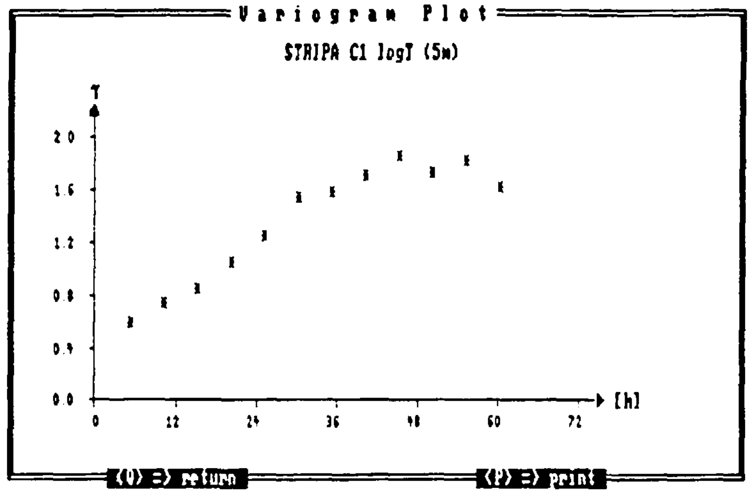

Variogram Plot
STRIPA W1 logT (1m)
γ
2.0
1.6
1.2
0.8
0.4
0.0
0
2
4
6
8
10
12
14
[h]
(Q) => return
(P) => print

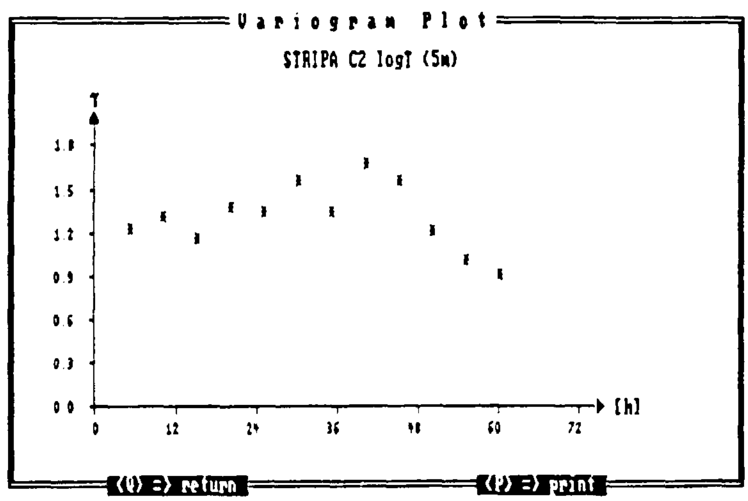

Variogram Plot
STRIPA W2 logT (1m)
γ
3.0
2.4
1.8
1.2
0.6
0.0
0
2
4
6
8
10
12
14
[h]
(Q) => return
(P) => print

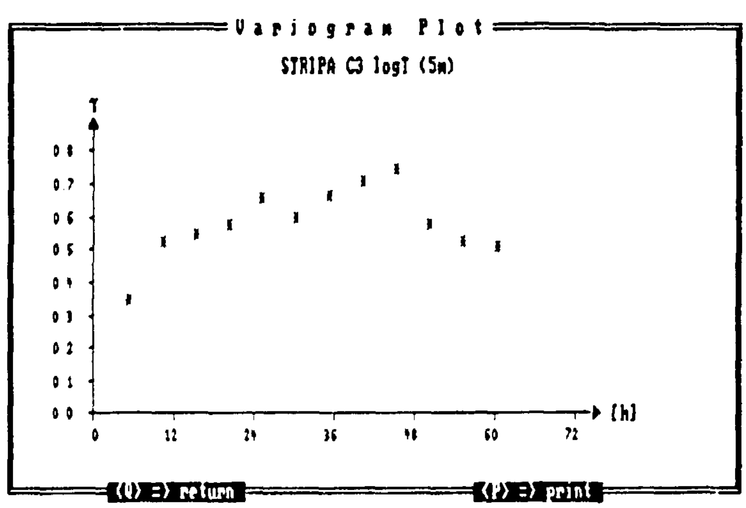

Variogram Plot
STRIPA N2 logT (3m)
T
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
7
14
21
28
35
42
[h]
(Q) => return
(P) => print

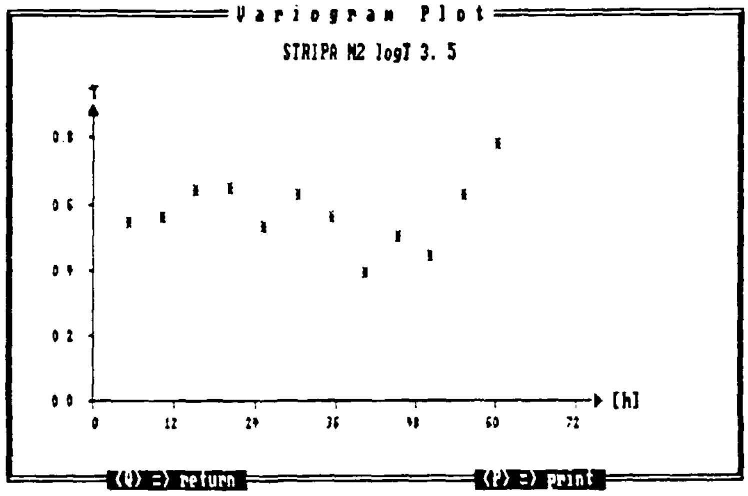

Variogram Plot
STRIPA N3 logT (5m)
T
1.0
0.8
0.6
0.4
0.2
0.0
0
12
24
36
48
60
72
[h]
(Q) => return
(P) => print

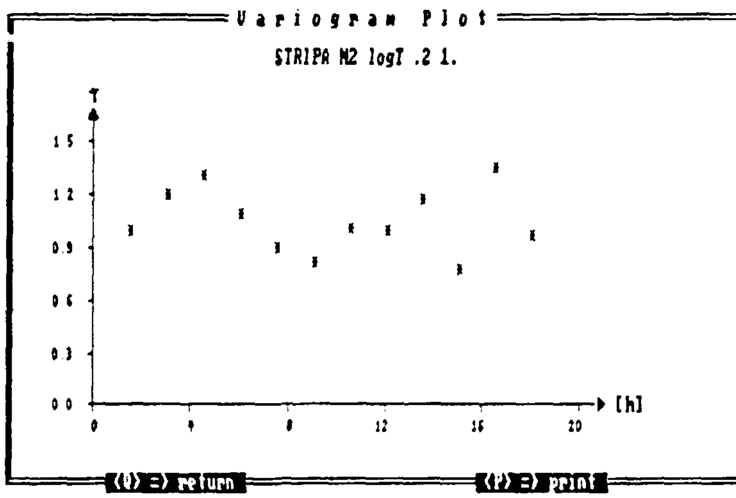

Variogram Plot
STRIPA N4 logT (3m)
T
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
[h]
(Q) => return
(P) => print

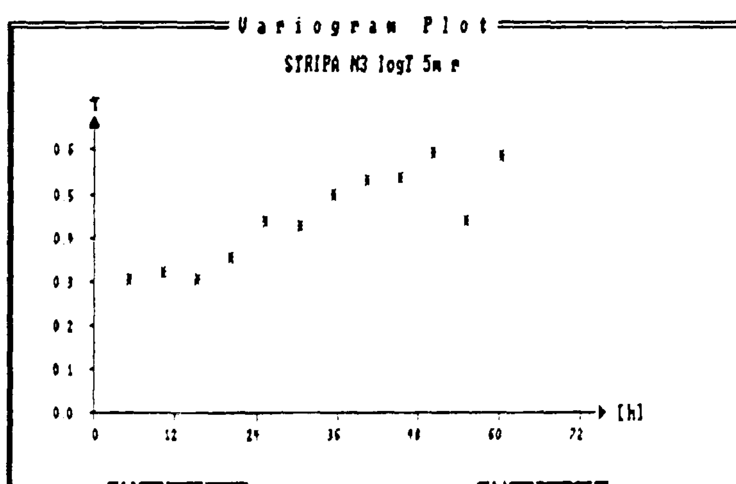

Variogram Plot
STRIPA C1 logT (5m)
2.0
1.6
1.2
0.8
0.4
0.0
0
12
24
36
48
60
72
[h]
<Q> => return
<P> => print

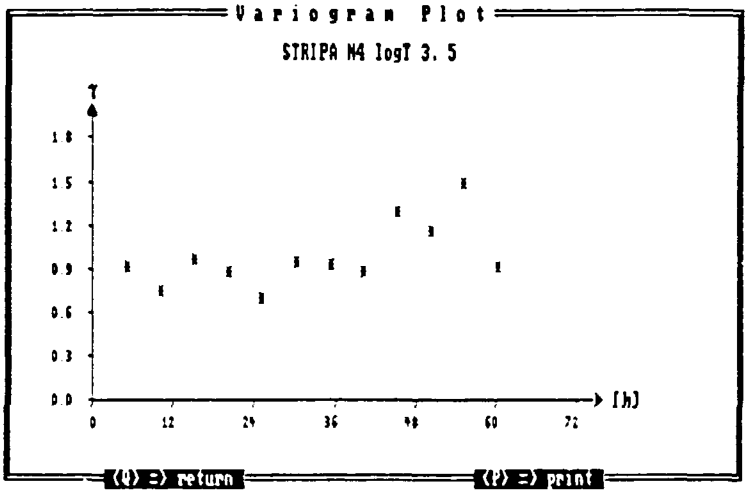

Variogram Plot
STRIPA C2 logT (5m)
1.8
1.5
1.2
0.9
0.6
0.3
0.0
0
12
24
36
48
60
72
[h]
<Q> => return
<P> => print

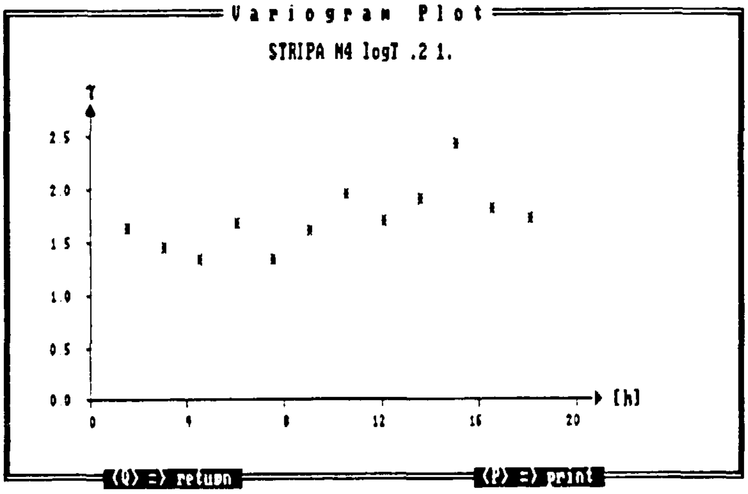

Variogram Plot
STRIPA C3 logT (5m)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
12
24
36
48
60
72
[h]
<Q> => return
<P> => print

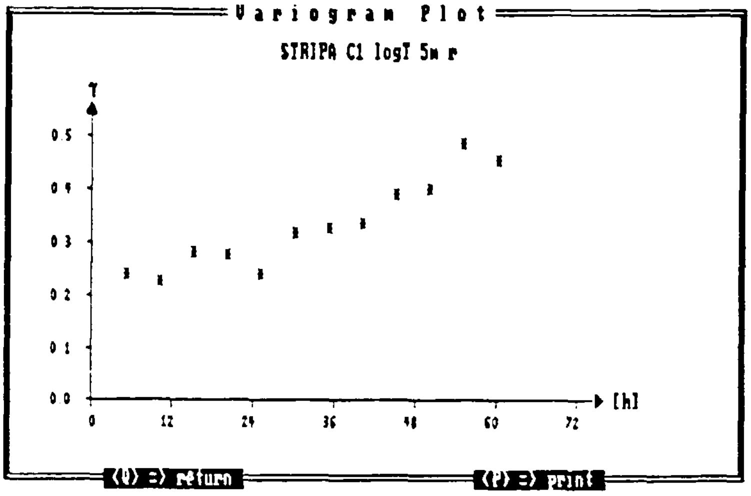

Variogram Plot
STRIPA M2 logT 3. 5
T
0.8
0.6
0.4
0.2
0.0
0
12
24
36
48
60
72
[h]
(Q) => return
(P) => print

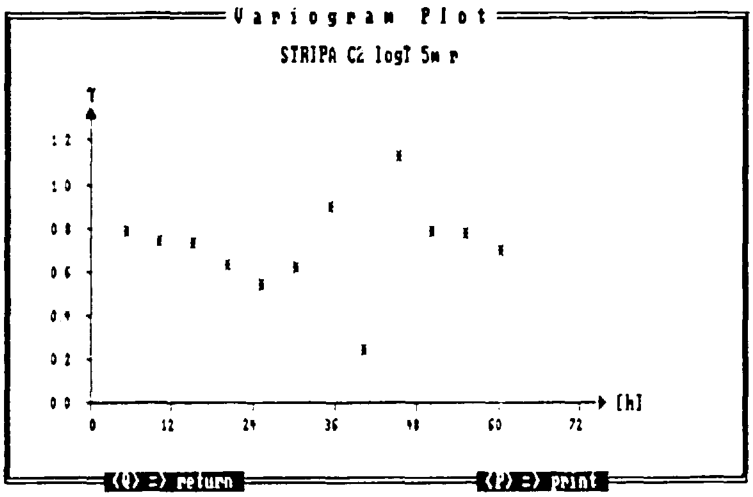

Variogram Plot
STRIPA M2 logT .2 1.
T
1.5
1.2
0.9
0.6
0.3
0.0
0
4
8
12
16
20
[h]
(Q) => return
(P) => print

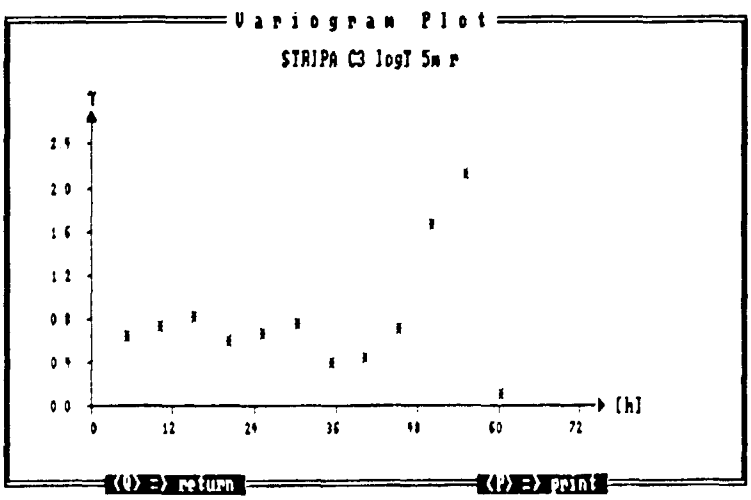

Variogram Plot
STRIPA M3 logT 5m r
T
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
12
24
36
48
60
72
[h]
(Q) => return
(P) => print

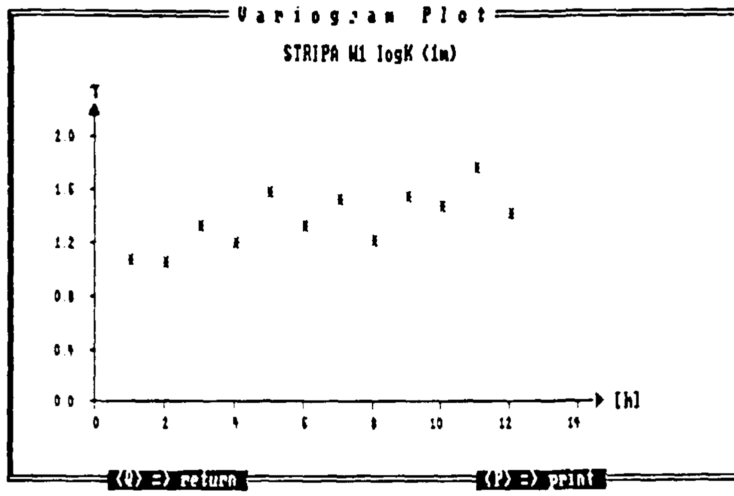

Variogram Plot
STRIPA N4 logT 3. 5
γ
1.8
1.5
1.2
0.9
0.6
0.3
0.0
0
12
24
36
48
60
72
[h]
<Q> => return
<P> => print

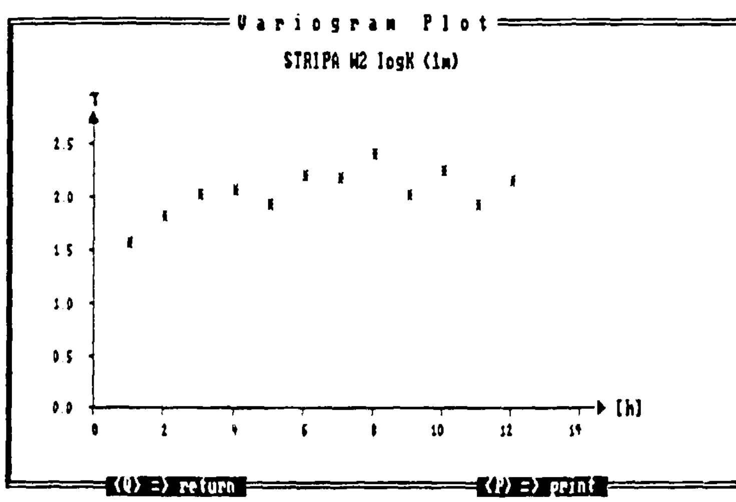

Variogram Plot
STRIPA N4 logT .2 1.
γ
2.5
2.0
1.5
1.0
0.5
0.0
0
4
8
12
16
20
[h]
<Q> => return
<P> => print

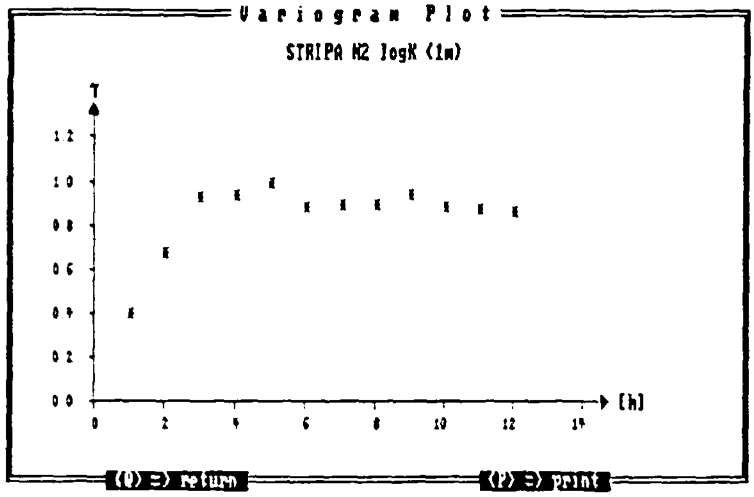

Variogram Plot
STRIPA C1 logT 5m r
γ
0.5
0.4
0.3
0.2
0.1
0.0
[h]
0
12
24
36
48
60
72
(Q) => return
(P) => print

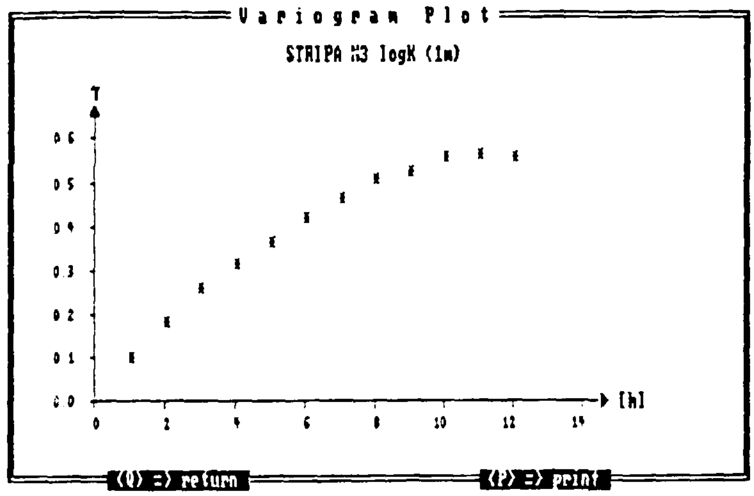

Variogram Plot
STRIPA C2 logT 5m r
γ
1.2
1.0
0.8
0.6
0.4
0.2
0.0
[h]
0
12
24
36
48
60
72
(Q) => return
(P) => print

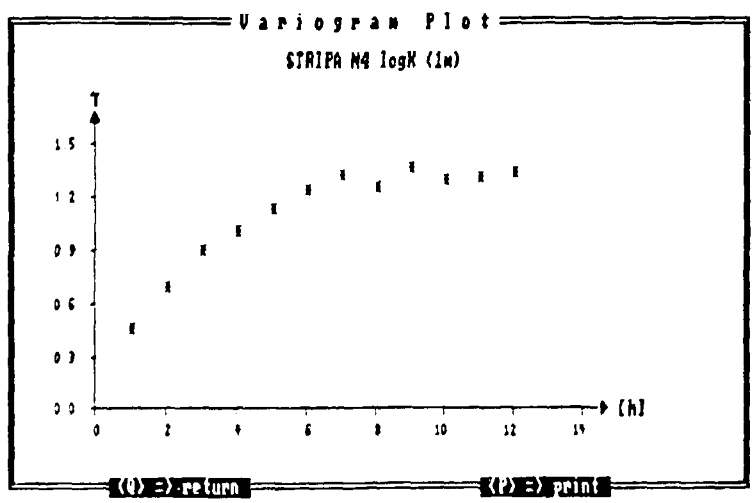

Variogram Plot
STRIPA C3 logT 5m r
γ
2.4
2.0
1.6
1.2
0.8
0.4
0.0
[h]
0
12
24
36
48
60
72
(Q) => return
(P) => print

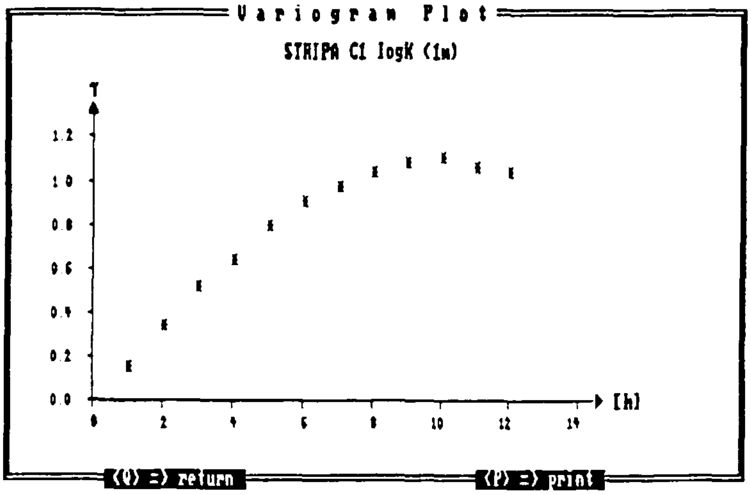

Variogram Plot
STRIPA W1 logK (1m)
2.0
1.6
1.2
0.8
0.4
0.0
0
2
4
6
8
10
12
14
[h]
<Q> => return
<P> => print

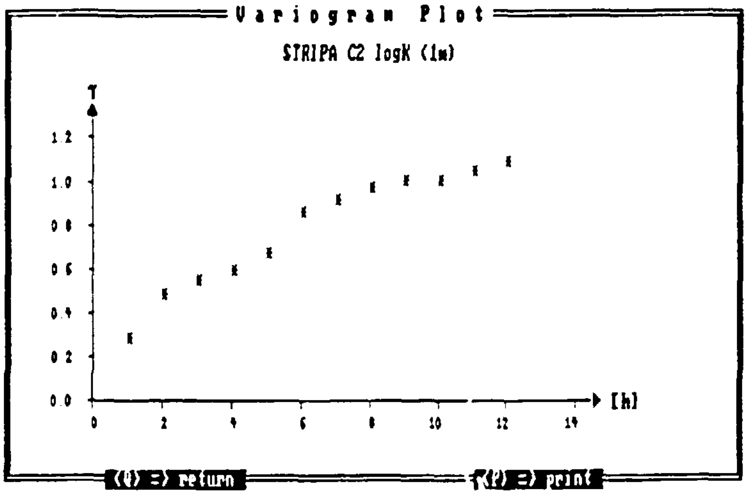

Variogram Plot
STRIPA W2 logK (1m)
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
[h]
<Q> => return
<P> => print

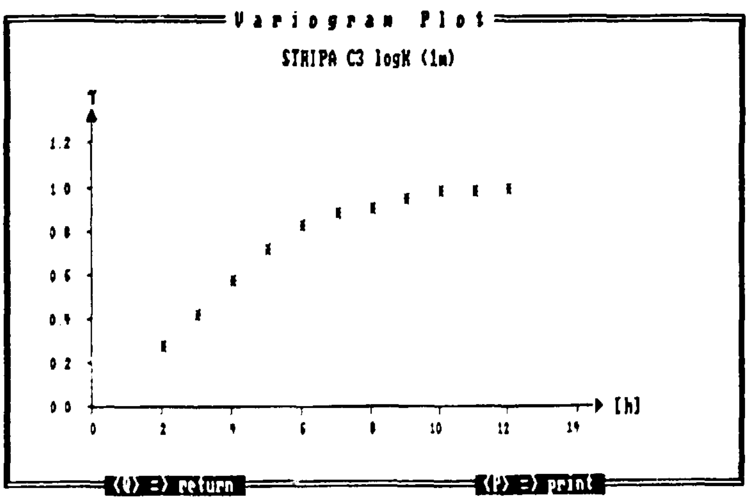

Variogram Plot
STRIPA N2 logK (1m)
γ
1.2
1.0
0.8
0.6
0.4
0.2
0.0
[h]
0
2
4
6
8
10
12
14
(Q) => return
(P) => print

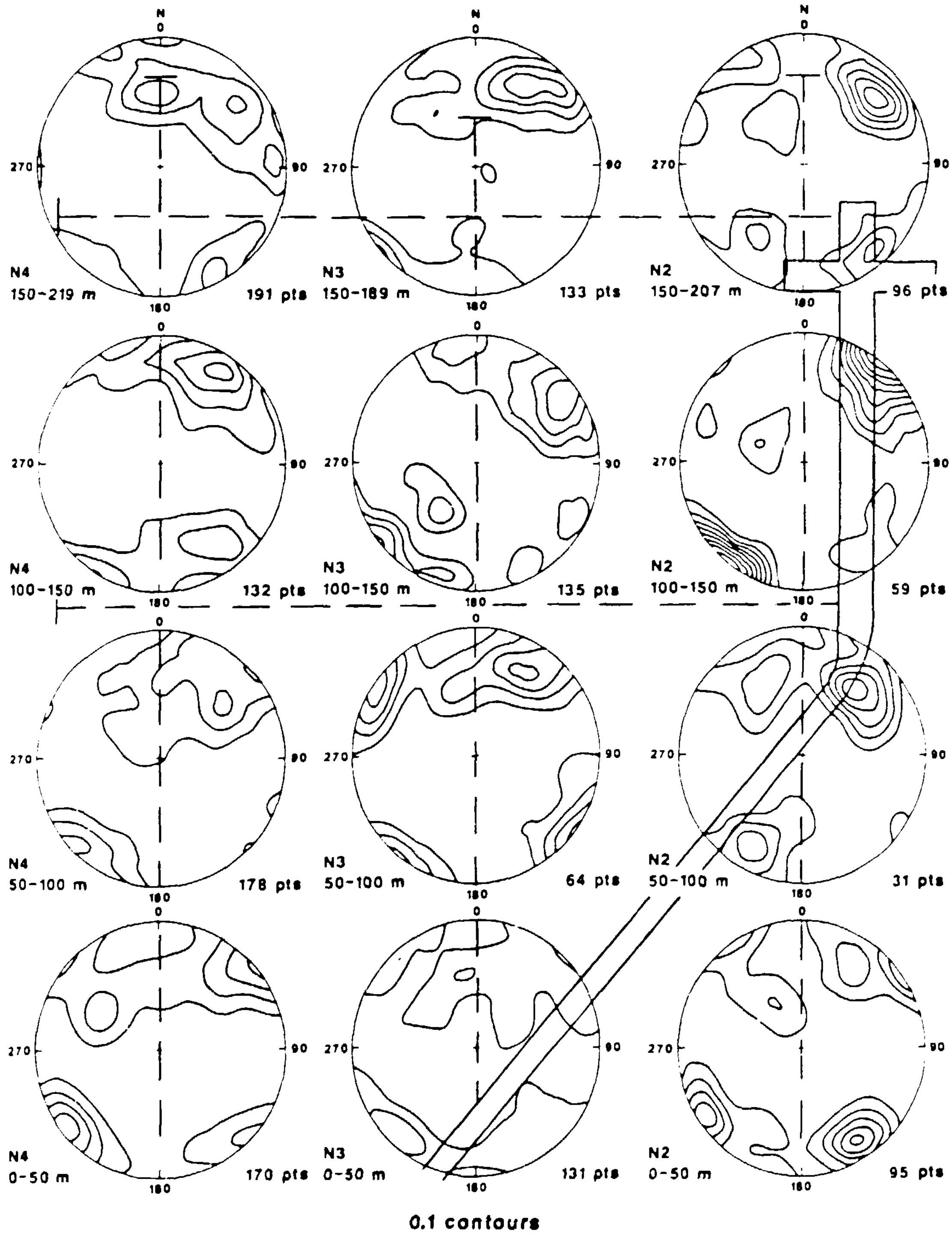

Variogram Plot
STRIPA N3 logK (1m)
γ
0.6
0.5
0.4
0.3
0.2
0.1
0.0
[h]
0
2
4
6
8
10
12
14
(Q) => return
(P) => print


Variogram Plot
STRIPA N4 logK (1m)
γ
1.5
1.2
0.9
0.6
0.3
0.0
[h]
0
2
4
6
8
10
12
14
(Q) => return
(P) => print


Variogram Plot
STRIPA C1 logK (1m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
[h]
(Q) => return
(P) => print

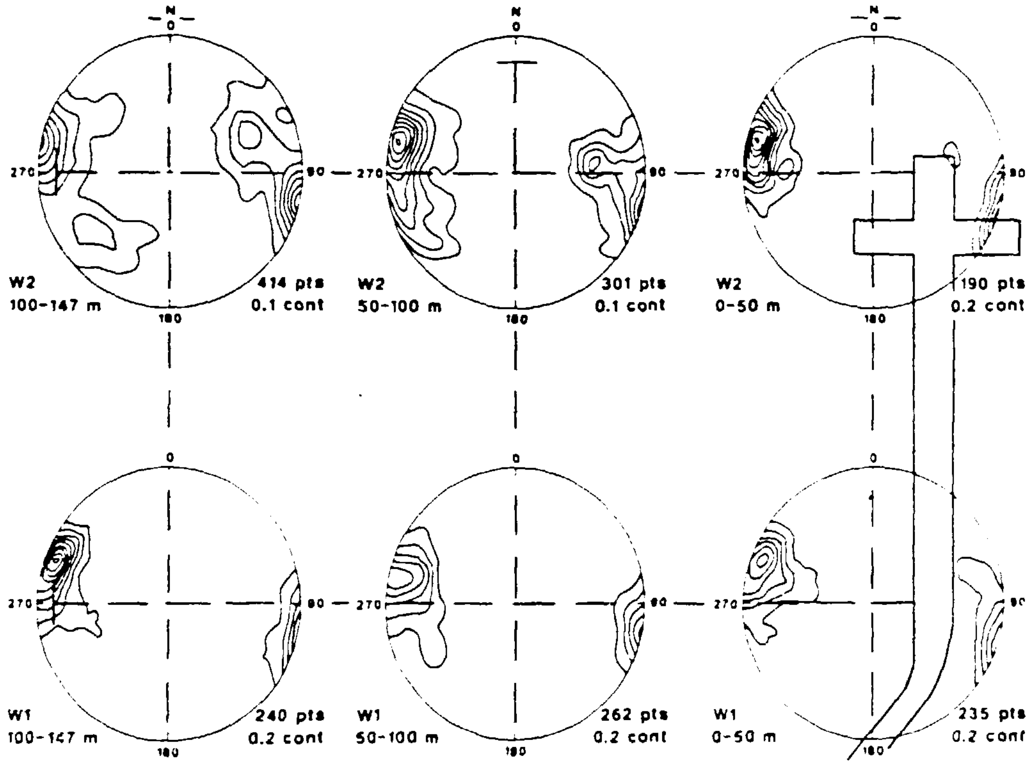

Variogram Plot
STRIPA C2 logK (1m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
[h]
(Q) => return
(P) => print


Variogram Plot
STRIPA C3 logK (1m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
14
[h]
(Q) => return
(P) => print

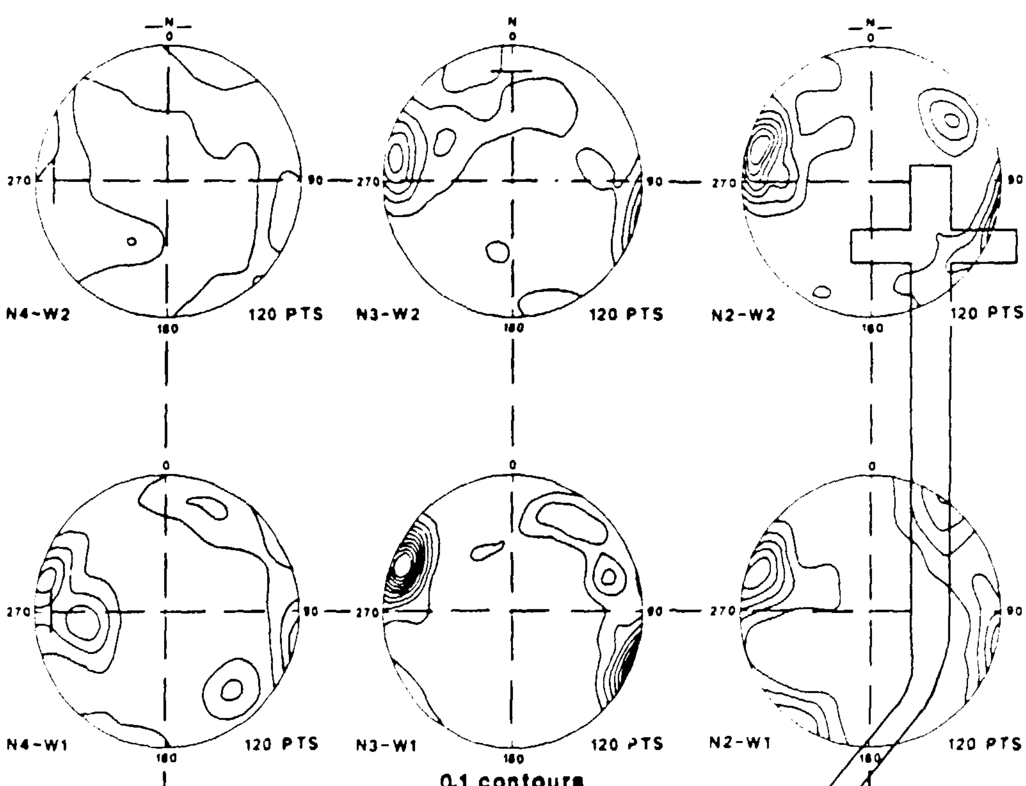


Pole plots of 50 m sections of the N holes.

(Gale and Stråhle 1988)

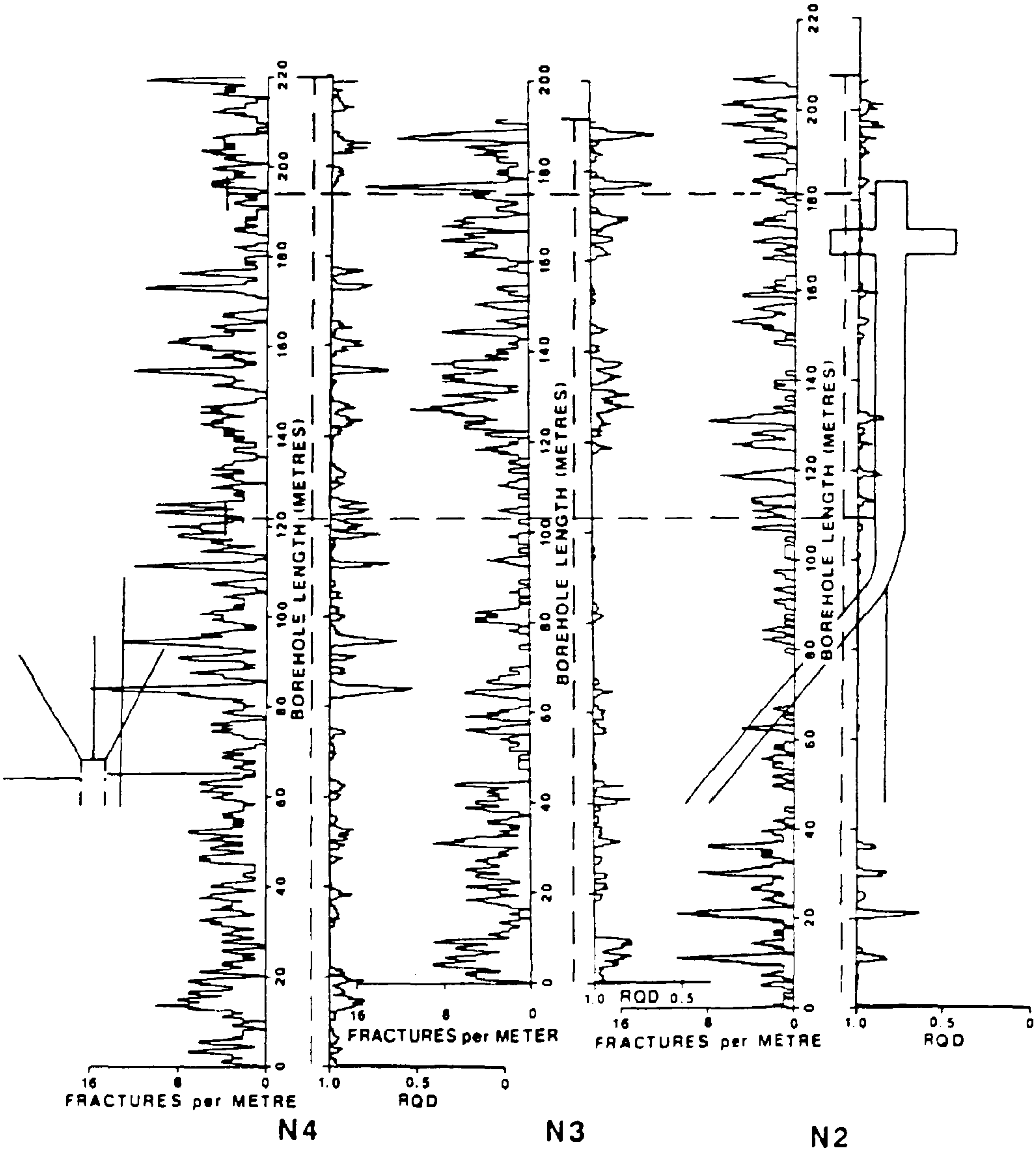


Pole plots of 50 m sections of the W holes.



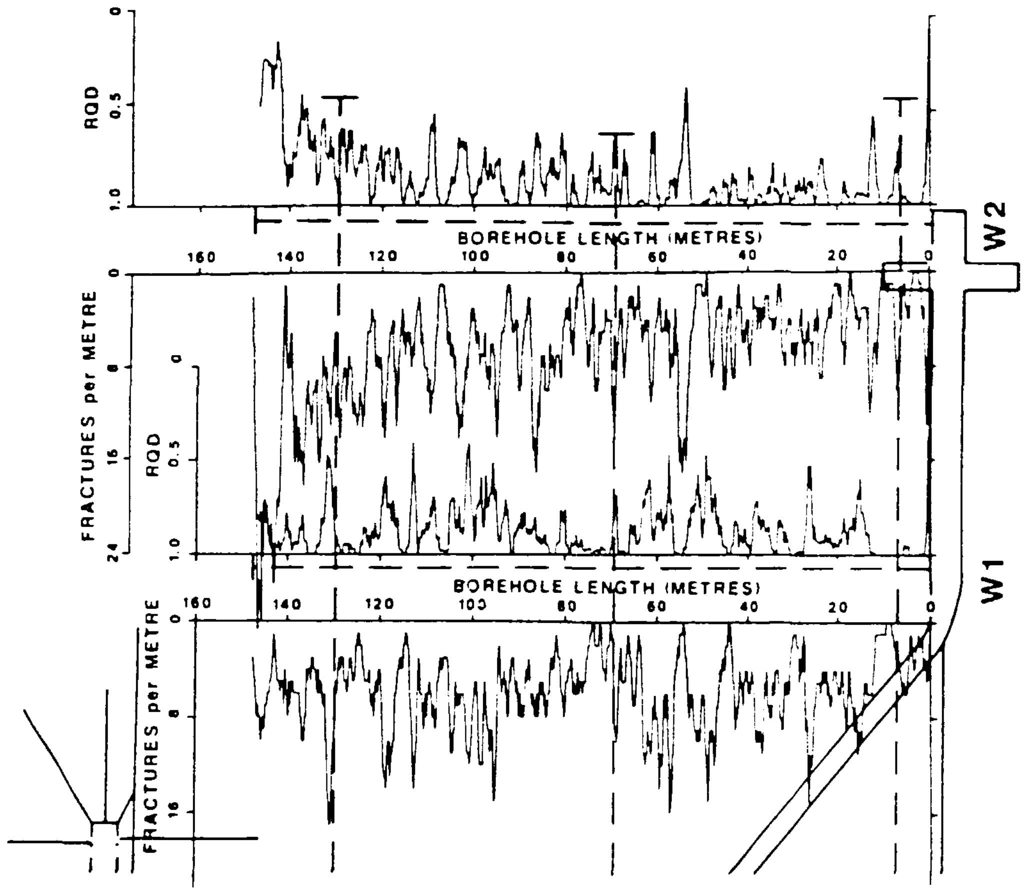
Pole plots of 60 fractures from each of the N and W boreholes at each of the points where the W boreholes cross over the N boreholes in the plan view.

(Gale and Stråhle 1988)



Frequency of fractures per metre and RQD values for the three N boreholes shown in their correct relative position. These plots are based on the coated, sealed and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.20 m.

(Gale and Stråhle 1988)



Frequency of fractures per metre and RQD values for the two W boreholes shown in their correct relative position. These plots are based on the coated, sealed and induced fractures and have been calculated using a moving average with a base length of 1.0 m and an increment of 0.20 m.

(Gale and Stråhle 1988)

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