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Regional Characterization of Hydraulic Properties of Rock Using Well Test Data

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Keywords: Hydraulic properties, Geostatistics, Depth dependence.

ABSTRACT (ENGLISH)

This study was aimed at investigating the possible use of data from the SGU well archive for characterisation of the hydraulic properties of the crystalline basement of Sweden at a regional scale. Two of SKB's study areas, Fjällveden and Gideå, were selected for the study. The SGU well data and the hydraulic conductivity data evaluated from packer tests in boreholes at the study sites were characterised statistically also considering possible spatial dependence. The two types of data were compared and the correlation between the data sets was investigated. This part of the study considered the uppermost 100 m of the packer test data, which is the approximate depth range covered by the SGU data. In a second part of the work the packer test data from the two study areas were analysed in terms of possible depth trends. It is argued that the bias in the SGU well data induced by the water well drilling procedure obscures the depth trends and must be compensated for in order to make depth dependence analysis worthwhile. No such attempts have been made in this study.

The exploratory statistical analyses suggested that the SGU data are useful for estimations of hydrogeological parameters for areas of different geologic settings. The geostatistical analysis provided further understanding of the spatial behaviour of the studied parameters. Block estimations gave plausible results.

The analysis of depth dependence in the SKB data indicates that at both sites there is a layer of higher hydraulic conductivity close to the surface. Within these layers, about 200 and 280 m thick, respectively, the conductivity decreases with increasing depth. At larger depths however, the decrease with depth is very slow or negligible. It was found that the scatter in the measured hydraulic conductivity data, both single boreholes and site compilations, is very large as compared to differences between the depth functions tested. Attempts were made to use a rock mechanical depth dependence model to match the in-situ hydraulic conductivity data. However, the difficulties to assign appropriate values of the rock mechanical input parameters in this model and the sensitivity of the model to this parameter choice, entail that our recommendation is to use a more simple depth dependence function for prediction of hydraulic conductivity at depth.

ABSTRACT (SWEDISH)

Avsikten med föreliggande studie var att undersöka möjligheten att använda SGUs Brunnsarkiv för karaktärisering av berggrundens hydrauliska egenskaper i regional skala. Två av SKBs typområden, Fjällveden och Gideå, valdes ut för undersökningen. Brunnsdata från SGU och data för hydraulisk konduktivitet från manschettmätningar i borrhål inom typområdena analyserades statistiskt vilket även inkluderade ett möjligt spatiellt beroende. De två dataseten jämfördes och korrelationen mellan dessa undersöktes. Denna del av studien avsåg endast de översta 100 m av manschettdata, vilket ungefär motsvarar djupområdet som täcks av SGU-data. I arbetets andra del analyserades alla manschettdata från de två typområdena med avseende på möjliga djuptrender. Det framförs skäl för att eventuella djuptrender i SGUs data ej kan utvärderas direkt utan lämplig matematisk korrektion på grund av att det använda brunnsborrningsförfarandet påverkar brunnsdata. Inga sådana försök till analys av dessa data har genomförts inom denna studie.

Den undersökande statistiska analysen antydde att SGUs data är användbara för uppskattningar av hydrogeologiska parametrar inom olika geologiska miljöer. Den geostatistiska analysen bidrog till en ytterligare förståelse för parametrarnas spatiella beroende. Blockskattningar gav goda resultat.

Analysen av djupberoende i SKBs data indikerar att båda de undersökta platserna har en ytlig zon med högre hydraulisk konduktivitet. Inom dessa ytliga zoner, vilka är ungefär 200 respektive 280 m mäktiga för de båda platserna, avtar konduktiviteten med ökande djup. Däremot är förändringarna vid större djup mycket små, alternativt försumbara. Spridningen i mätt hydraulisk konduktivitet är mycket stor jämfört med skillnaderna mellan olika testade djupmodeller. Detta gäller både för sammanställningar för respektive typområde och för enskilda borrhål. Försök gjordes även att passa uppmätta data med en modell för djupberoende som bygger på bergmekaniska samband. Emellertid visade sig modellen vara alltför känslig för valet av värden på de bergmekaniska indataparametrarna, vilka endast kunde ges som ett relativt stort intervall, för att modellen skall kunna användas som ett praktiskt prediktionsverktyg. Vår rekommendation är därför att använda en enklare modell för djupberoende vid förutsägelser av hydraulisk konduktivitet på djupet.

SUMMARY

This study was aimed at investigating the possible use of data from the SGU well archive for characterisation of the hydraulic properties of the crystalline basement of Sweden at a regional scale. Two of SKB's study areas, Fjällveden and Gideå, were selected for the study.

Two different data sets were employed, SGU well data and GEOTAB packer test data. Primarily 3-metre section packer data were used. The SGU data were recalculated to transmissivity values for further processing and analyses. The GEOTAB packer data were recalculated to transmissivity values and for comparison with the SGU data, the values were scaled to 100-metre sections.

The SGU well data and the hydraulic conductivity data evaluated from packer tests in boreholes at the study sites were characterised statistically also considering possible spatial dependence. The two types of data were compared and the correlation between the data sets was investigated. This part of the study considered the uppermost 100 m of the packer test data, which is the approximate depth range covered by the SGU data.

The exploratory statistical analyses suggested that the SGU data are useful for estimations of hydrogeological parameters for the two studied areas.

The spatial analysis of well data included variography, analysis of data clustering, cross validation and block estimations of transmissivity. The block estimation was performed using SGU data at the two selected sites. The spatial analysis verified some of the results from the exploratory statistics and provided further understanding of the spatial behaviour of the studied parameters. Block estimations of transmissivity produced plausible results.

In a second part of the work the packer test data from the two study areas were analysed in terms of possible depth trends. The analysis of depth dependence in the SKB data indicates that at both sites there is a layer of higher hydraulic conductivity close to the surface. Within these layers, about 200 and 280 m thick, respectively, the conductivity decreases with increasing depth. At larger depths however, the decrease with depth is very slow or negligible. It was found that the scatter in the measured hydraulic conductivity data, both single boreholes and site compilations, is very large as compared to differences between the depth functions tested. Attempts were made to use a rock mechanical depth dependence model to match the in-situ hydraulic conductivity data. However, the difficulties to assign appropriate values of the rock mechanical input parameters in this model

and the sensitivity of the model to this parameter choice, entail that our recommendation is to use a more simple depth dependence function for prediction of hydraulic conductivity at depth.

The depth dependence for the SGU well data was also studied. From these data it might be possible to investigate the trends for the uppermost 200 metres of the bedrock. Possible bias from the well drilling procedure was also evaluated. This bias depends on the fact that wells in less conductive parts of the bedrock are drilled to greater depth. The results indicate that there exists such bias for both areas studied. Furthermore, energy wells in the data base are generally deeper than water wells, and a specified yield is not a target of the drilling operation.

It is argued that the bias in the SGU well data induced by the water well drilling procedure obscures the depth trends and must be compensated for in order to make depth dependence analysis worthwhile.

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1 Introduction

1.1 Background

The continuing effort to locate suitable sites for deep-level repositories for spent nuclear fuel involves large amounts of hard data in order to assess ground conditions at the repository level. These data are in many cases expensive and time-consuming to collect. Especially when dealing with hydrogeological conditions at the regional scale, it is difficult to achieve an acceptable data density. In an initial phase of the siting, a preliminary assessment of the hydrogeological conditions prevailing in a specific area is important.

The use of pre-existing data at a regional scale would be valuable if they could provide a synoptic overview of hydrogeological conditions at some level of accuracy. This work will focus on one source of such pre-existing data, namely the well data from the SGU (Swedish Geological Survey) well archive. The well archive is a consequence of Swedish law, whereby the well driller is obliged to report to SGU the record of every well that is drilled. This archive contains information concerning position, depth, soil thickness, casing, yield, owner and use of the well.

During the period 1977-1986 SKB (Swedish Nuclear Fuel and Waste Management Co) carried out site characterization programmes for 14 study sites in order to assess their suitability as deep-level repositories. The studies comprised primarily surface and borehole investigations. Hydraulic tests, mainly injection tests, from several of these SKB study sites are currently available. These data are stored in SKB's database GEOTAB (Gerlach, 1991).

1.2 Objective

The main objective of this work is to investigate the possible use of SGU well data to characterize the hydraulic properties at a regional scale. The study also aims at developing a method to predict hydraulic properties in two or possibly three dimensions.

1.3 Performance

In the initial phase of this work, SGU well data and the corresponding SKB hydraulic data were characterized statistically also considering possible spatial dependence. The two types of data were compared and the correlation between well data and the hydraulic data was investigated. The first part of the analysis aimed at studying the correlation for the uppermost 100 metres, which is the interval covered by the SGU data.

Hydraulic data from SKB's database GEOTAB were then used to study the possible depth trend below 100 metres (figure 1-1).

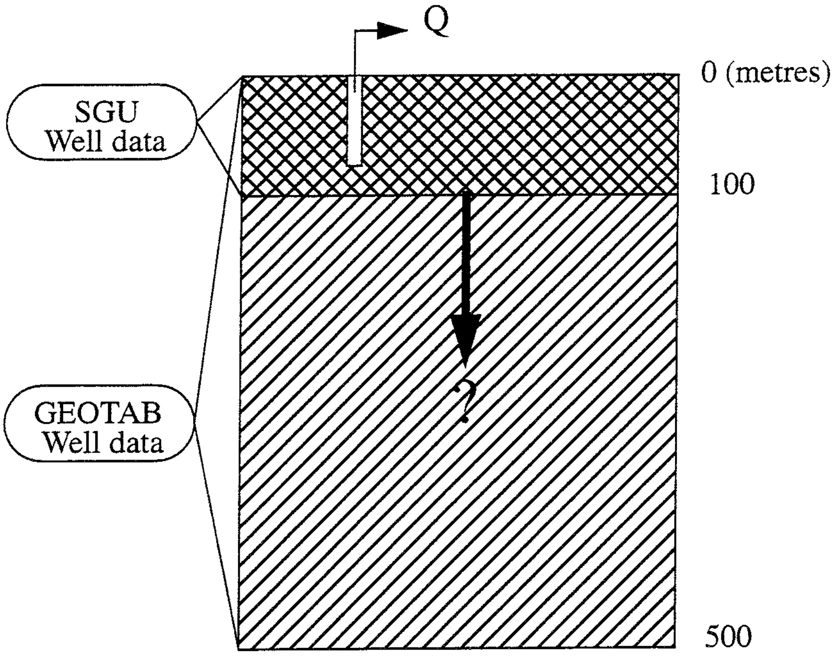


Figure 1-1. *Illustration of the depth intervals covered by the used data*

The relation between hydraulic conductivity and depth was studied with focus on evaluation of mathematical models and their performance at the two selected test sites.

2 Site description

2.1 Site selection

The main concern for the selection of SKB study sites was data density and distribution. In order to select suitable sites, the following criteria were used:

- Highest possible data density

- Maximum depth distribution

- Fairly homogeneous tectonic and/or geologic conditions

- Access to rock stress data

These criteria were considered at all the available sites and weighted together in the selection procedure. Following the selection criteria, the Gideå and Fjällveden study sites were decided upon (figure 2-1). However, rock stress data are only available for the Gideå site.

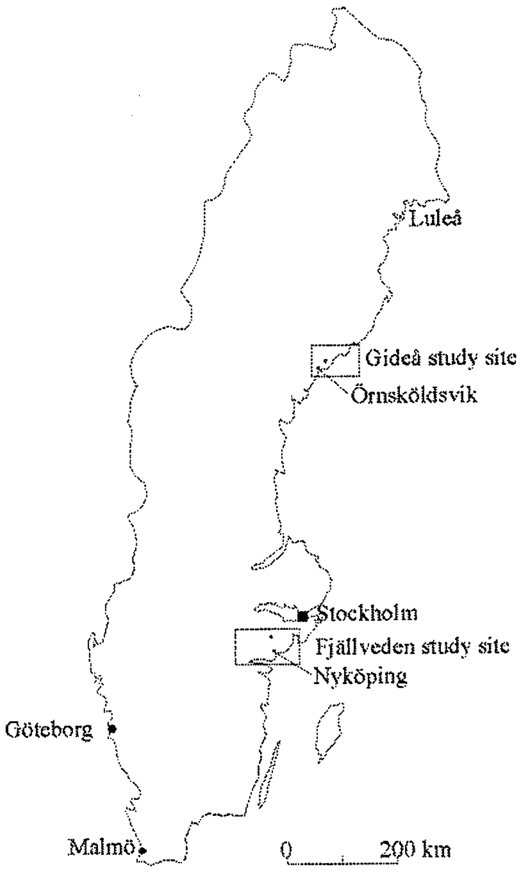


Figure 2-1. The locations of the two selected sites.

2.2 Gideå study site characterization

The description of the Gideå study site characterization is essentially following Ahlbom et al. (1991a). The Gideå study site is located in the county of Västernorrland, Örnsköldsvik municipality at the lake Gissjön, which is about 30 km NE of Örnsköldsvik. The areal extent of the site is 2 x 3 km.

2.2.1 Bedrock

The site is situated in a large domain of sedimentary gneiss. In this case it is a migmatized veined gneiss. Due to the migmatization of the sediments there are two main rock types of which the veined gneiss is the dominating and migmatite granite is the subordinate rock type. Late during the Svecokarelian orogeny granitic dykes intruded these rocks and the deformations during the orogeny resulted in a foliation of the total study area. The same deformation also transformed the granite to granite gneiss. The foliation in the Gideå area generally trends north-east with a gentle dip (10°-30° towards north-west). The area contains vertical dykes of dolerite which, with two exceptions, have a width less than one metre. The dolerite dykes have a spacing of 200-300 m. Also some minor bodies or smaller dykes of pegmatite occur in the site area.

2.2.2 Fractures

The fracture frequency in general is approximately 4 fractures/metre borehole (fr./m) and decreases with depth to 2 fr./m at 500 m depth. In some parts of the site the frequency increases to higher values, and for the dolerite the frequency is as high as 21 fr./m. At the site area 11 fracture zones have been further analysed. The main trends of the zones are NE and E-W. The widths of the zones vary up to 24 m. Commonly there are parts of clay-altered rock in the fracture zones and also in the dolerite dykes. This is thought to be the main reason for the generally low hydraulic conductivity in the study site area (Ahlbom et al., 1991 a).

2.2.3 Topography and hydrology

The topography is undulating with its highest parts to the east. The main recharge area is in the central parts of the study site and the discharge areas are often located in the local lineaments. Also the rivers Gideåälven, to the southwest, and Husån, to the east, are important in this respect.

2.2.4 Hydrogeology

The hydraulic conductivity for the veined gneiss is low. It is estimated to be approximately 10^{-11} m/s at 500 m depth. For the granite gneiss and for the fracture zones it is about one order of magnitude higher than for the veined gneiss (Ahlbom et al., 1991 a).

2.2.5 Rock stress data

Hydrofracturing rock stress measurements have been reported from borehole Gi1 at the Gideå site (Ahlbom et al., 1991a). According to these measurements, the minimum horizontal stress increases with depth at a rate close to that of the theoretical vertical stress, but there is an indication of a slight decrease in stress gradient at greater depth. Both horizontal principal stresses appear to be in excess of the vertical stress down to at least 400 m. The ratio of maximum horizontal stress / minimum horizontal stress is fairly stable, about 1.6, throughout the measured depth interval.

The orientation of the maximum horizontal stress has been determined as N67°E ±9°. No rotation with depth was observed. Ahlbom et al. (1991a) concluded that the standard deviation of the stress orientation was somewhat high, and that the orientation does not coincide with the NW-SE trend generally measured in Sweden.

2.2.6 Boreholes

At the site, a total of 24 percussion boreholes were drilled primarily for investigation of possible fracture zones. The boreholes were drilled to a depth varying from 40-153 m. Also 13 cored boreholes have been drilled.

2.3 Fjällveden study site characterization

The Fjällveden study site is located in the county of Södermanland, Nyköping municipality at the lake Båven, which is about 20 km NNW of Nyköping and 80 km SW of Stockholm. The areal extent of the site is 2 x 3 km. The following description is mainly from Ahlbom et al. (1991 b).

2.3.1 Bedrock

The region is dominated by a grey sedimentary gneiss with subordinate intercalated layers of weakly foliated dark-grey granodioritic rocks, greenstones and local bodies of granite and associated pegmatites. The regional foliation is subvertical and trends northeast and it is tightly folded along subhorizontal north-east trending fold axes and refolded along east-west trending fold axis. The bedrock was later distorted by regional north-west trending and regular spaced shear zones. The sedimentary gneiss is banded and composed of 0.1-0.2 m wide alternating medium grained quartzo-feldspathic layers and fine grained biotite rich layers. The banding is parallel to the regional foliation and mineral fabric in the rock. There are frequently occurrences of small lenses of dark amphibolite in the sedimentary gneiss parallel to the foliation. The amphibolite lenses are between 0.1 m to several metres in cross-section and the relative occurrence in the bedrock is 3.5%. The granodioritic rock is the dominating rock type in the northern part of the site, while it in the central part represents less than 3% of the drilled rock volume. In the central part the granodioritic rock occurs as relatively thin and very extensive layers, often situated within zones of intense mylonitic and cataclastic deformation. The youngest rocks in the site area are vertical, north-west trending doleritic dykes, which are oriented perpendicularly to the regional foliation and sub-parallel with the regional shear zones. The dykes are 0.4-4 m wide and occur most commonly in the northern part of the study site.

2.3.2 Fractures

The fracture frequency in boreholes at the study site is low, approximately 4 fr./m in the surface layer and roughly 2 fr./m from 200 m down to 700 m depth. In the central part of the site area 11 local fracture zones have been studied in more detail. The dominating orientations of the zones are NW and NNE and the width of the zones is up to 14 m. In the fracture zones there is a general low hydraulic conductivity which probably can be explained by the strongly clay-alteration within the zones (Ahlbom et al., 1991 b). Regional NW-trending lineaments bound the site in the east-west direction and a borehole through the eastern lineament showed signs of a major shear zone with a dip of 75°W and a width of around 90 m.

2.3.3 Topography and hydrology

The site topography is in general flat and most of the area is a recharge area for ground water. The only discharge area of importance is the lake system, which includes the lake Båven, to the west and south.

2.3.4 Hydrogeology

The hydraulic conductivity for the sedimentary gneiss is estimated at about 10^{-11} m/s, which is a comparatively low value. For the granodioritic rock the value of the hydraulic conductivity is more than two orders of magnitude higher and in the fracture zones the value is in the same order of magnitude as it is for the sedimentary gneiss (Ahlbom et al., 1991 b).

2.3.5 Boreholes

At the site, percussion drilling was used to investigate possible major fracture zones. A total number of 49 percussion boreholes were drilled. Borehole lengths varied between 30-175 m. 15 cored boreholes were also drilled at the site. The maximum vertical depth is 695 m and the boreholes were commonly drilled inclined, 60° from the horizontal.

3 Data characterization and preparation

3.1 Data sets

There are two main sources of data utilized in this report, the SGU well database for each municipality, and the SKB data-base GEOTAB which includes all data from each study site. These data are described in the following sections.

3.2 SGU well archive

Well data for the study areas comes from the well archive maintained by SGU. Well yields within the archive are mainly estimated by the driller himself using a simple air-lift test. These well data offers a possibility to assess the groundwater occurrence on a regional scale. For evaluations of single wells it is possible to reach a higher precision concerning yield, but for regional studies with large amounts of data, this cannot be accomplished. Apart from well yield, the archive contains data about for example the total well depth and soil thickness.

All soil wells and wells that could be considered to be more or less influenced by the soil aquifer, were removed. The criteria used to select bedrock wells were that the soil thickness should not exceed 20 m to avoid influence from the soil aquifer. Wells were also excluded if they were drilled less than 10 metres into bedrock and with at least 75% of the total well depth drilled in bedrock.

By dividing the yield of the well, Q, by the total well depth, d, for each well in the study area, a ratio dependent on the hydraulic properties of the bedrock is obtained. Q/d can be shown to be a conservative estimate of the specific capacity, Q/s_w, where s_w is the drawdown. In steady-state flow, the specific capacity is generally proportional to the transmissivity (T) of the aquifer (Carlsson & Gustafson, 1991). The correlation between specific capacity and transmissivity was studied by Rhén et al. (1997). From regression analysis, the following correlation was found:

$$T = 2,24 \cdot (Q/S_w)^{0,98} \tag{3.1}$$

Equation 3.1 confirms the proportionality discussed above. Furthermore, equation 3.1 is related to the Äspö study site, an environment consisting of crystalline, metamorphic bedrock. The Gideå, the Fjällveden, and the Äspö study site comprise dominantly of rocks of similar age. Consequently, it can be assumed that the tectonic influence of these three sites also shows similarities. Finally, the performance of the hydraulic tests for all three sites was similar. Therefore, equation 3.1 was applied to the two study sites in this work.

Jetel (1967) has shown empirically that the specific capacity is approximately log-normally distributed. Furthermore, it has been shown that this assumption is valid also for Swedish conditions (Carlsson & Carlstedt, 1976), which was supported also by Gustafson & Krásny (1994). Consequently, the $^{10}\log$ of the obtained transmissivity values were used for subsequent analyses. For simplification, in this work pT is used to denote $-^{10}\log T$.

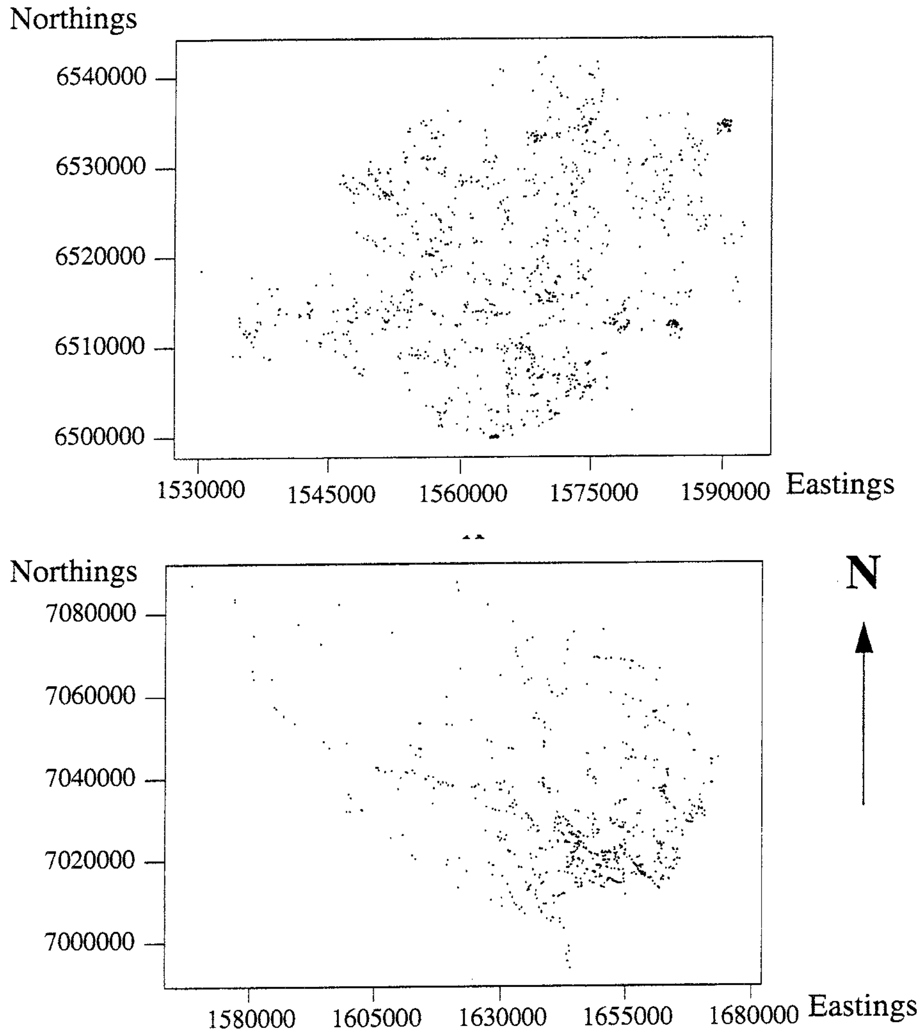


Figure 3-1. Sample maps showing the distribution of SGU well data for Nyköping (top) and Örnsköldsvik (bottom).

3.3 GEOTAB well data

The hydraulic conductivity data used in this study were obtained from single-hole injection tests. During these tests water was injected in isolated test sections of the boreholes. These sections were sealed off by inflatable rubber packers. Packer spacings were at the Gideå and Fjällveden test areas generally between 5 m and 25 m. In the present study we only used the tests carried out over test lengths of 20-25 m.

Single-hole injection tests can be conducted either at a constant flow rate or at a constant pressure head. The most common method used at the SKB study areas has been constant-head tests. Such injection tests can be evaluated either as transient tests or as steady-state tests. An evaluation according to theories for transient flow generally requires a rather long injection period and can also use the recovery period following the injection. This means that hydraulic parameters can be determined both during pressure build-up and during pressure fall-off.

In the SKB research programme a standardised procedure has been developed for constant-head, transient injection tests, as described by Almén et al. (1986). A test cycle starts with inflation of the packers during 30 minutes. After this inflation phase, a two hours long injection period follows when water is injected under constant pressure (ca. 0.2 MPa). In the third phase, the water flow into the test section is stopped by closing a test valve (shut-in), which causes the interval pressure to decline. During the entire test cycle pressures, flow rates and water temperature are registered and stored. The data sets are plotted in different diagrams, which make a determination of the hydraulic parameters of the test section possible by using equations based on theories for transient tests. A description of hydrogeological data in GEOTAB and the data acquisition systems used during the field tests are given in Gerlach (1991).

3.4 Comparison of SGU and SKB well data

For the purpose of comparing SGU and SKB data, it was assumed that no significant depth trend exists for the upper 100 metres. This assumption is supported for the upper 100-200 metres as an alternative interpretation by Ahlbom et al. (1991 a, b) for both the Gideå and the Fjällveden study sites.

The comparison of SGU and SKB well data is based on the correlation between the specific capacity (Q/s_w) and the transmissivity (T) discussed in section 3.2. However, the use of several K measurements determined from different packer lengths to characterize a larger volume, in this case the uppermost 100 metres, will inevitably lead to some uncertainties. Two of these questions are discussed by Norman (1992); (1) If different packer interval lengths are used, is it fair to assume the measurements as being drawn from the same population and, (2) are the results scale-dependent, i.e. dependent on packer interval lengths? A common approach to characterize a larger domain is the use of geometric mean. However, with the geometric mean the uncertainties discussed above are disregarded.

To solve for these uncertainties when upscaling the hydraulic field, Norman (1992) suggests the use of regularized conductivity, K_{reg}. For the case of constant section length, K_{reg} is computed as:

$$K_{reg} = \frac{\left(1 - \ln\left(\frac{2\rho_w}{nL}\right)\right)}{\left(1 - \ln\left(\frac{2\rho_w}{L}\right)\right)} \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} K_i \qquad (3.2)$$

where ρ_w is the borehole diameter, L denotes the packer section length and n represents the number of measurements.

For eight of the core boreholes at the Fjällveden study site, it was possible to calculate K_{reg} in the interval 0-100 metres. The remaining boreholes lack packer measurements in this interval. The choice of interval was based on the length distribution of SGU well data and the possibility to use at least three packer measurements for computation of each separate K_{reg}-value.

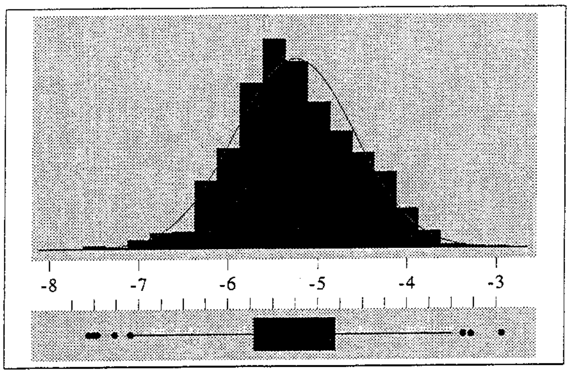
In order to obtain quantities comparable with SGU well data, each K_{reg} value was recalculated to transmissivity (T), by multiplying K_{reg} with the applied borehole length.

3.4.1 Exploratory statistics

A compilation of descriptive statistics for the pT values from the SGU well data is shown in figures 3-2 and 3-3. Dry wells, i.e. wells with yield=0, were regarded as outliers and have consequently been removed from the datasets. This procedure is assumed to introduce some bias to the statistics, but only approximately 4% of the wells in both study areas are listed as dry.

The same statistics are calculated for pT from the GEOTAB data for each study area (figures 3-4 and 3-5).

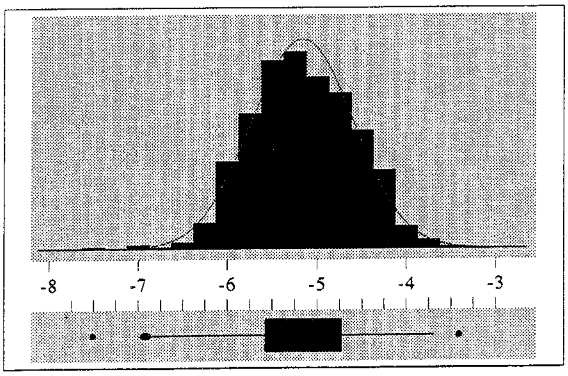
Descriptive Statistics



Mean	5.26
Std Dev	0.67
Variance	0.45
Skewness	0.06
Kurtosis	-0.02
n of data	1522.00
Minimum	7.56
1st Quartile	5.71
Median	5.31
3rd Quartile	4.80
Maximum	2.93

Figure 3-2. *Statistics for pT, SGU wells of the Nyköping municipality.*

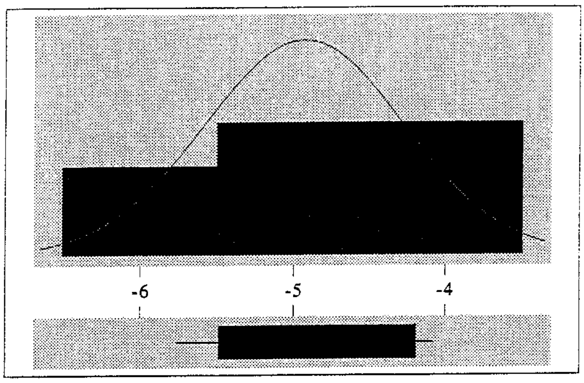
Descriptive Statistics



Mean	5.165
Std Dev	0.569
Variance	0.324
Skewness	-0.049
Kurtosis	-0.139
n of data	986.000
Minimum	7.508
1st Quartile	5.577
Median	5.187
3rd Quartile	4.730
Maximum	3.408

Figure 3-3. *Statistics for pT, SGU wells of the Örnsköldsvik municipality*

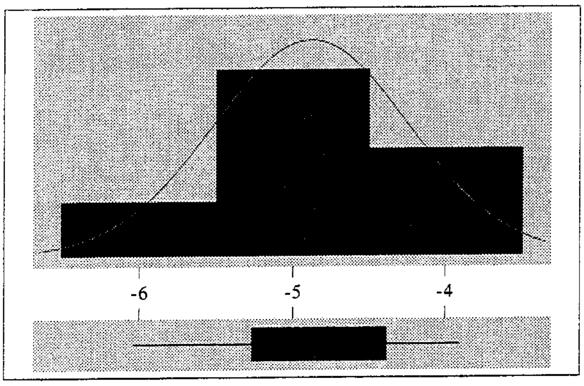
Descriptive Statistics



Mean	4.93009
Std Dev	0.65398
Variance	0.42769
Skewness	0.16662
Kurtosis	-1.84748
n of data	8.00000
Minimum	5.76199
1st Quartile	5.48670
Median	5.11062
3rd Quartile	4.19434
Maximum	4.07861

Figure 3-4. *Statistics for pT, GEOTAB data of the Fjällveden study site.*

Descriptive Statistics



Mean	4.8803
Std Dev	0.6381
Variance	0.4071
Skewness	-0.3004
Kurtosis	-1.1126
n of data	13.0000
Minimum	6.0366
1st Quartile	5.2676
Median	4.9467
3rd Quartile	4.3835
Maximum	3.9077

Figure 3-5. *Statistics for pT, GEOTAB data of the Gideå study site.*

Direct comparison of the SGU data with the SKB data is not considered appropriate or even possible. The large heterogeneity over larger areas both with respect to lithology and tectonic influence affect the hydraulic properties in such manner, that they cannot be related to the same population. Also the variograms (see chapter 4) support this assumption on spatial variability. Therefore, the SGU wells in a smaller area around each SKB site were extracted (figure 3-6 and 3-7). The selection of subareas is largely controlled by the structure of the datasets and the conditions prevailing at each site. The Örnsköldsvik municipality is sparsely populated in the vicinity of the site. Therefore, the area selected around the Gideå study site is roughly twice the size compared to the Fjällveden study site. Descriptive statistics were computed for each subarea (figure 3-8 and 3-9).

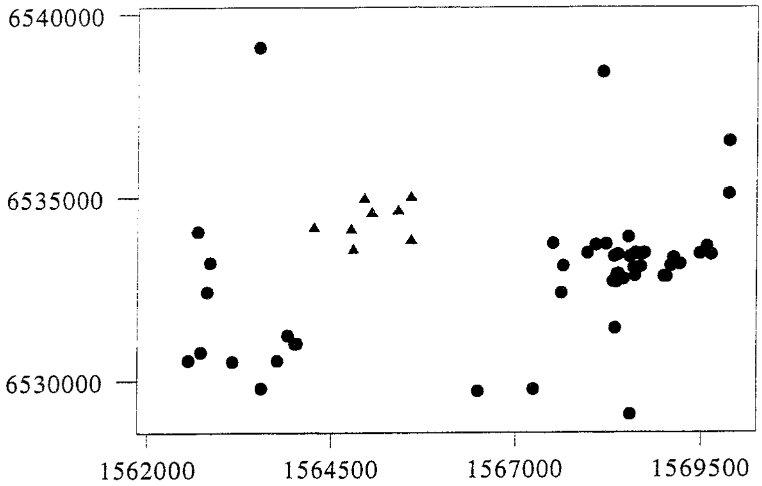


Figure 3-6. Well locations for the Fjällveden subarea. Circles indicate SGU wells and triangles GEOTAB hydraulic data.

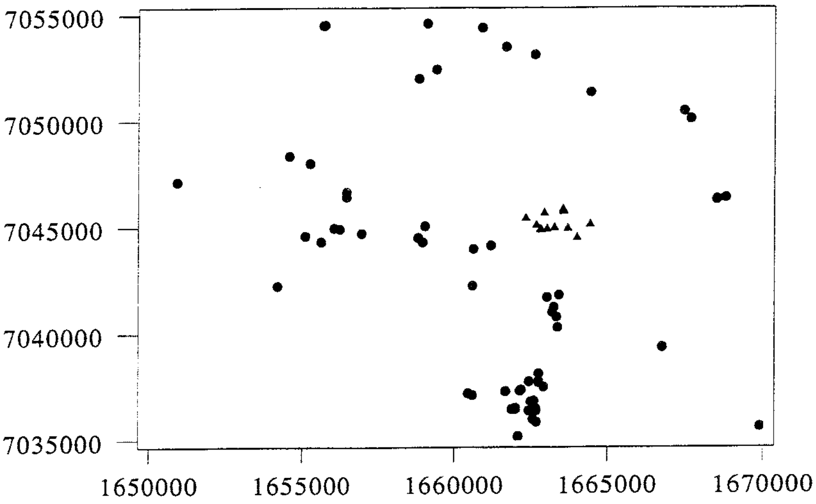
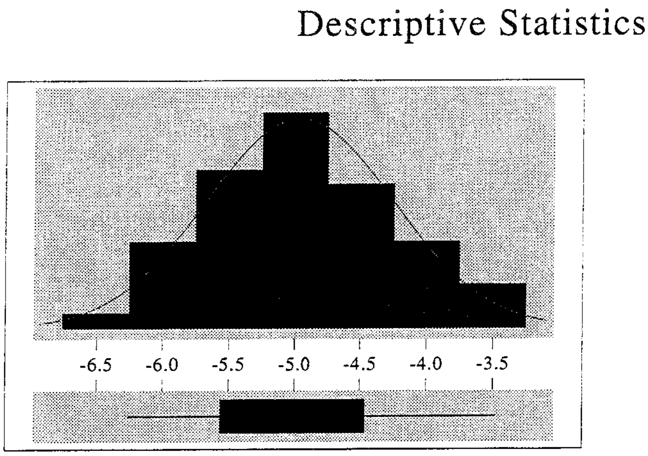
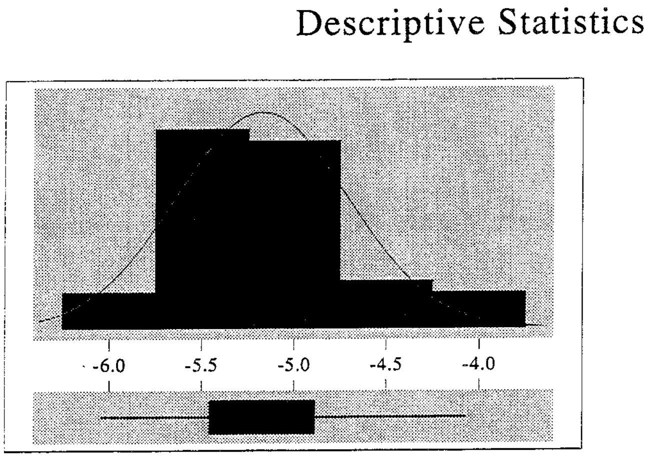


Figure 3-7. Well locations for the Gideå subarea. Circles indicate SGU wells and triangles GEOTAB hydraulic data.



Mean	4.9634
Std Dev	0.7095
Variance	0.5034
Skewness	0.1708
Kurtosis	-0.7690
n of data	52.0000
Minimum	6.2594
1st Quartile	5.5574
Median	5.0117
3rd Quartile	4.4615
Maximum	3.4803

Figure 3-8. *Statistics for pT, SGU wells of the Fjällveden subarea.*



Mean	5.1738
Std Dev	0.4649
Variance	0.2161
Skewness	0.6001
Kurtosis	-0.1249
n of data	43.0000
Minimum	6.0411
1st Quartile	5.4566
Median	5.2419
3rd Quartile	4.8848
Maximum	4.0650

Figure 3-9. *Statistics for pT, SGU wells of the Gideå subarea.*

In order to compare the SGU well data with the corresponding SKB site data there are different statistic tests that can be applied. But prior to that, it must be concluded whether the well data can be considered to be statistically independent random samples or not. Arguments in favour of the independency assumption include large representative element volume, heterogeneous bedrock, randomly oriented conductive fractures, short fracture lengths, and faulting with large offsets. Arguments in favour of the opposed assumption include oriented fracture sets, and homogeneous bedrock.

If statistical independence can be assumed, a one-way analysis of variance can be performed to test for similarity between SGU and SKB data, or the equivalent Two-sample T-test. The results of the one-way analysis of variance for the study area are presented in figures 3-10 and 3-11. The outcome of this test is not sensitive to smaller variations in size of the subarea nor are the descriptive statistics.

One-Way Analysis of Variance

```
Analysis of Variance on T
Source     DF         SS        MS        F        p
code        1      0.008     0.008     0.02    0.901
Error      58     28.667     0.494
Total      59     28.675
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
 Level      N       Mean     StDev  -+---------+---------+---------+-----
     1     52    -4.9634    0.7095           (------*-----)
     2      8    -4.9301    0.6540  (----------------*---------------)
                                    -+---------+---------+---------+-----
Pooled StDev =    0.7030          -5.40     -5.10     -4.80     -4.50
```

Figure 3-10. *Analysis of variance, SGU wells, Nyköping municipality, and cored boreholes, Fjällveden area (logT).*

One-Way Analysis of Variance

```
Analysis of Variance
Source     DF         SS        MS        F        P
Factor      1      0.889     0.889     3.37    0.070
Error      75     19.781     0.264
Total      76     20.669
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level       N       Mean     StDev  -----+---------+---------+---------+-
    1)     64    -5.1671    0.4862  (------*-----)
    2      13    -4.8803    0.6381         (-------------*-------------)
                                    -----+---------+---------+---------+-
Pooled StDev =    0.5136              -5.20     -5.00     -4.80     -4.60
```

Figure 3-11. *Analysis of variance, SGU wells, Örnsköldsvik municipality, and cored boreholes, Gideå area (logT).*

For the Nyköping area, the result strongly supports the hypothesis of similarity, whilst the result for the Gideå area does not support similarity.

In the Nyköping subarea, SGU well archive data and GEOTAB data produce similar results. Therefore, it can be assumed that geologic conditions are fairly homogenous and that SGU data can be used to predict hydraulic properties of the upper 100 metres of the rock. This is not the case for the Gideå area. Instead, the results of the Gideå area suggest heterogeneous hydraulic properties of the rock with larger horizontal variations, which is also important information in the case of locating a repository for spent nuclear fuel.

4 Spatial data analysis

4.1 Well data characteristics

If assumed that the well capacity data are correlated random variables, then a random function (R.F.) can be used to describe the spatial interdependence structure of the well capacity data. Since the data are distributed in space, they can be referred to as regionalized variables. The R.F. can be characterized by its statistical properties. In linear geostatistics, only the two first moments are of interest. Stationarity of a R.F. assumes that any statistical property including moments is invariant under translation. For second-order stationarity or weak stationarity, the mean is independent of location, and the covariance function depends only on the separation vector. If the variance increases with the area under consideration, i.e. the variance is not finite, the intrinsic hypothesis can be assumed. The intrinsic hypothesis can be seen as a reduction of the second-order stationarity to be valid for the increments of the R.F. (Journel & Huijbregts, 1978). The variance of the increments constitutes a function called the variogram. Further reading on this subject can be found in for example Delhomme (1978), Marsily (1986) and Journel & Huijbregts (1978).

Irrespective of the characteristics of the studied area, the spatial dependence must be taken into account. However, if assumed that the well capacity measurements are uncorrelated, it might very well be the case that traditional exploratory statistics is sufficient to characterize the geological properties. In this chapter, the spatial dependence is studied.

For the subsequent 2-D geostatistics the computed pT values of the SGU data have been used. The values were computed in accordance with equation 3.1. The objectives of this part of the study is to characterize the well data in terms of the spatial distribution and the spatial continuity including possible directions of anisotropy. The results are used to establish models of the spatial dependence. The models are also used in an attempt to estimate block values of transmissivity for the Gideå and Fjällveden study sites. These block estimates are purely for comparison of the GEOTAB data and should not be seen as an attempt to produce effective transmissivity values. For a further discussion on effective values, refer to e.g. Gomez-Hernandez & Gorelick (1989). The steps involved to accomplish the objectives include:

-Analysis of data clusters and data declustering.

-Variogram analysis.

-H-Scatter plots.

-Model fitting.

-Validation of models.

-Block estimations based on Kriging or BLUE (Best Linear Unbiased Estimate).

4.2 Data clustering

Data clustering might severely bias estimates of parameters such as the mean, the variance and the semivariograms of an underlying population. Often, it is fair to assume that each data sample has equal weight to all other data samples in a specific study, i.e. each sample represents the same information content. But if we assume that we are studying a regionalised variable, i.e. data are spatially dependent, clustered data are in fact representing redundant data. Therefore, clustered data should be weighted in relation to the size of the cluster.

Clustered data was identified from sample maps. In practice, clustered well data is related to villages and smaller communities. Therefore, data can be considered as spatially clustered, but not preferentially clustered in terms of anomalously high or low values.

4.3 Data declustering

Several methods can be utilized to provide declustered univariate parameters of a distribution, for example global kriging and polygonal declustering. The method employed herein is cell declustering. The implementation was facilitated by the use of the program *DECLUS*, developed by Deutsch (1989).

The idea of cell declustering, first proposed by Journel (1983), is to superimpose a regular grid over the area and weight each data sample within the cell to 1/n where n is the number of samples within the cell. The weights depend not only on the selected cell size but also on the origin of the grid. Both problems are solved for by *DECLUS*. A variable cell size can be applied as well as a moving origin of the grid.

As a rule of thumb, the cell size should be set so that there is approximately one datum per cell. Five different origin offsets have been used for calculation of the weight, a number of offsets which usually is enough (Deutsch, 1989). To determine the optimum cell size, a number of cell sizes were considered. The optimum cell size was determined from a plot of the declustered mean, i.e. the declustering weights, versus cell size. The appropriate cell size is selected from the graph when the declustering mean is stable (figure 4-1) (Deutsch, 1989). For the Nyköping data, a cell size of 500x500 metres produced a stable mean. For the Örnsköldsvik data, which are far less densely distributed, a grid cell size of approximately 3000 metres is necessary to reach a stable mean (figure 4-2). The plots of declustered mean versus cell size imply that the clustering has small influence on the mean.

Clustered data can severely affect the possibilities to produce measures of the spatial variability. Unfortunately, there is no general method for declustering of bivariate data. Because different measures of spatial variability, for example the correlogram, the madogram, and the rodogram, have different robustness properties for considering outliers, clustering, and other biases, various such measures might be tried in analysis of spatial data (Deutsch and Journel, 1992). Further consideration of declustering is beyond the scope of this work.

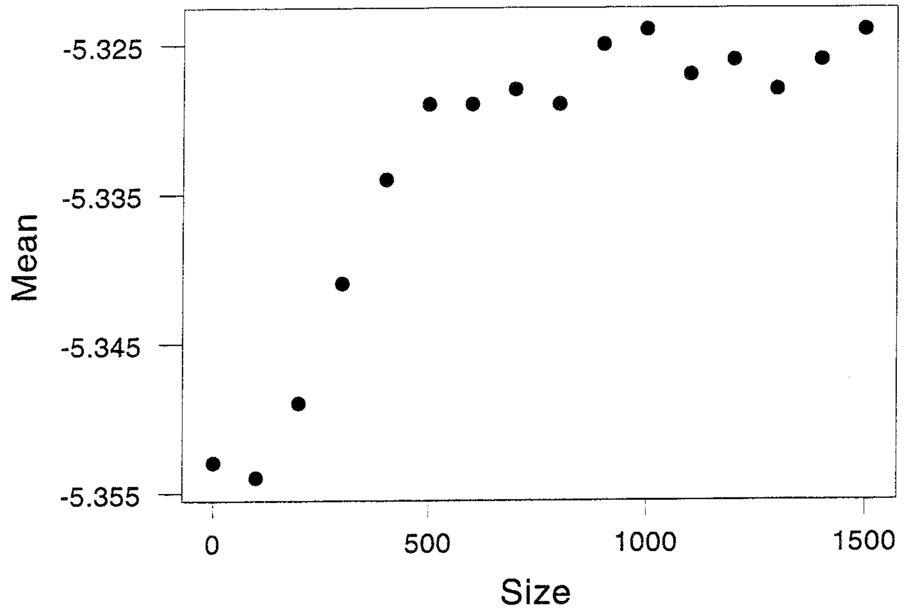


Figure 4-1. *Nyköping data: The declustered mean versus cell size for five origin offsets. A stable mean is reached at a cell size of about 500x500 metres.*

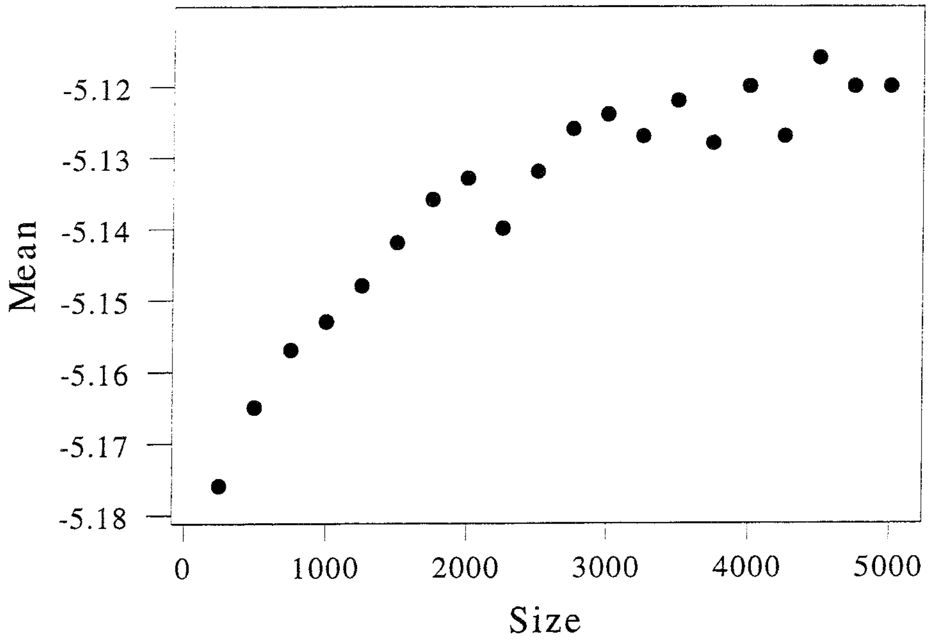


Figure 4-2. *Örnsköldsvik data: The declustered mean versus cell size for five origin offsets. A stable mean is reached at a cell size of about 3000x3000 metres.*

4.4 Variogram analysis

Experimental variograms as well as the subsequent model fitting were facilitated through the use of the software package Variowin 2.1. From the variogram analysis it can be concluded that both data sets display a pronounced nugget effect (Y-intercept). The nugget effect is commonly the result of sampling errors and short-scale variability (Isaaks & Srivastava, 1989). The small-scale variability can also be obscured due to both poor spatial resolution and errors in the SGU well data. Approximately 150 wells were located with identical coordinates as at least one other well for both the Nyköping data and the Örnsköldsvik data. These well locations are obviously erroneous in at least half of the cases but the errors are not necessarily large. Removing clustered data might offer an opportunity to get around the problem but it might be argued that removing data points implies a loss of information. However, removing all pairs with identical coordinates did not improve the appearance of the variograms or any other measure of spatial variability at short lag distances. The dotted line in the variograms represents the overall covariance. The variograms are displayed in figure 4-3.

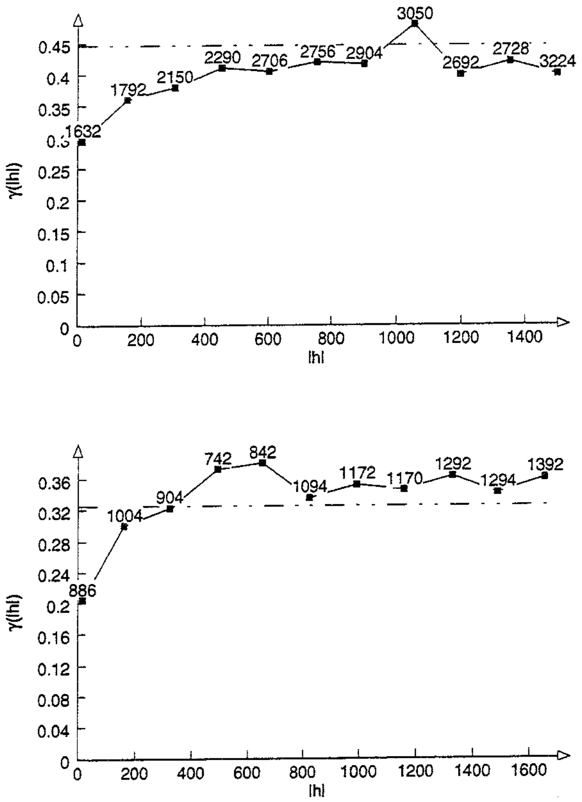


Figure 4-3. *The experimental omnidirectional variogram for the Nyköping area (top), and the Örnsköldsvik area (bottom).*

Both variograms suggest large short-scale variability. Large variability within short distances is commonly observed when dealing with hydraulic properties in fractured media (Marsily, 1986). However, the variograms also indicate a spatial correlation (*range*) for distances of the separation vector, |h|, up to approximately 400 and 500 metres respectively.

4.5 Model fitting

Model fitting aims at describing the spatial behaviour of data using a mathematical model. Models were fitted to the omnidirectional variograms.

The selection of model is facilitated within Variowin 2.1 by a *Indicative Goodness of Fit, IGF,* which represents a measure of fit in a least square sense for the selected model. The IGF can be used as a support to the visual fitting of models. The model, and choices between different models can also be evaluated using cross-validation.

For the Nyköping SGU well data, a spherical model with a sill=0.42, a range=493, and a nugget=0.29 provided a good fit.

For the Örnsköldsvik SGU data, a spherical model with a sill=0.35, a range=360, and a nugget=0.192 was selected.

4.6 Anisotropy

The hydraulic properties in fractured media might display a directional behaviour in terms of anisotropic covariances. Anisotropy of the covariance of the studied parameter can be shown to be related to the aniotropy tensor in a rather complex fashion (Gutjahr et al., 1978). In this work, only the anisotropy of the covariance will be considered and is studied as the variability of the range. Several geological factors can account for anisotropy. Examples include the lithology, the fracture pattern and the current stress field.

To investigate the possible anisotropy, directional variograms were produced. By combining the directional variograms together with the model fitted to the omnidirectional variogram, an indication of the anisotropy can be given (figure 4-4 and 4-5). The omnidirectional variogram can be seen as a mean for all directions. Directional variograms which plot below the fitted models indicate directions of larger spatial continuity. However, the directional variograms for both areas display high noise levels.

For the Nyköping area, in figure 4-4, the north-south and the northwest experimental variogram plots below the model, suggesting a longer range in these directions.

Despite the high noise level, the directional variograms for the Örnsköldsvik area (figure 4-5), suggest a direction of maximum continuity in east-west.

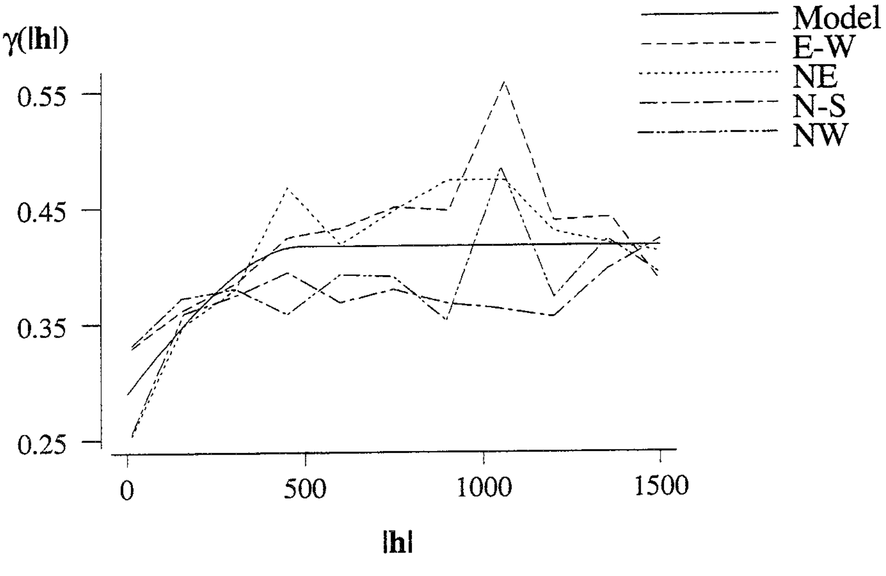


Figure 4-4. Experimental directional variograms for the Nyköping area.

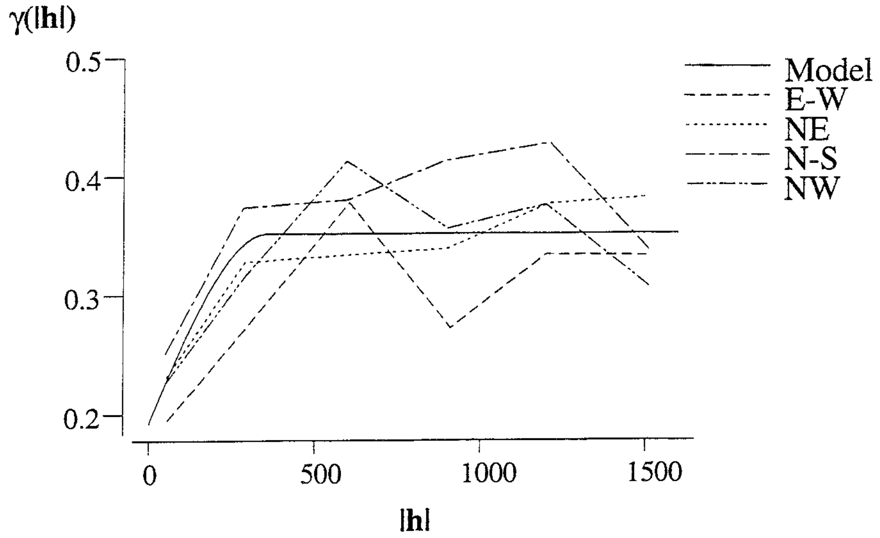


Figure 4-5. Experimental directional variograms for the Örnsköldsvik area.

Another way of investigating the spatial continuity is the use of variogram surfaces (Rendu, 1980, Isaaks & Srivastava, 1989). They are represented as pixel maps with the central cell corresponding to the separation vector (0, 0). Due to the noise level, directions of maximum and minimum continuity were not readily detectable from variogram surface plots.

It is worth noting that for both the Nyköping and the Örnsköldsvik SGU data, the range distance obtained from the omnidirectional variogram is considerably smaller than the size of the SKB study site. Therefore, the variability of the whole municipality might be contained in the site area. An area with each side ten times the range can be considered as a favourable case in practice. The variography provides the spatial behaviour of the studied parameter and for example the range distance for a given parameter might vary considerably within different geological environments.

4.7 Model validation

In order to validate the established models, cross-validation was employed. In cross-validation, the estimation method is tested at each sampled point of the data set. Each sample point is temporarily discarded from the data set and an estimate is produced using the remaining samples. When a sample point is estimated, the estimation value can be compared to the actual data point at that location. In this case, the estimation method used was ordinary kriging. The results can be compared using the mean (m), the median (M) and the kriging standard deviation (kσ). The statistics for each area are presented in table 4-1 and 4-2, where also the number of points (n), the minimum value (min), the maximum value (max), the lower (Q1) and upper (Q3) quartiles are listed. The tables provide descriptive statistics for the actual value, the estimated value, the kriging standard deviation, the kriging error (the difference between the estimate and the observed values, r in equation 4.1), and the zscore. The zscore is the ratio of kriging error to the kriging standard deviation. The cross validation was performed using GEOEAS version 1.1. Due to software limitations, not all values in the Nyköping area were used which explains why the statistical parameters for the actual values in table 4.1 are not identical to figure 3-1.

Table 4-1. *Comparison of pT estimates calculated by ordinary kriging to actual values (Nyköping SGU Well Data).*

	Actual value	Estimated value	Kriging σ	Kriging error	Zscore
n	1000	1000	1000	1000	1000
m	5.29	5.32	0.67	-0.023	-0.032
min	7.56	7.19	0.59	-2.27	-3.31
Q1	5.74	5.65	0.65	-0.45	-0.67
M	5.34	5.34	0.68	-0.033	-0.051
Q3	4.86	4.98	0.69	0.42	0.63
max	2.93	3.33	0.85	2.42	3.67
σ	0.66	0.31	0.03	0.68	1.021

Table 4.2. *Comparison of pT estimates calculated by ordinary kriging to actual values (Örnsköldsvik SGU Well Data).*

	Actual value	Estimated value	Kriging σ	Kriging error	Zscore
n	986	986	986	986	986
m	5.17	5.17	0.61	-0.006	-0.012
min	7.51	6.32	0.48	-2.00	-3.66
Q1	5.58	5.36	0.59	-0.411	-0.66
M	5.19	5.18	0.63	0.014	0.023
Q3	4.74	5.00	0.64	0.376	0.63
max	3.41	4.23	0.83	2.75	4.45
σ	0.57	0.30	0.04	0.555	0.91

The smoothing effect from kriging is obvious from the statistics with a standard deviation of estimated values of about half of the actual values.

The mean value of the kriging error is close to 0 which indicates unbiased results. The kriging error standard deviation is very close to the standard deviation of the actual values for both areas.

Ideally, the standard deviation of the zscore is 1 (Delhomme, 1978). The zscore standard deviation can be utilised for studying the fit of the variogram. For both areas, this value is very close to 1, indicating a good fit of the chosen model.

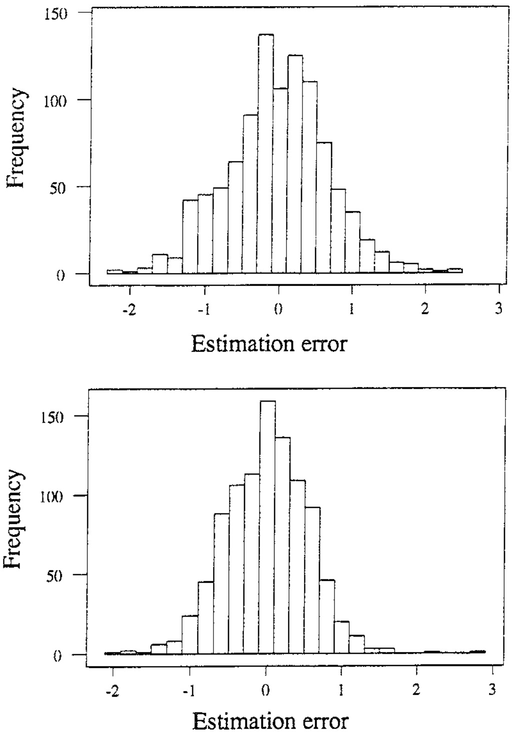


Figure 4-6. *Histograms of the estimation error for the Nyköping area (top) and the Örnsköldsvik area (bottom) indicating low bias in the estimates.*

Histograms of the estimation errors are shown in figure 4-6. Estimation errors are defined as:

$$error = r = \hat{v} - v \tag{4.1}$$

where v is the true value and $\hat{v}$ is the estimated value at each location. Both histograms are fairly symmetrical, with means close to zero. The skewness is also low, 0.043 and 0.054 for the Nyköping area and the Örnsköldsvik area respectively. Taken together, these properties of the histograms indicate a low level of bias in the estimates which was also indicated by the kriging average error.

Also scatterplots can be used to evaluate the estimates. The closer the data samples plot to the 45 degree solid line in figure 4-7, the less bias is in the estimates. For the Nyköping data, it seems like the data cloud is rotated 45° from the line. Even though the Örnsköldsvik data in figure 4-7 falls closer to 45° line, the major axis of the data cloud deviates from the 45° line. The large differences in standard deviation between the actual and the estimated values can at least partially account for this.

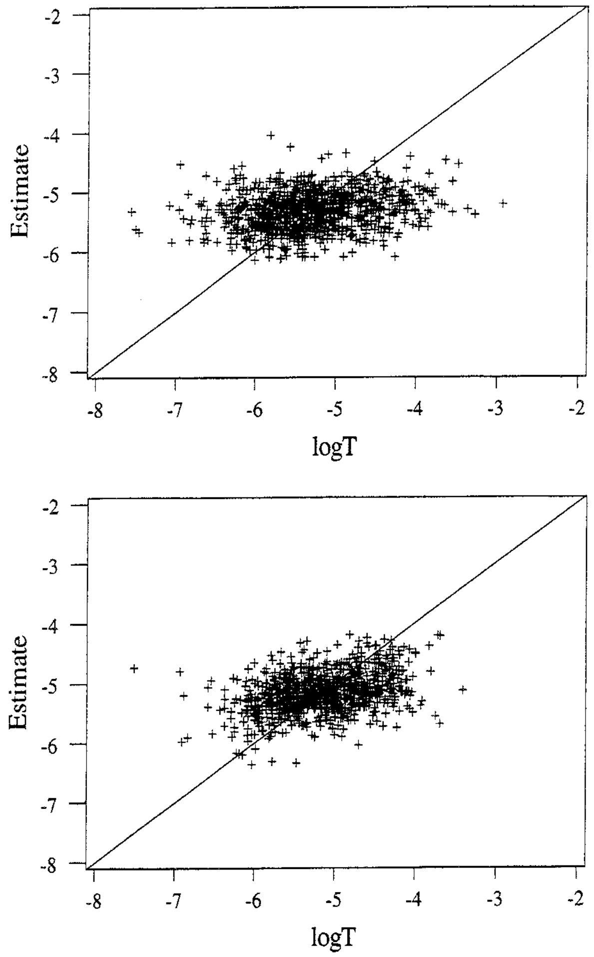


Figure 4-7. *Scatterplots of the true value versus the estimated value for the Nyköping area (top) and the Örnsköldsvik area (bottom).*

4.8 Estimation of block transmissivity

As the final step of the 2D-geostatistics, block transmissivity was estimated from the SGU well data. The purpose of performing block kriging is to compare the pT values obtained from the GEOTAB data with the pT values obtained from the SGU data.

The results of block kriging is dependent on the spatial correlation and the search strategy, e.g. the size and shape of the search neighbourhood and the number of samples. The search neighbourhood can be set slightly larger than the average distance between data points for irregularly spaced data (Isaaks and Srivastava, 1989). The number of data samples used in the estimations is limited by the small number of samples available in the vicinity of the sites. For both sites, a search window was established to include at least 12 data samples.

The two blocks estimated correspond to the Gideå and Fjällveden study sites. In block kriging the blocks are discretized into a number of points, in this case 4x4 points, and then the linear average of the estimates at these points give the estimate of the block.

The block corresponding to the Fjällveden study site is 2000 x 1500 metres and centered at x=1565000, y=6534250. The kriging estimate for *pT* for this block is 5.09 with a kσ of 0.22 compared to the m=4.93 and M=5.11 computed from the GEOTAB data. The block corresponding to the Gideå study site is also 2000x1500 metres and centered at x=1663500, y=7045200. The block estimate of *pT* using a search radius 1.5 times larger than the average distance between data samples, was computed to 4.93 (with a kσ of 0.21) compared to the m=4.88 and M=4.95 computed from the GEOTAB data. The results are both close to the M of the area computed from the GEOTAB data.

5 Depth Dependence

A trend, in general, can be described by a global function that relates the expected value to its spatial position. The type of bedrock considered in this study is not expected to show any structure-dependent systematic increase in fracture intensity. Hence, the primary trend to consider is whether it is possible to detect any regular variation of hydraulic conductivity with vertical depth. Many published studies have indicated a decrease with depth (e.g. Davis and Turk, 1964; Carlsson & Olsson, 1977; 1993) but a considerable scatter is generally detected both for the rock mass and for known conductive zones. On the other hand, some investigators argue that it is not reasonable to expect any regular trend below an upper layer of the bedrock (e.g. Voss and Andersson, 1991).

For the SKB study areas, regression analyses have been carried out on data from 3 to 30 m long sections. The same power function has been fitted to all conductivity data sets.

$$K = K_0 z^{-b} \tag{5.1}$$

where K is the effective hydraulic conductivity, K_0 is a reference value of conductivity at the surface, z is the vertical depth below ground surface and b is a constant.

As an alternative approach, Gustafson et al. (1989), when evaluating data from the Äspö area, assumed an exponential function:

$$K = K_0 10^{-z/c} \tag{5.2}$$

where c is a constant.

These two functions have been used for curve fitting by many other investigators as well. Several authors have discussed the observed decrease in conductivity with depth in relation to a measured rock stress increase with depth. For example, Carlsson and Olsson (1993) compared in-situ measured conductivity within the upper 500 m of crystalline bedrock in Sweden with theoretical stress-conductivity relationships and suggested a power function of the type given in equation 5.1 to describe the depth dependence. Although it is well known that there is a strong relationship between effective rock stress and fracture conductivity (Raven and Gale, 1985; Dershowitz et al., 1991) it is likely that other mechanisms and processes also affect the variation in hydraulic conductivity over a depth range of hundreds to thousands of metres.

More complex models of permeability variation with depth than equations 5.1 and 5.2 have been proposed by Oda et al. (1989) and Wei et al. (1995). These two models are similar and based on the assumption that the magnitude of permeability to a great extent is governed by the rock stress magnitude but also influenced by the fracture properties. The underlying assumption is that the fracture apertures in the bedrock decrease with increasing depth and stress in accordance with a hyperbolic relationship as suggested by Bandis et al. (1983) on the basis of laboratory tests on rock joints. The model by Oda et al. (1989) was expressed as:

$$k_{ij} = \lambda \cdot \frac{\langle {t_0}^3 \rangle \cdot N^{(q)}/h}{\langle |n \cdot q| \rangle} \cdot \left(1 - \frac{z}{z + \frac{h}{c \cdot \gamma'}} \right)^3 \cdot (\delta_{ij} - N_{ij}) \tag{5.3}$$

Where λ is the connectivity, t_0 is the fracture aperture at the surface (z = 0), *h* is a measure of the fracture stiffness, *c* is an aspect ratio (a measure of the fracture shape) and γ' is the effective unit weight of the rock. $N^{(q)}/h$ is the number of fractures crossed by a unit length of a scan line with a direction parallel to *q*, which is a direction vector.

5.1 Depth dependence analysis

In the first part of this study we have investigated whether there are any detectable differences between the GEOTAB data for the upper 200 m and data from larger depths. The results are summarised in table 5.1. The data from Gideå give a mean value for -log *K* as 7.95 above 200 m and 9.40 below 200 m, i.e. the difference is 1.5 orders of magnitude. For the Fjällveden site, the mean values are 8.16 (above 200 m) and 9.77 (below 200 m), i.e. about the same difference.

The GEOTAB data contain data from the measurement limit and upwards. The fact that the measurement limit is used as a data value will obviously bias the results. However, for the studied sites a small number of measurements are equal to the measurement limit, and the expected error is hence not very large.

Table 5-1. *Descriptive statistics for different test sections. Values are (-logK).*

Section	**Mean**	**Median**	**Variance**
Gideå, all data	8.80	8.89	2.57
Gideå, 0-200 m	7.95	7.75	2.41
Gideå, >200 m	9.40	9.53	1.81
Fjällveden, all data	9.07	9.21	2.23
Fjällveden, 0-200 m	8.16	8.18	2.10
Fjällveden, >200 m	9.77	9.87	1.22

A moving average analysis using all available data from the two sites was carried out. The analysis utilizes only two data values for each average value calculated to better visualize the scatter variability with depth.

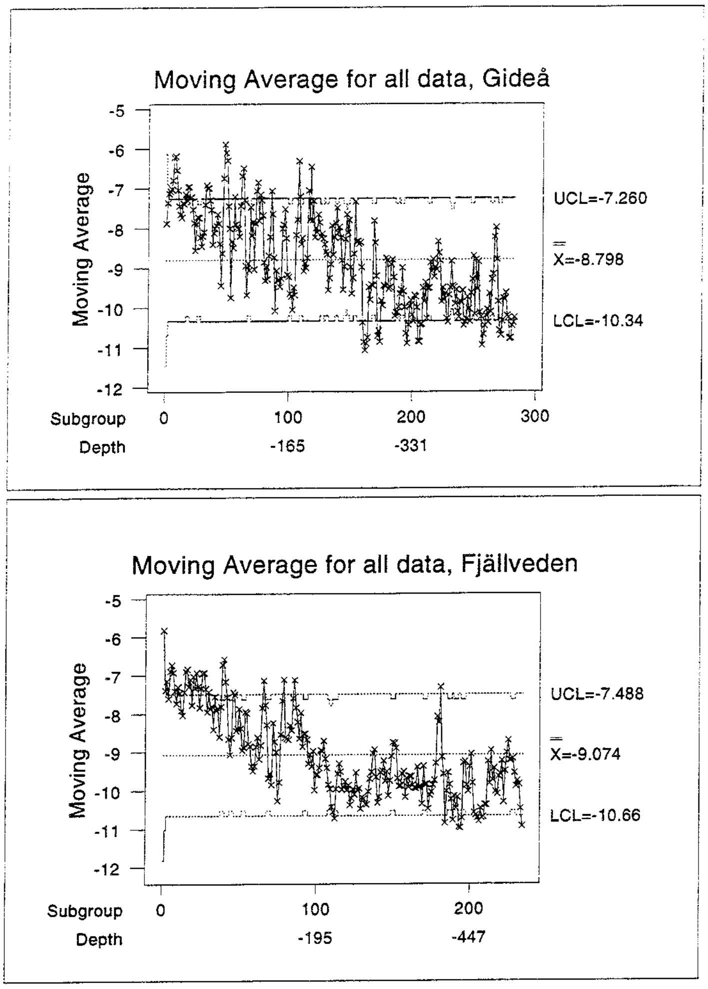


Figure 5-1. *Moving average for all data (logK) at Gideå (top) and Fjällveden.*

From the results for each site it is rather clear that there is a zone where the hydraulic conductivity changes considerably (figure 5-1). It can be noticed that at the Gideå site this change is occurring at a larger depth than at the Fjällveden site. A linear regression analysis for Gideå gives a decrease in the hydraulic conductivity by one order of magnitude for every 140 m within the surface layer. This layer is at the Gideå site 280 m thick. At Fjällveden the decrease is one order of magnitude for every 100 m and here the surface layer is 200 m thick. Below these levels the decrease with depth is very slow. In Gideå the hydraulic conductivity decreases by one order of magnitude for around 1000 m and in Fjällveden the same change is observed over a length of 8000 m.

5.1.1 Mathematical models

In the second part of the work we have used a modified version of the model by Oda et al. (1989) to match the depth-dependent data from

Gideå and Fjällveden. The equation derived by Oda et al. (1989) is in tensor form and our immediate interest is in one dimension only.

$$k = \lambda \cdot t_0^{\,3} \cdot c_f \cdot \left(1 - \frac{z}{z + \frac{h}{c \cdot \gamma}}\right)^3 \tag{5.4}$$

We have considered the parameters fracture connectivity, hydraulic aperture of a fracture at the surface and fracture frequency (Oda et al., 1989) to be constant for a single borehole in this analysis. Hence, we express the first part of equation (5.4) as a new constant A, which represents a "cubic law conductivity" at the surface.

Oda et al. (1989) only accounted for the vertical stress component as expressed as the weight of the overlying rock. We have considered it more appropriate to take the horizontal stresses into account as well, since there is not any information about the orientations of the water-bearing fractures in the boreholes. Hence, the expression within the brackets can be expressed as a function of the average, effective rock stress.

$$K = A \cdot \left(1 - \frac{B + C \cdot z}{D + B + C \cdot z}\right)^3 \tag{5.5}$$

where B and C are two constants describing the average effective rock stress versus depth, and D is the ratio h/c. The aperture value at the surface was in the study by Oda et al. (1989) selected as 200 microns. Adopting the range of values for h from Bandis et al. (1983), 200-2000 MPa, and estimating the typical range of fracture radii to be 0.5-5 m, we obtain a possible variation in D between 0.008 and 0.8.

The hydraulic fracturing measurements in Gi1, Gideå, are the only available data on the stress situation for these two sites. As a comparison we studied the hydrofracturing data from the Fennoscandian Rock Stress Data Base, FRSDB (Stephansson, 1993). Assuming a hydrostatic fluid pressure in the rock and a groundwater level close to the surface, B and C for Gideå are 1.7 and 0.017, respectively. The corresponding values from FRSDB are 1.7 and 0.020, respectively. We therefore concluded that the Gideå data are representative for Sweden and we decided to use them for Fjällveden as well, for simplicity.

For the connectivity, we chose the upper limit suggested by Oda et al. (1989), 1/12, which corresponds to fractures of infinite length. One parameter of special interest is the fracture frequency since it is easy to measure from surface investigations. An average fracture frequency of 3.0 fractures per metre was selected as representative both for Gideå and Fjällveden, which together with the assumptions above gives A as 2×10^{-5} m/s.

A total of 13 boreholes at the Gideå site and 10 boreholes at the Fjällveden site were evaluated in MATLAB. The MATLAB code did an unconstrained non-linear optimization that provided a best fit curve to the data from each borehole. The optimization gave a value of the constant D in equation 5.5 when A, B and C were given as input. The produced average values of D for the boreholes at Gideå is 0.335 and at Fjällveden 0.283. The produced values of D are shown in table 5-2.

Table 5-2. *Estimated D values (see equation 3.2) for the different boreholes at the Gideå and Fjällveden sites.*

Gideå borehole	D	Fjällveden borehole	D
Gi 1	*0.3436*	*Fj 1*	*0.1414*
Gi 2	*0.4496*	*Fj 2*	*0.2915*
Gi 3	*0.2947*	*Fj 3*	*0.3101*
Gi 4	*0.326*	*Fj 4*	*0.3057*
Gi 5	*0.4541*	*Fj 5*	*0.2261*
Gi 6	*0.166*	*Fj 6*	*0.2912*
Gi 7	*0.3494*	*Fj 7*	*0.2451*
Gi 8	*0.2477*	*Fj 8*	*0.2422*
Gi 9	*0.4346*	*Fj 9*	*0.2518*
Gi 10	*0.261*	*Fj 14*	*0.5227*
Gi 11	*0.2589*		
Gi 12	*0.3564*		
Gi 13	*0.4146*		

All D values obtained are within the range of theoretical values given above. The lower D values for Fjällveden reflect the generally lower conductivities at this site.

In figure 5-2, a compilation of data from four boreholes at Gideå is shown together with three types of depth dependence models. It can be observed that the scatter in measured hydraulic conductivity data is very large compared to the difference between the depth-dependence models. The modified model by Oda et al. (1989) has a slightly better regression coefficient than the other two models, but the difference is small and the general behaviour of the fitted curves may be a more sensitive parameter.

Sensitivity tests of the model in equation 5.5 were conducted by changing the constants one at a time. A higher value of A gives a more bended curve with a larger surface value of the hydraulic conductivity. The curve also has a more exponential behaviour and a relatively fast decrease in the hydraulic conductivity is observed. The curve is rather sensitive to the stress related constants, B and C, especially to the stress gradient C. A high B value and a low C value gives the curve a more linear and steep behaviour. However, the model is most sensitive to variations in D. We tested the range of the theoretical D value and found that the curve moves from a surface value of around 10^{-12} m/s to the much higher value of around 10^{-6} m/s.

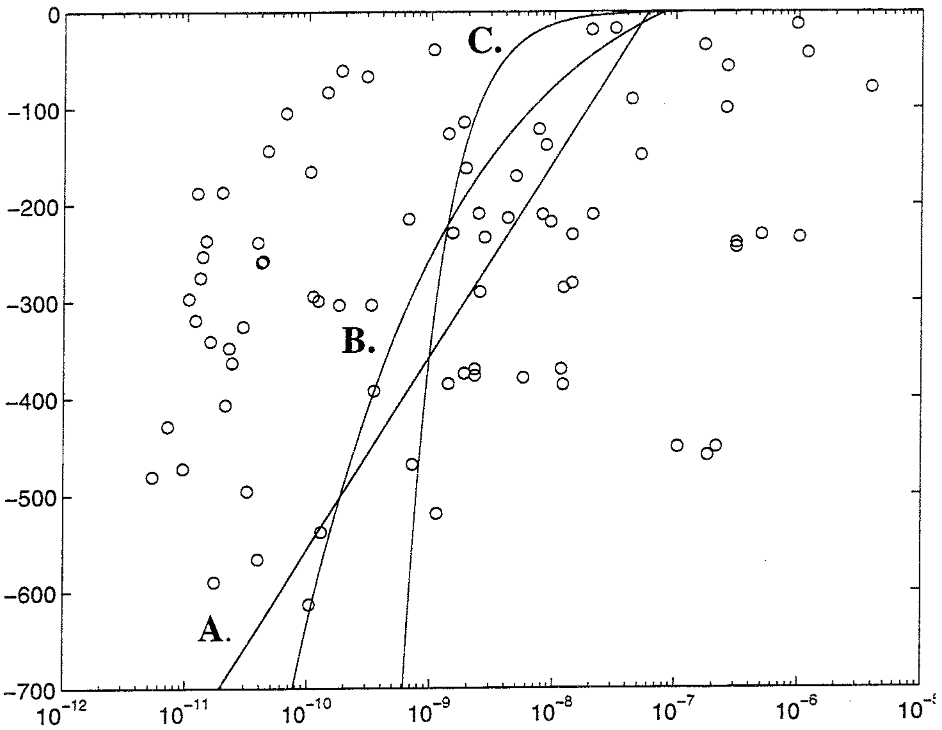


Figure 5-2. Models of depth dependence at the Gideå study site. The A curve represents the exponential function $K=K_0 10^{-z/c}$*, the B curve represents the model by Oda et al. (1989) and the C curve represents the power function* $K=K_0 z^{-b}$ *(The A and C curves are examples chosen to correspond with the B curve).*

5.2 Depth trend in SGU data

The depth dependence for *Q/d* has also been studied for the SGU well data. From these data it might be possible to study the trends for the uppermost 200 metres of the rock. The analysis includes data not only from the Nyköping and Örnsköldsvik areas but also from the Göteborg area for comparison. Table 5-3 and 5-4 show descriptive statistics for these three areas.

Table 5-3. Descriptive statistics for well depth.

	Nyköping all wells	Nyköping energy wells	Örnsköldsvik all wells	Örnsköldsvik energy wells	Göteborg all wells
n	1583	193	986	191	5058
mean	86	151	89	131	75
median	80	156	90	144	70

Table 5-4. Descriptive statistics for well yield (Q).

	Nyköping all wells	Nyköping energy wells	Örnsköldsvik all wells	Örnsköldsvik energy wells	Göteborg all wells
n	1583	193	986	191	5058
mean	1430	3495	1505	3048	1287
median	430	700	707	1000	480

Water wells are mainly private property, supplying water to a single or a few households. The are drilled to a depth sufficient to supply the consumer with enough water. The depth for energy wells on the other hand, is not determined by the hydraulic properties of the aquifer.

A factor that probably acts against a possible depth trend in the SGU data, is the bias caused by the well driller. It seems fair to assume that wells are drilled until they provide 'sufficient' amounts of water, i.e. the yield controls the depth of the well. In consequence, wells that are drilled in less conductive parts of the rock will generally reach larger depths. This should be valid to some 'cut-off' limit where the well driller considers the well as dry and retries at some other location. The 'cut-off' limit is based on the experience of the well driller and the specifications of the equipment but well depths of 120-150 metres can be assumed to be the limit. The bias caused by the well driller might be obscured to some extent by the large scatter in the data.

To study the possible bias, yield (*Q*) for all wells is plotted against well depth for the three areas, where the well depth is classed into 20-metre intervals. The graphs are shown below in figure 5-3a-c.

Both the Nyköping and Göteborg data show a decreasing *Q* for greater well depths down to class six, which is the 100-120 metre interval. At greater depths there is no decreasing trend for *Q*. The Pearson correlation coefficient or a regression analysis verifies this behaviour. For the Gideå area, the depth trend even appears to be periodical with an increasing trend for the upper 80 metres.

These results support the hypothesis that wells in less conductive parts of the rock are drilled to greater depths, and further, if the yield is low near the surface, it remains low at greater depths.

To further evaluate the well driller bias, energy wells are studied as a subsample in the Nyköping and Örnsköldsvik areas. These energy wells are generally deeper than ordinary wells and the yield is an unimportant issue during the construction of the well. Therefore, energy wells are not biased by the driller concerning yield.

The descriptive statistics for energy wells (table 5-3 and 5-4) indicate that the ratio *Q/d* for all wells and the energy wells are in close agreement for

The descriptive statistics for energy wells (table 5-3 and 5-4) indicate that the ratio *Q/d* for all wells and the energy wells are in close agreement for both areas. This will further support the hypothesis that the bias in the SGU well data induced by the well driller obscures the depth trend and must be compensated for if these data are to be used for detecting such a trend.

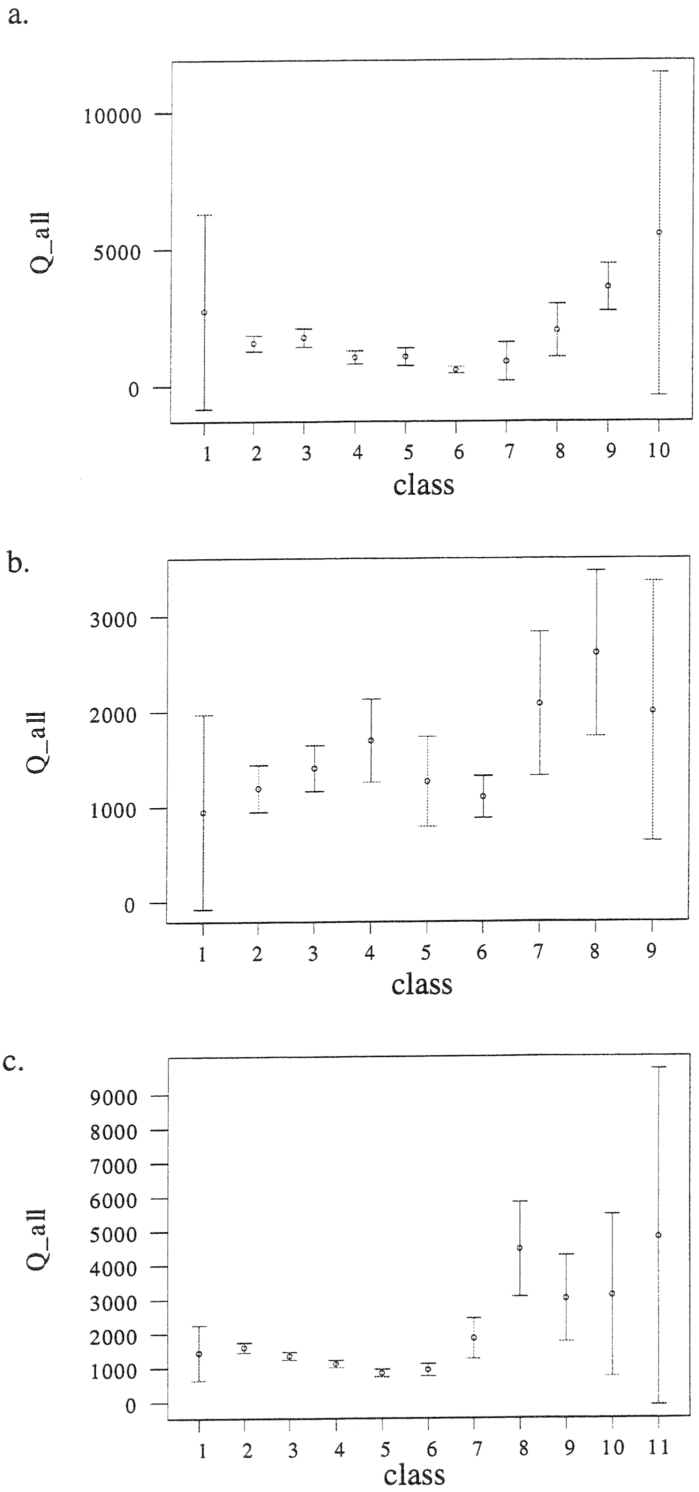


***Figure 5-3**. Interval plots of Q with the 95% confidence interval indicated versus depth where each class represents 20 metre intervals (a. the Nyköping area, b. the Gideå area, and c. the Göteborg area). Please note the different scales on the y-axes.*

6 Discussion and conclusions

6.1 SGU well data

It is probably useful to bear in mind the geology of the study areas when assessing the results. The bedrock in the Nyköping area consists dominantly of granitoids, and fairly homogeneous metasediments. The Örnsköldsvik area on the other hand, consists of more heterogeneous and metamorphosed rocks, including greywackes, shists, and sedimentary gneisses, commonly with strong migmatization.

For the two studied areas, SGU well data are useful for estimations of hydrogeologic parameters such as transmissivity using a statistical approach. The SGU well data provide a readily accessible tool to gain understanding also of the spatial behaviour of the studied parameter. Although spatial clustering existed in the SGU data, it is not assumed to bias the results to any large extent. The results from the block kriging provided plausible results which was, in part, indicated by the exploratory statistics. The results also imply that for both the Nyköping and the Örnsköldsvik area, there is a large data variability within short distances, not uncommon when dealing with hydraulic properties of fractured rock.

6.2 Depth dependence

A general feature observed in studies of hydraulic conductivity versus depth in different parts of the Swedish Precambrian basement is the comparatively high permeability within the uppermost 100-300 m. This is believed to depend on near-surface fracturing due to stress relief caused by erosion and isostatic rebound after glaciation, enhanced by weathering and solution of fracture minerals.

The depth to which we can expect a higher conductivity, and a clear decreasing trend, is hence likely to be site-specific. For the Fjällveden and Gideå sites, this upper zone was approximately 200 and 280 m thick, respectively. Below this upper zone, the depth trend was extremely vague. Both the sites in this study showed a very slow decrease.

The best choice of a model appeared, from the data analysis made, to be an exponential function with different exponents for the upper and lower part. This corresponds to our assumption that different mechanisms and processes govern the magnitude of conductivity over a depth range of at least 500 m. A model which is more correct in terms of mechanical fracture behaviour match the measured data somewhat better than more empirical models. However, since it was found to be difficult to accurately assign values of the bedrock-specific constants, this model is not considered feasible for predictive purposes.

Difficulties connected to the use of the SGU well data to study a possible depth has trend have been detected. Primarily, data include a bias which must be compensated for. The bias is introduced by the well driller and the equipment used, which depends on the fact that wells in less conductive parts of the rock are drilled to greater depths. It is also fair to assume that if the yield is low near the surface, it remains low at greater depths.

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