Technical Report

TR-98-12

Geological-structural models used in SR 97

Uncertainty analysis

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Oktober 1998

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Keywords: Geology, structural model, uncertainty, SR 97, Äspö, Finnsjön, Gideå, site characterisation, safety analysis

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

Information on SKB technical reports from1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40), 1990 (TR 90-46), 1991 (TR 91-64), 1992 (TR 92-46), 1993 (TR 93-34), 1994 (TR 94-33), 1995 (TR 95-37) and 1996 (TR 96-25) is available through SKB.

ABSTRACT

The uncertainty of geological-structural models was studied for the three sites in SR 97, called Aberg, Beberg and Ceberg. The evaluation covered both regional and site scale models, the emphasis being placed on fracture zones in the site scale. Uncertainty is a natural feature of all geoscientific investigations. It originates from measurements (errors in data, sampling limitations, scale variation) and conceptualisation (structural geometries and properties, ambiguous geometric or parametric solutions) to name the major ones. The structures of A-, B- and Ceberg are fracture zones of varying types. No major differences in their conceptualisation between the sites were noted. One source of uncertainty in the site models is the non-existence of fracture and zone information in the scale from 10 to 300 - 1000 m.

At Aberg the development of the regional model has been performed very thoroughly. At the site scale one major source of uncertainty is that a clear definition of the target area is missing. Structures encountered in the boreholes are well explained and an interdisciplinary approach in interpretation have taken place.

Beberg and Ceberg regional models contain relatively large uncertainties due to the investigation methodology and experience available at that time. In site scale six additional structures were proposed both to Beberg and Ceberg to variant analysis of these sites. Both sites include uncertainty in the form of many non-interpreted fractured sections along the boreholes.

Statistical analysis gives high occurrences of structures for all three sites: typically 20 - 30 structures/km^3. Aberg has highest structural frequency, Beberg comes next and Ceberg has the lowest. The borehole configuration, orientations and surveying goals were inspected to find whether preferences or factors causing bias were present. Data from Aberg supports the conclusion that Äspö subvolume would be an anomalously fractured, tectonised unit of its own. This means that the borehole investigations may not represent the site outside the covered volume.

Finally five different uncertainty indices were calculated for regional and site scale, borehole data, representativity and structural knowledge. High uncertainty exists for all site volumes in terms of structural knowledge. Uncertainty in representativity is rather high at Aberg. Beberg and Ceberg has high uncertainty indices when regional scale models are concerned.

SAMMANFATTNING

I säkerhetsanalysen SR 97 används platsspecifika förhållanden för tre platser, kallade Aberg, Beberg och Ceberg. Osäkerheten i de geologiska strukturmodeller som upprättats för respektive plats har här studerats. Utvärderingen omfattar både den regionala och den lokala skalan med tyngdpunkten på sprickzoner i den lokala skalan. Osäkerhet är en naturlig del av alla geovetenskapliga undersökningar. Detta beror dels på mätningarna (fel i data, begränsningar vid provtagning, skalproblem), dels på konceptualisering (geometri och egenskaper för strukturer, mångtydiga geometriska eller parametriska lösningar). Strukturerna för Aberg, Beberg och Ceberg är sprickzoner av olika slag. Inga större skillnader vid konceptualisering av strukturer har observerats för stukturmodellerna för de olika platserna. En källa till osäkerhet i den lokala skalan är frånvaron av sprick- och sprickzonsinformation i skalan mellan 10 och 300 - 1000 m.

För Aberg har ett omfattande arbete lagts ner på att utveckla en regional beskrivning av strukturer. En källa till osäkerhet i den lokala skalan är dock avsaknaden av ett tydligt definierat undersökningsområde. De strukturer som observeras i borrhålen förklaras väl av modellen. Denna har dessutom utvecklats genom samverkan mellan olika geovetenskapliga discipliner.

De regionala beskrivningarna för Beberg och Ceberg innehåller relativt stora osäkerheter beroende på den metodik och den erfarenhet som var tillgänglig vid tiden för undersökningarna. I den lokala skalan föreslås i denna studie sammanlagt ytterliggare 12 strukturer för kommande variationsanalyser inom SR 97. Båda platserna har ett flertal sprickzoner i borrhålssektioner som inte förklaras med de existerande strukturmodellerna.

Statistisk analys ger hög förekomst av strukturer på samtliga tre platser, typiskt 20 - 30 strukturer per km^3. Aberg har den högsta strukturella frekvensen, följt av Beberg och Ceberg. Borrhålskonfiguration, borrhålsorientering samt undersökningsmål studerades. Data från Aberg stödjer slutsatsen att Äspö subvolumen kunde vara en tektoniserad egen enhet med anomalisk sprickfrekvens. För Aberg betyder det att de geometriskt begränsade undersökningarna inte nödvändigtvis är representativa för hela platsen.

Slutligen har fem olika osäkerhetsindex beräknats i denna studie för den regionala och den lokala skalan. Dessa innefattar undersökningsmetoder, strukturer i borrhål, representativitet av data och kunskap om strukturer. När det gäller kännedom om strukturer finns en hög osäkerhet för samtliga platser. När det gäller representativitet är osäkerheten relativt stor för Aberg. Beberg och Ceberg har höga osäkerhetsindex när det gäller de regionala strukturmodellerna.

EXECUTIVE SUMMARY

The uncertainty of geological-structural models was studied for the ABCeberg sites. The evaluation covered both regional and site scale models, the emphasis being placed on fracture zones and on the site scale. Uncertainty is a natural feature of all geoscientific investigations. *One* part of uncertainty is issues *related to conceptualisation*: selected geological concepts, structural geometry and property concepts employed, and inconsistency may exist in the manner in which the concepts have been applied. The *second* type of uncertainty arises *from errors* in data, in interpretation and in data integration. The *third* type of uncertainty arises *from the sampling limitations* of the surveying techniques used. To mention *some others*, *scale variability* is also a source of uncertainty. The *sensitivity and detection capability* of measurements in respect to the desired targets vary in a spatial manner throughout the studied volume and in a complicated way. The composite uncertainty is a function of all the factors affecting and methods used.

The techniques used in this study included expert judgement, comparison using tables, assessment of borehole data deterministically and statistically. A comparison of applied conceptualisations have been made between the sites. Additional checks of the original data, methods used and interpretations have been made when possible.

The ABCeberg structures are fracture zones of varying types. No major differences in their conceptualisation were noted between the sites. One source of uncertainty in the site models is the non-existence of fracture and zone information in the scale from 10 to 300 - 1000 m. Except in the case of Aberg, local scale fracture zones are mostly (Ceberg) or completely (Beberg) missing.

At Aberg the development of the regional model has been performed very well since all available surveying methods have been used consistently. The Aberg site model contains 11 zones. One major problem and source of uncertainty is that a clear definition of the target area (i.e. the site) is missing. The characterisation process has profited from the fact that an interdisciplinary approach and the comprehensive integration of geoscientific disciplines has been possible.

The pre-investigation phase model explains 91% of the structures encountered in the boreholes. A review of the model from a later phase (Rhén et al., 1997) shows that only 54% of the structure intersections in the boreholes were explained after excavation (subhorizontal zones of the model were not verified). The statistical method now used for fracture zone analysis gives a high structural density value for Aberg. If interpreted using a statistical model of parallel structures, the structures are situated at 40 m

intervals. No new discrete structures were proposed for the Aberg regional and site models.

Development of the Beberg regional model has used about half of the characterisation techniques that are available today. The Beberg site model contains 14 zones. Six lineaments are proposed for consideration as additional structures. The existence of a deeper seated subhorizontal zone is possible.

The Beberg model fracture zones forms a 3-D system. This was used in statistical analysis and Beberg fracture zone structures seem to have an average separation of 110 - 130 m along each identified main orientation.

Development of the Ceberg regional model also used about half of the characterisation techniques available today. There is uncertainty whether regional fracture zones could be associated with the Ulvödiabase and Revsund granite formations. The Ceberg site model contains 12 zones. The largest uncertainty exists in the form of non-interpreted fractured sections in boreholes KGI03, KGI07, KGI08 and KGI12. These are all located in the southern part of the site.

Some known diabase dykes are proposed as supplementary structures. There is uncertainty whether some diabase dykes have still not been observed by measurements. Altogether six additional structures are proposed to be used in the variation analysis of the Ceberg site.

The model of the Ceberg structures consists in the main of subvertical fracture zones. In addition, a few SE or SSE running zones have been localised. Two 3-D fracture zone systems were analysed statistically. As a consequence of this, the Ceberg fracture zone structures seem to have an average distance of 140 - 160 m between the zones.

Statistical analysis based on fractured sections in the boreholes gives high occurrences of structures for ABCeberg sites: typically 20 - 30 units/km^3. Aberg has the highest structural frequency, Beberg comes next and Ceberg has the lowest. The borehole configuration, orientations and surveying goals were studied to establish whether some preferences or factors causing bias in the statistical results were present.

At the Aberg site, consideration was given to whether the borehole investigations which cover a relatively small volume are representative of site conditions in general. Some auxiliary data from Aberg supports the conclusion that the *Aberg subvolume (i.e. the Äspö volume) forms a separate, individual, anomalously-fractured and tectonised unit.*

Finally, five different uncertainty indices were calculated to indicate quantitatively the degree of knowledge at regional scale, at site scale, of borehole structural data, of representativeness and of structural understanding. A high level of uncertainty exists for all the site volumes in terms of structural knowledge, Aberg has the highest level. Uncertainty about representativeness is also quite high at Aberg. Both Beberg and Ceberg has high uncertainty indices as far as regional scale models are concerned. Borehole data and its structural interpretation has also prevailing uncertainties at relatively high level at Beberg and Ceberg.

In summary for the safety analysis SR 97, it can be stated that the site specific analyses will be based on geologic-structural models which are not fundamentally different in character. The differences found and deterministic structures considered will probably not cause any major effects to the SR 97 consequence analyses. However, a number of additional fracture zones have been proposed to increase realism of the models. They can provide the basis for forthcoming variation analyses within SR 97.

Our final conclusions arise from the statistical fracture zone analysis. The indication that the number of structures is potentially high may need further assessment. *One consequence may be that it is meaningless to consider the established discrete fracture zone models to be a "true" image of the site volume*. Naturally they are the best estimates of the rock mass available at the time of consideration. This conclusion is valid especially when modelling large volumes of rock using only a few boreholes. The second conclusion is that the realism of the models is not markedly increased if supplementary site assessments or updates suggest the existence of a few more zones.

In addition, the geologic-structural interpretation and modelling process should be rearranged to pay attention to the insufficient and limited data available. *Uncertainty analysis techniques and practical visualisation tools should be developed* so that the analysis could run parallel with the model development process in the future.

TABLE OF CONTENTS

A APPENDICES

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The characterisation of geological structures is a matter of essential importance in deep repository studies for the final disposal of spent nuclear fuel. The knowledge acquired is compiled into either two-dimensional (2-D) presentations or nowadays, into three-dimensional (3-D) models of the bedrock. These models describe both the geological processes and data involved, as well as the corresponding spatial distributions and relationships. Lithological and structural models play a central role in site characterisation by means of visualisation, communication of concepts, and data management. The models form the main geometric and parametric platform on which groundwater flow analysis, rock mechanical analysis, supplementary planning and design of repository layout are based. A computerised bedrock model is also an important tool in communicating information to a wider public.

The Swedish Nuclear Fuel Waste Management Company (SKB) is running an extensive safety analysis project called SR 97. The site-specific geoscientific data to be used has come from earlier characterisation work in Sweden. In this analysis, conditions from three different sites have been adopted and described as “Aberg”, “Beberg” and “Ceberg” sites. “Aberg” uses data from the Äspö site, “Beberg” from the Finnsjön site and “Ceberg” from the Gideå site.

A good background to the importance of geological parameters and the use of models in safety analysis can be found in a recent report by Andersson et al. (1996). The issues discussed in connection with geological models are topography, lithology, structural geology, discrete structures at regional, site and local scale and discrete fractures. These are termed in this report as “geological-structural models”. The evaluation allocates highest scores of importance to structures (fracture zones) between local and regional in scale.

Generally speaking, uncertainty studies of geological or structural models are not common in the geoscientific community. In the mining and oil industries the production rates are of crucial commercial interest. The uncertainty and variability of valuable resources are evaluated by means of geostatistics. This also means that the methodology for a wider assessment of uncertainty is poorly developed. Only a very limited number of previous case studies are available as support.

The use of geoscientific models in SKBs safety studies is shown in Figure 1-1. The geological model is the basis upon which other derivative models are built. Each model is supported by its own specific data.

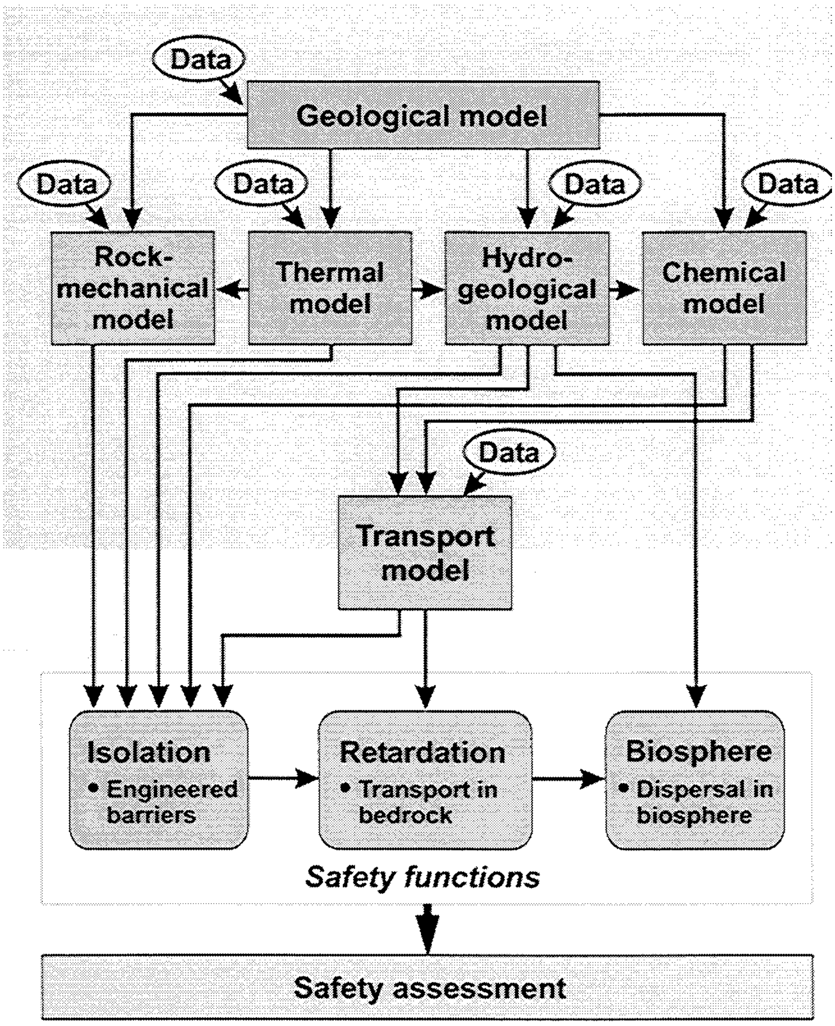


Figure 1-1. Use of geoscientific models in safety assessment (picture by courtesy of SKB).

The main task described in this report is the analysis of the uncertainties in the structural models of Aberg, Beberg and Ceberg. This involved a study of the methods and interpretations applied and scrutiny of the assumptions and concepts that were applied. The task has been twofold: firstly, to analyse the uncertainties at each site separately; and secondly, if possible, to analyse and make comparisons between the ABCeberg sites. For example, it was considered possible that systematic differences might exist between the three sites in

- the concepts applied,
- quantity of data,
- surveying methods,

- site coverage,
- interpretations or
- the use of data recorded.

Alternative structural solutions should be reported and realised if they are supported by the available data or findings. Lithology is a secondary theme and analysed to the extent that is linked to the structural models. Also, in SR 97 certain forms of model input and uncertainty data are used. Some of these are compiled in this work and presented in Appendix A of the report.

Chapters 2 and 3 contain the site independent and common parts of this study. Types of uncertainty are specified with examples. Methods used in uncertainty assessment are discussed in chapter 3. A new method for structural analysis is presented. Chapter 4 presents investigations carried out for each site. Definitions and concepts applied have also been studied in that particular chapter. Chapters 5, 6 and 7 include all the site-specific analyses. Chapter 8 is devoted to comparisons between the sites. Chapter 9 discusses the results and gives conclusive remarks.

The *purpose* of this work *has not been to reinterpret* the site data. The analysis is based on selected and relevant summary reports made available through SKB. Where accessible, digital CAD and other illustrative data has been used. However, in many cases the uncertainties may be traced back to specific data items and problems. For this reason, the items discussed for each site range from details to wider issues.

Other related studies within SR 97 currently in progress are the assessment of hydrogeological conditions at ABCeberg (Walker et al., 1997) and analysis of the uncertainties in hydrogeology and boundary conditions (Follin 1998). Munier et al., (1997) have studied the repository layouts for the three sites. Layouts can also be used in the evaluation of radionuclide transport escape from key areas.

The work on this report has included field trips to Finnsjön (Beberg) and Gideå (Ceberg) sites during late October 1997. The field trips provided an important opportunity to check general geographical site conditions, lithology and locations of special interest.

2 UNCERTAINTY OF STRUCTURAL MODELS

There are many types of uncertainty which exist as a natural feature of the results of geoscientific investigation. In spatial terms they vary from regional to local scale. Conceptualisation and geological preferences form another source of uncertainty. In addition, errors can exist in the original field data as well as in the interpreted structures. Analysis of uncertainty unavoidably highlights many weak details in the data, the argumentation on processing and interpretation, alternatives, additions and so on.

In the following, different issues related to the geological-structural models are discussed. All of them give rise to uncertainties in the models. For a full description, see the completed formal uncertainty questionnaires in Appendix A.1 (Hedin 1997).

Geological concepts:
A clearly-formulated, discussed and well-documented geological concept is of fundamental importance to any site, see for example Olsson et al. 1994. Practically everything in site investigations and interpretations is based on selected concept(s). These include a knowledge of geological evolution - stratigraphy, deformation history, age and cross-cutting relationships - and experience of analogous rock formations. In addition to the overall simplicity or complexity of the rock formation, homogeneity or heterogeneity must also be estimated. Because data is always limited in geoscientific studies, alternative geological concepts should be formulated and tested.

Part of the process of conceptualisation can be what is sometimes termed "geological style" or "preferences". Personal preferences and the making of subjective, non-traceable decisions are examples of this. Usually geological style is intended to make models to look like "real earth" without any hard data being used.

Structural geometry (density, form, extensions, planarity assumption)
Major and minor zones are interpreted with help of direct and indirect observations. Planar, elongated forms with large extension along strike and dip are the main geometrical parameters described and assumed. Usually good connectivity between the zones is supposed. Structures inferred in a deterministic way form the geometrical framework of the study site.

There may be a connection between structural geometry and lithological anisotropy. Metamorphosed rock formations can have strong anisotropy in the form of foliation, layering, banding, veins and fractures. Anisotropy can have an effect on the occurrence and orientation of fracture zones. If anisotropy is likely to exist but it is not well known, it increases uncertainty in the interpretation of data and in the representativeness of the results.

Anisotropy also increases the amount of investigation needed, makes the interpretation of models more difficult and causes errors in interpretation. All these are negative effects. On the other hand, when anisotropy is known it can also improve the predictability of structural extensions. The continuity of a property is greater along an anisotropy axis and predictability may be increased. Also on the positive side is the fact that a smaller number of oriented investigations and boreholes can be used to achieve representative imaging of subsurface conditions. It should be remembered that the degree of anisotropy can vary within the confines of a site and this is a further source of uncertainty.

Structural properties (generic data, discrete data, variability):
Structural units are characterised by their <u>increased</u> degree of fracturing, mechanical discontinuity and permeability. If direct observations on the property are missing, the values given are estimates. Typically, a threshold level is specified to separate fracture zones from the rock mass. The variability in the property and its implications might have been studied.

Errors in data, in the interpretation model, in integration:
Errors ranging from measured data values to erroneous concepts in the integration phase can occur in site characterisation. These errors may have negligible, minor or possibly even major consequences in relation to the model structures. For instance, errors in field data values may change the orientation of an interpreted mafic dyke, or incorrectly-correlated borehole sections may result in a completely false structure description.

Inconsistency and scale problems:
If definitions and concepts are not given, site characterisation may suffer from inconsistency. Applied rules may change over the course of time - such as the fracture frequency limit (cut-off value) used to separate fracture zones from the rock mass. A classical example is a minor structure which is included in a model at later stage because it appears to be an interesting new finding. In such cases, similar findings from earlier investigations should be reconsidered, but often they remain unrecognised.

Geological-structural modelling utilises data and interpretations at many scales - ranging from regional scale (such as 1:1000 000) down to outcrop scale (such as 1:10 - 1:100). Details investigated at small scale explain the larger ones and provide data on properties and geometry with an accuracy which is not possible at larger scales. Moving from a small scale to a larger one is a very typical characterisation procedure which helps to focus limited resources on areas and volumes of further interest.

The issue of scale is also a source of uncertainty. Accuracy and variance of the interpretations of structures are scale variant. The detectability of a lithological body or fracture structure is dependent on the scale at which it is examined. The transfer of structural modelling results (maps, images, lists) between different scales and the superimposition of results obtained at varying scales must be done with great care. For example, a continuous and planar form regional fracture zone may be a discontinuous, undulating multi-part structure at local scale. The combination of results obtained at many different scales into a single entity may lead to a biased total model. Models are normally at their best when they are close to the original scale at which they were composed.

Unknown geometry and properties of structures:
This is a difficult problem which arises from the data sampling limitations of geoscientific surveys. Put simply, "We don't know what we don't know". Model geometries rely largely on indirect interpretations such as lineaments, geophysical anomalies etc. There is no one to one correspondence between interpreted physical values and fracture frequency, for instance.

We can lean on similar previous projects and surveys. Experience is valuable. The best understanding comes from prediction-outcome studies if the geosphere circumstances are comparable.

Unknown structures resulting from the site investigation methodology:
This problem is linked to site coverage, site conditions, methods used, directionality of measurements, plus instrumental and geological noise. Our surveys cover a sub-area or sub-volume for each method. Geological mapping for example is restricted to outcrops and excavations. Geophysical Slingram-type electromagnetic surveys have uncovered volumes between measurement lines and within subsurface below its detection limit. Instrumental noise obscures the geological targets. Geological noise is that part of the signal which cannot be interpreted in the light of available knowledge. Normally the geological noise component is larger than the instrumental.

The composite uncertainty is a function of all the methods used. Analysis requires extensive method by method study of the original observations and measurement data and is very laborious. Currently, no readily-applicable technology or software products exist.

3 METHODS OF UNCERTAINTY ASSESSMENT

3.1 ANALYSIS TECHNIQUES

Different uncertainty types call for varying treatment methods. In the following the existing possibilities are listed first. Further on it is stated what methods have been applied in this particular study.

Uncertainty analysis techniques which are generally available or applied:

Geological concepts:
Expert judgement of concepts, ideas, lithological and deformation history presented in reports; analysis of supporting data and analogues if these exist; documentation of alternative concepts; discussion of the geological style applied (if any such exists); checking whether the presented concept has been applied systematically (for instance, whether age or faulting relationships in structures have been analysed and if they are consistent with the given model geometry).

Structural geometry (density, form, extensions, planarity assumption):
Analysis of the cut-off values of the structure widths, lengths, depth extensions and forms given in the model; comparison against structural data from boreholes; analysis of non-modelled structures found in boreholes; statistical analysis of undulation and bifurcations; statistical analysis of a given structural network in relation to borehole data.

Structural properties (generic data, discrete data, variability):
Analysis of the cut-off values of structural properties; comparison with borehole data; analysis of non-modelled properties in boreholes.

Errors in data, in the interpretation model, in integration:
Checking of original field data from reports and against re-runs in the field; analysis of interpretation models, concepts and sensitivity; alternative modelling tests, error-tree analysis of error propagation effects; expert judgement.

Inconsistency problems:
Comparisons of model structure data from different phases of a project against original data; tabulation of structural model parameters; work on developing new models.

Unknown geometry and properties of structures:
Calculation of possible features which would remain undetected by the investigations carried out; calculation of the limits of detectability for different types of structure (geometry, property); expert judgement.

Unknown structures resulting from the site investigation methodology:
Estimates of individual survey methods can be carried out to a limited extent. Problem (i.e. model structure)-specific scope calculations can be realised on a case-by-case basis.

QUANTIFICATION OF UNCERTAINTIES IN THIS STUDY

Major part of the study has utilised the classical expert review of the site investigation and modelling results. To supplement this, the following treatment of uncertainties has been carried out:

- analysis of concepts and definitions (all sites) in chapter 4.2,
- statistical fracture zone analysis of structural system (all sites) in chapters 5 – 7 covering
  - raw borehole and surface data (all sites),
  - calculations with statistical structural analysis method (all sites),
- error and sensitivity analyses of Ceberg diabases in chapter 7,
- analysis of discrete geological-structural units for Beberg and Ceberg in chapters 6 and 7,
- alternative and additional structures for all sites in chapters 5 - 7 and
- calculation of thematic uncertainty indices for all sites in chapter 8.2.

In addition, the structural-geological models have been compared by statistical means in chapter 8.1.

3.2 STATISTICAL STRUCTURE DENSITY ANALYSIS

The most important subject in the analysis of structural models is the spatial distribution and density of structures. Density means here the number of the structures existing per unit volume. Some questions to be faced: - Are the quantities of discrete fracture zones representative of the particular site conditions?, How many would there be in the whole volume of interest? Or, do our models reflect the real differences between the sites?

A deterministic analysis of the spatial distribution would require a vast and complex re-analysis and reinterpretation of most of the available site data and reports. This is naturally not possible. It can also be argued whether the outcome would be much more realistic than it is now. Quite probably, some improvements could be achieved in the interpretation process, mainly for

Beberg, because much experience in nuclear waste site investigations has been gathered during the last 10 - 20 years and the computerised data processing tools have been improved.

Another possibility is to use statistical estimates and calculations. Borehole data is most suitable for this purpose. The first estimate of the uncertainties in connection with the structures can be made by assessing the number of structural intersections in boreholes and how many of them are incorporated into the current bedrock model. This estimate assumes no a priori knowledge of the structural framework itself. The estimate is only valid for a small volume - the boreholes and their immediate vicinity. Anything outside the drilled boreholes and their geophysical soundings is unknown and speculative.

Another supplementary method was developed and applied in this study. This simulates the fracture zone framework of a given type. The theoretical method is documented here. Data and calculations for ABCeberg are presented in chapters 5.2, 6.2 and 7.2. Consequences and mutual comparisons are analysed in Chapter 8.

The input data used is the locations of the structural sections in boreholes and their mutual separation (measured along the boreholes). This simulation was developed and calibrated for five geometrically-different structural systems. The structures are described by plane surfaces with no thickness. Systems are shown in Figure 3-1 and described as follows.

• System 1 is called a <u>regular cubic 3-D framework model</u>. It has three major fracture zone orientations perpendicular to one other and separated by a constant distance ΔA.

• System 2 is a <u>regular 3-D framework 60° model</u> with three major fracture zone orientations. The angle between the strikes of the two vertical zone orientations is 60 degrees and the third zone orientation is horizontal and perpendicular to the first two. The edge length is constant ΔA.

• System 3 is a <u>regular 3-D framework 30° model</u> with three major fracture zone orientations. The angle between the strikes of the two vertical zone orientations is 30 degrees and the third zone orientation is horizontal and perpendicular to the first two. The edge length is a constant ΔA.

• System 4 is a <u>column 2-D model</u> with two vertical, major fracture zone orientations perpendicular to one another and separated by a constant distance ΔA.

• System 5 is a <u>layer 1-D model</u> with only one major fracture zone orientation. The planar structures are separated by a constant distance ΔA.

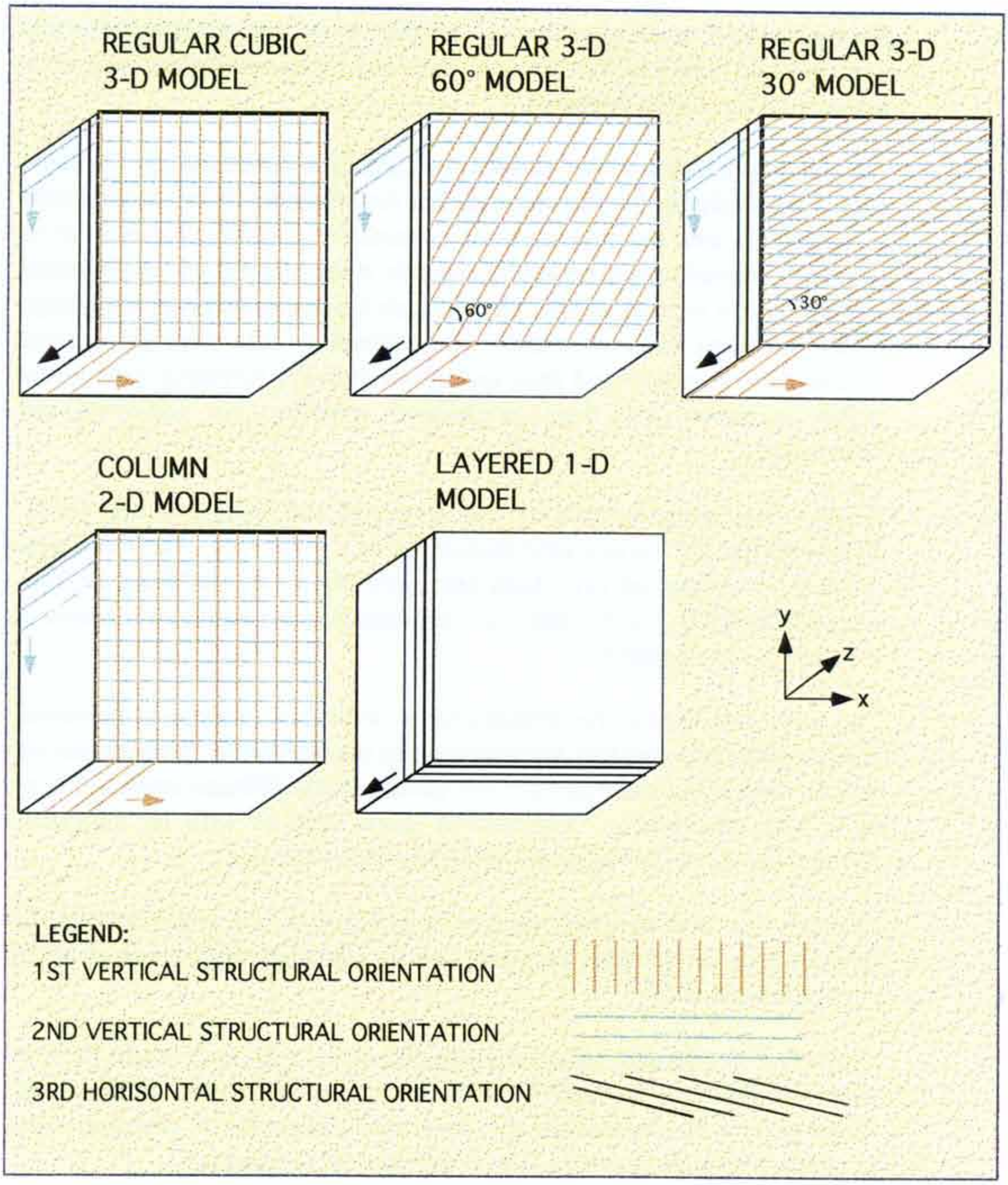


Figure 3-1. Simulation models for the structural systems.

It is to be noted that the distance ΔA is the interval between the intersections of structural planes and is measured along the edge (along the strike) for each plane structure. Regular 30° and 60° models have a shorter perpendicular distance between each set of vertical structure planes.

The theoretical simulations used a borehole sampling line inserted into a selected network structure. The borehole length used was 1000 m, and 100 m was used as the distance between fracture zones in model cases 1, 4 and 5 and as the edge length in model cases 2 and 3. The borehole origin was located at the centre of one block in the XY (East/North) plane. The borehole inclination varied from 0 to 90 degrees with a step of 10 degrees and the azimuth varied from 0 to 180 degrees with a step of 10 degrees. The azimuths from 180 to 360 degrees were not considered as the Y-axis (pointing North) is the system's axis of symmetry. Figure 3-2 illustrates the calculations.

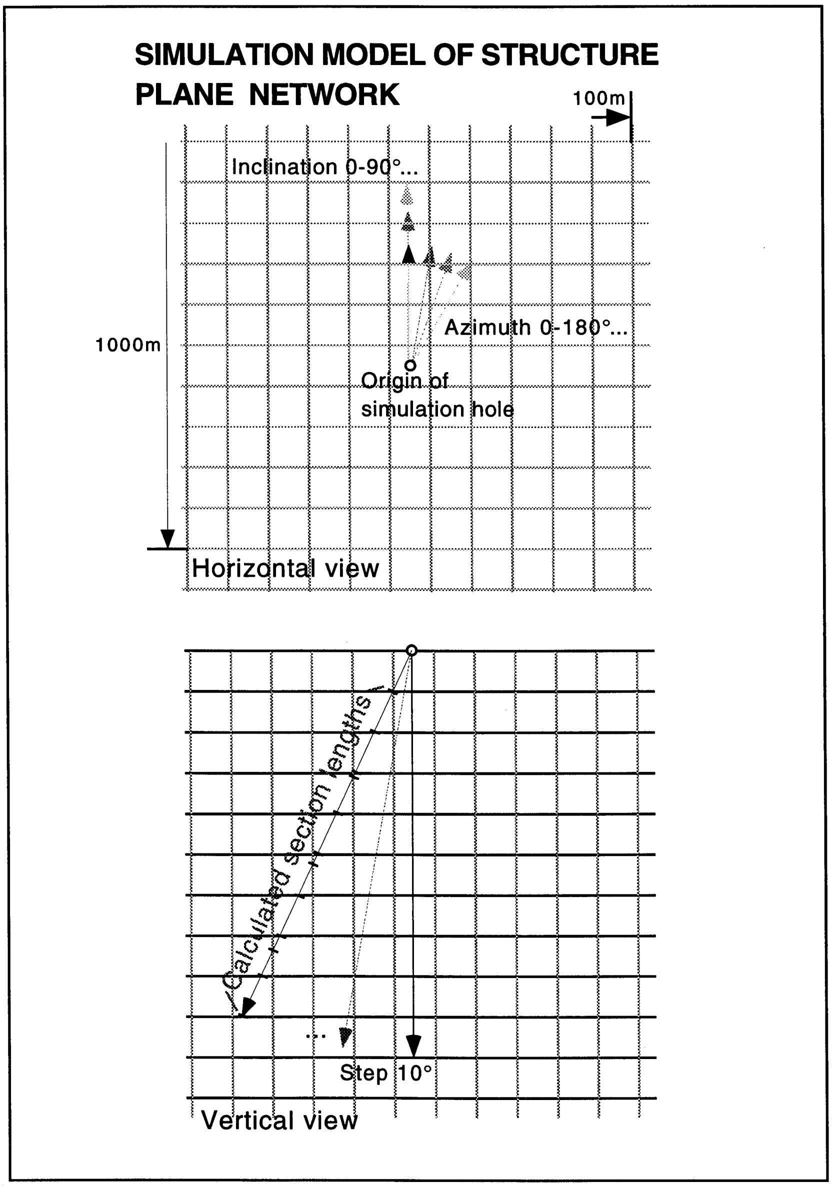


Figure 3-2. Model used in structural density analysis.

The data values used in analysis have been the partial lengths between structure midpoints in the boreholes. The effects of artificial start and end sections caused by finite borehole lengths (truncated sampling lines) were also studied. The cumulative lengths were plotted and 50% cumulative values were calculated for the borehole set. Normal and log-normal distributions were analysed as well as the statistical representativity of the sample population.

Figure 3-3 exemplifies the theoretical simulation results with two systems. Cumulative 50% plot values are the main values used. The distribution of the values may be characteristic for each system also.

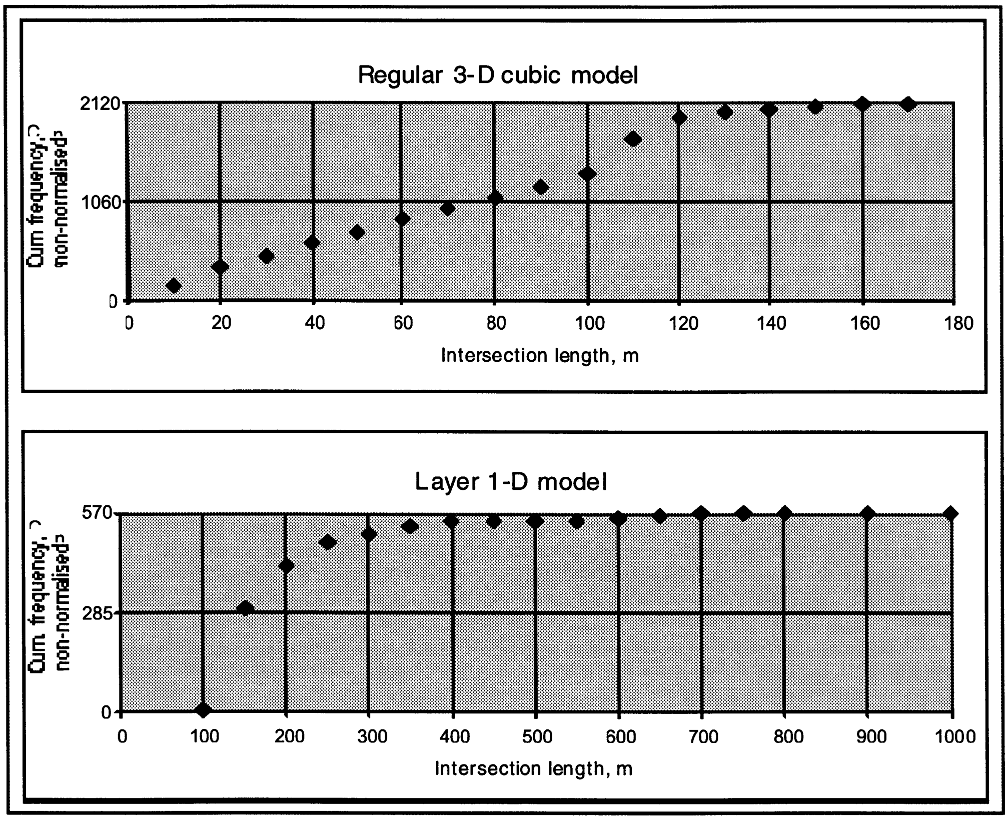


Figure 3-3. Intersection length distributions with two example systems (edge lengths ΔA were 100 m).

The following relationship between the average distance (= 50% cumulative plot value, geometric mean) between fractured sections ΔL and mutual structure distance interval ΔA was obtained by theoretical simulations:

Regular 3-D cubic model:	$\Delta A = 1.4 \cdot \Delta L$	(std.dev of ΔL was 0.40ΔL)
Regular 3-D 60° model:	$\Delta A = 1.6 \cdot \Delta L$	(std.dev of ΔL was 0.37ΔL)
Regular 3-D 30° model:	$\Delta A = 2.3 \cdot \Delta L$	(std.dev of ΔL was 0.31ΔL)
Column 2-D model:	$\Delta A = 0.9 \cdot \Delta L$	(std.dev of ΔL was 0.74ΔL)
Layer 1-D model:	$\Delta A = 0.56 \cdot \Delta L$	(std.dev of ΔL was 1.05ΔL)

The following example clarifies the practical application. Assume that a site volume of 1.0 km^3 with size 1.0 • 1.0 • 1.0 km has an interpreted regular 3-D 60° system. This means that there are two subvertical structural orientations which have an intersection angle close to 60° and a single subhorizontal. All the orientations have the same assumed or interpreted frequency of occurrence in the rock mass. Let us assume that the calculation of the average lengths from the borehole data gives a ΔL value of 100 m. The average structure distance is then 160 m. The regular 3-D 60° model is skewed in its geometrical form and the number of the structures crossing the test volume varies for each volume boundary orientation. With 100 m structure separation there are 35 planes intersecting the 1 km^3 volume. Some planes only have a small intersecting trace, some are longer than 1 km. But on average, a total of 22 structures having a length of 1 km (area 1km^2) or more intersect the test volume when ΔA is 160 m.

The layer-like 1-D structural model yields a ΔA of 56 m when ΔL is 100 m. Similarly there are on average 19 structures in the rock volume of 1.0 km^3. In the case of a layered structural system the lengths of intervals between the intersections are naturally longer than in reality. In fact, on average, they are two times longer than the actual plane spacing. Larger standard deviations describe the sensitivity of the borehole directions in respect to the 2-D column and 1-D layered structural systems. This is easy to understand. A borehole parallel to the 1-D plane system never cuts any plane if it does not start at a point located on the plane itself.

The method developed provides the best estimate of the frequency of occurrence of geometrically continuous structures in a site volume. Different structural configurations can be tested. It is at a tentative stage, meant to analyse the sites in a generic sense and can be elaborated more in the future when necessary.

Structures can be discontinuous and each be treated as discrete units. In such cases the number of discrete units is given by dividing the total surface area occupied by continuous units by the average discrete unit surface area.

3.3 UNCERTAINTY INDICES

The uncertainty which exists in the models is made up of components which vary in type. Some of these components have been assessed in this study. Comparisons between the sites call for absolute indices or relative ratings. The measures considered in the following are those which can be derived from presented data and which are therefore traceable. It is useful to normalise the values between 0.0 (very low uncertainty) and 1.0 (very high uncertainty).

Structural models at regional scale could probably be best rated by comparing the use of geological and geophysical investigation methods. The five main categories of methods used are listed at the beginning of Chapter 5.1 (Aberg). The uncertainty relates to the Regional Scale Uncertainty (RSU) index. Factor RSU = 1 / (1 + X), where X is the number of methods used.

The use of a surveying method requires that the data has been interpreted and utilised in modelling accordingly.

A second estimate of uncertainty would be useful for the site scale models. Once again the geological and geophysical surveying methods used could be the rating factor. In total, 19 methods were separately analysed from Table 4-1. Drilling and percussion drilling were considered to be separate methods. Integrating interpretations resulted in an additional term. Uncertainty is rated by the Site Scale Uncertainty (SSU) index. SSU = 1 / (1 + X), where X is the number of methods 1...20 used. The amount or extent of the use of each method has been analysed and normalised to the highest value found at any of the three sites. This leads to somewhat overestimated values of SSU. For example, if crosshole seismics has used only in one borehole section at one site, the partial index still gets the maximum value of 1.0 for that method.

A third factor causing uncertainty could possibly be related to boreholes, structural intersections and the degree to which they are explained by the bedrock model. One uncertainty index is simply the percentage of structural borehole sections which remain unexplained. Data on this is available in the chapters 5 – 8 per site. The index is called as Borehole Data Uncertainty (BDU).

A fourth issue affecting uncertainty could be the representativeness of the investigations in respect to the site conditions. Complete and dense coverage of the volume studied is certainly better than incomplete and sparse coverage. There are many individual investigations which cover discrete lines along the surface or along boreholes, subareas, subvolumes etc. Individual scoring and comparison of these is too complex in the context of this study. As an alternative, we can use the data on borehole configurations given in Table 8-2 later, but it is as well to remember that this relates to boreholes and associated data only.

The relative representativity is given by the product of values in Table 8-2 scaled logarithmically between maximum and minimum values possible. For borehole density the value 100 000 m/km^3 was used as maximum. Minimum, when uncertainty is 100 %, is set by using values 0.1 km^3, 1 % and 100 m^3/km. The index is called Borehole Representativity Uncertainty (BRU).

The fifth theme assessed in this study is structural density and its uncertainty. The statistical analysis method of structure density provides an estimate of the total number of the structures in the site volume. This estimate can then be compared to the number of discrete structures described by the bedrock models. The Structural Knowledge Uncertainty SKU = 1 - X, where X is the ratio between the quantity of fracture zones and the number predicted by statistical analysis.

4 INVESTIGATIONS AT ABCEBERG

4.1 SURVEYS AND METHODS

The extent of the investigations performed at each site is shown in Table 4-1. The table summarises the geological and geophysical investigations which have had a major impact on the development of a geological-structural model. Concerning the Aberg site, only pre-investigation phase data has been considered because the Aberg is then comparable with the other sites. Also, the amount of the data on the Äspö site from the Hard Rock Laboratory construction phase is very large. It could not have been handled within a pre-decided working plan. Table 4-1 contains some related data such as topography differences, main stress direction etc. which is useful in the evaluation of site uncertainty.

All sites have been the subjects of varying survey goals and survey extent during the period from the late 1970s to the early 1990s. The Aberg (Äspö) site had a clear focus on the process of laboratory siting at a relatively early phase. Consequently, investigations were concentrated on Äspö island and along the planned access tunnel area. Beberg (Finnsjön) had as its impetus the KBS-1 and KBS-2 site investigation in 1977- 83, and investigations continued in the form of the Fracture Zone Project from 1985 - 92 (Ahlbom et al., 1992). The Fracture Zone Project has mainly characterised the Finnsjön subhorizontal Zone 2 and the Brändan zones. Characterisation of Ceberg has been carried out in a single phase during KBS-3 related activities (Ahlbom et al., 1991).

Regional and site scale structural models have been explored in this work with a help of a few selected summary reports. For Aberg, the information sources have been the reports by Wikberg et al. (1991), Stanfors et al. (1997) and Saksa et al. (1993). Some supplementary checks were made from the report in which the geoscientific models were evaluated (Rhén et al., 1997). It was possible to check some details from the report by Almén et al. (1994) which evaluated the investigation methods. The Beberg information has been collected from the summary reports by Ahlbom et al. (1992), Ahlbom & Tirén (1991) and the Brändan area report by Ahlbom et al. (1986). The Ceberg site investigation and modelling results have been described very well in a condensed way in the reports of Ahlbom et al. (1991) and Hermanson et al. (1997). All the other reports used are mentioned in conjunction with the particular data or results being assessed. The structural interpretations and models used are taken from the sources underlined above.

One map from each site has been compiled to show the site limits, coordinates, surveying methods, the areas and lines plus the drilled borehole locations. Figure 4-1 is a surface map of the Aberg site. A separate legend in Figure 4-2 explains the notation used. The map of the Beberg investigation and its legend are shown in Figures 4-3 and 4-4, respectively. The Ceberg surface investigations are shown and explained in Figures 4-5 and 4-6. These figures together with Table 4-1 detail the surface and borehole investigations made at each site. Geohydrological methods have not been considered in this context.

Table 4-1. ABCeberg investigations, methods and other related data.

	ÄSPÖ	FINNSJÖN	GIDEÅ
SURVEYING METHOD	**ABERG**	**BEBERG**	**CEBERG**
Regional surveys			
Topography data	5 m contour map	12.5 and 5 m contour maps	5 m contour map
Lineament analysis data	Satellite & air-photos, Digital terrain model (DTM) & relief maps	Satellite & air-photos (1:20000), topo contour & relief maps	400 km2 from air-photos, 1:50 000 topo map
Lithologic-tectonic maps	1:50 000 base map	1:50 000 base map	1:50 000 base map
Fracturing maps	20x30 km area, OKG plant, CLAB	Not available	5 localities, Gissjö tunnel
Boreholes or other holes	KLX01-02,HLX01-07, OKG, CLAB	SFR & Singö fault zone boreholes	Not available
Airborne geophysics	Available	Not available	Not available
Regional gravimetry data	Available	Not available	Not available
Recoinnaissance geoph.	20 short lines, total 10 km; 4 E-W + 2 N-S lines, total 18 km	Not applied	Total 19 km, 6 lines
- methods	Mag, VLF EM, Refract. seism.		Mag, Slingram EM, VLF EM
- interpreted...	Yes		Yes

Site surveys

Topography data	1-2 m contour map	2m contour map	2 m contour map
Lineaments analysis	Satellite & air-photos, DTM model, 1:10 000 map	1:20 000 air photos, IR photos	Not applied
Detailed lineament analysis	For Äspö in 1:4000 (1.0 m contour)	For northern block in 1:10 000	Not applied
Lithological mapping	Ävrö, Bussvik, L.Laxemar, Glostad in 1:10 000, >10 km^2 area	6,25/~30 km^2 area, northern block in detail	6 km^2, two mappings, reports from 1983 and 1986
Fracturing mapping	at Äspö outcrops, 3 trenches	2 scan lines, outcrops, trench	2 scan lines,
- surface density	0.5-1.1 cps/m	2.9 cps/m	1.2 cps/m
Deformation analysis	For same area as in lithol. mappping	Not applied	Reported in R-97-05

Drilled boreholes, number	15 + 3 KAS02-14,KBH02,KAS16 + KAV01-03	11	13
- max. vertical depth, m	993	691	701
- total length, m	8807	6016	8255
- density, m/km^3	47922	8338	10658
- oriented core	in KAS02 - 04	Not available	Not available
- average fracture density	3.7 cps/m (crushed sections excluded)	3.0 cps/m	0-400 m 4.0 cps/m, >500 m 2.0 cps/m
Percussion holes, number	37 (HAS01-21,HLX08-9,HMJ01,HBH01-5,HAV01-08)	20	24
- max. length, m	175	459	153
- total length, m	4034	2556	2848

Table 4-1 (page 2).

SURVEYING METHOD	ÄSPÖ ABERG	FINNSJÖN BEBERG	GIDEÅ CEBERG
Ground geophysics, area	Grid 1: Bidirectional 200 m spacing, are 5.0 km^2. Grid 2: ~1.0 km^2 on Ävrö Grid 3: Äspö island E-W lines w/ 40/10 m line spacing; Set 1: 5 complementary profiles at Äspö & Hålö, total ~1km	N20W lines w/ 40/80m spacing, area 1.6-2.4 km^2	N-S lines with 40 m spacing, 5 km^2
- Slingram EM 18 kHz	Grid 1: 20 m st interval	20 m st interval, 80 m line sp., 10 sep. profiles over Zone1	20 m station interval
- VLF EM	Grid 2: 3 profiles at Äspö tot. 1.5 km; Set1	10 sep. profiles over Zone1	20 m st interval, 16 E-W lines
- Ground radar	5 lines, total ~500 m		
- Resistivity/IP	Grid 2: Grid 3: 10 m st interval, 40 m line sp.; 6 VES soundings; Set1	20 m st interval, 40 m line sp. gradient configuration	20 m st interval, gradient configuration
- Magnetic (total field)	Grid 1: 5 m st interval; Grid 3: 5 m st interval, 10 m line sp.; Set 1	As for Slingram EM (see above)	20 m st interval
- Gravimetric	Not used	Not used	Not used
- Refraction seismics	18 lines at Äspö and surrounding sea area	11 lines over Zone1, total 1.6 km	2 lines, total 4 km
- Reflection seismics	Two lines at Äspö, total ~2km	One 2 km ENE-WSW line	Not used
Borehole geophysics			
- Radar (omnidir. 22 MHz / directional 60 MHz)	Omnidir.22 MHz in KAS02-KAS11, range 40-60m Directn.60 MHz in KAS12-14, range 30-40m	Omnidir. used 590m in KFI09-11, BFI01-02,HFI01, range30-50m	Not used, KGI01 200-300m omnidir.
- Standard geophysics	All boreholes except KAS10, KBH02 *)	Applied excluding KF102-04	KGI01 - KGI13
- Mise-á-la-masse	Not used	Perc. holes G4, G5, G10	KGI02, KGI05, KGI07
- Seismic tomography	Not used	Not used	KGI01-KGI02-KGI11 3-D tomogr., Perc.13-KGI1 and perc.6-13 2-D tomogr.
- Vertical Seismic Profiling	Used in KAS07 section 0-410m	Not used	Not used
- Petrophysical characterisation	212 samples from core drilled holes	6 samples from KFI05, 14 samples from KFI08	111 samples from core, 38 from dolerite dykes

Auxiliary data

Site elevation difference	28 m with underwater area included	15 m	45 m
Overburden conditions	Peat/organic,... at Äspö max. interpreted 10 m	Peat/organic,sand,(sandy) clays, 2-7m plus moraine at bottom	Moraines, peat bog areas, no clays, thicknesses 0-16m
Underwater area	40 % (nautical chart and fair sheet data available)	12 %	None
Exposed bedrock area	60-70 %	~15 %	~15 %
Glacial ice flow direction	NNW-SSE	N-S	S10°E
Maximum hor. stress dir.	N35°W±30°	N48°W±10°	N67°E ±19°

*) Standard geoph. logging also applied in most HAS percussion holes

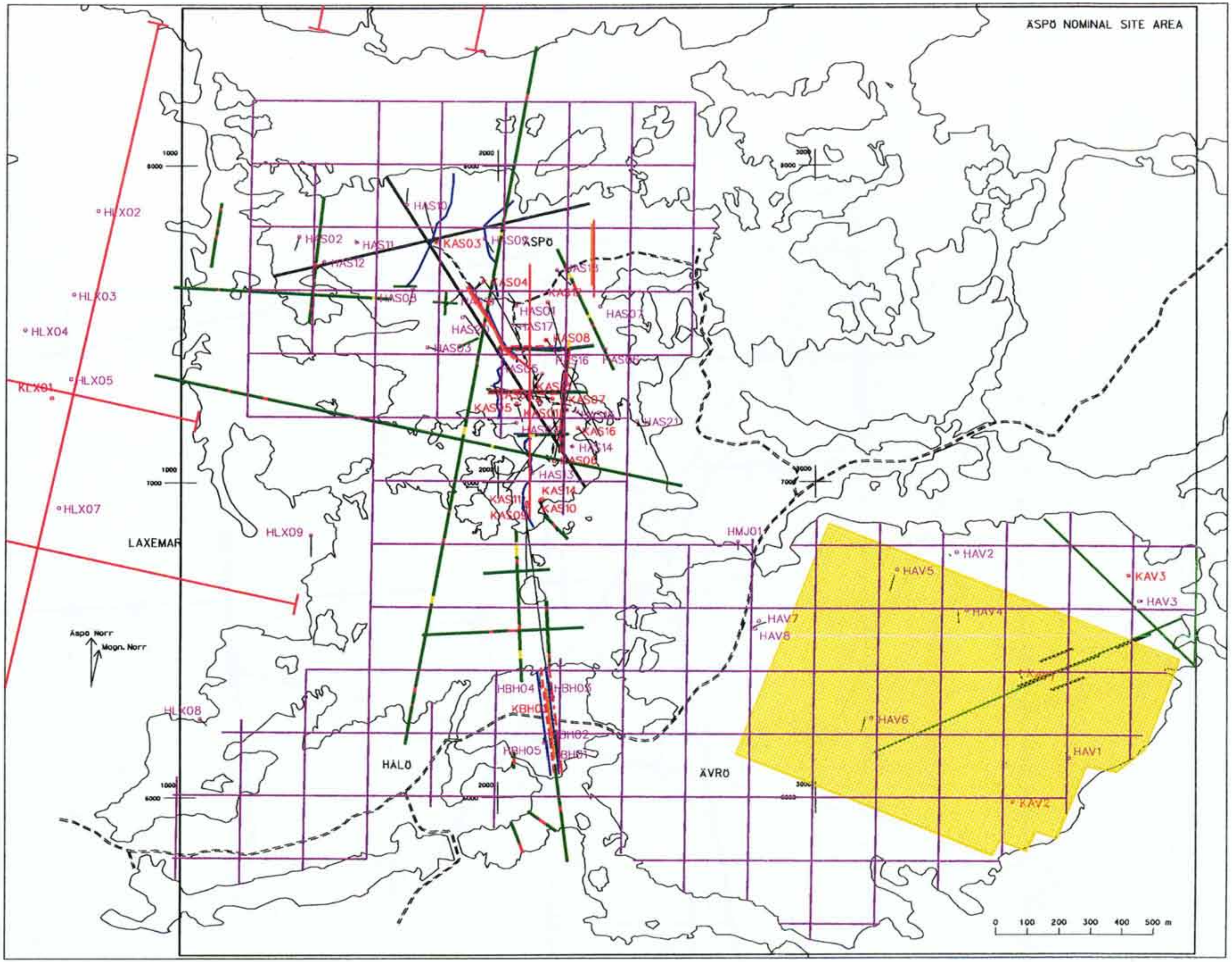
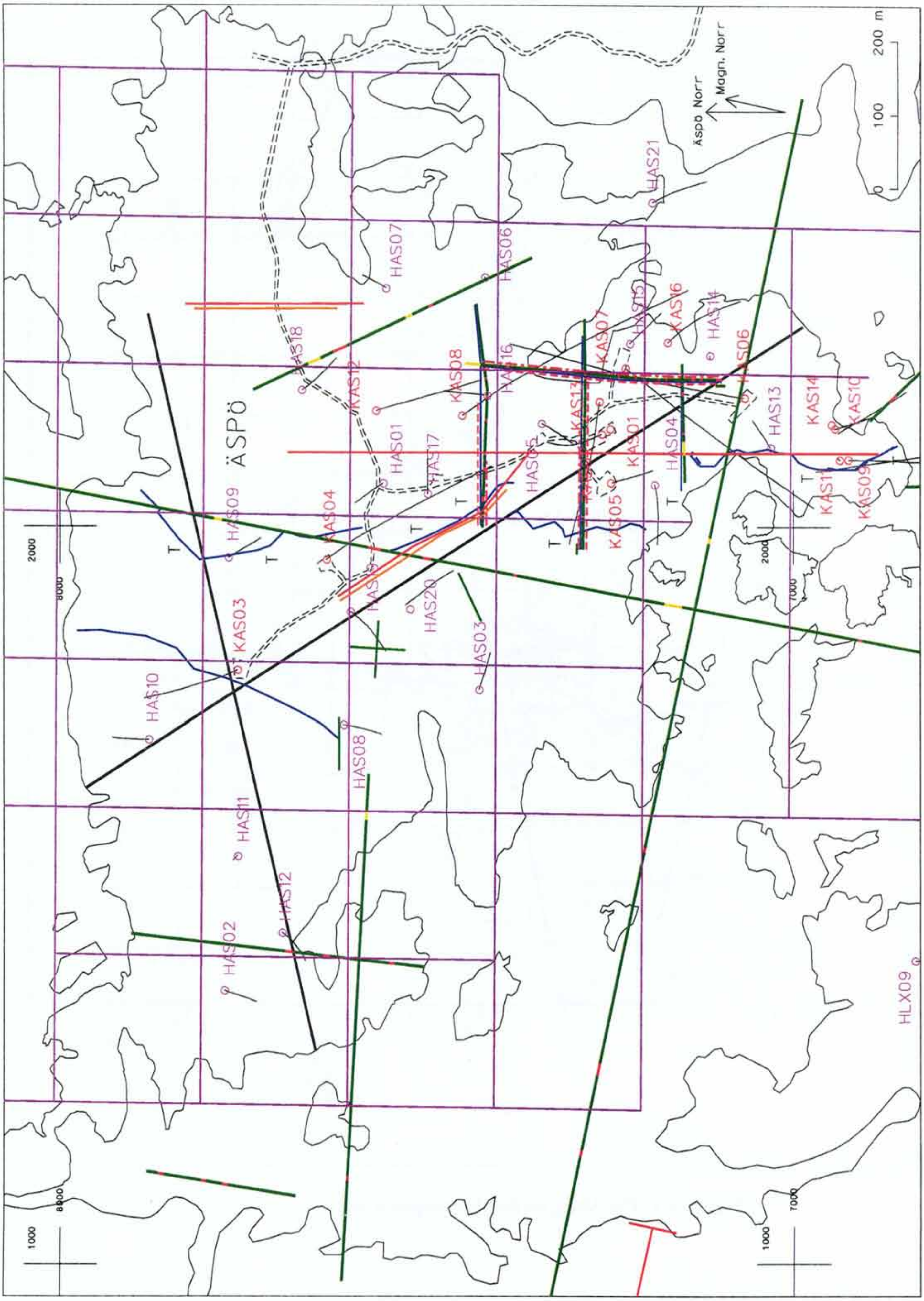


Figure 4-1. The Aberg surface investigation map.



Detail map from Fig. 4-1 Äspö island area.

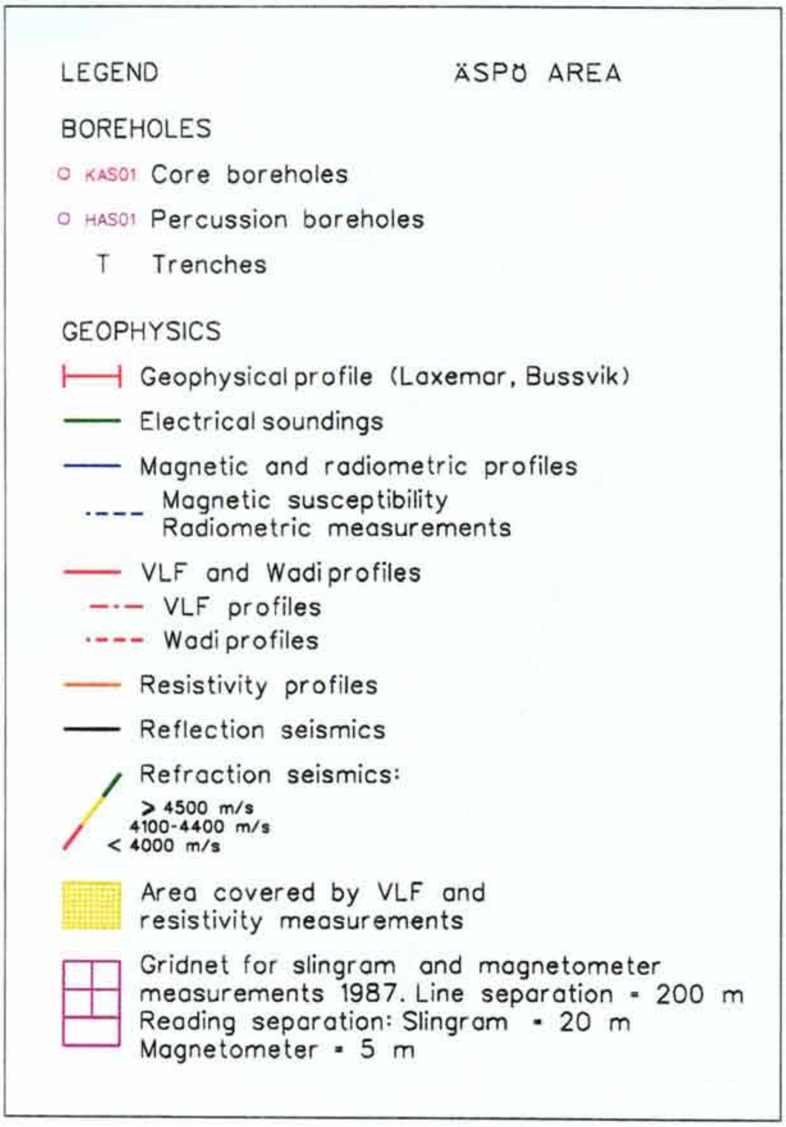


Figure 4-2. Legend for Figure 4-1.

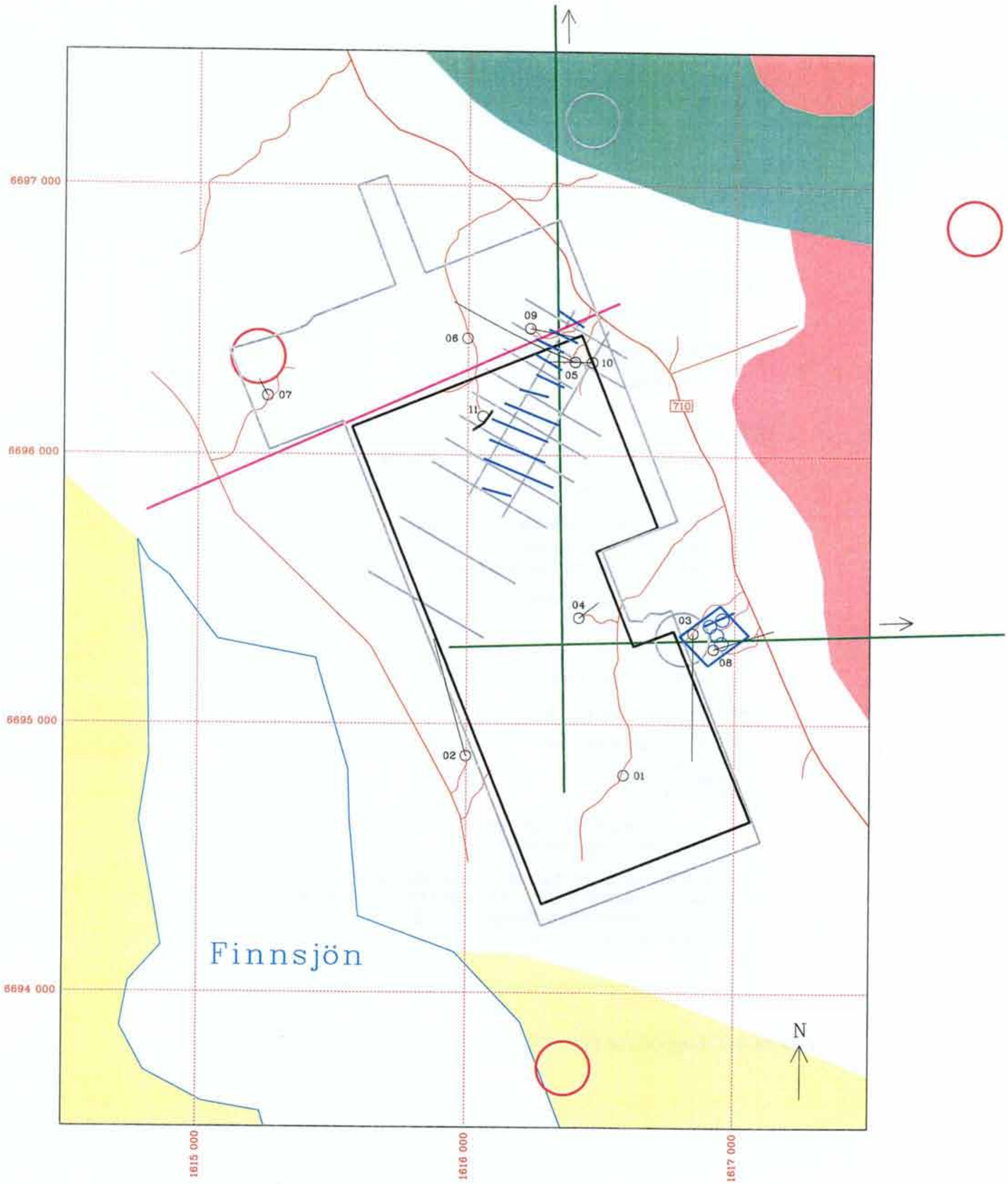


Figure 4-3. The Beberg surface investigation map.

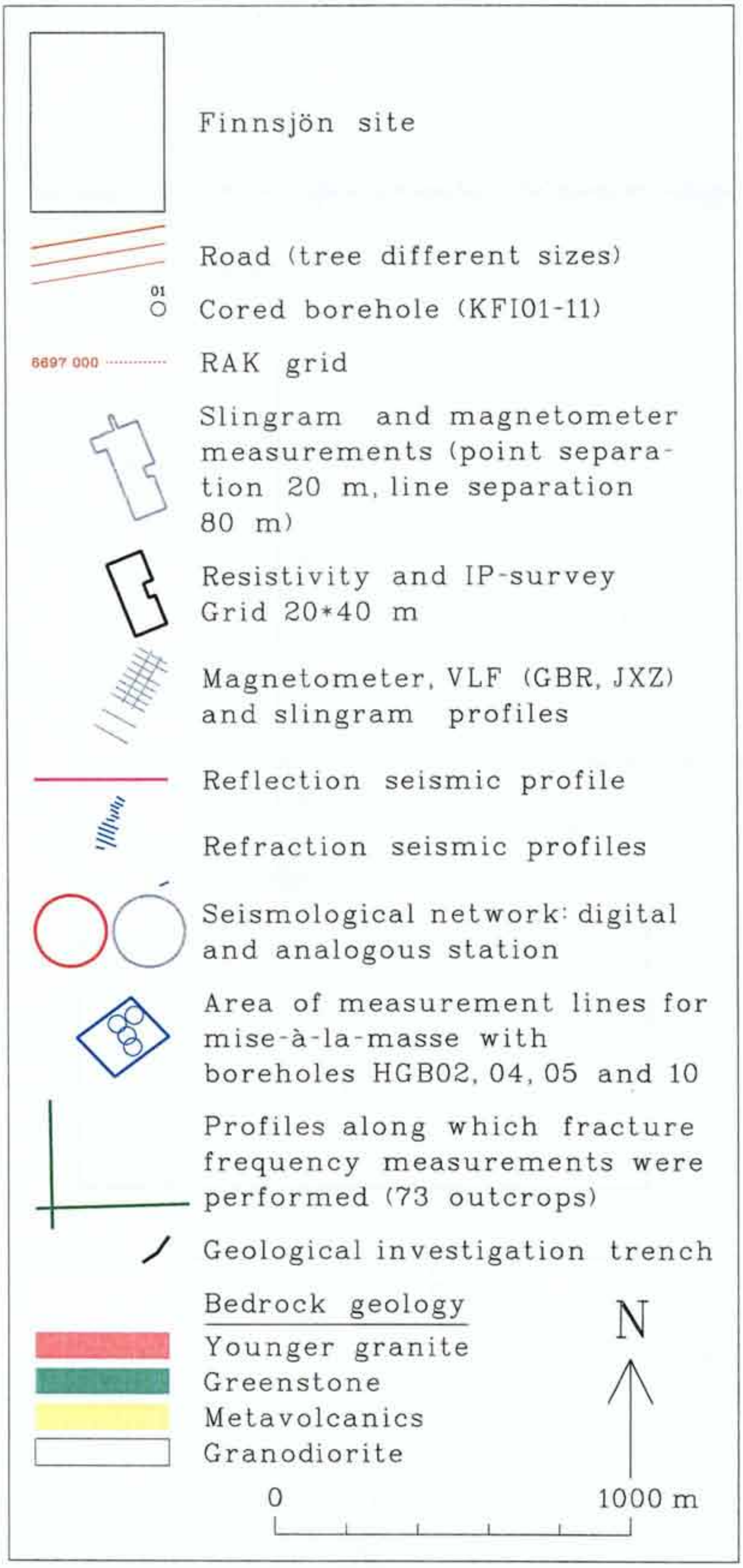


Figure 4-4. Legend for Figure 4-3.

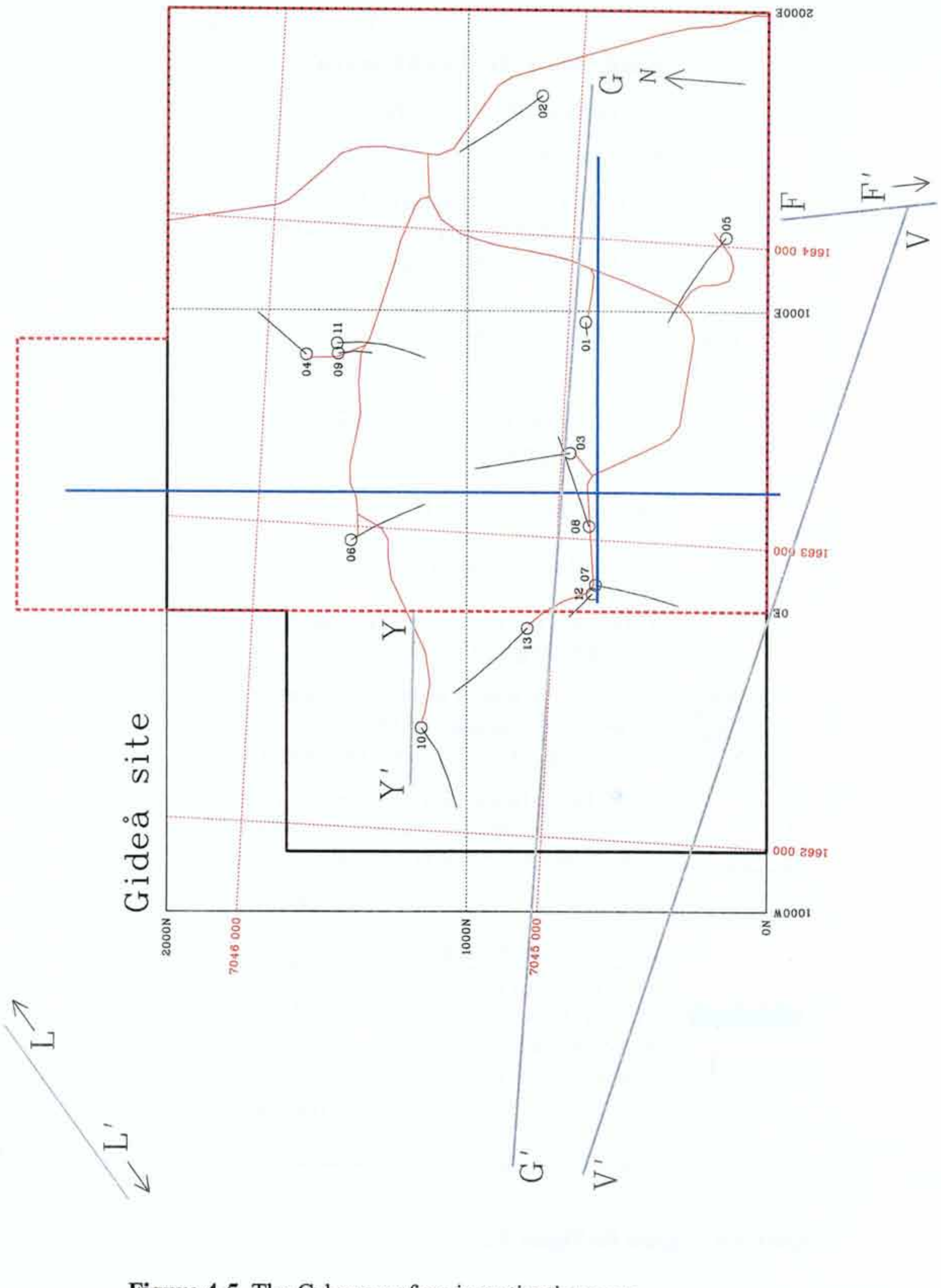


Figure 4-5. The Ceberg surface investigation map.

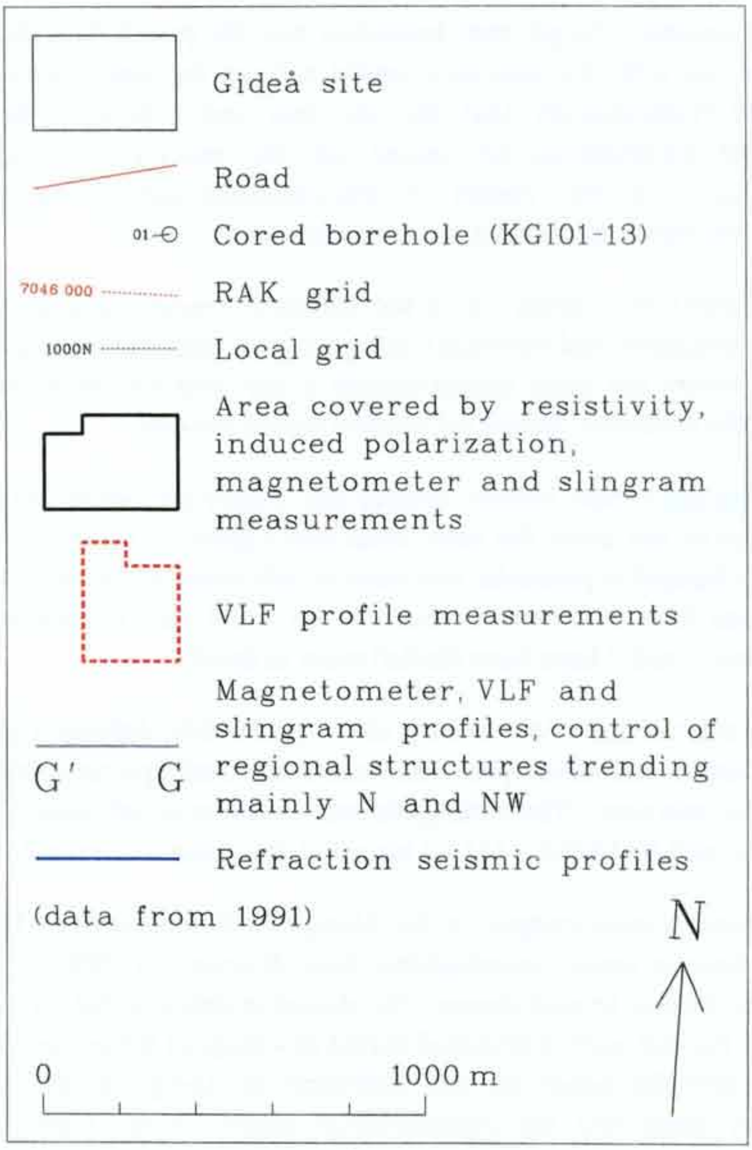


Figure 4-6. Legend for Figure 4-5.

4.2 DEFINITIONS AND CONCEPTUALISATION

4.2.1 Site definition

The site concept - target area limitation and its practical realisation - is important for both the structural model and for the uncertainty analysis. The more systematically that the site area and volume is defined and consequent investigations are carried out, the easier it is to analyse the uncertainties. The “site concept” is both important and necessary if mutual comparisons between the sites are to be carried out.

In this context, the Ceberg site is the simplest. Geophysical ground measurements (magnetic and electrical) and geological mapping have all been carried out within the same approximately 6 km^2 area shown in Figure 4-5. Also, all the boreholes drilled are situated within the area.

The Beberg has a more loosely defined site. Major geological and geophysical surveys do not cover the same areas (see Figure 4-3). Many geosurveys have been limited to particular sub-areas or sub-volumes. Supplementary investigations have also been focused on the small sub-area where the two major zones 1 and 2 have been studied more in detail.

The area and volume of the Beberg site is preferably defined implicitly by the structural model developed. The outermost local structures more or less outline the “site area”. The rectangular area between coordinates Y: 6695.0 - 6697.0 km and X: 1615.0 - 1617.2 km is 6.6 km^2 (part of Figure 4-3 area).

The situation is most complex at the Aberg site (two pictures in Figure 4-1). Firstly, because many investigations have focused on different sub-areas during the various project phases. The second problem is that an explicit site boundary has not been determined during any stage of the project. It is most probable that the reason for the differences at Aberg was the process of laboratory siting and the constructional nature of the work. After the regional characterisation was completed the focus turned to the potential laboratory targets in the Simpevarp area, and soon all interest was concentrated on Äspö island. Within the area of the Äspö island the southern part and the volume along the intended access tunnel were of the greatest practical interest.

Aberg has a bipartite site concept. In its own way the Äspö island is a clear site area and volume boundary. The problem is its small size (approximately 1 km^2) which is not comparable to the other sites. The area is also too small by general site consideration aspects - such as distinguishing between site scale (< 1000 m) and regional scale (> 1000 m) structures. The larger area surrounding the island partly consists of an unsurveyed sea area. The regional area around the Aberg site has been established in the normal way.

The investigations at the Aberg site seem to have been planned and selected with great care, but they leave open the question of where the site actually is. Also, the results and investigations from Aberg are not fully comparable to those from the Beberg and Ceberg sites. In this study the nominal site area at Aberg was fixed as Y: 5500 - 8500 m and X: 1000 - 4200 m in the local Äspö coordinate system. The area shown in Figure 4-1 is 9.6 km^2. If the non-surveyed north-eastern area of 2.4 km^2 is omitted, the area is 7.2 km^2.

4.2.2 Conceptualisation and consistency of the geological-structural models

Before the regional and site models can be studied in closer detail, it is important to know which type of conceptual model has been used. It is also useful to check which limits for geometry and properties have been applied.

At all the sites the general fracture and crushed zone concept was applied by dividing the bedrock into intact rock mass and fracture zone units. The fracture zones are classed as being of major or minor type. At the Aberg and Ceberg sites, the hydraulically conductive zones are separated as their own class of features. Figures 5-7, 6-6 and 7-9 displays structure models discussed for Aberg, Beberg and Ceberg, respectively, in succeeding paragraphs.

ABERG:

At Aberg the development of definitions for the structural units has been an extensive part of the project. For example, the nomenclature published by Bäckblom (1989) has in part formed a guide for the practical work. Concerning structures it is stated that: "A fracture zone is a fracture zone - only and only if - geological field evidence supports zones with the peculiarity that the intensity of natural fractures is at least two times higher than in surrounding rock." Additional peculiarities can be added, for example, "a hydraulically conductive fracture zone" or "a non-conductive fracture zone".

Fracturing degree:

Fracture density is one of the most essential parameters used in conceptualisation of the fracture zone and structural units. The average fracture frequency is 0.5 - 1.1 pcs/m (pieces per meter) at surface and 3.7 pcs/m in boreholes when crushed sections >20 pcs/m are excluded (Table 4-1). The detection limit of the fracture zone would therefore be 7 - 8 pcs/m in the boreholes. Instead of the fracture frequency, the RQD-index has been used extensively as an indicator of fracturing and fracture zones. RQD-values equal and less than 25% have been attached to the identified structural units. This corresponds to a fracture frequency 10 pcs/m or more.

Some structural units have been defined as being hydraulic zones - such as the units labelled NNW. These are used to describe hydraulically-active, continuous single fractures or fracture swarms - of great interest in both hydraulical modelling and from the constructional point of view. The use of these structural units is well differentiated from conventionally-used fracture zone structures.

Extensions:
The Aberg site characterisation programme became a laboratory siting process at a relatively early phase. From the structural point of view it is natural that the interpreted major zones and those with expected long continuity would be of prime interest. A limit for the minimum thickness applied has been about 5 metres. Thickness means in this context the total length of the fractured rock part along the borehole axis. This is close to the observed values for many minor fracture zones. In some boreholes the fractured sections attached to zones are shorter - such as EW-X in KAS11 at 245 - 249 m or EW-5 in KAS06 at 351 - 354 m.

The used lengths of structure extensions in strike direction are several hundred metres and more. Extension downwards is a difficult matter which has also probably been considered. In the CAD file a_zones.dgn (provided by SKB) structures are illustrated to a vertical depth of 1350 - 2650 m from the surface.

Peculiar character:
Investigations of the properties of the major zones have been both the main and a pragmatic focus at Aberg. This means characterisation of fracturing, rock mechanical properties and the hydraulical character of those zones within the planned laboratory and construction volume.

In the classification applied no defined character for the structural units was assumed to exist such as alteration, brecciation or weathering. However, during the tunnel excavation phase the tectonic/kinematic constraint "as shearing, faulting and clay alteration" was added to the criteria for a structural unit (Rhén et al., 1997). This was due to the high degree of fracturing in the fine-grained granites. Without this step, many of them would have been classified as fractured, structural units. Zone EW-1 is an example of a major zone classified as a shear zone unit (Wikberg et al., 1991).

Hydraulic conductivity:
The fracture zone units all have a hydraulic transmissivity greater than 10^{-6} m^2/s. Accordingly, hydraulic conductivity has been 10^{-7} m/s or higher. There are no fractured structures which exhibit low conductivity in the model. Spatial variations in hydraulic conductivity may occur. One example of this is

zone EW-X in borehole KAS11 at section 245 - 249 m, which is not hydraulically conductive (Wikberg et al., 1991).

Summary of the basis for conceptualisation of Aberg:
At site scale, the structure at the Aberg site can be said to be a fracture zone with a fracture frequency of 10 pcs/m or higher and an interpreted length extension of 300 - 400 m or more. No peculiar geological character is presumed but all site structures were hydraulically conductive during the pre-investigation phase.

BEBERG:
The structural conceptualisation at Finnsjön has been studied from summary reports.

Fracturing degree:
At Beberg the average fracture frequency is 2.9 pcs/m at surface and almost the same (3.0 pcs/m) in boreholes (see Table 4-1). In boreholes KFI03, KFI05 and KFI10 the average fracture frequency lies between 4.7 - 5.8 pcs/m. Fracture density does not vary with increasing depth. The nomenclature (Bäckblom 1989) established at the Aberg site would indicate that the fracture frequency for zones should be higher than 6.0 pcs/m. In the boreholes already mentioned, the detection limit of a fracture zone would be 10 - 12 pcs/m.

Some of the site fracture zones appear to have a relatively low fracture frequency. The wide subhorizontal (major) Zone 2 has an average fracture frequency of 5 pcs/m. The bounding contact regions of Zone 2 have higher fracture frequency. Zone 9 is stated to have fractures less than 5 pcs/m. Zones 5 and 10, intersected by core drilled holes, have no established degree of fracturing. Zone 6 has been characterised by the statement "strongly fractured". Zone 11 is a wide subhorizontal structure which is said to be comprised of "gently dipping fractures".

Extensions:
The limit for minimum zone thickness applied has been about 5 metres. This is close to the widths given for the directly observed Zones 5 (2 - 6 m), 6 and 10 (Ahlbom & Tirén 1991). The minimum surface extension given has been 1 km for Zone 4. On the other hand, surface maps depicts a longer, continued strike length for this zone. Major subhorizontal Zone 2 has 1.5 km as its approximate length parameter. Depth extensions of the structures have been tentatively described to a depth of 1000 m by the CAD file b_zones.dgn.

Peculiar character:
Alteration, mylonitisation, brecciation and haematitisation are typical for Zones 1 and 3. Zone 2 has a special structural composition and change in the

groundwater chemistry is a characteristic feature. Many of the local NW trending zones have been specified as shear zones (Ahlbom & Tirén 1991). No peculiar characteristics were reported in Zones 9 and 11.

Hydraulic conductivity:
Many of the fracture zone units at Beberg have relatively high hydraulic conductivity values. Examples are Zones 1 - 3. On the other hand, Zone 9 has a rather low k-value of $5 \cdot 10^{-8}$ m/s and Zones 6 and 10 have a k-value of $6 \cdot 10^{-9}$ m/s (Ahlbom et al., 1992). Zones 9 and 10 have been intersected by drilled holes in the vertical depth range 40 - 150 m.

Remarks: Some of the site model structures have only a few, associated anomalous features. Zone 9 has no anomalous degree of fracturing, no peculiar characteristics and no significantly-increased hydraulic conductivity. Zone 10 is thin (5 m) with low hydraulic conductivity and its degree of fracturing is not reported. Zone 6 is thin, 2 - 6 m, but it has significant hydraulic conductivity and its character is specified as a shear zone.

Summary of the basis for conceptualisation of the Beberg site:
Zone 9 does not fulfil the established fracture zone criteria. Zone 10 would need numerical values for fracture frequency in order to be qualified as a fracture zone.

At Beberg a site scale structure can be stated to be a fracture zone with a minimum fracture frequency of 6 pcs/m or higher, thickness 5 m and an interpreted length of more than 1000 m. No peculiar geological and hydraulic characteristics need to be recognised.

CEBERG:
Characterisation at the Gideå site has used the conceptualisation described below (see also Table 4-1).

Fracturing degree:
At Ceberg the average fracture frequency is 1.2 pcs/m at the surface outcrops and 4.0 pcs/m (0 - 400 m in boreholes) and 2.0 pcs/m (> 500 m depth in boreholes). In some boreholes the average fracture frequency reaches high values (KGI02: 7.4, KGI04: 5.1, KGI05: 5.4, KGI07: 5.2, KGI08: 5.4 and KGI09: 7.1 pcs/m). The detection limit for a fracture zone would be 10 - 14 pcs/m or greater in the boreholes mentioned above.

Some structural units have a fairly low average degree of fracturing - such as Zone 1: 7 - 12 pcs/m in KGI02 and/or in KGI05. Zone 2B has a value of 6 pcs/m in KGI05, Zone 3B 3 -10 pcs/m and Zones 11A - B 8 - 9 pcs/m in KGI02.

Extensions:
The value of minimum thickness applied in the zones has been about 5 metres. This is close to the observed values of Zones 6, 12 and 3B. It is also the value assumed for Zones 9 and 10. Minimum strike length applied is 700 - 800 m for Zones 7 and 9 (Ahlbom et al., 1991). Zone 10 has an extension of 500 m in the updated model (Hermanson et al., 1997).

Depth extensions are not known. In the CAD file c_zones.dgn they are sketched to a vertical depth of 680 - 800 m from the surface.

Peculiar character:
Zone 3 has been specified as a shear zone (Hermanson et al., 1997). It is unclear whether Zones 6 and 12 are fault zones. In Zone 2 clay alteration and weathering is reported. In Zone 4, alteration is mentioned. For Zone 6 brecciation is mentioned, in some cases other zones occasionally contain weathering.

Hydraulic conductivity:
Many of the fracture zone units have a very low hydraulic conductivity - such as Zone 1, 3B, 4 and part of 7 - less than 10^{-10} m/s. In addition, Zones 6 and 12 have interpreted hydraulic conductivity values which are close to 10^{-10} m/s or less (Hermanson et al., 1997).

Remarks: Some of the site model structures have relatively few anomalous associated features. Major Zone 1 has a low fracture frequency, no peculiar characteristics and low hydraulic conductivity. Also, a major unit 3B has low fracture frequency, low hydraulic conductivity, small thickness but peculiar character as an interpreted shear zone. Zone 7 has a small value of extension, low hydraulic conductivity and no peculiar characteristics. Zone 6 is characterised by low hydraulic conductivity and thickness values but it is brecciated.

4.2.3 Summary of the basis for conceptualisation of the Ceberg site

The Ceberg site scale structure can be stated to be a fracture zone with fracture frequency 10 -14 pcs/m or higher, interpreted length 500 m or more. No peculiar geological and hydraulic characteristics need to be associated.

All three sites are summarized in the Table 4-2 below. It should be noted that the Beberg and Ceberg models include zones which would not have been considered as structures in the Aberg model because of their low fracture frequency and low hydraulic conductivity.

Table 4-2. Summary of ABCeberg conceptualisation of structures for fracture zones.

Parameter	ABERG	BEBERG	CEBERG
Fracture frequency criteria,	≥ 10 pcs/m	≥ 6 pcs/m	≥ 10 - 14 pcs/m
Zones below that	No	Yes	Yes
Zone thickness	≥ 5 m	≥ 5 m	≥ 5 m
Zone extension (length)	≥ 300 - 400 m	≥ 1000 m	≥ 500 m
Peculiar character	Not required	Not required	Not required
Zone hydraulic conductivity	≥ 10^{-7} m/s	Not required	Not required

One source of uncertainty in the site models is the non-existence of fracture and zone information in the scale from 10 up to 300 - 1000 m. In the study by Andersson et al. (1996) structures were divided into classes of regional (length > 10000 m), local (1000 - 10000 m) and local minor (10 - 1000 m). Below that is the network of individual fractures. The structure class between 10 - 1000 m was rated as being a very important one in the study. The conceptualisations in Table 4-2 indicate that except in the case of Aberg, local scale structures are mostly (Ceberg) or completely (Beberg) missing. The local structures at Aberg are mostly so-called hydraulic zones (coded as NNW or NW). Fractures, fracture swarms and zones certainly exists in that scale as the photo in Figure 4-7 from Ceberg displays.

This gap in the range of structures may be worth noting in SR 97 studies. The main reason behind it is simply that it is very difficult to detect and interpret structures in the 10 - 1000 m scale. Other reasons for the gap are sparsely distributed boreholes and the fact that borehole radar or high-resolution seismics has not been available or used extensively. On the other hand, descriptions of individual fractures and fracture systems are available for each site.

Figure 4-7. Example of outcropping fracture in length scale 50 m and above that encountered at Ceberg (Gideå) site near borehole KGI05.

5 ABERG

5.1 REGIONAL SCALE

The structural model of the Aberg site at regional scale is primarily based on large area lineament interpretations. The technique utilises topographical maps, thematic satellite imagery, aerial photographs and when available, the digital 3-D terrain models. These images of the earth's surface use visible and non-visible reflected (electromagnetic) radiation bands. Digital terrain models can be further processed to emphasise large/small scale features, edges, gradients, directional information and areas at differing heights.

The other main method used to study geology and structures is regional scale mapping of the lithology and structural history. Airborne geophysics usually applies several methods of measurement concurrently. Quite often regional gravimetry data is collected. Reconnaissance geophysics lines can be realised over interesting areas and targets. A regional scale geological-structural model is most reliable if all of the methods mentioned have been applied. To be useful, the results must be interpreted and used in model development.

In the Aberg region all of the methods mentioned have been used. The investigation methods and some data is collected in Table 4-1 in a condensed format. In addition there is two deep boreholes KLX01 and KLX02 which are outside the Aberg site area as shown in Figure 4-1. It is not quite clear whether KLX01 and -02 are regional or site boreholes. They are considered here to be boreholes for the regional studies. The boreholes neither characterise structures which are part of the site model nor have they been interpreted in connection with the development of the site model.

The regional model is presented in Figure 5-1 (Rhén et al., 1997). No new structures could be interpreted in this connection. Some comments on regional model structures are presented in Chapter 5.3.

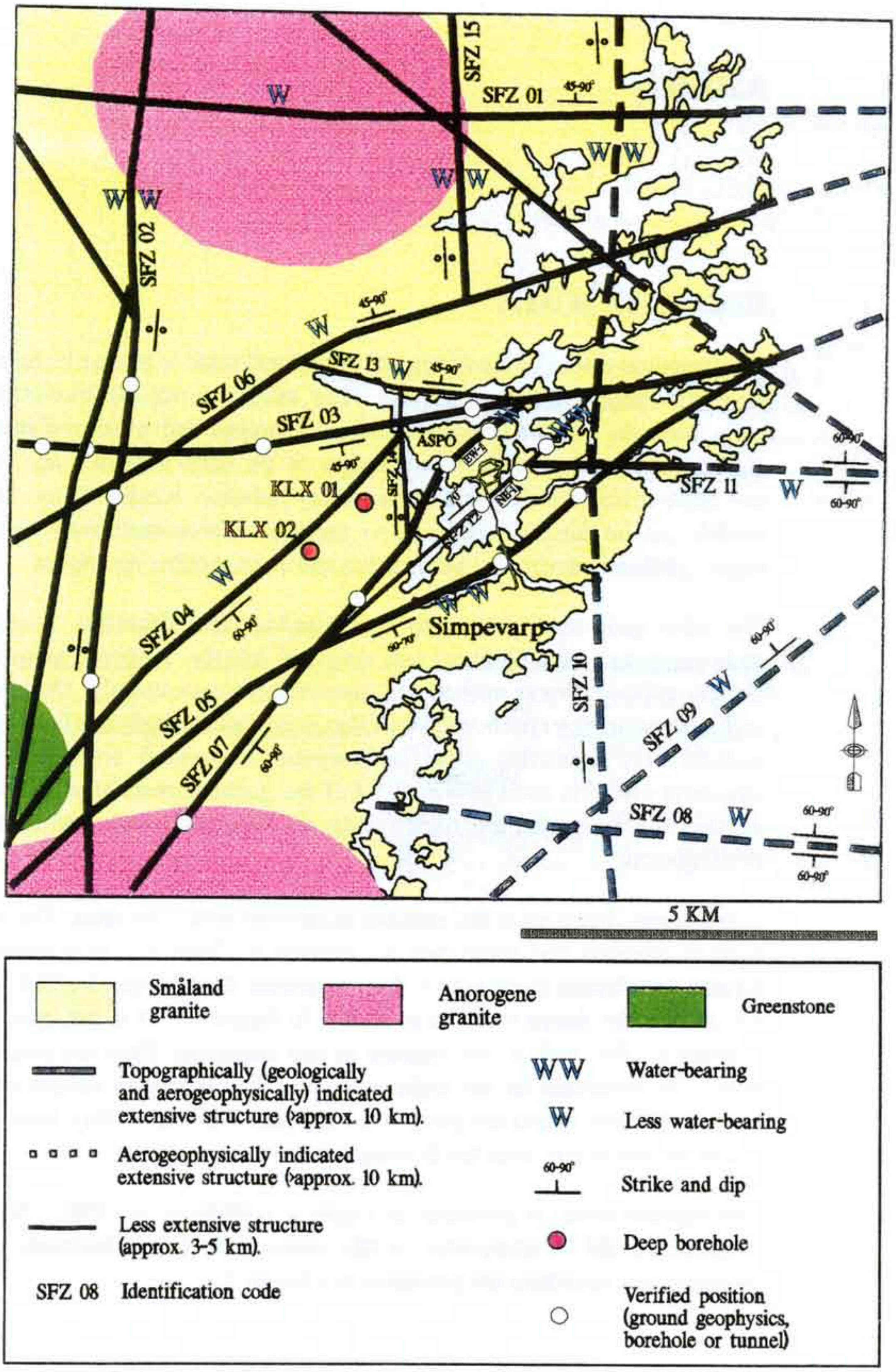


Figure 5-1. Surface map of the Aberg regional scale model (Rhén et al., 1997).

5.2 SITE SCALE

General

At the Aberg sitethe area used as a nominal site is 9.6 km^2 or 7.2 km^2 (see text in Chapter 4.2.1). Within the nominal site area the topography level varies by less than 28 m measured from sea bottom to hill tops.

The dominant bedrock is 1700-1800 million years old Småland granite. Rock mass is intruded by fine-grained granites of several generations. Younger anorogenic granite formed massifs in the older bedrock. Greenstone bodies are remnants of old volcanics at regional and site scale. The dominant foliation trends NE-ENE in granitoids. The main vertical fracture orientations occur in N-S, N50°W and in E-W direction.

The lithological description is based on dominant Småland granite in which irregularly-shaped and random occurrences of fine-grained granites and greenstones are encountered. Within the Äspö island volume a more basic and heavier Äspö diorite was differentiated from the Småland granites. Locally, Äspö diorite is the most common rock type.

The mapped maximum horizontal stress field direction is N35°W±30°. Some topographical lineaments and their continuity may be over-represented along the S35°E direction which is the direction of the ancient glacial ice flow. On the contrary features running WSW-ENE may be masked.

With an area of ~1 km^2 the Äspö island forms a detailed investigation area of its own. Shallow overburden conditions prevail with an interpreted maximum thickness of 10 m. The soil is primarily composed of peat and organic material. Clays can be present is depressions. The Äspö island has a high degree of exposed bedrock, approximately 65%. In the surrounding land area some 60 - 65% of the surface is expressed as exposed bedrock.

Sea covers about 40% of the so-called nominal site area. Very little information exists about this sub-area. The presence of the sea inhibits geological and the geophysical studies of the bedrock, except magnetic airborne and seismic refraction lines (see Figure 4-1). Interpretation of the lineaments has been made with the help of nautical charts and fair sheets (Tirén & Beckholmen, 1988).

Surveying

Several sub-areas, lines, sets of lines and grids have been used for the geological and geophysical measurements. The reader is referred to Table 4-1 and Figures 4-1 and 4-2 to follow the review. Grid 1 is a set of bidirectional lines along which Slingram EM and magnetometer measurements were taken.

This grid covers more than a half the nominal site area. Some lines also cover underwater terrain around Äspö island and to the south of it. The line separation is 200 m which is sparse for site surveying.

Grid 2 is a separate, compact grid area at Ävrö (yellow area in Fig. 4-1). VLF and resistivity measurements have been made. Grid 3 is the Äspö island itself where systematic resistivity/IP and magnetic surveying along E-W lines have been utilised. In addition to these, there is Set 1: 5 complementary lines to which many methods have been applied. Reflection and refraction seismics, galvanic resistivity mapping and soundings, ground penetrating radar and VLF EM have been used along their own lines. Some regional geophysical profiles also enter the site area.

Geological and structural analysis has covered its own areas at Äspö, Ävrö, Laxemar and Bussvik. Combined evaluation of geological, hydrological and geophysical information has covered the Äspö, Ävrö, Laxemar and Simpevarp (to the south of Fig. 4-1) areas (Stanfors et al., 1997).

Interpretation and modelling

A great deal of characterisation work has been done at Aberg. The coverage by measurement grids and lines is complex and irregular. It is impossible to estimate the total effect of grids and lines and covered and non-covered areas on structural modelling. The consequences described below are the most possible. Integration of all the data must have been a very demanding task. Large areas exist where no (or only one) type of investigation has been used and the uncertainties are of course largest there (see Fig. 4-1). It is quite plausible that the geological and geophysical data obtained contains information which is not currently present in the Aberg structural model.

An interdisciplinary approach has been applied when developing the site model - a comprehensive integration of geology, geohydrology, geophysics, geochemistry and rock mechanics. Model iterations have been a frequent occurrence. Comprehensive discussion of the results, the individual parameters and their meaning has been undertaken (Rhén et al., 1997). The result of this is that conceptualisation and consistency have been at a high level for Aberg (Olsson et al., 1994). In the conceptualisation of the geological-structural model no special geological or personal preferences were noted as having had an impact on the models.

The structural model of the Aberg site contains 11 fracture zones. Assessment of the Aberg site model has focused on borehole data which is available from the summary reports. Data for each borehole was first studied separately. The density of structures of interest was obtained by analysing data from all the boreholes.

The original data used for the core-drilled boreholes is from the report by Wikberg et al. (1991). Practical data was collected from the ROCK-CAD modelling report on the Äspö site. This report listed the structures in the borehole intersections and was readily accessible (Saksa et al., 1993). At Aberg, discrimination between fractured sections has been achieved using RQD-values. A RQD-value equal or less than 25% (fracture density equal to or more than 10 pcs/m) has been used to determine fracture zones. Lengths larger than 5 metres in the boreholes have been used.

At the end of the pre-investigations the 14 boreholes covered 63 interpreted intersections of the structural zones (Table 5-1). Review of the core mapping results indicated that some 6 additional zones could also be defined. The structural model explained 91% of the total number of zones encountered in the boreholes. The remaining 9 % of the sections were all related to fracture zones of minor type (width about 5 m).

At the pre-investigation phase the bedrock model also included subhorizontal zones coded as EW-5, EW-5W and EW-X. These were not, however, observed during the laboratory excavation phase (Rhén et al., 1997). EW-5, EW5-W dipped gently at 25 - 35° and EW-X was subhorizontal. As such they explained quite many of the structural intersections in the boreholes. In the second and third columns of Table 5-1 the figures in brackets show the number of structural zones and additional zones without these three particular structures. In such a case the structural model explains 37 borehole sections (54%) and 32 (46%) remain unexplained. The uncertainty degree is remarkably higher than prior to the excavation phase. The properties of EW-5 are those of a major zone. Zones EW-5W and EW-X are mainly classed as minor, local scale units.

In spite of the notes on EW-5 and EW-X above, the fracture zones EW-5, EW-X, NE-1A, NE-1B and NE-2 all have more than three borehole intersections describing them. This makes the zones more certain in character and more accurately localised. It also increases the general maturity of the structural model within the volume studied.

Three additional fractured sections in the boreholes manifest themselves within the fine-grained granites. They have been discovered during tunnelling works and are densely-fractured, lithological units.

Table 5-1. Fractured sections in boreholes. Data is from the reports of Wikberg et al. (1991) and Saksa et al. (1993). Numbers in brackets exclude zones EW-5, EW-5W and EW-X (see text on previous page).

Bore-hole	The amount of structural zones in the boreholes	The amount of additional frac.sections	Structural remarks	Lithological remarks
KAS02	6 (1)	1 (6)		Section at 670m is fine gr. granite
KAS03	4 (4)	1 (1)	EW-1W at 455-475 m is not a fracture zone	Section at 720 m is in finegr. granite
KAS04	10 (9)	1 (2)	334 - 340 m is so-called zone I	
KAS05	5 (0)	0 (5)		
KAS06	5 (2)	1 (4)		Section 505-510 m is in fine gr. granite
KAS07	5 (3)	0 (2)		
KAS08	3 (3)	0 (0)		
KAS09	5 (1)	1 (5)		Sections at 390- 400 m + 405-410 m
KAS11	4 (1)	0 (3)	EW-X at 245-249 m is not hydraulically conductive	
KAS12	1 (1)	1 (1)		
KAS13	5 (5)	0 (0)		
KAS14	4 (1)	0 (3)	EW-X at 150-200 m is a major zone	
KAS16	2 (2)	0 (0)		
KBH02	4 (4)	0 (0)		
Total	**63 (37)**	**6 (32)**	-	-

Another way to analyse the borehole data is to use the statistical method introduced in Chapter 3.2. Lengths between structural intersections in the boreholes are plotted in Figures 5-2 a-b. The log-normal behaviour of the data can be seen. The significance level is high. As input data the real distances between the fractured sections can be used (see Fig. 5-2b). The cumulative 50% value is 1.85 which corresponds to ΔL = 70 m. The Aberg structural model has a dominating SSW-ENE and E-W trend so the closest equivalent model is the layer-type 1-D model. The column 2-D model represents Aberg in the best way if the NNW and NW oriented structures are also taken into account.

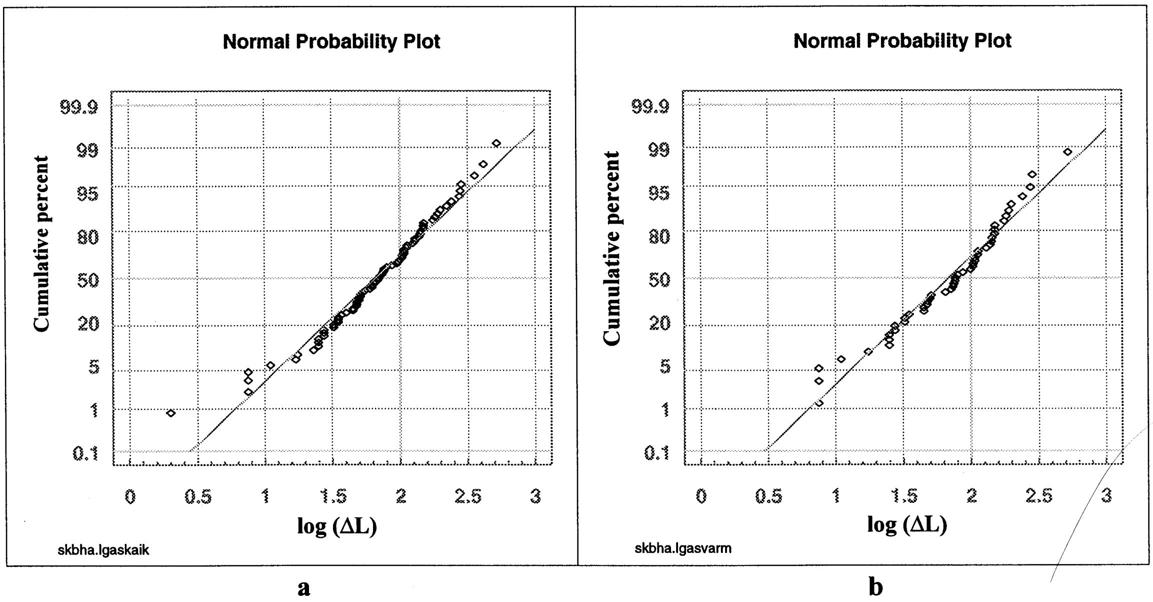


Figure 5-2. Statistical plot of structural density at Aberg. Fig. 5-2a covers all the borehole sections (including start and end parts), 5-2b only the real sections.

Both models gives high structural density values to the Aberg site. In the layer model scheme, the average perpendicular distance between parallel structures is 40 m. The column 2-D model describes a system with two sub-vertical structural orientations. It suggests an average distance of 63 m between the structures.

There are several possible reasons for the high values at Aberg:
A) most of the boreholes are in a small area between the major zones EW-1 and NE-4. The bedrock could be exceptionally fractured inside this volume.
B) boreholes are oriented so as to locate the interpreted major fracture zones. They may therefore not be representative of the Aberg site as a whole.
C) most boreholes are drilled towards NNW or SSE. They are maximum coupled to the dominant SSW-ENE trend and do not provide balanced data on the general structural distribution.

The structural-geological model of Aberg depicts anisotropy having its main component and continuation along the ENE-WSW and E-W directions both in its lithology and its structural nature. In the main, fracture zones along this direction dip towards the NNW. Items B) and C) above are related to one another because boreholes have been oriented to intersect and locate structures in preferred positions and also to cross the anisotropy plane.

The orientations of the Aberg boreholes were collected together to form the 3-D diagram shown in Figure 5-3. Data covers the holes KAS02-14, KAS16, KBH02 and Ävrö holes KAV01-03. All orientations are shown in respect to RAK north. In the plot in Figure 5-3 borehole azimuths and inclinations are classified into 30° sectors. Vertical holes are all in the category azimuth = 0°, inclination = 90°.

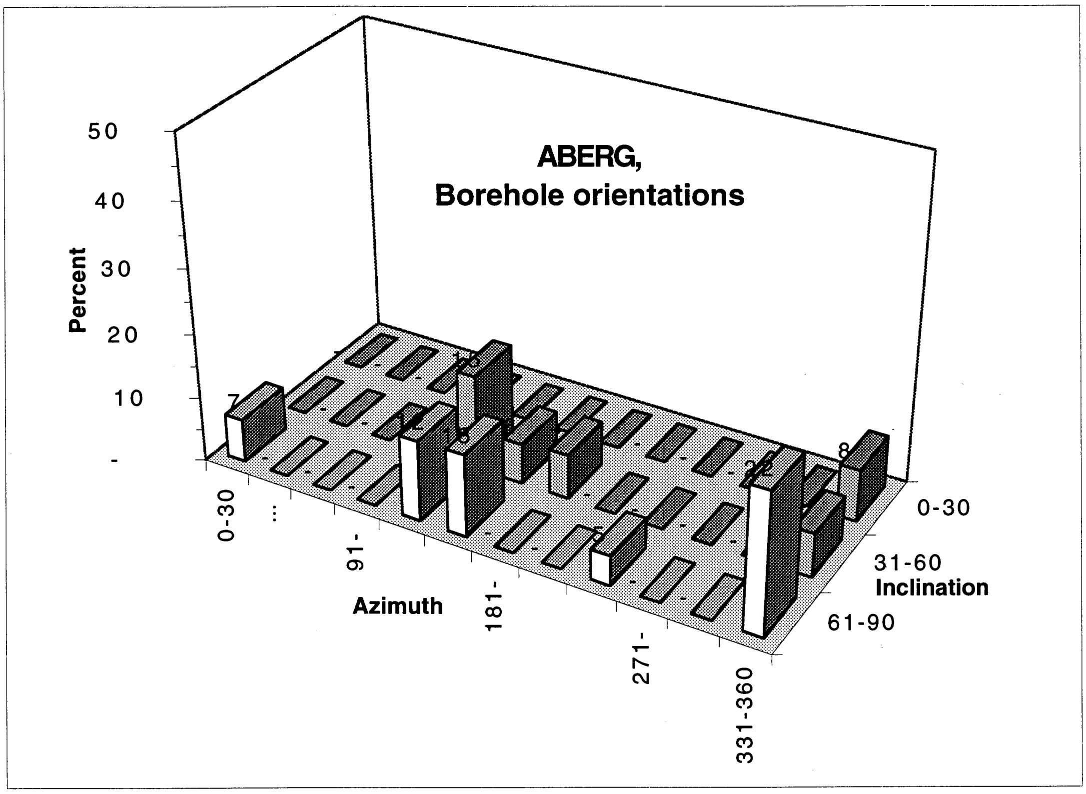


Figure 5-3. Orientation classes of the Aberg site area boreholes.

Two orientation groups dominate the setting shown in Figure 5-3. Towards southeast and south are found 53% of the boreholes with a moderate or steep dip. This is the direction with a steep or close to perpendicular angle to the anisotropy. One borehole, KBH02, is in the class of gently-dipping boreholes. Boreholes KAS02, KAS03, KAS06, KAS13 and KBH02 take a northern plunge and are more closely parallel to the anisotropic plane. These boreholes cover 37% of the borehole lengths. The structural intersection data associated with these boreholes was analysed separately to highlight the effect of borehole orientation. The resulting plot is shown in Figure 5-4. The cumulative 50% value is 1.95 which corresponds to ΔL = 90 m. Compared to all the boreholes, the distance between structures is 30% larger in the NNW-oriented holes. This is most likely a reflection of the anisotropic earth.

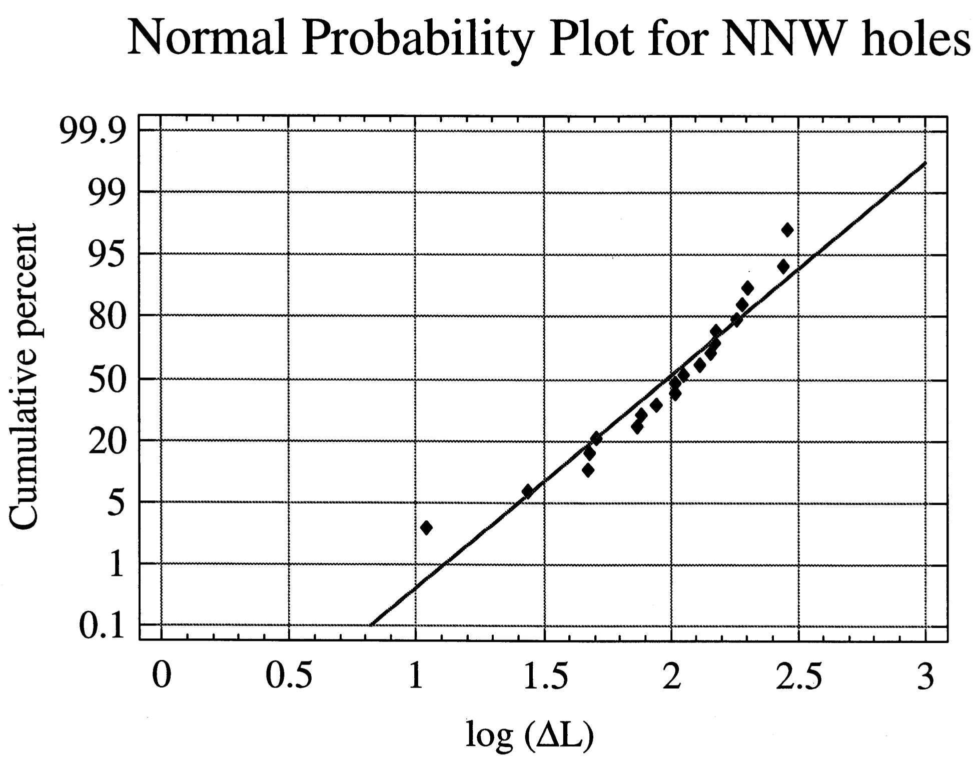


Figure 5-4. Statistical plot of structural density at Aberg NNW oriented boreholes, data from the real sections used only.

5.3 DISCRETE SITE STRUCTURES AND THEIR CONSIDERATIONS

5.3.1 Alternative structures

No new alternative structures are suggested for incorporation into the regional model. The same consideration also applies to the site model - no new alternative structures are proposed. The uncertainty analysis did not reveal alternatives which could have been suggested to further consideration.

5.3.2 Additional structures

Regional model

No new structures are proposed. Deep boreholes KLX01 and KLX02 in the Laxemar area contain many fractured sections. Some of these are displayed in Figure 5-5. These could represent unknown regional structures.

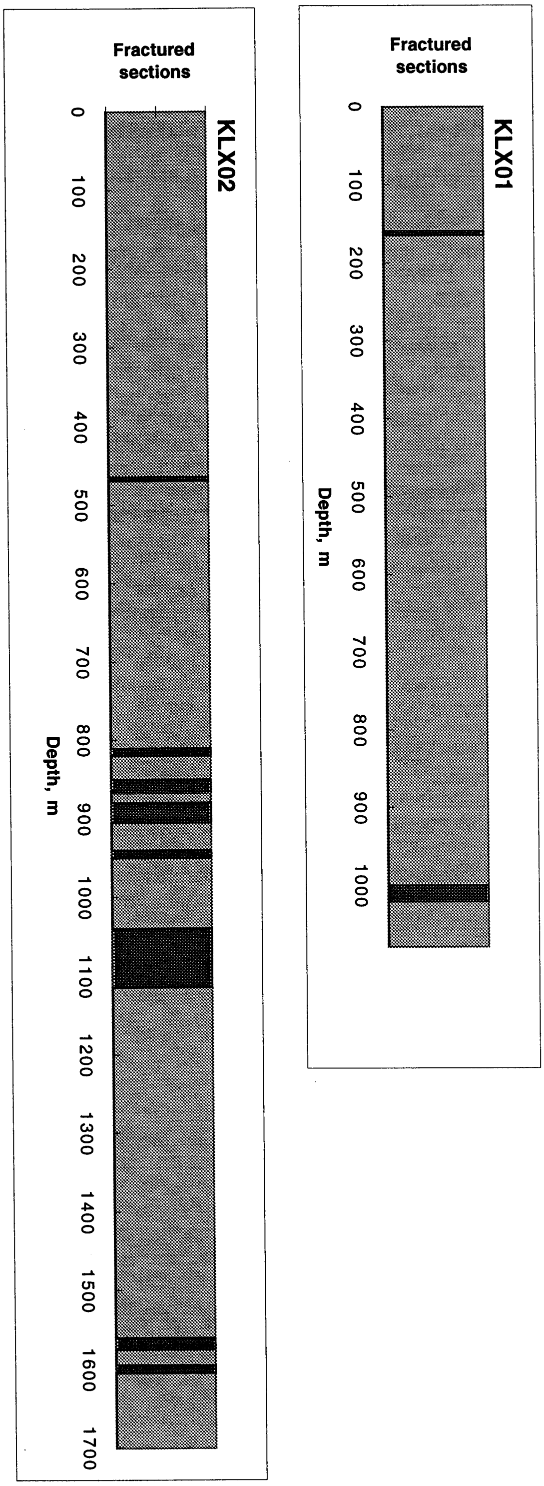


Figure 5-5. KLX01 and KLX02 fractured sections.

Site model
No new discrete and specified structures are proposed for the Aberg site. However, the high density of the structures resulting from statistical analysis should be noted. Additional structures could possibly be deduced from the structural interpretation data such as:

A) The refraction seismic lines (see Figure 4-1) were reviewed in the area surrounding the Äspö island. Interpreted low velocity (< 4000 m/s) sections are potential candidates for fracture zone intersections. There were 26 low velocity sections. A total of 62% (16) could be explained by the site structures shown in Figure 5-7 (with ±50 m accuracy). Ten low velocity sections (38%) are unexplained by the site model.

B) In addition, during the Äspö tunnelling phase no subhorizontal fracture zones were observed. A total of 46% of the fracture zone sections in the boreholes will remain unexplained. Most of them are classed as minor fracture zones. Their possible orientations cannot be interpreted at this time. One explanation could be deduced from the main orientations of the natural fractures mapped on the surface, see Figure 5-6. In addition to major structural trends E-W and ENE-WSW, orientations NW-SE and approximately N-S might be the most likely for supplementary site structures.

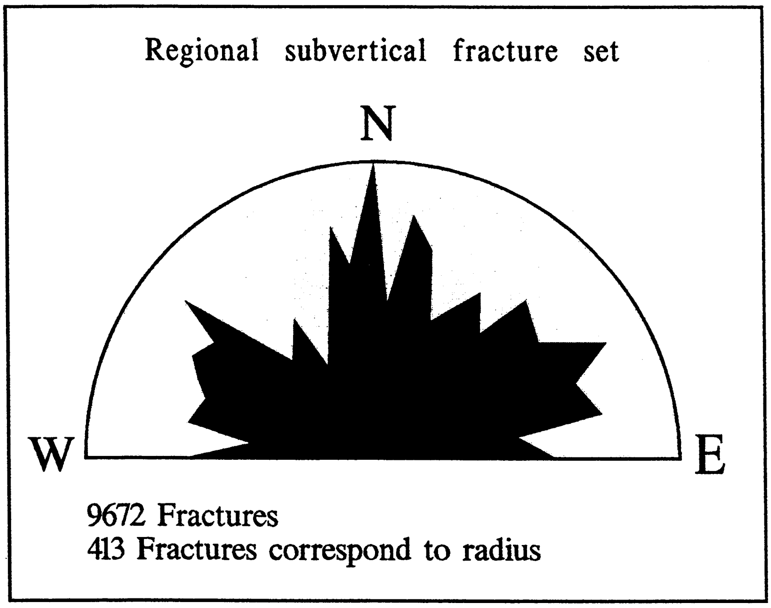


Figure 5-6. Directions of the subvertical main fracture sets at Aberg (Rhén et al., 1997).

C) Bodies of fine-grained granites having extensions larger than 300 - 400 m could be structures in the site model. They seem to be fractured. Geological surface mapping indicate some bodies of this size (Wikberg et al., 1991). If the granite bodies are not outcropping they may be difficult to detect and locate as deterministic structures.

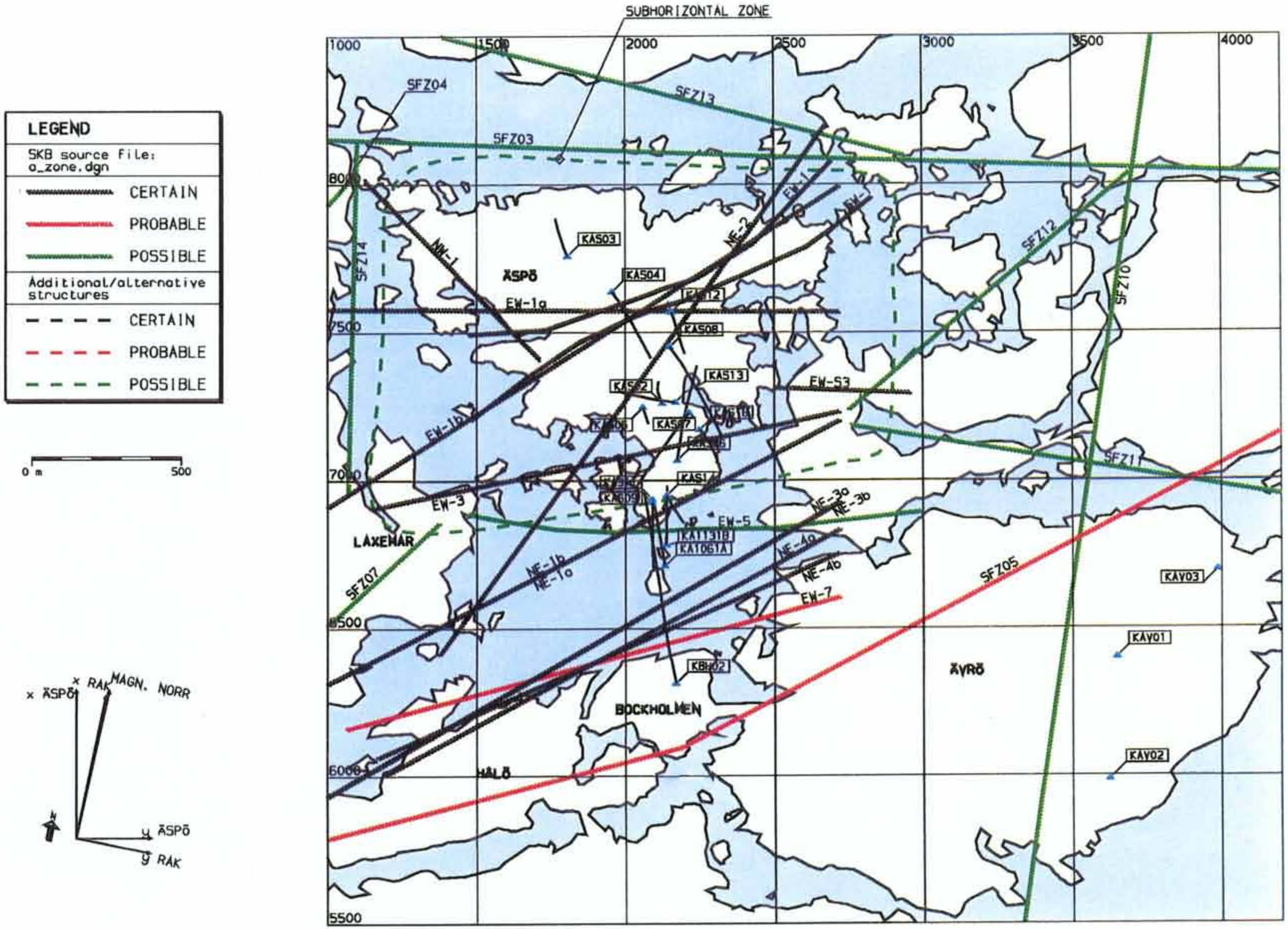
D) The interpretation of lineaments in the sea area was carried out by Tirén & Beckholmen (1988). They used nautical charts, 1:50,000, and fair sheets, 1:20,000, as data. In their study, Sub-area 2 covers the Aberg site area. As a summary, 207 lineaments were inferred, the average lineament length was 300 metres and the density of lineaments was 5.46 km/km^2. This means that there exists approximately 18 discrete lineaments per km^2. The most frequently-occuring orientations for lineaments were N85°E-N85°W, N-N5°W, N35-50°E and N35-55°W.

Subhorizontal zone:
It is stated (Wikberg et al., 1991) that seismic reflection studies have indicated a possibility of a subhorizontal fractured zone at a depth of 1000 - 1150 m. This could have been considered in the modelling process. On the other hand the reliability of the seismic interpretation is not known. There are no other investigations which could exclude the presence of such a zone. Probably such a zone is not of major type. The deepest borehole at Äspö, KAS03, reaches a vertical depth of 993 m.

The structural surface map for the Aberg site is shown in Figure 5-7. The map actually replicates the current bedrock model. No new structures have been interpreted or noted. Some regional SFZ-coded zones are located within the Aberg site area and these are also illustrated. The location of the subhorizontal zone discussed above is only tentative and sketched-in.

(next page)

Figure 5-7. Structural surface map of the Aberg site.


LEGEND
SKB source file:
a_zone.dgn
CERTAIN
PROBABLE
POSSIBLE
Additional/alternative structures
CERTAIN
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SUBHORIZONTAL ZONE
1000
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ÄSPÖ
LAXEMAR
BOCKHOLMEN
HÅLÖ
ÄVRÖ
KAS03
KAS04
KAS08
KAS13
KAS07
KA1131B
KA1061A
KBH02
KAV01
KAV02
KAV03

6 BEBERG

6.1 REGIONAL SCALE

The development of the regional scale model has utilised the available topographical and morphological data quite extensively and in a versatile manner. Regional lithological-structural maps have also been used. No geophysics has been available from outside sources such as SGU or used in the characterisation. Altogether, the Beberg regional scale model has used half the tools that are theoretically available. Reconnaissance and airborne geophysics as well as digital terrain model processing tools have not been available or used. Table 4-1 in Chapter 4 lists the regional scale surveys conducted.

A semi-regional scale model is presented in Figure 6-1 (Andersson et al., 1991). No new structures were interpreted from the material studied in this connection. Some comments on regional scale model structures are presented in Chapter 6.3.

Some additional knowledge exists about regional zones which arose from the site investigations carried out at the Forsmark nuclear power station and for the SFR facility. Observations of the Singö regional fault zone can be considered to be useful and descriptive for other similar NW-SE trending major zones.

At regional scale, rock formations have not been considered as being any structural units. Younger granites, greenstone, metasediments and metavolcanites have been reported (Ahlbom & Tirén, 1991). Some fractured units in the site model may be connected to the younger granites. Some uncertainty exists in at the regional scale if there is no data which would support or deny the homogeneity of the rock formations.

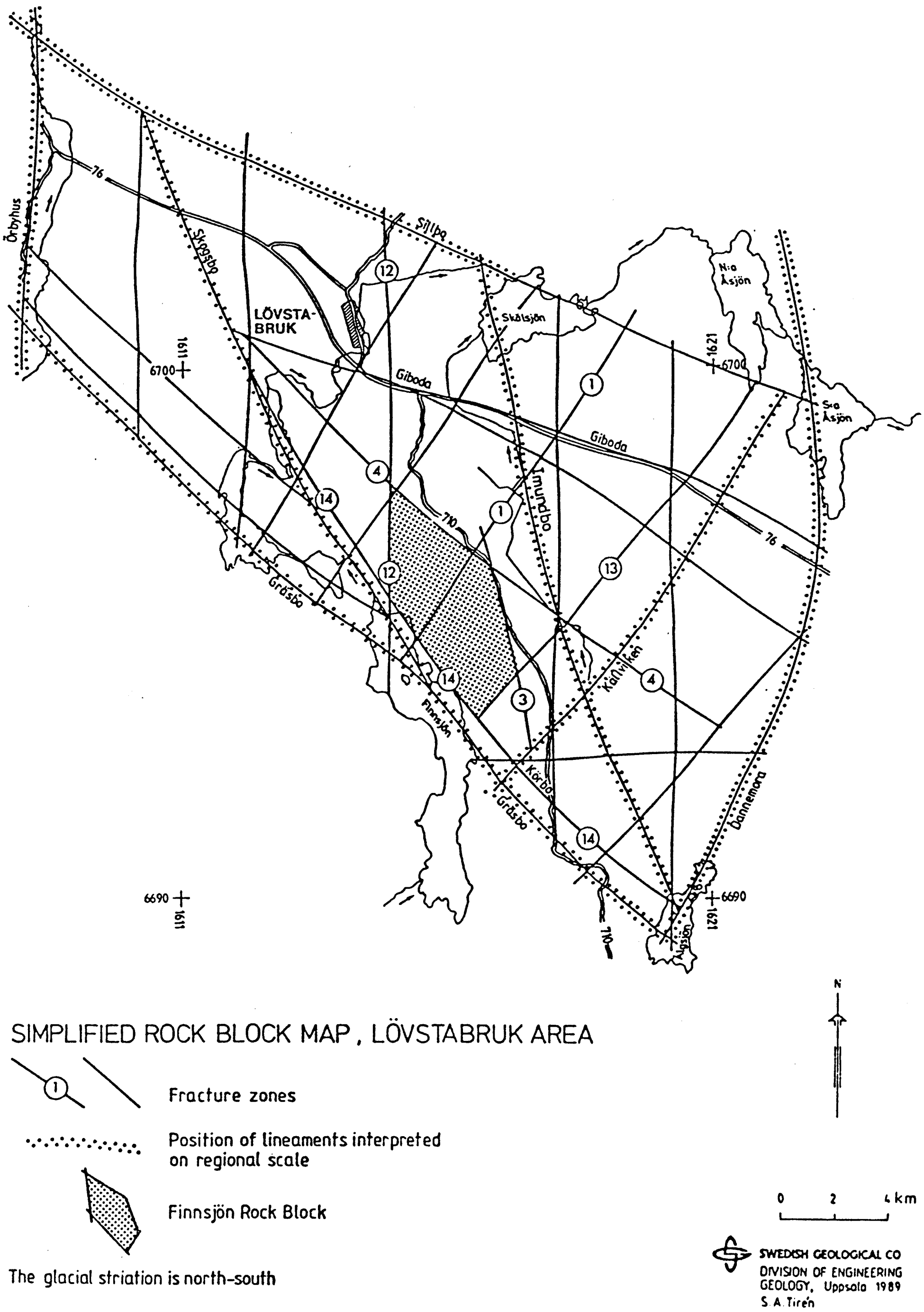


Figure 6-1. Surface map of the Beberg model at semi-regional scale (Andersson et al., 1991).

6.2 SITE SCALE

General

At Beberg the area used as a nominal site is 6.6 km^2. In the main, it is bordered by the rectangular area between Y: 6694 - 6697 km and X: 1615 - 1617.2 km in Figure 4-3. Within the site area the topography level varies within a range of 20 m (15 m in the central area). Shallow overburden conditions prevail with a maximum thickness of 7 m. The soil is primarily composed of peat, organic material and sand. Clays and till can be present against the rock surface and in depressions. At Beberg, approximately 15% of the earth surface is exposed which means that the rock is not necessarily outcropped but situated very close to the surface.

The dominant bedrock is 1850 Ma old granodioritic gneiss body bordered in the east by younger granite and in the north by gabbroic-dioritic greenstones (Fig. 4-3). The dominant foliation trends NW-SE. The main steeply-dipping fracture orientations occur in the NE, NNW-WNW. Flat-lying fractures dip predominantly towards the SW (Ahlbom et al., 1991). The model of the lithology is based on the concept of homogeneous granodioritic rock formation.

The horizontal stress field has a maximum in the direction N48°W±10°. Some topographical lineaments and their continuity may be over-represented along the N-S direction which is the direction of the ancient glacial ice flow. On the contrary, features running E-W may have been masked.

Surveying

At the Beberg site many varying line and sub-area configurations of geological and geophysical studies have been applied over the course of the years, see Figures 4-3 and 4-4. Fracture mapping, refraction seismics, reflection seismics and magnetometer & VLF & Slingram lines form an irregular network of lines (see Figure 4-3). Both the data from the surface investigations and from the boreholes has been reviewed for the Beberg site.

Modelling

The Beberg structural model has 14 deterministic zones. They explain 19 fractured sections out of the total of 28 encountered in the 11 core drilled boreholes. During the preparation of this report the available core logs were briefly reinspected to check the consistency of interpretation of the fractured sections. The data used was from boreholes KFI01 - 07 and are reported in Scherman et al. (1978) and in Olkiewicz et al. (1979). Data from the Ahlbom et al. (1986) report were used for the boreholes KFI08 - 09.

This also provided the possibility of discovering whether there are fractured sections which could represent structural units within the applied conceptual framework (see the summary of the conceptualisation used in Chapter 4.2.2). Any section longer than 5 m and having fracture density of 10 pcs/m or more is a potential candidate for a fracture zone at Beberg. Borehole KFI01-11 results are shown in Table 6-1 below.

At the Beberg, two deep 288 - 459 m percussion-drilled holes BFI01-02 are located in the central study area. These were excluded from closer inspection because the geological information available from them is limited and uncertain. They have however provided useful hydrological and structural data which has been used during development of the model.

Table 6-1. Analysed fractured sections in the Beberg boreholes.

Bore-hole	The amount of structural zones in boreholes	The amount of additional frac. sections *)	Structural remarks	Lithological remarks
KFI01	1	0		
KFI02		1 (676-689m)	Section 499 - 506 m	
KFI03	2	4	0	Long granitic sections
KFI04	1	0	Section 484-490m angle 45-80°; 560-566m, angle 5-35°	Long granitic sections
KFI05	3	1	Sections 79-103m, 137-142m	
KFI06	2	1 (675-691m, zone steep 50-90°	Section 458-464m (dips 75°)	
KFI07	3	0	0	
KFI08	2	no core log,	Resist. log in Rep. TR86-05 depicts 200-215m and 410-430m zones	Long granitic sections
KFI09	2	2 (65 - 67 m and 74 - 77 m could the same zone)	Section 245-250 m	
KFI10	2	0	0	
KFI11	1	0 (no printed log)	0	
Total	**19**	**9**	**9**	-

*) Data refers to the report by Ahlbom et al., 1992. Sections listed have fracturing higher than 10 pcs/m and length greater than 10 m.

The nine fractured sections which are unexplained represent 32% of the total number of classified sections. If the proposed new sections are included in the analysis, 49% of fractured hole sections are possibly unidentified indications of zones.

The five boreholes in the southern Beberg block covers 10 non-modelled fractured sections. In particular, boreholes KFI03 and KFI02 seemed to detect structural and hydraulically-conductive units which are missing from the current bedrock model. In addition, the fractured sections in KFI04 and KFI08 may represent new structural zones or they might be explained by zones in the current model.

The six holes situated in the northern block covered eight fractured sections not explained in the site model. In particular, boreholes KFI05, 06 and 09 which are situated nearby each other have several unexplained fractured and hydraulically-conductive rock sections. The borehole radar yields a steep dip of 75° to a fractured section between 458 - 464 m in KFI06. The deeper section at 675 - 691 m has dominant fracturing which dips at a steep angle between 50 - 90°.

Note 1: Many of the fractured sections observed are non-interpreted. A rough statistical estimate would be that up to 30 - 45% more discrete structures could exist in the volume covered by core drilled holes. The best known, most critical volumes are around KFI02-03-04 and KFI05-06-09.

Note 2: The boreholes in the eastern part of the Beberg site show the frequent occurrence of non-modelled sections in connection with long granitic rock sections. Younger granites border the granodioritic main lithological body in the east. The contact zone has been conceptualised by Zone 11 in the Beberg model. If the additional deeper-seated fractured sections are part of Zone 11, it is a substantially larger (i.e. thicker) structure towards the east than now specified. A 30-40° dip westwards would be the most likely. A gentle dip ~20° to the north would also fulfil the core fracture intersection angles. It would also leave the structure undetected by other boreholes.

Data on borehole orientations is plotted in Figure 6-2 below. All 11 boreholes have a steep or moderate dip. Orientations form a scattered distribution. Set of vertical holes is the largest single category (26%).

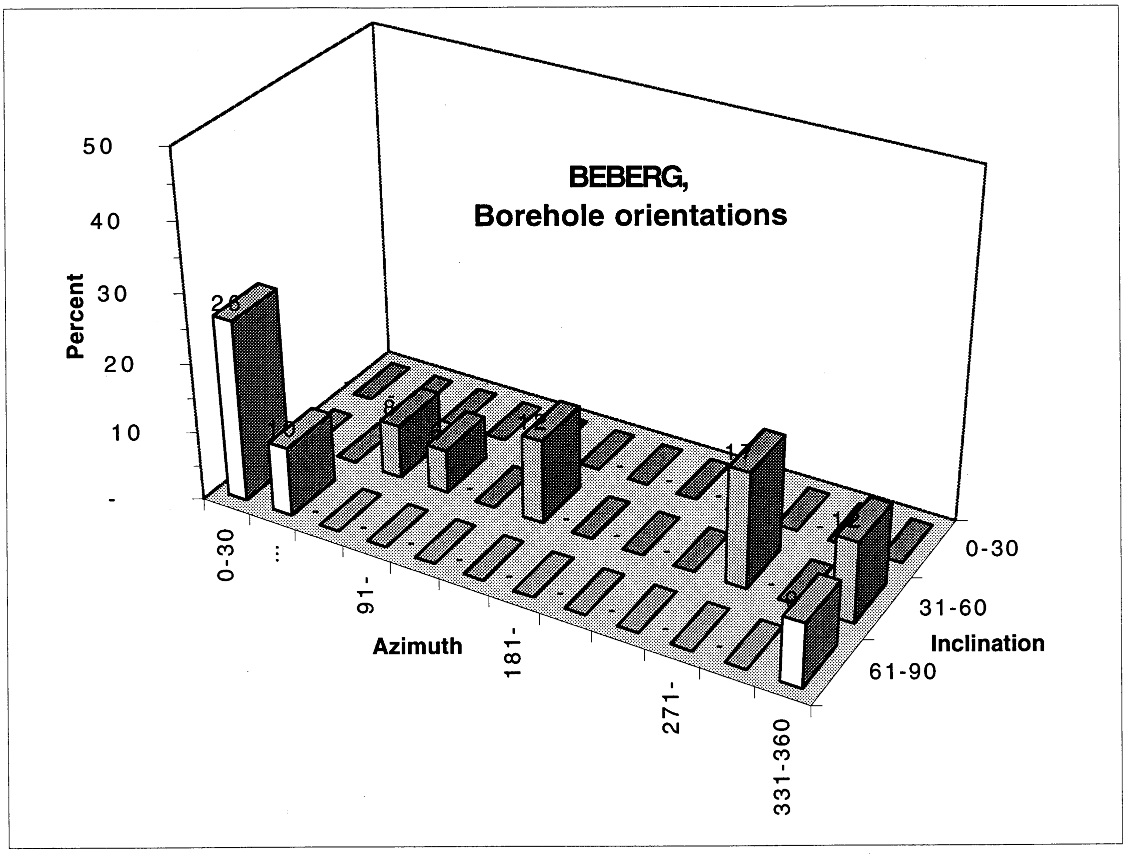


Figure 6-2. 3-D diagram of Beberg borehole orientations.

Another way to analyse the borehole data is to use the statistical method detailed in Chapter 3.2. The frequency of fractured sections in the boreholes is an indicator of the structural framework. The distances between the structural intersections in the boreholes are plotted in Figures 6-3a-b. The log-normal behaviour of data can be seen and the statistical significance level is high. The smallest data set did not allow χ^2 statistical significance test. For the Beberg the 50% cumulative value is the same for boreholes with (a) or without the end sections (b). Only the real lengths between the section intervals are therefore used for analysis. The cumulative 50% value is 1.9 which corresponds to $\Delta L = 80$ m.

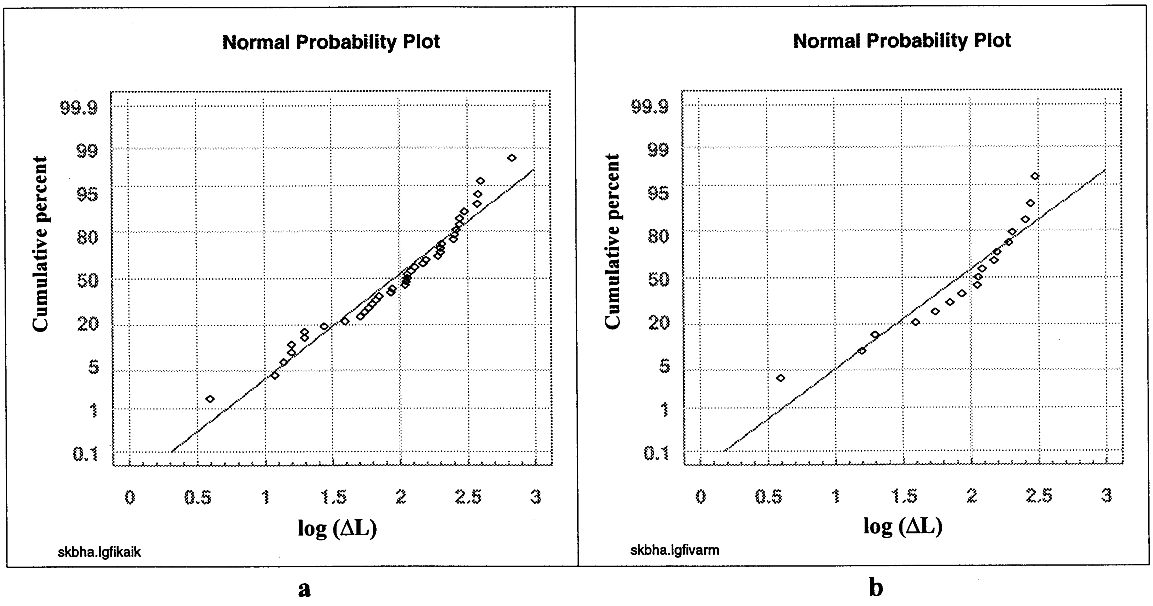


Figure 6-3. Statistical plot of structural density at Beberg. Plot 6-3a has all the borehole sections (including end sections), 6-3b only the real sections.

The Beberg model has WNW-ESE and N-S main structural subvertical orientations. In addition, a few subhorizontal or gently dipping zones have been inferred. The regular 3-D 60° model is then the most representative and preferred network type. The model gives an average zone interval of 130 m. If occasional NE-SW zones are also considered a regular 3-D cubic model would apply. In this case the average distance interval between the structures would be 110 m. As a whole, Beberg fracture zone structures can have an average separation of 110 - 130 m along each identified main orientation.

The values obtained seem realistic in the light of the borehole data. The boreholes cover the site geometrically and have varying orientations. They have been drilled to perform both general mapping and the study of discrete structures.

Supplementary mise-à-la-masse measurements have been made within a small 150 • 160 m area surrounding percussion holes G2-G5, G8-G10 and drilled hole KFI08 (Fig. 4-3 and 4-4). Electrical current groundings have been placed in G4, G5 and G10. Electrical potentials have been measured along 9 surface lines. The measurements at Beberg benefit from the fact that shallow borehole groundings less than 80 m below the surface have been used. The interpretation is qualitative and supports the major structural Zones 3 and 11. In addition, new NW zones dipping steeply towards the NE are suggested at local scale (Jämtlid et al., 1981).

6.3 DISCRETE SITE STRUCTURES AND THEIR CONSIDERATIONS

6.3.1 Alternative structures

Regional model:
No new alternatives for structures are proposed. The data and reports inspected did not exhibit observations leading to new interpretations.

It is interesting to note that both in the regional- and site-scale maps lineaments frequently occur in the direction N10°E. However, the bedrock model at site scale has no structures in that direction, except Zones 11 and 12 (see the map in Figure 6-6). The N-S lineament direction could be over-represented by the movement of ancient glacial ice along the particular N-S traverse. This is more especially true the smaller the length or class parameter that has been attached to the lineament in question.

Site model:
No new structures are proposed. The data and reports inspected did not show observations leading to new interpretations.

6.3.2 Additional structures

There are no new additional structures which are proposed for addition to the regional model. The data and reports inspected did not exhibit observations leading to new interpretations.

Site model:
A) Some new site-scale structures might be considered. These can be found from the results of regional and detailed lineament analysis (Ahlbom & Tirén, 1991). Figure 6-4a-b shows several highlighted N-S and E-W third order lineaments in the southern block area. All have a length of approximately 1000 m or more.

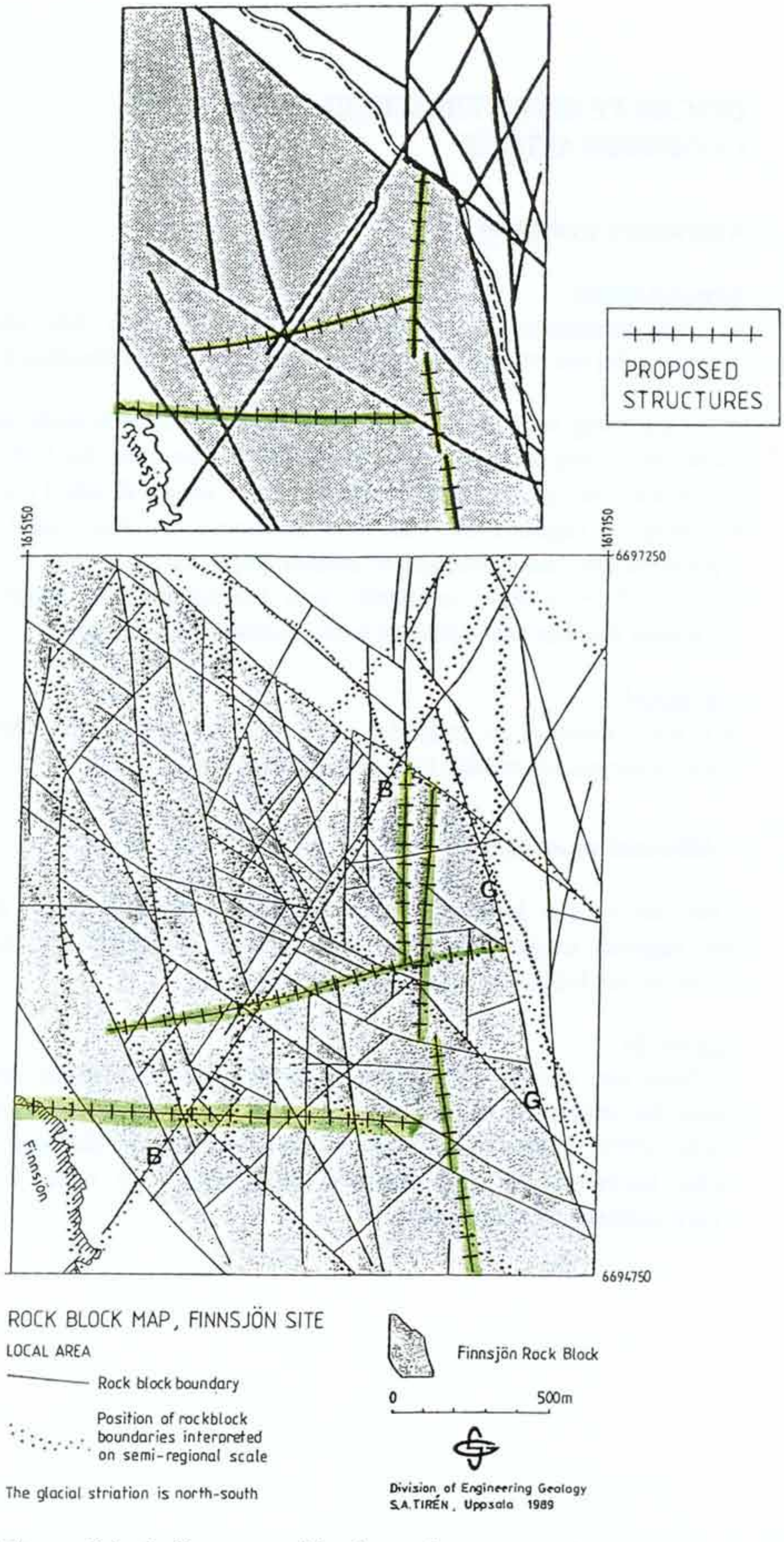


Figure 6-4a-b. Some possible site-scale structures based on the interpreted lineaments (Ahlbom et al., 1991). Fig. 6-4a shows "third order" lineaments, 6-4b is a composite rock block map.

B) The analysis of regional lineaments has been conducted with great care. It has utilised in a versatile way all the available map and photographic material. Interpretation has been carried out in a thorough way. The rock block map at semi-regional scale has been published by Ahlbom et al. (1991). Maps in the report show a well defined regional lineament in the southern side of the Beberg which runs N-S (highlighted in Figure 6-5). This enters the Beberg rock block from the southern lake area and ends within the so-called southern block of the site. Since this is the only regional lineament interpreted as being situated within the Beberg rock block, it might be considered and tested in the SR 97 modelling efforts.

C) Existence of a subhorizontal major or minor zone.
The available core information is limited to a vertical depth range of 0 - 600 m in the southern block area and 0 - 700 m in the northern block area. In deterministic groundwater modelling, subhorizontal generic Zone 2u at a vertical depth of 600 m has been assessed previously in the SKB91 study (Ahlbom et al., 1992). The only data sets which cover depths of 600 m and more are the magnetic surface measurements and seismic reflection profile data. As there are no large mafic rock bodies which could be connected to a major zone at the Beberg, the magnetic survey has no detection capability in respect of such a deep-seated zone.

The outcome of the seismic reflection profile is briefly described by Ahlbom & Tirén (1991). The subhorizontal Zone 2 could not be mapped while the steeply dipping Zone 1 was clearly identified. Below Zone 2 no information was obtained until below a depth of approximately 1500 m. It is possible that a major zone such as Zone 1 (large extensions, thickness ca. 20 m, 8 - 20 fractures per meter, altered and haematitised) could be interpreted from the seismic data. However, a minor zone with characteristics comparable to Zone 2 (thin fractured sections, generally low degree of fracturing) would remain undetected. The southern block on the south-eastern side of the Brändan zone is not covered by seismic reflection information. Consequently, any type of fracture zone can, in principle, exist there below a depth of 600 m.

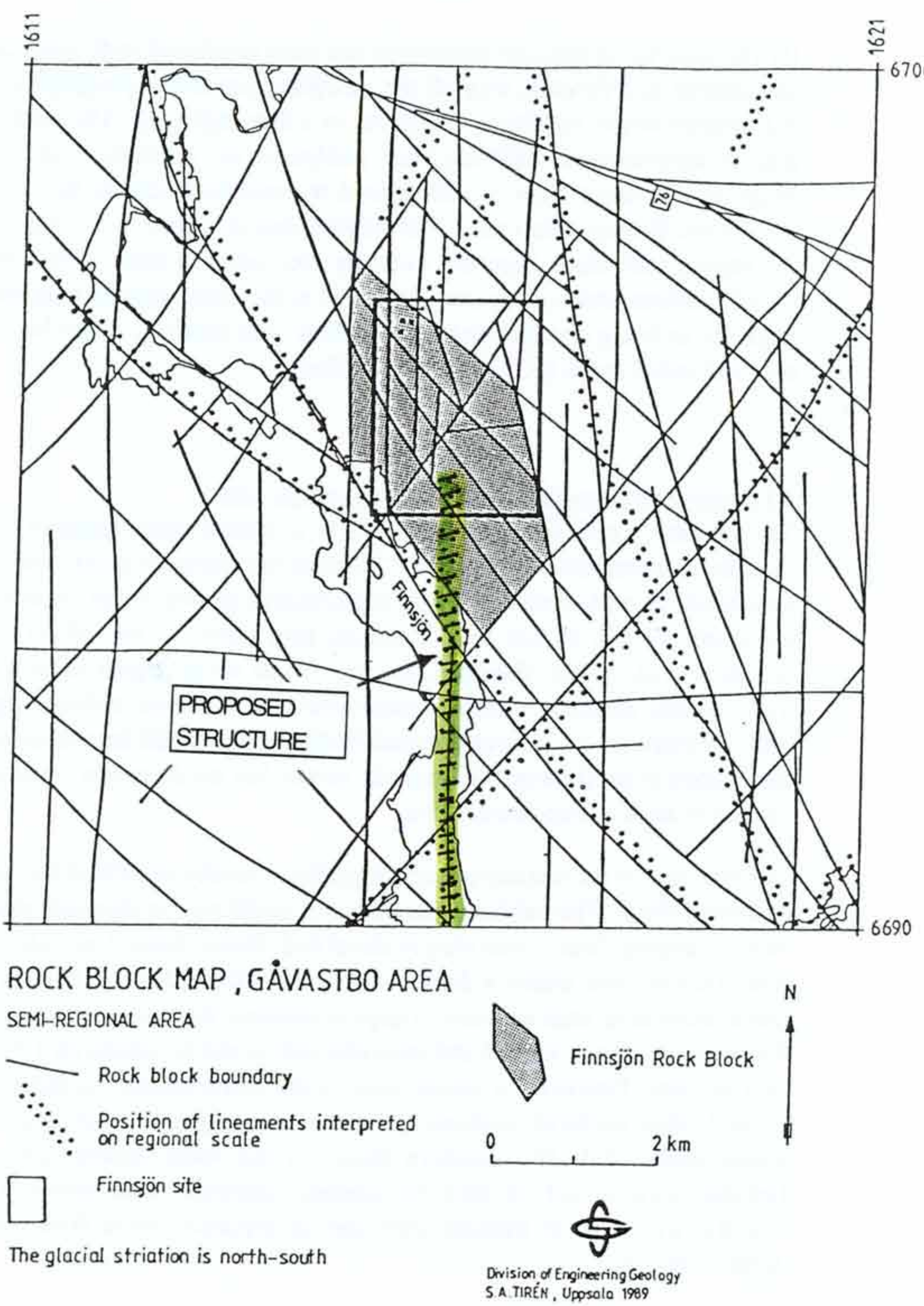


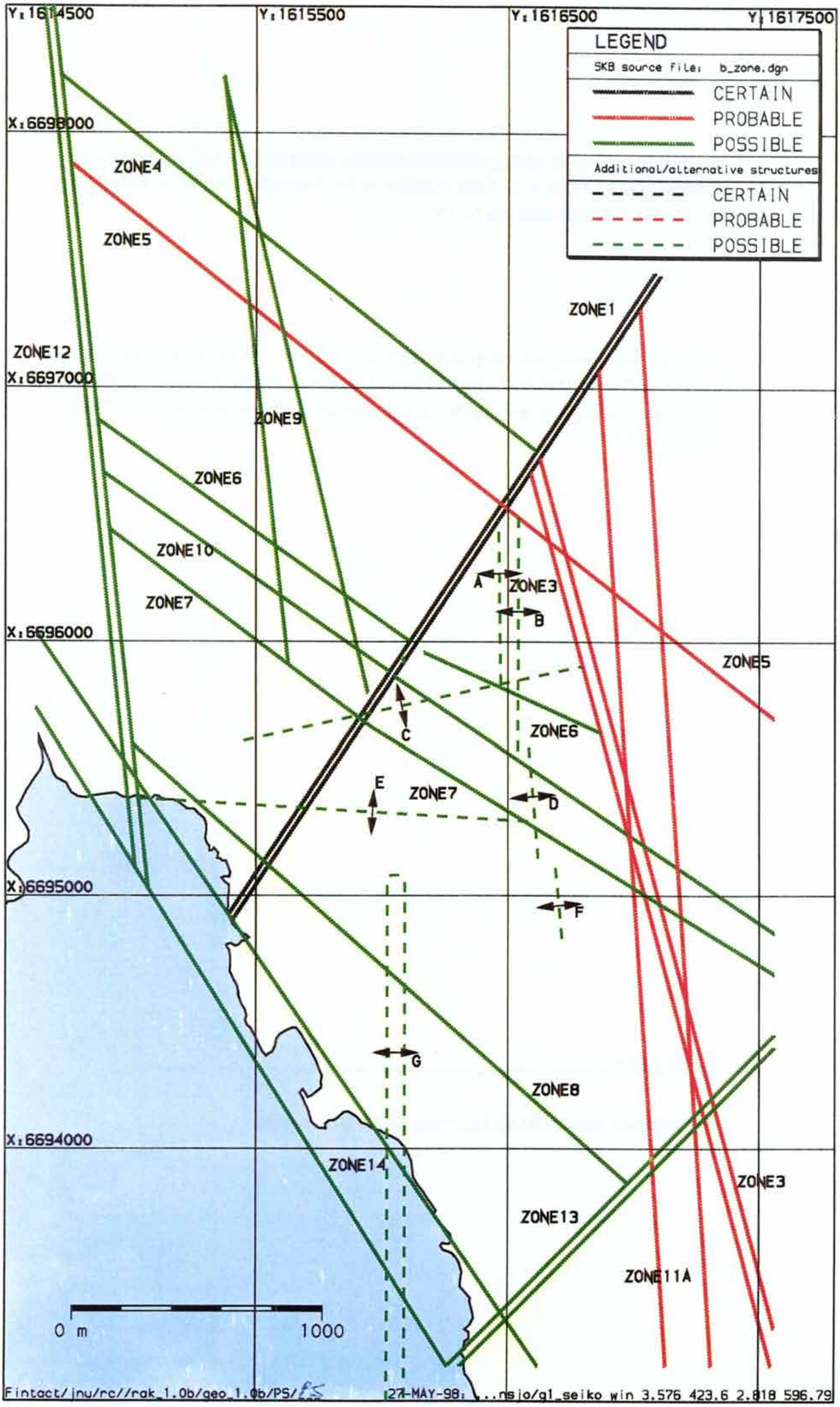
Figure 6-5. One highlighted N-S regional scale lineament and its possible location in the area of the site model (after Andersson et al., 1991).

D) KFI06 may have new identifiable steeply dipping and hydraulically-conductive zones (Table 6-1). One example is the fractured section at 458 - 464 m which has a probable dip of 75°.

The revised Beberg site map is shown in Figure 6-6. The additional structures and their notation is also shown. Locations of the lineaments shown previously in Figures 6-4 and 6-5 are illustrated with the notation A - F and G, respectively.

(next page)

Figure 6-6. Structural surface map of the Beberg site.


Y: 1614500
Y: 1615500
Y: 1616500
Y: 1617500
LEGEND
SKB source file: b_zone.dgn
CERTAIN
PROBABLE
POSSIBLE
Additional/alternative structures
CERTAIN
PROBABLE
POSSIBLE
X: 6698000
X: 6697000
X: 6696000
X: 6695000
X: 6694000
ZONE4
ZONE5
ZONE1
ZONE12
ZONE9
ZONE6
ZONE10
ZONE7
ZONE3
A
B
C
D
E
F
G
ZONE8
ZONE14
ZONE13
ZONE11A
0 m
1000
Fintact/jnu/rc//rak_1.0b/geo_1.0b/PS/
27-MAY-98:
...nsjo/g1_seiko win 3.576 423.6 2.818 596.79

7 CEBERG

7.1 REGIONAL SCALE

The regional bedrock model is largely based on the lineament interpretation. No regional geophysics has been available from outside sources such as SGU or used in the characterisation. Altogether, the Ceberg regional scale model has used half the surveying methods that are theoretically available. A set of reconnaissance geophysical lines were measured (some shown in Figure 4-5 previously). However, geophysics seem to be unused in development of regional model. Digital terrain model processing tools have not been available or used. Table 4-1 lists the relevant regional scale surveys of the Ceberg site.

Regional model has been based on lineament interpretation and the map of it is shown in Figure 7-1. Four regional lineaments cross the Ceberg site area. Zone 8 in the southwest corner is part of the regional feature. One NNE trending regional lineament coincides with the site structure, Zone 1.

Zone 7 in the site model is a section of a longer regional NNW feature. In the regional interpretation this feature intersects the site. Accordingly, it could be more continuous than is currently presented in the site model.

A long regional N-NNW-running feature intersects the site area at the north-eastern corner where a swampy area at low topographical level is dominant. Distinct lineament in electrical geophysical results supports its existence (Albino et al., 1982). The structure has a trace length of about 1 km within the site boundary which would suggest that the lineament should also be included in the site model. All the lineaments discussed here are added to the proposed site model (see Figure 7-9 later).

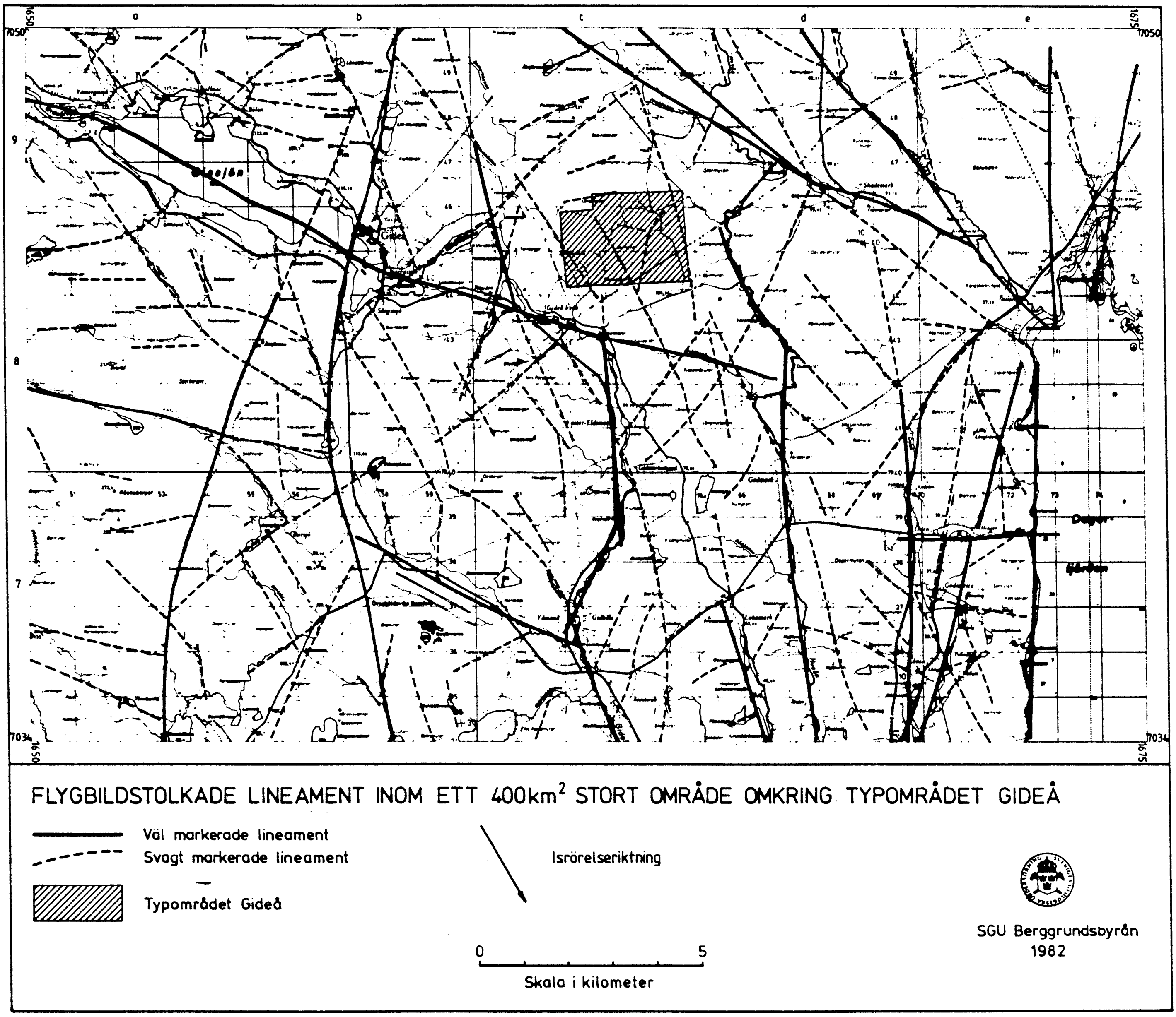


Figure 7-1. Regional lineament interpretation map (Albino et al., 1982).

The regional lithological map shows some bedrock units which may be of concern from uncertainty point of view. An excerpt from the map is shown in Figure 7-2. In the southeastern part the NE-SW trending Ulvödiabase is likely to be a gently dipping structural unit. More about this is said later in connection with subhorizontal diabase, see Section 7.3.2. On the western side of the site there is a large outcrop of Revsund granite, coarse-grained and porphyritic in texture. Amphibolites and granite-granodiorites occur along the formation boundary. The rock formation and its discontinuity area might be a structural unit if it is fractured. There have been also cases when the permeability in coarse-grained rocks has been higher (See for example the study of drilled wells by Rönkä, 1983).

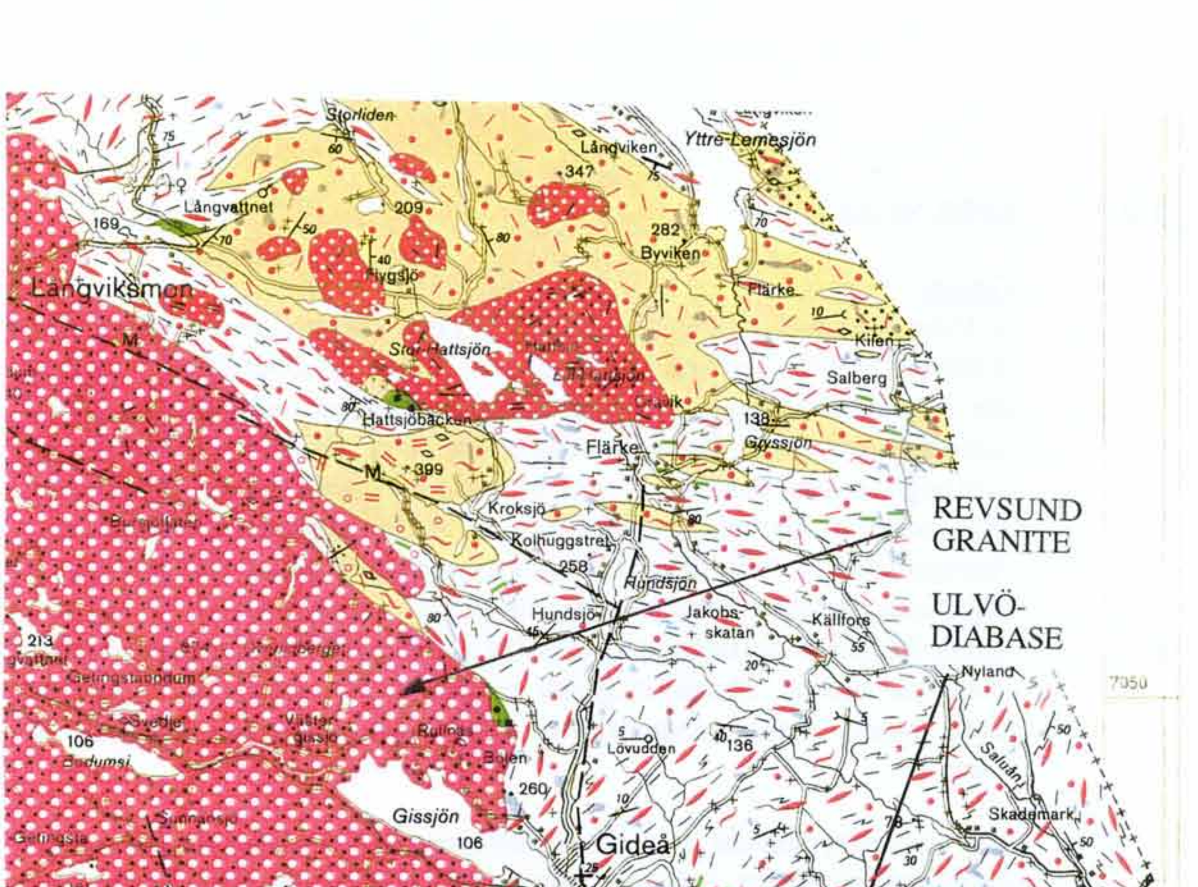


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Figure 7-2. Excerpt of the regional lithological map (Lundqvist et al., 1990).

7.2 SITE SCALE

General

At Ceberg the area used as a target area is clearly defined and covers 6 km^2. Within the site the level of the topography varies by about 45 m. Overburden conditions have been mapped using two seismic refraction lines, the maximum interpreted thickness being about 16 m. The soil is composed of peat bog areas and moraines. Clays are not encountered but the topography level suggests that clays could exist in the topographical depressions. Approximately 15% of the bedrock is exposed which means that the rock is either outcropped or very close to the ground surface. At the Ceberg site simple line and area configurations of the geological and geophysical studies have been applied. The investigation programme was carried out in a single phase project. Measurement and line configurations are shown in Figures 4-5 and 4-6.

The dominant bedrock is 1900 million years-old metamorphosed veined gneiss and migmatite. Intrusive granites and pegmatites which occur have been interpreted as being conformant with the foliation and folding or being post-orogenic. The dominant foliation trends NE-SW. A distinct feature is the occurrence of diabase (dolerite) dykes, mainly in the E-W direction. A large regional diabase dyke outcrops on the southeastern side of the study area.

The steeply dipping fractures occur mainly in the N-S, NE-SW and WNW-ESE directions. The modelling of the lithology is based on a folded orto-paragneiss structure concept which is intersected by thin and steeply-dipping diabase dykes.

The maximum of the horizontal stress field is mapped as lying in the N67°E±19° direction (Ahlbom et al., 1991). Some topographical lineaments and their continuity may be over-represented in the WNW-ESE direction which is the flow direction of the ancient glacial sheet. On the other hand, features close to the N-S direction are hard to detect.

Modelling

Assessment of the model for Ceberg at site scale has focused on the borehole data which is available from summary reports. Data for each separate borehole was studied first. The boreholes as a whole were analysed. The uncertainty of both the discrete structures and the structural system as a whole was studied.

The recently updated Ceberg structural model includes 12 deterministic zones (Hermanson et al., 1997). Some of these have been observed by borehole investigations, see Table 7-1 below. Fracture zones explain 20 fractured sections of the total of 42 encountered in the core drilled boreholes. The diabases provide an explanation for five more. The remaining 17 unexplained fractured sections are 40% of the total amount (42).

Table 7-1. Fractured sections in boreholes.

Bore-hole	The amount of structural zones in the boreholes *)	The amount of additional frac. sections *)	Structural remarks	Lithological remarks
KGI01	0	1		
KGI02	1 (4)	6 (4)	Previous Zone 1 section is now unexplained	4 mafic dykes, (D1 and D3 are frac. sections)
KGI03	2	2		Long ~110 m greenstone section
KGI04	3	0		
KGI05	2	1 (0)		
KGI06	3	2		(Diabase D3 is a frac. section)
KGI07	1	2		Greenstone at 360 - 460 m
KGI08	0	5		
KGI09	1	1		Diabase D4b is part of zone 3A
KGI10	1	1		(Diabase 2 is a frac. section)
KGI11	2	3		(Diabase 4a is a frac. section)
KGI12	1	1		
KGI13	0	0		
Total	**17 (20)**	**25 (22)**	-	-

*) Data refers to the report of Ahlbom et al., 1991. The values and clauses in parenthesis refer to the report of the updated structural model (Hermanson et al., 1997). Fractured sections have more than 10 pcs/m and length more than 10 m.

Most non-conceptualised and non-interpreted fractured sections occur in boreholes KGI03, KGI07, KGI08 and KGI12, which are located near each other in the southern part of the site (displayed in Figure 4-5). KGI02 and KGI06 both contain two non-interpreted fractured sections. The majority of the fractured sections in boreholes KGI07 and KGI08 are also associated with increased or highly increased hydraulic conductivity.

Conclusion 1: Many of the fractured sections observed directly are non-interpreted. An estimate is that as many as 40 - 50% more discrete structures could exist in the volume covered by the core drilled holes. When conceptualised as site structures the diabase dykes explain ~10% of the fractured sections in the boreholes.

Conclusion 2: The south-western part of the Ceberg site is highly likely to include several undetected structural units. In the group of boreholes KGI03, KGI07, KGI08 and KGI12 some structural sections may belong to the same units. The bedrock block itself occupies a region of flat topography with swamps which has obscured the detection of topographical lineaments. Detailed lineament analysis of the Ceberg area has not been carried out. The existing stronger forest vegetation and strong variations in the galvanic resistivity maps may indicate thick and variable overburden conditions. The overburden may also have masked some of the structural units not detected by the surface geophysics.

In the southwestern part of the site the fracture map produced by Ericsson & Ronge (1986) indicates major fracture strike directions towards the N-S, NNE-SSW, ENE-WSW and WNW-ESE. The supplementary site structures may conform to these. The extension of Zones 9, 11a, 11b and 12 (Fig. 7-9) (Hermanson et al., 1997) to the west and southwest could be considered.

Ceberg borehole orientations were plotted and are shown in Figure 7-3. All 13 holes have a steep or moderate dip. Three loosely-definable groups can be identified: boreholes towards southwest - north (47%), boreholes towards southeast - south (28%) and steeply-dipping boreholes to the north - northeast (25%).

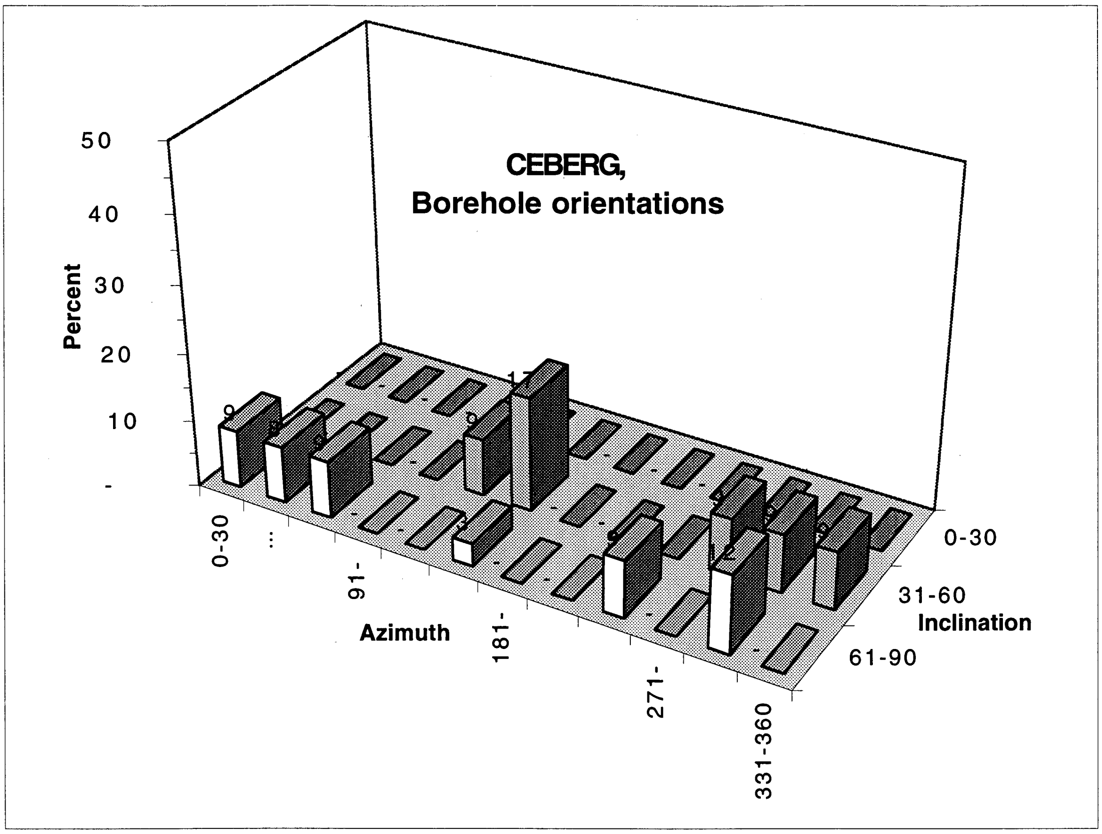
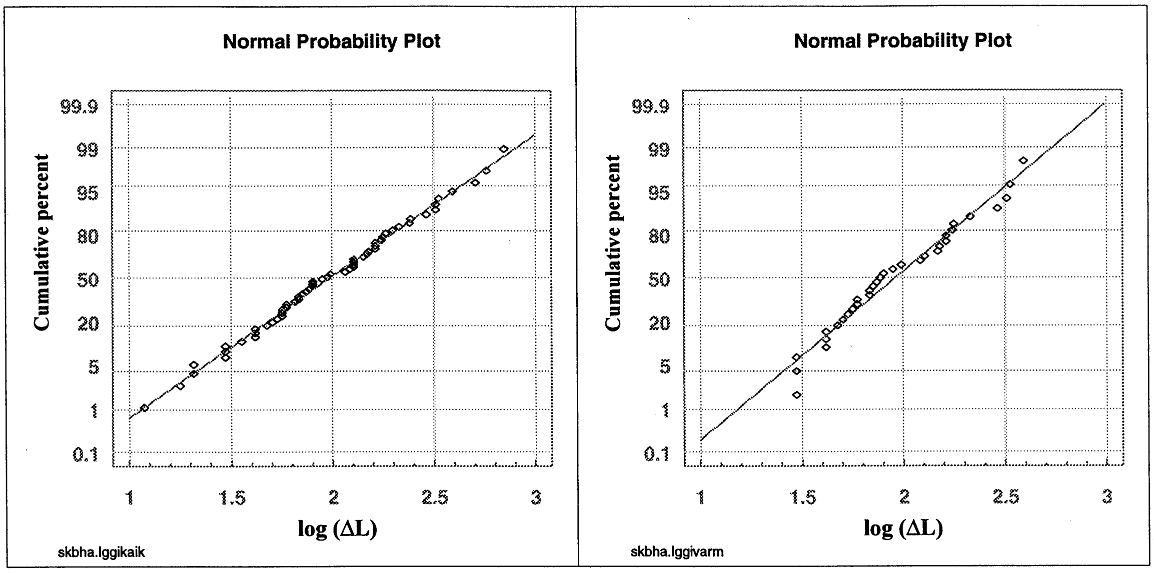


Figure 7-3. Orientation distribution of Ceberg boreholes.

A supplementary way of analysing the Ceberg borehole data is to use the statistical method developed. The purpose here is to obtain an estimate of the frequency of the zones in the bedrock volume. The lengths between the structural intersections in the boreholes KGI01 - 13 are plotted as input data in Figures 7-4 a-b. The log-normal probability plots show excellent fit and the statistical significance level for the Ceberg data is high. The cumulative 50% value for the boreholes is almost the same with or without the end sections. Only the real lengths between the fractured sections are therefore used in the estimation process. In Fig. 7-4b the cumulative 50% value is 2.0 which corresponds to $\Delta L = 100$ m for the Ceberg.



a **b**

Figure 7-4 a-b. Statistical plot of the Ceberg structural density. Plot a) includes all borehole sections, b) real sections only.

The model of the Ceberg structures consists in the main of subvertical fracture zones. These have dominant E-W and NNE-SSW orientations. In addition, a few SE or SSE running zones have been localised. A regular 3-D 60° model is the most representative structural system but regular 3-D cubic model is also applicable. The regular 3-D 60° model gives an average zone interval of 160 m. The regular 3-D cubic model gives a value of 140 m as the average distance between structure planes. As a consequence of this, the Ceberg fracture zone structures seem to have an average distance of 140 - 160 m between the zones along each main orientation.

The value for average separation of structures is the highest of the three sites studied. At Ceberg the boreholes cover the site well from a geometrical point of view and represent many orientations. They were drilled to assist with general mapping as well as studies of discrete structural units. The location and orientation of the boreholes should not impose any bias on the analysis results.

Geological conceptualisation and structural model:

In the Ceberg area, the surface traces of the site structures are typically undulating. Zones 3, 4, 5 and 9 can be noted particularly in this respect (see Fig. 7-9). The forms of the zones are replicates of the anomaly forms found in interpolated galvanic resistivity and Slingram EM anomaly maps. It is possible that the winding forms are partly artefacts resulting from the variations in overburden.

The lowest electrical resistivities (< 2000 Ohmm) occur where the sediment is at its thickest and where peat and/or clays exist (for example, at the N-S refraction seismic line where 16 m of sediments were interpreted at the location of Zone 5). In contrast to this, the high resistivity anomalies are met over moraine hills where thick layer of unsaturated sediments exist. The anomalies originating from the bedrock are likely to be of smaller magnitude.

The gradient method has been used in electrical resistivity profiling at Ceberg. Theoretically the gradient method is a good choice for bedrock investigations because the intention is to pass the largest part of the electric current through the bedrock. As a result it has a relatively high depth penetration and detection capability concerning electrically conductive targets. The percentage of the current flowing within the overburden layer can be expressed in terms of dimensionless parameter $\alpha = 2S\rho/L$, where S is the conductance of the overburden, ρ is the resistivity of bedrock, and L is the distance between the two sources of the current (Edwards & Howell, 1976). For bedrock studies the distance L should be chosen so that $\alpha < 1.0$. At the Ceberg L was 1500 m and typical values of S between 0.005 - 0.05 and ρ of around 20000 Ωm yields values of 0.13 - 1.33 for α. This means in addition that 10 - 55 % of electric current flow is channelled through the Quaternary overburden layer. However, surface features can cause a variety of anomalies. It is also a fact that discrimination between the anomalies originating in bedrock and overburden is difficult.

A resistivity map (Albino et al., 1982) uses a linear scale for apparent resistivities. Resistivity is a logarithmic unit. It is most likely that the intention has been to emphasise low end resistivity anomalies in the presentation. A possible negative effect is the over-emphasisation of soil type variation-related factors. The other resistivity method, horizontal coil Slingram EM with a frequency f = 18 kHz, has also maximal electromagnetic coupling with the horizontal, conductive layers that happen to be present at this site.

Finally, the conceptualisation and style preference at Ceberg can be traced to geophysical resistivity maps which incorporate an overprint effect of soil variations at the site. At least some of the winding trace details are artefacts. Uncertainty of the locations of structures is increased.

Mise-à-la-masse measurements:

The charged potential (mise-à-la-masse) measurements and their interpretations are very unreliable and speculative at the Ceberg site. The basic uncertainty arises from the fact that measurement configurations extended too great a distance from the current sources have been used, anomalies are speculative and that no advanced modelling techniques were available at the time when the interpretation was made (Magnusson, 1985). These mise-à-la-masse results should not be used for judgement on or interpretation of the geometry of the structures. This is of concern for Zones 1 and 2 and for Zone 6.

Seismic 2-D and 3-D tomography experiment:
An ambitious and demanding seismic 2-D and 3-D tomography experiment was carried out at Ceberg during the period of the Stripa project (Pihl et al., 1987). Tests were made in 2-D configuration between percussion hole 13 and the core drilled hole KGI01 at coarse scale and between holes 6 and 13 in more detail. The 3-D tomography survey took place between holes KGI01 - KGI02 - KGI11 (locations shown in Figure 4-5). They were used as shot holes and additional shot points were located in the percussion holes and at the surface. After the 3-D inversion some structural information can be seen at depths between 25 and 225 m below the surface. The results have been used in a recent model update by Hermanson et al. (1997). Seismic velocity anisotropy has been discussed but not analysed using the Ceberg lithology model or data. The gneissic host rock at Ceberg is likely to account for some small anisotropic effects.

7.3 DISCRETE SITE STRUCTURES AND THEIR CONSIDERATIONS

7.3.1 Current model structures

The Ceberg site has two sets of geological-structural features. One of these is the fracture zone set, the other is the set of observed or interpreted diabases.

Following the diabase theme, the mapped subvertical, mainly E-W trending dykes are considered together with the possible existence of a major, deep-seated subhorizontal one. The dykes have been investigated by surface mapping and from borehole intersections. Frequently the dykes are narrow, 1 - 2 m in thickness and are either fractured or intact. The diabase has been intruded during the Jotnian age, opening faults and fracture zones and filling them with igneous material. The dyke itself can be fractured or intact depending on the extent of fracture generation during cooling or subsequent movements along and across the strike. However, in several cases the fractured borehole section is located in the vicinity of the dyke and can be attached to it both genetically and geometrically. This phenomena has been observed several times in connection with the older diabase dykes in Finland (for instance, at the Romuvaara and Veitsivaara nuclear waste study sites, (in reference Saksa et al., 1992)).

SUBVERTICAL DIABASES:

The east-west trending diabase dykes could be considered to be fracture zone structures at the Ceberg site. Those dykes which have a thickness larger than 3 - 4 m in boreholes can be site-scale structures. Their conceptual parameters are comparable with the other existing Zones 1 - 12. The dykes to be considered are D1, D2, D3, and possibly D5a-b, D6 and D7. The data on diabase dykes is given in Table 7-2.

Table 7-2. Main conceptual modelling parameters for diabases.

Diabase code	Bore-hole	Thickness	Dyke fractured	Increased k in dyke	Contact zone fractured	Increased k in contact zone
D1	KGI02	2.4 m	No	Yes	Yes	Yes
	KGI03	4.1 m	No	partly	No	Yes
	KGI13	4.8	No	No	No	No
D2	KGI06	12.8	No	No	No	No
	KGI10	4.8	Yes	No	No	Yes
	KGI11	2.6	No	No	No	No
D3	KGI02	12.8	Yes	No	Yes	No
	KGI06	25.8	Yes	No	Yes	No
	KGI11	1.8	No	No	No	No
D4a	KGI09	1.9	No	No	No	No
	KGI11	1.0	Yes	No	No	No
D4b	KGI09	2.4	Yes	No	No	No
	KGI11	1.8	No	No	Yes	No
D5a,b	No data					
D6, D7	No data					
D8	KGI08	1.4	No	No	No	No

Diabase dyke D1 is the most likely for inclusion as a model fracture zone. Dyke D3 is definitely a major zone if fracturing degree and thickness are the dominant factors used in discrimination. Parallel dykes D4a and D4b may form a local fracture zone but no increased hydraulic conductivity has been measured. Dyke 5 is connected to Zone 4 and Dyke 6 to Zone 5 in the current structural model. In Figure 6-7 (Hermanson et al., 1997), four borehole sections contain sections of diabase longer than 5 metres. Two out of four dykes have a calculated hydraulic conductivity (k value) higher than 10^{-8} m/s.

Dyke D7 is a E-W trending diabase along the southern border of the Ceberg grid area. Magnetic data interpretation has yielded an estimate of a steep dip towards the south. Interpretation of the resistivity map (Albino et al., 1982) also indicates an east-west running low resistivity zone at the same location.

Dyke D7 may be connected to a fracture zone running from the east outside the grid area towards the west. The dyke may end after crossing the seismic refraction N-S survey line. There is an interpreted low velocity section at the southernmost end of the line which is probably related to Dyke 7.

To summarise, the following facts about diabase bodies would support their being considered to be model structures :
- elongated bodies with high continuation,
- thickness between 1 - 10 m,
- related to fractured borehole intersections,
- increased hydraulic conductivity either within the zone or in the contact zone. Locations of diabase dykes D1 and D7 are shown in structural model surface map, Figure 7-9.

7.3.2 Additional structures

Subhorizontal regional diabase has been discussed previously in connection with the regional and site scale modelling (Ahlbom et al., 1991, Hermanson et al., 1997). The possibility and uncertainty stems from the fact that there is a major regional diabase dyke (Ulvödiabase in Fig. 7-2) which outcrops near-by with a gentle ~15° dip towards the SE. The width of the dyke is about 1 km at the surface. The properties of the dyke have not been mentioned but it is both a major discontinuity and a major heterogeneity in the veined gneiss and migmatite host rock.

Concerning the site model the possibility of a major fractured, subhorizontal diabase dyke, below a vertical depth of 700 m has been checked by forward geophysical modelling. Modelling results are shown in Figure 7-5. The magnetic anomaly is very small, less than 10 nT increase in the total field. It shows that the dyke is not detectable by the applied surface geophysical magnetic measurements. Consequently, there is no hard data available which could exclude its presence.

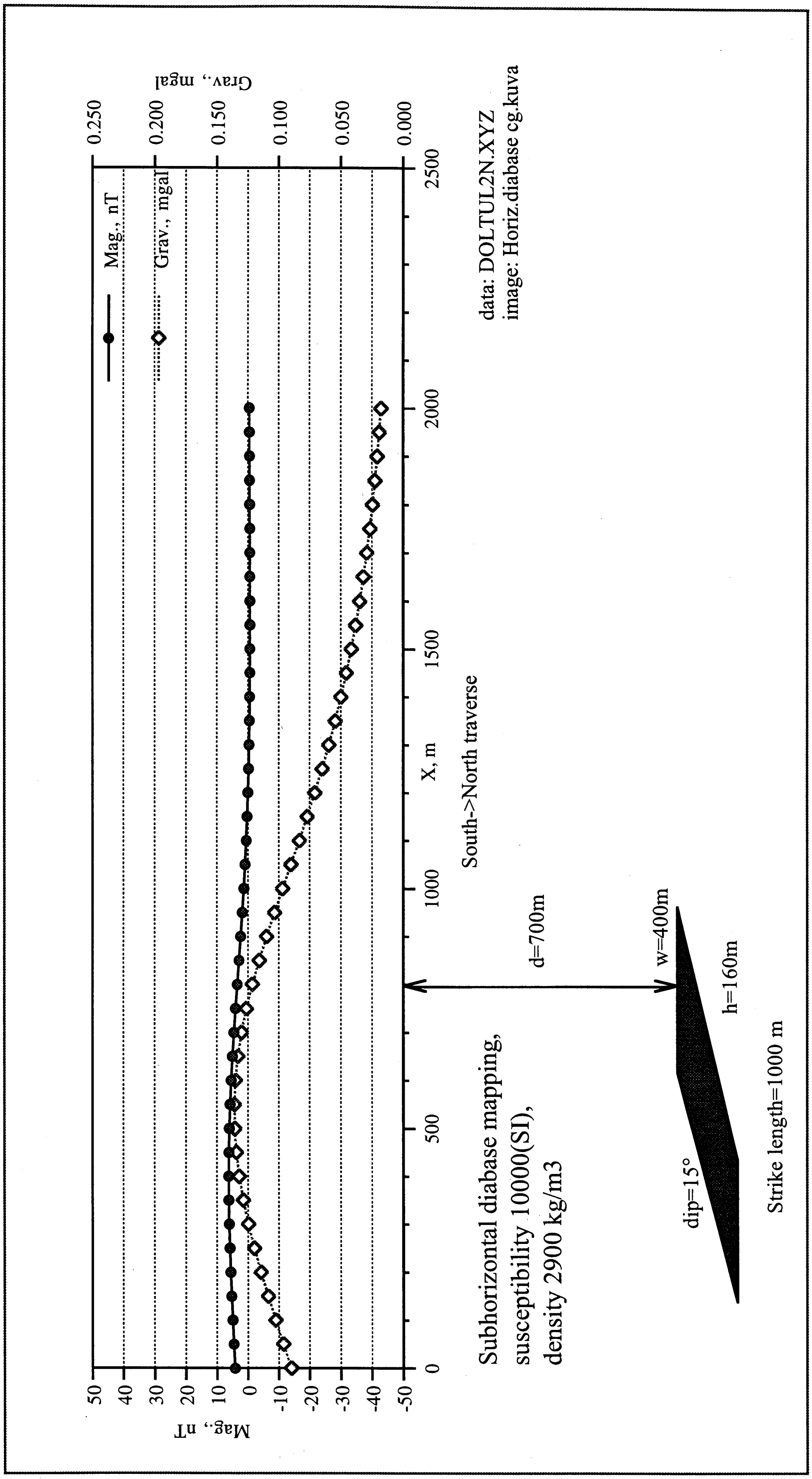


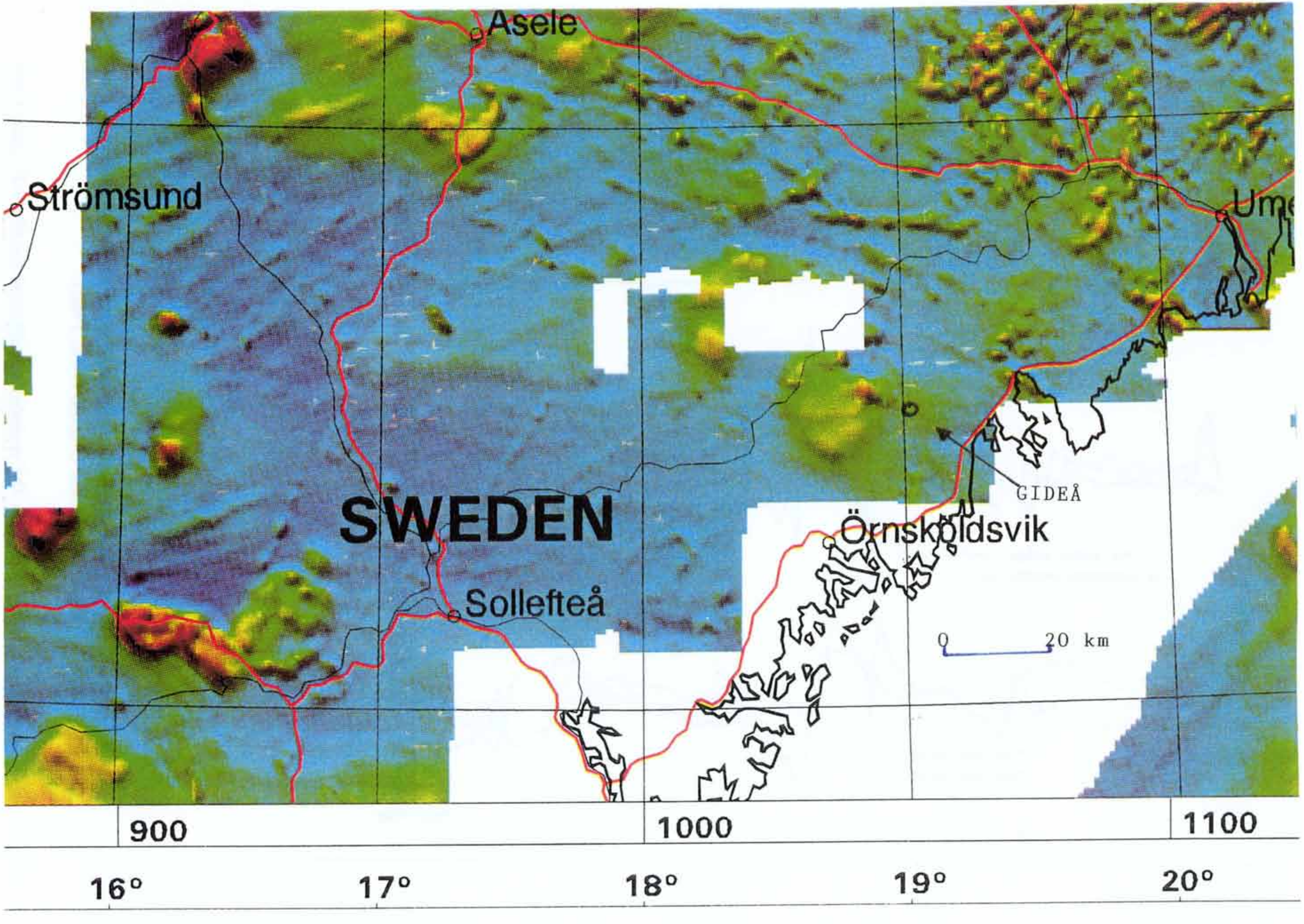
Figure 7-5. Thick subhorisontal 3-D diabase, magnetic and gravity profile over in S-N direction. Model parameters: 3-D plate area in horizontal plane 1000 x 1000 m, dip 15°S, upper surface h=700m, width=400m, susceptibility k=10000 (SI), height=160m, external field F0=51000 nT, field inclination I=74°, declination D=1°. Plate vertical thickness is 103 m.

There is the interesting detail that the magnetic contour map of the site displays a small trend in increasing magnetic total field values from south to North. At the south the base level is ~-20 nT and in the North it is ~+20 nT. This fits quite well to a situation of a regional diabase dyke which would dip gently to south and would have its upper surface on the Northern part of the Ceberg site.

The regional lithological map indicates two possible outcropping sources for this. One possible source for the anomalous trend could be the southward-dipping large diabase body (Ulvödiabase), but anomalies from this are very small as can be seen from Fig. 7-7 later. The other and most probable source of the increasing trend could be the Revsund granite formation in the west (see Figure 7-2). However no good magnetic map is available either in map sheet or in regional scale. The source is difficult to identify from Mid-Norden 1:2000 000 map, part of which has magnified for Figure 7-6 (Mid-Norden Project, 1997). Using a little imagination, the trend can be seen. The source of the magnetic anomalies is not known.

(next page)

Figure 7-6. Örnsköldsvik region in Mid-Norden magnetic map, scale magnified to 1:1,000.000 (Mid-Norden Project, 1997).


Asele
Strömsund
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SWEDEN
GIDEÅ
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0 20 km
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17°
18°
19°
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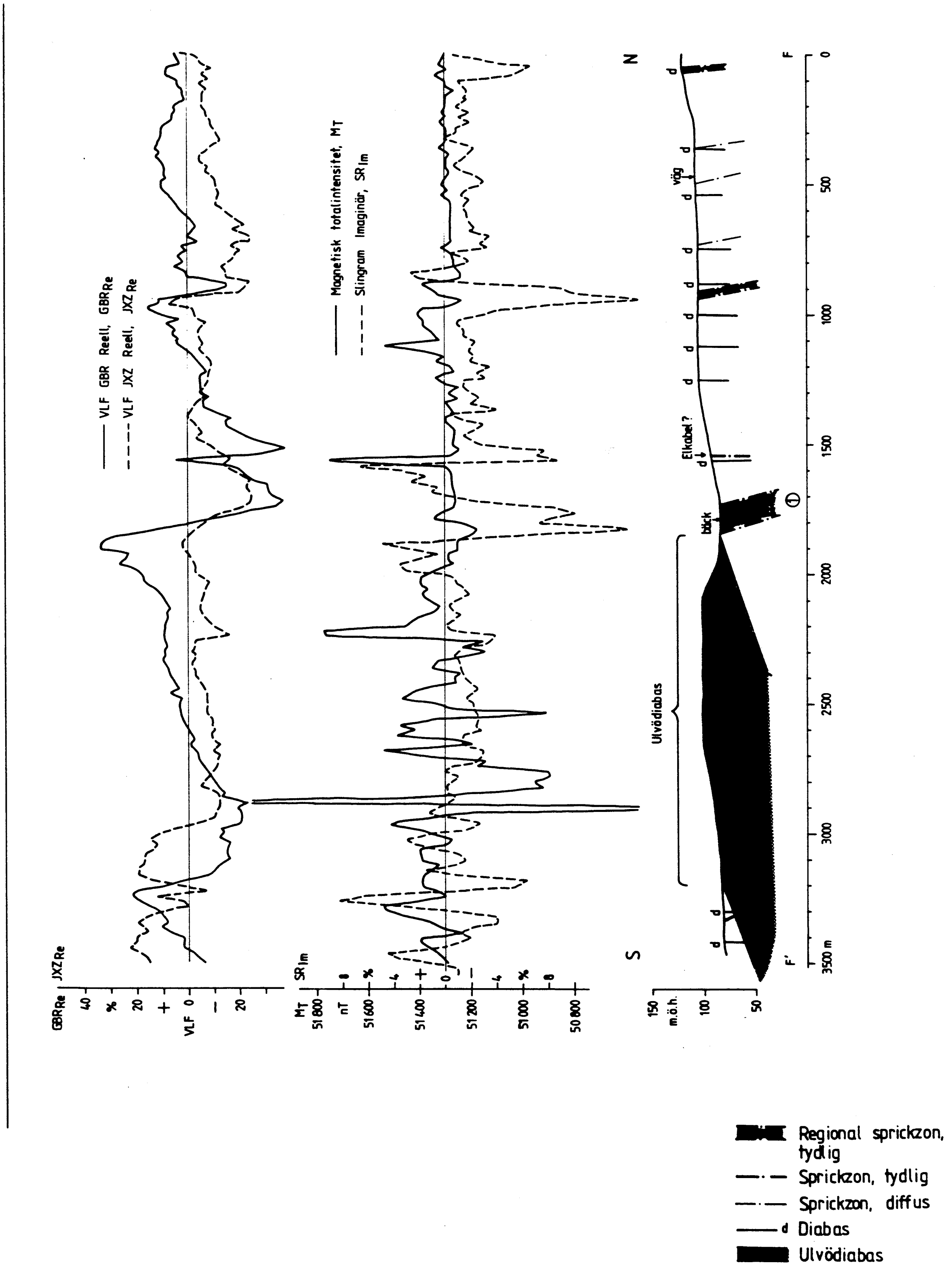


Figure 7-7. Geophysical magnetic and electromagnetic measurement profiles F-F' over Ulvö diabase (Albino et al., 1982).

Albino et al. (1982) reports the regional geophysical profile F-F' over Ulvö diabase which is reproduced in Figure 7-7. Magnetic anomalies are only local peaks and surprisingly small. Strong heterogeneity and variation seems to occur within the dyke. Clear anomalies both in VLF and Slingram EM are found at the foot-wall and hanging-wall contacts with the diabase. This supports the concept that the diabase dykes are linked to the fracture zones. The fracture zones may either be conformant to the dyke contacts or separate. A slight increasing trend from south to north in the total magnetic field can be detected.

It was noticed that the results of the geophysical reconnaissance lines were interpreted in Albino et al. (1982). Numerous locations of major and minor fracture zones, and the diabase dykes, were mapped. The results describe the Ceberg site at semi-regional scale. They have not however been used in development of the structural model.

Pegmatite dyke:
One major north-south trending pegmatite vein might be reconsidered as a major or minor fracture zone in the bedrock model. The dyke location is shown in Figure 7-9 by the label PGM. Hermanson et al. (1997, Figure 6-5) have analysed the hydraulic conductivities of intersected pegmatite sections. If a section width equal to or greater than 5 m is used as a threshold value, 4 sections out of 13 (30%) have hydraulic conductivities higher than 10^{-8} m/s. Although very few samples are available, some of the longest pegmatite sections seems to be hydraulically conductive. The rock type surface map indicates one (set of) N-S running pegmatite(s), total strike length 500 - 1300 m. Typical width appear to be around 5 m. During field excursions the outcrops at ground surface level exhibited a high degree of fracturing).

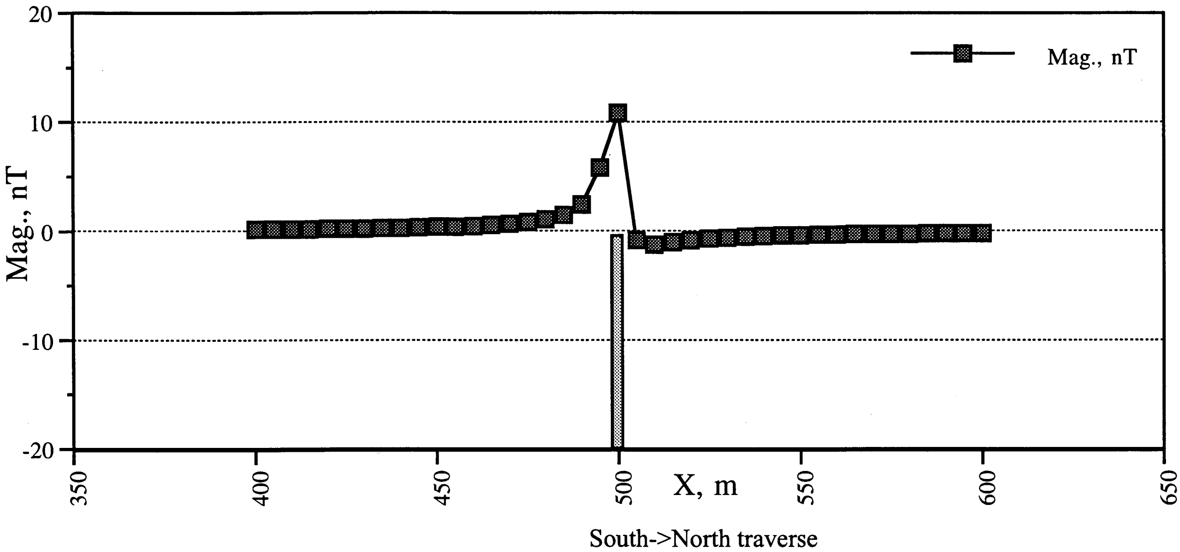
Supplementary zone:
It could also be considered whether the fractured sections at KGI01 (500 m) and KGI02 (400 m) can form an ENE-WSW striking zone. Granitic veins are found in both holes. The structure may follow the mapped foliation direction and, if conformant, would dip tentatively 41 - 60° towards NNW. The trace at the surface would run through locations approximately 400 m to the south of KGI01 and 150 - 200 m to the south of KGI02. Interpretation of the resistivity map shows several weak electrical anomalies along the zone. A tentative location for the structure is given in Figure 7-9 and is marked with the code SZ.

7.3.3 Uncertainty of diabase dyke interpretations

There is a certain degree of uncertainty about diabase dyke widths and interpreted dips. During the surface investigation phase the diabase thicknesses mapped have varied between 0.5 - 10 m (Ahlbom et al., 1991). Jotnian age diabases were found to be steeply dipping. In magnetic ground measurements the station interval has however been rather sparse (20 m) along N-S profiles. This may have several consequences concerning the interpretation of dykes:

A) Detectability of diabase dykes:
Several of the dykes D1-D7 establish themselves as weak (less than 50 - 60 nT) magnetic anomalies on surface maps (Hermanson et al., 1997, Fig. 3-3). Depending on the position of the closest sampling station in respect to the location of the dyke, the anomaly may vary from profile to profile or almost vanish. To see this, take every 4th point along the profile in Figure 7-8 below (sample interval 5 m) using a random start point and see the varying or vanishing forms of the dyke anomalies! Some weakly magnetised anomalies (dykes) may have been missed or only partly detected and some interpreted faulting indications may only be apparent. This is especially true when account is taken of the realistic magnetic geological noise level at the Ceberg site (estimated to be about ±10 nT).

B) Dip interpretation of diabase dykes:
Interpreted dips (vertical and steep) possess uncertainty. Again, the interpreted value is dependent on the location of the stations in respect to the location of the narrow dyke. The uncertainty level increases when less magnetised diabase dykes are of interest.



Magnetic mapping of vertical diabase:
2-D dyke: w=5m, d=2m, dip=90°, k=1000 (SI)

data:DOLTUL1N.XYZ
image: Vert.diabase cg.kuva

Figure 7-8. Magnetic field profile over a thin diabase dyke. Station interval 5 m. Model parameters: 2-D E-W plate, thickness=5m, dip=90°, k=1000 SI, depth to upper surface h=2m, height=1000m, I=74°, D=1°, F0=51000 nT.

The structural map of the Ceberg site is shown in Figure 7-9. The model covers both the current structures and proposed variants. Proposed additional structures and their notation has already been discussed in this chapter. The location and form of the subhorizontal major diabase is only a sketch.

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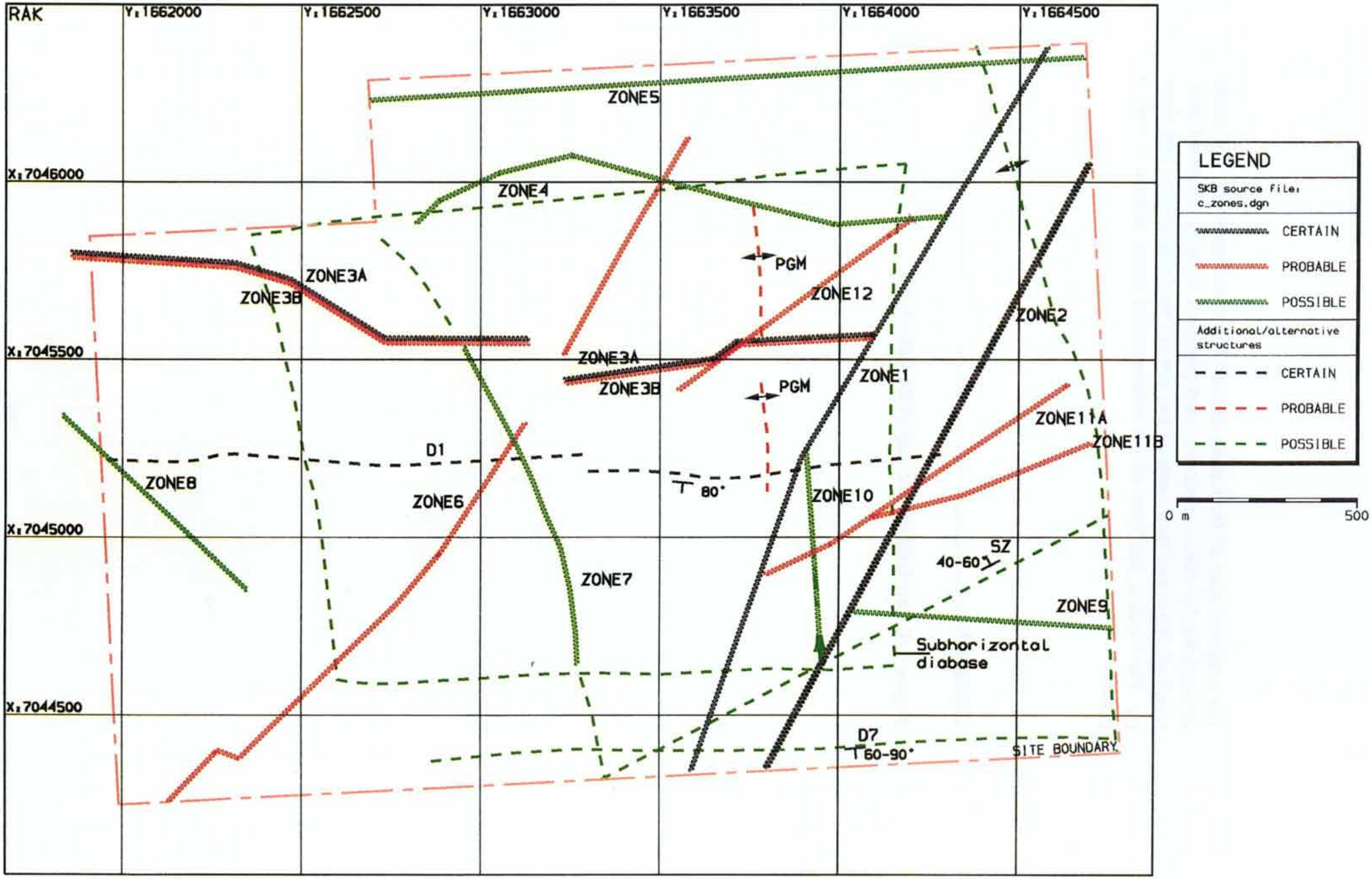
Figure 7-9. Structural surface map of the Ceberg site.


RAK
Y:1662000
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Y:1663000
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Y:1664500
X:7046000
X:7045500
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X:7044500
ZONE5
ZONE4
ZONE3A
ZONE3B
ZONE3A
ZONE3B
PGM
PGM
ZONE12
ZONE2
ZONE1
ZONE11A
ZONE11B
D1
80°
ZONE8
ZONE6
ZONE10
ZONE7
SZ
40-60°
ZONE9
Subhorizontal
diabase
D7
60-90°
SITE BOUNDARY
LEGEND
SKB source file:
c_zones.dgn
CERTAIN
PROBABLE
POSSIBLE
Additional/alternative
structures
CERTAIN
PROBABLE
POSSIBLE
0 m
500

8 COMPARISON AND UNCERTAINTY RATING OF THE ABCEBERG SITES

8.1 COMPARISON BETWEEN THE SITES

It is interesting to discuss and compare the differences between the three sites. All of them have used predominantly the same conceptual basis for the fracture zones. The site models contain local and regional structures having thicknesses of 3 - 5 m and above. Beberg has the lowest threshold value for structures in terms of fracture frequency. This can increase the number of the structures deduced. On the other hand, smaller structures in terms of size have been inferred at Aberg and at Ceberg. On the whole no substantial differences should arise from the conceptual basis as such.

Statistical analysis of the structure frequency (i.e. quantity) yields high values. If the boreholes are representative samples of real earth conditions, a very high number of structures of both local and regional type exist within the site volumes. Large majority of them is of local and minor zone type. An estimate is given in Table 8-1 together with varying structural systems. The number of the structures is calculated per cubic kilometre. Typical values are 26 - 32 at Aberg, 23 - 28 at Beberg and 19 - 22 at Ceberg.

For Ceberg, for instance, this means that in 6 km^3 of rock volume there would exist 115 - 130 fracture zones ranging from local several metre thick zones to regional thick crushed zones. The current bedrock model of the site contains 12 zones. This is less than 10% of the statistical estimate of the number of zones present.

It is important to note that the intersection lengths of the structures in the boreholes are equal to or longer than the real, perpendicular thicknesses of the structures. Quite often a threshold length of 10 m and more has been applied to screen fractured sections. So the real thicknesses of structures are on average half of the section length and certainly less than the observed intersection lengths.

The indication that the number of structures is potentially high may need further assessment. <u>One consequence may be that it is meaningless to consider the established discrete fracture zone models to be a "true" images of the site volumes</u>. This conclusion is valid especially when modelling large volumes of rock using only a few boreholes. The second conclusion is that the realism of the models is not markedly increased if supplementary site assessments or updates suggest the existence of a few more zones. The portion of the structures observed directly and knowledge of structural properties will increase.

Table 8-1. Number of ABCeberg structures with varying structural systems (normalised as km^2 of structure plane per km^3 of rock). The most characteristic structural system is in bold face, underlined.

Site	1-D layer model	2-D column model	3-D regular cubic model	3-D 60° regular model	3-D 30° regular model
Aberg	**<u>26</u>**	32	30	31	31
Aberg with NNW data	**<u>21</u>**	25	23	24	24
Beberg	23	28	27	**<u>27</u>**	27
Ceberg	19	22	21	**<u>22</u>**	22

Aberg seems to have the highest frequency of structure occurrence. Beberg has a lower value and the Ceberg has the lowest. One possible source of bias or error is the borehole configuration itself. The statistical analysis used can yield erroneous values if the drilled boreholes have been predominantly located and oriented to discover many fractured and crushed rock zones. On the other hand, randomly-positioned or intact rock-oriented boreholes should detect equal or less structural units than exist in reality.

Structural-geological trends and anisotropy may be another source of error in structural density results. If we take Aberg "NNW" boreholes which conform to the anisotropy and use data from them, we get a lower structural density. This has been discussed previously with reference to Figure 5-4 and to Chapter 5.2. The density of structures in the case of Aberg NNW data is also shown in Table 8-1. In terms of NNW data, values from Aberg are positioned between values from Beberg and Ceberg. It should be noted that the NNW data takes Aberg to an extreme which is not representative of the site in general. From the anisotropy and structural trend point of view, Aberg and Ceberg are quite closely-related. The Ceberg rock mass has a strong foliation component, folding of orthogneiss, E-W diabases and many boreholes drilled at a steep angle across the NE trend.

Borehole orientations are a good explanation of the general investigation method which is to drill across the anisotropy and the major geological-structural trends. The data presented in the previous chapters can be essentially summarised by stating that the homogeneous geology of the Beberg volume justifies the diverse hole orientations. Aberg and Ceberg both have anisotropic rock conditions, the investigation of which calls for specific hole orientations.

The pre-set goals for the boreholes may cause bias in the structural modelling results and this effect was investigated. The goals for the boreholes were either general bedrock studies, fracture zone checking, or both of these. Each borehole and its length was divided to these classes by using the weights 0.0, 0.5 or 1.0. The weight took values 0.0 for "not studied", 0.5 for "partly studied" and 1.0 for "exclusively studied". Results of this classification are illustrated in Figure 6-1. At Aberg and Ceberg half the borehole lengths fell in the class of general bedrock investigations. The other half was fracture zone-devoted investigations. At Beberg two thirds of the hole lengths fell in the category "general bedrock studies". One third of the number of holes concentrated on fracture zones.

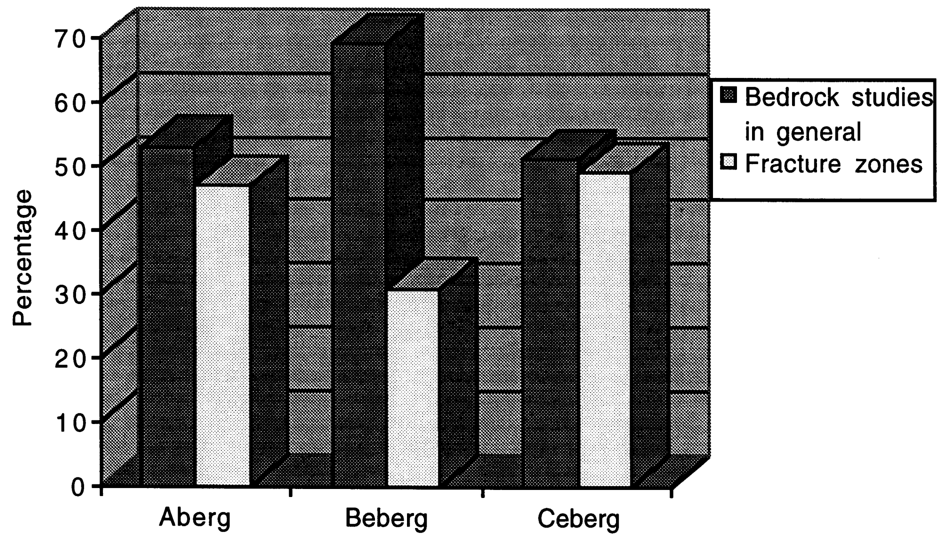

Figure 8-1. Investigation purposes of the ABCeberg boreholes.

Borehole and structural data can be further used to analyse the coverage achieved by the investigations and to compare the sites. The following parameters were tested:

a) Borehole covered volume, (km^3),

b) Borehole covered volume in respect to the volume of the nominal site, (volume per nominal site volume %),

c) The total length of the boreholes per the volume covered by the borehole, (length per borehole covered volume m/km^3).

The volume covered by the core drilled boreholes was defined by the start and end points of each hole. The perimeters were formed by connecting these points on the earth surface and at depth. The volume is then closed by connecting the perimeter areas. In most cases, the boreholes (i.e. lines) form the edges of a polyhedron-shaped volume. The effects of measurement and sounding geometries around the boreholes were neglected in the volume calculation. The solution of the problem is ambiguous and details are beyond the scope of the study. The total length of the boreholes within the volume covered can be termed the borehole density, with the unit m/m^3.

The meaning behind these parameters is to explain the distribution of boreholes and the number of boreholes or borehole-related studies carried out. These can be understood qualitatively. When a site is characterised by a few boreholes which are widely spread, the borehole covered volume is large but the borehole density is low (case a). When the few boreholes are close to each other they have a small borehole covered volume and the borehole density can be high (case b). Boreholes drilled along a line or aligned to the same orientation have a small(er) borehole covered volume but high borehole density (case c). An array of boreholes made from the same starting point with different orientations can cover a relatively large volume and typically, have moderate borehole density (case d). Example situations are depicted in Figure 8-2.

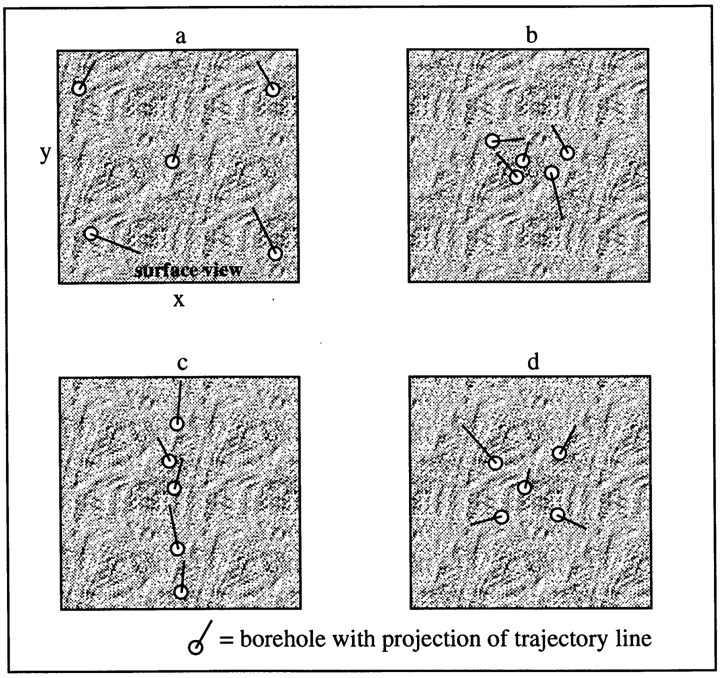

Figure 8-2. Examples a-d of different borehole configurations.

This data on ABCeberg boreholes has been used to produce Table 8-2. All three parameters should be considered in parallel. From the uncertainty point of view, if parameters have high values, uncertainty is decreased for the site in question. Small values of borehole covered volume, borehole covered volume per nominal site volume and borehole length per covered volume, mean problems. In such cases, only a few boreholes exist, they do not cover the site well and they are clustered. The opposite situation is a large number of boreholes which are evenly distributed around the site.

Table 8-2. The characteristic parameters of the borehole configurations.

Parameter	Aberg	Beberg	Ceberg
Borehole covered volume, km^3	very small: 0.186	medium: 0.722	medium: 0.775
Borehole covered volume per nominal site volume, % 1)	very small: 1.9	small: 10.9	small: 12.9
Borehole length per borehole covered volume, m/km^3	high: 47922	small: 8338	small: 10658

1) Nominal site volume is nominal site area • 1000m (depth range).

Optimal values for comparison would be 9.6, 6.6 and 6.0 km^3 for borehole covered volume, 100 % for the borehole coverage for the ABCeberg sites. From Table 8-2 it can be concluded that the situation at Aberg is problematic - clustered boreholes which leave a large volume outside them unsurveyed. Beberg and Ceberg are comparable to one other and have better characteristics. Borehole covered volume is four times larger at Beberg and Ceberg than at Aberg. Borehole clustering is highest at Aberg and less in Beberg and Ceberg. Very large volume of the bedrock 87 - 98 % situates outside the borehole covered volume. There is quite a lot of room for uncertainty because borehole densities (m/km^3) are rather low at both Beberg and Ceberg. The values of quantity m/km^3 mean 48, 8 and 11 m of hole per each 100 • 100 • 100 m block of rock at each site, respectively.

Table 8-3 below shows how many meters of borehole has been drilled per observed structural section in the borehole. It can be assumed that boreholes focussing on fracture zones should find more structural zones and units than general purpose boreholes. This is the case for all the sites in Table 8-3. At Aberg however, the difference is insignificant.

Table 8-3. The average length of intact rock sections in the boreholes.

Average length of intact rock between structures:	Aberg	Beberg	Ceberg
"General bedrock boreholes", m	156	320	1055
"Fracture zone boreholes", m	153	266	404

Figure 8-1 as well as anisotropy considerations show that the concept of bedrock characterisation using boreholes has been much the same at Aberg and Ceberg. But Aberg still has a much higher frequency of occurrence for fracture zones. When it is also noted that the average length of intact rock is the same at Aberg in both borehole categories (Table 8-3), this suggests that the volume of rock covered by the Aberg boreholes is truly more fractured than at Beberg and Ceberg.

There is one more interesting issue to consider for Aberg. It is the question whether the borehole investigations which cover a relatively small volume are representative of the site constitution in general. In other words, whether the volume of the rock investigated at Aberg - namely Äspö island - could be an anomalously-fractured, tectonised unit of its own. This truly could be the case. Quantitative proof of this is impossible here but the following additional facts support this conclusion:

- The frequency of occurrence of fracture zones in the Laxemar boreholes (see Figure 5-5) is a great deal lower than in the Äspö boreholes.
- The refraction seismic lines (see Figures 4-1 and 4-2) were reviewed from the area surrounding the Äspö island. Interpreted low velocity (< 4000 m/s) sections are potential candidates for fracture zone intersections. There were 26 low velocity sections. A higher number of low velocity sections are encountered within Äspö island and its immediate vicinity than elsewhere. If there should be as dense a structural framework elsewhere than in the Äspö subvolume, there should have been many more seismic low velocity anomalies.

8.2 UNCERTAINTY RATING OF ABCEBERG

The uncertainty which exists in the models is made up of components which vary in type. Some of these components have been assessed in this study. Comparisons call for absolute indices or relative ratings. The measures has been considered in the Chapter 3.3 . They all can be derived from presented data and are therefore traceable. Values have been normalised between 0.0 (very low uncertainty) and 1.0 (very high uncertainty).

The uncertainty of structural models at regional scale is rated by the Regional Scale Uncertainty (RSU) index. Factor RSU = 1 / (1 + X), where X is the number of methods used. In this way Aberg has the lowest uncertainty at 0.15, Beberg and Ceberg achieve an equal rating of about 0.33. The Ceberg RSU index is increased by the fact that the reconnaissance geophysics that was carried out has remained unused when developing the model.

A second estimate of uncertainty is calculated for the site scale models. In total, 19 geological and geophysical surveying methods were separately analysed from Table 4-1. Uncertainty is rated by the Site Scale Uncertainty (SSU) index. SSU = 1 / (1 + X), where X is the number of methods 1...20 used. Aberg has value of 0.06, Beberg is 0.11 and Ceberg is 0.08.

A third factor causing uncertainty could possibly be related to boreholes, structural intersections and the degree to which they are explained by the bedrock model. The uncertainty index is simply the percentage of structural borehole sections which have remained unexplained. Data on this is available in the previous chapters from Tables 5-1, 6-1 and 7-1. Borehole Data Uncertainty (BDU) indices are as follows: 0.09 (Aberg), 0.32 or 0.49 (Beberg), and 0.40 (Ceberg). Beberg value 0.49 comes from fracture zones noted in Table 6-1 “structural remarks” -column. Situation at Aberg during post-excavation phase yields a higher value 0.46.

A fourth issue affecting uncertainty could be the representativeness of the investigations in respect to the site conditions. The relative representativity is given by the product of values in Table 8-2 scaled logarithmically between maximum and minimum values possible. Borehole Representativity Uncertainty (BRU) index of Aberg is 0.54, Beberg 0.46 and Ceberg 0.41. All values are rather high. The borehole coverage is in the background of the highest value of Aberg.

The Structural Knowledge Uncertainty SKU = 1 - X, where X is the ratio between the quantity of fracture zones established and the number predicted by statistical analysis. All three sites achieve high values: 0.94 - 0.96 (Aberg), 0.94 (Beberg), and 0.91 (Ceberg). A value close to 1.0 means high uncertainty.

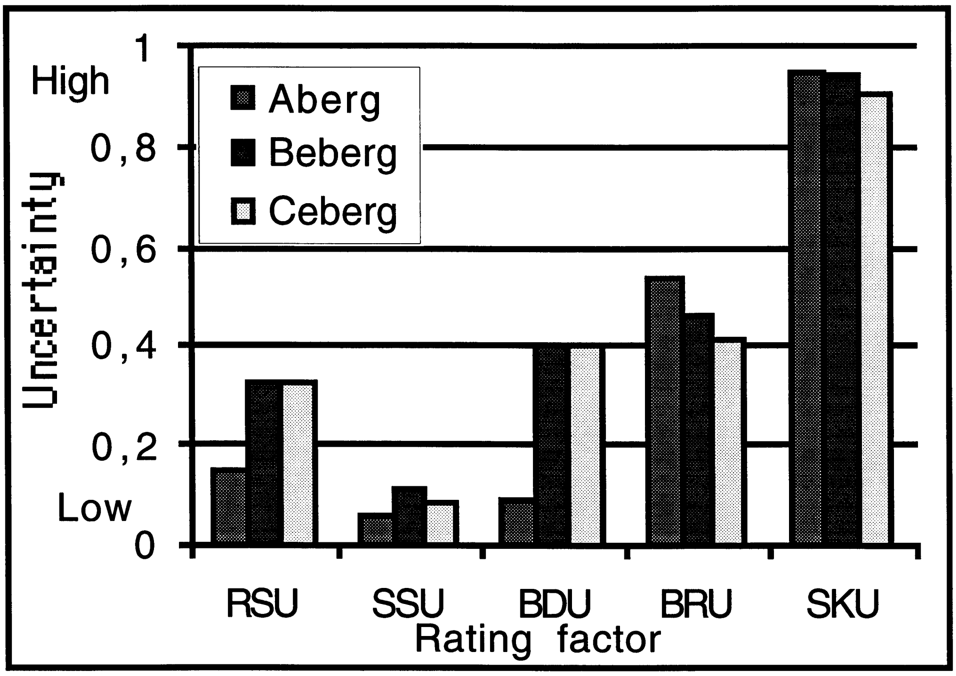

Figure 8-3. Thematic composition of uncertainty estimates. RSU is Regional Scale Uncertainty, SSU is Site Scale …, BDU is Borehole Data …, BRU is Borehole Representativity … and SKU is Structural Knowledge Uncertainty. Indices are explained more in the text part.

Figure 8-3 presents the uncertainty ratings. Although each of the indices have a different basis and theme some conclusions can still be drawn. The Beberg and Ceberg sites have similar kinds of uncertainty and higher values than Aberg for both the RSU and BDU indices. The first of these indices originates from regional scale modelling and the second from the interpretation of borehole data. The size of the indices are a function of the methodology and experience available at the time when the site was surveyed.

The uncertainty about the degree of borehole representativeness is highest at the Aberg site, second highest at Beberg and lowest at Ceberg. The high uncertainty about the Aberg site comes from the clustered boreholes located in the main in the volume of southern Äspö island.

The uncertainty of site structural knowledge SKU is high for all three sites, at Aberg the uncertainty is highest. This shows that achieving comprehensive knowledge is beyond our current levels of expertise. The safety of nuclear waste repositories and their construction must be based on adequate knowledge (the level is to be determined). Further on, it will be necessary to carry out detailed studies of volumes smaller than a whole site.

The fact that all the sites have geological-structural data which could be used to develop a model which would cover a larger area/volume and possess a higher level of realism holds promise for the efforts at characterisation and site analysis.

9 DISCUSSION AND CONCLUSIONS

The uncertainty of geological-structural models was studied for the ABCeberg sites. The evaluation covered both regional and site scale models, the emphasis being placed on fracture zones and on the site scale. The investigation was based on selected summary reports, the inspection of certain items of the most important underlying data, and included a field trip to the Beberg and Ceberg sites. The main tasks set were to estimate where the uncertainties lay, to establish similarities and differences between the site interpretations, to propose possible additional and alternative structures in regional and site scale, and finally to provide forms and parameter tables for use in SR 97 studies.

The high quality and comprehensive nature of the work already carried out at the ABCeberg sites is clearly demonstrated in the reports studied from each site. However, it is not the present authors' job to only say that. Once identified, uncertainties may give rise to new possibilities for analysing the sites in an even more versatile way and thus help to develop the planning of future site investigations by SKB.

Uncertainty is a natural feature of all geoscientific investigations. <u>One</u> part of uncertainty is issues <u>related to conceptualisation</u>: selected geological concepts, structural geometry and property concepts are employed, and inconsistency may exist in the manner in which the concepts have been applied (Olsson et al., 1994). The <u>second</u> type of uncertainty arises <u>from errors</u> in data, in interpretation and in data integration. The interpretation of many geoscientific investigation methods - such as applied geophysics - is indirect and the interpretation models employed do not have unambiguous geometric or parametric solutions. The <u>third</u> type of uncertainty arises <u>from the sampling limitations</u> of the surveying techniques used. Measurements do not cover the whole volume of interest. To mention <u>some others</u>, <u>scale variability</u> is also a source of uncertainty. The <u>sensitivity and detection capability</u> of measurements in respect to the desired targets vary in a spatial manner throughout the studied volume and in a complicated way.

The composite uncertainty is a function of all the factors affecting and methods used. Analysis requires extensive method by method study of the original observations and measurement data and is very laborious. Currently, no readily-applicable technology or software products exist. It would be possible to study this type of uncertainty if methods of geosurveying analysis in this field of application were to be developed. There appears to exist a real need for this.

The techniques used in this study included expert judgment, comparison using tables, assessment of borehole data deterministically and statistically.

A comparison of applied conceptualisations have been made for each site. Additional checks of the original data, methods used and interpretations have been made whenever possible. Since analysis of the uncertainty of structural models has seldom been conducted in the past and no good examples are available, some additional experimental measures and indices were developed and calculated.

The ABCeberg structures are fracture zones of varying types. No major differences in their conceptualisation were noted. Beberg had the lowest fracture frequency criteria. Aberg and Ceberg had smaller size structures included in their models. One source of uncertainty in the site models is the non-existence of fracture and zone information in the scale from 10 up to 300 - 1000 m. Except in the case of Aberg, local scale structures are mostly (Ceberg) or completely (Beberg) missing.

At Aberg the development of the regional model has been performed very well. In the light of the material studied, no new structures could be proposed. The Laxemar borehole KLX01 and -02 data was not used in development of the existing regional structural model.

The Aberg site model contains 11 zones. One major problem and source of uncertainty is that a clear definition of the target area (i.e. the site) is missing. The reason for this has been the laboratory and construction character of the work. After regional characterisation the focus rapidly turned to the southern part of the Äspö island. The uncertainty outside the Äspö island is quite large due to the sea area (coverage 40%) where only very few investigations have been possible. Also, at Aberg, a complicated geological and geophysical surveying configuration has been used. The characterisation process has profited from the fact that an interdisciplinary approach and the comprehensive integration of geoscientific disciplines has been possible.

Structures encountered in the boreholes explain 91% of the pre-investigation phase model. A review of the latest model shows that only 54% of the structures were found after excavation (subhorizontal ones were not observed). The statistical method used for zone analysis gives a high structural density value for Aberg. If interpreted using a model of parallel structures, the structures are situated at 40 m intervals. For Aberg anisotropy reasons an auxiliary statistical analysis was done by using a NNW subset of boreholes. This yields 30 % lower structural frequency. The main uncertainty in site structures is related to the larger fine-grained granites and additional structures in the NW-SE and N-S directions. The existence of a potential subhorizontal zone cannot be excluded. No new discrete structures are proposed for the Aberg regional and site models.

Development of the Beberg regional model has used about half the techniques that are available today. This leaves room for uncertainty in addition to the fact that lithology has not been considered from a structural point of view.

The Beberg site model contains 14 zones. The site target area is somewhat unclear. The reason for this is most probably the two-phase characterisation of the site and the fairly complicated surveying patterns that were used. The model explains 51% of the structures in the boreholes. A great deal of data is non-interpreted (e.g. 49% of the borehole fracture zones). Statistical zone analysis yields moderate structural density: cubic fracture system structures are located at 110 - 130 m intervals. Six lineaments are proposed for consideration as structures. The existence of a deeper seated subhorizontal zone (such as Zone 2) is possible. The non-interpreted borehole sections probably represent local and minor type of fracture zones.

Development of the Ceberg regional model also used about half the techniques available today. There is uncertainty whether fracture zones could be part of the Ulvödiabase and Revsund granite formations.

The Ceberg site model contains 12 zones. The target area is clearly defined. The model explains 60% of the structures in the boreholes. The largest uncertainty exists in the form of non-interpreted fractured sections in boreholes KGI03, KGI07, KGI08 and KGI12. These are all located in southern part of the site. Statistical zone analysis yields the lowest structural density for Ceberg: cubic fracture zone system structures have 140 - 160 m spacing in different directions.

Some known diabase dykes are proposed as supplementary structures. There is uncertainty whether some diabase dykes are still not observed. Also, the occurrence of a major subhorizontal diabase zone is possible. One pegmatite and another supplementary zone are suggested as additional structures. Altogether six additional structures are proposed to be used in the variation analysis of the Ceberg. Some site structures have a winding form. These are probably artefacts resulting in part from larger topography and overburden variations which are a particular feature of Ceberg and in part from the manner the galvanic resistivity gradient method was applied.

Statistical analysis gives high occurrences of structures for all three sites: typically 20 - 30 structures/km^3. Aberg has highest structural frequency, Beberg comes next and Ceberg has the lowest. It might be reconsidered if the established discrete fracture zone models are “true” images of the site volumes. One consequence of this is that the significance of simulations and availability of averagely fractured rock mass for repository is low.

The borehole configuration, orientations and surveying goals were studied to establish whether some preferences or factors causing bias in the statistical results were present. At Aberg and Ceberg, half the borehole lengths fell in the class of general bedrock investigations, the other half were fracture zone-devoted investigations. At Beberg two thirds of the borehole lengths fell in the category of general bedrock investigations, one third of the boreholes were concentrated in the fracture zones. The analysis also showed that the bedrock covered by the Aberg boreholes is truly more fractured than at Beberg and Ceberg. At the Aberg site, consideration was given to whether the borehole investigations which cover a relatively small volume are representative of site conditions in general. Some auxiliary data from Aberg supports the conclusion that the Aberg subvolume (i.e. the Äspö volume) forms a separate, individual, anomalously-fractured and tectonic unit.

Finally, five different indices were calculated to indicate the degree of uncertainty at regional scale, at site scale, of borehole data, of representativeness and of structural density and its understanding. A high level of uncertainty exists for all the site volumes in terms of structural knowledge, Aberg has the highest level of uncertainty. Uncertainty about representativeness is also quite high at Aberg. Both Beberg and Ceberg has high uncertainty indices as far as regional scale models are concerned. Borehole data and its structural interpretation has also prevailing uncertainties at relatively high level at Beberg and Ceberg.

ACKNOWLEDGEMENTS

Many colleagues and organisations participating in SKB's SR 97 studies have provided valuable help and comments during the work described here. We would like to thank Jan-Åke Jacobsson, Göran Nilsson and Pirkka-Tapio Tammela who helped with the field trip arrangements and acted as guides. Per Askling and Ingemar Markström assisted by compiling drawings of field investigations from ABCeberg sites. Valuable background information was also received from Ingvar Rhén, Johan Andersson and Ragnar Ström.

This report has benefited significantly from comments and criticisms made during review meetings. In particular, comments from Raymond Munier, Alan Geoffrey Milnes, Sven Follin and Douglas Walker are acknowledged. Rick McArthur was responsible for checking and editing the language used in the report.

Practical help and useful comments were also received from Timo Äikäs and Jussi Palmu, both from Posiva Oy. At Fintact, Henry Ahokas, Eero Heikkinen and Pirjo Hellä provided additional technical and editorial assistance.

Finally, we are particularly indebted to Anders Ström and Lars O Ericsson of SKB. Their interest in the topic, their continual support and their patience have together made this study possible.

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A APPENDICES

A.1 UNCERTAINTY QUESTIONNAIRE

In the following the uncertainties of the structural models are described according to the outline presented by Hedin (1997).

GENERAL

The geological-structural models are descriptions of the locations, geometries and properties of fracture zones at the given site. The Aberg model was established by interpretation during a pre-investigation laboratory phase by Wikberg et al. (1991) and updated recently by Rhén et al. (1997). At Beberg the structural model was summarised by Ahlbom et al. (1992). The geological-structural model of Ceberg has been recently described and updated by Hermanson et al. (1997). Much of the original interpretation work at Ceberg was carried out and reported by Albino et al. (1982).

Geological-structural models are based on direct and indirect observations and the interpretation of these. One example of direct observation is the mapping of outcrops. Geophysical measurements are observations of physical properties which are indirectly attached to earth properties with the help of interpretation models. Interpretation models are required to represent, interpolate and extrapolate spatial distributions. Interpretation models can be very simple - such as homogeneous earth. More advanced models are the 1-D (layer), 2-D (dyke), 3-D (prism) and polyhedron types.

A geological-structural model is a combination of all the available geoscientific knowledge about a site. The model connects surface data to borehole data and possibly utilises cross-borehole data. A lithological model is largely based on an adopted geological concept and geological style. The cornerstone of a fracture zone model is the assumption of planar like units and their relatively-uniform continuation along strike and dip directions.

USE IN SR 97

Structural models of all three sites are used as the geometrical basis for groundwater flow simulation at both regional and site scale. The studies of repository layouts utilise site-scale structural models as well as analyses of nuclide transport out of the repository volume.

DEPENDENCIES ON OTHER PARAMETERS, RANGES OF VALIDITY, SENSITIVITIES

There are many factors which influence the model data, most of them are the result of geographical-geological conditions. One important factor is the overburden. Thick layers of overburden prevent the execution of outcrop mapping and effectively mask targets from geophysical ground surface measurements. If the thicknesses of overburden vary greatly and electrically-conducting clays are present, the situation is unfavourable. The same applies to underwater areas. Overburden conditions are not a part of geological-structural model but their influence can be implied when more or less structures are interpreted per site or the spatial distribution of structures is skewed.

Sensitivity analyses have not been performed since there are currently no tools to perform such analyses.

TYPES OF UNCERTAINTY AND THEIR ANALYSIS

Types of uncertainty are discussed below.

Geological concepts:

A clearly-formulated, discussed and well-documented geological concept is of fundamental importance to any site. Practically everything in site investigations and interpretations is based on the selected concept(s). Part of the process of conceptualisation is what is sometimes termed "geological style" or "preferences". Personal preferences and the making of subjective, non-traceable decisions are examples of this. Usually, geological style is intended to make models to look like "real earth" without any data being used.

Uncertainty analysis technique available/applied:

Expert judgement of concepts, ideas, lithological and deformation history presented in reports; analysis of supporting data and analogues if these exist; documentation of alternative concepts; discussion of the geological style applied (if any such exists); checking whether the presented concept has been applied systematically (for instance, whether age or faulting relationships in structures have been analysed and if they are consistent with the given model geometry).

Structural geometry (density, form, extensions, planarity assumption)

Major and minor zones are interpreted with help of direct and indirect observations. Planar, elongated forms with large extension along strike and dip are the main geometrical parameters described and assumed. Deterministically-inferred structures form the geometrical framework of the study site.

Uncertainty analysis technique available/applied:

Analysis of the cut-off values of the structure widths, lengths, depth exten-

sions and forms given in the model; comparison against structural data from boreholes; analysis of non-modelled structures found in boreholes; statistical analysis of undulation and bifurcations; statistical analysis of a given structural network in relation to borehole data.

Structural properties (generic data, discrete data, variability):
Structural units are characterised by their increased degree of fracturing, mechanical discontinuity and permeability. If direct observations of the property are missing, the values given are estimates. Typically, a threshold level is specified to separate fracture zones from the rock mass. The variability in the property and its implications might have also been studied.

Uncertainty analysis technique available/applied:
Analysis of the cut-off values of structural properties; comparison with borehole data; analysis of non-*modelled properties in boreholes.*

Errors in data, in the interpretation model, in integration:
Errors ranging from measured data values to erroneous concepts in the integration phase can occur in the site characterisation. These errors may have negligible, minor or possibly even major consequences in relation to the model structures. For instance, errors in field data values may change the orientation of an interpreted mafic dyke, or incorrectly-correlated borehole sections may result in a completely false structural description.

Error propagation is almost never analysed in connection with structural investigations. Some geophysical interpretation software is known to contain "sensitivity analysis functions". These can be used to study the sensitivity of the interpreted model to errors in data values.

Uncertainty analysis technique available/applied:
Checking of original field data from reports and against re-runs in the field; analysis of interpretation models, concepts and sensitivity; alternative modelling tests, error-tree analysis of error propagation effects; expert judgement.

Inconsistency problems:
If definitions and concepts are not given, site characterisation may suffer from inconsistency. Applied rules may change over the course of time - such as the fracture frequency limit (cut-off value) used to separate fracture zones from the rock mass. A classical example of this is a minor structure which is included in a model at a later stage because it appears to be an interesting new finding. In such cases, similar findings from earlier investigations should be also reconsidered, but they often remain unrecognised. Inconsistency is partly a problem of data management and publication.

Uncertainty analysis technique available/applied:
Comparisons of model structure data from different phases of a project against original data; tabulation of structural model parameters; work on developing new models.

Unknown geometry and properties of structures:
This is a difficult problem which arises from the limitations of data sampling in geoscientific surveys. Put simply, "We don't know what we don't know". Model geometries rely largely on indirect interpretations such as lineaments, geophysical anomalies etc. For instance, there is no one to one correspondence between interpreted physical values and fracture frequency.

We can lean on previous similar projects and surveys. Experience is valuable here. The best level of understanding results from prediction-outcome studies if the geosphere circumstances are comparable.

Uncertainty analysis technique available/applied:
Calculation of possible features which would remain undetected by the investigations carried out; calculation of the limits of detectability for different types of structure (geometry, property); expert judgement.

Unknown structures resulting from the site investigation methodology:
This problem is linked to site coverage, site conditions, methods used, directionality of measurements, plus instrumental and geological noise. Our surveys cover a subarea or subvolume for each method. For example, geological mapping is restricted to outcrops and excavations. Geophysical Slingram-type electromagnetic surveys have uncovered volumes between measurement lines and within subsurfaces below its detection limit. Instrument noise obscures geological targets. Geological noise is that part of the signal which cannot be interpreted <u>at the time of the consideration</u>. It is important to note the time-dependence which accounts for our evolving understanding, concepts and methodology. Normally the geological noise component is larger than that of instrument noise.

The composite uncertainty is a function of all the methods used. Analysis requires extensive method by method study of the original observations and measurement data and is very laborious. Currently, no readily-applicable technology or software products exist. The study of composite uncertainty would be possible if methods of analysing geosurveys in this field of application were to be developed. A real need appears to exist for such development.

Uncertainty analysis technique available/applied:
Estimates of individual survey methods can be carried out to a limited extent. Problem (i.e. model structure)-specific scope calculations can be realised on a case-by-case basis.

QUANTIFICATION OF UNCERTAINTIES

The following treatment of uncertainties has been carried out in this report:
- analysis of concepts and definitions (all sites),
- statistical analysis of structural system (all sites),
  raw borehole and surface data (all sites),
  calculations with structural system (all sites),
- error and sensitivity analyses (Ceberg diabases),
- analysis of discrete geological-structural units (Beberg, Ceberg),
- alternative and additional structures (all sites) and
- calculation of thematic uncertainty indices (all sites).

DEPENDENCIES ON OTHER PARAMETERS, CORRELATIONS

In some cases, there may exist a lithological control for structural models. If this is so it is a useful and traceable aid for use in structural modelling. At Aberg, some fine-grained granites have a high degree of fracturing but their shape and continuity are not known. Beberg has no site-scale three-dimensional lithological model and control. At Ceberg, the diabases and the interpreted folded gneiss lithology are useful indicators of potential structures which can be attached to them.

TREATMENT IN SAFETY ASSESSMENT

Some additional structures identified in this report should be considered for analysis in the SR 97 study. Statistical density analysis of structures provides a model for each site of what the real situation could be. It is quite clear that the currently-established structural models of all three sites provide only a very much oversimplified picture of the real situation. On the other hand, it is also possible that the types and properties of the structures inferred are indeed characteristic and function as reliable samples of the group to which they belong.

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A.2 UPDATED PARAMETER TABLES FOR ABERG AND BEBERG

In the SR 97 safety analysis, formalised lists of the available geoparameters are used. In connection with the Aberg site the parameter list is shown in Table A-1.

Table A-1. The Aberg parameter table.

Next two table pages.

The geoparameter list for Beberg is shown in Table A-2. The list for Ceberg has been published by Hermanson et al. (1997) previously.

Table A-2. The Beberg parameter table.

Next two pages after Table A-1.

ABERG - Pre-investigation phase (references from construction phase are in parenthesis)

Subject area \ Influence, meaning	Input data to the structural model uncertainty analysis		Output from the structural model uncertainty analysis		
	Type	**Source**	**Treatment**	**Output**	**Reference**
GEOLOGY					
Topography					
Topography					
Lithology					
Rock mass lithology					
Rock distribution	Core logs, surface map	Wikberg et al. p.11-14,p22-25, p.41-45	Assessment		
Xenolites	Report text	(Rhén et al.-97 p.87-91,p.95-102)	Assessment		
Veins and dykes	Report text	as above	Assessment		
Rock contacts	Report text	as above	Assessment		
Age	Report text	(Rhén et al.-97 p.87-90)			
Ore potential, industrial mineralisations					
Rock type description					
Mineralogy					
Grain size					
Mineral orientation					
Micro fracturing					
Density					
Porosity					
Susceptibility/gamma radiation etc.					
Alteration and weathering					
Structural geology					
Ductile structures					
Folds	Report text	Wikberg et al. p.16-17			
Foliation	Report text	Wikberg et al. p.16-17			
Schistosity					
Mylonites					
Banding					
Rods					
Age	Report text	Wikberg et al. p.16-17	Assessment		
Regional and local discontinuities					
Location	Regional structures	Rhén et al. 1997	Assessment		Figure 5-1.
	Site structures	Wikberg et al. 1991, Saksa et al. -93	Assessment	Recompilation in site scale	Figure 5-7.
Orientation		Rhén et al. 1997	Assessment	Recompilation in site scale	Figure 5-1.
Length		Rhén et al. 1997	Assessment	Recompilation in site scale	Figures 5-1 and 5-7.
Width		Rhén et al. 1997	Assessment		Figure 5-1.

Table A-1.

Influence, meaning / Subject area	Input data to the structural model uncertainty analysis: Type	Source	Output from the structural model uncertainty analysis: Treatment	Output	Reference
Movement (amount, direction, age)					
Genetic type					
Characteristics:					
no. fracture groups	Structural model		Statistical analysis		Chapter 5.2
spacing	Structural model		Statistical analysis		Chapter 5.2
block size	Structural model		Statistical analysis		Chapter 5.2
fracture roughness					
mineral filling					
alteration					
Local smaller discontinuities					
(data for stochastic and deterministic description)					
Location	Structural model	Wikberg et al.			
Orientation	Structural model	Wikberg et al.			
Length	Structural model	Wikberg et al.			
Width	Structural model	Wikberg et al.			
Movement (amount, direction, age)					
Genetic type					
Characteristics:					
no. fracture groups	Structural model		Statistical analysis		Chapter 5.2
spacing	Structural model		Statistical analysis		Chapter 5.2
block size	Structural model		Statistical analysis		Chapter 5.2
fracture roughness					
mineral filling					
alteration					
Single fractures					
(stochastic description)					
Frequency (different groups)	Report text	(Rhén et al. 1997 p.130-136)			
Orientation	Report text	as above			Figure 5-6.
Length					
Termination					
Fracture width					
Roughness					
Mineral filling	Report text	(Rhén et al. p.130-136)			
Alteration and weathering	Report text	(Rhén et al. p.130-136)			

Table A-1.

BEBERG

Influence, meaning / Subject area	Input data to the structural model uncertainty analysis: Type	Source	Output from the structural model uncertainty analysis: Treatment	Output	Reference
GEOLOGY					
Topography					
Topography					
Lithology					
Rock mass lithology					
Rock distribution	Core logs, surface maps	Ahlbom&Tirén p.7-8,Ahlbom et al. p.41-43,45-46, 134-137	Assessment		
Xenolites		Ahlbom et al. p.46	Assessment		
Veins and dykes	Report text	Ahlbom et al. p.47	Assessment		
Rock contacts					
Age	Report text	Ahlbom et al. p.41-42	Assessment		
Ore potential, industrial mineralisations					
Rock type description					
Mineralogy	Report text	Ahlbom&Tirén p.14-15			
Grain size					
Mineral orientation					
Micro fracturing					
Density					
Porosity					
Susceptibility/gamma radiation etc.					
Alteration and weathering	Report text	Ahlbom&Tirén p.14-15			
Structural geology					
Ductile structures					
Folds					
Foliation		Ahlbom&Tirén p.8			
Schistosity					
Mylonites					
Banding					
Rods					
Age		Ahlbom et al. p.41-43			
Regional and local discontinuities					
Location	Surface maps	Andersson et al. p.88, Ahlbom&Tirén p.33	Assessment	Recompilation in site scale	Figure 6-1., Figure 6-6.
Orientation	Surface map	Ahlbom&Tirén p.33 and Table2 p.30	Assessment	Recompilation in site scale	Figure 6-6.
Length	Surface map	Ahlbom&Tirén p.33 and Table2 p.30	Assessment	Recompilation in site scale	Figure 6-6.
Width	Surface map, Report text	Ahlbom&Tirén p.33 and Table2 p.30			Figure 6-1., Figure 6-6.
Movement (amount, direction, age)					
Genetic type	Report text	Andersson et al. p.54-70			
Characteristics:		Ahlbom et al. p.138-145			
no. fracture groups	Structural models		Assessment		Chapter 6.2

Table A-2.

Subject area \ Influence, meaning	Input data to the structural model uncertainty analysis: Type	Source	Output from the structural model uncertainty analysis: Treatment	Output	Reference
spacing	Structural models		Statistical analysis in site scale		Chapter 6.2
block size	Structural models		Statistical analysis		Chapter 6.2
fracture roughness					
mineral filling					
alteration					
<u>Local smaller discontinuities</u>					
(data for stochastic and deterministic description)					
Location	Structural model	Ahlbom&Tirén p.33			
Orientation	Structural model	and Table2 p.30			
Length	Structural model				
Width	Structural model				
Movement (amount, direction, age)					
Genetic type					
Characteristics:	Structural model	Ahlbom et al. p.138-145			
no. fracture groups					
spacing			Statistical analysis		Chapter 6.2
block size					
fracture roughness					
mineral filling					
alteration					
<u>Single fractures</u>					
(stochastic description)					
Frequency (different groups)	Report text	Ahlbom&Tirén p.21-21			
Orientation	Report text	Ahlbom&Tirén p.21-22			
Length					
Termination					
Fracture width					
Roughness					
Mineral filling	Report text	Ahlbom&Tirén p.21-21			
Alteration and weathering	Report text	Ahlbom&Tirén p.21-22			

Table A-2.

A.3 DISCUSSION OF LINEAMENTS AND THE REGIONAL BEDROCK MODEL

Regional-scale structural models are primarily based on large area lineament interpretations. The technique utilises topographical maps, thematic satellite imagery, aerial photography and when available, digital 3-D terrain models. Images of the earth surface use both visible and non-visible reflected (electromagnetic) radiation bands. Digital terrain models can be further processed to emphasise large- or small-scale features, edges, gradients, directional information and areas of differing height above sea level.

Lineament interpretation is a powerful method for handling huge quantities of earth surface information. Data embedded in the total information also reflects geological and structural subsurface conditions. The difficulties connected with lineament interpretation are related to the unknown properties of interpreted features and in the subjective nature of the process itself. An example of the first of these issues is a long linear trace along the earth's surface that may be a particular rock type dyke or a zone of weakness, or both of these. The second issue is well illustrated by examining the varying realisations of lineament maps which have been compiled by different persons. The preferences adopted and geological style are probably visible in lineament results. Interpretation of lineaments is discussed further, for example, by Andersson et al. (1991) in Chapter 7 concerning the Finnsjön area. In Chapter 1.4.2 of Walker et al. (1997) there is a consideration of lineaments used to infer the regional hydraulic properties of structures for the SR 97 study.

However, in spite of its obvious weaknesses, the main information to be gained from lineament maps is the position of anomaly locations and their boundaries. Generally, longer (i.e. >10 km) topographical depressions are well known as representing major zones of tectonic movement which divide the crystalline bedrock into its mosaic structure. Anomalies can be further characterised by regional and reconnaissance geophysics. This gives an insight on continuity and the properties of lineaments and, at a later stage, provides local data which is accurate enough to determine suitable sites for drill and percussion boreholes, trenches and bedrock sampling.

In this study the fundamental concepts of lineament interpretation have not been studied in greater detail because the subjectivity and ambiguity discussed above would makes such an assessment more or less fruitless.

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1977-78
TR 121
KBS Technical Reports 1 – 120
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Stockholm, May 1979

1979
TR 79-28
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KBS Technical Reports 79-01 – 79-27
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The KBS Annual Report 1980
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Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
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Stockholm, April 1982

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Stockholm, July 1983

1983
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1984
TR 85-01
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1986
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1989
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1993
TR 93-34
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1994
TR 94-33
SKB Annual Report 1994
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TR 98-01
Global thermo-mechanical effects from a KBS-3 type repository. Summary report
Eva Hakami, Stig-Olof Olofsson, Hossein Hakami, Jan Israelsson
Itasca Geomekanik AB, Stockholm, Sweden
April 1998

TR 98-02
Parameters of importance to determine during geoscientific site investigation
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ISSN 0284-3757
CM Gruppen AB, Bromma, 1999