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Research

Alternative Lineament Maps and Structural Model of the SFR - Forsmark Region

A Comparison with SKB Structural Models

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SKI perspective

Background

The Swedish repository for low- and intermediate level radioactive operational waste, SFR 1, is used for final disposal of waste produced in the Swedish nuclear power programme, industry, medicine and research. The repository is located close to the Forsmark nuclear power plant about 120 km north of Stockholm.

As part of the license for the SFR 1 repository a renewed safety assessment should be carried out at least every ten years for the continued operation of the repository. The safety assessment shall include both the operational and long-term aspects of the repository. SKB has during year 2001 finalised their first renewed safety assessment (project SAFE) which evaluates the performance of the SFR 1 repository system.

Purpose of the project

The purpose of this project is to review SKB's modifications of the structural model of SFR 1 and its surroundings. The alternative structural model described in this report, both in a regional and a local scale, is based on data interpreted by SKB.

Results

In the present study most of the structures identified in previous SKB models are confirmed. However, some additional zones in the present three-dimensional fracture zone model have been identified. Of special interest are two zones intersecting the SFR 1 underground construction: one gently inclined zone located just above the rock cavern and another zone, steep to vertical, transecting the four rock vaults.

Effect on SKI's future work

The review of the structural model of the SFR 1 area and its surroundings will be used in SKI's review of SKB's site investigations of a possible deep underground repository of high level waste in the Forsmark area.

Project information

Responsible at SKI has been Fritz Kautsky.
SKI ref.: 14.9-001330/00213 and 14.9-011176/01254.

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Alternative Lineament Maps and Structural Model of the SFR - Forsmark Region

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Summary

The location of the SFR 1 repository, the Final Repository for Radioactive Operational Waste repository, at Forsmark c. 120 km north of Stockholm has been described in local and regional perspectives by several SKB reports. The regional geological and structural setting of the SFR 1 repository is described by maps, while the pattern of fracture zones in the proximity of the repository is presented as three-dimensional structural models.

The objective of the present study is to construct an alternative structural description of the SFR 1 repository both in a regional and a local perspective. The base data for the construction of the alternative model are digital topographical data, airborne geophysical measurements (magnetic and electromagnetic data) and descriptions of the area presented in SKB reports.

The SFR 1 repository is located in a c. 35 km wide WNW-ESE trending fault belt, initially formed as a regional shear zone. The belt is characterized by an anastomosing pattern of faults outlining lensoidal rock blocks comprising relatively intact rock. The relation between early shears and later formed brittle structures is not simple. The ground surface is distorted, tilted and displaced, along the belt. The belt is transected and partly distorted by brittle structures oblique to its trend.

The SFR 1 repository is located just north of a regional fault, the Singö Fault. Trends of fracture zones in the proximity of the repository are NW-SE, NNW-SSE, NNE-SSW and NE-SW. The dominant inclination of zones is steep to vertical. Notable is the occurrence of zones gently inclined south-eastward.

The outcome of the present study confirms most of the structures expressed in previous models. However, the present three-dimensional fracture zone model has included some additional zones. Of special interest are two zones intersecting the SFR 1 underground construction: one gently inclined zone located just above the rock cavern and another zone, steep to vertical, transecting the four vaults.

Contents

1 Introduction

SFR 1, the Final Repository for Radioactive Operational Waste, is conducted by the Swedish Nuclear Fuel and Waste Management Co. (SKB) and has now been in operation for about ten years. In accordance with the licence a renewed safety assessment should be carried out at least every ten year for the continued operation of the SFR 1 repository. The function of the facility is under review. The Swedish Nuclear Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI) make the review and the present report is a part of the review.

SFR 1 is a shallow located bedrock storage under the Baltic Sea close to the Forsmark Nuclear Power Plant at the north-eastern coast of Uppland c. 120 km north of Stockholm, Figure 1.1. The SFR 1 repository is constructed to be the final disposal for low-level and intermediate-level radioactive operational waste, i.e. operational waste like filters, tools, spares, protective clothing etc.

The SFR 1 repository is located in Precambrian crystalline bedrock more than 50 metres below the seabed. The actual repository is reached by a double ramp and consists of four large rock vaults, one rock cavern and transport drifts, Figure 1.1. A concrete silo is built in the cavern and it is isolated from the rock by a bentonite fill. This is also a part of the technical barrier to prevent groundwater to transport and redistribute radioactive elements. The rock itself is the natural barrier.

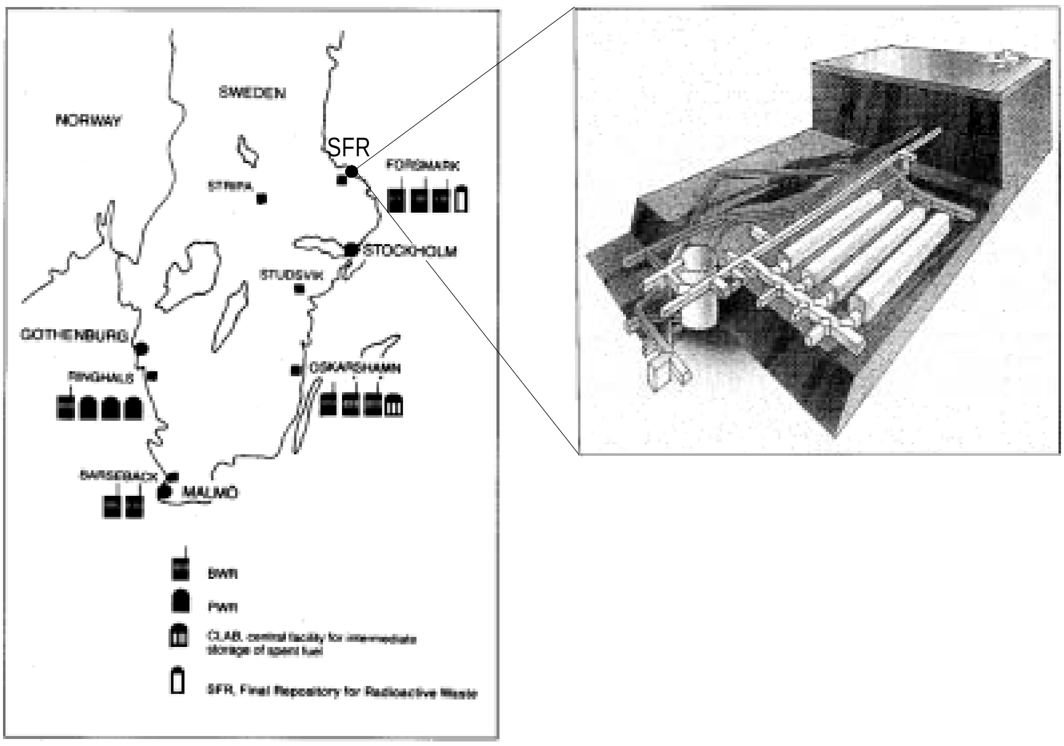


Figure 1.1. *Location of Forsmark and SFR 1 in perspective of the Swedish nuclear power programme. The SFR 1 repository, inserted, consists of four large rock vaults, one rock cavern and transport drifts (modified from SKB, 1996).*

The SFR 1 repository is located below sea water in the south-western part of an embayment, Öregrundsgrepen (Figure 1.2), bounded to the east by a large island, Gräsö. At Öregrund there is a strait between Gräsö and the mainland. The area shown in Figure 1.2 is a part of the Östhammar municipality and the town Östhammar is located c. 10 km south of Öregrund. Singö, giving the name to a regional fault, the Singö Fault, is located c. 25 km south-east of Öregrund. A former SKB study site, the Finnsjön area, is located c. 18 km south-southwest of SFR 1.

The SFR 1 repository is reached by road via an old Walloon ironwork, Forsmark, going northward passing the Forsmark Nuclear Power Plant (FNPP, own by Forsmarks Kraftgrupp AB), Figure 1.2. There is also a harbour to allow sea transport of the radioactive waste to be stored in the SFR 1 repository.

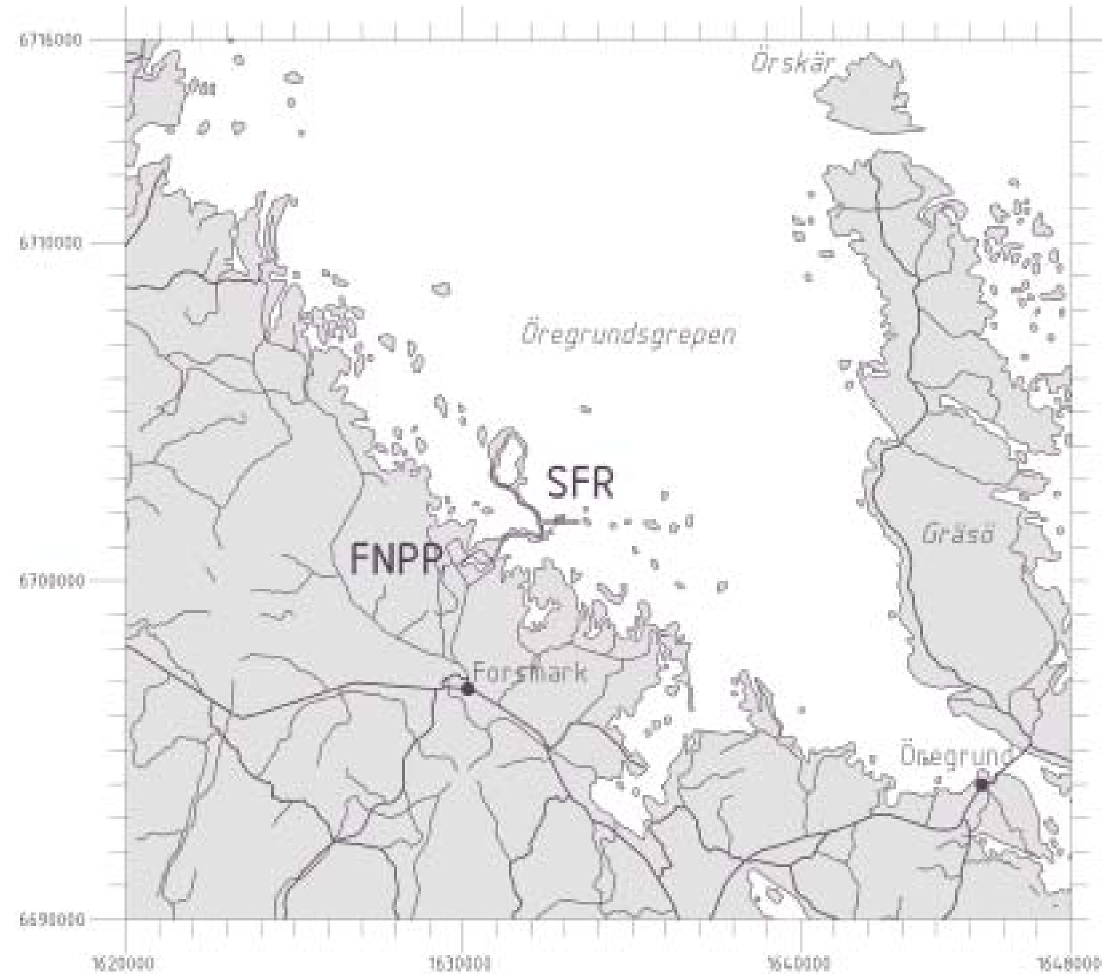


__Figure 1.2.__ Location of the SFR 1 repository. FNPP is the Forsmark Nuclear Power Plant. The map area is the area of regional lineament interpretation (cf. Figures 4.1 and 6.1).

2 Scope of the study

The scope or the present study is twofold:

- To provide descriptions of the structural geological setting of SFR 1 on regional and local scales:
  - regional structural pattern presented as a map (26 by 28 km)
  - the local structural pattern presented as a three dimensional model (2 by 2 km large and 0.5 km deep).
  The study is based on interpretation of topographical data (elevation and bathymetric data, achieved from SKB), airborne geophysical measurements and SKB reports.
- Review SKB modifications of the structural description of the fracture zone at SFR 1.

3 Base data

The base data or input data to this study have been provided by SKB and consist of:

- Two sets of primary data (digital bathymetric and elevation data, and airborne geophysical measurements).
- Digital three dimensional model of SFR 1 (underground construction and location of fracture zones).
- Reports (see below).

3.1 Primary data

One set of primary data is the elevation and bathymetric data describing the topography of the area on land and sea area. The land data originates from the elevation database (50 by 50 m grid) compiled by the Land Survey of Sweden (LMV). The bathymetric data has partly been obtained from the digital chart (the Swedish National Administration of Shipping and Navigation, SjöV) and partly from analogue base maps displaying soundings. Brydsten (1999) describes the procedure of producing the database for the sea area north of Forsmark, Öregrundsgrepen, a database similar to the LMV base (25 by 25 m grid close to the coast and 50 by 50 m in the outer parts). However, neither the spatial distribution of the primary data (soundings) nor the accuracy of presented data are presented.

The other set of primary data used is airborne magnetic and electromagnetic (VLF) measurements. For the national mapping programme performed by the Geological Survey of Sweden (SGU) airborne geophysical measurements are carried out with a nominal flight line separation of 200 m and a ground clearance of 60 m (until 1995 it was 30 m). Measurements are made with a point separation of approximately 17 m. The primary data was gridded (50 by 50 m) using a minimum curvature gridding technique.

3.2 Digital three dimensional models

The following three dimensional models in digital format (3D CAD, MicroStation dgn-files) have been achieved from SKB:

- A digital model of the underground SFR 1 facilities.
- The SKB 1993 structural model of SFR 1 (Carlsson and Christiansson, 1987; SKB, 1993).
- An alternative/updated structural SKB model of SFR 1 (Axelsson and Hansen, 1998).

3.3 Reports

Structural descriptions of the regional area surrounding Forsmark and the local SFR 1 site area are presented in several reports. The base data for the review of the framework of fracture zones at the SFR 1 repository are listed below.

3.3.1 Formark area

Hagkonsult, ALMA – *Slutförvar i berg. Översikt geologisk-bergteknisk studie för alternativ lokalisering och placering av berganläggning för slutlig förvaring av låg- och medelaktivt avfall,* Hagkonsult, Stockholm 1980.

Bergman, S., Isaksson, H., Johansson, R., Lindén, A., Persson, C., and Stephens, M., *Förstudie Östhammar, Jordarter, bergarter och deformationszoner*. SKB Djupförvar PR D-96-016, Stockholm 1996.

SKB, *Förstudier Östhammar, Slutrapport (Preliminär).* Swedish Nuclear Fuel and Waste Management Co. (SKB), SKB Djupförvar Lokalisering, Stockholm 1997.

Bergman, S., Bergman, T., Johansson, R., and Stephens, M., *Förstudie Östhammar, Delprojekt jordarter, bergarter och deformationszoner, Kompletterande arbeten 1998.* Swedish Nuclear Fuel and Waste Management Co. (SKB), SKB report R-98-57, Stockholm 1998.

SKB, *Förstudie Östhammar, Slutrapport.* Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm 2000.

3.3.2 SFR 1

Hagkonsult, *ALMA – Översiktliga bergundersökingar för förstahandsalternativet i Forsmark, Studsvik och Simpevarp,* Stockholm 1980.

Axelsson, C.-L. and Hansen, L. M., *Update of structural models at SFR nuclear waste repository, Forsmark, Sweden.* Swedish Nuclear Fuel and Waste Management Co. (SKB), SKB rapport R-98-05, Stockholm 1987.

SKB, *Slutförvar för radioaktivt driftavfall – SFR 1. Slutlig säkerhetsanalys*. Reviderad utgåva – maj 1993. (SKB Final repository for radioactive waste – SFR 1. Final safety report. Revised edition – May 1993). Swedish Nuclear Fuel and Waste Management Co. (SKB), Stockholm 1993.

4 Basic concepts and definitions

The following issues determine the outcome of a study:

- Extent of the study, i.e. delimitation of investigation (regarding, e.g. type of base data, processing techniques, interpretation approach and execution) and demarcation of study area (size and location).
- Resolution (defined below), including base data (concerns both primary data - airborne geophysical data and elevation data- and SKB structural models) and study performance (eg. sampling bias - censoring of interpreted structures).

The issues above supplement each other - compare studies of so called scale effects, which are "a major consequence of the inhomogeneous and discontinuous pattern of rock masses" (Cunha, 1990).

Elevation and bathymetric data are used in this report to describe the topography; including both land and sea areas.

Airborne geophysical data are used to characterize the physical properties of the bedrock.

Information density does not depend on the scale of observation or the scale of the representation of the observed object. It is an absolute measure, e.g. the 50 by 50 m grid used in the LMV elevation database.

Resolution is in general, "a measure of the finest detail distinguishable in an object or phenomenon. Commonly, it is considered a measure of the finest detail distinguishable in an image" (Glossary of the Mapping Sciences, 1994).

It may be difficult to determine the general level of resolution that is necessary for regional studies. It all depends on the aim of the study and the object/the geological terrain. However, working on different scales makes it possible to apply the results gained during the regional studies to the local studies and to verify that the structural pattern that has been interpreted locally corresponds to the regional pattern and vice versa.

There is a difference between cartographic scales and geological scales. The *cartographic scale* refers to the size of the represented area, the map, in relation to the size of the actual area (cf. model scale). The *geological scal*e refers to the size of the studied object. In general, it could be said that structures represented on geological maps are large-scale while structures studied on outcrops and hand specimens are small-scale. In geological descriptions of an area, analogue designations are used to denote the size of the area, for example, the *local scale* corresponds to the site investigation area, while the *regional scale* covers the region surrounding the site investigation area.

In general, *visualization* is fundamentally a translation from computer representations (such as tables and data sheets) to understandable representations, choosing encoding techniques to maximise human understanding and communication. In other words, scientific visualization concerns exploring data and information in such a way as to gain understanding and insight into the data. In geoscientific work, visualization techniques are used to analyse and display large volumes of data, models, to extract significant features.

A *model* (Bates and Jackson, 1980) is "a working hypothesis or precise simulation, by means of description, statistical data, or analogy, of a phenomenon or process that cannot be observed directly or that is difficult to observe directly." Modelling comprises an initial stage of data manipulation (for example sorting, discrimination and classification) and organization (for example formatting, storage of uniform data in reference files) and a subsequent stage of correlation and extrapolation of data within the model space. Models used in this report are topographical relief maps, magnetic relief maps, lineament maps and three-dimensional structural models.

The term *remote sensing* commonly designates techniques that "sensing an object without touching the object, detecting or inferring the properties of an object without touching the object, or detecting, sensing and/or inferring the property of an object which is far from the detector or sensor….. Remote sensing is a composite term and usually implies detection rather than merely sensing" (Glossary of the mapping Sciences, 1994). Structural interpretations of topographical and magnetic relief maps (cf. Figures 4.1 and 4.2) are examples of remote sensing studies.

Lineaments are defined by Hobbs (1912) as "Significant lines in the landscape which reveal the hidden architecture of the basement". A lineament is a two dimensional feature, that is the intersection line between a structure in the bedrock and the bedrock surface express at the ground surface. In lineament studies remote sensing techniques are used and the interpretation is based on some type of image of the ground surface (topographical maps, aerial photos, satellite images or computer-processed models based on elevation data). In this study a type of digital terrain model (DTM), topographical relief map (c.f. Figure 4.1), is used.

Analogue to lineament studies are structural interpretation of geophysical measurement, that is when the measurements cover an area (generally performed as a sequence of profiles). Distortions in the geophysical pattern are then mapped. In this study both magnetic and electromagnetic airborne measurements are used (Figure 4.2).

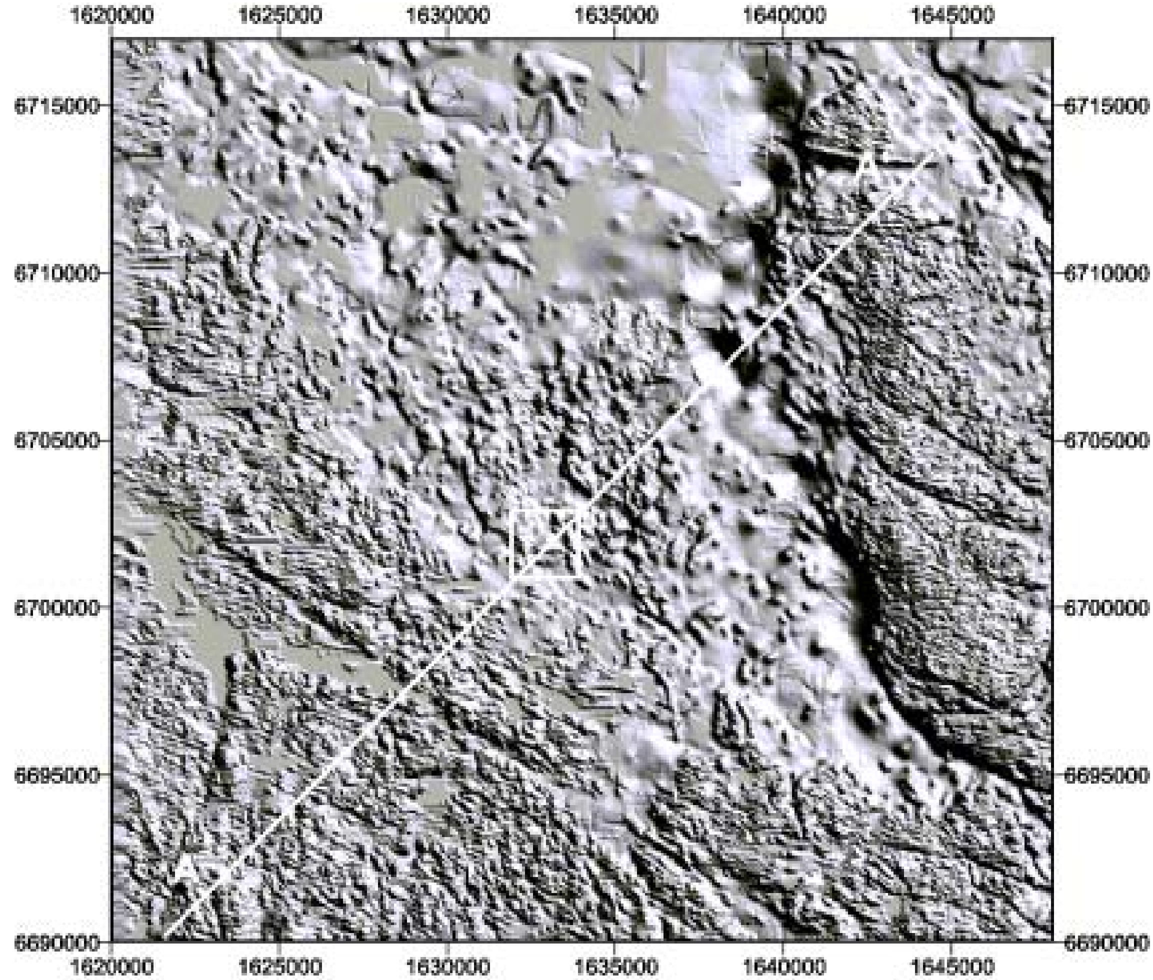
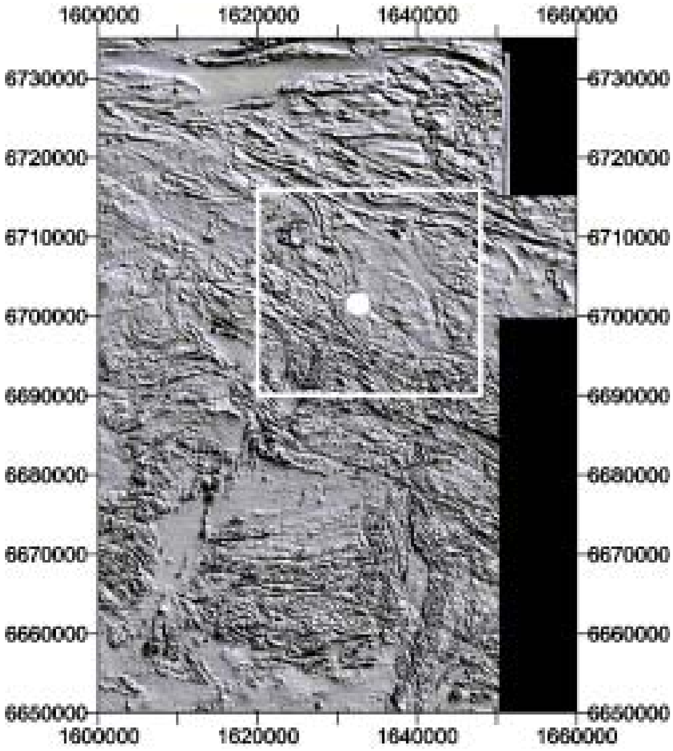
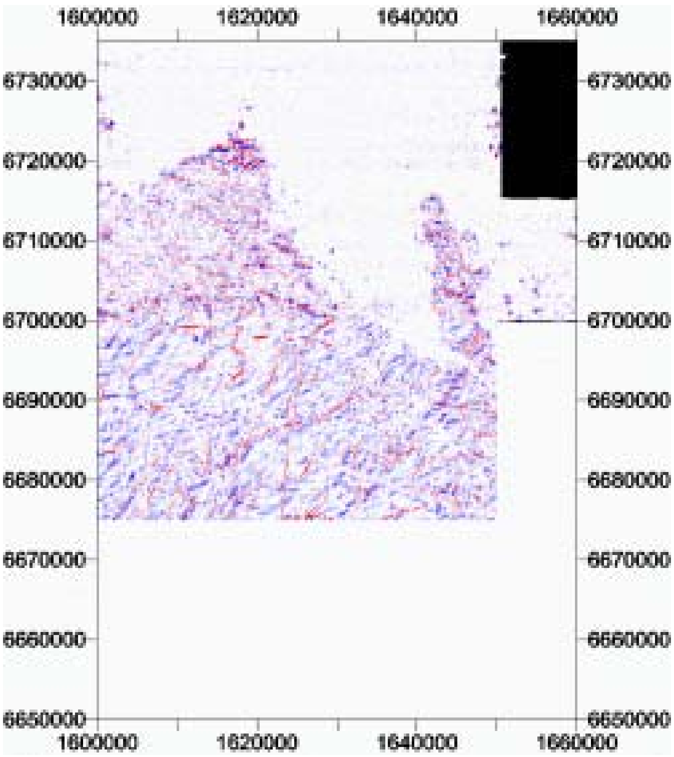


Figure 4.1. *Topographical relief map illuminated from north-east. The topography along the profile is presented in Figure 6.2. The square gives the location of the 2 by 2 km large local SFR 1 area (Figure 6.8). The elevation data grid is 50 by 50 m (from Brydsten, 1999, LMV and SjöV elevation database, permission to publish register number 507-96-1524 and 9709388, respectively).*



a)



b)

Figure 4.2. *Airborne geophysical data: a) magnetic data. The regional scale map area and the SFR 1 repository is indicated in the figure, and b) VLF data. Note that data in the area north of x = 6700000 is processed in a different manner compared to the data south of x = 6700000.*

5 Methodology

5.1 Lineament interpretation

Lineament interpretation was made on a regional scale (26 by 28 km) and a local scale (2 by 2 km).
Topographical data were visualized as a sequence of five relief maps illuminated from W via N to ENE, that is one image every 30 degrees going clockwise. This is done to get an equal enhancement of all topographical features. For the regional lineament interpretation the demarcation of the interpreted area was 26 by 28 km with SFR 1 in the centre. For the local lineament map it was 2 by 2 km (based on the same data set as for the regional map, a higher resolution in the performance of the interpretation though). Lengths of lineaments are drawn in accordance to the corresponding topographical traces on the relief maps.

Based on the five relief maps five primary lineament maps are gained. The primary maps are then compiled in a composite lineament map. Lineaments displayed on three or more of the primary lineaments interpretations and having an extension of more than four kilometres are designated as “extensive and topographically well expressed” on the compiled regional lineament map, Figure 6.1. Remaining lineaments shown on the composite regional and local maps are those identified on at least two of the five primary lineament interpretations. Finally, all structures on the compiled map are checked against the base data. On the regional lineament map most features are longer than one kilometre, minimum length is 400 m. On the local map the corresponding minimum length is 250 m, Figure 6.7. The trace length of separate lineaments on the composite map represent the optimal extension of the lineament as it is expressed on the primary lineament maps.

The accuracy in position of the lineaments is less than 50 m relative to base data. However, the accuracy of some of the base data has not been properly defined. For the sea area the data do not represent measured values but interpolations (Brydsten, 1999).

An alternative way to describe lineaments is to describe the geometrical pattern of lineaments (thematic presentation), or to try to recognize simple or primitive geometrical configurations that by interference and/or overprinting form the actual structural pattern in the rock. To do this during the actual lineament interpretation is to apply or test the fitness of a selected and, must presumably, well documented structural pattern on the base information. The result may well be that structures that do not fit the proposed pattern are discriminated. Therefore, at the first step, lineament interpretation is to delineate all structures expressed by topographical forms, to construct a high-resolution interpretation. Thereafter, the interpretation can be simplified and structures could be connected, rejected and combined to express structural geological interpretations (cf. thematic maps). However, there is always a risk that the performance of a lineament study could shift from an objective mapping of topographical features to test the fit of structural patterns.

The aim of this report is to present if there exist any structural anisotropy in the rock and therefore the lineament map is not adjusted in any sense (no thematic maps are produced). The extension of lineaments is drawn according to the length indicated on topographic and magnetic relief maps.

The glacial erosion enhances mainly bedrock structures conform to the direction of movement of the ice. In the Öregrundsgrepen-Forsmark area the direction of ice movements is complex and two overprinting glacial striations occur. One set of glacial striation is predominantly southward, while the other is south-eastward along the coast.

5.2 Structural interpretation of airborne geophysics

In order to analyse the data and interpret lineament features, shaded relief maps were produced, based on the geophysical grids. By interactively changing the shading parameters, using mapping software, multiple relief maps were produced. Initially, four prominent directions of the shading (NE, SE, SW, and NW) were used. In the next stages, different shading parameters (direction and inclination of the sun) were combined to obtain additional information. The final geophysical interpretation map were produced containing only structures which could be found in the proximity of the SFR 1 area or regional structures with features (direction, magnitude) which could affect the SFR 1 area.

VLF anomalies are strongly enhanced in the direction of the transmitter, thus creating ambiguous interpretation patterns emphasising the transmitter direction. Therefore, the electromagnetic data has merely been used to correlate anomalies interpreted from the magnetic data.

The result of the interpretation of the geophysical data has been used in conjunction with the evaluation of the interpreted lineaments based on topography data. Due to the spatial resolution of the airborne geophysical data (200 m line spacing), the geophysical interpretation has mainly been used to verify lineaments based on topography data.

5.3 Comparison of local structural models

Both the previous SFR 1 structural model (Carlsson and Christiansson, 1987, SKB, 1993) and the later model (Axelsson and Hansen, 1998) are available in digital form (MicroStation, dgn-files). The comparison of the two models is done by visualization in three dimensions. The two models can either be compared side by side or corresponding structures in the two models can be copied on top of each other and compared. It has not been the task of the present study to check the SKB models against base data (e.g. fracture maps of the tunnels etc. of the SFR 1 underground construction).

The three-dimensional SKB SFR 1 structural models can be compared with lineament maps of the present study by extending structures in the SKB model up to the sea bottom.

6 Results

6.1 Regional lineament map

The lineament map of the Öregrundsgrepen- Forsmark area, Figure 6.1, covers a part of the northern coast of Uppland, just north of the Roslagen archipelago. The central part of the map is a major embayment, Öregrundsgrepen. The land area in the eastern part is a larger island, Gräsö, and there is channel passing south of Gräsö (cf. Figure 1.2). Except from a N-S trending furrow along the western side of Gräsö the topographical relief of the area is low. The highest and lowest points are located in the very south-west corner of the area and in the middle of the above mentioned N-S trending furrow, respectively. The ground surface in general is flat, dipping very gently north-eastward (Figure 6.2). In the central part of the maps there are minor steps in the landscape, stepping up going northward. The separation of these landform breaks is approximately five kilometres and they outline NW-SE trending land laths. In the southern part of the map there is interference between tilting, block faulting, along NW-SE and N-S trending tilt-axis (Tirén, 1991). Gräsö is related to the tilting, block faulting, along a N-S axis.

On the lineament map two types of lineament are differentiated. However, when performing a lineament study the lineaments should be at least separated into three groups. This argument is met by considering the length and orientation of the lineaments in the presentation of the lineament map.

The number of lineaments on the lineament map is 242 (Figure 6.1) and data on their length distribution is presented in Table 6.1 and Figures 6.3 and 6.4.

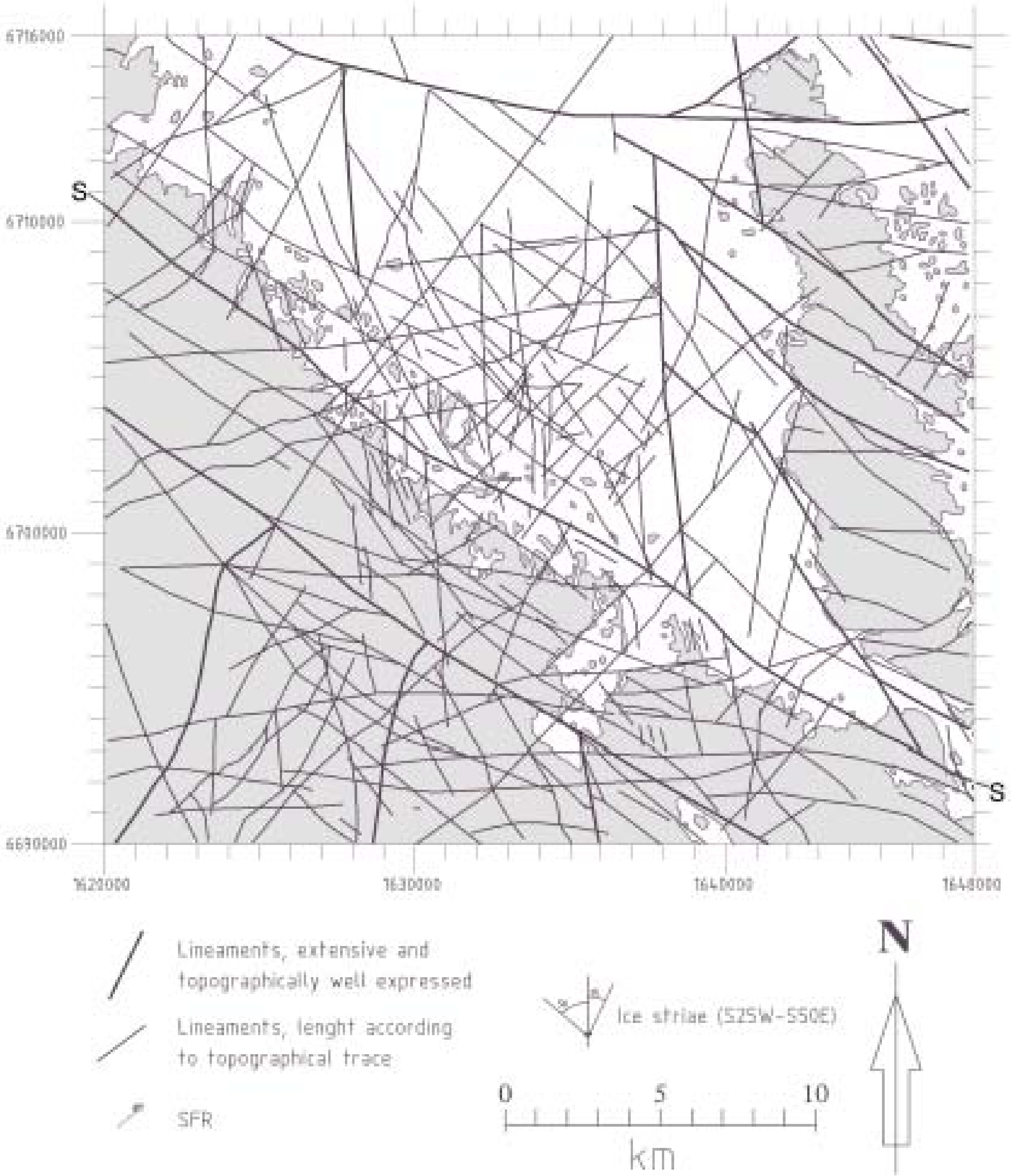


Figure 6.1. *Lineament map of the Öregrundsgrepen-Forsmark area (26 by 28 km), north-eastern Uppland, Sweden. The location of the Singö Fault (S) is displayed (cf. Figures 6.7, 6.9a, 7.1 and 7.2). The RAK co-ordinate of the SFR 1 repository is c. 6701800, 1632850 (cf. Figure 6.7).*

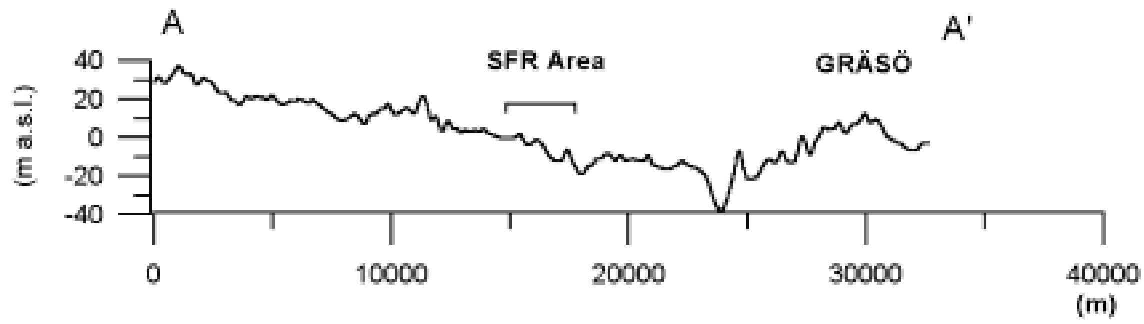


__Figure 6.2.__ Topographical cross-section in SW-NE from the highest topographical point (37 m a.s.l.) across SFR 1 to a low topographical point west of the Gräsö island (the lowest point 57 m b.s.l. is located next to the profile). Location of the cross-section is given in Figure 4.1. The regional topographical gradient across SFR 1 is c. 22 m/km.

__Table 6.1.__ Lineament data in the Öresundsgrepen-Forsmark area as displayed in Figure 6.1

Parameter	Data
Number of lineaments	242
Mean length	4.9 km
Median length	3.2 km
Standard deviation	4.8 km
Max length	33.5 km
Min length	0.4 km
Total length	1184.9 km
Lineament density	1.62 km/km^2
Lineament density	0.33 number/km^2

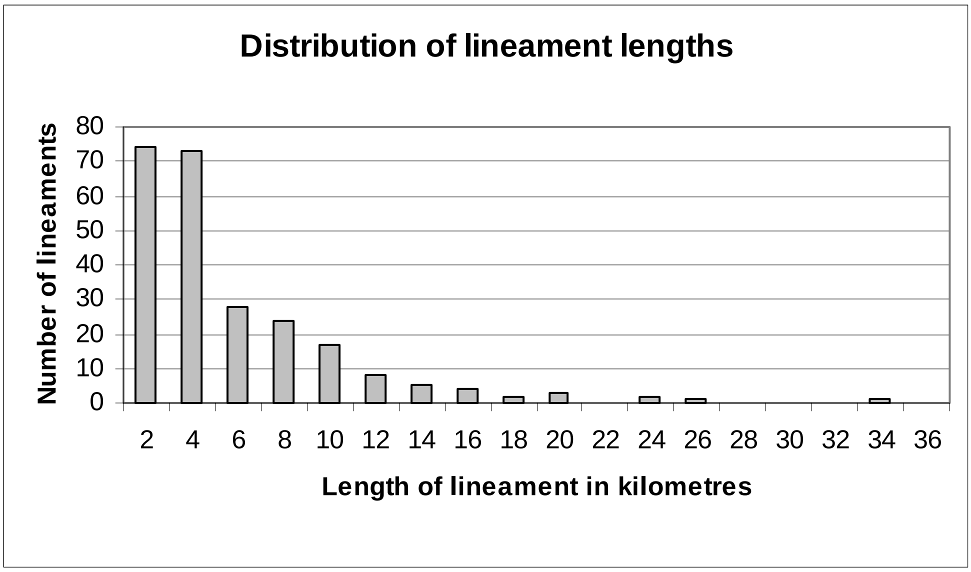


__Figure 6.3.__ Length distribution of lineaments in the Öregrundsgrepen-Forsmark area (cf. Figure 6.1).

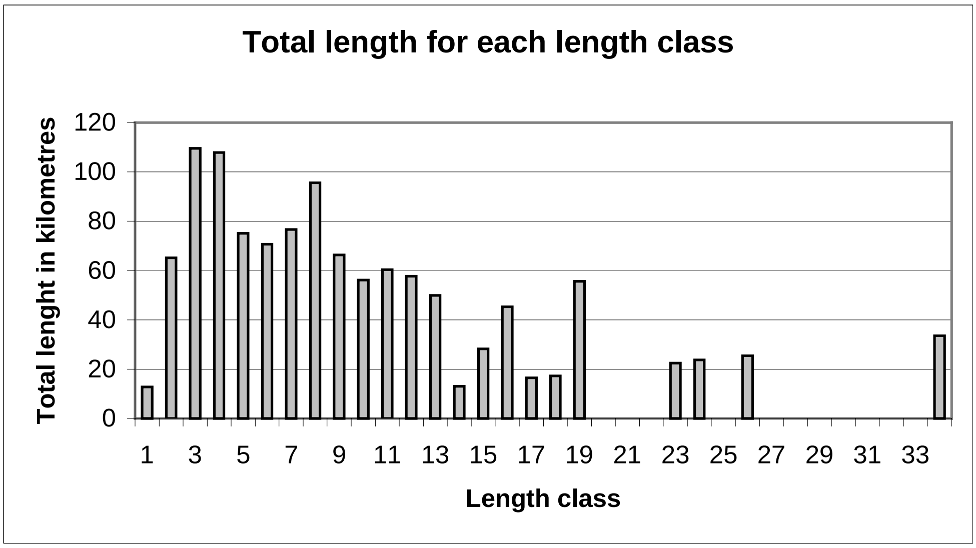


Figure 6.4. *Total length for lineaments of different length classes (0-1, 1-2,3-4,…... 33-34 km long lineaments), lineaments in the Öregrundsgrepen-Forsmark area (Figure 6.1). Orientation and number of lineaments for some of the length classes are presented in Figure 6.5.*

The most common orientation of lineaments according to their frequency is NW-SE, Figure 6.5. Other pronounced orientations are NE-SW, N-S and NNW-SSE. When considering shorter lineaments (less than 5 km long, cf. Table 6.1), the NW-SE lineaments are equally frequent as NE-SW, N-S and NNW-SSE trending lineaments. For lineaments equal to 5 km or longer the NW-SE trending lineaments dominate.

When consider lineaments noted on the lineament map as extensive and topographically well expressed the dominating orientation is again NW-SE, but NNE-SSW are also outstanding (Figure 6.5). The longest lineament, the surface expression of the Singö Fault, has its both terminations outside the map area and 33 km of the lineament is located inside the map area.

In the diagram showing distribution of lineament lengths (Figure 6.3) there is a marked change in the frequency of lineaments shorter than 4 km. To just consider lineaments shorter and longer than 4 km as two groups do stress the importance of the long NW-SE trending lineaments. A somewhat different pattern appears when the lineaments are divided into a sequence of length classes (0-1 km, 1-2 km, 3-4 km, 4-5 km, 5-10 km and 10-40 km; lengths equal to upper class boundary are not included in the class), Figure 6.6. Notable is that for shorter lineament, 0-2 km, the dominant orientation is N-S. Furthermore, the 2 to 3 km long lineaments have orientated mainly in NW-SE, while the 3 to 4 km long lineaments have additional frequent NE-SW and N-S lineaments. Notably is that 4 to 5 km long lineaments are pronounced in the NE-SW direction. Long lineaments, 10 to 40 km long, are generally orientated in NW-SE.

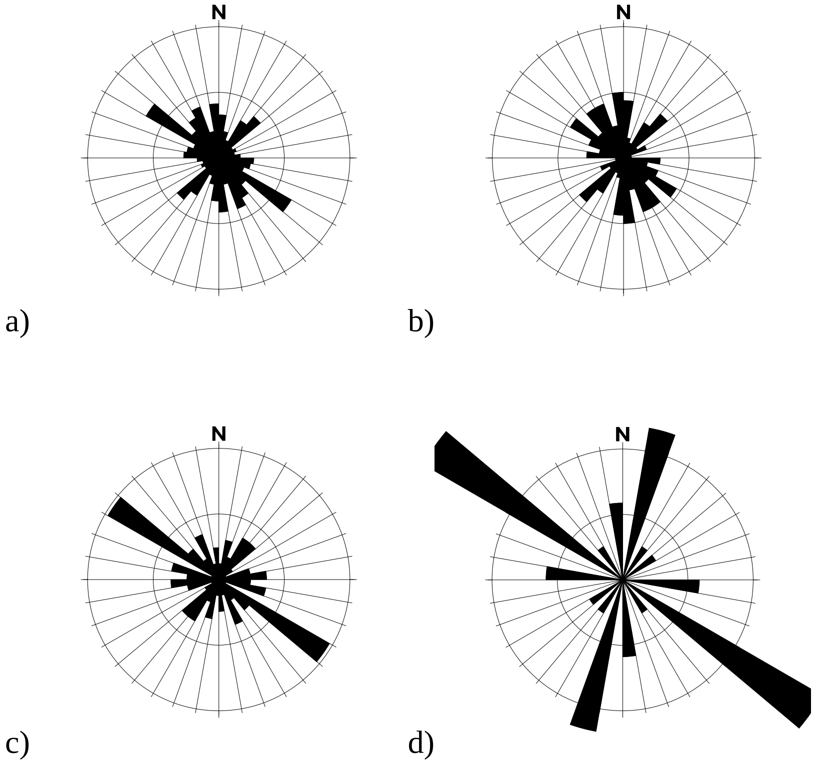
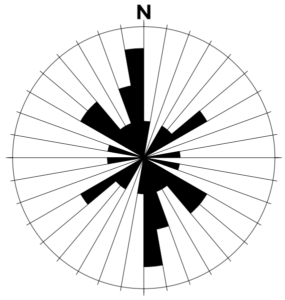
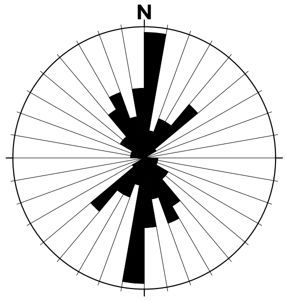


Figure 6.5. *Rose diagrams showing orientation of lineaments in the Öregrundsgrepen – Forsmark area, regional area (Figure 6.1): a) all lineaments (n=242), b) lineaments shorter than 5 km (n=160), c) lineaments equal or longer than 5 km (n=82), and d) extensive and topographically well expressed lineaments (n=17), see legend Figure 6.1. The outermost scale ring represent 10 %.*

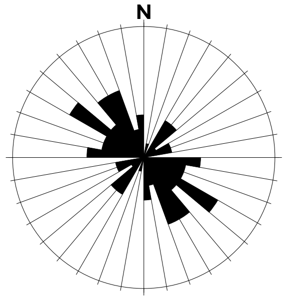
It is apparent that the grouping presented in Table 6.2 has too tight ranges in orientation, at least for N-S trending lineaments. The four most dominant lineament directions according to number (cf. Table 6.2), comprise 58 % of all mapped lineaments and the sum of their lengths is 59 % of the total lineament length.

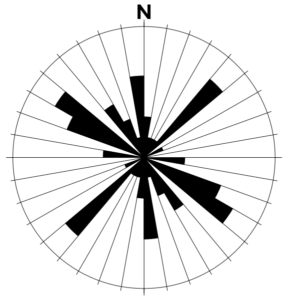
The scatter in orientation of lineaments for the dominant lineament groups is not uniform. The range of the orientation for the lineament groups could be increased or adjusted in order to incorporate lineaments with a small deviation (5 to 10°) in orientation. For example such adjustments can be made for N-S trending lineaments and NW-SE trending lineaments, cf. Table 6.3. The new grouping will include 67 % of all lineaments. For the NW-SE trending lineament group, several shorter lineaments are added, while for the N-S trending lineament group some long and several short lineaments are added. In the latter case the mean length of lineaments increases, while for the former it decreases. Despite these adjustments the four groups of lineaments trending NW-SE, NNW-SSE, N-S and NE-SW comprises just 64 % of the total lineament length. However, there is an additional group of lineaments trending E-W, Table 6.3. These lineaments have a wider range in orientation, have irregular forms and are relatively extensive.



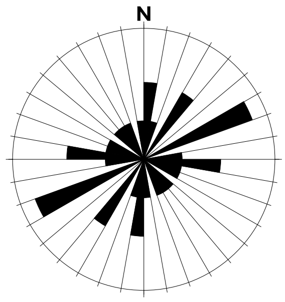


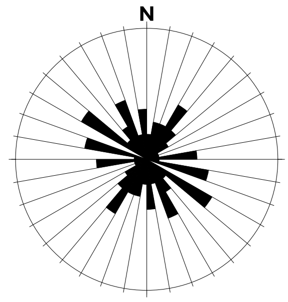
a) b)



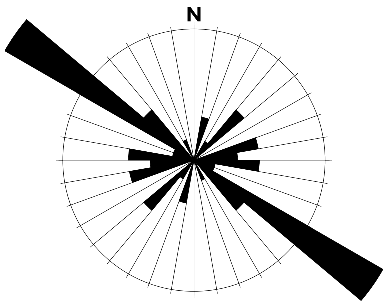


c) d)





e) f)



g)

Figure 6.6. *Rose diagram showing orientation of lineaments according to their length: a) 0-1 km long (n=18, total length (t.l.)=12.8 km), b) 1-2 km long (n=47, t.l.=65.2 km), c) 2-3 km long (n=46, t.l= 109.5 km), d) 3-4 km long (n=32, t.l.=107.9 km), e) 4-5 km long (n=17, t.l.=75.1 km), f) 5-10 km (n=52, t.l.=365.5 km) and g) 10-40 km long (n=30, t.l.=448,9 km). The Upper limit is not included in the group. Outer scale ring represent 10 %.*

Lineament patterns expressed on the lineament map of the Öregrundsgrepen- Forsmark area do generally give an impression of overprinting without distortion. The only pattern found that shows an interaction between “lineaments” is the eastward bend of two N-S trending lineaments where they meet a similar NW-SE trending lineament (lower left part of the lineament map, Figure 6.1). In the southern part of the lineament map the ground surface dips very gently eastward, has a serrated shape (stepping down going from east to west). North of the NW-SE trending lineament a NW-SE grain is apparent. However, the landform is again serrated, climbing upward minor distinct slopes when going down the gentle northward dipping ground surface.

NNW-SSE trending lineaments display locally a curved form, concave eastward. Apparently they are related to the extensive and topographically well expressed NW-SE lineaments. However, the offset of the ground surface along the topographically well expressed N-S and NW-SE trending lineaments indicate that they represent traces of bedrock structures, faults. NE-SE, N-S and E-W trending lineaments appear to overprint the pattern of NW-SE and N-S trending lineaments, some are extensive and topographically well expressed.

Notable is that lineaments can be grouped together to form pseudo-orthogonal sets, a structural configuration that occur in most parts of Sweden.

Table 6.2. *Characteristics on lineament, the four most pronounced orientations NW-SE NNW-SSE, and NE-SW.*

Number, Length (km), Percentage/ Azimuth	**NW-SE 300-310°**	**NNW-SSE 320-240°**	**N-S 350-10°**	**NE-SW 30-50°**
Number	31	37	36	36
Total length	234.1	129.5	102.2	172.0
Mean	7.6	3.5	2.8	4.8
Median	5.4	2.6	2.2	3.3
Standard deviation	7.4	2.5	2.1	3.9
Max	33.5	10.1	8.0	15.0
Min	0.8	0.8	0.4	0.5
Percentage of total length	19.8 %	10.9 %	8.6 %	14.5 %

Table 6.3. *Characteristics on NW-SE (extended interval), N-S (extended symmetrically around north, now ±15°) and E-W trending lineaments (not shown in Table 6.2).*

Number, Length (km), **Percentage/ Azimuth**	**NW-SE 300-320° (extended interval)**	**N-S 345-15° (extended interval)**	**E-W 75-90°, 270-290°**
Number	43	47	37
Total length	296.7	156.5	252.5
Mean	6.9	3.4	6.8
Median	3.4	2.6	5.1
Standard deviation	6.8	2.9	5.9
Max	33.5	14.2	25.4
Min	0.8	0.4	0.8
Percentage of total length	25.0 %	13.2 %	21.3 %

6.2 Local lineament map

The local area is 2 by 2 km large with the SFR 1 repository located in its centre, Figure 6.7. In this area 42 lineaments are noted and the lineament characteristics are given in Table 6.4. Statistics on lineament lengths are not presented as only few lineaments have both ends inside the local area.

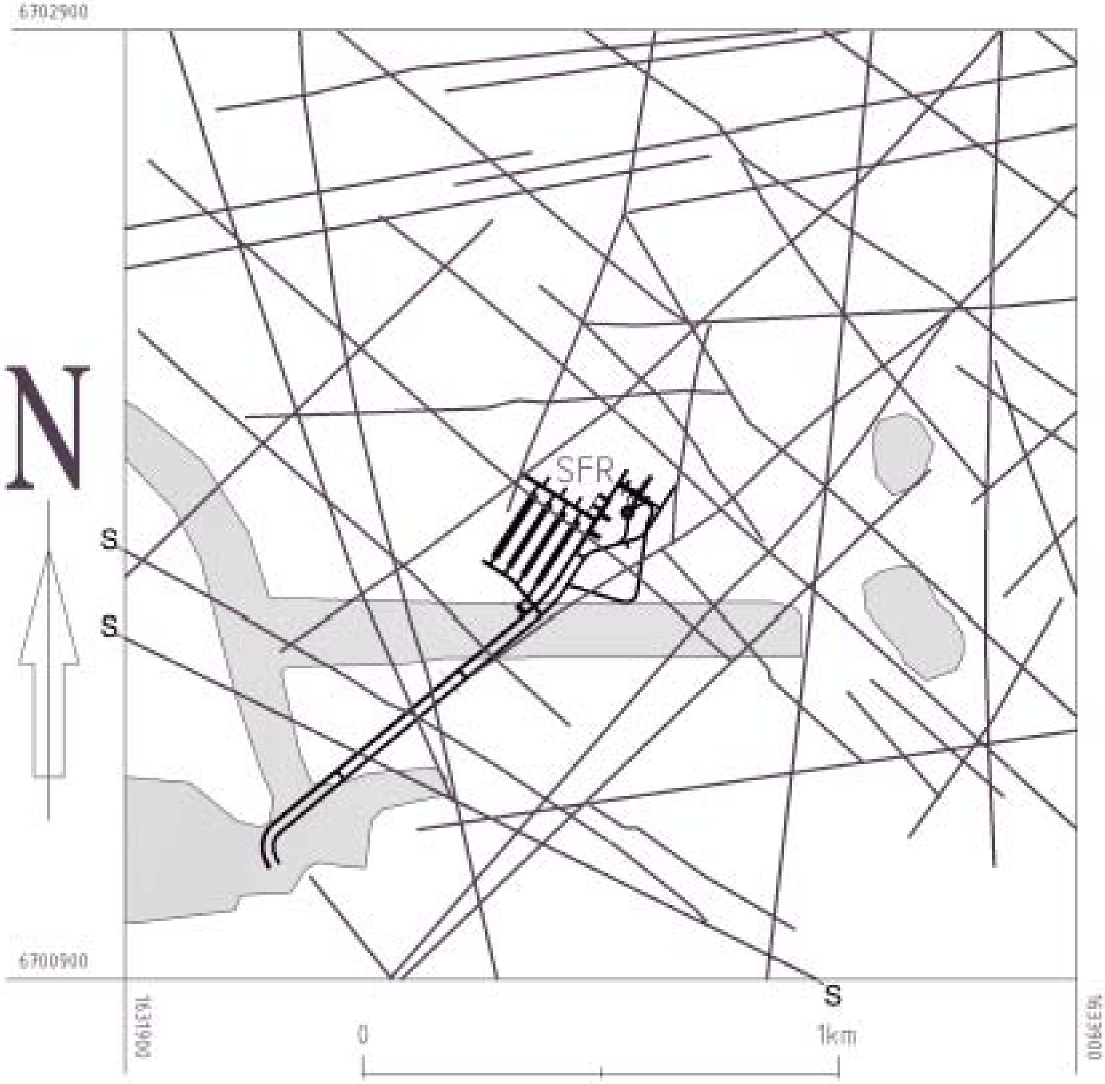


Figure 6.7. *Lineament map (2 by 2 km) of the local SFR 1 area, Forsmark, north-eastern Uppland. The continuos and closed forms represent embankments and islands. The location of the Singö Fault (S) is displayed (cf. Figures 6.1, 6.9a, 7.1 and 7.2).*

Table 6.4. *Data on lineaments in the local SFR 1 area (cf. Figure 6.7).*

Parameter	Data
Numbers of lineaments	42
Percentage of lineaments with both ends outside the local area	14.3 %
Percentage of lineaments with one end outside the local area	59.5 %
Percentage of lineaments with both ends inside the local area	26.2 %
Total lineament length in the local area	53.0 km
Lineament density	13.3 km/km^2
Lineament density	10.5 number/km^2

Dominant lineament directions in the local SFR 1 area are NW-SE, NE-SW and W-E. N-S trending lineaments are not so frequent, but these lineaments are extensive. Noteworthy is the relative high number of relatively short NW-SE trending lineaments. The Singö fault zone is represented by a WNW-ESE trending lineament transecting the lower left corner of the map. Notable is also the swarm of E-W trending lineaments in the northern part of the map, north of the SFR 1 repository.

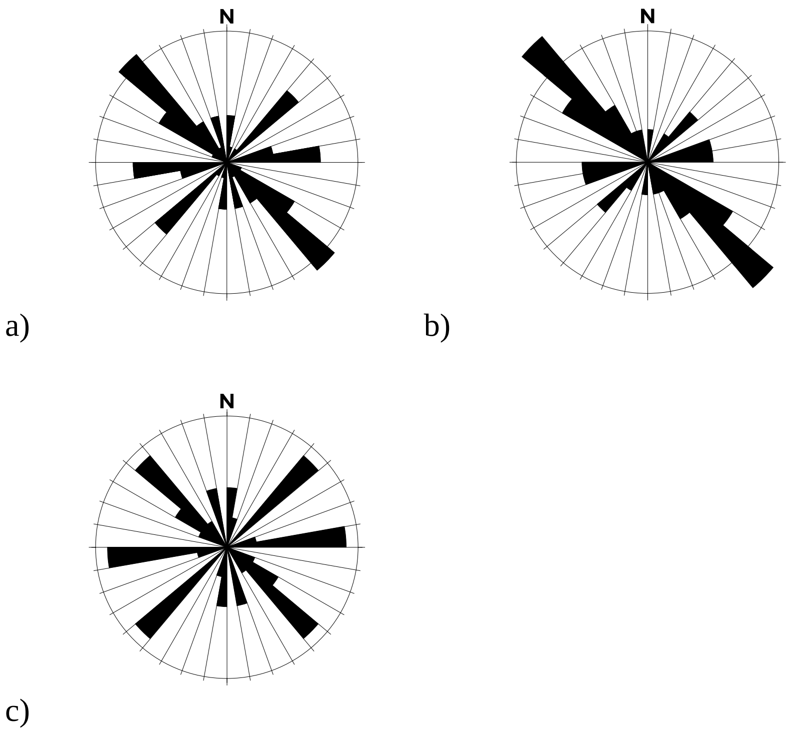
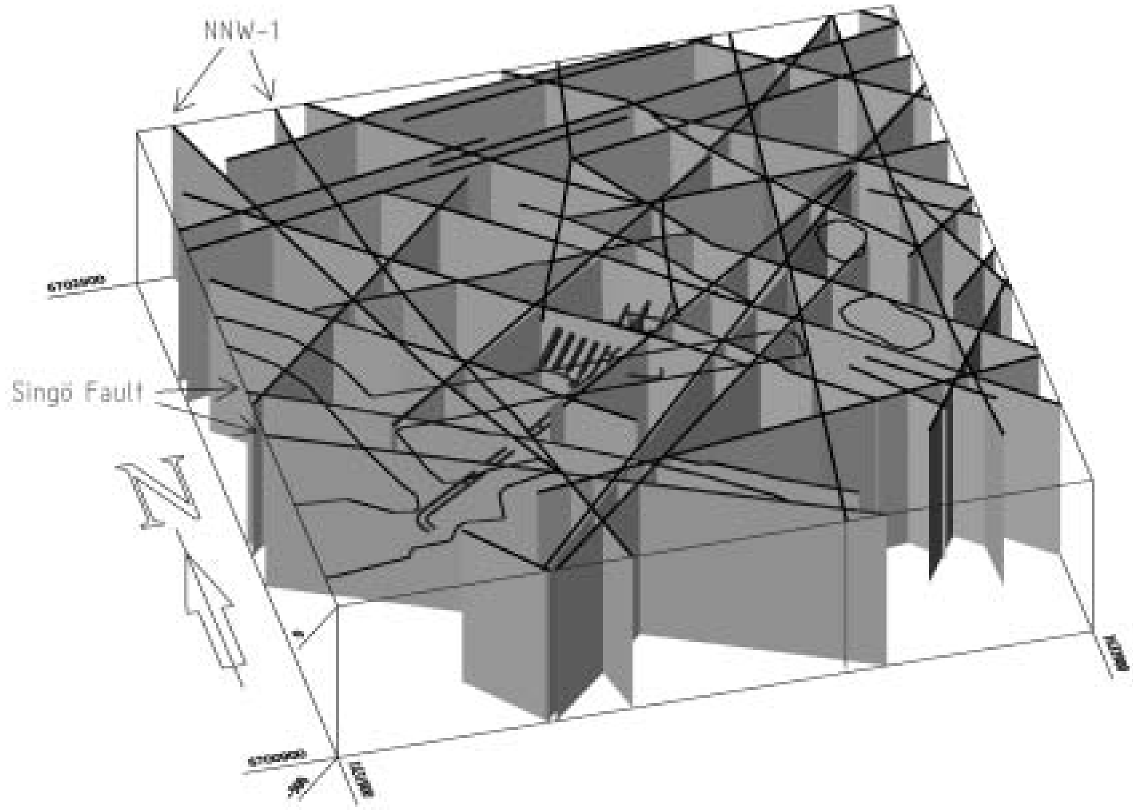


Figure 6.8. *Rose diagram showing orientation lineaments in the local SFR 1 area: a) all lineaments (n=42), b) lineaments equal to or shorter than 1000 m (n=20), and c) lineaments longer than 1000 m (n=22). The outer scale ring represents 10 %.*

6.3 Structural model of the local SFR 1 area

To construct a three-dimensional model, data indicating the dip of structures is needed. A detailed study of mapped fractures of the SFR 1 underground facility is very time consuming and not within the scope of this study. Instead is it assumed that the structures incorporated in the SKB structural models of SFR 1 represent the most prominent structures in the vicinity of the SFR 1 underground construction. The outcome of this study will point out similarities with the SKB SFR 1 model, or suggest modifications of the SKB model or argue whether new structures should be looked for. However, structures in the SFR 1 underground construction could be distinct and mappable in the tunnels, rock caverns and vault, but do not have to be elucidated by the topographical data. It is a matter whether the structure has a surface expression (mappable as a lineament). or not and the base data resolution. Furthermore, in the present study the real density of topographical information (density of measurements in the sea area) is not apparent (cf. Brydsten, 1999). This means that the resolution is not uniform in the map area.

All topographical features mapped as lineament in this study are considered as tectonic structures, zones, in the bedrock. The extent of the zones fully corresponds to the lineaments, which implies that that structures drawn on the map are not extended along strike. Zones are extended to the bottom of the model, to a depth of 500 m. Most structures are vertical and some are steeply dipping, Figure 6.9. Gently inclined zones (cf. the H2 Zone in the SKB models) dipping south-eastward are displayed in Figure 6.10.



(to be continued)

Figure 6.9a. *Three-dimensional structural model of vertical to steeply dipping fracture zones in the SFR 1 local area, 2 by 2 km and 0,5 km deep, viewed from a point south-southwest at an inclination of 35° above the horizon.*

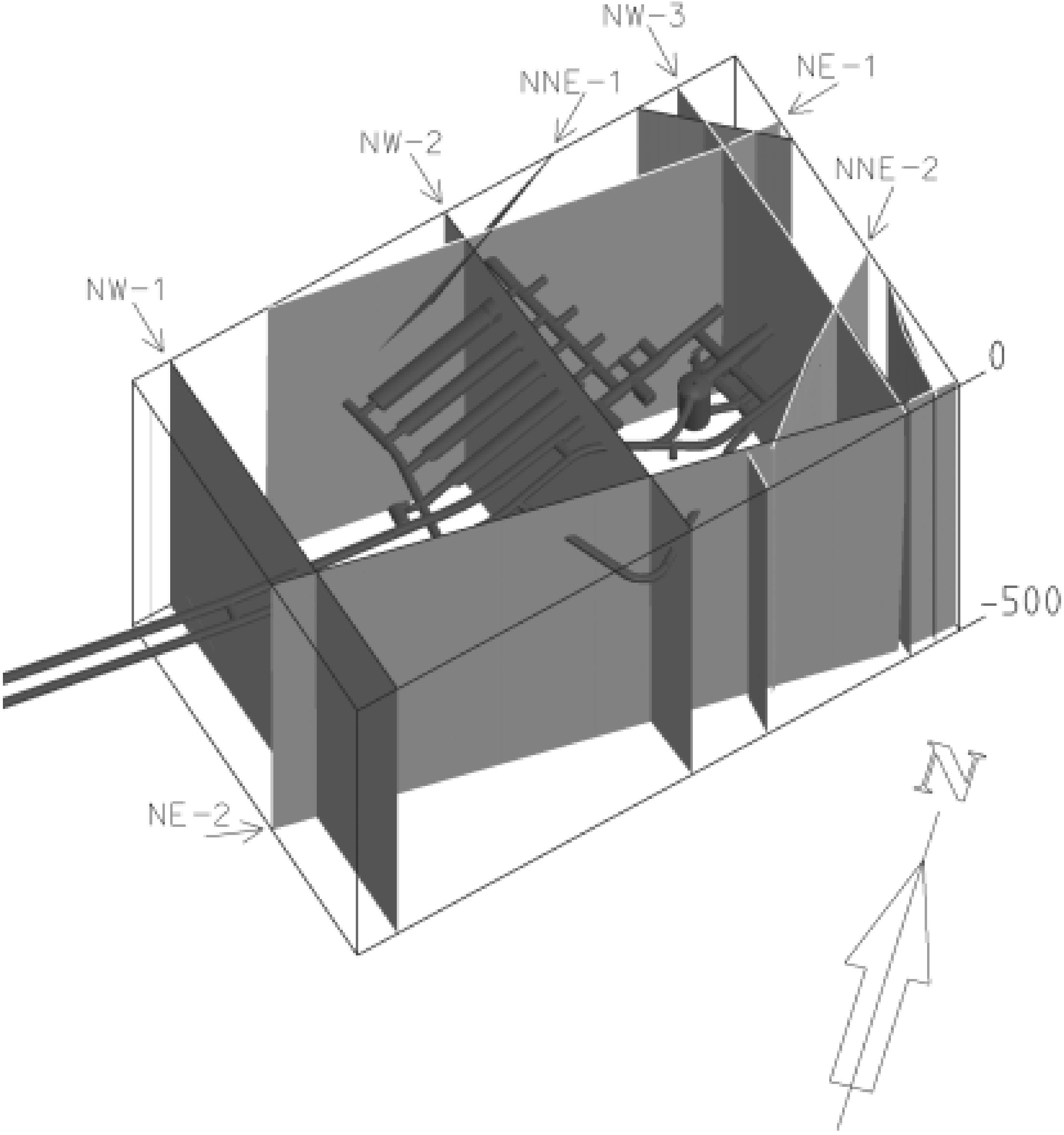
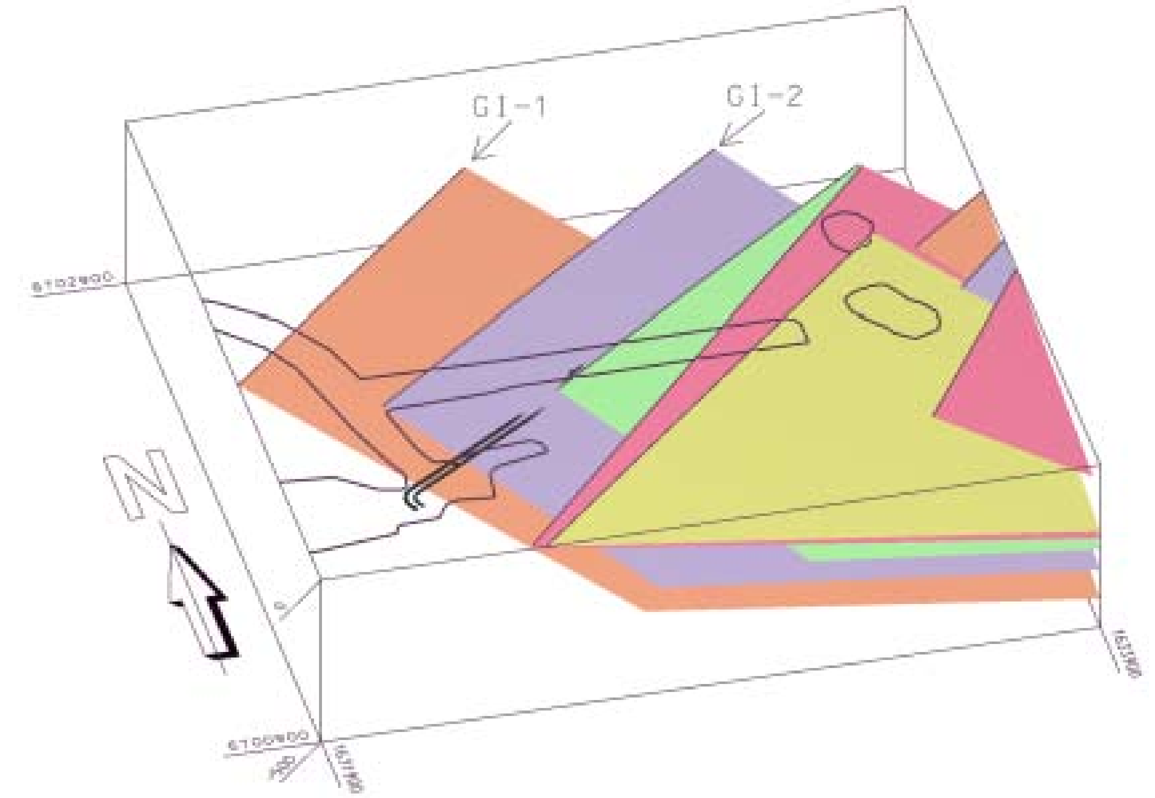
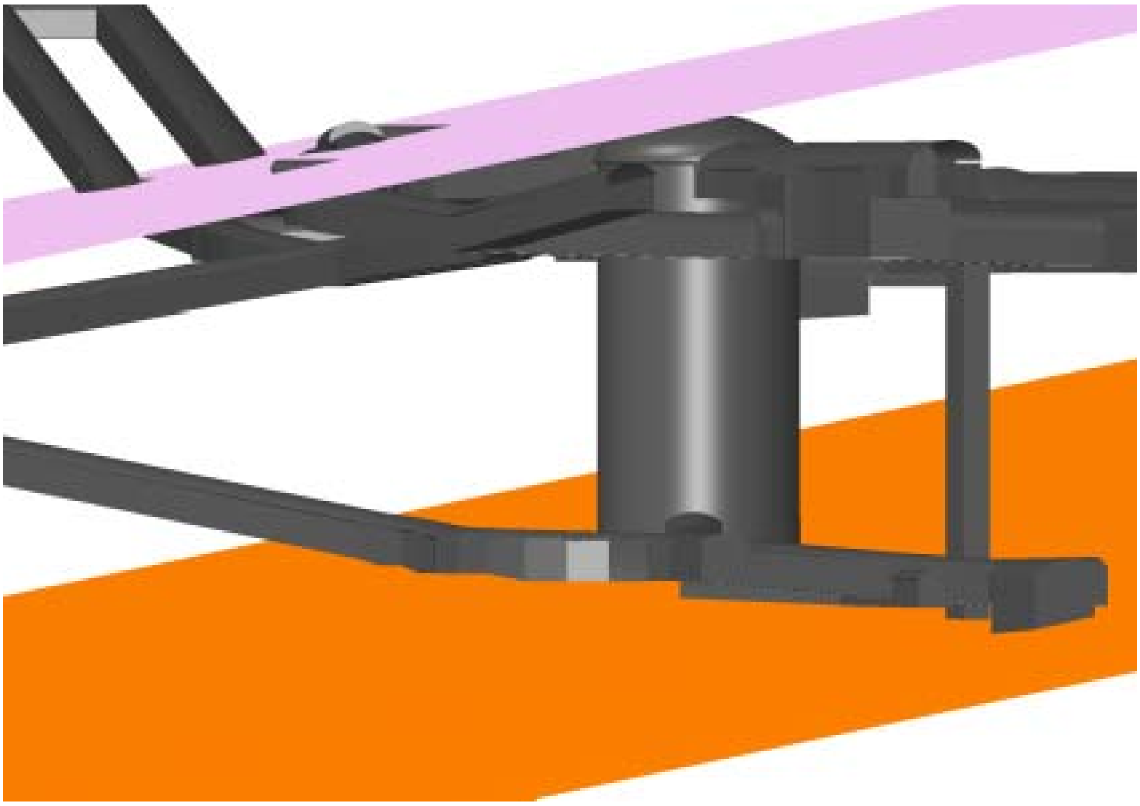


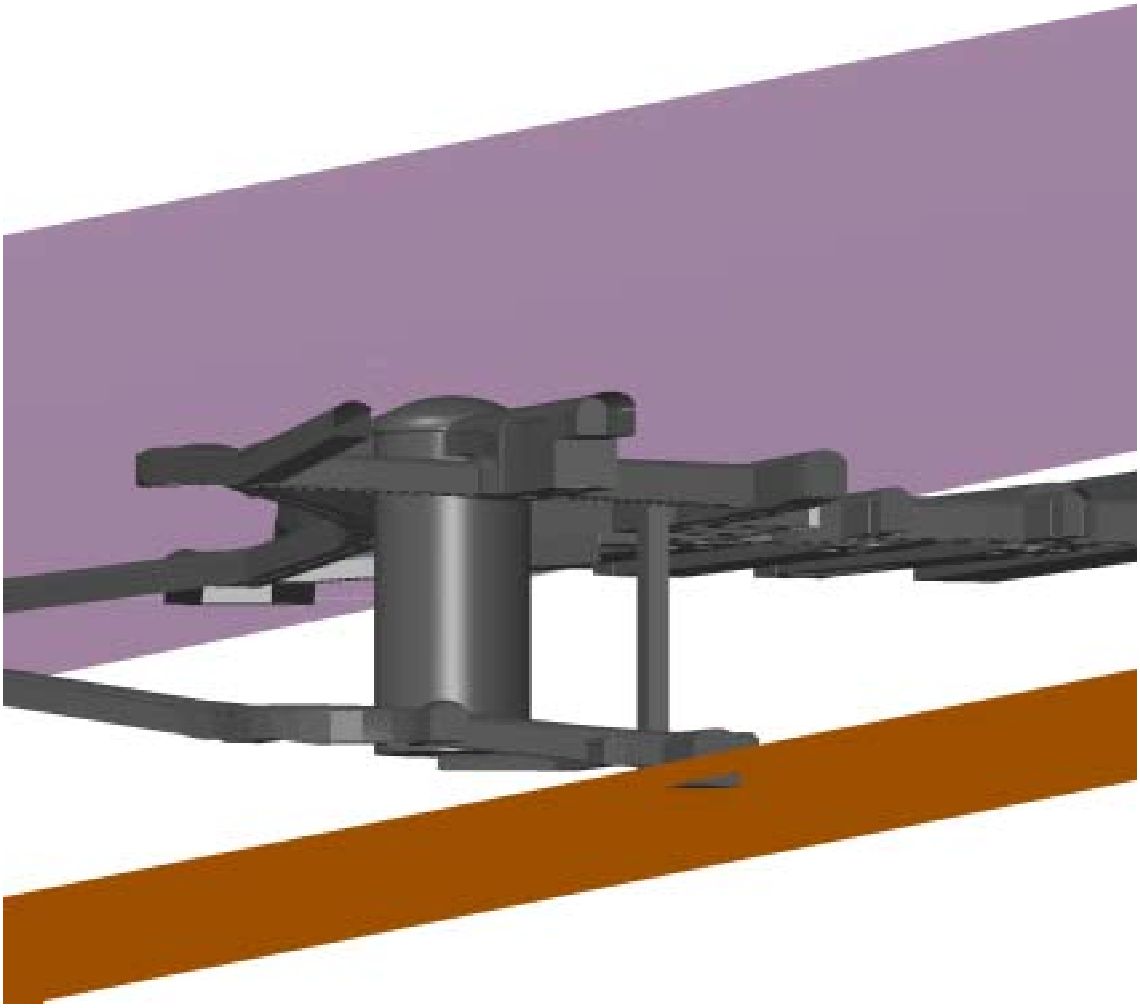
Figure 6.9b. (continued). *Three-dimensional structural model of vertical to steeply dipping fracture zones in the SFR 1 local area, detail of the local area, 650 by 400 m and 500 m deep, showing relations between fracture zones and the SFR 1 repository, viewed from a point south-southeast at an inclination of 60°.*



a)



b) (to be continued)



c)

Figure 6.10. *Three-dimensional structural model of gently inclined fracture zones in the SFR 1 local area: a) the whole local SFR 1 area, 2 by 2 km and 0,5 km deep, viewed from a point south-southwest at an inclination of 35° above the horizon, b) detail of the local area emphasising the relation between a shallow gently inclined fracture zone (GI-2) at the upper part of SFR 1 repository, viewed from a point east-southeast at an inclination of 2.5° "above the horizon", and c) detail of the local area showing the relation between a gently inclined fracture zone (GI-1) and the lower parts of the SFR 1 repository, viewed from a point south-southeast at an inclination of 2.5° "below the horizon". The diameter and height of the rock cavern are c. 30 and 70 m, respectively.*

If the gently inclined zone, zone GI-1 (Figure 6.10) corresponding to Zone H2 (Carlsson and Christiansson, 1987, SKB, 1993), found at the base of the rock cavern is extrapolated upward it will appear c. 500 m to the west of the repository and close to a NE-SW trending lineament. However, if the lineament is the surface expression of Zone H2 then it should have a more gentle inclination than suggested by SKB. Furthermore, if NE-SW trending lineaments represent gently inclined zones then the NE-SW trending structure located just west of the SFR 1 repository may pass just above the ceiling of the rock cavern (Figure 6.10).

Orientation of structures just in the vicinity of the SFR 1 repository or intersecting the underground construction is listed in Table 6.5.

Table 6.5. *Fracture zones at the vicinity of the SFR 1 repository (cf. Figures 6.9 and 6.10). The inclinations of zones are inferred from SKB reports (cf. Axelsson and Hansen, 1998) as primary subsurface data have not been available in the present study.*

Fracture zone ID (generally shown in Fig 6.9b)	**Strike** (degrees)	**Dip** (degrees)	**Notation**
GI-1 (GI=gently inclined)	N46E	22SE	Below the rock cavern, intersecting tunnel
GI-2	N50E	22SE	Above the rock cavern, crossing the ramp and intersecting tunnel (cf. NE-1)
NW-1	N47W	90	Crossing the ramp
NW-2	N50W	90	Crossing the rock vaults and tunnels
NW-3	N48W	90	Just north-east of the repository
NNE-1	N21E	70	Just north-west of the rock vaults
NNE-2	N10E	90	East of the rock cavern
NE-1	N50 E	90	North-west of rock vaults, outcrops along same lineament as GI-2
NE-2	N50E	90	Just south-east of the ramp, crossing tunnel
Singö Fault (cf. Fig 6.9a)	N63W	90°	Two branches, crossing the double ramp
NNW-1 (cf. Figure 6.9a.)	N14W	90	Two branches, crossing the ramp between the Singö Fault and NW-1

7 Discussion

7.1 Previous lineament interpretations and structural maps

7.1.1 Regional maps

Bergman et al. presented in 1998 the latest and most detailed SKB interpretation of the regional structural pattern in the bedrock in the Öregrundsgrepen-Forsmark area (extension: 40 km in E-W and 25 km in N-S; the map is not shown in this report). The map reflects mainly a pattern of continuos ductile shear zones and also that the majority of all ductile structures are reactivated and transformed to brittle shears, labelled as fracture zones in the legend of the map (ductile shears with a negative topographical expression). The structures have in general not straight but curved or somewhat uneven traces. The dominant orientation of structures is WNW-ESE. The SFR 1 repository is located north of a regional WNW-ESE trending fracture zone, the Singö Fault and south-west of a north-west trending splay (zone 8 in the SKB SFR 1 model, cf. Figures 7.1 and 7.3) emanating from the Singö Fault. The map shows that the Singö Fault is not a unique structure in the area, but one of several faults forming a wide WNW-ESE trending fault belt. The southern border of this belt (Tirén, 1991) is located just south of the site Finnsjön, c. 18 km south-southwest of SFR 1, and the northern border is located north of Gräsö. This implies that the belt, the Östhammar Fault Zone (Tirén, 1991), has a lateral width of at least 35 km. The deformation within this zone or belt has taken place preferentially along a network of anastomosing shears leaving rhombohedral shaped rock volumes less effected by deformation.

7.1.2 Semi-regional maps

On a semi-regional scale there are two structural maps (one 4 by 6 km large, Bergman et al., 1996, and another 9 by 10 km large, Bergman et al., 1998). The former map is characterized by rectilinear structures oriented in NNE-SSW, NNW-SSE, NW-SE and WNW-ESE. The NNW-SSE trend structures have a regular spacing of approximately 1.5 km and NE-SW trending structures with a separation of 1.4 km.

There is no apparent relation between rock type distribution and the occurrence of tectonic zones. However, NW-SE and WNW-ESE trending zones parallel the axial traces of asymmetric folds. The map from 1998, a blow up of a regional structural map (Bergman et al., 1998), also showing the extent of ductile deformation in the bedrock (Figure 7.1). Local SFR 1 structures (Axelsson and Hansen, 1998) are also displayed on the map. Notable is that the major WNW-ESE trending fracture zones are located in wide ductile shear zones (c. 2 to 3 km wide). A shear zone, similar to and south of the Singö Fault, has an increased density of internal brittle deformation zones compared to the surrounding rock. This is in contrast to the ductile deformed rock along the Singö Fault, which contain just a few fracture zones according to map. The SFR 1 repository is located within the ductile sheared rock along the Singö Fault (which previously also has been denoted: the Singö Fault Line, the Singö Line and the Singö Fault Zone).

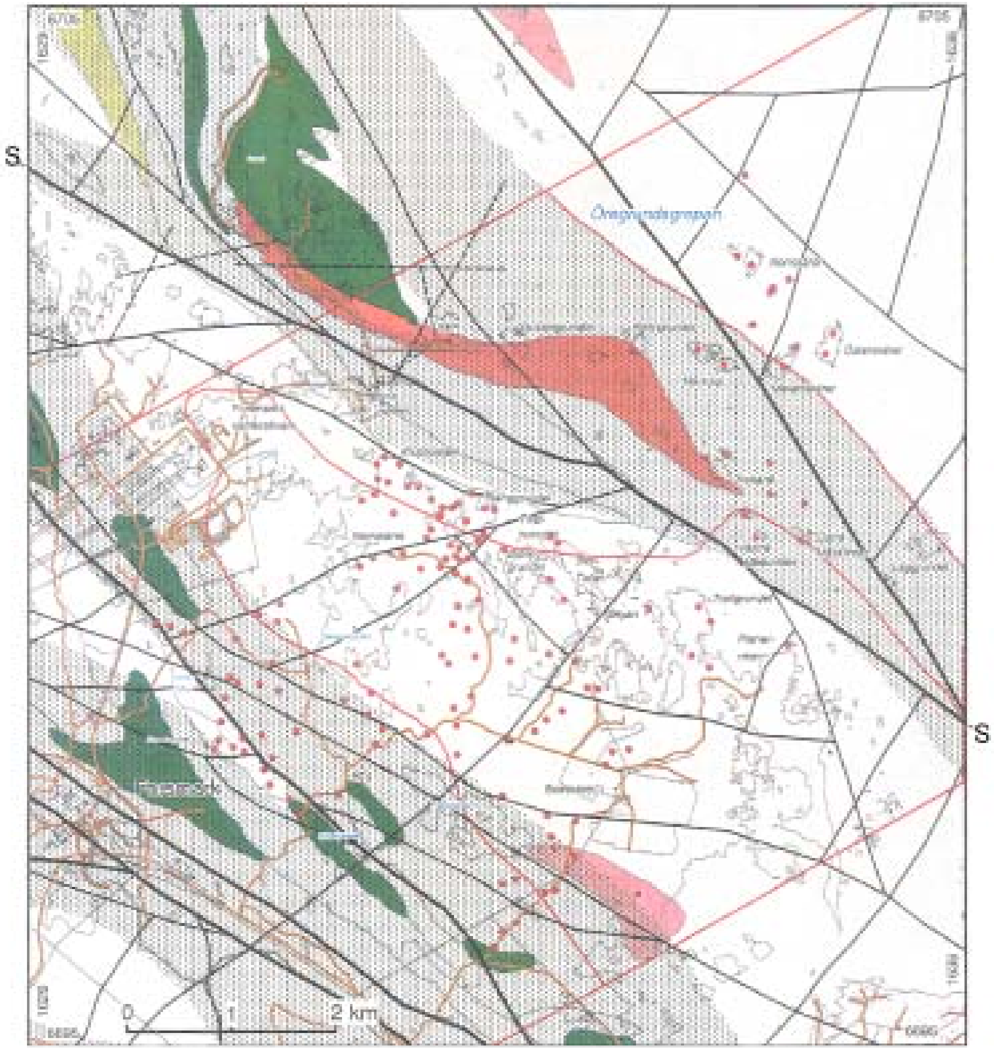


__Figure 7.1.__ Semi-regional bedrock map of the Forsmark area (Bergman et al., 1998). The SFR 1 repository is located in a ductile shear zone (dotted area) north of a regional fault (Singö Fault, S). The dominant rock type is a foliated granitoid (white background), younger granite is marked red and old greenstone is green. Red dots are outcrops. Regional and local faults are displayed by thick and thin lines, respectively. Dashed lines are structures inferred from Axelsson and Hansen (1998).

7.1.3 Local maps

On the local scale there are three SKB maps presenting the structural pattern at SFR 1, Figure 7.2.

Hagconsult (1982) show in their local lineament map, Figure 7.2a, a dominance of N-S trending lineaments, at least south of the Singö Fault. The N-S lineaments have locally a fairly regular spacing, from 100 to 500 m. In the vicinity of the SFR 1 repository the map only show structures on the western and southern side of the repository. The orientation of these structures is NNE-SSW, WNW-ESE (e.g. the Singö Fault), NW-SE, N-S and E-W.

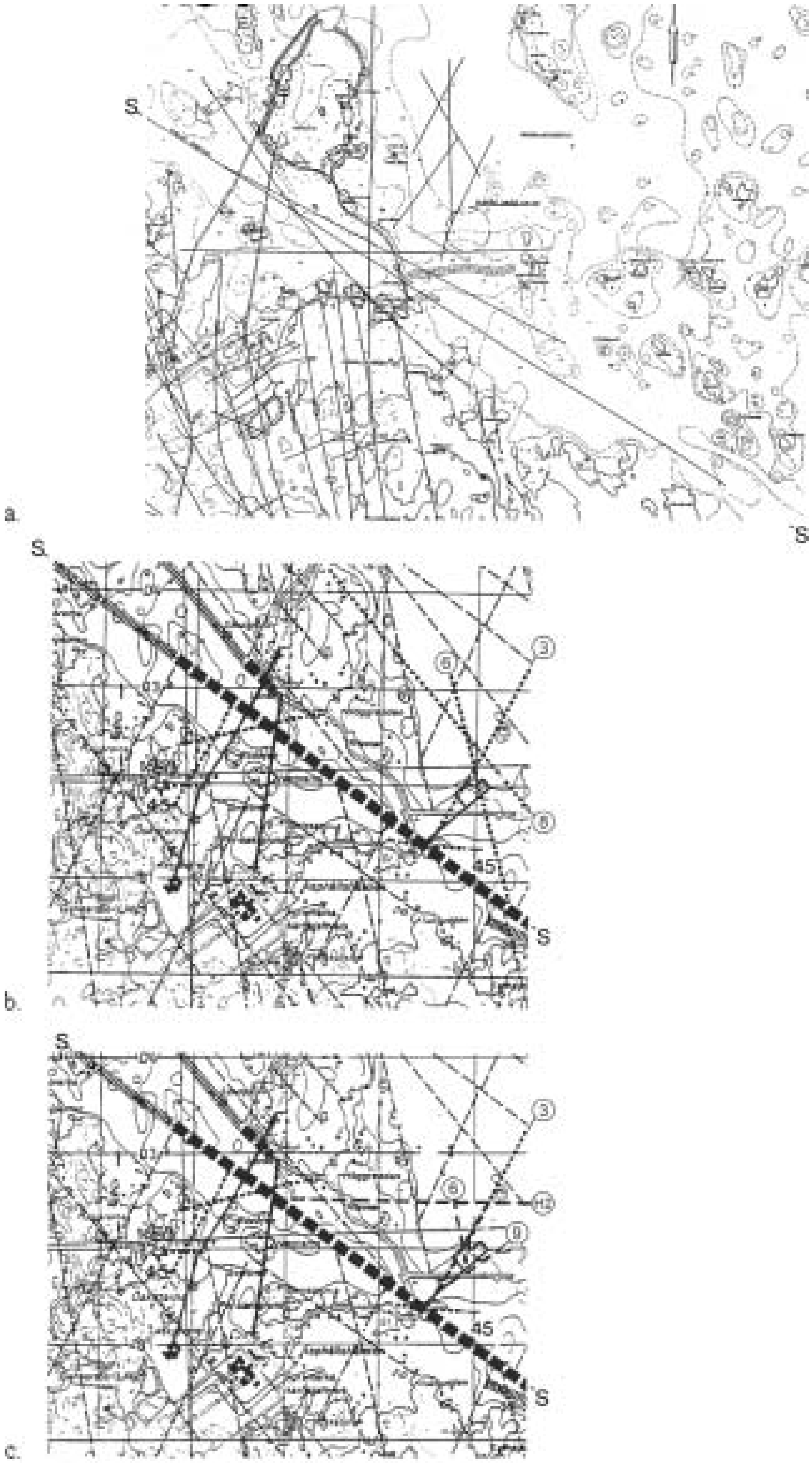


Figure 7.2. *Local structural maps: a) Hagkonsult (1982), b) Carlsson and Christiansson (1978) and SKB (1993), and c) Axelsson and Hansen (1998), Zone H2 is the W-E trending zone north of SFR 1. Uniform scale: the grid in 7.2b. and c. is 1 by 1 km. The location of the Singö Fault (S) is displayed (cf. Figures 6.1 6.7, 6.9a, and 7.1). ID of zones at SFR is inserted (cf. Table 7.1).*

Table 7.1. *Comparison of mapped structures in the proximity of the SFR 1 repository presented on four sets of lineament or structural maps (Figures 6.7, 7.1 and 7.2b-c).*

Zone ID **(ID codes adopted from the SKB 1993 structural model, cf. Figure 7.3a)**	**SKB (1993)** **"older SKB structural map"** **(Figure 7.2b)**	**Axelsson and Hansen (1998)** **"alternative /updated structural map"** **(Figure 7.2c)**	**Bergman et al. (1998)** **(Figure 7.1)**	**Present report** **(ID codes presented in Figures 6.9b and 6.10a and Table 6.5)** **(Figure 6.7)**
Singö Fault	NW-SE	NW-SE, same	Adjusted, a more westerly trend	Adjusted, a more westerly trend
Zone H2	Not indicated	E-W trace, inferred	Copied from Axelsson and Hansen (1998)	Adjusted to NE-SW (GI-1)
Zone 3	NE-SW	NE-SW, same	Copied from Axelsson and Hansen (1998)	NE-SW, shorter, slightly oblique trend (NNE-1)
Zone 6	NNW-SSE	NNW-SSE, moved westward	Not indicated	Not indicated
Zone 8	NW-SE	Not indicated[1]	NW-SE, > 4km long branch emanating from the Singö Fault	NW-SE, two structures (NW-3)
Zone 9	Not indicated	NE-SW, inferred	Not indicated	NE-SW, cf. Axelsson and Hansen (1998), more extensive eastward (NE-2)

Note 1. Axelsson and Hansen (1997) states that "Zone 8 – The seismic surveys do not indicate a major vertical zone. The indications of the zones found in boreholes can be interpreted as a subhorizontal zone parallel to Zone H2 and outcropping at the sea bottom north of SFR. There might be a vertical connection between this zone (Zone F1) and Zone H2. A minor zone may exist."

On the structural map presented by Carlsson and Christiansson (1978) and SKB (1993), Figure 7.2b, the orientation of the Singö Fault is slightly adjusted. The location of the four other zones at SFR 1 are modified (two trending NE-SW, and the other two trending NW-SE and N-S) while the other structures are excluded (cf. Figures 7. 1 and 7.2). However, new structures trending NNW-SSE and NW-SE are inferred.

Axelsson and Hansen (1998) proposed an alternative/updated map, Figure 7.2c, with the following modifications of the SKB 1993 structural map:

- A NE-SW trending zone parallel to the ramp down to the repository is added (Zone 9, cf. Figure7.2 b).
- A NNW-SSE trending zone located across the repository is shortened and moved approximately 100 m westward (Zone 6).
- A NW-SE trending structure just east of the repository is excluded (Zone 8, see Table 7.1 note 1).
- An E-W trending structure located north of the repository is inferred as the outcropping of a gently dipping zone (Zone H2) found in the SFR 1 repository.

However, the location and orientation of the surface expression of Zone H2 proposed by Axelsson and Hansen could not be correct as the zone dips south-eastward (see Section 7.3).

It is not within the scope of the present study to make a detailed comparison of structures presented on different local lineament and structural maps. However, structures in the vicinity of the SFR 1 repository is of special interest of this study and therefore compared in Table 7.1.

7.2 Comparison – previous and present structural maps

There is an inconsistency in pattern displayed on various SKB maps describing lineaments or bedrock structures of the Forsmark area. However, the more impressive structures, such as the Singö Fault and the Forsmark Fault (cf. Figure 7.1), are uniformly presented. Assuming that all structures displayed on previous maps represent real structures and that the individual maps just show selected structures, then a compilation of all maps should give a more complete description of the structure pattern in the bedrock. Compared to such a compiled structural map of the SFR 1 area the present structural map has a higher number of structures.

The maps presented by SKB (1993), Axelsson and Hansen (1998), Bergman et al. (1998) is compared to the present map (regarding confirmed and not confirmed structures in the vicinity of the repository) in Table 7.1.

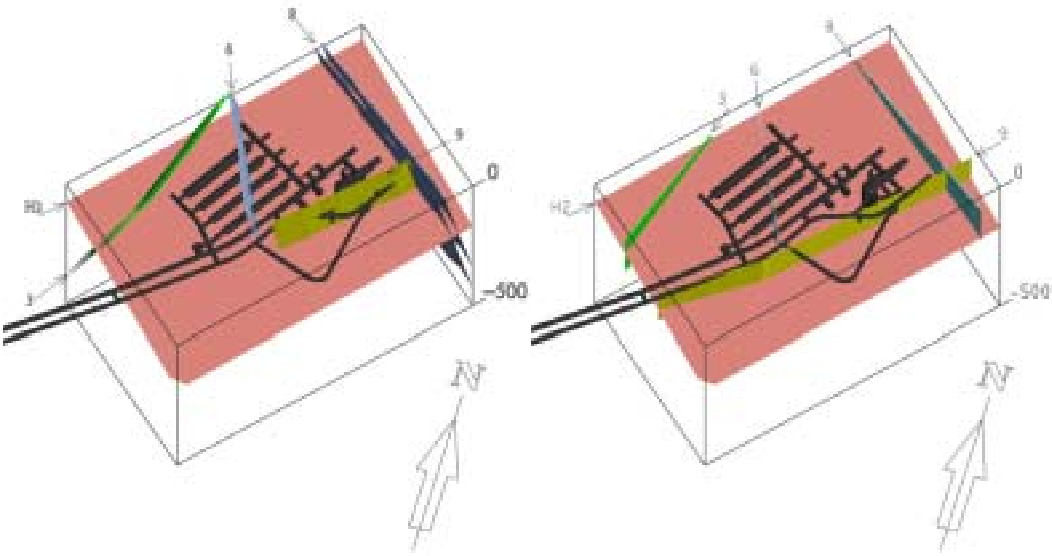
The Singö Fault in the present study as well as in the map by Bergman et al. (1998) is located slightly to the east and has a more westerly trend compared to the previous maps. The orientation and location of Zone H2 is adjusted. Zone 3 terminates just above the vaults and is not traced to stop against the Singö fault. Zone 6 is not indicated. Zone 8 appearing on the SKB 1993 map, removed by Axelsson and Hansen on their map, is expressed as an extensive structure on the map by Bergman et al. and the present map. Axelsson and Hansen indicate Zone 9 to be a long structure. On the present map this structure is relatively extensive. The present map has an additional structure, parallel to Zone 8, and located just above the easternmost part of the rock vaults.

7.3 Comparison of previous and present three-dimensional structural models

Two three-dimensional structural models have been presented:

- The model presented in the final safety report for the SFR 1 storage (Carlsson and Christiansson, 1987, SKB, 1993), the older SKB model.
- An alternative/updated structural SKB model of the SFR 1 storage (Axelssson and Hansen, 1998).

In the comparison of the present and previous three-dimensional models the label of zones used by SKB (1993) and Axelsson and Hansen (1998) are used, Figure 7.3.



a) b)

Figure 7.3. *SKB structural models of the local SFR 1 area: a) the older model (SKB, 1993), and b) the alternative/updated SKB model (Axelsson and Hansen, 1998). The models are modified from the originals only in that sense that they are viewed in the same direction as the present model shown in Figure 6.9b and have the same cut of the block diagrams.*

Comparison of the alternative/updated SKB model (Axelsson and Hansen, 1998) *and the older SKB model* (Carlsson and Christiansson, 1987, SKB, 1993) yields (Figure 7.3):

- In the alternative/updated model Zone H2 extends up to the surface east of the Singö Fault and point out that it "extends at depth probably beyond the Singö Zone" (read; the Singö Fault).
- "Shortening of Zone 6 in accordance with tunnel mapping" and the inclination of Zone 6 is slightly changed, to be vertical.
- "Downward termination of Zone 6 towards Zone H2".
- "Longer Zone 9 in accordance to tunnel mapping".
- "Reduction of Zone 8 to a local zone with limited depth" (stops against Zone H2, see Table 7.1 note 1).
- The dip of Zone 3 is changed to vertical, the zone was steeply inclined westwards in the older model.

In the alternative/updated SKB model, no new zones have been introduced and no old zone has been excluded. The adjustment of zones concerns modification of inclination (Zones 3 and 6), extension (Zones 6, 8 and 9) or order of magnitude (including width; Zones 3 and 8). The alternative/updated SKB structural model is in principal a hydrogeological model.

The older SKB model (Carlsson and Christiansson, 1987, SKB, 1993) *compared to the present model (Figures 6.9, 6.10 and 7.3a)*:

- The Singö Fault has a more westerly trend in the present model (Figures 6.1, 6.7, 6.9a and 7.2b).
- In the present model the NNW-SSE trending zone just north of the ramp is confirmed and indicated to approach the ramp close to the location of the Singö Fault (Figures 6.7, 6.9a and 7.2b).
- The NE-SW trending zone (Zone 3 in Figure 7.3a) is indicated and have in the present model (Figure 6.7, and zone NNE-1 in Figure 6.9b) a somewhat more northerly trend and is not traceable westward from the repository to the Singö Fault.
- The NE-SE trending zone (Zone 6) crossing the repository is not indicated in the present model.

The present model (Figures 6.9 and 6.10, Table 6.5) compared to the alternative/updated SKB model presented by Axelsson and Hansen (1998, Figure 7.3b):

- A zone (NE-2) located south of the repository and trending NE-SW corresponds to Zone 9.
- A NNW-SSE trending zone (Figure 7.2c) just north of the ramp is confirmed (NNW-1 in Figure 6.9a) and indicated to cross the ramp close the location of the Singö Fault.

- In the present model an upper gently inclined zone (GI-2 in Figure 6.10) is proposed (cf. Table 7.1 note 1; Zone H1).
- A lower gently inclined zone (GI-1 in Figure 6.10) corresponds to Zone H2.
- The E-W trending surface trace of Zone H2 north of the repository (Figure 7.2c) has not been confirmed. However there are E-W trending structures in the present model but they could not represent Zone H2 as it dips south-eastward.
- A zone (NE-1) parallel to Zone 9, but located just north-west of the rock vaults, is proposed.
- A NW-SE trending zone (NW-3) is a semi-regional structure, presumably a structure with branches, corresponds to Zone 8.
- A proposed vertical zone (NW-2) parallel to Zone 8 transects the easternmost parts of the rock vaults.

No primary data on fracture and fracture zones in the SFR 1 underground construction has been available in the present study. Therefore, the proposed additional structures have not been checked. Notable is that the vertical zone just west of the rock vaults (zone NE-1, cf. Figure 6.9b) and the gently inclined upper zone (zone GI-2, cf. Figure 6.10) outcrop along the same lineament.

8 Conclusions

The SFR 1 repository is located in a more than 35 km wide WNW-ESE trending deformation belt which initially was formed as a major ductile shear zone, which later was transformed into a fault zone as the more extensive ductile shears were reactivated during brittle conditions. Thus, the ductile shears formed an anastomosing pattern outlining lozenge shaped rock volumes with tectonically less effected rock. The ductile zones were relatively wide, locally several kilometres wide. However, the structural relation between the later fault pattern and early ductile deformation does not appear to be simple (cf. Figure7.1). For example, the regional faults appear to merely follow the ductile shears, but splay faults may well leave the ductile shears. However, in the Formark area the regional faults appear to be located on the southern side of the wide ductile shears.

South of the WNW-ESE trending deformation belt the structural trend in the bedrock is approximately N-S. Interference deformation, block faulting, along the two sets of structures is indicated by offsets and tilting of the bedrock surface. The WNW-ESE deformation belt is overprinted and transected by brittle structures.

The SFR 1 repository is according to Bergman et al. (1998) located in a ductile shear zone, which along its southern side has the regional WNW-ESE trending Singö Fault. A splay fault (Zone 8) emanating from the Singö Fault is located just east of the SFR 1 repository. Both structures are identified in previous studies and confirmed by the present study. The splay (Zone 8) appears to be a significant structure.

Concerning the more local structures in the proximity of the SFR 1 repository the present study have found indications of the existence of all previously proposed structures except one minor structure. The structure trends NNW-SSE and is mapped to cross the four rock vaults (Zone 6).

The present study indicates the existence of additional local structures, which could be checked in the SFR 1 underground construction by mapping. One vertical structure trending NW-SE and transecting the eastern part of the rock vaults and a gently inclined structure, parallel to Zone H2, located just above the rock cavern.

There are also some structures indicated in the present study that do not intersect the SFR 1 repository. One is located just north-east of the SFR 1 repository and is parallel to the NE-SW trending structure mappable along the ramp. Another is a NNE-SSW trending vertical structure located east of the rock cavern.

The proposed structures could be checked against the results of refraction seismic measurements (not available in the present study) performed in an initial state of the location of the SFR 1 repository (Hagkonsult, 1980).

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