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## An alternative model within version 1.2 of the Forsmark modelling project


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Geological Survey of Finland (GTK)


September 2004


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# Abstract

The work reported in this document is a part of the Forsmark site descriptive model project, Version 1.2, carried out by the Swedish Nuclear Fuel and Waste Management Co. (SKB). It includes an alternative interpretation of lineaments from airborne geophysical and topographic data at the Forsmark site. The data used in the interpretations comprised four data sets (magnetics, EM, VLF, and topographics). The purpose of the work was to identify and interpret linear features, which may correspond to deformation zones.

The work comprised processing of the delivered data, map compilation, and lineament interpretation. The interpretation was divided into three stages. In the first stage, each of the four data sets was interpreted separately. Following the interpretation of each data set, the different interpretations were integrated to produce coordinated lineaments. In the last stage, the various segments of the coordinated lineaments were linked together along what were judged to form single lineaments. This was the final lineament interpretation. At each interpretation stage, unique attributes were coupled with the interpreted features.

The interpretations of the magnetic, EM, VLF, and topographic data produced a total of 854 method-specific lineaments. The integration of the method-specific lineaments resulted in the production of 926 coordinated lineaments (of which 102 are magnetic lineaments from the sea area). Finally, the linked lineaments comprise 536 separate features.

# Sammanfattning

Denna rapport redovisar resultaten av en alternativ samtolkning av flyggeofysiska och topografiska data i Forsmarks platsundersökningsområde och är en del av SKB:s platsbeskrivande modell, version 1.2. Tolkningsdata består av fyra datamängder (magnetiska, EM, VLF och topografiska). Målet på tolkningen var att identifiera och tolka linjära strukturer, som kan representera deformationszoner men även andra förklaringar kan finnas.

Arbetet består av bearbetning av basdata, kartproduktion och lineamenttolkning. Tolkningen är uppdelad i tre faser. I den första fasen tolkades alla data separat. I nästa fas, kopplades de fyra metodspecifika tolkningarna ihop till s k ”coordinated lineaments”. Slutresultatet utgörs av s k ”linked lineaments” där separata segment av ”coordinated lineaments” sammankopplades längs lineament som bedömts bilda ett kontinuerligt lineament. I varje fas beskrivs varje tolkat lineament med parametrar som belyser lineamentets ursprung och karaktär.

Tolkningen av flygmagnetiska, flygelektromagnetiska (EM), VLF och topografiska data resulterade i 854 metodspecifika lineament. Sammanslagningen av de metodspecifika lineamenten producerade 926 s k ”coordinated lineaments”, av vilka 102 är endast flygmagnetiska lineament från sjöområdet. Slutligen, s k ”linked lineaments” består av 536 separata objekt.

# Contents

# 1 Introduction

This document reports the results gained in the project entitled "Interpretation of lineaments from airborne geophysical and topographic data", which is one of the activities performed within the site investigation modelling work, Version 1.2, at Forsmark.

The work was carried out by the Geological Survey of Finland (GTK) during the spring and summer of 2004. The purpose of the work was to present an alternative lineament interpretation to that described in /1/ using the same basic data. The data comprised helicopter-borne magnetic, electromagnetic, very low frequency electromagnetic, and topographic data.

The work was carried out in four stages. First, the delivered data were processed and compiled into several maps visualizing the various data sets. Following this procedure, each data set was interpreted separately producing method-specific lineaments. The third stage involved an integration of the method-specific lineaments. This stage in the procedure aimed to reduce redundant information. Finally, the coordinated lineament segments that formed longer, continuous features were combined into linked lineaments. The linked lineaments constitute the final joint interpretation of airborne geophysical and topographic data.

# 2 Objective and scope

The purpose of the work was to carry out an alternative, joint interpretation of airborne geophysical and topographic data in a part of the Forsmark regional model area. An earlier interpretation of lineaments in this area has been provided in /1/.

The geophysical data comprised helicopter-borne magnetic, electromagnetic (EM) dipole source, and very low frequency (VLF) EM data. The topographic data comprised infrared orthophotos, height models, and a terrain map. Data sets were delivered for the complete modelling area that has been defined for the Forsmark site descriptive model project. However, the area selected for interpretation in this study was limited to c 50 km$^2$ (5.4 km × 9.3 km) (Figure 2-1).

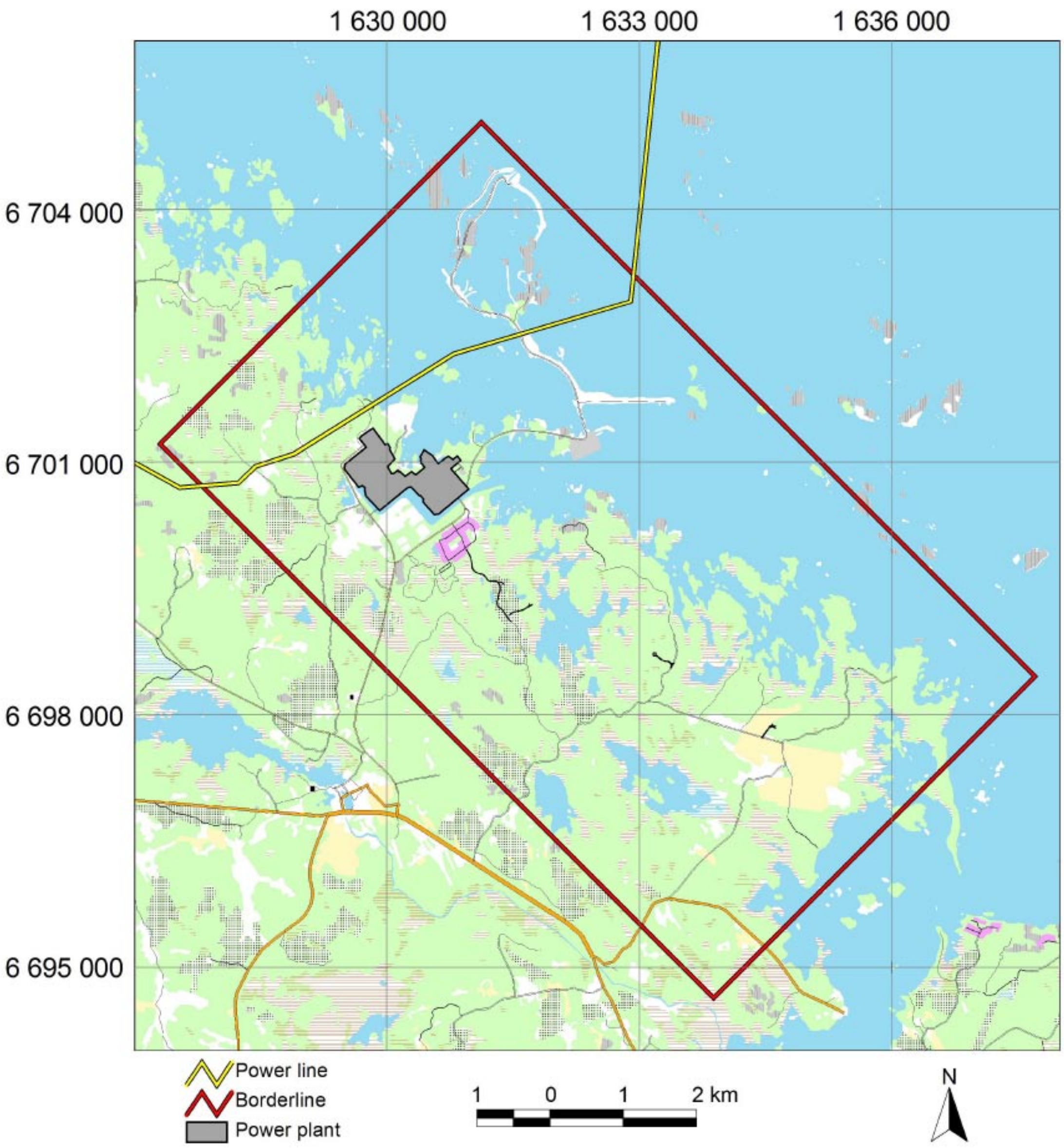



*Figure 2-1. An overview of the Forsmark site investigation area. The map shows the Forsmark nuclear power plant, the borderline giving the extent of the interpretation area for this work, and the DC transmission power line going to Finland.*

# 3 Equipment

## 3.1 Description of interpretation tools

The work was carried out using PCs and professional geophysical and GIS software. The names of the software packages and their usage is listed in Table 3-1.

**Table 3-1. The software packages and their usage.**

| Software package | Usage |
|---|---|
| Geosoft Oasis montaj v5.0 | Data processing and map compilation. |
| ArcView GIS v3.2 | Lineament interpretation. |
| ArcView GIS v8.0 | Data processing, map compilation, and lineament interpretation. |

# 4 Methodology

## 4.1 Introduction

The work proceeded in the following stages:

1. Preparatory work.
2. Method-specific lineament interpretation.
3. Coordinated lineament interpretation.
4. Linked lineament interpretation.

The end product of the linked lineament interpretation stage constitutes the final interpretation, the joint interpretation of airborne geophysical and topographic data.

The interpretation of lineaments was carried out according to the methodologies described in the method descriptions SKB MD 120.001 (Metodbeskrivning för lineamentstolkning baserad på topografiska data) and SKB MD 211.003 (Metodbeskrivning för tolkning av flyggeofysiska data). The coordination of geophysical and topographic lineaments was completed in the same manner as that described in /1/.

All interpretations were carried out utilizing GIS software and techniques. The end product of each interpretation stage constitutes one or more GIS themes with accompanying attribute tables. The lineaments are stored in the themes as polylines having unique attributes stored in the table.

## 4.2 Preparatory work

Preparatory work comprised data processing and map compilation. Data processing was required to process raw data into a form that is more suitable for map compilation, and to enhance data. Several maps were compiled from the processed data to act as the basis for lineament identification.

Data processing comprised mostly gridding raw data. The raw line data had to be gridded into uniform grids to make map compilation and further data processing possible. Besides gridding, the data were further processed using geophysical filtering.

Several maps were compiled from the gridded data. Both sunshaded and contour maps were produced. The sunshaded maps were either colour or grey-scale maps shaded from different directions to facilitate identification of lineaments that strike in different directions.

However, not all data needed processing. Some data, such as infrared photographs and terrain maps, were used in the original format.

## 4.3 Interpretation of method-specific lineaments

Each method-specific data set was interpreted separately. The maps compiled from a data set were used as the basis for the interpretation of that data set.

The interpretations were carried out by visually inspecting several method-specific maps at different scales. If a linear feature seen on a map was judged to represent a deformation zone (Figure 4-1a) it was digitized as a polyline (Figure 4-1b) and stored in a method-specific GIS theme. Once the lineament was stored its attributes were determined and entered in the accompanying attribute table.

The interpretation of a method-specific data set was considered completed when all feasible linear features were identified. The end product of this stage comprises several GIS themes, one theme for each method-specific data set.

Generally, any linear and continuous feature on the method-specific maps can be regarded as a lineament. However, since this study is focused on those lineaments that may present deformation zones in the bedrock, certain criteria were needed in the interpretation. In a normal case, the following features were judged to reflect a deformation zone:

- Magnetic minimum.
- Discontinuity/displacement of magnetic anomalies.
- Magnetic step.
- Resistivity minimum (dipole source EM maps).
- Total field or quardature maximum (VLF).
- Topographic depressions.

In general, the magnetic properties of a deformation zone may change according to its metamorphic history (/2/, /3/, and /4/). The following changes are possible:

1. Oxidizing fluid intrudes into the rock during the metamorphism: deposition of magnetite; magnetic susceptibility increases.
2. Reducing metamorphic fluid intrudes into the rock: magnetite is decomposed; susceptibility decreases.
3. Low temperature (< 250°C) weathering in a fracture zone: magnetite is decomposed; susceptibility decreases.

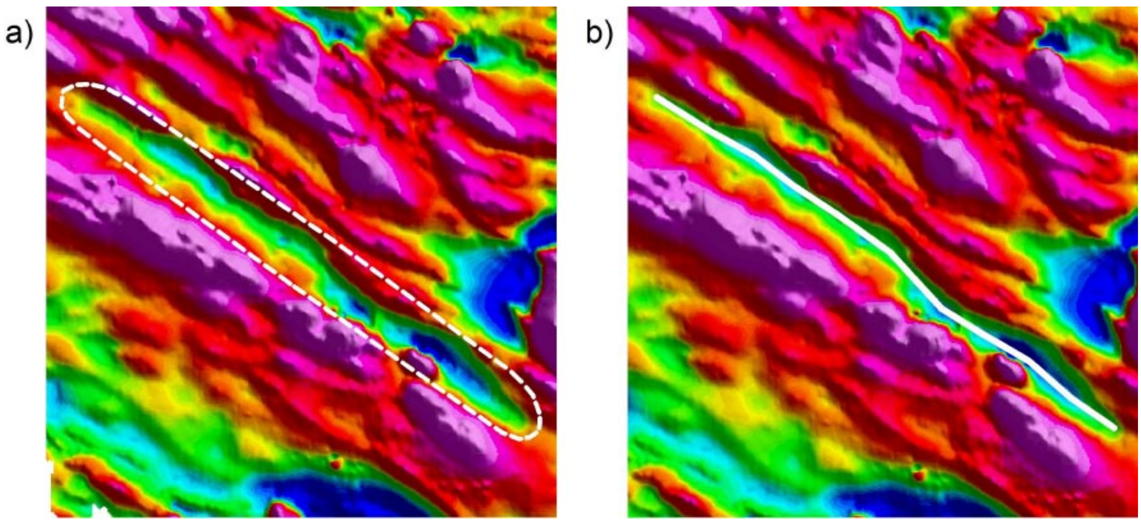



***Figure 4-1.*** *The principle of method specific lineament interpretation. a) A linear feature, a minimum, seen on a sunshaded colour map is judged to represent a deformation zone. b) The feature is digitized as a polyline.*

According to this, a deformation zone can be observed as a magnetic minimum or a maximum. However, in practice, a minimum is more common, indicating probably more brittle deformation. Also a discontinuity of magnetic anomalies ("disturbance" characterization in the attribute tables) is a typical indication of a deformation zone. Furthermore, if the anomaly zones are sharply displaced, it is an indication of brittle faulting. In addition to these, there are five cases, in which the magnetic lineament is interpreted on the basis of a "magnetic step". It is a sharp level change in the magnetic field, probably related to a rock type contact. This interpretation is based on the idea that rock type contacts are often highly fractured. However, since this indication is indirect, it is considered more uncertain that the other magnetic indications.

Deformation zones can often be distinguished from their surroundings according to their decreased electric resistivity. This may be due to the occurrence of various conducting minerals (clays, sulphides etc) and, in the brittle case, increased fracture porosity and groundwater. Deformation zones are often located at bedrock depressions, filled with soil material, peatlands, rivers or lakes. According to electromagnetic modellings (e.g. /5/ and /6/), the response from the overburden may be dominating compared to the typical response from a deformation zone below. Thus, it is possible that some lineaments are interpreted at a topographic depression with no deformation zone below.

During the interpretation of the topographic data, all the lineaments identified as linear depressions ("valleys") in the digital elevation models and contour maps, were considered to be possible fracture zones. However, there remains considerable uncertainty with this interpretation. Small scale features only occurring as slopes (edges) in the areas of thick overburden were not interpreted to indicate fracture zones and are, thus, not included in the interpretation.

Clearly anthropogenic features (electric cables, pipes, roads etc) were excluded from the population of method specific lineaments. In this study, the lineaments were not classified according to their possible geological character (e.g. ductile or brittle deformation).

## 4.4 Interpretation of coordinated lineaments

Each method-specific data set describes the same area. Thus, there is a high probability that some of the method-specific lineaments interpreted from different data sets describe the same linear features. The goal of the coordinated lineament interpretation stage was to integrate the method-specific lineaments that describe the same linear feature. The basis for the coordinated lineament interpretation was the method-specific lineaments and the maps used for their interpretation.

The interpretation was carried out by viewing all the method-specific lineaments together and visually inspecting the corresponding method-specific maps at different scales. If several neighbouring method-specific lineaments were judged to represent the same linear feature they were integrated into a coordinated lineament.

The coordination procedure was done by first determining the method-specific lineament that gives the best representation of the linear feature (Figure 4-2a) and copying it to the GIS theme for coordinated lineaments. Then, the copied lineament was split into segments according to the neighbouring method-specific lineaments judged to represent the same feature. The splitting was done so that a new segment was started when a new method-specific lineament identifies the coordinated lineament (Figure 4-2b). Finally, each segment was assigned unique attributes that were based on the attributes of the method-specific lineaments identifying the segment. If only one method-specific lineament identified a linear feature, it was simply copied to the GIS theme for coordinated lineaments and it retained all its attributes.

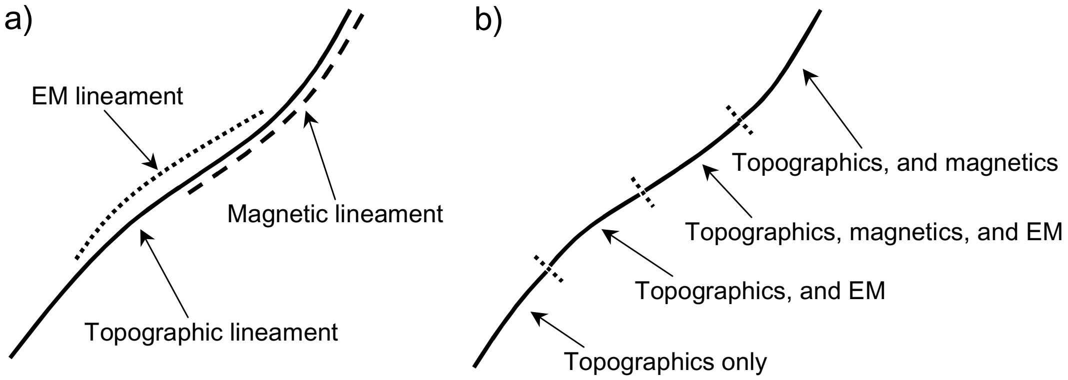



***Figure 4-2.*** *The principle of lineament coordination. a) Three lineaments are judged to represent the same linear feature; the topographic lineament gives the best representation. b) The coordinated lineament is split into segments according to the neighboring method-specific lineaments identifying it; a new segment is started when a new method-specific lineament identifies the coordinated lineament.*

The splitting of a coordinated lineament was based solely on the methods that identify it. That is, the attributes of the method-specific lineaments played no role in the segmentation procedure. This means that those coordinated lineaments that are based on only one method-specific lineament were not split.

The coordinated lineament interpretation stage was completed when all method-specific lineaments were processed in the way described above. The end product of this stage was one GIS theme containing the coordinated lineaments and their attributes.

The uncertainty attribute of the coordinated lineaments comes from the classification of uncertainties of the individual method-specific lineaments, which form the coordinated lineament. It is not, however, mathematically calculated but it rather results from the qualitative judgement of the certainty of different method-specific lineaments. E.g. if two method-specific lineaments with an uncertainty factor 2 are integrated into one coordinated lineament, the uncertainty factor may have been lowered to 1.

## 4.5 Interpretation of linked lineaments

The last stage of the interpretation process comprised a linking of the coordinated lineaments that were judged to represent the same linear feature. The coordinated lineaments and the maps used in the previous stages were used as the basis for the linked lineament interpretation.

The interpretation was carried out by viewing the coordinated lineaments and visually inspecting the relevant method-specific maps at different scales. All coordinated lineaments that were judged to represent the same linear feature (Figure 4-3a) were combined into a single lineament called a linked lineament (Figure 4-3b) and stored in a GIS theme. The attributes of a linked lineament were determined on the basis of the coordinated lineaments that were used to identify the linked lineaments.

The linked lineament interpretation stage was completed when all the coordinated lineaments were processed. The end product of this stage was one GIS theme containing the linked lineaments. This theme was considered the end product of the joint interpretation process.

The linking of the coordinated lineaments is based on visual inspection, and no systematic limit value for the gap between the lineaments has been used. If the gap has been very small compared to the lineament lengths and the data do not show any contradicting evidence, the linking has been performed.

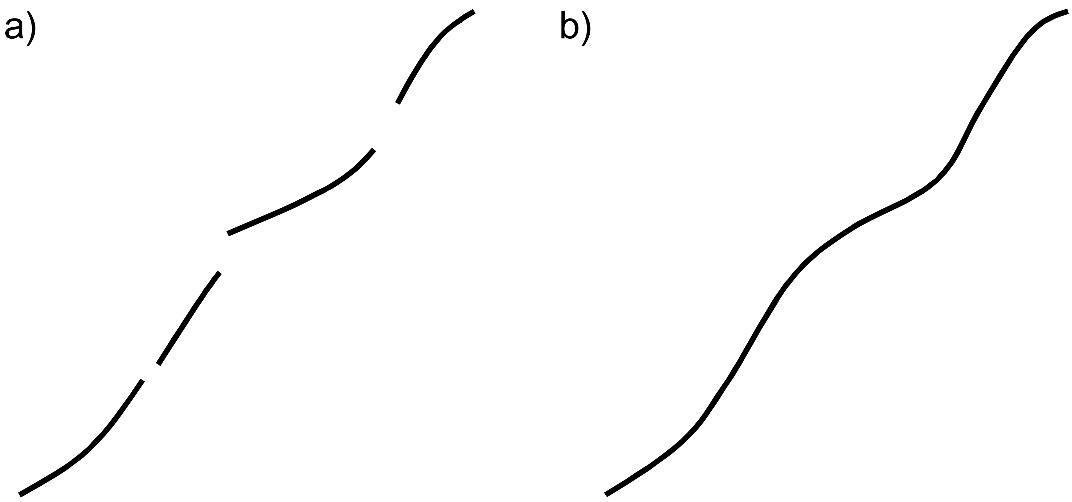



***Figure 4-3.*** *The principle of lineament linking. a) Four coordinated lineaments are judged to represent the same linear feature. b) The coordinated lineaments are combined into one continuous linked lineament.*

# 5 Execution

## 5.1 Input data

The input data comprised helicopter-borne geophysical data and topographic data. The geophysical data comprised data sets acquired with the magnetic, EM dipole source, and VLF methods (a detailed description of the measurements and the data can be found in /7/). The topographic data comprised infrared orthophotos and elevation data sets (more fully described in /8/), and a terrain map.

### 5.1.1 Geophysical data

The two magnetic data sets contained line data of the total magnetic field intensity from the NS and EW surveys. The data was corrected for diurnal variations and the effects produced by the DC transmission power line located in the area (see Figure 2-1).

The two EM data sets contained line data of the responses measured using the 880 Hz, 6,606 Hz, 7,001 Hz, and 34,133 Hz frequencies from the NS and EW surveys. The data sets contained the in-phase and quadrature components with calculated apparent resistivity values.

The VLF data set contained line data of the VLF total field and quadrature component from the NS and EW surveys measured using two different sensors aligned in-line and orthogonal to the transmitting VLF station. The VLF station used for the in-line sensor in the NS survey was GBR (16 kHz) and NAA (24 kHz) for the ortho sensor. The stations were reversed for the EW survey.

### 5.1.2 Topographic data

The topographic data comprised infrared orthophotos taken at the altitude of 2,300 m, and two 10-m elevation grids (one grid in the ESRI format and the other included in a Geosoft database) produced from the photos. Also, a terrain map was used.

## 5.2 Data processing and map compilation

All geophysical data sets were interpolated into 10-m grids using the minimum curvature algorithm. The blanking distance of 50–100 m was used to exclude areas with no data coverage. The grid for the NS magnetic survey was further processed with a vertical gradient filter.

Topographic data processing included the calculation of slopes and aspects from the ESRI elevation grid.

Ten sunshaded colour and grey-scale maps of the magnetic total field intensity were compiled from the NS and EW survey grids. The elevation angle of the sun was 45°. Table 5-1 shows the compiled magnetic maps.

**Table 5-1. The sunshaded maps compiled from the NS and EW magnetic survey grids.**

| Mapped quantity | Survey | Colour scheme | Shading direction |
|---|---|---|---|
| Total intensity | NS | Grey-scale | NE |
| Total intensity | NS | Grey-scale | SE |
| Vertical gradient | NS | Full colour | NE |
| Total intensity | NS | Full colour | NE |
| Total intensity | NS | Full colour | E |
| Total intensity | NS | Full colour | SE |
| Total intensity | NS | Full colour | S |
| Total intensity | EW | Grey-scale | NE |
| Total intensity | EW | Grey-scale | SE |
| Total intensity | EW | Full colour | NE |

Eight sunshaded colour maps of EM apparent resistivity were compiled from both the NS and EW survey grids. The maps comprise four sunshaded colour maps of 880 Hz, 6,606 Hz, 7,001 Hz, and 34,133 Hz responses for both survey directions. All EM maps were shaded from NE having the sun at an elevation of 45°.

Eight sunshaded colour maps of the measured VLF responses were compiled. The maps comprise total field in-line and quadrature maps for both survey directions (NS and EW) and for both stations (in-line and ortho station). Similarly to the EM maps, all VLF maps were shaded from NE having the sun at an elevation of 45°.

Twenty one maps were compiled from topographic data. The maps comprise:

- Eight hillshaded grey-scale maps of elevation from the ESRI grid; shaded from N, NE, E, SE, S, SW, W, and NW having the sun at an elevation of 45°.
- One elevation contour map from the ESRI grid, the contour interval being 1 m.
- One sunshaded colour map of elevation from the Geosoft grid; shaded from NE having the sun at an elevation of 45°.
- Five maps showing the slopes, and six showing the aspects.

The Z values for the hillshaded maps were exaggerated, the Z factor ranging from 10 to 20.

All geophysical data processing and map compilation as well as the compilation of the sunshaded elevation map from the Geosoft grid were carried out using Geosoft Oasis montaj v5.0. The slope and aspect calculations, the compilation of the hillshaded elevation maps, the elevation contour map, and the slope and aspect maps were carried out using ArcView GIS v8.0.

## 5.3 Lineament interpretation

### 5.3.1 Method-specific lineaments

Magnetic, EM, VLF, and topographic data were interpreted separately. Geophysical lineaments were interpreted using the ArcView GIS Version 3.2 while the topographic lineaments were interpreted using the ArcView GIS Version 8.0. For each identified method-specific lineament, unique attributes were assigned (Table 5-2).

**Table 5-2. The attribute table structure for method-specific lineament themes.**

| Field name | Attribute name | Attribute description | Attribute value |
|---|---|---|---|
| Origin_t | Origin | Major type of basic data. | E.g. “Magnetic data”. |
| Method_t | Method | The type of data from which the lineament was identified. | E.g. “Helicopter magnetic data, NS survey, 10 m grid”. |
| Char_t | Character | The character of the observation. | E.g. “minimum”. |
| Uncert_n | Uncertainty | A judgment concerning the clarity of the lineament. | “1” (low), “2” (medium), or “3” (high). |
| Comment_t | Comment | Specific comments to the interpretation if necessary. | Free text. |
| Process_t | Processing | Data processing carried out. | E.g. “sunshaded from NE (inclination of 45 degrees)”. |
| Date_t | Date | The calendar date when the interpretation was carried out. | E.g. “1.6.2004”. |
| Scale_t | Scale | The scale at which the interpretation was carried out. | E.g. “1:20,000”. |
| Platform_t | Platform | The measurement platform for the basic data. | E.g. “airborne geophysics, 50 m altitude”. |
| Precis_t | Precision | An estimate of the uncertainty in the position of the lineament. | E.g. “20 m”. |
| Sign_t | Signature | The name and organization of the interpreter. | E.g. “Seppo Paulamäki / GTK”. |

The interpretation of magnetic data was carried out using the maps listed in Table 5-1 as the basis for lineament identification (Figure 5-1). The criteria and the basis of the interpretation are described in Section 4.3. Most lineaments were identified as magnetic minima inferred to be caused by deformation zones. The maps were viewed at scales ranging from 1:20,000 to 1:60,000. The interpretation resulted in 318 lineaments.

The interpretation of EM data was carried out using the eight apparent resistivity maps described above as the basis for lineament identification (Figure 5-2). The criteria and the basis of the interpretation are described in Section 4.3. Most lineaments were identified as apparent resistivity minima caused by deformation zones. The maps were viewed at scales ranging from 1:10,000 to 1:50,000. The interpretation resulted in 150 lineaments.

The interpretation of VLF data was carried out using the eight total field and quadrature component maps described above as the basis for lineament identification (Figure 5-3). No lineaments were identified from the maps visualizing the quadrature component due to their low quality (see for example Figure 5-3b). All identified lineaments were total field maxima that were inferred to be caused by deformation zones. The maps were viewed at scales ranging from 1:10,000 to 1:40,000. The interpretation resulted in 168 lineaments.

A total of 218 topographic lineaments were interpreted. The interpretation was carried out using the twenty one maps described above as the basis for lineament identification (Figure 5-4). The interpreted lineaments were mainly depressions (“valleys”), or slopes. Most of the lineaments were identified using a combined analysis of the hillshaded reliefs and the 1-m contours. The maps were viewed at scales ranging from 1:10,000 to 1:50,000, mostly in the range of 1:10,000 to 1:20,000.

Slopes were used to enhance sharp changes in slope values. They were used to identify the maximum rate of change of slope and measure degrees of slope of the hillside. Aspect was used to identify the orientation of the hillside.

The infrared orthophotos were not actively used in the interpretation but each interpreted lineament was checked against them. The area around the power plant was not included in the interpretation because it is mostly composed of a landfill.

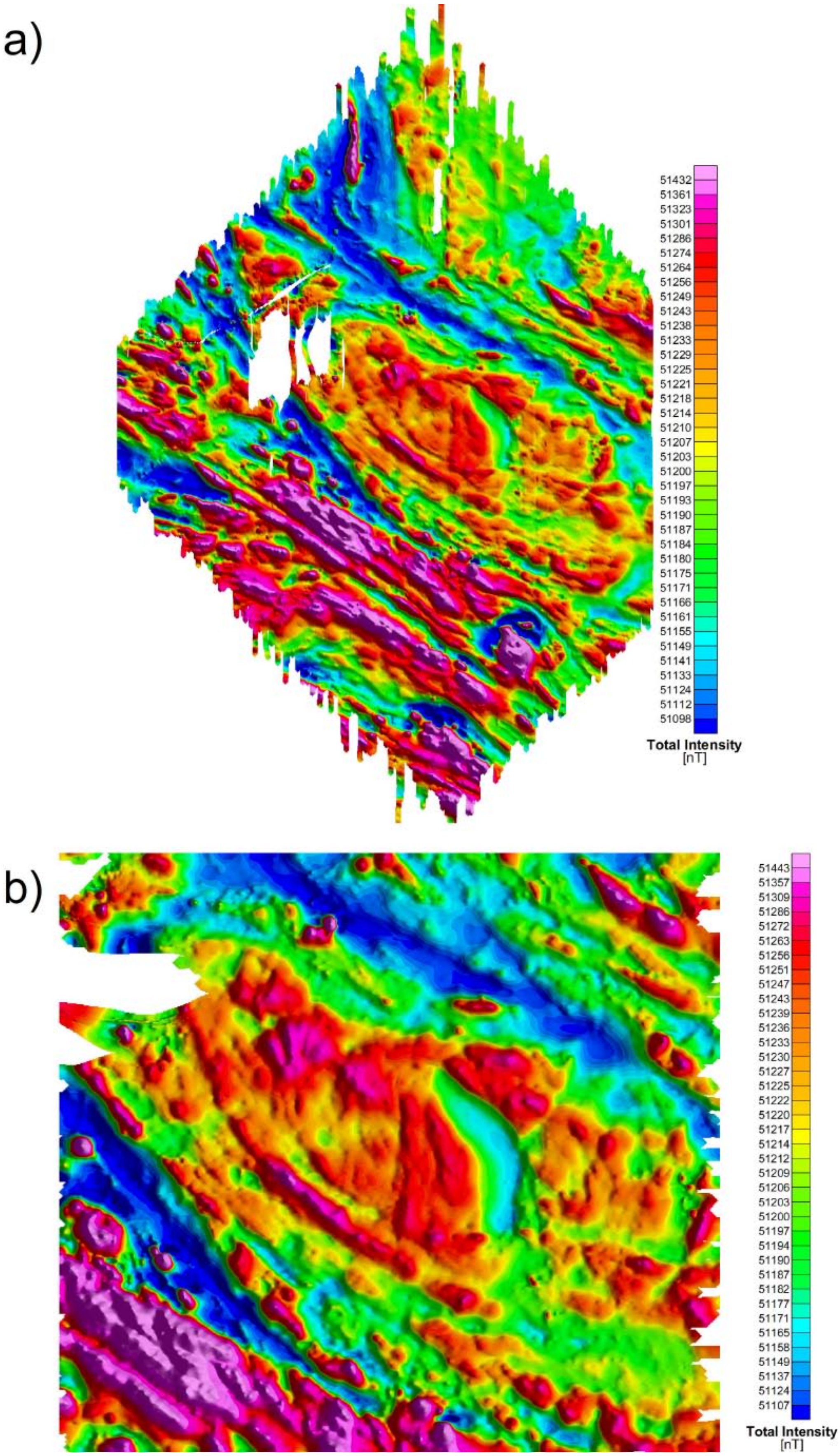



***Figure 5-1.*** *Examples of sunshaded colour maps used in the interpretation of magnetic lineaments. Maps of the total intensity of the magnetic field from the a) NS, and b) EW surveys. Sunshading from NE.*

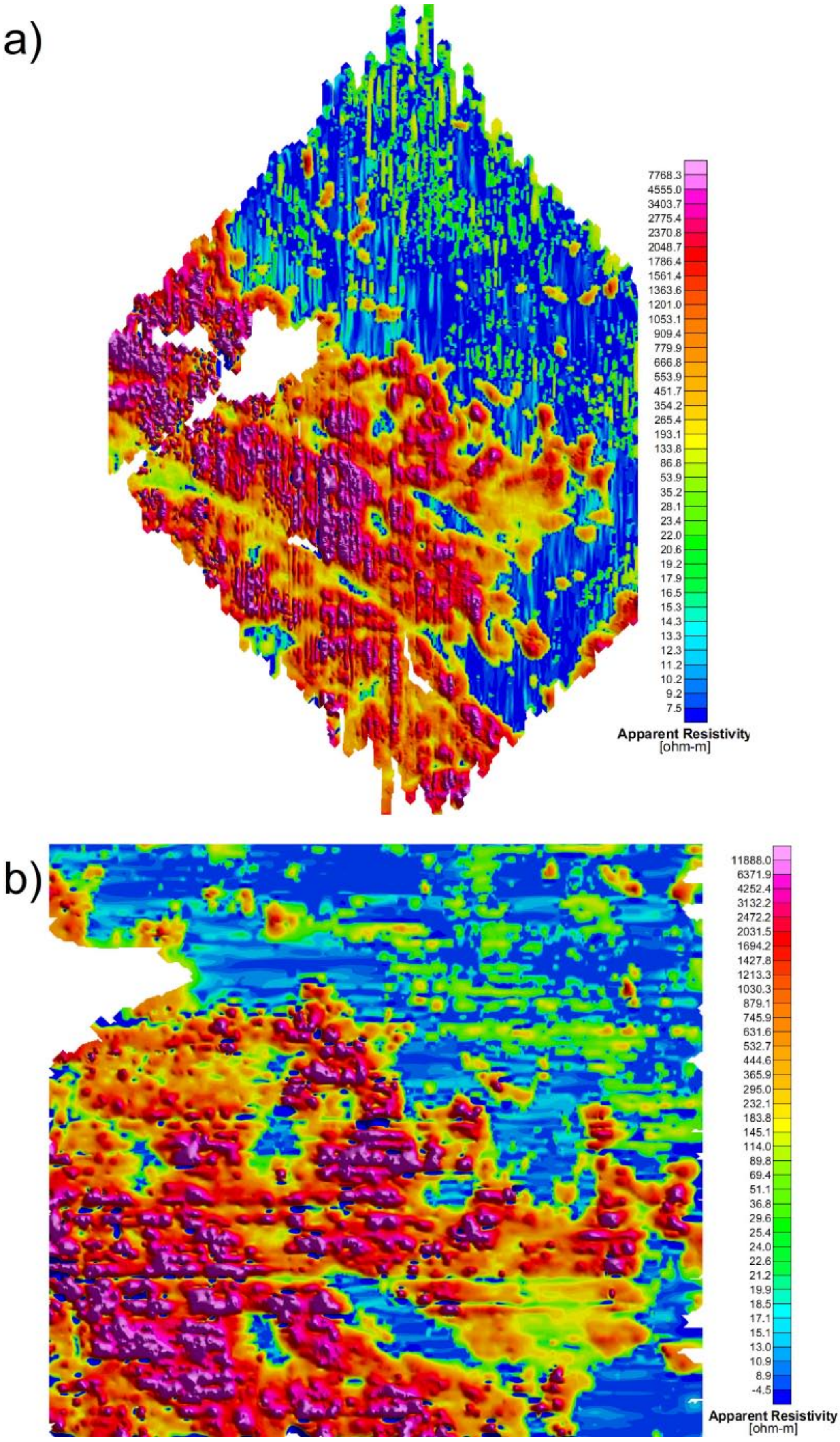



***Figure 5-2.*** *Examples of sunshaded colour maps used in the interpretation of EM lineaments. Maps of apparent resistivity of a) the 6,606 Hz sensor response from the NS survey, and b) the 7,001 Hz sensor response from the EW survey. Sunshading from NE.*

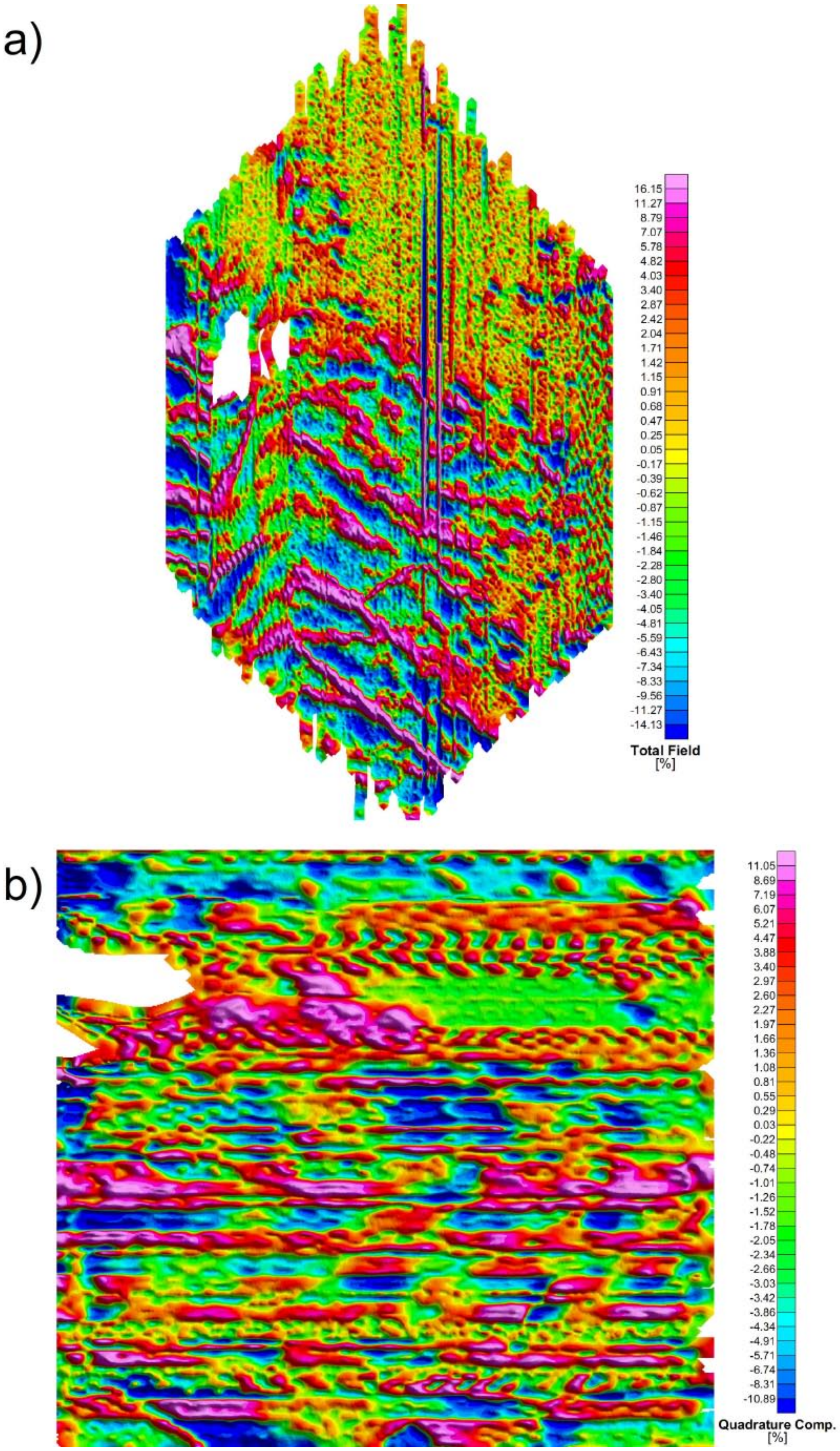



***Figure 5-3.*** *Examples of sunshaded colour maps used in the interpretation of VLF lineaments. Maps of a) the total field from the NS survey, and b) the quadrature component from the EW survey. Sunshading from NE.*

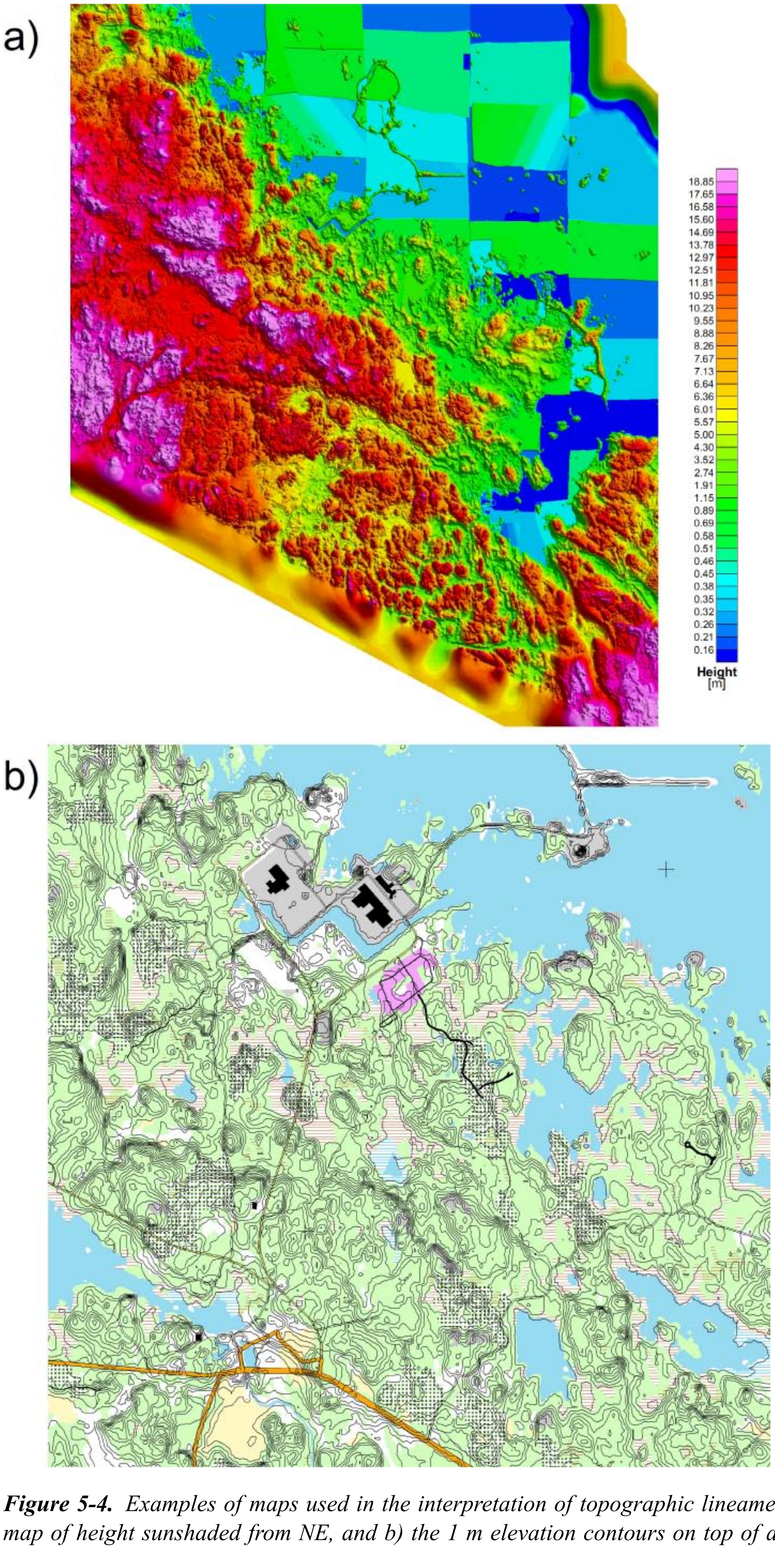



***Figure 5-4.*** *Examples of maps used in the interpretation of topographic lineaments. a) A colour map of height sunshaded from NE, and b) the 1 m elevation contours on top of a terrain map.*

### 5.3.2 Coordinated lineaments

The magnetic, EM, VLF, and topographic lineaments and all method specific maps described above were used as the basis for the coordinated lineament interpretation. Each coordinated lineament was assigned unique attributes listed in Table 5-3.

The coordinated lineament interpretation was carried out by viewing the method-specific lineaments and the relevant method-specific maps at scales ranging from 1:10,000 to 1:60,000. Some of the shortest and most uncertain EM and VLF lineaments were removed at this stage. Furthermore, some coordinated lineaments were slightly repositioned with respect to the identifying method-specific lineaments. The interpretation resulted in 926 lineaments.

**Table 5-3. The attribute table structure for the coordinated lineament theme.**

| Field name | Attribute name | Attribute description | Attribute value |
|---|---|---|---|
| Origin_t | Origin | Major type of basic data | "Method specific lineaments" |
| Method_t | Method | The type or types (in order of prority) of the basic data from which the lineament was interpreted from | E.g. "magn", or "topo,magn,em" |
| Char_t | Character | The character of the lineament | "Coordinated lineament" |
| Uncert_n | Uncertainty | An overall judgment concerning the clarity of the lineament | "1" (low), "2" (medium), or "3" (high) |
| Comment_t | Comment | Specific comments to the interpretation if necessary | Free text |
| Process_t | Processing | Data processing carried out | "Image analysis" |
| Date_t | Date | The calendar date when the interpretation was carried out | E.g. "1.6.2004" |
| Scale_t | Scale | The scale or scale range at which the interpretations were carried out | E.g. "1:20,000", or "1:20,000-1:60,000" |
| Platform_t | Platform | The measurement platform or platforms (in order of priority) for the basic data | E.g. "Airborne geophysics", or "Airphoto, airborne geophysics" |
| Precis_t | Precision | An estimate of the uncertainty or uncertainty range in the position of the lineament | E.g. "20 m", or "20,100 m" |
| Sign_t | Signature | The names and organization of the interpreters | "K. Korhonen, M. Paananen, S. Paulamäki / GTK" |

### 5.3.3 Linked lineaments

The coordinated lineaments and all the method-specific maps were used as the basis for the linked lineament interpretation. Each linked lineament was assigned unique attributes listed in Table 5-4.

The linked lineament interpretation was carried out by viewing the coordinated lineaments and the relevant maps at scales ranging from 1:10,000 to 1:60,000. If the corresponding method-specific maps displayed a basis for an adjustment, the end points of some linked lineaments were modified so that they start and/or end at neighbouring lineaments (Figure 5-5).

**Table 5-4. The attribute table structure for the linked lineament theme.**

| Field name | Attribute name | Attribute description | Attribute value |
|---|---|---|---|
| Id_t | Identity | Identity of the lineament | E.g. "LL0012" |
| Origin_t | Origin | Major type of basic data | "Method specific lineaments" (on land), or "Magnetic lineaments" (on sea) |
| Count_n | Count | The number of coordinated lineament segments building up the linked lineament | An integer number |
| Cond_n | Conductivity | Shows how much of the linked lineament was identified by EM and/or VLF | A numerical value in the range of 0 to 1 |
| Magn_n | Magnetics | Shows how much of the linked lineament was identified by magnetics | A numerical value in the range of 0 to 1 |
| Topog_n | Topographics | Shows how much of the linked lineament was identified by topographics | A numerical value in the range of 0 to 1 |
| Uncert_n | Uncertainty | A weighted average of the uncertainties of the coordinated lineament segments | A numerical value in the range of 1–3 |
| Comment_t | Comment | Specific comments to the interpretation if necessary | Free text |
| Process_t | Processing | Data processing carried out | "Image analysis" |
| Date_t | Date | The calendar date when the interpretation was carried out | E.g. "1.6.2004" |
| Scale_t | Scale | The scale or scale range at which the interpretations were carried out | E.g. "1:20,000", or "1:20,000-1:60,000" |
| Platform_t | Platform | The measurement platform or platforms (in order of priority) for the basic data | E.g. "Airborne geophysics", or "Airphoto, airborne geophysics" |
| Length_n | Length | The length of the linked lineament in meters | E.g. "551.0 " |
| Trend_n | Trend | An estimate of the trend of the linked lineament in degrees | E.g. "55.0" |
| Precis_t | Precision | An estimate of the uncertainty or uncertainty range in the position of the lineament | E.g. "20 m", or "20,100 m" |
| Sign_t | Signature | The names and organization of the interpreters | "K. Korhonen, M. Paananen, S. Paulamäki / GTK" |

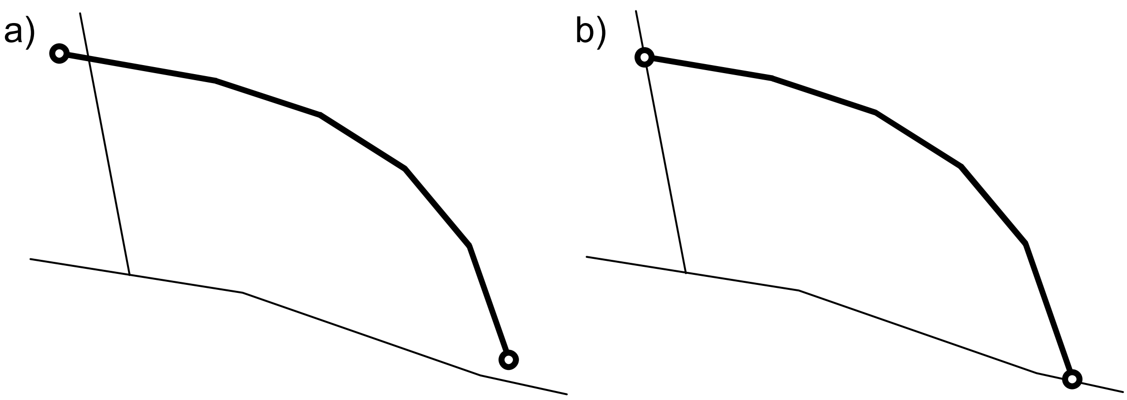



***Figure 5-5.*** *An example of linked lineament end-point adjustment. a) A linked lineament with end points not located on neighbouring lineaments. b) The lineament with its end points adjusted to lie on the neighbouring lineaments.*

The values of the conductivity, magnetics, topographics, and uncertainty attributes were calculated in ArcView GIS 3.2 using custom Avenue scripts. The value of the conductivity attribute c was calculated using

$$c = \frac{\sum_{i=1}^{N} b_i \cdot l_i}{l_{\mathrm{TOT}}},$$

where $N$ is the number of coordinated lineament segments identifying the linked lineament; $b_i$ is 1 if the ith segment is identified by an EM and/or VLF segment, otherwise 0; $l_i$ is the length of the ith segment; and $l_{\mathrm{TOT}}$ is the total length of the linked lineament. The values for the magnetics and topographics attributes were calculated similarly. The values for the uncertainty attributes $u_{\mathrm{TOT}}$ were calculated using

$$u_{\mathrm{TOT}} = \frac{\sum_{i=1}^{N} u_i \cdot l_i}{l_{\mathrm{TOT}}},$$

where $u_i$ is the uncertainty factor of the ith segment.

The lengths and trend estimates for the linked lineaments were also calculated in ArcView GIS 3.2 using custom Avenue scripts. The lengths for the linked lineaments were simply calculated as the sum of the lengths of the coordinated lineaments describing the linked lineament. The trend estimates were calculated by considering the vertices of the polyline representing the lineament as individual data points (Figure 5-6a), fitting a least-squares (LSQ) line to the points, and taking the angle that the LSQ line makes with the North direction as the trend estimate (Figure 5-6b). The slope $m$ of the LSQ line was calculated using

$$m = \frac{N\sum_{i=1}^{N} x_i y_i - \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2},$$

where $N$ is the number of data points, and $(x_i, y_i)$ is the ith data point. The angle $\alpha$ that the LSQ line makes with the $x$ axis is given by

$\alpha = \tan^{-1} m.$

The trend estimate $\theta$ in degrees was then calculated using

$$\theta = 90^{\circ} - \frac{180^{\circ}}{\pi} \cdot \alpha.$$

The interpretation resulted in 536 linked lineaments. This was considered the final joint interpretation of airborne geophysical and topographic data.

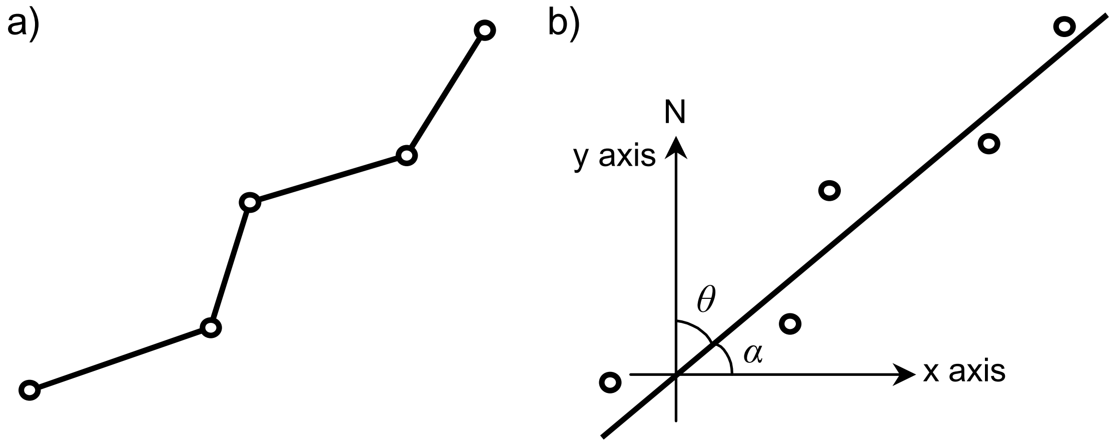



***Figure 5-6.*** *The principle of trend estimation for linked lineaments. a) The vertices of the polyline representing a linked lineament are considered as individual data points. b) A least-squares line is fitted to the points, and the angle it makes with the North direction is taken as the trend estimate.*

# 6 Results

## 6.1 Method-specific lineaments

The interpretations of the magnetic, EM, VLF, and topographic data sets resulted in the production of four ArcView GIS themes containing a total of 854 method-specific lineaments. Figures 6-1 to 6-4 show the interpreted lineaments and Table 6-1 summarizes some statistics.

**Table 6-1. Some statistics of the method-specific lineaments.**

| Method | Number of lineaments<br>Low uncertainty | Medium uncertainty | High uncertainty | Total |
|---|---|---|---|---|
| Magnetic | 73 | 96 | 149 | 318 |
| EM | 21 | 23 | 106 | 160 |
| VLF | 0 | 19 | 149 | 168 |
| Topographic | 30 | 98 | 90 | 218 |
| Total | 124 | 236 | 494 | 854 |

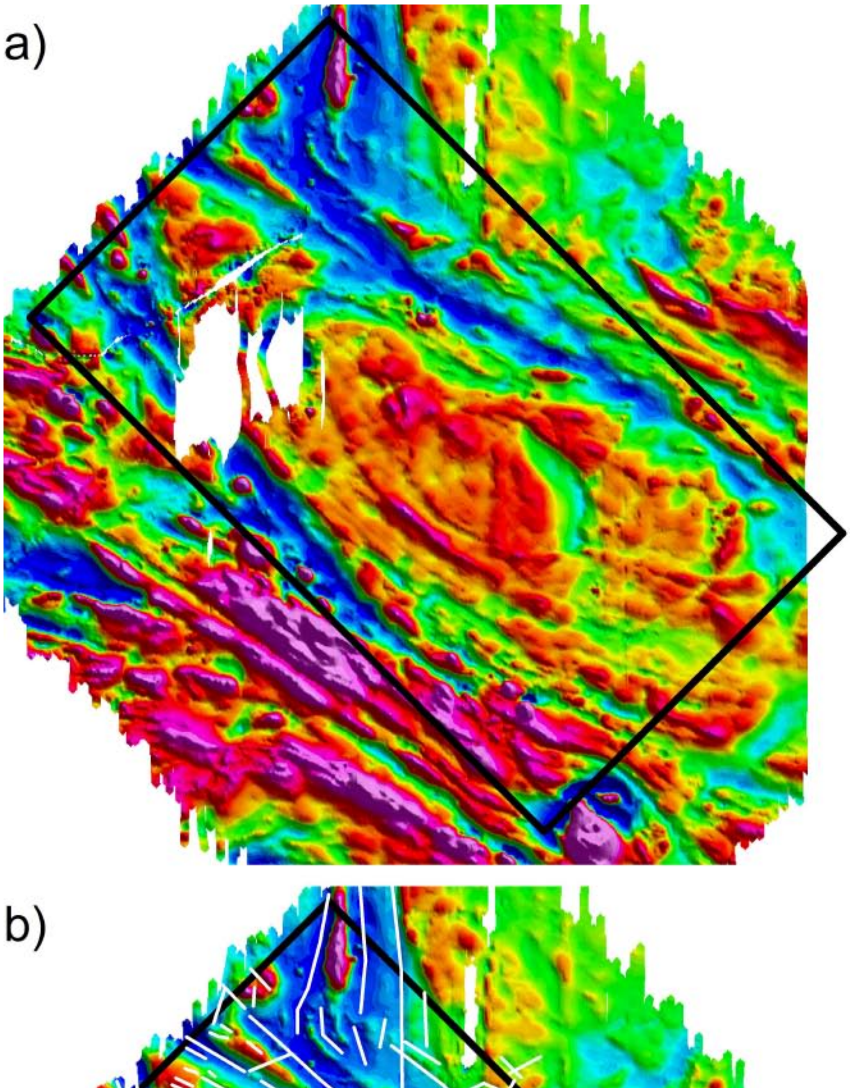



***Figure 6-1.*** *The interpreted magnetic lineaments. a) A colour map of the total intensity of the magnetic field from the NS survey sunshaded from NE, and b) the same map with the magnetic lineaments (thin white lines) superposed. The thick black line shows the borderline of the modelling area.*

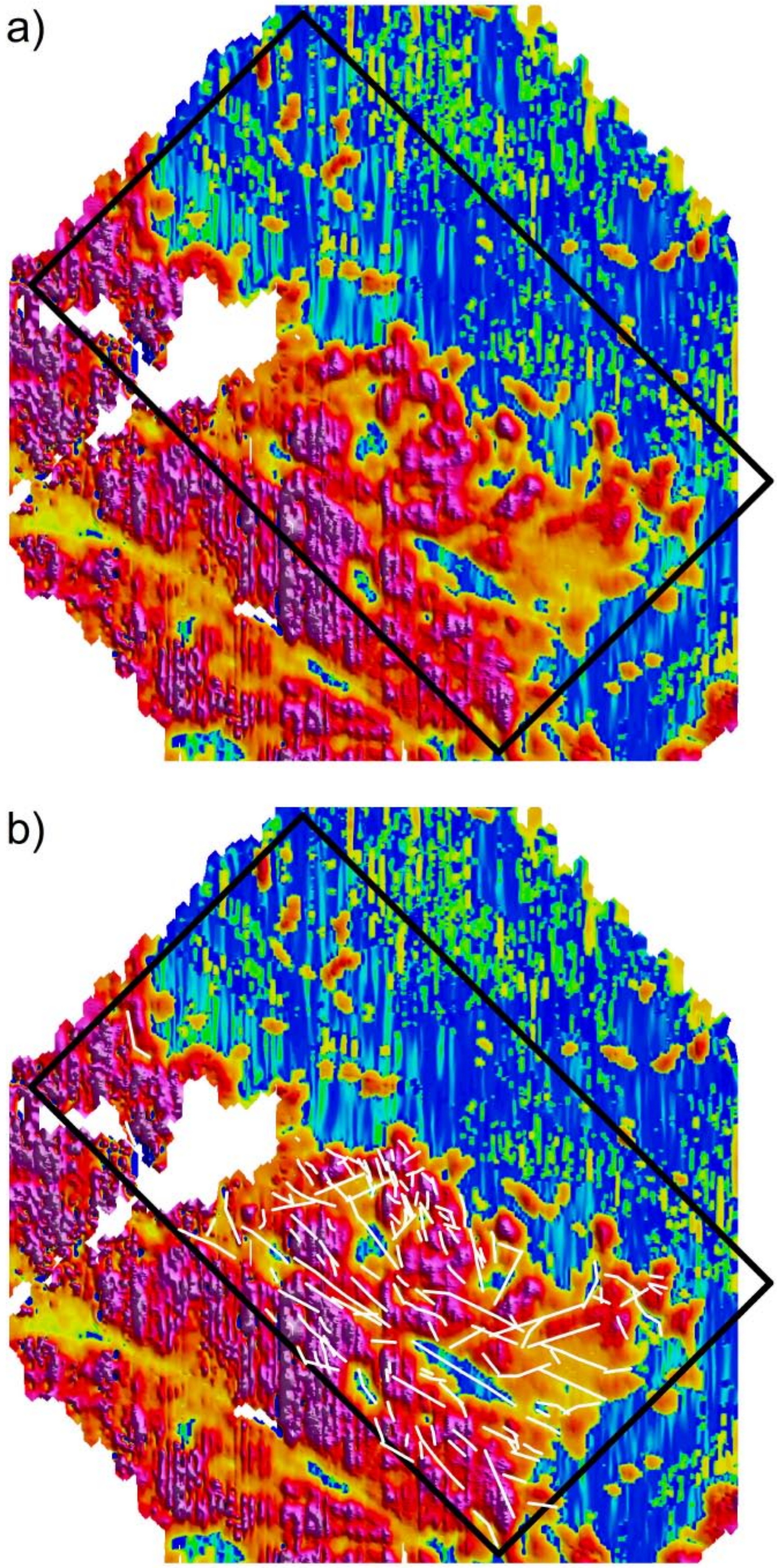
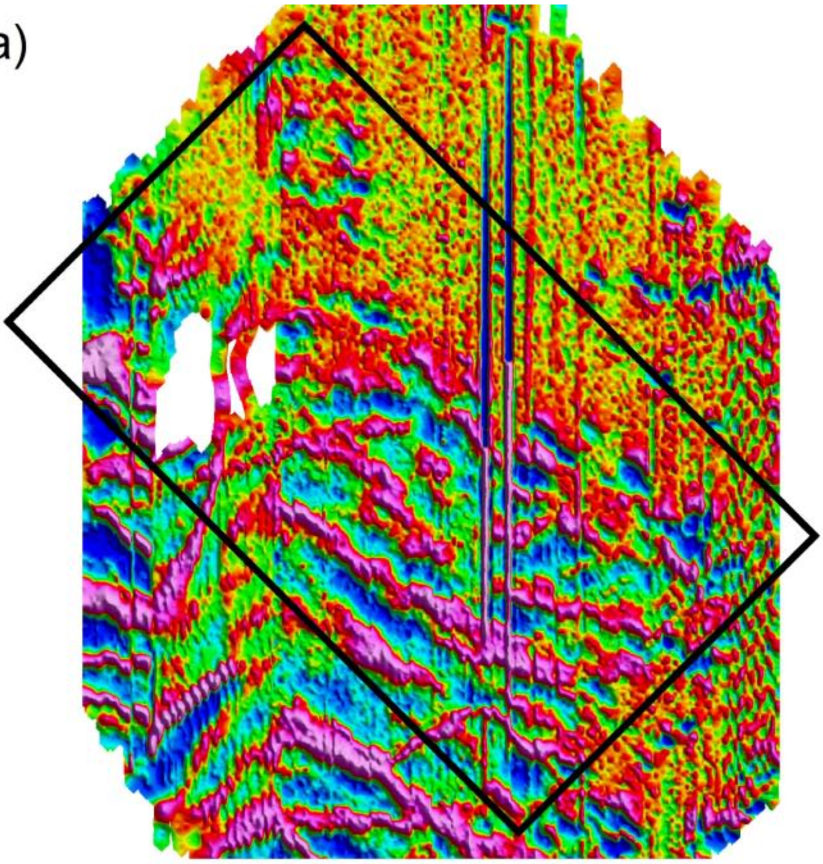



***Figure 6-2.*** *The interpreted EM lineaments. a) A colour map of the apparent resistivity of the 6606 Hz sensor response from the NS survey sunshaded from NE, and b) the same map with the EM lineaments (thin white lines) superposed. The thick black line shows the borderline of the modelling area.*

a)



b)

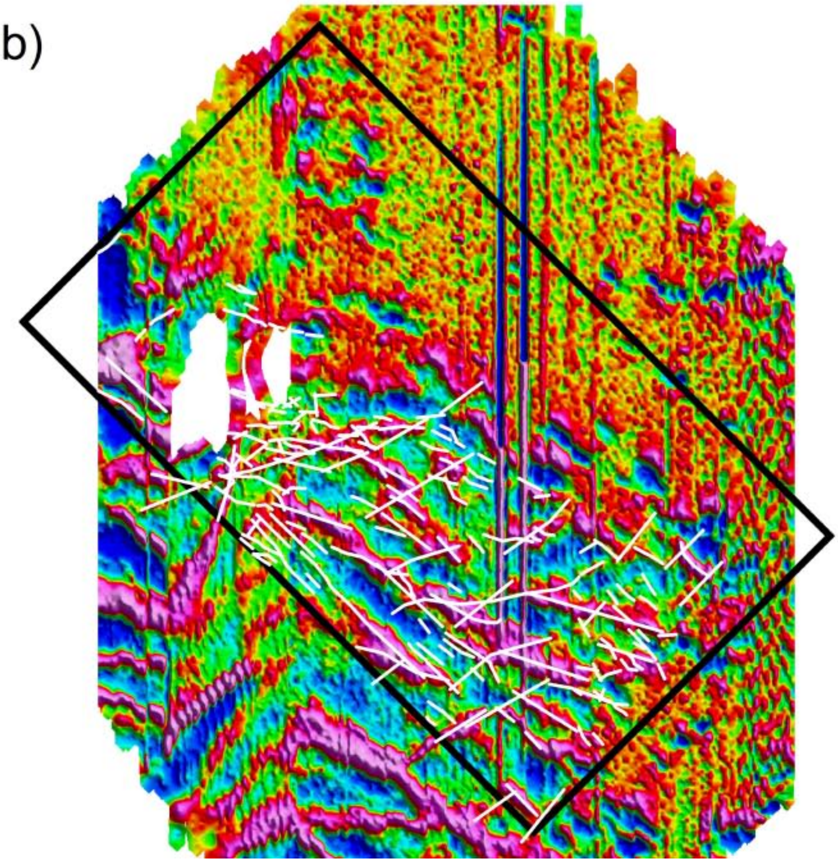


***Figure 6-3.*** *The interpreted VLF lineaments. a) A colour map of the VLF total field of the ortho sensor response from the NS survey sunshaded from NE, and b) the same map with the VLF lineaments (thin white lines) superposed. The thick black line shows the borderline of the modelling area.*

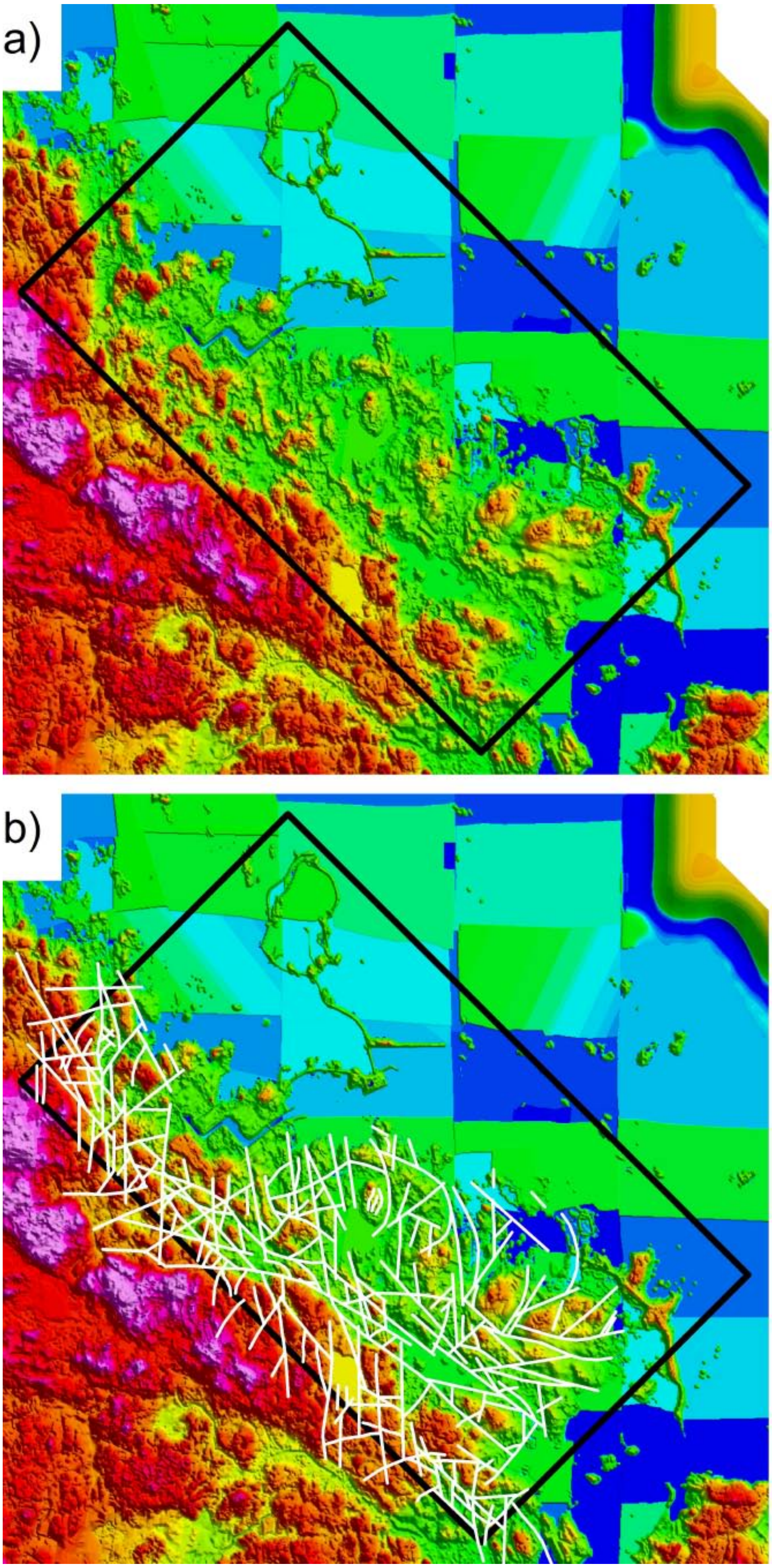



***Figure 6-4.*** *The interpreted topographic lineaments. a) A colour map of the height sunshaded from NE, and b) the same map with the topographic lineaments (thin white lines) superposed. The thick black line shows the borderline of the modelling area.*

## 6.2 Coordinated lineaments

The integration of the magnetic, EM, VLF, and topographic lineaments resulted in the production of one ArcView GIS theme containing 926 coordinated lineaments (of which 102 are magnetic lineaments from the sea area). Figure 6-5 shows the resulting coordinated lineaments and Table 6-2 summarizes some statistics.

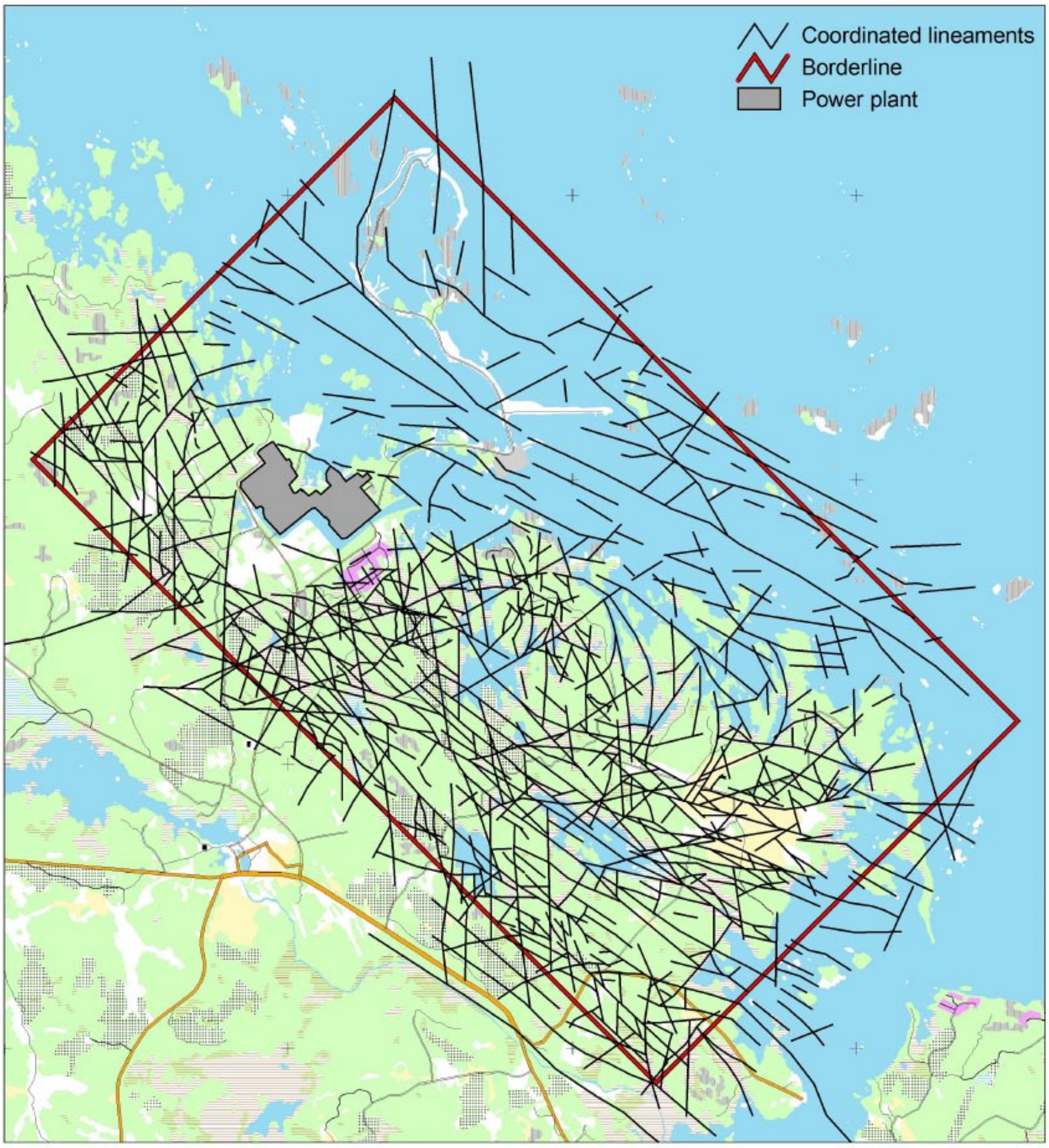



***Figure 6-5.*** *The results of the coordinated lineament interpretation stage.*

**Table 6-2. Some statistics of the coordinated lineaments.**

| Identified in | Number of lineaments<br>Low uncertainty | Medium uncertainty | High uncertainty | Total |
|---|---|---|---|---|
| Magnetic only | 83 | 91 | 125 | 299 |
| EM only | 8 | 9 | 37 | 54 |
| VLF only | 0 | 17 | 77 | 94 |
| EM and VLF | 2 | 8 | 6 | 16 |
| Topographic only | 41 | 113 | 80 | 234 |
| One method | 132 | 230 | 319 | 681 |
| Two methods | 73 | 72 | 24 | 169 |
| Three methods | 36 | 17 | 1 | 54 |
| Four methods | 15 | 7 | 0 | 22 |

## 6.3 Linked lineaments

The linked lineament interpretation resulted in the production of one ArcView GIS theme containing 536 linked lineaments constituting the final joint interpretation of airborne geophysical and topographic data. Figures 6-6 and 6-7 show the resulting linked lineaments, Figure 6-8 shows the trend distribution of the lineaments, and Table 6-3 summarizes some statistics.

**Table 6-3. Some statistics of the linked lineaments.**

| Length | Number of lineaments<br>Uncertainty <1.5 | Uncertainty 1.5–2.5 | Uncertainty >2.5 | Total |
|---|---|---|---|---|
| <1 km | 44 | 135 | 229 | 408 |
| 1–5 km | 48 | 56 | 22 | 126 |
| >5 km | 2 | 0 | 0 | 2 |
| Total | 94 | 191 | 251 | 536 |

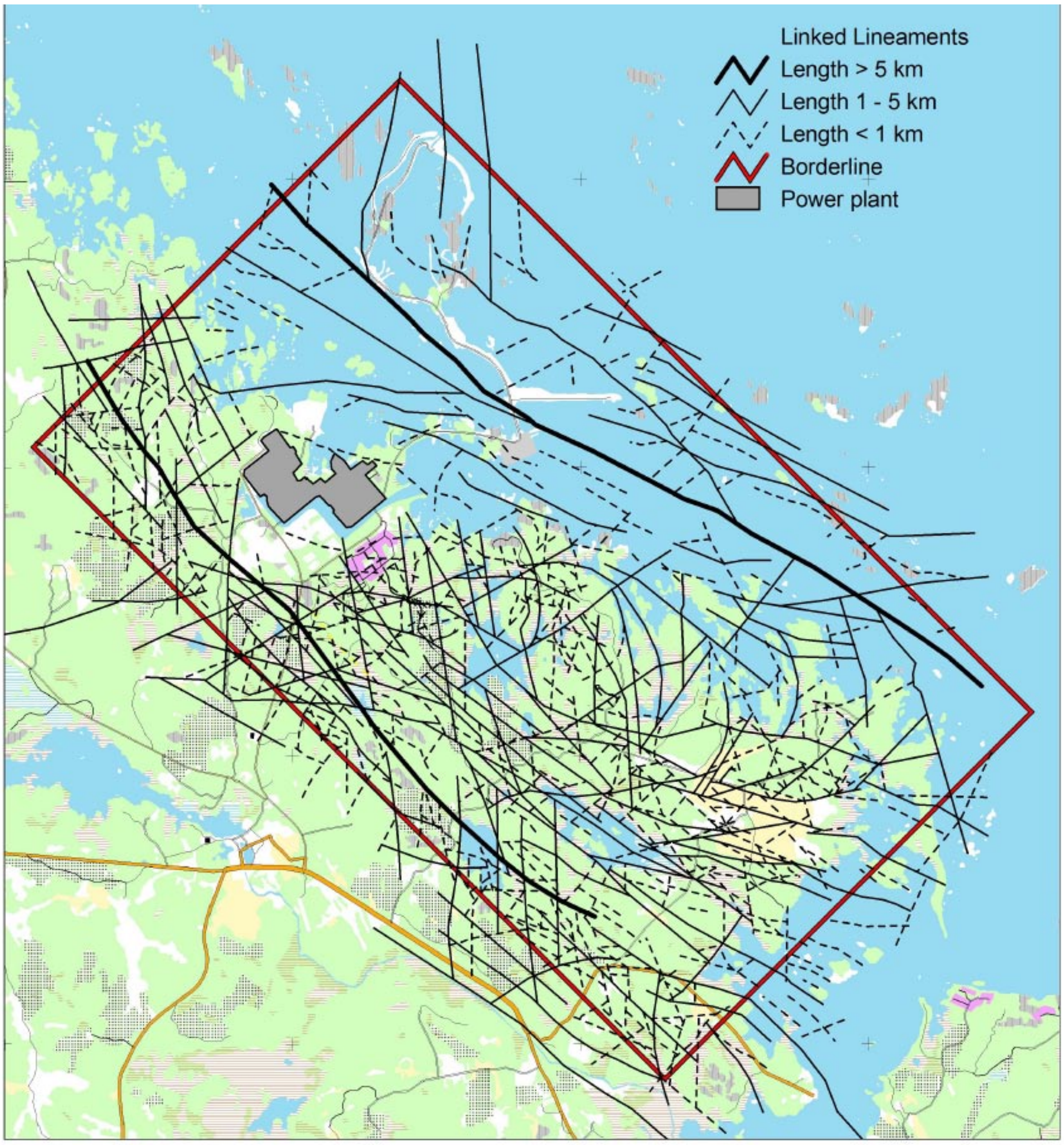



***Figure 6-6.*** *The linked lineaments classified by their lengths.*

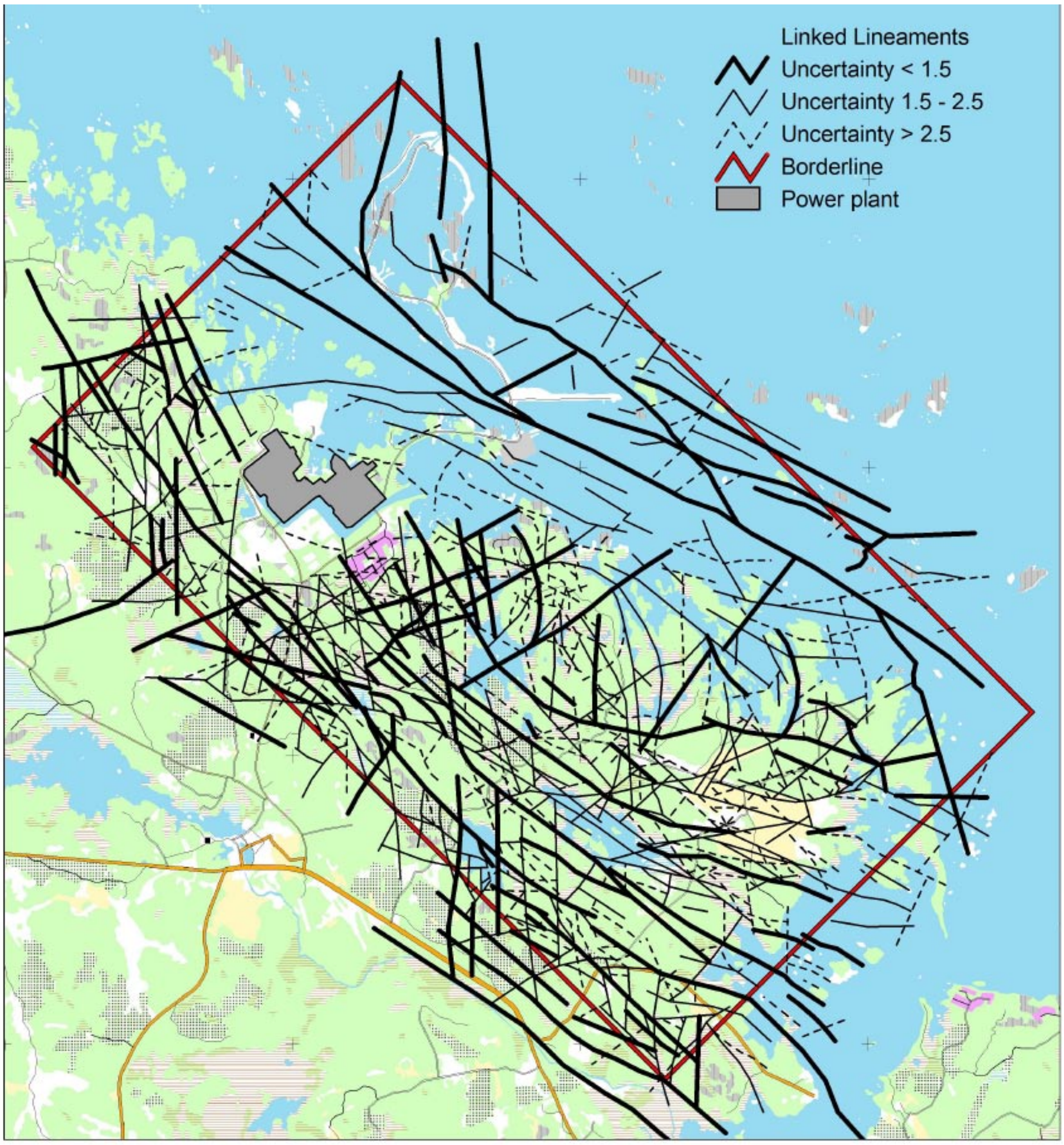



***Figure 6-7.*** *The linked lineaments classified by their uncertainties.*

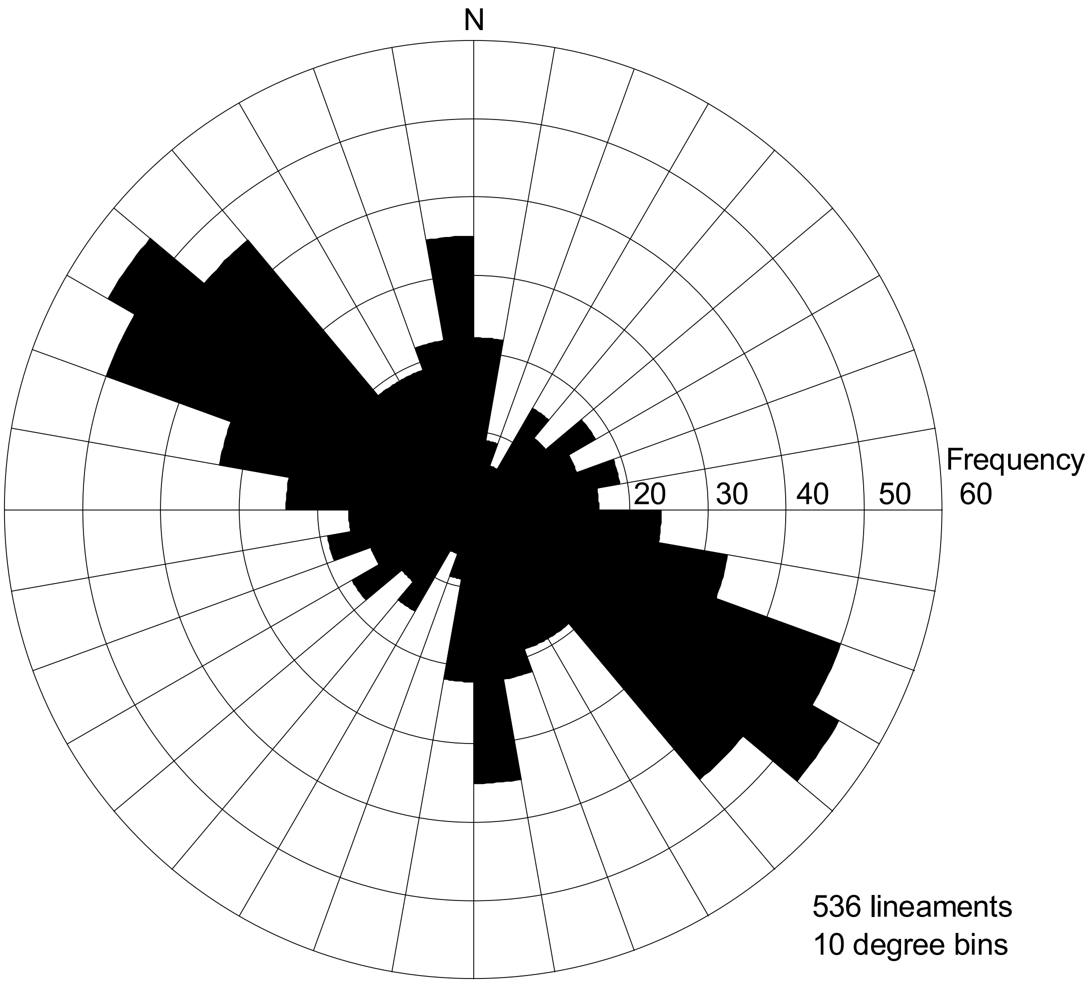



***Figure 6-8.*** *A rose diagram showing the distribution of linked lineament trends. The frequencies give the number of 1 km segments within a bin.*

# 7 Assessment of the methodology

The methodology used in this study documents in a highly satisfactory manner the interpretation process. In every stage of the work (method-specific interpretation, coordination and linking), lineament-specific attributes are stored, indicating the basis, uncertainty and precision of the interpretation etc. This enables an assessment of each stage of the interpretation.

The coordination process is a systematic, albeit laborious process to combine the interpretations of separate methods. Furthermore, it enables the assessment of the weight of the methods in the linking stage. However, there are some intrinsic problems. In the coordination procedure, two or more spatially more or less coinciding method-specific lineaments are integrated into one single coordinated lineament. Since the individual method-specific lineaments, which are forced together, may represent different tectonic or other features, this procedure may lead to errors. Naturally, errors of this kind may have occurred in the present work. The judgement concerning whether adjoining method-specific lineaments should be separated or integrated into coordinated lineaments requires a deeper analysis (e.g. surface geological investigations and/or detailed ground geophysical surveys) of the individual lineaments. This procedure was beyond the scope of the present study.

Since the present study did not include a geological characterisation of the lineaments, subsequent evaluation based on, for example, analysis of structural data from outcrops, borehole investigations etc is needed prior to their upgrading to fracture zones.

# 8 References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