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Geological Survey of Finland (GTK)

October 2005

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*Keywords:* Simpevarp, Airborne geophysics, Magnetic data, Electromagnetic data, VLF data, Topographic data, Digital Elevation Model, Elevation contours, Lineament, Lineament interpretation, Coordinated lineament interpretation, Linked lineament interpretation.

# Abstract

This document reports the results of an integrated lineament interpretation of geophysical and topographic data carried out for the Simpevarp area as part of the Oskarshamn site investigations. The work was performed by the Geological Survey of Finland (GTK) during the spring and summer of 2005.

The data used for the interpretations comprised geophysical and topographic data. The geophysical data included helicopter borne magnetic, electromagnetic and VLF data. The topographic data included a 10-m Digital Elevation Model of the Simpevarp area and 1-m elevation contours. Maps of roads, shorelines, power lines, Quaternary deposits, and bedrock outcrops were also used.

The work was carried out in four stages. The first stage comprised data processing and map compilation to facilitate lineament interpretation. In the second stage, each method-specific data set was interpreted independently. In the third stage, those method-specific lineaments that were judged to describe the same possible deformation zones were integrated to produce the so called coordinated lineaments. Finally, those coordinated lineaments that were judged to represent the same possible deformation zones were joined together to produce the so called linked lineaments.

The results comprise 202 magnetic lineaments, 48 electromagnetic lineaments, 54 VLF lineaments, and 1,792 topographic lineaments. The 2,096 method-specific lineaments were integrated into 1,351 coordinated lineaments. The final integrated interpretation of geophysical and topographic lineaments comprises 846 linked lineaments.

# Sammanfattning

Denna rapport redovisar resultaten från en samtolkning av flyggeofysiska och topografiska data inom Simpevarpsområdet och är en del av platsundersökningar i Oskarshamn. Arbetet utfördes av Finlands Geologiska forskningscentral (GTK) våren och sommaren 2005. Tolkningsdata bestod av flygmagnetiska, flygelektromagnetiska, flyg-VLF och topografiska data.

Arbetet innehöll bearbetning av basdata, kartproduktion och lineamenttolkning. Tolkningen utfördes i tre faser. I den första fasen tolkades alla fyra datamängder självständigt. I nästa fas, sammankopplades de fyra metodspecifika lineamenttolkningarna till så kallade koordinerade lineament. I den sista fasen, sammankopplades de koordinerade lineamenten till så kallade länkade lineament som utgör slutprodukten.

Tolkningen av magnetiska, elektromagnetiska, VLF och topografiska data resulterade i 2 096 metodspecifika lineament. Sammanslagningen av de metodspecifika lineamenten producerade 1 351 koordinerade lineament. Länkning av de koordinerade lineamenten producerade 846 länkade lineament.

# Contents

# 1 Introduction

This document reports the results gained in the project ”Interpretation of lineaments from airborne geophysical and topographic data”, which is one of the activities performed by the Swedish Nuclear Fuel and Waste Management Co. (SKB) as part of the Oskarshamn site investigations.

The work was carried out by the Geological Survey of Finland (GTK) during the spring and summer of 2005. The goal of the work was to perform an integrated interpretation of geophysical and topographic lineaments for the Simpevarp area. The GTK interpretation will serve as an alternative interpretation to that described in /Triumf 2004/.

The work was carried out in four successive stages. The first stage comprised preparatory work including data processing and map compilation. In the second stage, lineaments were identified from each method-specific data set independently. In the third stage, all method-specific lineaments judged to represent the same deformation zone were integrated into coordinated lineaments. In the last stage, those coordinated lineaments that were judged to represent the same deformation zone were joined together into linked lineaments. The linked lineaments constitute the final integrated lineament interpretation.

# 2 Objective and scope

The objective of the work was to carry out an integrated interpretation of geophysical and topographic lineaments for the Simpevarp area (Figure 2-1). The work was carried out in four stages.

Geophysical lineaments were identified from airborne magnetic, dipole-source electromagnetic (EM), and VLF data. Topographic lineaments were identified from a 10-m Digital Elevation Model (DEM) and 1-m elevation contours. Figure 2-1 shows the areas within which lineaments were interpreted. The integrated interpretation (coordinated and linked lineament interpretations) covers an area of approximately 114 $km^2$ (14.8 km × 7.7 km).

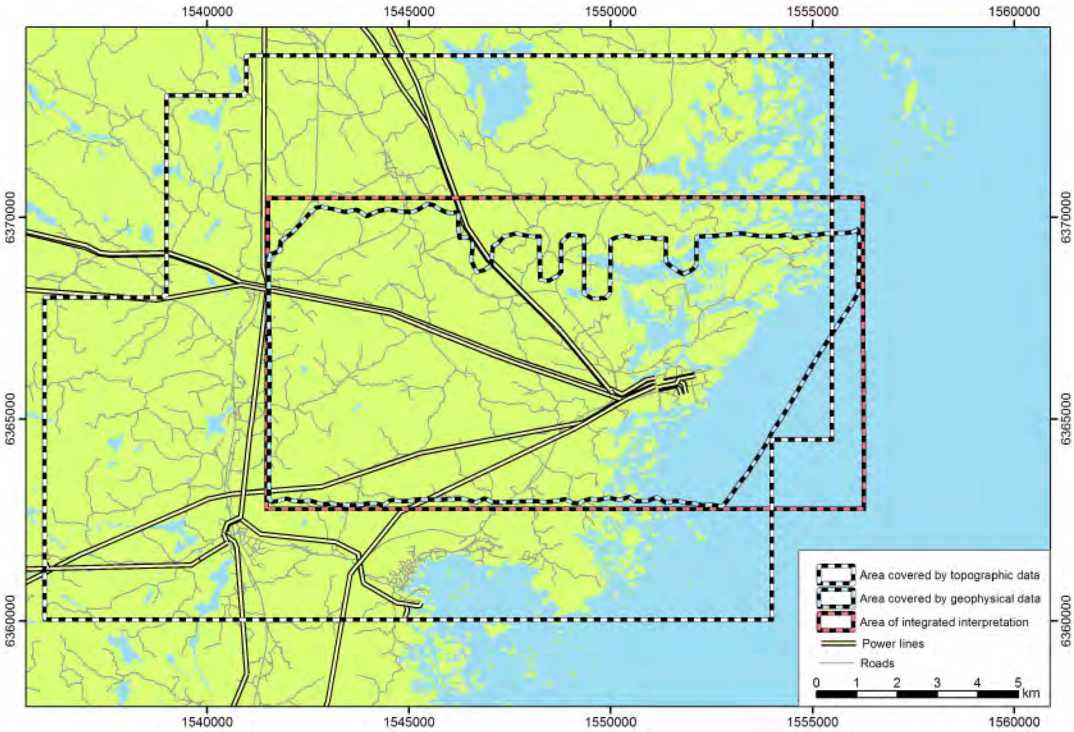


***Figure 2-1.*** *An overview of the areas of interpretation. The interpretation of topographic lineaments was carried out within the full extent of topographic data (Area covered by topographic data). The interpretation of geophysical lineaments was carried out within the full extent of geophysical data (Area covered by geophysical data). The coordinated and linked lineament interpretations were carried out within the Area of integrated interpretation.*

# 3 Equipment

## 3.1 Interpretation tools

The work was carried out utilising geophysical and Geographic Information Systems (GIS) software running on PC workstations. The names and purposes of the programs are listed in Table 3-1.

**Table 3-1. The names and purposes of the programs used in this work.**

| Name | Purpose |
|---|---|
| Geosoft Oasis montaj v6.0 | Processing of geophysical data and map compilation |
| ESRI ArcView GIS v3.2 | Processing of topographic data, map compilation, and lineament interpretation |
| ESRI ArcMap v8.3 | Creation of buffer zones |
| ESRI ArcToolbox v8.3 | Assignment of projections to shapefiles |

# 4 Methodology

## 4.1 Introduction

The methodology used in this work was adopted from /Isaksson et al. 2004/ and /Korhonen et al. 2004/ and conforms with 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) which are internal SKB documents.

In the context of this work, lineaments were considered to be linear features that are visible on maps and represent possible deformation zones in the bedrock.

## 4.2 Preparatory work

Preparatory work comprised data processing and map compilation. Data processing was used to make the airborne geophysical data suitable for map compilation and to enhance features in the geophysical and topographic data sets. Once the data was processed, several hillshaded colour and greytone maps were compiled from the processed data sets to be used as the basis for lineament interpretations.

The geophysical data were measured from a helicopter /Rønning et al. 2003/. Thus, the geophysical data sets required gridding (interpolation to regular grids) before they could be further processed because airborne data is more or less irregularly spaced.

Filtering was applied to the gridded geophysical data sets and the 10-m DEM. The aim was to enhance features already present in the data sets. Standard operations such as convolution, hillshading, and slope calculations were performed.

## 4.3 Interpretation of method-specific lineaments

Each method-specific data set was interpreted independently utilising GIS software. The interpretations comprised:

1. The identification of lineaments from the maps.
2. The digitisation of the identified lineaments.
3. The parametrisation of the lineaments by assigning unique attributes to them.

The identification of lineaments from a method-specific data set was carried out by viewing the maps and systematically searching for lineaments that represent possible deformation zones. When a lineament was identified (Figure 4-1a), it was digitised as a polyline (Figure 4-1b) and stored in a method-specific shapefile. Each digitised lineament was assigned unique attributes describing its properties. The attributes were stored in an attribute table associated with the shapefile. The interpretation of a method-specific data set was completed when all feasible lineaments were identified, digitised and parametrised.

a)

b)

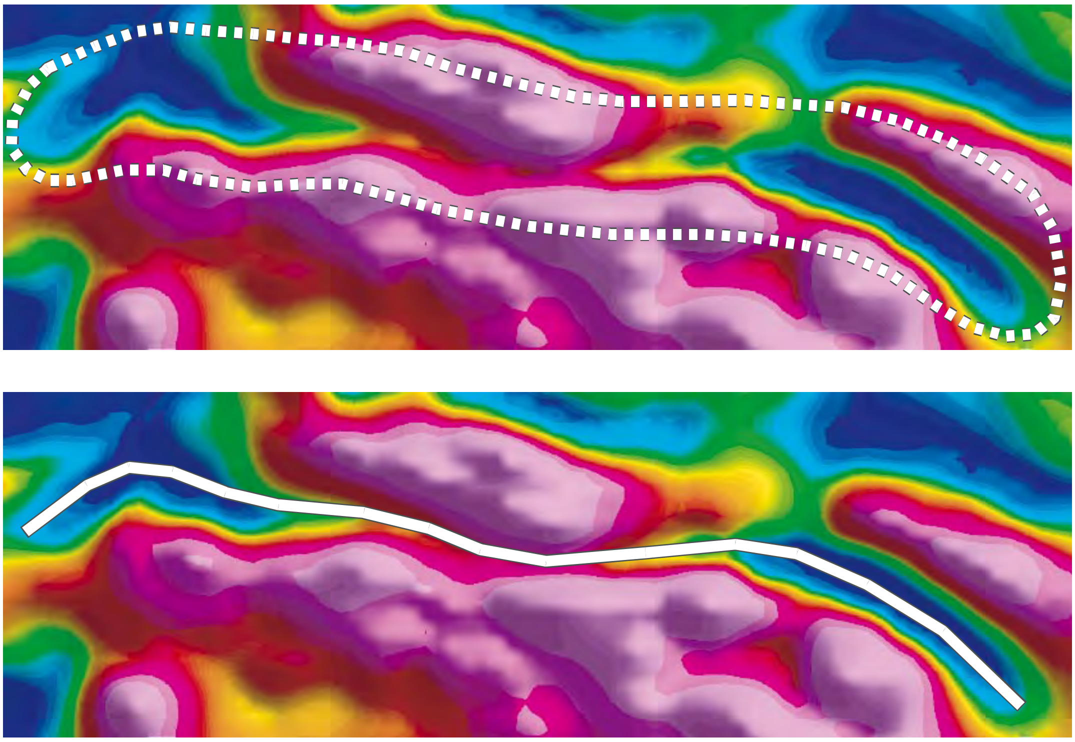

***Figure 4-1.*** *An example of method-specific lineament interpretation. a) A minimum (indicated by the dashed white outline) identified on a magnetic map is judged to represent a possible deformation zone. b) The lineament is digitised as a polyline (indicated by the solid white line).*

## 4.4 Interpretation of coordinated lineaments

The method-specific data sets reflect the geology of the same area. Thus, it is likely that some of the method-specific lineaments represent the same possible deformation zones. The purpose of the coordination stage was to integrate those method-specific lineaments that may represent the same deformation zone.

The coordinated lineament interpretation comprised:

1. The identification of the method-specific lineaments representing the same possible deformation zone.
2. The integration of those lineaments into coordinated lineaments.
3. The parametrisation of the coordinated lineaments by assigning unique attributes to them.

The coordinated lineament interpretation was carried out in the following manner. All the method-specific lineaments were viewed together on top of the method-specific maps. Each method-specific lineament was systematically compared against the other method-specific lineaments in order to determine whether it represents a possible deformation zone by itself or belongs to a group of lineaments representing the same possible deformation zone.

If a method-specific lineament was judged to be the sole descriptor of a possible deformation zone, it was copied to the shapefile for the coordinated lineaments without modifications and its attributes were determined on the basis of the method-specific lineament.
If two or more method-specific lineaments were judged to represent the same possible deformation zone, they were integrated using the following procedure:

1. The method-specific lineament that was judged to give the best representation of the possible deformation zone was chosen (Figure 4-2a) and copied to the shapefile for the coordinated lineaments.
2. The copied lineament was split into segments so that a segment begins or ends whenever a method-specific lineament describing the same possible deformation zone begins or ends (Figure 4-2b).
3. Each segment was considered as an independent lineament and its attributes were determined on the basis of the method-specific lineaments that were integrated together.

The attributes were stored in an attribute table associated with the shapefile. The coordinated lineament interpretation was completed when all the method-specific lineaments were processed in the above manner.

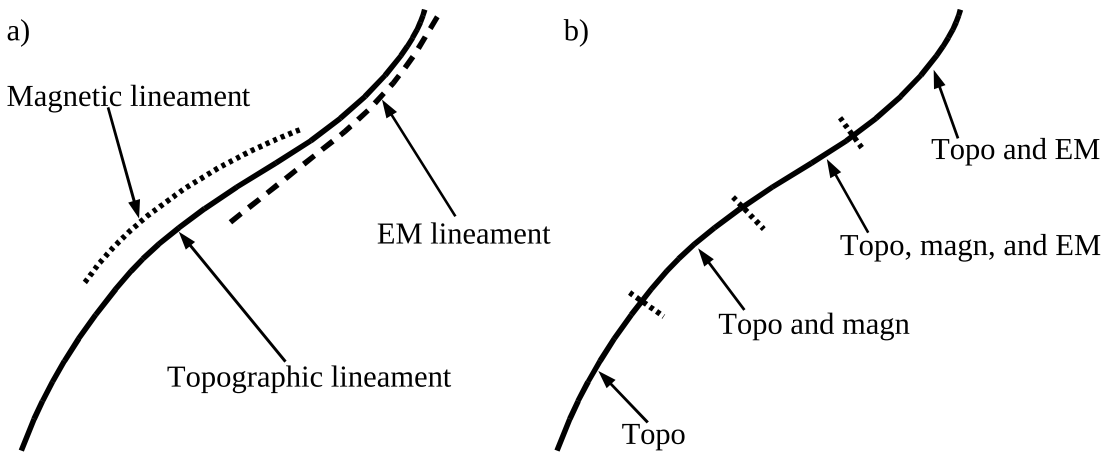


***Figure 4-2.*** *The principle of coordinated lineament interpretation. a) Three lineaments (topographic, magnetic, and EM) are judged to represent the same possible deformation zone; the topographic lineament is judged to give the best representation of the zone and is made a coordinated lineament. b) The new coordinated lineament is split into four segments so that a segment begins or ends whenever a method-specific lineament describing the same zone begins or ends.*

## 4.5 Interpretation of linked lineaments

The final integrated interpretation of geophysical and topographic lineaments was produced by joining together those coordinated lineaments that represent the same possible deformation zone.

The linked lineament interpretation comprised:

1. The identification of the coordinated lineaments representing the same possible deformation zone.
2. The integration of those lineaments into a linked lineament.
3. The parametrisation of the linked lineament by assigning unique attributes to it.

The linked lineament interpretation was carried out by viewing the coordinated lineaments on top of the maps visualising the method-specific data sets and systematically going through each coordinated lineament. If two or more coordinated lineaments were judged to represent the same possible deformation zone (Figure 4-3a) they were joined together into a single linked lineament (Figure 4-3b) and copied to the shapefile for the linked lineaments. If a coordinated lineament was the sole descriptor of a possible deformation zone, it was copied to the shapefile for the linked lineaments without modifications. Each lineament was assigned unique attributes based on the coordinated lineaments that were joined together. The attributes were stored in an attribute table associated with the shapefile. The linked lineament interpretation was completed when all the coordinated lineaments were processed in the above manner.

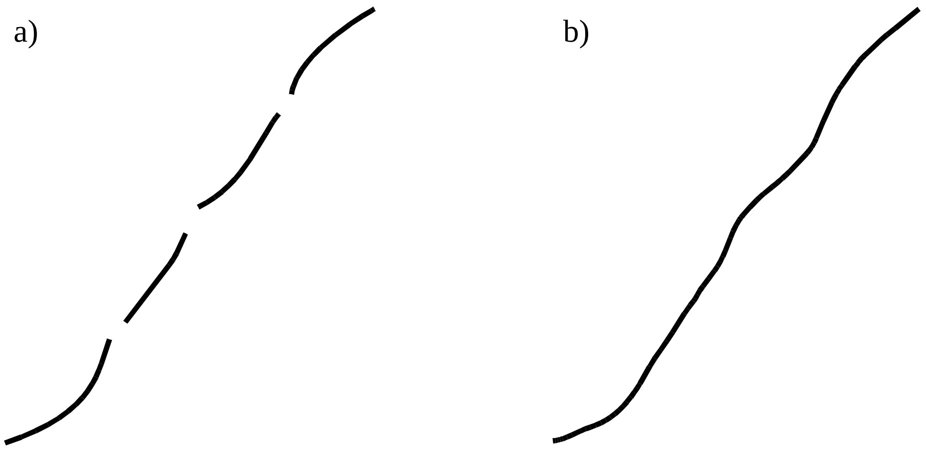


***Figure 4-3.*** *The principle of linked lineament interpretation. a) Four coordinated lineaments are judged to represent the same deformation zone. b) The lineaments are joined together into a single linked lineament.*

# 5 Execution

## 5.1 Input data

The data used in the interpretations comprised mainly of geophysical and topographic data. The geophysical data sets included airborne magnetic, dipole-source EM, and VLF data. The topographic data included a 10-m DEM and 1-m elevation contours. Maps of roads, power lines, shorelines, Quaternary deposits, and outcrops were used as additional information in the interpretations.

### 5.1.1 Geophysical data

The geophysical data were measured from a helicopter /Rønning et al. 2003/. The survey direction was N-S with a nominal line spacing of 50 m and a nominal flight altitude of 60 m. Tie lines were flown in the E-W direction at 500 m line spacing. The data was provided by SKB as two Geosoft XYZ files: one file contained dipole-source EM data (Simpevarp EM NS.XYZ) while the other contained magnetic and VLF data (Simpevarp Mag NS.XYZ).

The magnetic data set comprised measurements of the magnetic total field. The sample spacing was ~ 3 m (10 samples per second). The data were corrected for diurnal variations of the Earth's field using base station data. The data were of very good quality in general /Rønning et al. 2003/ but show levelling errors when gridded /Byström et al. 2003/.

The dipole-source EM data comprised in-phase and quadrature component data along with apparent resistivity data calculated using the measured components. The in-phase and quadrature component data were measured using a 5-frequency Helicopter EM (HEM) sonde (Table 5-1). The sample spacing was ~ 3 m (10 samples per second). The data quality was good in general /Rønning et al. 2003/, however, the measurements were somewhat disturbed in the neighborhood of the major power lines and contain some levelling errors /Byström et al. 2003/.

The VLF data comprised total field and quadrature component data measured using in-line and orthogonal stations (VLF stations that are either in the direction of the line or, respectively, in a direction perpendicular to the line). The GBR station (16 kHz) was used as the in-line station and the NAA (24 kHz) station as the orthogonal station. The sample spacing was ~ 6 m (5 samples per second). No quality control was performed for the VLF data; at times, however, the GBR and NAA stations were not transmitting and other stations were used /Byström et al. 2003/.

**Table 5-1. Specifications of the HEM measurement system.**

| Frequency (Hz) | TX-RX geometry |
|---|---|
| 34,133 | Coplanar |
| 7,001 | Coaxial |
| 6,606 | Coplanar |
| 980[a] | Coaxial |
| 880 | Coplanar |

[a] Apparent resistivity estimates were not available for this frequency.

The magnetometer was installed in the HEM sonde which was towed on a 30-m long cable while the VLF sensor was towed on a 10-m long cable. Thus, the altitudes of the magnetometer and the EM sensors were ~ 30 m and the VLF sensor ~ 50 m.

### 5.1.2 Topographic data

The Simpevarp DEM was based mainly on infrared (IR) photos taken at the altitude of 2,300 m; black-and-white (BW) photos taken at the altitude of 4,600 m were used on areas where IR photos were not available /Wiklund 2002/. The accuracy in elevation was ± 1 m (± 2 m on forest) on the areas based on the IR photos while it was ± 2 m (± 4 m on forest) on the areas based on the BW photos. The horisontal resolution of the DEM was 10 m. The DEM was provided by SKB as an ESRI binary raster (sde_grid/met_hoj_1302).

The topographic data included also 1-m elevation contours that were provided by SKB as an ESRI shapefile (SDEADM_MET_OH_HOJ_1049).

### 5.1.3 Additional data

In addition to the geophysical and topographic data, maps of roads, power lines, shorelines, Quaternary deposits, and bedrock outcrops were also used in the interpretations. The maps were provided by SKB as ESRI shapefiles.

## 5.2 Data processing and map compilation

### 5.2.1 Magnetic data

All data processing and map compilation was carried out using Oasis montaj. The magnetic data set was gridded using the minimum curvature method /Briggs 1974/. Grids of 4-m and 20-m cell sizes were produced. Both grids were further processed with filters. The following derivative grids were produced from the 4-m and 20-m base grids:

- Two shaded relief grids were produced from the 4-m base grid (illumination declinations were 45° and 315° while the illumination inclination was 45°).
- Two shaded relief grids were produced from the 20-m base grid (illumination declinations were 45° and 315° while the illumination inclination was 45°).
- Two grids were produced from the 4-m base grid by the application of two convolution filters of kernel sizes 5×5 and 9×9 grid cells.
- One shaded relief grid was produced from the 5×5 convolution grid (illumination declination was 315° while the illumination inclination was 45°).
- One shaded relief grid was produced from the 9×9 convolution grid (illumination declination was 315° while the illumination inclination was 45°).

Hillshaded colour and greytone maps were compiled from the grids. The following maps were produced:

- Two 3-grid composite colour maps were produced using the 4-m and 20-m base grids and the respective shaded relief grids produced from them. (Dual shaded colour maps: the base grid was used as a colour layer and the respective shaded relief grids as illumination layers.)

- One 2-grid composite greytone map was produced using the shaded relief grids produced from the 4-m base grid. (Dual shaded greytone map: the shaded relief grids were used as illumination layers.)

Figure 5-1 shows the 3-grid composite colour map produced from the 4-m base grid and the respective shaded relief grids produced from it.

### 5.2.2 Dipole-source EM data

All data processing and map compilation was carried out using Oasis montaj. The fourteen dipole-source EM data sets (the five in-phase component, five quadrature component, and four apparent resistivity data sets) were gridded using the minimum curvature method /Briggs 1974/. Fourteen grids of a cell size of 10 m were produced.

Fourteen hillshaded colour maps were compiled from the grids:

- Five hillshaded colour maps from each of the in-phase component grids (shaded from NW).
- Five hillshaded colour maps from each of the quadrature component grids (shaded from NW).
- Four hillshaded colour maps from each of the apparent resistivity grids (shaded from NW).

Figure 5-2 shows the hillshaded colour map visualising the Coaxial 7001 Hz apparent resisitivity data set.

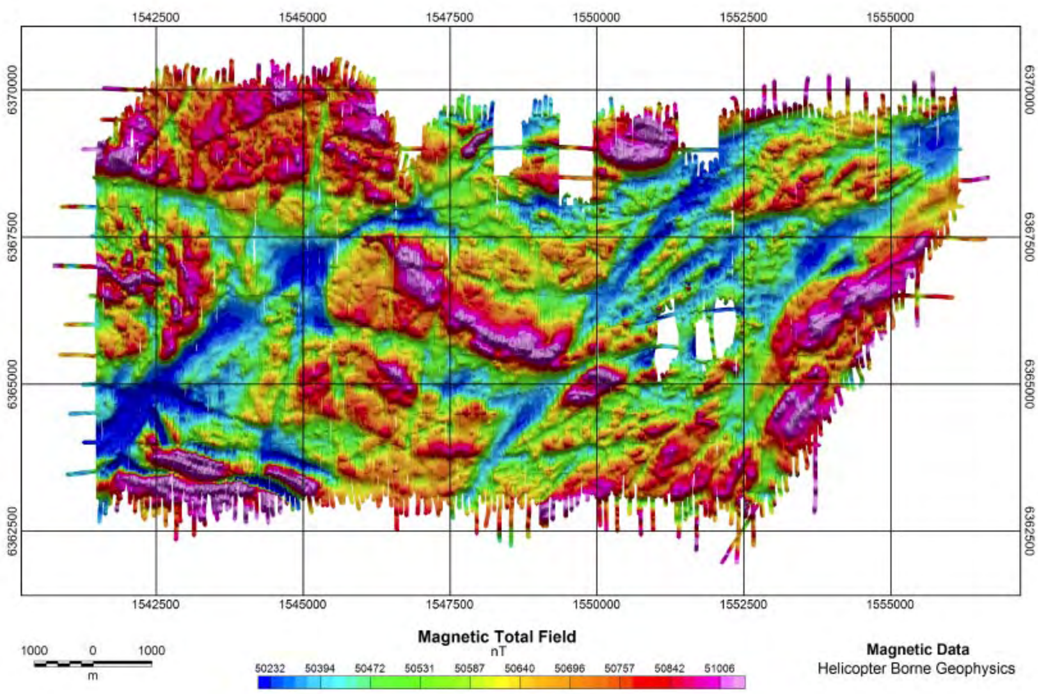


***Figure 5-1.*** *The 3-grid composite colour map (produced from the 4-m base grid) used in the interpretation of magnetic lineaments.*

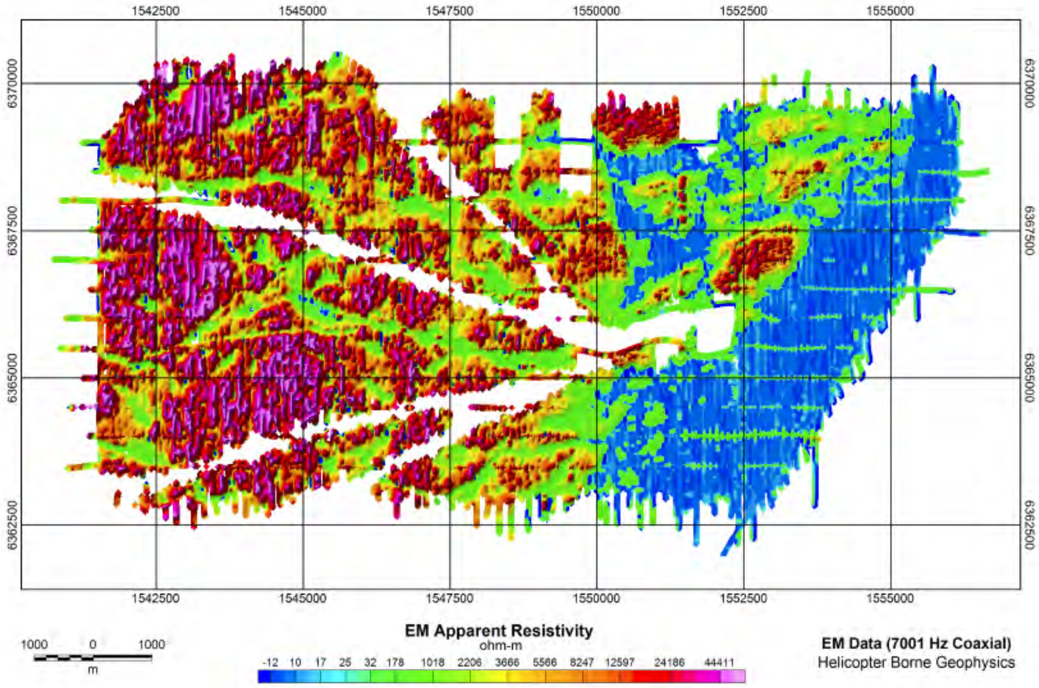


***Figure 5-2.*** *The hillshaded colour map visualising the Coaxial 7001 Hz apparent resistivity data set used in the interpretation of dipole-source EM lineaments.*

### 5.2.3 VLF data

All data processing and map compilation was carried out using Oasis montaj. The four VLF data sets (the quadrature component in-line and orthogonal station data sets; and the total field in-line and orthogonal station data sets) were gridded using the minimum curvature method /Briggs 1974/. Four grids of a cell size of 5 ms were produced.

Four maps were compiled from the grids:

- Two hillshaded colour maps of total field from both the in-line and orthogonal station grids (shaded from NW).
- Two hillshaded colour maps of quadrature component from both the in-line and orthogonal station grids (shaded from NW).

Figure 5-3 shows the hillshaded colour map visualising the orthogonal station VLF total field data set.

### 5.2.4 Topographic data

The DEM raster was further processed using the Spatial Analyst extension of ArcView. The following derivative rasters were produced:

- Four hillshaded rasters of elevation (shaded from NE, SE, SW, and NW).
- One slope raster.

Six maps were compiled from the rasters using ArcView:

- One greytone map of elevation.
- Four hillshaded greytone maps of elevation (shaded from NE, SE, SW, and NW).
- One slope map.

Figure 5-4 shows a hillshaded greytone map of elevation used in the interpretation of topographic data.

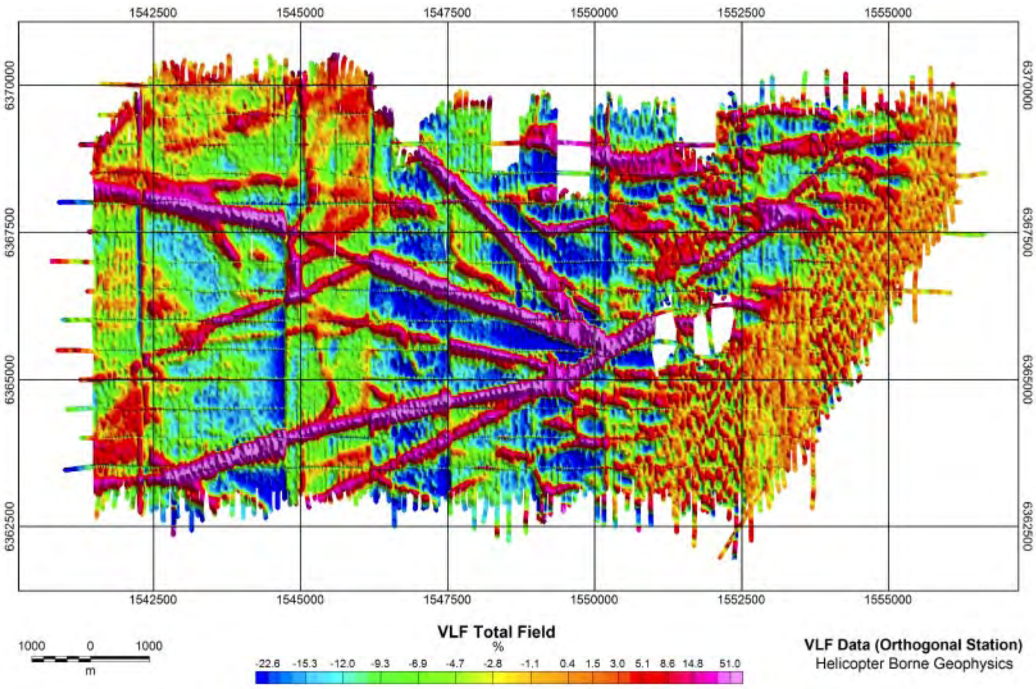


***Figure 5-3.*** *The hillshaded colour map of the orthogonal station VLF total field used in the interpretation of VLF lineaments.*

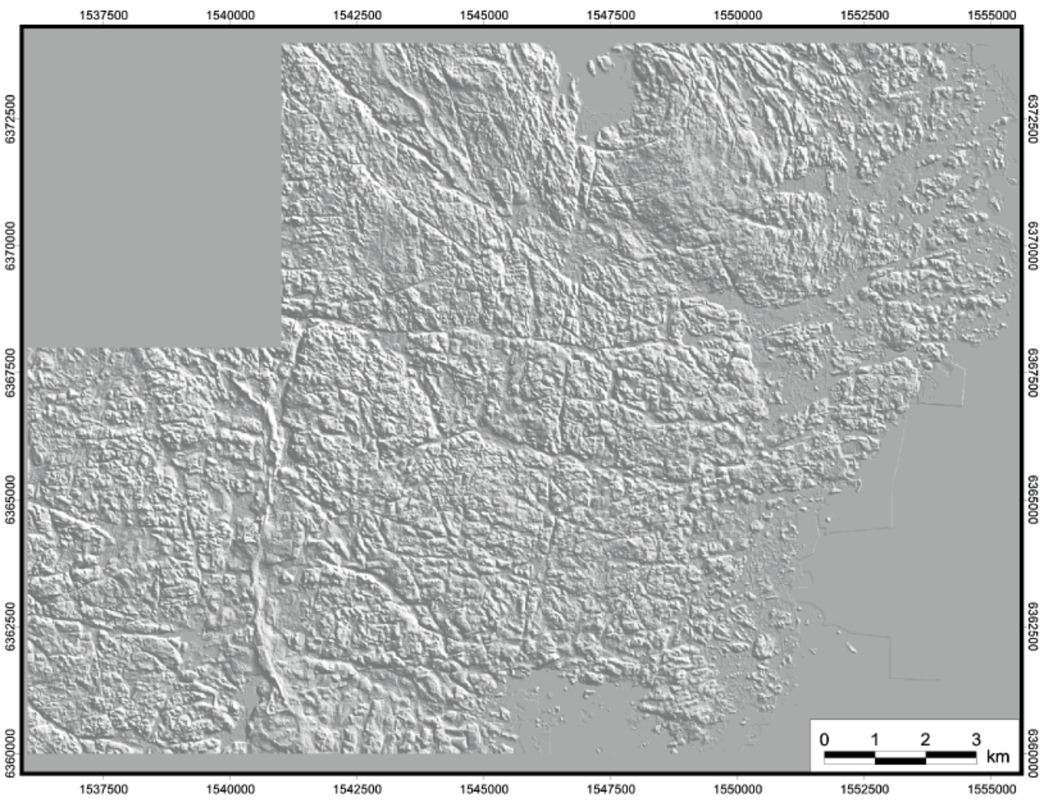


***Figure 5-4.*** *A hillshaded greytone map of elevation (shaded from NE) used in the interpretation of topographic lineaments.*

## 5.3 Lineament interpretation

### 5.3.1 Method-specific lineaments

The magnetic, dipole-source EM, VLF, and topographic data sets were interpreted independently. All interpretation work was carried out using ArcView GIS v3.2. The digitised lineaments were stored in four method-specific ESRI shapefiles while their attributes were stored in four dBASE files associated with the shapefiles.

#### *Magnetic lineaments*

The three maps described in Section 5.2.1 were used as the basis for the interpretation of magnetic lineaments. The maps were viewed at scales ranging from 1:50,000 to 1:20,000.

Magnetic lineaments were identified and digitised mainly on the basis of the 3-grid composite colour map (Figure 5-1). This map was considered to give the most unbiased representation of the measured data because of minimum smoothing of data and dual shading (unidirectional shading would have introduced bias because it enhances features trending in one direction only). A total of 202 lineaments were identified from the magnetic data.

The magnetic lineaments were identified as minima from magnetic maps. The basis for this interpretation is that oxidising fluids flowing in a fracture zone may have caused the alteration of magnetite into paramagnetic hematite /Henkel and Guzmán 1977/ resulting in a negative susceptibility contrast in the deformation zone. The negative contrast manifests itself as a magnetic minimum on maps.

#### *Dipole-source EM lineaments*

The fourteen maps described in Section 5.2.2 were used as the basis for the interpretation of dipole-source EM lineaments. Maps of roads, power lines, and shorelines were used to aid the interpretation. The maps were viewed at scales ranging from 1:50,000 to 1:30,000.

Most of the lineaments were identified and digitised on the basis of the Coaxial 7001 Hz apparent resisitivity map (Figure 5-2). This was due to the fact that the noise component was strong in the other maps (especially the in-phase and quadrature component maps). Lineaments in the N-S direction were avoided due to strong noise component in that direction. Furthermore, the interpretation of dipole-source EM anomalies above roads and power lines as lineaments were avoided. Moreover, the sea area was completely excluded from the interpretation. The total number of lineaments identified from the dipole-source EM data was 48.

The dipole-source EM lineaments were identified either as apparent resistivity minima or quadrature component maxima from the maps. This interpretation is based on the idea that electrical conductivity is increased or, analogously, electrical resistivity decreased above a deformation zone due to the following factors /Henkel and Eriksson 1981, Soonawala and Hayles 1986, Korhonen et al. 2004/:

- A deformation zone may contain more groundwater than its surroundings due to increased secondary porosity.
- A depression may have formed above a deformation zone and conducting soil may have deposited on the depression.
- The deformation zone may contain conducting minerals (such as clay) due to alteration.

The increased conductivity contrast above a deformation zone manifests itself as a conductivity maximum on dipole-source EM in-phase and quadrature component maps. Analogously, the decreased resistivity contrast manifests itself as an apparent resistivity minimum on apparent resistivity maps.

### VLF lineaments

The four maps described in Section 5.2.3 were used as the basis for the interpretation of VLF lineaments. Maps of roads, power lines, and shorelines were used to aid the interpretation. The maps were viewed at scales ranging from 1:50,000 to 1:20,000.

All lineaments were identified and digitised on the basis of the total field maps. The quadrature component maps were too noisy to be used for interpretation because of systematic levelling errors. Lineaments in the N-S direction were avoided due to a strong noise component in that direction. Furthermore, interpretation of anomalies on the islands were avoided due to possible influence by saline sea waters (even though they may indicate possible fractures). The interpretation of VLF anomalies over roads and power lines as lineaments were avoided. The sea area was completely excluded from the interpretation. A total of 54 lineaments were identified from the VLF data.

The VLF lineaments were identified as total field maxima from VLF maps. This interpretation is based on the idea that electrical conductivity is increased in a deformation zone due to the factors listed above. The increased conductivity contrast manifests itself as a maximum on a VLF total field map.

### Topographic lineaments

The six maps described in Section 5.2.4 were used as the basis for the interpretation of topographic lineaments. Maps of shorelines, Quaternary deposits and bedrock outcrops were also used in the interpretations. The interpretation proceeded from regional interpretation scale (1:60,000) to local scale (1:20,000 to 1:10,000).

First, the longest and most distinctive lineaments (lineaments completely visible on the screen at the scale of approximately 1:60,000) were drawn roughly. Then, the positions of these lineaments were studied in more detail at scales ranging from 1:20,000 to 1:10,000.

In the first stage, the interpretations were made on the basis of the greytone map of elevation and, especially, the four hillshaded greytone maps. During the detailed interpretation, the 1-m elevation contours and the slope map were used along with the other maps. The most difficult subareas for topographic lineament interpretation were the coastal area in the East and the N-S trending esker area in the West.

A total of 1,792 lineaments were identified from topographic data mostly either as topographic depressions (valleys) or slopes on topographic maps. This interpretation is based on the idea that the deformation zones in bedrock have eroded more easily than the surrounding intact bedrock. The eroded landforms manifest themselves as valleys and slopes on topographic maps.

### Parametrisation of method-specific lineaments

When the identification and digitisation of the method-specific lineaments were completed, the lineaments were parametrised by assigning unique attributes to them. Each lineament was revisited and its attributes were determined and stored in an attribute table (Table 5-2).

The most critical parametres were the level of uncertainty (Uncert_t) in the interpretation of the lineament and the spatial precision (Precis_t) in the determination of the position of the lineament. The other attributes were more or less trivial to determine.

**Table 5-2. The attribute table structure for the method-specific lineaments.**

| 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, 60 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 organisation of the interpreter. | E.g. “Aimo Kuivamäki/GTK” |
| Id_t | Identifier | A unique identifier for the lineament. | E.g. “MAGN0123” |

### 5.3.2 Coordinated lineaments

All the maps used in the interpretation of the method-specific lineaments were used as the basis for the coordinated lineament interpetation. The maps were viewed at scales ranging from 1:40,000 to 1:5,000.

The interpretation was carried out by systematically comparing each method-specific lineament to its neighbouring lineaments and viewing the maps used in their interpretation to determine which lineaments represent the same possible deformation zones. If one or more neighbouring lineaments were found to be closely aligned to the lineament being currently processed, and the minima or maxima upon which the interpretations were based on were also closely aligned, the lineaments were integrated using the coordination procedure described in Section 4.4.

Sometimes it was difficult to determine whether magnetic and topographic lineaments should be coordinated or not. This was due to higher resolution of the topographic data set. Thus, the same possible deformation zone may manifest itself as a single lineament on magnetic maps and as several lineaments on topographic maps. In these cases, buffer zones were used to aid the interpretation (Figure 5-5). The zones were created with ArcMap using the values of the spatial precision attributes (Precis_t) of the interpreted lineaments as the widths of the zones. Then, if two zones were overlapping, it was considered to be an indication that the lineaments may be coordinated.

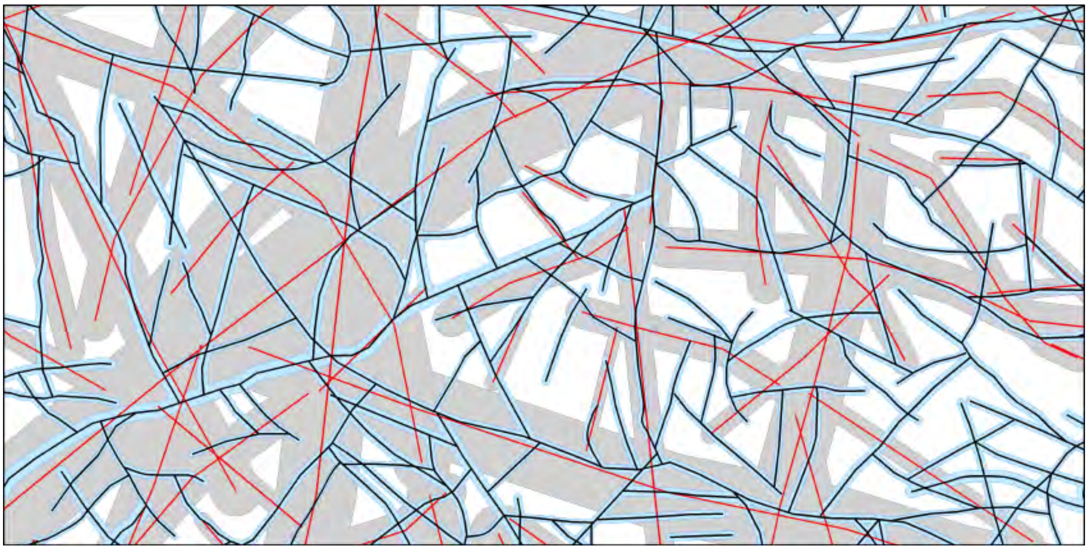

***Figure 5-5.*** *An example of buffer zones. Magnetic and topographic lineaments (red and black lines) and their buffer zones (grey and blue areas).*

When all the method-specific lineaments were processed into 1,351 coordinated lineaments, they were parametrised by assigning unique attributes to them. Table 5-3 shows the attribute table structure for the coordinated lineaments.

The parametrisation was carried out using custom made ArcView Avenue scripts. The value of the references attribute (Refs_t) of a coordinated lineament was used to determine the method-specific lineaments that were integrated together. Then, the attribute values of the method-specific lineaments were retrieved and used to calculate the attribute values of the coordinated lineament.

The value of the precision attribute (Precis_t) was determined as the value of the method-specific lineament that gave the best representation of the possible deformation zone. The value of the uncertainty attribute (Uncert_t) was determined using the following algorithm:

- Go through each method-specific lineament used to produce the coordinated lineament and record the uncertainty values of the method-specific lineaments.
- If the smallest uncertainty value is 1, set the uncertainty value of the coordinated lineament to 1.
- If the smallest uncertainty value is 2, set the uncertainty value of the coordinated lineament to 2. However, if there is at least one other method-specific lineament with the uncertainty value 2, lower the uncertainty value of the coordinated lineament to 1.
- If the smallest uncertainty value is 3, set the uncertainty value of the coordinated lineament to 3. However, if there are least two other method-specific lineaments with the uncertainty value 3, lower the uncertainty value of the coordinated lineament to 2.

The values of the other attributes were trivially determined by the scripts.

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

| 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 priority) 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 "IR-ortophoto, airborne geophysics". |
| Property_n | Property | The number of physical properties on which the interpretation was based on. | A numerical value in the range of 1–3. |
| Weight_n | Weight | An indicator combining the number of properties on which the lineament was based on and the uncertainty of the lineament. | A numerical value in the range of 1–5. |
| 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 organisation of the interpreters. | E.g. "Kimmo Korhonen/GTK". |
| Id_t | Identifier | A unique identifier for the coordinated lineament. | E.g. "COORD0123". |
| Refs_t | References | Identifiers of the method-specific lineaments that were used to produce the coordinated lineament. | E.g. "TOPO1234, MAGN0123,VLF0012". |

### 5.3.3 Linked lineaments

All the maps used in the interpretation of the method-specific lineaments were used as the basis for the linked lineament interpetation. The maps were viewed at scales ranging from 1:50,000 to 1:10,000.

The interpretation was carried out by systematically comparing the alignments of neighbouring coordinated lineaments. If two or more lineaments were judged to represent the continuation of the same possible deformation zone, they were joined together and copied to the shapefile for the linked lineaments. The judgments were based on the maps visualising the method-specific data sets and the alignments of the coordinated lineaments.

When all the coordinated lineaments were integrated into 846 linked lineaments, they were further processed by slightly adjusting the end points of some lineaments to make them begin and/or end at neighbouring lineaments (Figure 5-6). The adjustments were done only to those lineaments that had end points close to their neighbours. No adjustments were made unless the data allowed for them.

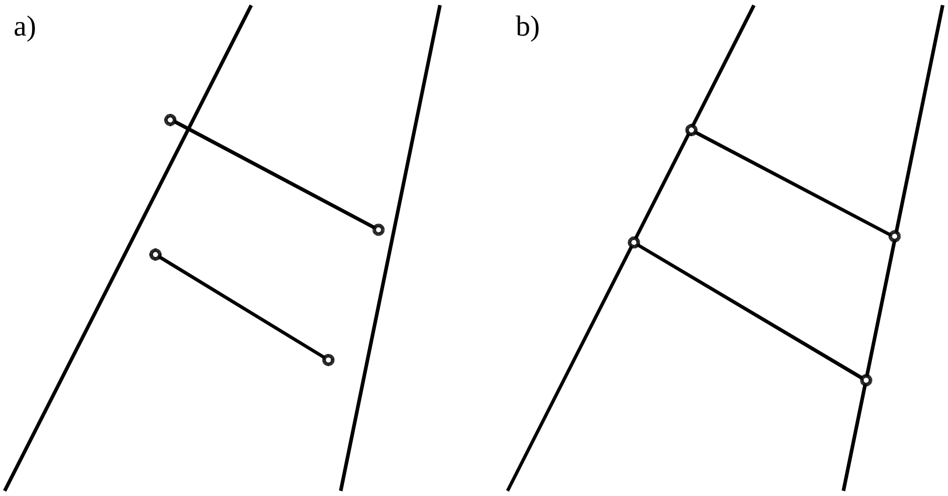


***Figure 5-6.*** *The principle of end-point adjustments of linked lineaments. a) Two lineaments have end points close to neighbouring lineaments. b) The end points of the lineaments are adjusted to make them begin and end at the neighbouring lineaments.*

After the end point adjustments were done, the linked lineaments were parametrised by assigning unique attributes to them. Table 5-4 shows the attribute table structure for the linked lineaments. The values of the scale and date attributes (Scale_t and Date_t) were recorded during the linking stage. The other parametres were calculated using custom made ArcView Avenue scripts.

The value of the references attribute (Refs_t) of a linked lineament was used to determine the coordinated lineaments that were joined together. Then, the attribute values of the coordinated lineaments were retrieved and used to calculate the attribute values of the linked lineament.

The values of the uncertainty, property, and weight attributes (Uncert_n, Property_n, and Weight_n) were calculated as weighted sums using

$$a_{\mathrm{TOT}} = \frac{\sum_{i=1}^{N} a_i \cdot l_i}{l_{\mathrm{TOT}}}, \qquad (1)$$

where $a_{\mathrm{TOT}}$ is the value of the attribute, $N$ is the number of the coordinated lineaments used to produce the linked lineament, $a_i$ is the value of the attribute of the $i$th coordinated lineament, $l_i$ is the length of the $i$th coordinated lineament, and $l_{\mathrm{TOT}}$ is the sum of the lengths of the coordinated lineaments. The values of the conductivity, magnetics, and topographics attributes (Cond_n, Magn_n, and Topog_n) were also calculated using Equation (1) but now $a_i$ was set to either 1 or 0 depending on whether the $i$th coordinated lineament was defined in the data set or not.

To calculate the value of the trend attribute (Trend_n), the vertices of a linked lineament were considered as a set of points (Figure 5-7a). Then, the trend was calculated using the slope of a straight fitted to the points in the least squares sense (Figure 5-7b). The slope *m* was calculated as

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

where $N$ is the number of the points ($x_i$, $y_i$). The angle α that the line makes with the $x$ axis (the W-E axis) is

$$\alpha = \tan^{-1} m. \qquad (2)$$

The trend θ is now

$$\theta = 90° - \frac{180°}{\pi} \cdot \alpha. \qquad (3)$$

The values of the other attributes were trivially determined by the scripts.

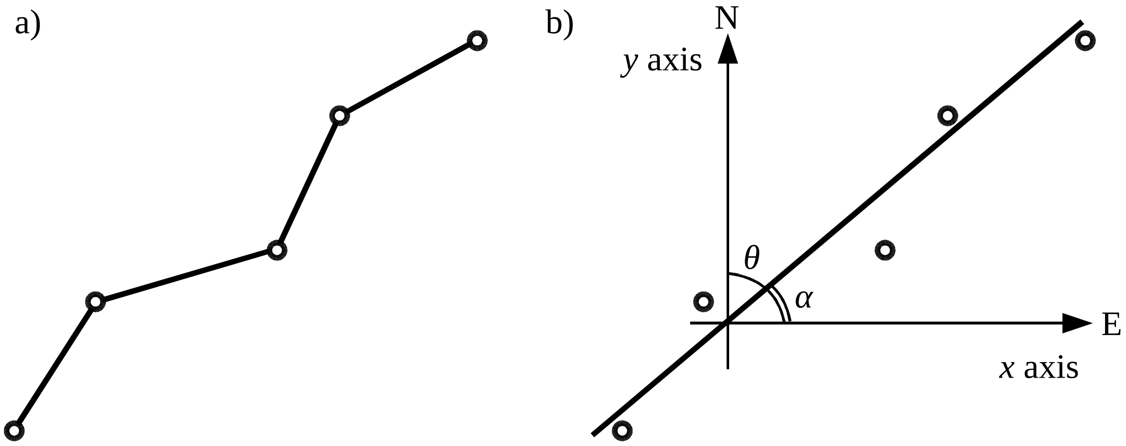


***Figure 5-7.*** *The principle of linked lineament trend calculation. a) The vertices of a linked lineament are considered as a set of five points. b) A straight line is fitted to the points in the least squares sense. The line makes the angle α with the x axis; the trend θ is 90°–α.*

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

| Field name | Attribute name | Attribute description | Attribute value |
|---|---|---|---|
| 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_t | 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 for the basic data. | E.g. “Airborne geophysics”, or “Airphoto, airborne geophysics”. |
| Length_n | Length | The length of the linked lineament in metres. | E.g. “551”. |
| Trend_n | Trend | An estimate of the trend of the linked lineament in degrees. | E.g. “55”. |
| Property_n | Property | A weighted average of the property attributes of the coordinated lineament segments. | A numerical value in the range of 1–3. |
| Weight_n | Weight | A weighted average of the weight attributes of the coordinated lineament segments. | A numerical value in the range of 1–5. |
| 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 organisation of the interpreters. | E.g. “Kimmo Korhonen/GTK”. |
| Id_t | Identifier | A unique identifier for the linked lineament. | E.g. “LINKED0123”. |
| Refs_t | References | Identifiers of the coordinated lineaments that were used to produce the linked lineament. | E.g. “COORD0012, COORD0123”. |

# 6 Results

## 6.1 Method-specific lineaments

The interpretations of the magnetic, dipole-source EM, VLF, and topographic data sets resulted in the production of four ESRI shapefiles containing the 2,096 method-specific lineaments and four dBASE files containing the attributes of the lineaments.

Table 6-1 summarises the results of the method-specific lineament interpretation stage. Figures 6-1 to 6-4 show the method-specific lineaments plotted on the maps of Figures 5-1 to 5-4.

**Table 6-1. Summary of the results of the method-specific lineament interpretation stage.**

| Data set | Number of lineaments | | | |
|---|---|---|---|---|
| | Low uncertainty | Medium uncertainty | High uncertainty | Total |
| Magnetic | 25 | 39 | 138 | 202 |
| EM | 6 | 18 | 24 | 48 |
| VLF | 11 | 22 | 21 | 54 |
| Topographic | 89 | 774 | 929 | 1,792 |
| Total | 131 | 853 | 1,112 | 2,096 |

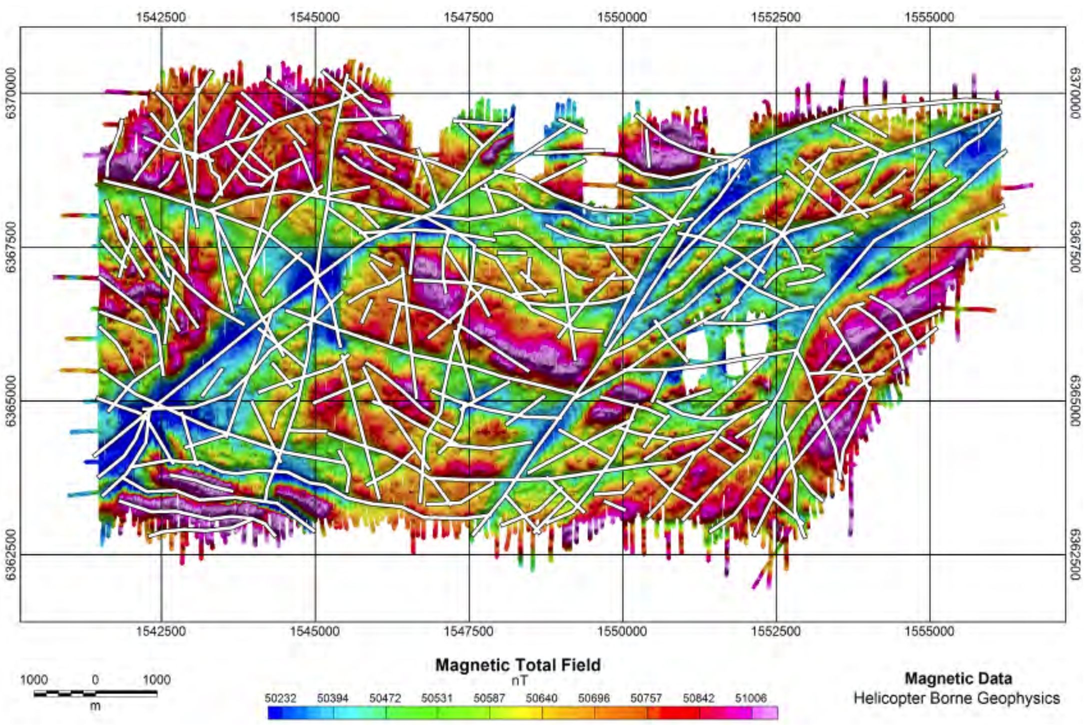


*__Figure 6-1.__ The magnetic lineaments (white lines) plotted on the map of Figure 5-1.*

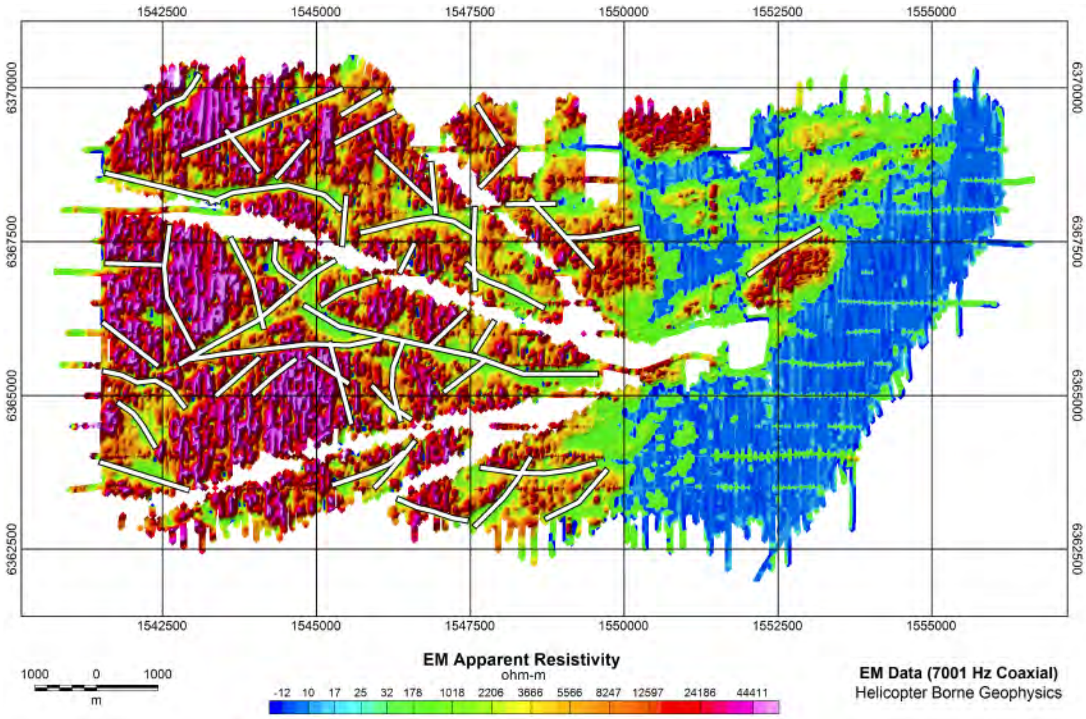


***Figure 6-2.*** *The dipole-source EM lineaments (white lines) plotted on the map of Figure 5-2.*

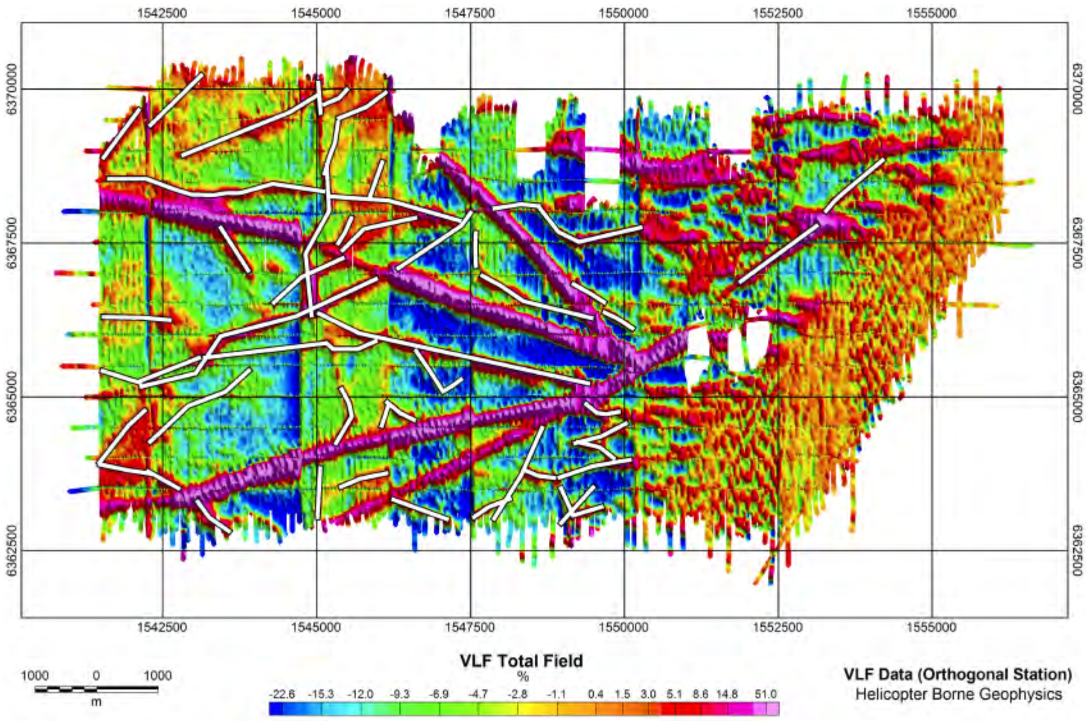


***Figure 6-3.*** *The VLF lineaments (white lines) plotted on the map of Figure 5-3.*

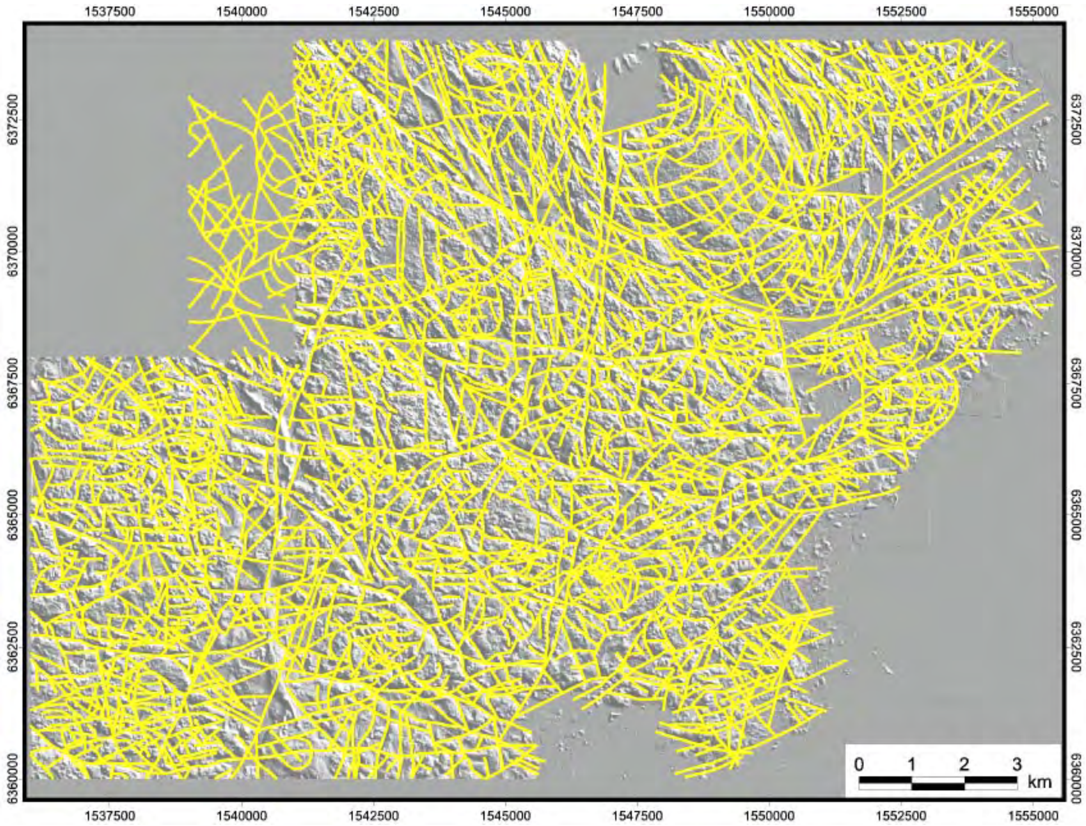


*Figure 6-4. The topographic lineaments (yellow lines) plotted on the map of Figure 5-4.*

## 6.2 Coordinated lineaments

The integration of the magnetic, dipole-source EM, VLF, and topographic lineaments resulted in the production of one ESRI shapefile containing the 1,351 coordinated lineaments and one dBASE file containing the attributes of the lineaments.

Table 6-2 gives a summary of the results of the coordinated lineament interpretation stage. Figure 6-5 shows the coordinated lineaments plotted on a map of the Simpevarp area.

**Table 6-2. Summary of the results of the coordinated lineament interpretation stage.**

| Identified in | Number of lineaments<br>Low uncertainty | Medium uncertainty | High uncertainty | Total |
|---|---|---|---|---|
| Magnetic only | 39 | 38 | 118 | 195 |
| EM only | 2 | 7 | 6 | 15 |
| VLF only | 1 | 10 | 5 | 16 |
| Topographic only | 57 | 376 | 319 | 752 |
| 1 physical property | 107 | 431 | 449 | 987 |
| 2 physical properties | 151 | 87 | 47 | 285 |
| 3 physical properties | 70 | 9 | 0 | 79 |

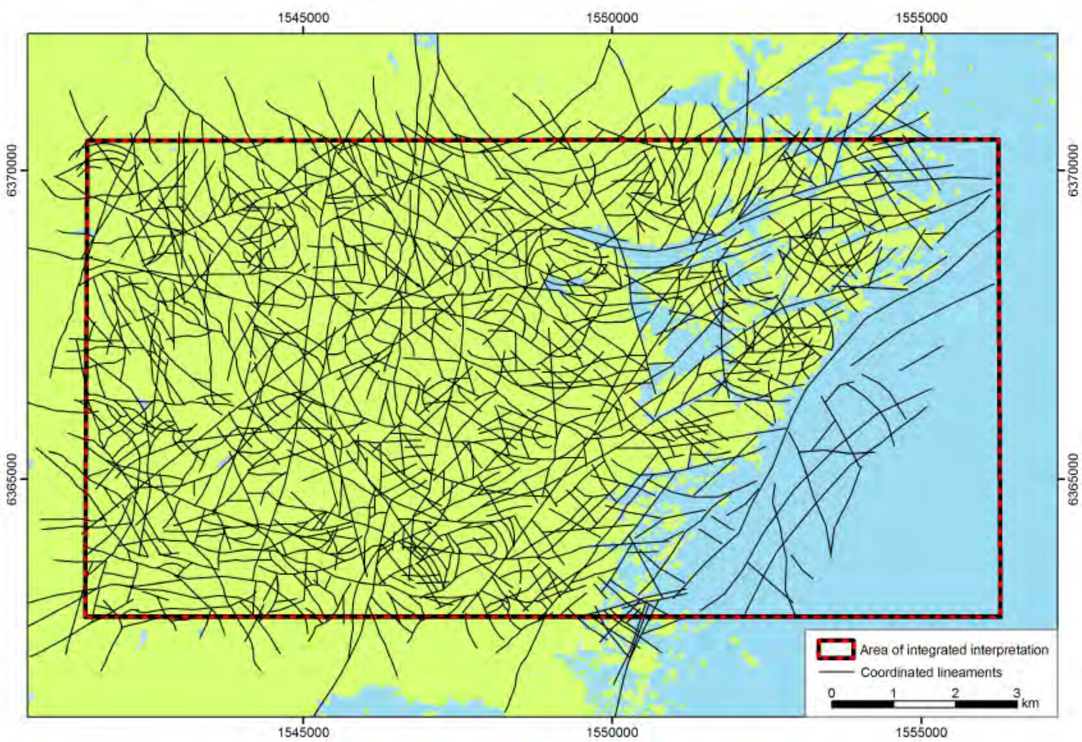


*Figure 6-5. The coordinated lineaments plotted on a map of the Simpevarp area.*

## 6.3 Linked lineaments

The linking of the coordinated lineaments resulted in the production of one ESRI shapefile containing the 846 linked lineaments and one dBASE file containing the attributes of the lineaments.

Table 6-3 gives a summary of the results of the linked lineament interpretation stage. Figures 6-6 and 6-7 show the linked lineaments classified by their uncertainties and lengths plotted on a map of the Simpevarp area. Figure 6-8 shows the trend distributions of the linked lineaments.

**Table 6-3. Summary of the results of the linked lineament interpretation stage.**

| Length | Number of lineaments | | | |
|---|---|---|---|---|
| | Uncertainty < 1.5 | Uncertainty 1.5–2.5 | Uncertainty > 2.5 | Total |
| < 1 km | 7 | 247 | 306 | 560 |
| 1–5 km | 59 | 146 | 64 | 269 |
| > 5 km | 16 | 1 | 0 | 17 |
| Total | 82 | 394 | 370 | 846 |

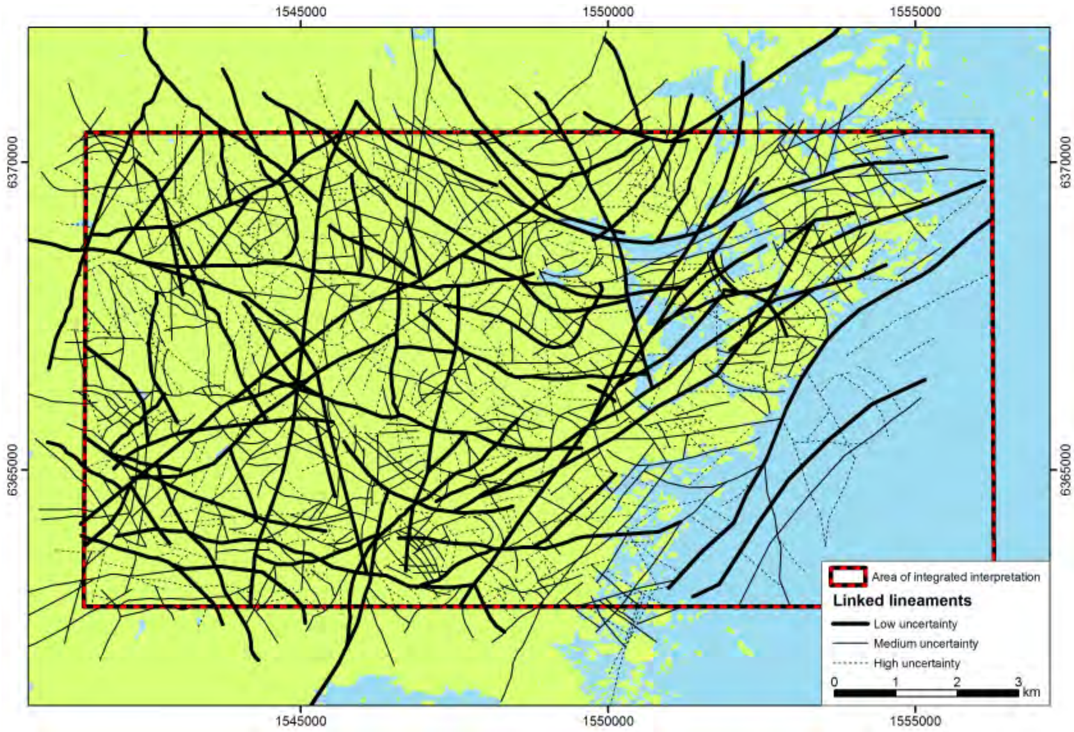


***Figure 6-6.*** *The linked lineaments classified by their uncertainties plotted on a map of the Simpevarp area.*

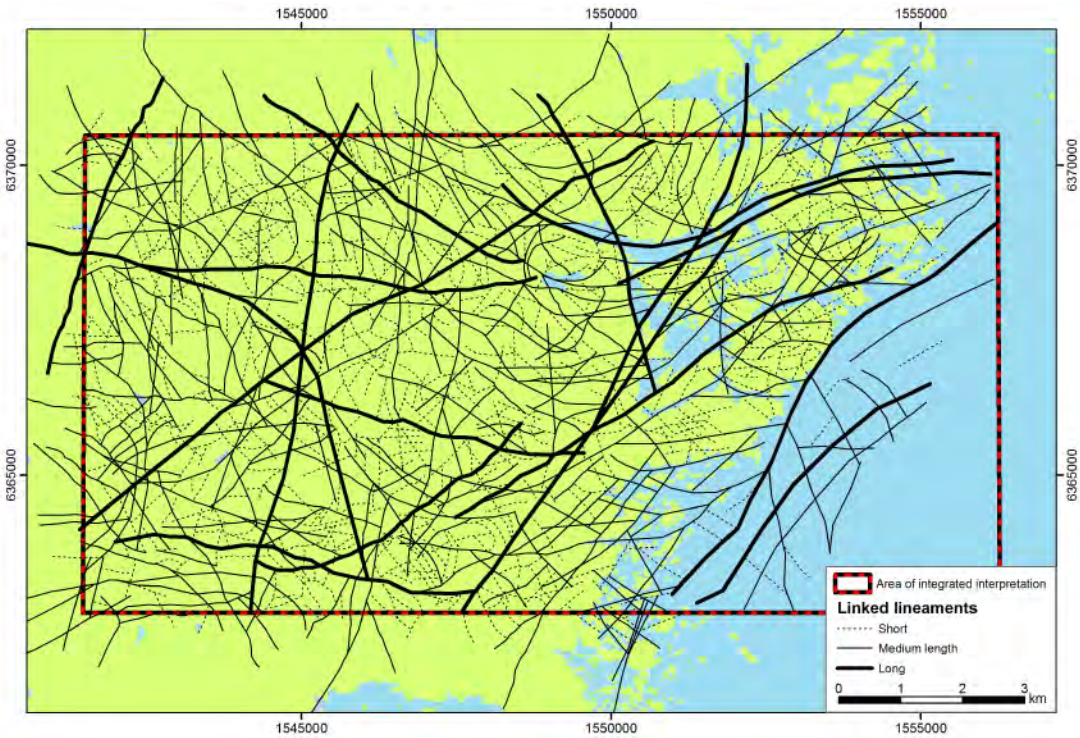


***Figure 6-7.*** *The linked lineaments classified by their lengths plotted on a map of the Simpevarp area.*

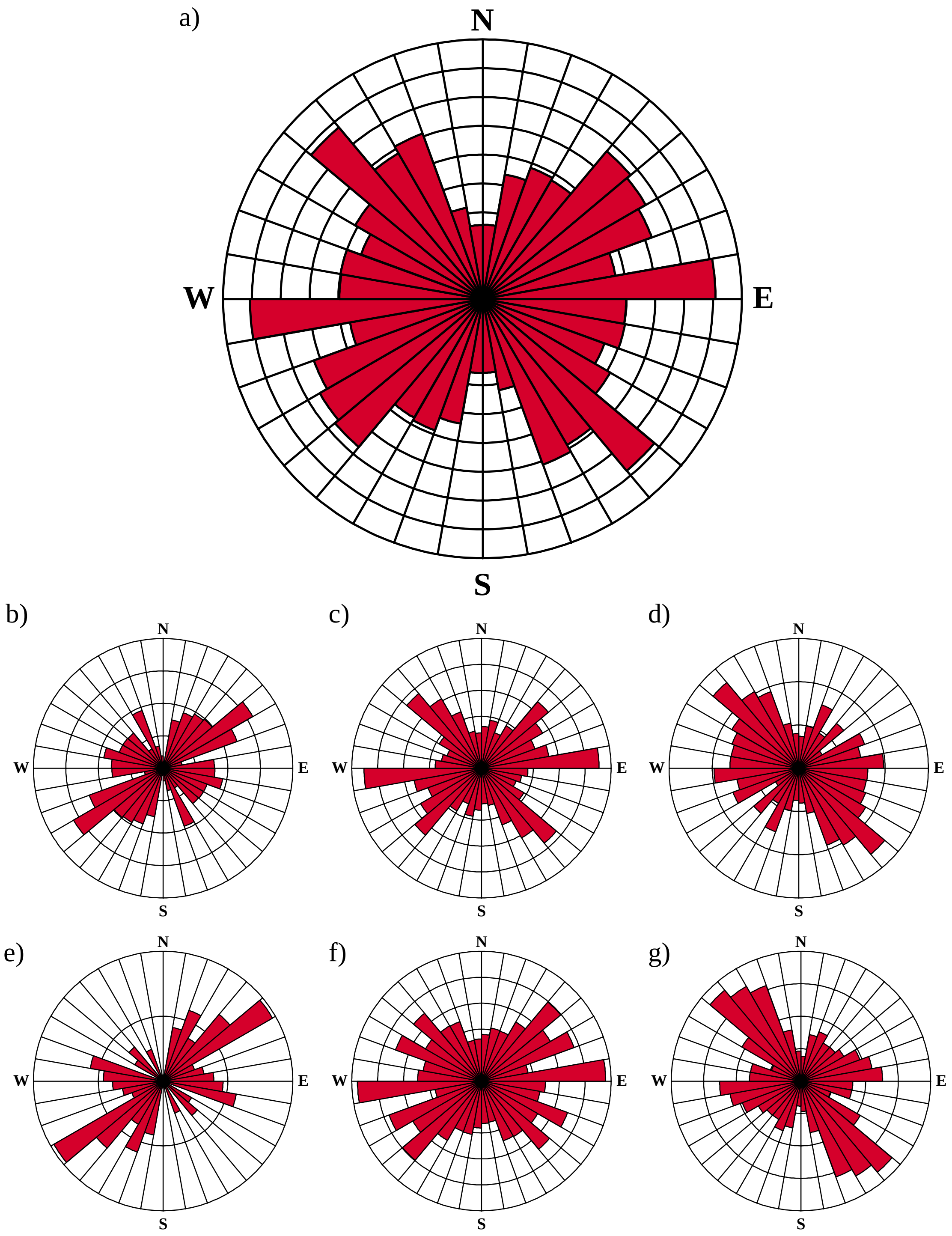


***Figure 6-8.*** *Trend distributions of the linked lineaments (the length of a bar indicates the total length L of the lineaments found within a category). a) All linked lineaments (N = 846, $L_{max}$ = 81 km). Linked lineaments of b) low uncertainty (N = 82, $L_{max}$ = 32 km), c) medium uncertainty (N = 394, $L_{max}$ = 45 km), d) high uncertainty (N = 370, $L_{max}$ = 26 km), e) long length (N = 17, $L_{max}$ = 19 km), f) medium length (N = 269, $L_{max}$ = 48 km), and g) short length (N = 560, $L_{max}$ = 37 km). The sector width is 10 degrees; rings are at every 10 km.*

# 7 Discussion and conclusions

The quality of the magnetic and topographic data was high and the quality of the dipole-source EM and VLF data was low. The magnetic data contained some levelling errors. The EM and VLF data contained considerably more levelling errors and anthropogenic noise (e.g. disturbances caused by power lines and roads). The VLF quadrature data set was rendered completely unusable due to systematic levelling errors.

Furthermore, the spatial resolutions of the data sets were different. The topographic data showed more details than the magnetic data. The dipole-source EM and VLF data were even less detailed than the magnetic data. This is at least partly due to the nature of the methods; the magnetic and EM fields decay rapidly with increasing distance.

The influence of the quality and resolution of the data is reflected in the number of the interpreted lineaments (see Table 6-1). The interpretations of the topographic and magnetic data produced considerably more lineaments than the interpretation of the dipole-source EM and VLF data. However, it should be noted that the topographic data covers an area that is roughly twice the area covered by the geophysical data.

The topographic and geophysical lineaments were interpreted by different interpreters. Furthermore, the coordinated and linked lineament interpretations were carried out by a third interpreter. Thus, the interpretations (topographic, geophysical, and integrated) represent individual assessments rather than the result of a teamwork. This may be considered either as a positive or negative factor depending on the perspective taken.

Notwithstanding the above problems and shortcomings in the data, we consider our interpretations of the Simpevarp area to be of higher quality than our earlier lineament interpretations of the Forsmark and Olkiluoto areas /Korhonen et al. 2004, Korhonen et al. 2005/. The quality and resolution of the topographic and magnetic data for the Simpevarp area are higher than those for the corresponding data for the Forsmark and Olkiluoto areas. Tectonic features of the Simpevarp area are more readily visible from the topographic and magnetic maps, which may either be due to the high quality and resolution of the data, the suitability of the area for lineament interpretation, or different data processing and map compilation procedures. The data for Forsmark also revealed tectonic features rather clearly on a larger scale but the interpretations were, nevertheless, hampered by lower spatial resolution. In the case of Olkiluoto, the data sets were inhomogenous (data from aeroplane, helicopter and ground surveys) and the quality and resolution considerably lower than for the Simpevarp area which made the former interpretations very difficult.

We consider the employed methodology to be very useful. The documentation of the lineaments by the assignment of attributes allows for later reviews of the interpretations and statistical analyses of the lineaments. However, we feel that using a constant value for the precision attribute (Precis_t) is in some, if not most, cases inadequate for describing the spatial precision of the whole lineament. Also, it should be noted that the coordinated and linked lineament interpretations are somewhat biased towards the topographic lineaments because the area covered by the topographic data is larger than the area covered by the geophysical data. Thus, some topographic lineaments extend outside the area for the integrated lineament interpretation (see Figures 6-5 to 6-7).

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