P-10-49

Interpretation of detailed ground magnetic data, resistivity and topographic data from Äspö

Håkan Mattsson, GeoVista AB

Carl-Henric Wahlgren, Geological Survey of Sweden

December 2010

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1651-4416
SKB P-10-49

Interpretation of detailed ground magnetic data, resistivity and topographic data from Äspö

Håkan Mattsson, GeoVista AB

Carl-Henric Wahlgren, Geological Survey of Sweden

December 2010

Keywords: Magnetic, Resistivity, Topography, Lineament, Geophysics, Geology, Bedrock, Fractures, Äspö, Deformation zone.

Abstract

This report presents the interpretations of data from detailed ground magnetic and resistivity surveys, and also elevation data, from the island of Äspö. The ground magnetic and geoelectric data were collected in 1988 as part of the pre-investigations that were carried out before the construction of the Äspö Hard Rock Laboratory (HRL).

The major aim of this work is to identify lineaments in the geophysical and topographic data. The lineaments that have been identified in the different data sets have been coordinated and subsequently linked together. The interpretation products of this work, in particular the linked lineaments, are important data sets and a prerequisite for the deterministic modelling of deformation zones at Äspö.

The magnetic and resistivity data processed and interpreted within the scope of this work show high quality; there are few outliers, physically reliable amplitude ranges, smooth and natural anomalies. The topographic grid is partly affected by noise or erroneous data that, for example, appears as distinct straight north-south trending lines in the maps. However, the artifacts have not had a significant effect on the interpretation of the elevation data.

A total of 103 magnetic, 55 resistivity (geoelectric) and 85 topographic lineaments were identified. The coordination and linking procedure resulted in 37 final lineaments.

The results of the lineament identifications based on the three data sets show a great deal of consensus; in location as well as in orientation of the lineaments. A large part of the lineaments have northeast-southwest orientations and are located in a low magnetic belt trending northeast-southwest across the central part of the Äspö island. The c. 200–250 m wide low magnetic belt is interpreted to reflect the existence of a low-grade ductile shear zone. This belt is generally known as the Äspö shear zone. The shear zone interpretation is also supported by the partly decreased resistivity, which indicates increased fracturing and/or increased occurrences of clay minerals, and also by the spatial distribution of topographic lows.

Within the areas northwest and southeast of the indicated shear zone there are several distinct lineaments. The majority of these have northeast-southwest or northwest-southeast trending orientations. In the magnetic data it is obvious that many of the lineaments define boundaries between bodies with positive magnetic susceptibility contrast. Hence a possible explanation is that the lineaments constitute deformation zones within blocks of more well preserved Äspö diorite or Ävrö granodiorite. However, we cannot exclude the possibility that some lineaments are related to dykes of, for example, fine-grained granite.

Sammanfattning

Föreliggande rapport presenterar resultat och tolkningar av detaljerade data från markburna magnetiska och elektriska resistivitetsmätningar, samt topografiska data, från Äspö. De magnetiska och elektriska mätningarna utfördes unders 1988 i samband med förundersökningar inför byggandet av Äspölaboratoriet.

Huvudsyftet med arbetet var att identifiera lineament i de geofysiska och topografiska data. De olika metodspecifika lineamenten kombinerades först till s.k. koordinerade lineament och slutligen till länkade lineament. De olika tolkningsprodukterna och framförallt de länkade lineamenten utgör viktiga data och är en förutsättning för modelleringen av deterministiska deformationszoner på Äspö.

De geofysiska data som processerades och tolkades uppvisar hög kvalitet; det förekommer endast få s.k. ”outliers”, amplitudvariationer är fysikaliskt rimliga, anomalierna är mjuka och naturliga. Höjdmodellen är dock behäftad med artefakter som tydligt syns i framställda kartor, bl.a. i form av skarpa nord-sydligt orienterade linjer tvärs över land och vatten. Dessa utgjorde dock inga avgörande problem i tolkningsarbetet.

Totalt identifierades 103 magnetiska lineament, 55 lineament i resistivitetsdata (geoelektriska data) och 85 topografiska lineament. Samtolkningen, koordinering och länkning, resulterade i 37 länkade lineament.

De metodspecifika lineamenten uppvisar en god samstämmighet både med avseende på läge och orientering. En stor andel av lineamenten har en ca nordost – sydvästlig orientering och flera längre lineament förekommer i ett bälte med avvikande låg magnetisering som också sträcker sig i nordost – sydvästlig riktning tvärs över Äspö. Området är ca 200–250 m brett och tolkas utgöra en del av den s.k. Äspö skjuvzonen. Inom det lågmagnetiska området förekommer flera delområden med sänkt resistivitet, vilket tyder på förhöjd sprickfrekvens och/eller leromvandling, samt utbredda topografiska sänkor, vilket sammantaget stödjer tolkningen av en större deformationszon.

Både nordväst och sydost om den tolkade skjuvzonen förekommer flertalet lineament. De flesta av dem har antingen ca nordost – sydvästlig eller ca nordväst – sydostlig orientering. I det magnetiska anomalimönstret är det tydligt att många av de magnetiska lineamenten utgör gränser mellan kroppar som har positiv susceptibilitetskontrast i förhållande till omgivningen, vilket kan tyda på att lineamenten definierar deformationszoner inom block med mer välbevarad Äspödiorit eller Ävrö granodiorit. Det kan dock inte uteslutas att vissa lineament är kopplade till t.ex. gångar av finkornig granit.

Contents

1 Introduction

This document reports the interpretations of data from detailed ground magnetic and resistivity surveys performed at Äspö in1988, see Figure 1-1. The interpretation also includes topography data. The work was carried out in accordance with activity plan AP TD F140-10-026. In Table 1-1 controlling documents for performing this activity are listed. Activity plans and method descriptions are SKB's internal controlling documents.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	**Number**	**Version**
Tolkning av detaljerade markgeofysiska mätningar utförda 1988 på Äspö	AP TD F140-10-026	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för lineamentstolkning baserad på topografiska data.	SKB MD 120.001	1.0

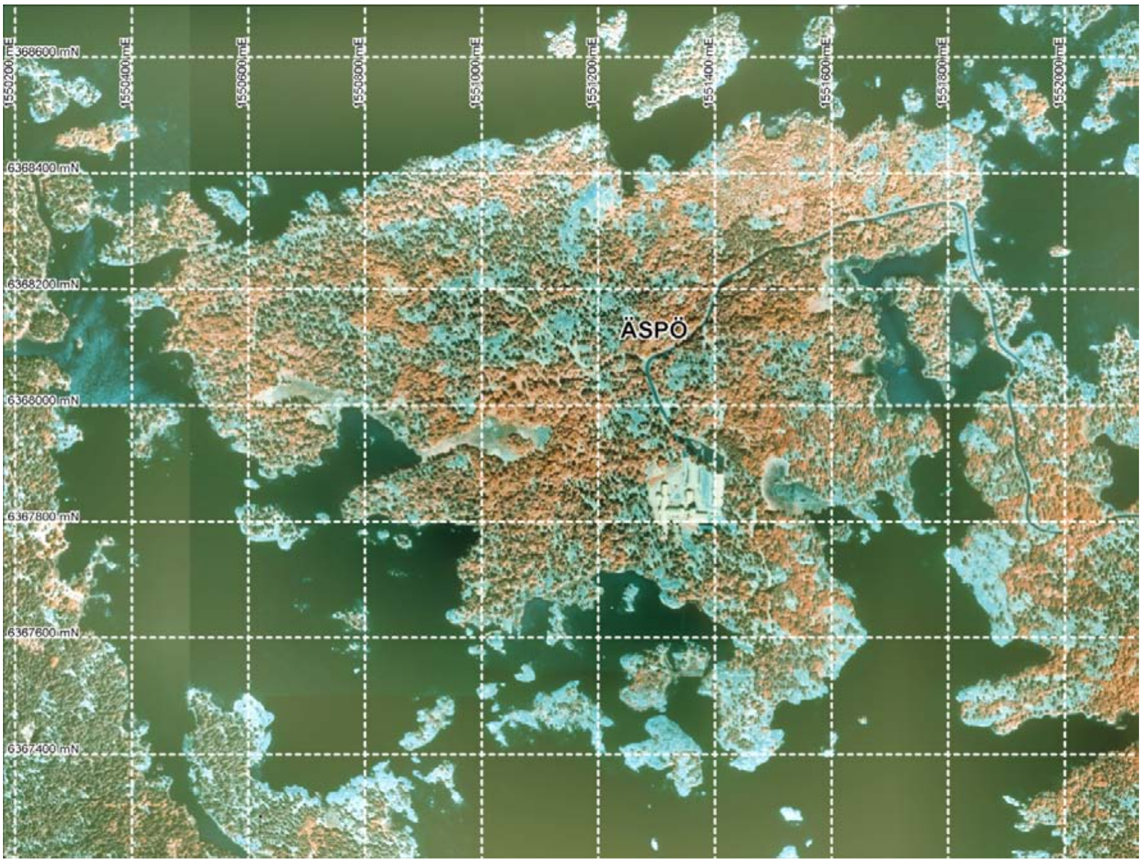


Figure 1-1. General overview over the island of Äspö from aerial photo, © Lantmäteriet.

The ground magnetic and geoelectric data were collected in 1988 as part of the pre-investigations that were carried out before the construction of the Äspö Hard Rock Laboratory (HRL). The data were processed and interpreted by use of the standard techniques at that time and all interpretation products and deliveries were analogue maps. With today's state of the art processing and visualization software it is possible to identify more subtle anomaly patterns and the interpretation products are digital and connected to databases. Now days it is also much easier to make combined interpretations and simultaneously view details in different datasets. This work will present the Äspö data and interpretation products in the same format as corresponding data from the site investigations at Oskarshamn and Forsmark.

Individual interpretations of lineaments in the magnetic, geoelectric and topographic data are presented. The three sets of lineaments were co-ordinated and linked to one single GIS-layer of combined lineaments. The lineaments have mainly been identified as topographic lows, magnetic lows and resistivity lows. All lineaments have an individual id-code and are related to database tables containing information regarding length, orientation and other characteristic properties with reference to /Curtis et al. 2009/.

The interpretation presented in this report is performed by GeoVista AB in accordance with the instructions and guidelines from SKB under supervision of Leif Stenberg.

The data and interpretation products are stored in the database Sicada and are traceable by the activity plan number.

2 Objective and scope

The general aim of lineament identification is to identify linear features in the different datasets. Linear features, or lineaments, can provide important information on the extension of deformation zones in the bedrock. The magnetic susceptibility of rocks is often low in strongly deformed, fractured, altered or porous bedrock due to destruction of ferromagnetic minerals, which forms a basis for magnetic lineament interpretation. Linear topographic lows can indicate depressions in the bedrock related to brittle deformation zones along which the bedrock is more easily eroded by ice e.g. glaciers due to the decreased mechanical strength. The electric resistivity of rocks is closely related to the porosity and also to the mineralogy. Increased fracture frequency and/or clay alteration significantly decreases the electric resistivity of rocks. Hence, the work presented in this report forms a basis for the interpretation and deterministic modelling of deformation zones at Äspö.

The specific aim of this work is to identify lineaments in detailed ground magnetic, geoelectric and topographic data collected on the island of Äspö. The lineaments are co-ordinated and combined into so called linked lineaments. The lineaments, in particular the linked lineaments, are important data sets and a prerequisite for the deterministic modelling of deformation zones.

3 Equipment

3.1 Description of interpretation tools

The processing, interpretation and reporting included the use of the following specialized software:

Profile Analyst Professional v. 9.0 (Encom)

Surfer 8 (Golden software)

MapInfo Professional 8 (Pitney Bowes)

Discover 8 (Encom Technology Pty Ltd).

4 Data processing

4.1 Data preparation

All data were acquired from the Sicada database and delivered by SKB via email. The magnetic and geoelectric data were delivered as point data in Microsoft Excel-files and the elevation data were delivered as a grid with 10 m cell size. The point data were measured with reference to the local co-ordinate system ÄSPÖ96. The data were transformed to the system RT90 2.5 gon west, standard, by use of transformation parameters enclosed with the data delivery. The correctness of the transformation procedure was checked by control data points with given co-ordinates in both systems.

4.2 Magnetic data

The magnetic total field data were collected with a proton precession magnetometer and a base station for diurnal corrections. The line spacing is 10 m and point distance is 5 m (Figure 4-1). The survey covers the entire island of Äspö, apart from a few minor areas most likely disturbed by human installations, indicated by the holes in the yellow point cover in Figure 4-1. Some of the minor land tongues were omitted in the survey. No data were collected on water.

There are no comments regarding the data quality, disturbances or problems during the survey, and no potential post processing is discussed. In Figure 4-2 the distribution of the magnetic data is presented in a histogram. The distribution is smooth and lognormal, which is normally expected for high quality data. Profile plots and test gridding also indicates natural variations and there are no indications of outliers or physically unreliable anomalies. Hence, the quality of the magnetic dataset appears to be high.

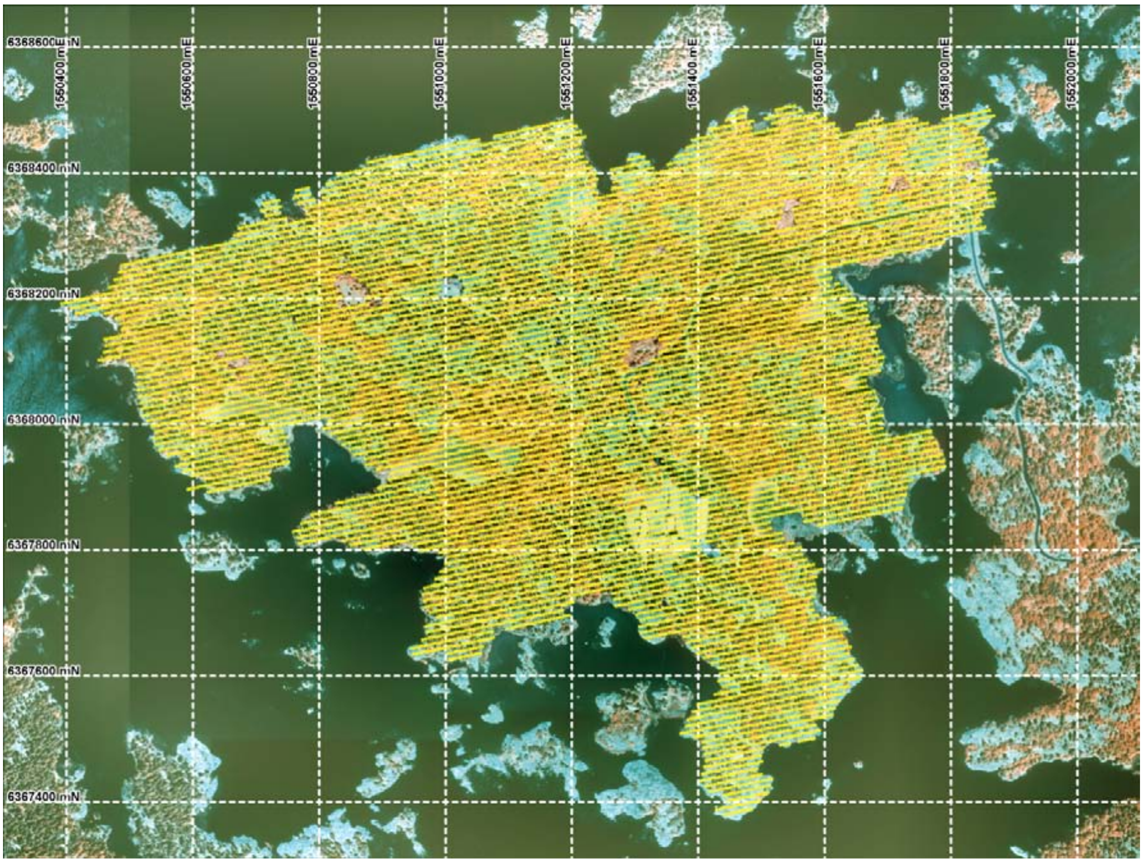


Figure 4-1. Coverage of measurement points for the magnetic total field survey, © Lantmäteriet.

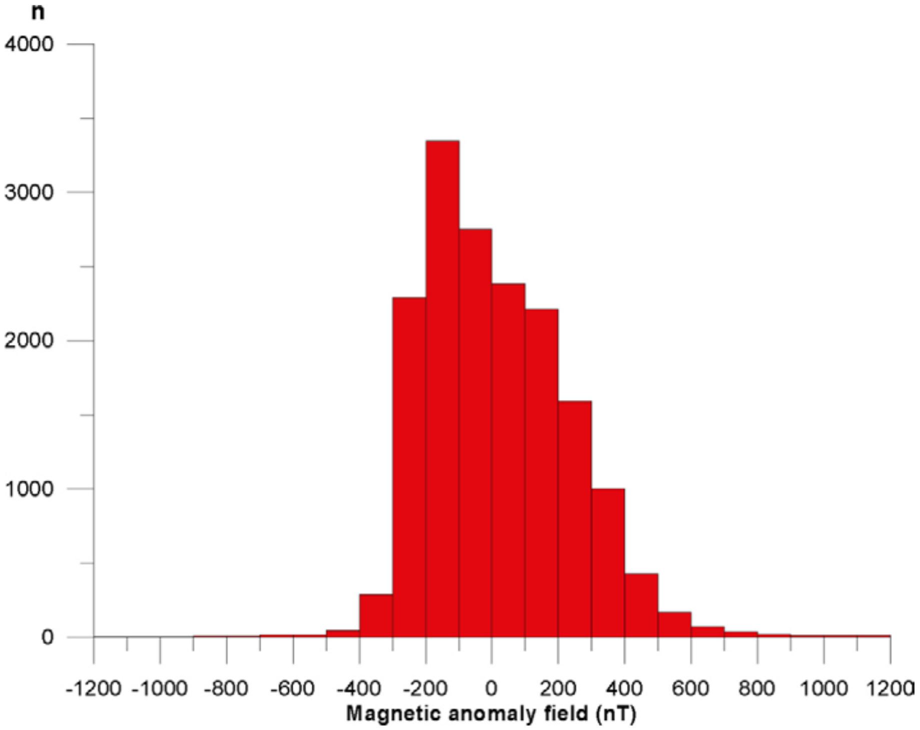


Figure 4-2. *Histogram showing the distribution of the total magnetic anomaly field data.*

4.3 Resistivity data

The resistivity survey was conducted with 5 m point distance and 40 m line spacing. There is no information regarding the type of instrument used. Electrode configuration was dipole-dipole (5-10-5 m), which means one pair of current electrodes (5 m spacing) and one pair of potential electrodes (5 m spacing), with 10 m separation between the adjacent electrodes (see Figure 4-3). This particular electrode configuration is popular for mapping narrow near surface low resistivity targets, such as sub-vertical fracture zones. The location of the resistivity survey profiles are shown in Figure 4-4. As was the case with the magnetic survey there are no comments regarding the data quality of the resistivity data. In Figure 4-5 the distribution of the 10logarithm of the apparent resistivity is shown. The data distribution appears "normal" for resistivity data of crystalline rocks, with a majority of data in the range 1,000–25,000 Ωm. The very low resistivity values (< 100 Ωm) are most likely effects caused by saltwater in wetlands close to the shore and/or clay.

The dipole-dipole electrode configuration is known to be sensitive for narrow, sub-vertical low resistivity zones, but it is also known to produce an anomaly pattern that under some conditions can be difficult to interpret. In order to avoid misinterpretations of the resistivity data, modelling was performed with the software Res2DMod. Resistivity models of low resistivity deformation zones (fracture zones) with different geometrical characteristics were created. Hypothetical "rawdata" of dipole-dipole surveys were created, and these data were then processed and modelled with the interpretation software Res2DInv. One example of a resistivity model of a fracture zone and the corresponding data are presented in Figure 4-6. The model (top of Figure 4-6) consists of three parts, 1 m thick horizontal soil cover, a homogenous high resistivity rock volume and a 10 m wide, vertical, low resistivity zone, centered at distance 56 m. In the lower plot of Figure 4-6 the apparent resistivity distribution from a hypothetical dipole-dipole survey with various electrode distances is presented. Close to the surface there is a significant rectangular shaped low resistivity anomaly (blue colour), centered at the same co-ordinate as the location of the model deformation zone. Below c. 3 m depth the anomaly distribution becomes complex, with two narrow low resistivity zones with a clear dip away from the zone centre. Between these two low resistivity anomalies the resistivity is actually slightly increased.

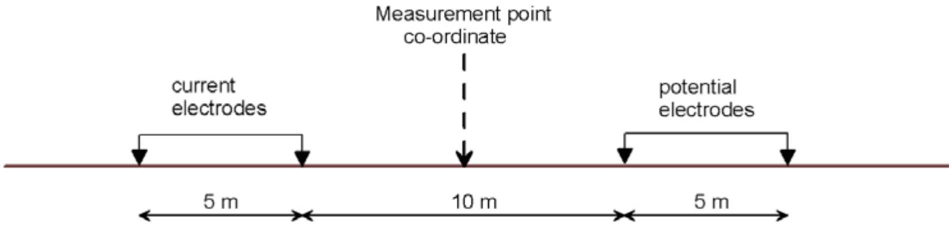


Figure 4-3. *Principle sketch of dipole-dipole electrode configuration.*

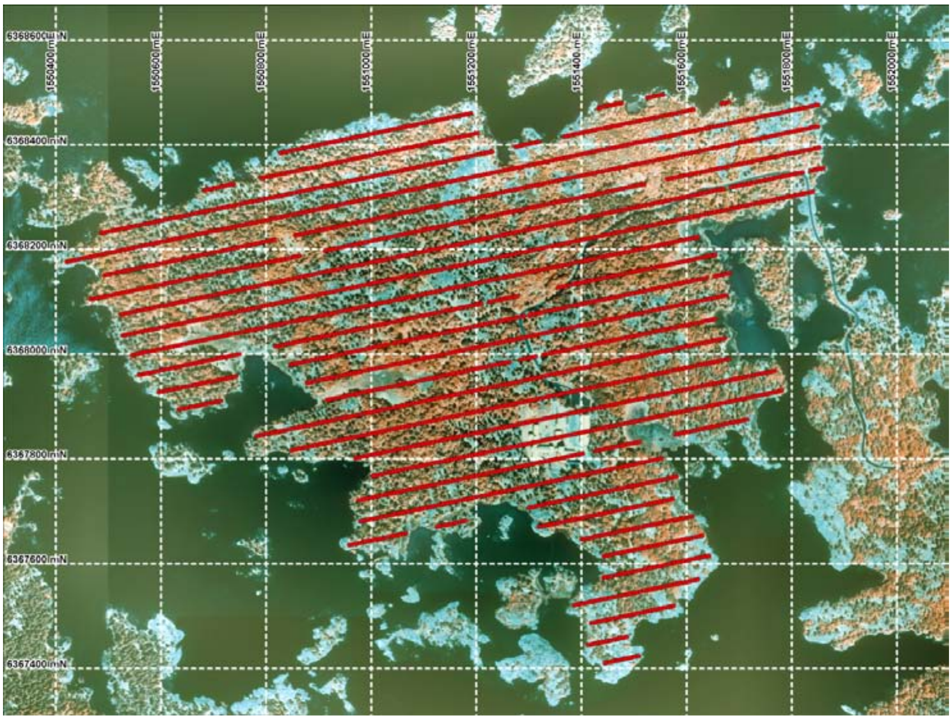


Figure 4-4. *Map showing the location of the resistivity survey profiles as red lines, © Lantmäteriet.*

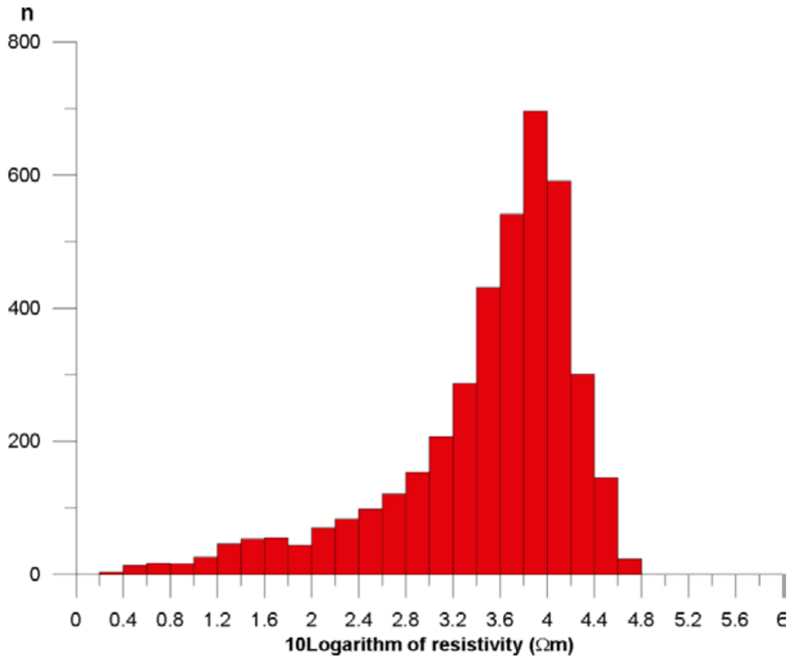


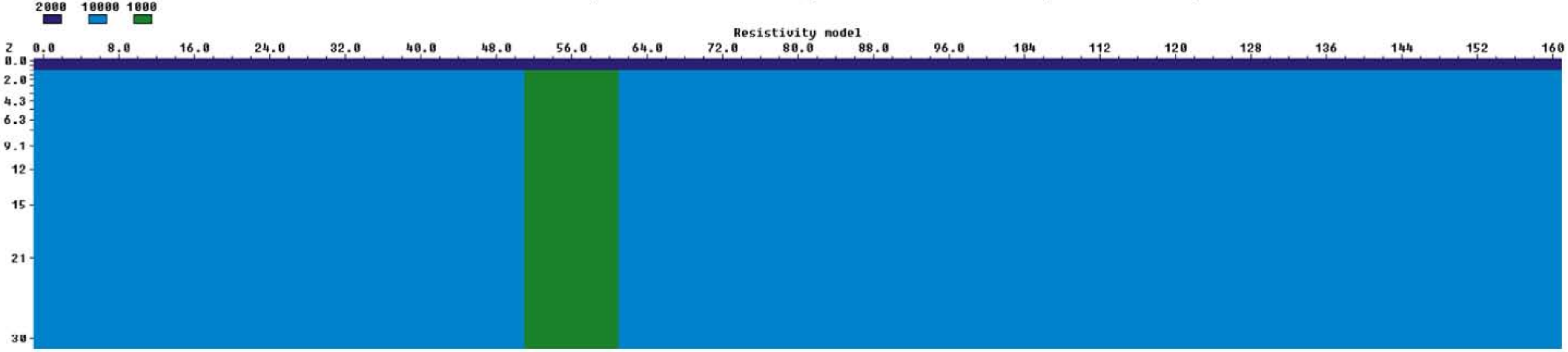
Figure 4-5. *Histogram showing the distribution of the 10logarithm of the apparent resistivity data.*

The 2D section data in Figure 4-6 can be produced since the theoretical survey was performed with different distances between the current and potential electrode pairs (the 10 m distance in Figure 2-3). In the Äspö survey this distance was fixed at 10 m, which means that the resistivity response, in theory, is focused at a certain depth level. This implies that the Äspö data can only be plotted as line diagrams, not 2D pseudo sections. In Figure 4-7 line diagrams are presented for various types of deformation zone geometries and also for some different dipole-dipole electrode configurations. In the figure it is evident that only for large distances between the two dipoles the complexity of the anomaly pattern becomes significant (e.g. grey full line). From all six examples the anomaly is detectable and located at its correct position. However it is worth noting that for 5 of the 6 examples the intact bedrock resistivity of 10,000 Ωm is clearly underestimated, which is an effect by the low resistivity soil cover.

4.4 Topographic data

The topographicdata (digital elevation model) were delivered as an adf-grid with square 10 m sized cells. The grid was converted to Golden Software Surfer format. A coloured map of the elevation model of Äspö and its surroundings is presented in Figure 4-8. The contour of the island perimeter is fairly easy to identify and it is also possible to identify significant topographical variations such as valleys and heights. However, it is also clear that the model is impaired by some significant artefacts, such as the north-south trending step-like anomaly in the water south of the island in the central part of the figure. Tests were performed with different enhancement filters and in the filter products north-sound trending stripes, that are clear artefacts, occur. Some tests were made to reduce the artificial anomalies (low pass, median and average filtering) but the blurring effects of these filters were considered too high. The interpretation of the elevation model was performed on the original grid and on a vertical derivative of the grid, without any other filtering applied.

2D section of resistivity model of 10 m wide, vertical fracture zone (1 m soil cover)



2D section of Dipole-Dipole resistivity tomography measurement across the model above.

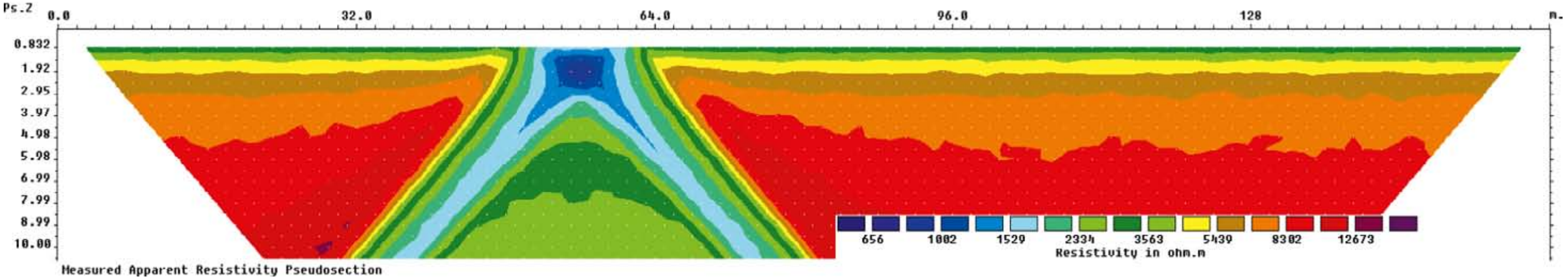


Figure 4-6. *Resistivity model (top figure) of 10 m wide vertical low resistivity deformation zone (green colour) in homogenous high resistivity rock. In the bottom figure data from a theoretical dipole-dipole resistivity tomography survey across the model above are shown as a 2D pseudo section colour diagram.*

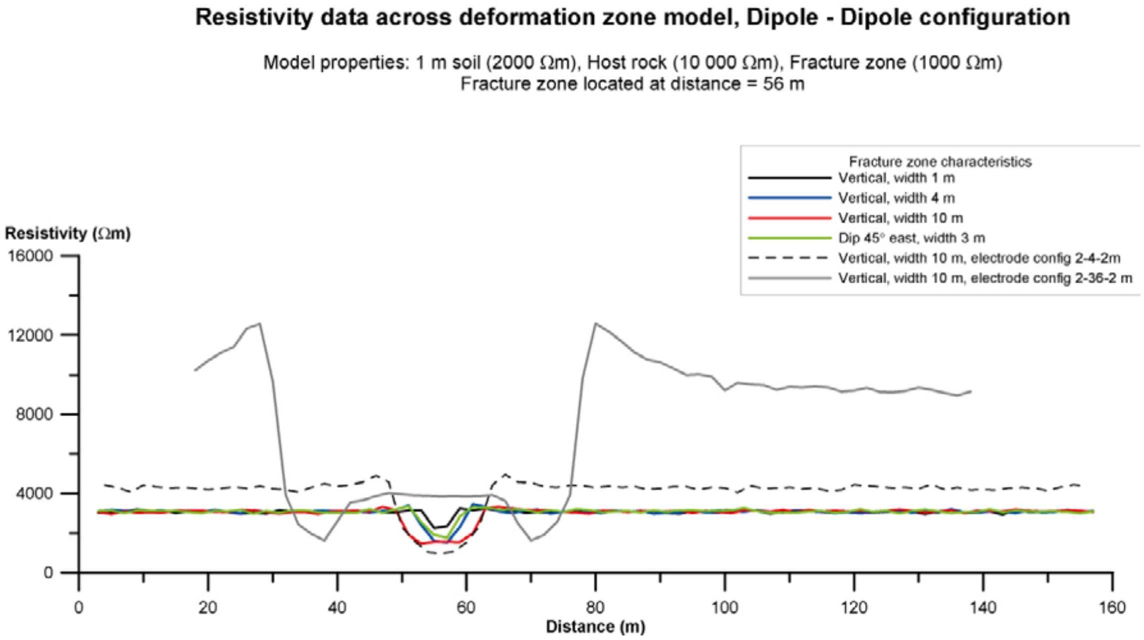


Figure 4-7. *Theoretical apparent resistivity curves for different types of low resistivity zone (fracture zone) models and different dipole-dipole configurations.*

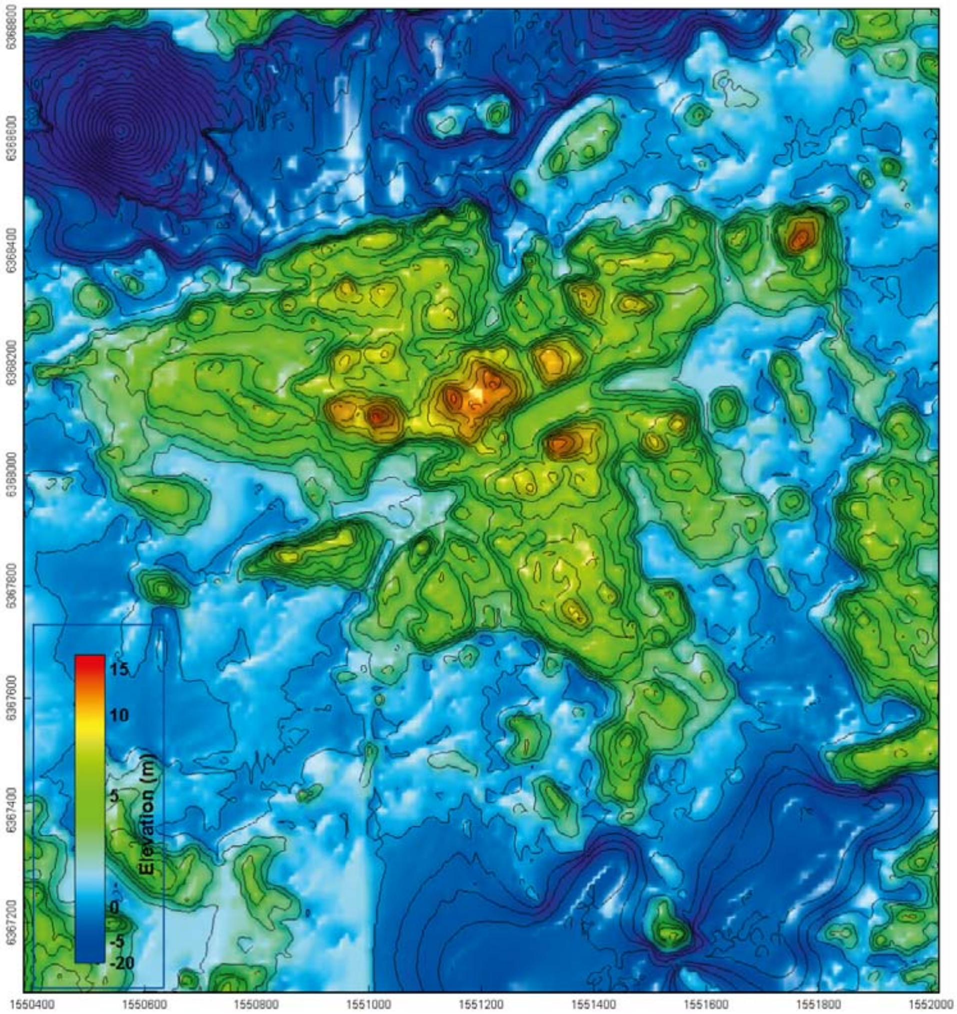


Figure 4-8. *Coloured map showing the elevation model of Äspö and surroundings (10 m grid). Black lines show elevation contours, interval 1 m.*

5 Identification of lineaments

The identification of lineaments follows the same procedure as the interpretation work during the site investigations at Forsmark and Oskarshamn, see e.g. /Mattsson and Triumf 2007/. Individual, method specific, interpretations were performed separately for the magnetic, geoelectric and topographic data sets. Each lineament was assigned attribute data according to specifications listed in Table 5-1. The general cutoff length of lineaments is 100 m. The method specific lineaments were combined to one set of first co-ordinated and then linked lineaments (see chapter 5-4).

Table 5-1. Attribute table for the identified lineaments. The table is based on Table 4-2 in /Isaksson et al. 2007/.

Field name	Name	Description	Further comments on attributes used to describe lineaments
Id_t	Identity	Identity of a lineament.	All lineaments are given separate identities, "M" for magnetic, "R" for resistivity, "T" for topography, followed by "AS" for Äspö, then "10" for year 2010 and finally by individual numbers, starting with 0001.
Origin_t	Origin	Major type of basic data.	Basic data used. Magnetic, resistivity or topography.
Class_t	Classification	Classification of a lineament.	Regional (>10 km), local major (1-10 km) and local minor (<1 km).
Method_t	Method	The type of data in which the lineament is observed.	Magnetic, resistivity or topography.
Weight_n	Weight	A combination of uncertainty and number of properties (methods). An overall assessment of the confidence of the lineament. This assessment is based on both the number of properties upon which the lineament has been identified and the degree of uncertainty.	Only used for the linked lineaments.
Char_t	Character	Character of the lineament in letters	Characteristics of the anomaly representing the lineament, like minima, edge, minima connection, dislocation, or characteristics of the lineament itself.
Char_n	Character	Character of the lineament translated into an integer.	0 = minima connection, 1 = minima, 2 = edge, 3 = dislocation.
Uncert_t	Uncertainty	Gradation of the lineament in terms of uncertainty. In effect, this attribute involves both the degree of clarity of the lineament as well as a judgement regarding the possible cause of the lineament	1 = low, 2 = medium, 3 = high.
Comment_t	Comment	Specific comments regarding the lineament	
Process_t	Processing	Data processing performed	Grid, image analysis, GIS
Date_t	Date	Date for the identification	Date
Scale_t	Scale	Scale of the image used in the identification	1:5000
Width_t	Width	Width on average	Not assigned.
Precis_t	Precision	Spatial uncertainty of position. An estimate of how well the lineament is defined in horizontal position.	Not assigned.
Count_n	Count	The number of original segments along the lineament.	
Cond_n	Conductivity	Shows how much of the lineament that has been identified in resistivity data.	
Magn_n	Magnetic	Shows how much of the lineament that has been identified in magnetic data	
Topo_n	Topography	Shows how much of the lineament that has been identified in topography data.	
Topog_n	Ground surface	Shows how much of the lineament that has been identified by topography in the ground surface.	Not used
Topor_n	Rock surface	Shows how much of the lineament that has been identified by topography in the bedrock surface.	Not used.
Prop_n	Property	Shows in average, how many properties (complementary investigation methods) that have been identifying the lineament.	
Length_n	Length	The length of the lineament	In metres.
Direct_n	Direction	The average trend of the lineament.	In degrees.
Platform_t	Platform	Measuring platform for basic data.	Ground survey grid.
Sign_t	Signature	Work performed by.	Håkan Mattsson GeoVista performed all method specific interpretations. Coordination and linking was performed in co-operation between Håkan Mattsson, GeoVista and Carl-Henric Wahlgren, SGU.

5.1 Magnetic lineaments and the magnetic anomaly pattern

In Figure 5-1 a coloured map of the total magnetic anomaly field is presented. Based on the magnetic field properties Äspö can roughly be separated into three areas. In the northwestern and southeastern parts of the island the magnetic pattern shows dominant occurrences of fairly smooth positive anomalies of magnitude 200–500 nT that are traversed by narrow low magnetic linear features. The central part of the island is intersected by a c. 200–300 m wide, northeast-southwest trending low magnetic belt. The magnetic anomaly field of the low magnetic belt has amplitudes in the range –200 to –500 nT, which is in significant contrast to the northwestern and southeastern parts of the Äspö island. It is clear that the bedrock in the low magnetic belt has a lower content of ferromagnetic minerals (e.g. magnetite), or different magnetic mineralogy, compared with the two other areas.

The bedrock of Äspö is dominated by Äspö diorite but Ävrö granodiorite also occur. In addition, there are occurrences of fine-grained granite (occurs as dykes and bodies of irregular shape), gabbroid-dioritoid rocks and pegmatite. Petrophysical measurements on core samples from KAS02 show that unaltered Äspö diorite has geometric mean susceptibility of 0.015 SI (20 samples) and altered/deformed Äspö diorite has geometric mean susceptibility of 0.006 SI (17 samples). Unaltered Ävrö granodiorite shows a similar magnetization as the Äspö diorite, with a geometric mean susceptibility of 0.017 SI (27 samples). There are too few samples of altered Ävrö granodiorite to allow a statistical evaluation.

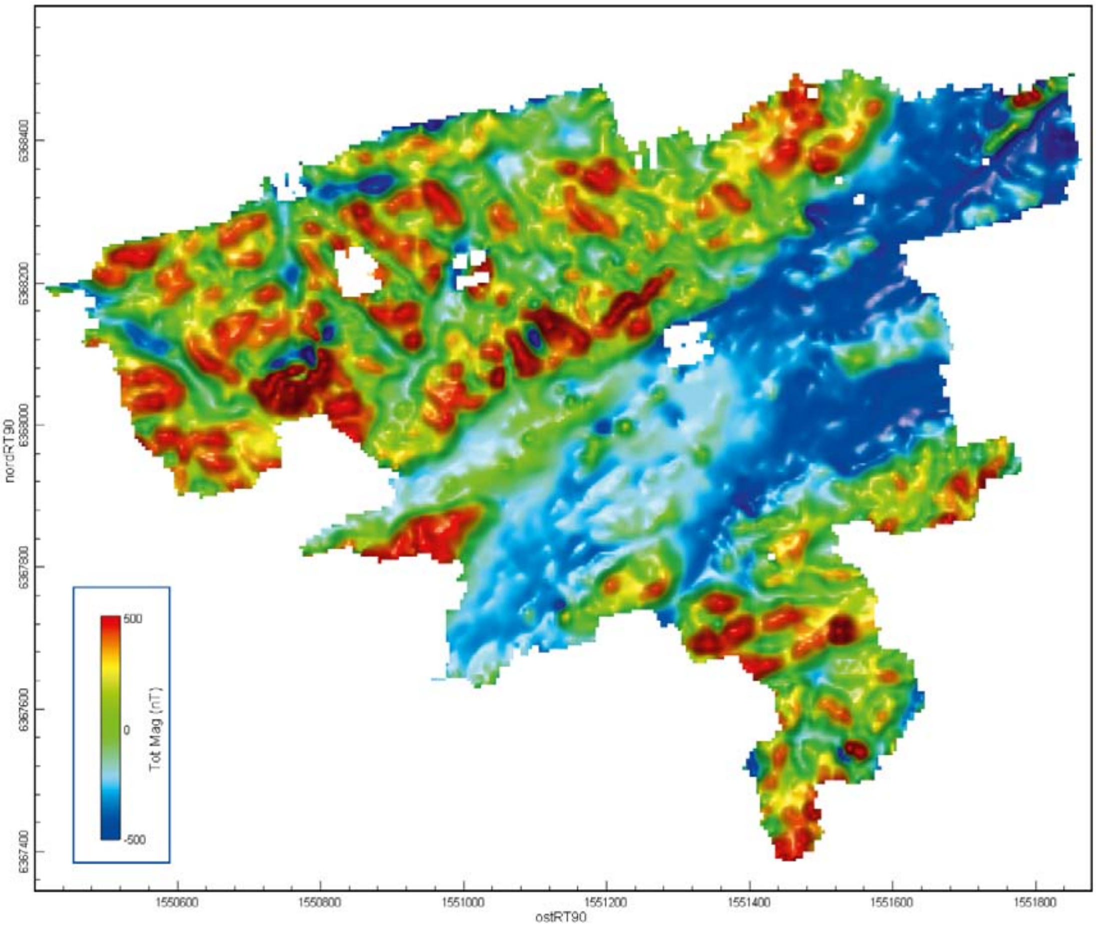


Figure 5-1. Coloured map showing the total magnetic anomaly field.

The petrophysical data indicate that a majority of the Äspö diorite and Ävrö granodiorite in the northeast-southwest trending low magnetic belt across the central part of Äspö, have suffered from alteration and/or deformation. The alteration/deformation has significantly reduced the magnetization of these rocks, most likely either by destruction of magnetite or oxidation of magnetite to hematite. Also the low magnetic lineaments in the two areas with increased magnetization are, in most cases, inferred to reflect deformation zones and/or alteration. However, some of these may also be caused by dykes of fine-grained granite, a rock type which is known to carry only minor amounts of ferromagnetic minerals. In KAS02 the geometric mean susceptibility of the fine-grained granite is 0.006 SI (16 samples).

In order to increase the possibility to identify magnetic lineaments the so called tilt derivative (TDR) of the magnetic field was created /Verduzco et al. 2004/. The TDR can be compared with an automatic gain control, which normalizes the magnetic field image and enhances subtle anomalies. As a complement, the zero crossing of the TDR is close to the edge of the structure, so by applying a threshold of 0.0 and plotting the "zero-contour" it is possible to isolate all bodies with a positive susceptibility contrast. The TDR of the magnetic data from Äspö is presented in Figure 5-2.

When comparing the total magnetic anomaly field (Figure 5-1) with the TDR (Figure 5-2) there is a significant increase in contrast, especially in the northeast-southwest trending low magnetic belt. In the TDR anomaly map it is possible to identify several distinct lineaments that are very difficult to detect in the map of the total magnetic anomaly field.

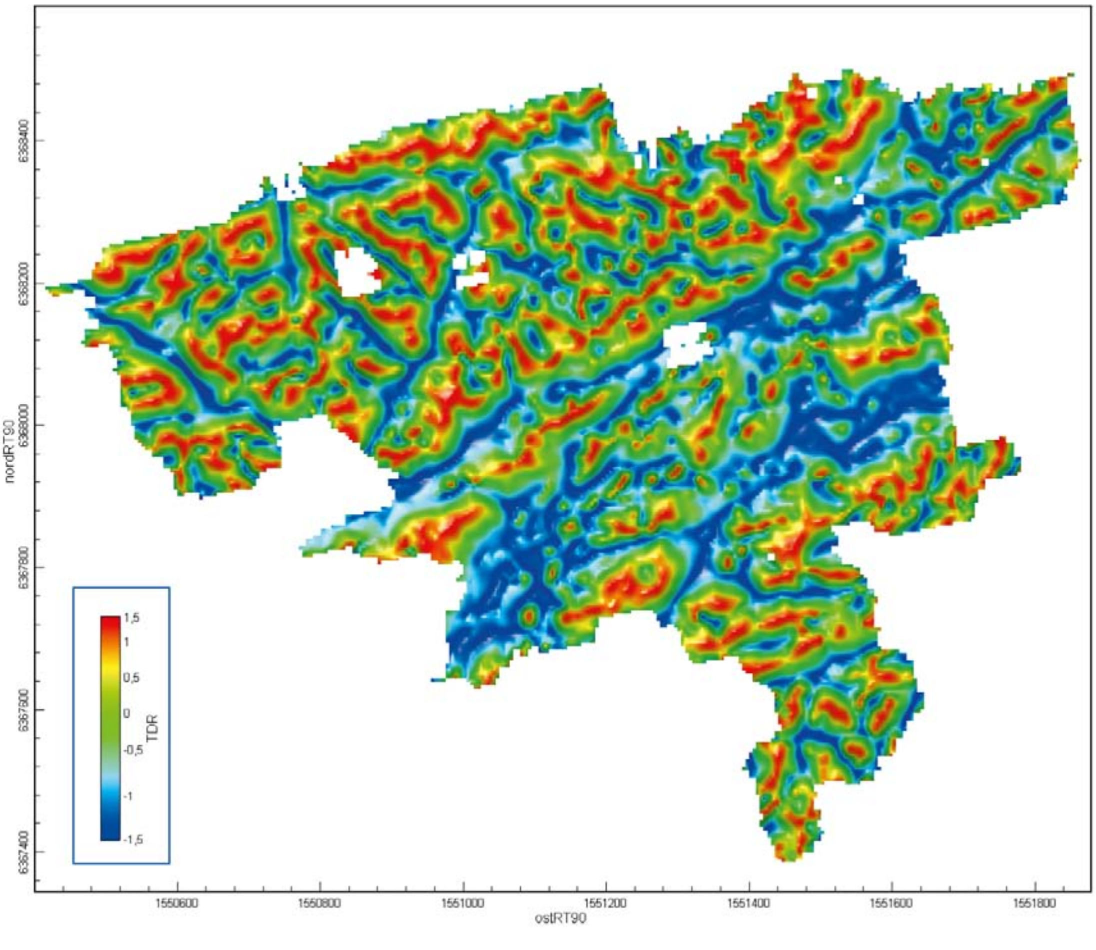


Figure 5-2. *Coloured map showing the tilt derivative (TDR) of the total magnetic anomaly field.*

The identification of magnetic lineaments is presented in Figure 5-3 in which the zero contour of the TDR is shown as yellow lines. Bodies with positive susceptibility contrast are shown in red, the green colour indicates partly decreased magnetization and blue colour indicates significantly decreased magnetization. A total of 103 magnetic lineaments were identified. Mean length is 193 m (range 46–560 m). A few lineaments shorter than the cutoff length of 100 m were included, since they were regarded as clear and distinct. However, they are given a lower confidence.

There is a clear dominance of northeast-southwest (c. N55°E) trending lineaments (Figure 5-4). The second most prominent orientation is c. N45°W, and there is also a fair amount of NNE-SSW oriented lineaments. The boundaries of the low magnetic area have an orientation of c. N60°E and within this area the northeast trending lineaments are orientated at c. N40°E. This structural configuration may reflect a relation between shear surfaces (C) striking N60°E and shear bands (C´) striking N40°E. If so, it may indicate that the low magnetic belt constitutes a sinistral shear belt and that many of the northeast-southwest trending lineaments primarily are related to ductile deformation.

The northwest-southeast oriented lineaments seem to cross-cut the northeast-southwest structural pattern, which could suggest that the northwest-southeast oriented lineaments represent deformation zones dominated by brittle deformation, possibly overprinting original ductile structures.

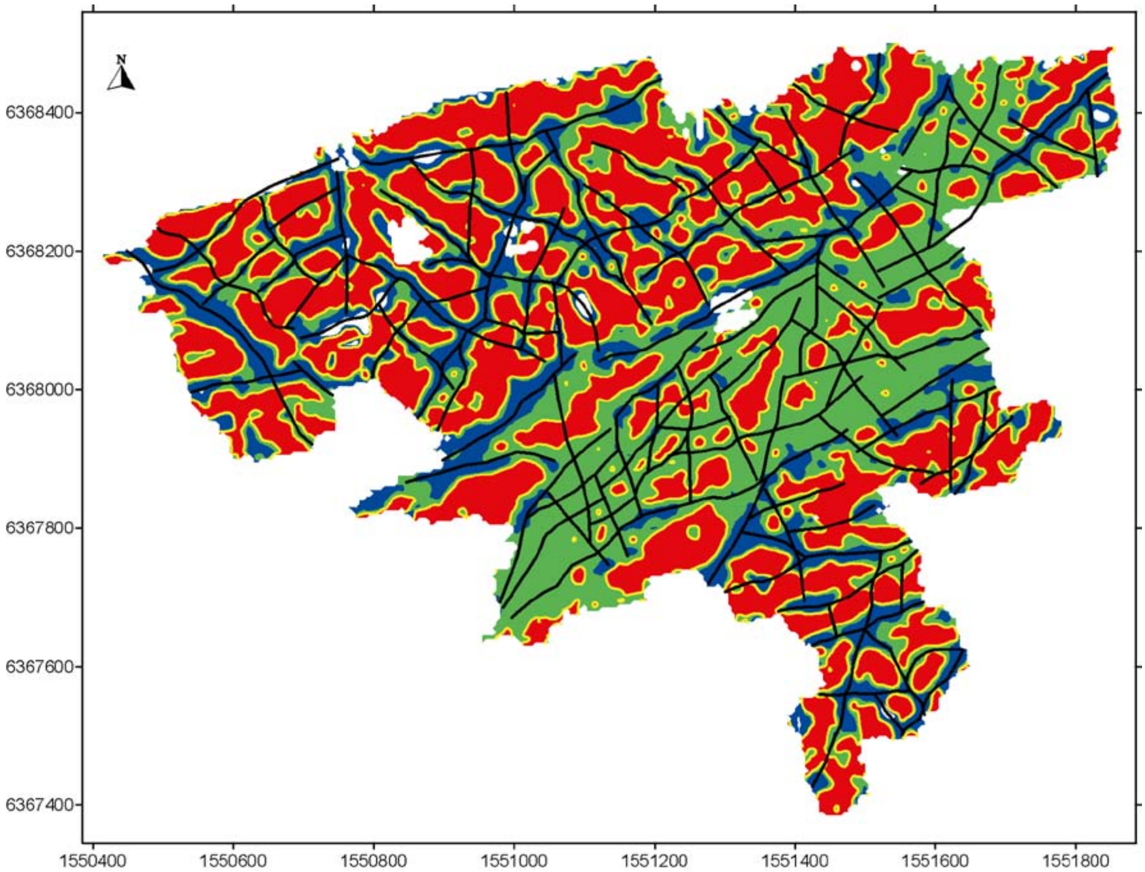


Figure 5-3. Coloured contour map showing magnetic lineaments (black lines) in a combined plot of the tilt derivative (TDR) and the vertical derivative of the total magnetic anomaly field. The yellow lines show the TDR zero contour line, and the red areas indicate bodies with a positive magnetic susceptibility contrast.

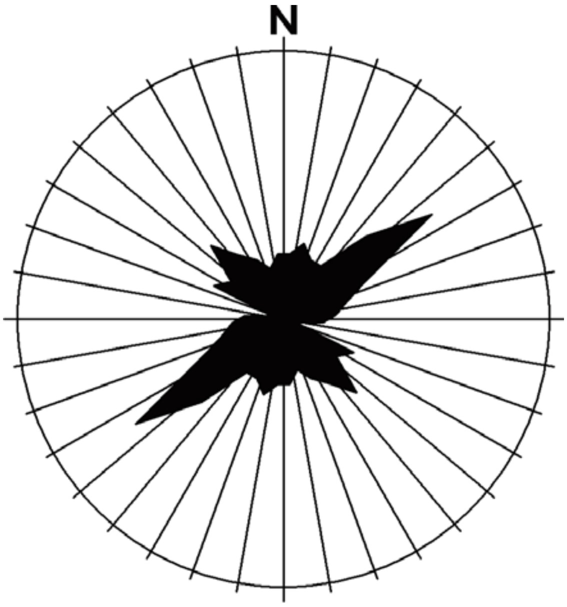


Figure 5-4. Rose diagram (bidirectional) showing magnetic lineament orientations.

5.2 Resistivity lineaments

A coloured map of interpolated apparent electric resistivity is shown in Figure 5-5 together with elevation contours. The data resolution is clearly poorer compared with the magnetic data, mainly due to the four times larger line spacing used in the geoelectric survey. The main information achieved from the gridded map in Figure 5-5 is the possibility to locate larger areas of significantly decreased resistivity (dark blue areas). There is a clear spatial relation between larger areas of significantly decreased resistivity and valleys or lowlands close to the waterside. The major cause of these anomalies is most likely an effect by saline sea water occurring in the shallow sediments. In more elevated areas the resistivity is generally higher. However, also in valleys and other topographic lows inlands, away from the waterside, there is a clear tendency of decreased resistivity. These anomalies may very well be related to brittle deformation zones and/or areas (rock volumes) characterized by increased fracturing.

The lineament interpretation of the resistivity data is mainly based on profile information, and uses the possibility of connecting low resistivity anomalies between closely located profiles. The elevation model was used in the background to serve as guidance for probable orientations. The ENE-WSW trending survey lines strongly favors north-south to northwest-southeast oriented structures and makes it more difficult to identify linear low resistivity anomalies that are sub-parallel to the survey lines. The interpreted lineaments are presented in Figure 5-6 on top of coloured profiles of the apparent resistivity. The identification of lineaments is not only done with reference to the amplitude of the resistivity anomaly but also to the resistivity contrast between the anomaly and the surrounding data, and also with respect to anomaly shape.

A total of 55 resistivity lineaments were identified and there is a fairly even spatial distribution of the lineaments across the island of Äspö. A majority of the lineaments have northeast-southwest trending orientation (Figure 5-7). These are mainly located in the central part of Äspö, overlapping the low magnetic belt discussed in chapter 5-1. There is also a fairly large number of NNW-SSE and northwest-southeast oriented lineaments. Some of the more extensive lineaments are interpreted to intersect the low resistivity anomalies at low angles, which would present a reasonable explanation to the long wavelength of these anomalies. However, many of these are, as mentioned before, located in lowlands close to the waterside, and may thus be influenced by saline water. All resistivity lineaments have been assigned moderate, or lower, confidence in order to indicate that their orientation is generally difficult to determine.

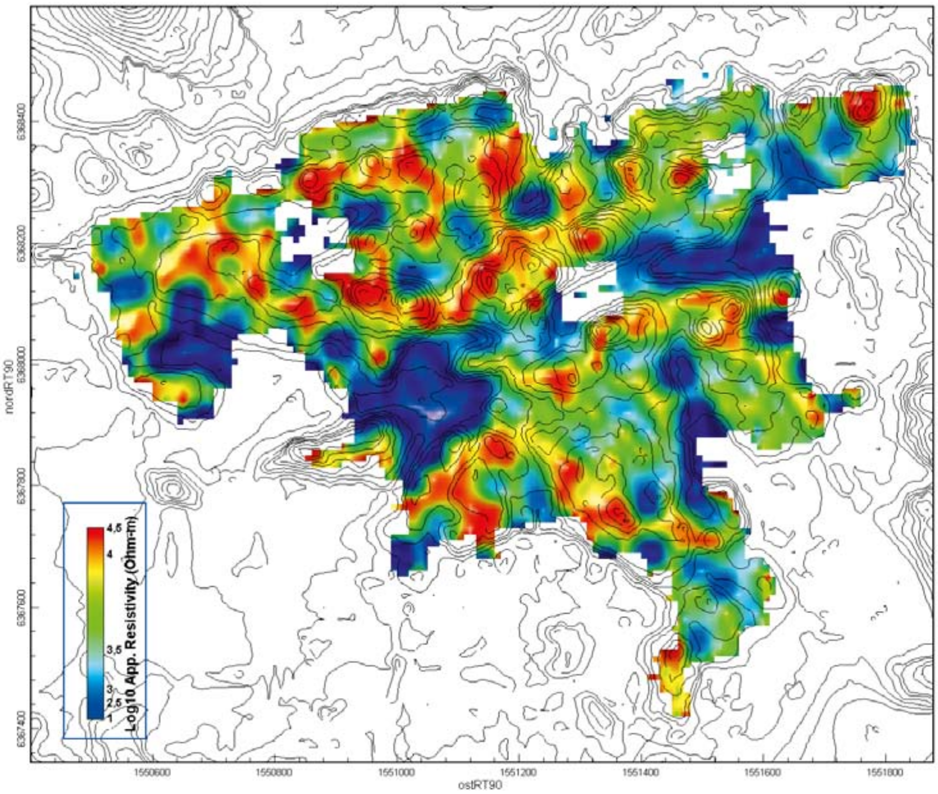


Figure 5-5. *Coloured map of 10-logarithm of apparent resistivity. Elevation contours are indicated by black lines.*

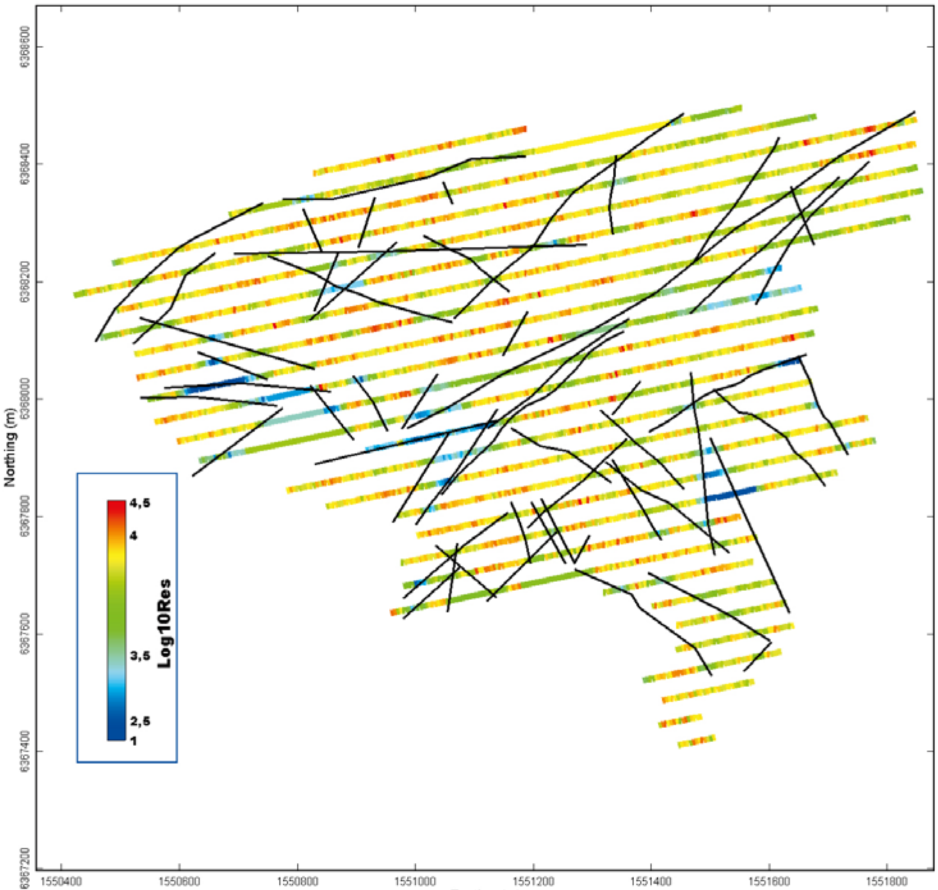


Figure 5-6. *Lineaments interpreted from resistivity data (black lines) and coloured profiles of the apparent resistivity.*

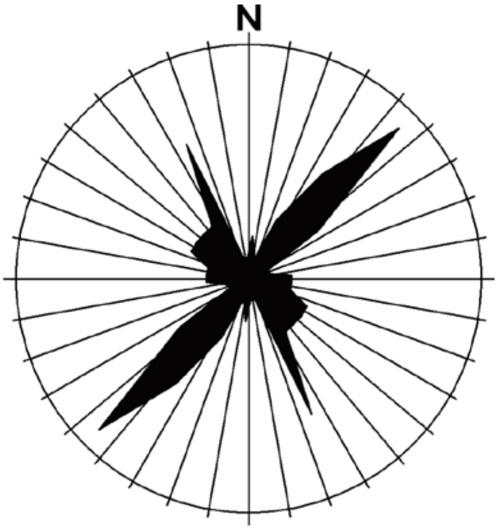


Figure 5-7. Rose diagram (bidirectional) showing resistivity lineament orientations.

5.3 Topographic lineaments

The identification of topographic lineaments is based on interpretation of the elevation grid (unaltered data) and the vertical derivative of the elevation grid, with support from aerial photos (Figure 5-8). The topographic lineaments are interpreted from linear valleys and topographic lows. A total of 85 topographic lineaments were identified. The majority have an orientation of c. N50°E, i.e. very similar to the magnetic and resistivity lineaments (Figure 5-9). There are also NNW-SSE and northwest-southeast oriented topographic lineaments. In the central part of Äspö, in the belt of decreased magnetization, the elevation model partly constitutes more of a widespread lowland area than a well defined linear feature. A few other topographic low areas are also characterized by an irregular shape and do not show the clear linearity expected from a single distinct lineament. These areas are shown in grey colour in Figure 5-8. The grey areas may very well be related to deformation zones, and the reason for their irregular shape can, for example, be explained by a zone with varying fracture frequency, shallow dipping zones, or crossings between two or more deformation zones.

5.4 Lineament co-ordination and linking

The process of co-ordinating and linking lineaments was performed in co-operation between Håkan Mattsson (GeoVista AB) and Carl-Henric Wahlgren (Geological Survey of Sweden). The co-ordination of lineaments is a process of combining the method specific lineaments (magnetic, geoelectric and topographic) into one single lineament. This single lineament is called a co-ordinated lineament. In the process of co-ordinating lineaments the first step is to construct such co-ordinated lineaments and then to assign attributes to the lineament. The attributes indicates in what kind of data the co-ordinated lineament was visible, the judged level of uncertainty in the visibility etc. The list of parameters describing every co-ordinated lineament is given in Table 5-1. Since the data resolution varies between the different datasets, the certainty in positioning of lineaments varies markedly. It was therefore decided that the magnetic lineaments were ruling when positioning the coordinated lineaments. If no magnetic lineament was included in the co-ordinated lineaments the topographic lineament was used to determine the position. The linking of lineaments means linking of several co-ordinated lineaments, which are interpreted to form a geometrically continuous structure along its strike, to one single continuous linked lineament. It is also possible that a linked lineament corresponds to a co-ordinated lineament.

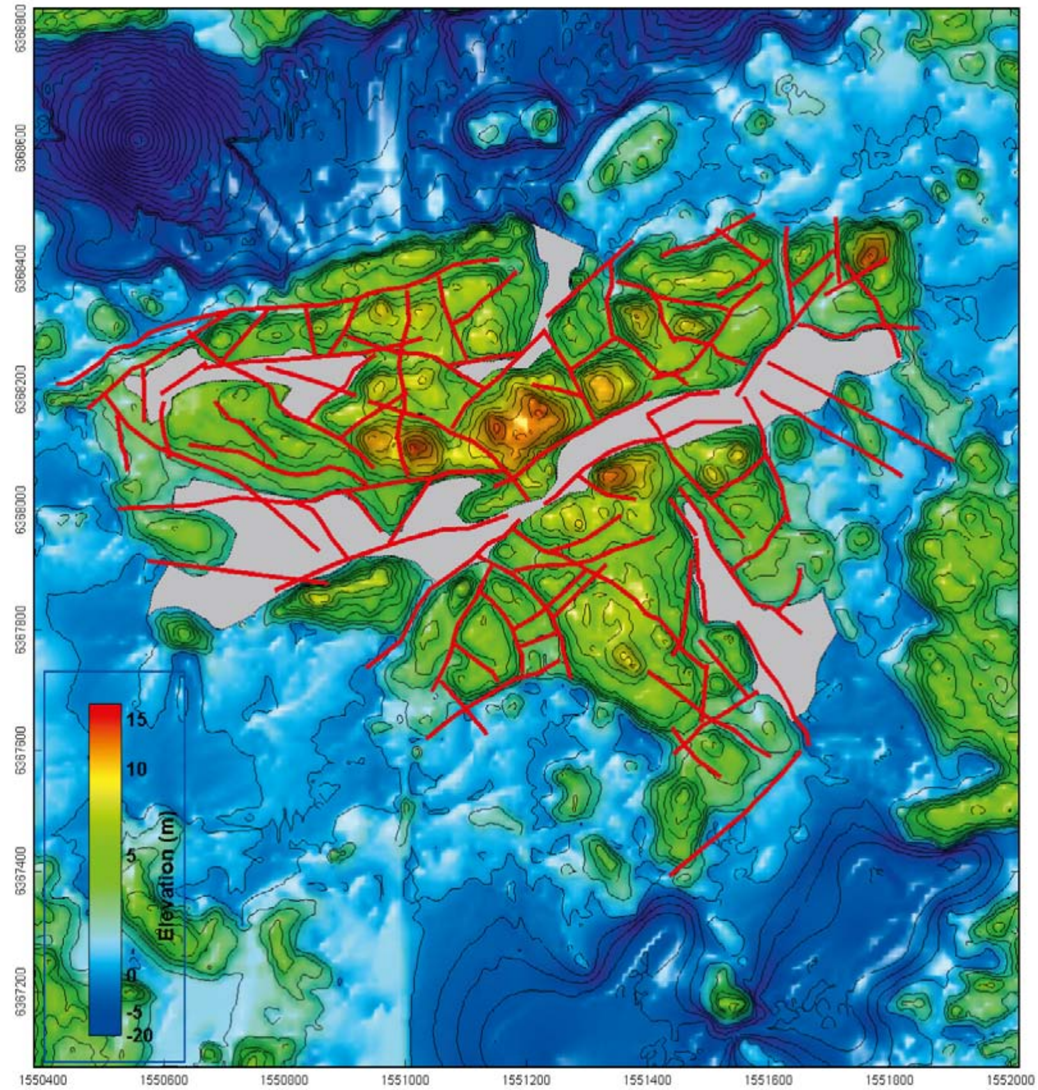


Figure 5-8. Coloured map showing the digital elevation model of Äspö with elevation contours shown as thin black lines and topographic lineaments shown as red lines. Grey coloured areas indicate topographic lows without distinct linear shape.

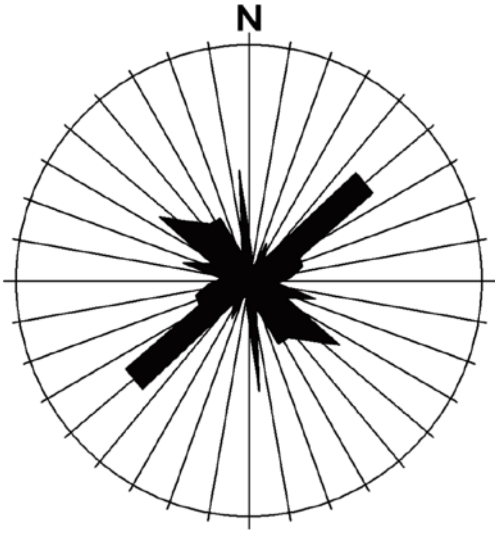


Figure 5-9. *Rose diagram (bidirectional) showing topographic lineament orientations.*

In Figure 5-10 all method specific lineaments are displayed in one single plot; magnetic lineaments as black lines, topographic as red and resistivity as green. There is a clear spatial and directional correlation between the three sets of lineaments. Some lineaments follow each other along fairly long distances and in some cases there is only partial overlap. It is very rare that lineaments interpreted from different data sets follow each other exactly, which is most likely a combination of data resolution and actual variations in physical properties of deformation zones.

The linking process resulted in a total of 37 linked lineaments (Figure 5-11). Average length is 346 m (range 59–1,108 m). It is evident from Figure 5-11 that the majority of the lineaments have northeast-southwest or northwest-southeast trending orientations. The lineaments are in many cases interpreted to constitute fairly well defined boundaries that separate bodies with positive susceptibility contrasts, as indicated by the red TDR zero contour lines. In the rose diagram in Figure 5-12 there is also a third group of lineaments with orientation c. NNE-SSW.

5.5 Uncertainties

The interpretation work of the various data sets and the identification of method specific lineaments, as well as the subsequent co-ordination and linking process are based on expert judgments and thereby subjective to a certain extent. The lineaments are graded in low, medium and high uncertainty basically with respect to the clarity in which they appear. However, also some other specific uncertainties can be pointed out regarding the lineaments and their character. Differences in the physical properties in the bedrock, as well as within and along a possible deformation zone, give different opportunities to identify lineaments. A higher magnetic and homogenous rock unit makes it easier while an inhomogeneous or low magnetic rock unit will make it harder to identify magnetic lineaments.

Differences in thickness of the overburden also give different conditions for lineament identification. Large areas with a thin overburden, which is the general case on the island of Äspö, give a better spatial and dynamic resolution of the magnetic pattern and hence, lineaments are more easily identified. Horizontal to sub-horizontal structures are more difficult to identify, and when they occur they often appear as curved features following the topography.

The ENE-WSW direction of the magnetic and geoelectric surveys makes it easier to identify structures with NNW-SSE orientation. However, for the magnetic data this effect is most likely negligible because of the rather small difference between the line spacing and point distance.

When linking two co-ordinated lineaments, there is in some cases more than one way of doing it. How the linking is made will also have a major influence on the final length of the linked lineament. Several lineaments are not terminated, but have an open end at the interpretation boundary. This is, for example, very likely the case for the group of northeast-southwest trending lineaments that crosscut the central part of Äspö in a low magnetic region. Consequently these lineaments are only given a minimum length.

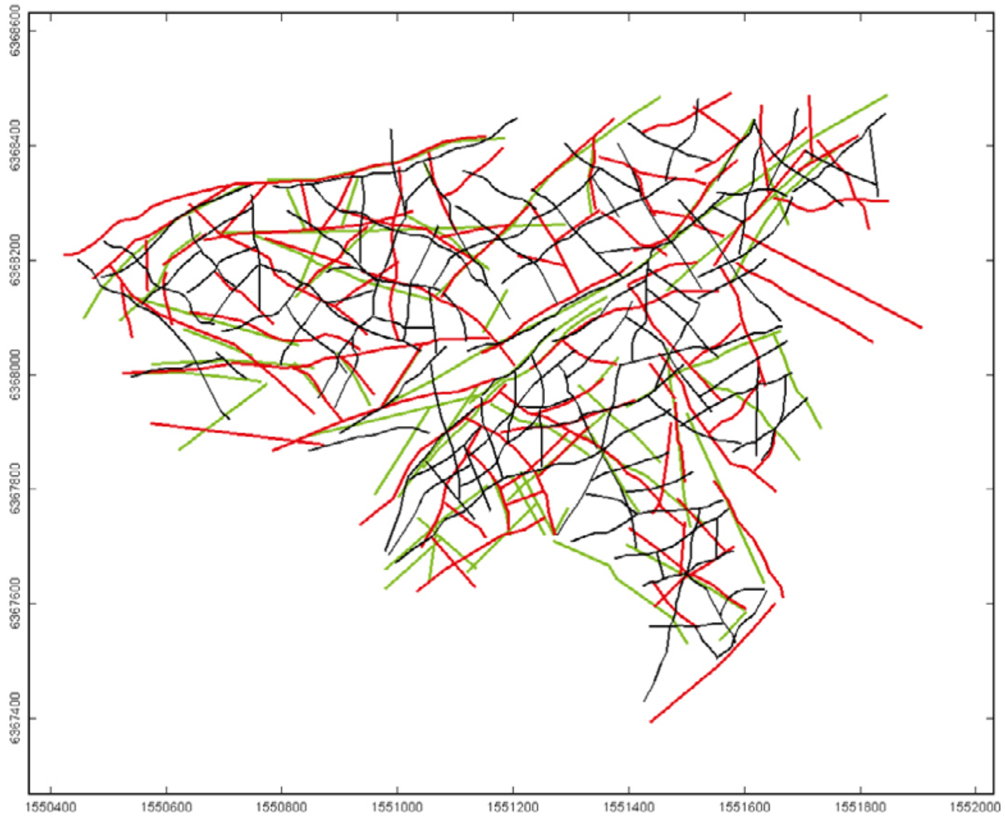


Figure 5-10. *All method specific lineaments that are identified on the island of Äspö; magnetic (black lines), topographic (red lines) and resistivity (green lines).*

Figure 5-11. *Linked lineaments (black lines) plotted together with zero contour lines of the TDR.*

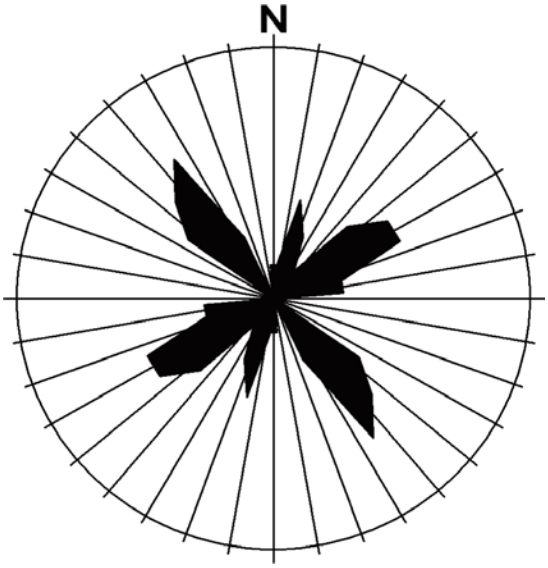


Figure 5-12. *Rose diagram (bidirectional) showing linked lineament orientations.*

6 Discussion and conclusions

The magnetic and resistivity data processed and interpreted within the scope of this work show high quality; there are few outliers, physically reliable ranges, smooth and natural anomalies. The topography grid is partly affected by noise or erroneous data that, for example, appears as distinct straight north-south trending lines in the maps. However, the artifacts have not had significant effect on the interpretation of the elevation data.

A total of 103 magnetic lineaments, 55 resistivity (geoelectric) lineaments and 85 topographic lineaments were identified. The coordination and linking procedure resulted in 37 lineaments. Average length of the coordinated lineaments is 346 m (range 59–1,108 m). The lengths should be regarded as minimum lengths, since the area of investigation is quite restricted and one can clearly see in regional views of the topographic data that some of the coordinated lineaments continue for several kilometers on the mainland.

The results of the lineament interpretations based on the three sets of data show a great deal of consensus; in location as well as in orientation of the lineaments. A large part of the lineaments have northeast-southwest orientation and are located in a low magnetic belt trending northeast-southwest across the central part of the Äspö island. It is likely that the low magnetic belt constitutes part of a c. 200–250 m wide shear belt, generally known as the Äspö shear zone /SKB 2004/. The dominant rock types are Äspö diorite and Ävrö granodiorite, and these are known to carry fair amounts of ferromagnetic minerals /Mattsson et al. 2004/, so the significant decrease in magnetization most likely reflects alteration and/or destruction of magnetite, which is often related to deformational processes. The shear zone interpretation is also supported by the partly decreased resistivity within the zone, which indicates increased fracturing and/or increased occurrences of clay minerals, and also by the spatial distribution of topographic lows. The boundaries of the low magnetic belt have an orientation of c. N60°E and within the belt the northeast trending magnetic lineaments are orientated at c. N40°E. This structural pattern may indicate a sinistral so-called C-C´relationship, i.e. a relation between the master shear orientation (C) and shear bands (C´), which is known to develop in low grade shear zones.

Within the areas northwest and southeast of the indicated shear belt there are several distinct lineaments. The majority of them have northeast-southwest or northwest-southeast trending orientations. In the magnetic data it is obvious that many of the lineaments define boundaries between bodies with positive magnetic susceptibility contrast; hence a possible explanation is that the lineaments constitute deformation zones within blocks of more well preserved Äspö diorite or Ävrö granodiorite. We can, however, not exclude the possibility that some lineaments are related to dykes of, for example, fine-grained granite.

7 Delivered data

With this report the following data were delivered:

- Magnetic lineaments
- Resistivity lineaments
- Topographic lineaments
- Linked lineaments
- Areas of topographic lows
- Magnetic total field grid
- Tilt derivative (TDR) of the magnetic total field
- Grid of the apparent electric resistivity
- All report figures

8 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Curtis P, Petersson J, Triumf C-A, Isaksson H, 2009. Deformation zone modelling. Model version 0.1. Site investigation SFR. SKB P-09-48, Svensk Kärnbränslehantering AB.

Isaksson H, Thunehed H, Pitkänen T, Keisu M, 2007. Forsmark site investigation. Detailed ground magnetic survey and lineament interpretation in the Forsmark area, 2006–2007. SKB R-07-62, Svensk Kärnbränslehantering AB.

Mattsson H, Thunehed H, Triumf C-A, 2004. Oskarshamn site investigation. Compilation of petrophysical data from rock samples and in situ gamma-ray spectrometry measurements. Stage 2 – 2004 (including 2002). SKB P-04-294, Svensk Kärnbränslehantering AB.

Mattsson H, Triumf C-A, 2007. Oskarshamn site investigation. Detailed ground geophysics at Laxemar, spring 2007. Magnetic total field. SKB P-07-168, Svensk Kärnbränslehantering AB.

SKB, 2004. Preliminary site description Simpevarp area – version 1.1. SKB R-04-25, Svensk Kärnbränslehantering AB.

Verduzco B, Fairhead J D, Green C M, MacKenzie C, 2004. New insights into magnetic derivatives for structural mapping. The Leading Edge, 23, pp 116–119.