R-07-62

Forsmark site investigation

Detailed ground magnetic survey and lineament interpretation in the Forsmark area, 2006–2007

Hans Isaksson, Hans Thunehed,
Timo Pitkänen, Mikael Keisu
GeoVista AB

December 2007

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 250, SE-101 24 Stockholm
Tel +46 8 459 84 00

ISSN 1402-3091
SKB Rapport R-07-62

Forsmark site investigation

Detailed ground magnetic survey and lineament interpretation in the Forsmark area, 2006–2007

Hans Isaksson, Hans Thunehed,
Timo Pitkänen, Mikael Keisu
GeoVista AB

December 2007

Keywords: Geophysics, Geology, Magnetometry, Lineament, Deformation zone, Marine, Seaborne, Forsmark, AP PF 400-06-034, AP PF 400-05-082.

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

A pdf version of this document can be downloaded from www.skb.se.

Abstract

The report presents the execution and the results from detailed ground magnetic measurements carried out on an 11.1 km² area in the Forsmark site investigation area. The main objective of this activity is to determine a detailed ground magnetic representation of the bedrock. The results from previous surveys were encouraging and have led to a broad geophysical programme for investigation of lineaments at Forsmark. This report comprises the results from the second and final phase of the extended survey programme and a compilation and summary of all phases in the programme.

On ground and on lake ice, a grid with parallel lines was staked. Measurements of the magnetic total field were carried out along profiles, perpendicular to the staked lines, with a profile spacing of 10 m and a station spacing of 5 m. Measurements on the ice-covered sea bays were carried out by a two man crew. One crew member walked along the survey lines, carrying a RTK-GPS guiding the other crew member who measured the magnetic total field. No seaborne survey was carried out in the final phase. Previously, using a high accuracy RTK-GPS unit for boat navigation gave a seaborne survey grid of on average 10 m line spacing and 2–3 m station spacing. In total 427,238 magnetic survey stations have been measured and an area of 4.7 km² (42%) has been surveyed from boat. Data processing has included a complex correction for influence from a high-voltage DC-cable (Fenno-Skan) occurring in the Forsmark area.

The magnetic pattern in the survey area can be divided into six main areas with different magnetic character. Along the southwest margin of the survey area the magnetic pattern is intensely banded with rapidly changing low and highly magnetic bands striking southeast-northwest, which to the northeast changes to a gentler, banded pattern of low to moderate magnetic intensity. To the northeast, at the SFR office and along the coastline to the southeast, the pattern is again intensely banded with, southeast-northwest trending, rapidly changing low and highly magnetic bands. These two banded structures probably forms fold limbs of a common fold with a northwest oriented fold axis. The fold is U-shaped and opens to the southeast. Within the fold the magnetic pattern is more varied with gently banded to more irregular patterns and from low to high magnetic intensity. The fold pattern is most prominent in the Asphällsfjärden area but is also repeated recurrently from northwest to the southeast. The area between Bolundsfjärden and the road to drill site DS6 forms the core of the fold structure with a more irregular magnetic pattern. Northeast of the SFR office the pattern is characterised by a broad, southeast-northwest trending magnetic low, coincident with the Singö deformation zone. The low magnetic relief give less information on the structural pattern within this area. Further northeast of this structure and in the area around the SFR underground facilities, the magnetic pattern is less regular and gently folded, indicating a varying and complex folding pattern.

The interpretation of the magnetic data has been directed towards identification of linear features but also a few areas with very low magnetisation and low magnetic relief has been outlined. Destruction of ferromagnetic minerals is a probable cause; however, the origin of these features is uncertain and would require further investigations. Areas with a diffuse magnetic pattern might indicate larger depth to the magnetic source or occurrences of fractured and/or altered bedrock surface.

Narrow, low magnetic linear features occurring concordant with the general bedrock foliation are difficult to determine as related to fracture zones or to rock types with low magnetization. In this work, these linear features are identified as lineaments with a separate character called "minima connections". From all detailed magnetic surveys a total of 1,855 magnetic lineaments have been identified of which 811 are characterized as "minima connections", 380 and 733 magnetic lineaments have a low and high uncertainty, respectively. The lineaments are graded in low, medium and high uncertainty mainly with respect to the clarity in which they appear but also in some cases involving an expert judgement regarding the specific geological situation and considering the possible cause of the lineament.

The magnetic lineaments have been co-ordinated and linked giving a total of 855 linked magnetic lineaments of which 377 are characterized as mainly "minima connections". 2 and 91 linked lineaments are classified as regional and local major lineaments, respectively.

The lineament pattern in the candidate area shows mainly east-northeast, discordant lineaments and northwest trending, mostly minima connections. In the SFR office area the pattern is strongly affected by the Singö deformation zone. Northeast of the zone, around the SFR underground facility, the lineament pattern is less well defined. Recognizing a lineament pattern with mainly north-northeast direction around Asphällsfjärden is an important discovery that previously has been poorly known.

Southwest of Bolundsfjärden, some magnetic anomalies and lineaments of dyke-like character have been identified. The validity and possible origin of these features are not yet known.

It is clear that due to the high resolution, ground magnetic data provides the possibility to identify more and shorter lineaments than the airborne survey data. The detailed magnetic, ground and seaborne survey data give a much better understanding of the local-scale structural framework and distribution of magnetic lineaments. The data also give detailed information on the extension and fragmentation of large scale magnetic lineaments.

The interpretation results are delivered in GIS-format and each lineament has an attribute table attached. The table is the same adapted for linked lineaments in previous work. Besides scrutinizing the lineaments as possible fracture zones the comprehensive attributes table also provide a basis for further statistical analysis.

Several examples of the magnetic survey and processed magnetic data, forming the basis for identifying lineaments are presented in the report.

Sammanfattning

Denna rapport presenterar utförande och resultat av detaljerade, markgeofysiska mätningar utförda med magnetometer i ett 11,1 km² stort mätområde inom Forsmarks kandidatområde. Målsättningen med insatsen är att erhålla en detaljerad bild av berggrundens magnetfält som underlag främst för att bestämma utbredning och kontinuitet av lineament i området. Resultaten från tidigare detaljmätningar har gett goda resultat och utmynnade i ett utvidgat program av detaljmagnetiska mätningar på marken, havsfjärdar och sjöar. Rapporten beskriver resultaten från den sista fasen av programmet men sammanfattar också tidigare faser.

På marken och på sjöisar har linjer stakats ut med ett avstånd av 100 m. Vinkelrätt mot dessa linjer utfördes magnetiska mätningar med 10 meters linjeavstånd och med 5 meters punkttäthet. Magnetisk mätning och inmätning ute på havsfjärdarnas is utfördes av säkerhetsskäl samtidigt av två man. Inga båtmätningar har utförts i sista fasen, i tidigare faser har dock mätningar med ett RTK-GPS baserat system utförts i ett rutnät med ca 10 m linjeavstånd och 2–3 m punktavstånd. Totalt har 427 238 magnetiska mätningar registrerats och en yta på 4,7 km² (42 %) har uppmätts från båt. Bearbetning av data har inkluderat en komplex korrektion för den magnetiska effekten från HVDC-anläggningen Fenno-Skan.

Det magnetiska mönstret i området kan delas in i sex huvudområden. Längst i sydväst är mönstret intensivt bandat med snabbt växlande, låg- till hög-magnetiska band i riktning sydost-nordväst, som mot nordost övergår till ett mjukt bandat magnetiskt mönster och låg-måttlig magnetisk intensitet. Mot nordost, vid SFR och längs kusten mot sydost, är mönstret återigen intensivt bandat med snabbt växlande låg- till hög-magnetiska band. Dessa två strukturer är troligen veckben av ett gemensamt veck med en nordväst orienterad veckaxel.

Veckstrukturen är U-formad och öppen mot sydost. Inom strukturen är det magnetiska mönstret mer varierat med bandat-irreguljärt mönster med låg-hög magnetisk intensitet. Veckmönstret är tydligast vid Asphällsfjärden men återkommer vidare mot sydost. Området mellan Bolundsfjärden och borrplats BP6 utgör kärnan av veckstrukturen med ett dominerande irreguljärt mönster. Nordost om SFR kontoret kännetecknas magnetmönstret av ett brett lågmagnetiskt område med utbredning i sydost-nordväst, vilket sammanfaller med Singö deformationszon. Området har låg magnetisk intensitet och även liten magnetisk kontrast vilket lokalt ger lite information om strukturer i berggrunden. Längre mot nordost vid SFR berglager är det magnetiska mönstret mindre regelbundet och indikerar troligen en mer komplex veckning.

Tolkningen av data har inriktats på att identifiera lineament men också områden med låg magnetisk intensitet och liten kontrast har markerats. Orsaken till sådana områden är oklar och kan behöva ytterligare undersökningar, omvandling av magnetit i berggrunden relaterat till deformation kan vara en orsak. Områden med ett diffust anomalimönster har också markerats eftersom dessa kan indikera större djup till den magnetiska källan och/eller förekomst av uppsprucken och omvandlad bergyta.

Magnetiska lineament har identifierats och dessa har liksom i tidigare arbeten dokumenterats i attributtabeller. Lineamenten karaktäriseras av diskordanta magnetiska minima, kanter och dislokationer samt magnetiska minima parallella med den magnetiska foliationen. Lineamenten uppdelas vidare i låg, måttlig och hög osäkerhet. Totalt har 1 855 lineament identifierats av vilka 811 utgörs av magnetiska minima parallella med bandningen. 380 respektive 733 lineament har en låg respektive hög osäkerhet.

De magnetiska lineamenten har sammanlänkats till totalt 855 länkade lineament av vilka 377 har en karaktär av magnetiska minima parallella med foliationen i berggrunden. 2 lineament har klassificerats som regionala (längd > 10 km) och 91 lineament som lokalt betydande lineament (längd 1–10 km).

Lineamentsmönstret i kandidatområdet visar huvudsakligen på ostnordostliga diskordanta lineament och nordvästliga, minima konnektioner. Vid SFR kontoret är mönstret tydligt påverkat av Singö deformationszon. Mot nordost är riktningarna på lineament inte väldefinierade. Ett mönster med lineament i nordnordostlig riktning, kring Asphällsfjärden, har tidigare inte noterats i sådan omfattning och kan ses som en ny observation som för första gången kommit fram i och med den detaljerade markmagnetiska mätningen.

Sydväst om Bolundsfjärden, har magnetiska anomalier av gånglik karaktär identifierats. Giltigheten av samt det möjliga ursprunget till dessa är dock inte känt.

Det är uppenbart att den högupplösande magnetiska markmätningen möjliggör identifiering av fler och kortare lineament än i tidigare flyggeofysiska arbeten. Detta ger också en bättre förståelse av lineamentsfördelningen och berggrundsstrukturer lokalt liksom utbredning och uppdelning av större lineament i området.

Rapporten innehåller flera exempel på magnetiska data och bearbetningar som utgjort underlag för tolkningsarbetet. Lineamenten levereras i GIS-format som vektorer med en attributtabell. Tabellen kan användas som underlag för att bedöma huruvida lineamenten kan representera en möjlig deformationszon samt vidare som en bas för statistiska analyser.

Contents

1 Introduction

The work presented in this report has been carried out by GeoVista AB in accordance with instructions and guidelines presented by SKB in the method descriptions MD 212.004 for the fieldwork, and MD 120.001 as well as SKB R-03-07 /1/ for the interpretation work.

The document reports the results gained from the detailed, ground geophysical measurements of the magnetic total field in an area of 11.08 km² at Forsmark, which is one of the activities performed within the site investigation at Forsmark. This work was carried out in accordance with the activity plan AP PF 400-06-034. The controlling documents for performing this activity are listed in Table 1-1. Both the activity plan and the method descriptions form SKB's internal controlling documents.

Identification of topographic and airborne geophysical lineaments has been carried out in the site investigations at Forsmark /2, 3, 4, 5, 6/. The lineaments have mainly been identified as magnetic lows, topographic lows and, in some cases, resistivity lows. In several cases, linked lineaments /5/ have been verified as representing deformation zones in the bedrock or have been explained by other grounds /7/.

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 fractured, altered or porous bedrock due to destruction of ferromagnetic minerals. Hence, the work forms a basis for the geological bedrock mapping and the site descriptive models in the Forsmark area /8, 9, 10/.

In a previous study, "Ground magnetic survey and lineament interpretation in an area northwest of Bolundsfjärden", AFM100206 /11/, the purpose was to assess the continuity of the linked lineaments XFM0060A0 and XFM0061A0, which have formed, in part, a basis for the definition of the deformation zones ZFMNE0060 and ZFMNE0061, respectively /8, 9, 10/. The results were encouraging and led to a broader geophysical programme for investigation of lineaments at Forsmark. The report "Detailed ground magnetic survey and lineament interpretation in the Forsmark area – 2006" /12/ reports the results from the first phase of the extended magnetic survey programme.

This report describes the results from the second and final phase of the extended programme but also includes a compilation and summary of all the phases in the programme. The programme has been carried out in separate surveys and areas, described in Figure 1-1 and Table 1-2.

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

Activity plan	Number	Version
Mark- och sjöbaserad magnetometri i Asphällsfjärden och områden NV och NÖ om Bolundsfjärden.	AP PF 400-06-034	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för magnetometri.	SKB MD 212.004	1.0
Metodbeskrivning för lineamentstolkning baserad på topografiska data.	SKB MD 120.001	1.0

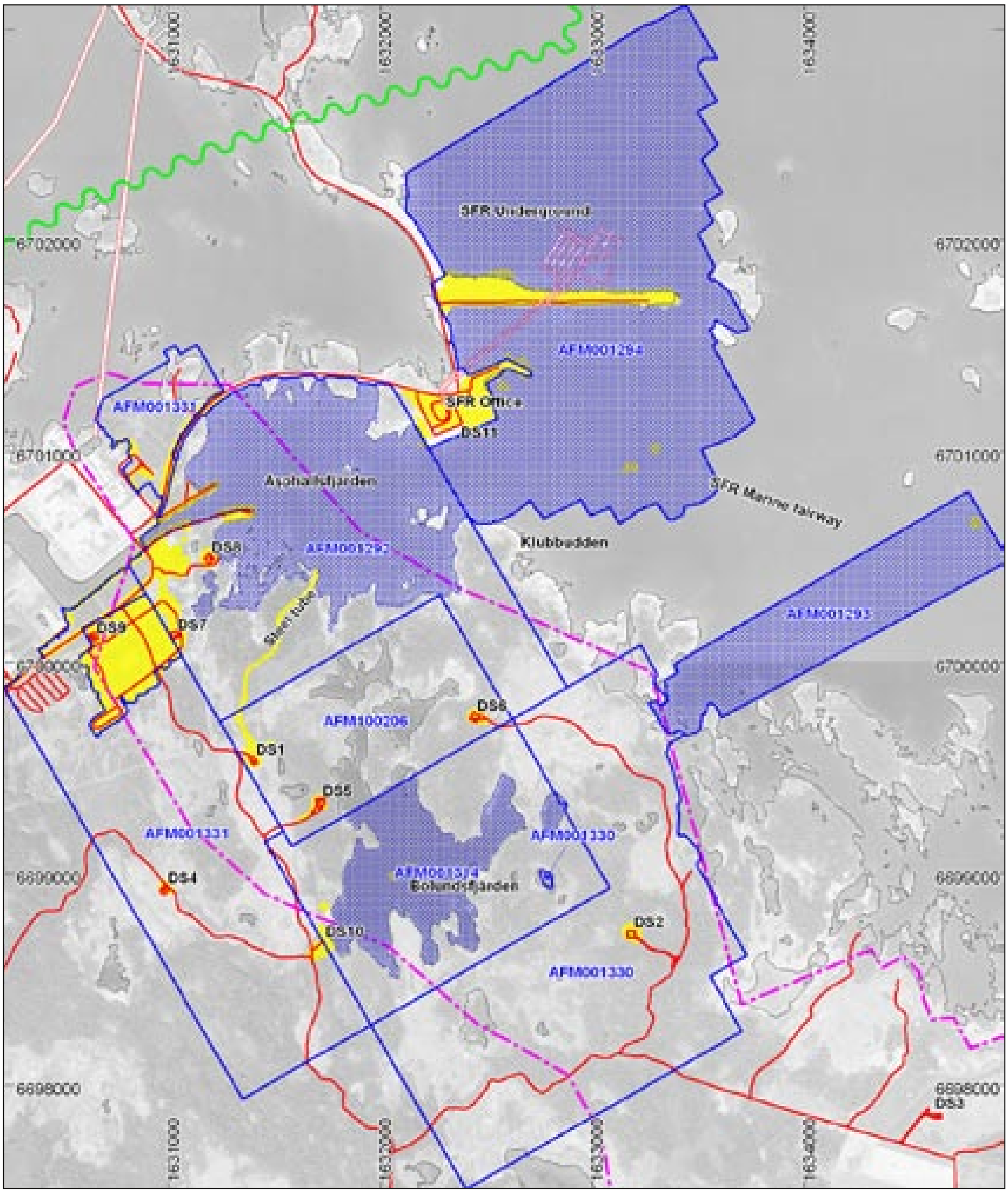

Figure 1-1. Location and extension of all detailed ground magnetic survey areas in blue. Blue dotted areas show the seaborne surveys. Magnetic surveys in phase 2 comprise area AFM001330 and AFM001331. Disturbed areas are shown in yellow. The Fenno-Skan HVDC cable between Sweden and Finland is shown as a green wave-line north of the survey areas. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with red lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, magenta line. Roads and drill sites in red. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.

AFM100206, initial phase

- On land over the suggested deformation zone ZFMNE0060. Surveys on lakes were carried out on ice.

AFM001292, phase 1

- By boat on the sea at Asphällsfjärden and the inlet channel.
- On land, southwest of Asphällsfjärden and northwest of the previous survey AFM100206. The measurements were carried out up to the housing area at Forsmark.
- On land, southeast of Asphällsfjärden and northeast of the previous survey.
- On a narrow land area, northwest of Asphällsfjärden and up to the SFR harbour road.

AFM001293, phase 1

- By boat on the sea, about 2 km southeast of the SFR office and over the suggested deformation zone ZFMNE0062.

AFM001294, phase 1

- By boat on the sea, south, east and north of the SFR harbour area and above the SFR underground facilities. A small, narrow area on a pier above SFR has also been measured on the ground.

AFM001314, phase 1

- By boat and on land on Bolundsfjärden and its surroundings, southwest of the previous survey area AFM100206.

AFM001330, phase 2

- On land, between Bolundsfjärden and the sea and further to the southeast of Bolundsfjärden. The measurements fill the area between AFM001293 and AFM001314 to fully cover the deformation zone ZFMNE0062. Surveys on lakes and sea inlets were carried out on ice. In this phase, a small lake within area AFM001314 was measured on the ice.

AFM001331, phase 2

- On land, southwest of previous surveys AFM100206, AFM001292 and AFM001314. The measurements were carried out up to and around the housing area at Forsmark. Surveys on lakes were carried out on ice.
- A smaller portion of the survey was carried out on the peninsula northeast of Forsmarksverket, reactor I and II and northwest of the SFR harbour road. Surveys on sea inlets were carried out on ice.

The staking of a survey grid as well as the ground and seaborne magnetic measurements were carried out by GeoVista AB in three phases during the periods May 22–June 21, 2006, June 28–July 21, August 7–October 4, 2006 and November 22, 2006–March 8, 2007. The new survey areas cover an area of 3.84 km² and in total 11.08 km² is covered by detailed ground magnetic data, Table 1-2. 42% of the area, or 4.67 km², has been surveyed by boat, Figure 1-1. The previous interpretation /12/ is only carried out on three of the four areas in phase 1. Interpretation of the survey area AFM001294 has been carried out in this second phase.

Table 1-2. Survey areas, coverage and number of survey stations.

AFM	Area [km²]	Stations	Of which, boat survey area [km²]	Phase
AFM100206	0.82	16,297		initial
AFM001292	1.94	104,715	1.06	1
AFM001293	0.60	34,644	0.60	1
AFM001294	2.68	123,882	2.56	1
AFM001314	1.20	70,435	0.44	1
AFM001330	2.01	40,661		2
AFM001331	1.83	36,604		2
Sum:	**11.08**	**427,238**	**4.67**	

This report includes field results from the phase 2 areas; AFM001330 and AFM001331 and the data is stored in the primary data bases (SICADA and GIS) and they are traceable with the help of the activity plan number AP PF 400-06-034. Previous survey data /12/ is traceable by the same activity plan number and by the activity plan number AP PF 400-05-082 for the initial survey /11/.

2 Equipment

2.1 Description of survey equipment and interpretation tools

To establish the grid, a real-time kinematic, RTK-GPS Trimble R8 GNSS Rover system with a built in GPRS (General Packet Radio Service) was used. The SWEPOS national network of permanent reference stations was used as base stations. Every morning, before using the RTK-GPS, a benchmark (PP1202) or another known point was visited to secure the quality of the survey. The co-ordinate system used in this survey was a local grid adapted to the Swedish National Grid RT90 2.5 gon W with the geoid model SWEN 01L. The RTK-GPS was also used for navigation during the magnetic measurement on the ice covered bays and lakes and during boat measurements.

The measurement of the magnetic field was carried out with two to five Gem Systems GSM-19 magnetometers of which one was used as a diurnal base station.

The magnetometers are calibrated at the factory and a quality controlled performance is assured by following the method descriptions and the quality assurance plan of the activity as presented to the client before the survey started.

The magnetic data were affected by the D.C. current in the Fenno-Skan HVDC cable that runs to the north of the survey area. Data from the magnetic observatory at Fiby, supplied by the Geological Survey of Sweden, were used to estimate and to correct for this effect.

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

Trimble Geomatics Office v.1.63

Surfer 8 (Golden software Inc)

Oasis Montaj 5.0 (Geosoft Inc)

Geomatica 10.1 (PCI Geomatics Enterprises Inc)

MapInfo Professional 8.5 (Mapinfo Corp.)

Discover 8 (Encom Technology Pty Ltd)

MathCAD 2001 (MathSoft Engineering & Education, Inc)

Compaq Visual Fortran 6.6 (Compaq Computer Corporation)

3 Measurements and processing

3.1 General

The detailed geophysical survey at Forsmark has consisted of the following main sub activities:

- preparation of grid system,
- measurements of the magnetic total field on ground or on ice,
- measurements of the magnetic total field by boat,
- processing, interpretation and reporting.

On ground and on lake ice, a grid with parallel lines was staked and marked on preferably every 20 metre. Measurements of the magnetic total field were carried out along profiles, perpendicular to the staked lines, with a profile spacing of 10 m and a station spacing of 5 m. Measurements on the ice covered sea bays were carried out by two men, with a RTK-GPS units and a magnetometer, respectively. No seaborne survey was carried out in this phase. However, using a high accuracy RTK-GPS unit for navigation gave a boat survey grid of on average 10 m line spacing and 2–3 m station spacing in previous work.

3.2 Preparation of a grid system

Preparation of the grid system was carried out during four periods; May 22–June 21, 2006, June 28–July 21, August 7–October 4, 2006 and November 22, 2006–March 8, 2007, using a RTK-GPS, a compass and measuring-tape. The RTK-GPS was used to locate and mark as many points as possible along several parallel lines perpendicular to the survey direction and also along lake and sea shore lines and around bogs. Normally, the distance between these lines was 100 m, but due to the large amount of bogs and small lakes some of the lines had to be shifted. With the help of the RTK stations, all of these lines were staked with a marker positioned every 20 metres. All measurements on ice covered sea water surfaces were carried out by a two man crew. One crew member walked along the survey lines, carrying a RTK-GPS, and made a temporary mark on every 25 metre and the other crew member followed and measured magnetic total field.

The origin of the local grid system 0/0 is 1631540 E, 6699200 N in the Swedish grid RT90 2.5 gon W, and the azimuth of the grid is 330°, Figure 1-1. The coverage of the different survey areas as well as the number of magnetic survey stations are listed in Table 1-2.

3.3 Measurements of the magnetic total field

In the final two phases of the magnetic survey, the first period was carried out on Asphällsfjärden during May 22–June 21 2006 with two Gem Systems GSM-19 magnetometers. During June 28–July 21 2006, the second period of the survey, four Gem Systems GSM-19 magnetometers were used. Also the third period, during August 7–October 4 2006, was carried out with four magnetometers. The last period, during November 22, 2006–March 8, 2007, was carried out with three to five magnetometers. In all cases, one of the magnetometers was used as a diurnal base station. At the base station, one reading was registered every 10 seconds and that data was used to make a diurnal correction of the data collected with the mobile magnetometers.

The base station was located close to the survey area to minimize errors due to diurnal variation as well as the influence from the HVDC cable, which runs adjacent to the northern part of area AFM001294, and at most c. 5.5 kilometres to the north of survey area AFM001330 and close to the northern part of area AFM001331. The position of the base station for the first phase of measurements, AFM100206 /11/, was not the same as for the later phase's /12/. The new base station was found to have a base level that is 22 nT (nanoTesla) lower than the previous station. The base level difference between the base magnetometer used in /11/ and the Fiby observatory has been estimated to 311 nT, in the absence of current in the Fenno-Skan cable. As a final step in the processing described below, all data were referenced to the base station of /11/ to enable the creation of data mosaics.

The diurnal base station characteristics for the first survey, AFM100206, are given in /11/ and the second station characteristics are given in /12/. Basic characteristics for the base station are listed in Table 3-1.

One of the roving magnetometers, with a built-in GPS-unit, was time synchronized to "Coordinated Universal Time", called UTC, every morning. Subsequently, the other magnetometers in use were synchronized to the UTC-synchronized instrument.

During the ground surveys, magnetic readings were taken along profiles with a station interval of 5 metres and with a profile spacing of 10 metres. The profiles were directed perpendicular to the staked lines, which means that the survey direction was 330° or 150°. On all stations the surveyor turned so that the magnetometer sensor was oriented in the same direction. The maximum deviation from the nominal survey lines is estimated to be no more than 2 to 3 metres and the deviation from nominal station positions is estimated to be no more than one metre along the line.

The seaborne surveys, Figure 1-1, were carried out using a magnetometer with a built-in GPS-unit set to "walking" mode, Figure 3-1. Measurements were made along nominal profiles in the same direction as the for the land surveys. The final positions for the survey stations were taken from the RTK-GPS, except in a few cases when the RTK signal was lost. Magnetometry readings were taken every 2 seconds and RTK-GPS readings every second. The RTK-GPS was also used to navigate along the nominal survey lines. An example demonstrating how the field crew managed to keep the instrument along nominal lines can be seen in Figure 3-2. In general, the deviation from the nominal survey lines during boat measurements is within 3 to 4 metres. The accuracy of the final magnetometer positions is estimated to be better than ± 1 metre, except for the few point where the RTK signal was lost during surveying where the absolute position accuracy is estimated to be within ± 5 metres and a relative position better than ± 5 m.

Table 3-1. Magnetic base station, basic characteristics.

Characteristics	First base /11/	Second base /12/
Co-ordinates, local grid.	200E/86S	78W/811N
Co-ordinates, local grid.	1631756.2E/6699225.5N	1631072.1E/6699866.3N
Median, total intensity (without HVDC correction).	51,353 nT	51,310 nT
Median, total intensity (HVDC correction applied).	51,390 nT	51,385 nT
Calculated total intensity /13/ (2006-07-01).		51,330 nT
Calculated inclination /13/.		73.2°
Calculated declination /13/.		4.5°

***Figure 3-1.** Magnetic seaborne survey on Asphällsfjärden using a small boat. The magnetic sensor is placed on a wooden frame in front of the boat, underneath the RTK-GPS-antenna. Photo: Alf Sevastik.*

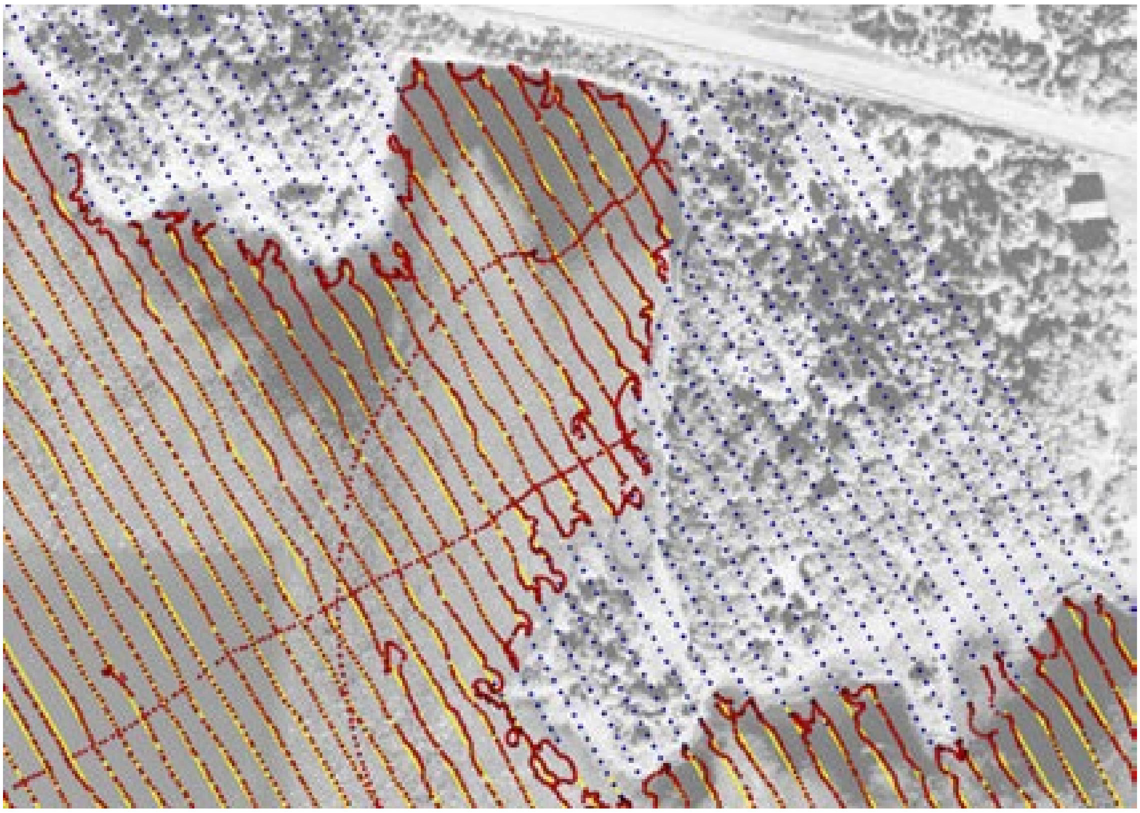

***Figure 3-2.** Survey station distribution on land (blue dots) and on water (red dots), in an area immediately west of the SFR office. The yellow lines show the nominal line location on water. The survey line running perpendicular is a tie-line. Line spacing is 10 m, station spacing on land 5 m. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

3.4 Data processing

3.4.1 Corrections for the Fenno-Skan HVDC cable

The data recorded by the local base magnetometer was compared with data from the Fiby magnetic observatory outside Uppsala. The Fiby data indicated that no major magnetic activity occurred during the survey periods. Magnetic activity with short wave-numbers (< 2 to 3 hours) might be of different magnitude at Fiby compared to Forsmark due to the distance (c. 75 km) between the places. It is estimated that the errors in diurnal corrections due to the use of base magnetometer data from a distant location are within ± 10 nT during these survey periods, and for the large majority of data, the errors are much smaller than that.

The current in the Fenno-Skan HVDC (high-voltage direct current) cable produces a magnetic field that decreases the total magnetic field at the base magnetometer stations at Forsmark, Figure 3-3. The current in the cable is often fairly stable but might change rapidly when the power transmission changes. This can create changes in the total magnetic field in the survey area of up to several hundred nT. Figure 3-3 shows magnetometer data for the two base magnetometers at Forsmark and magnetic observatory data from Fiby. The curves in the figure are parallel, except for sudden level changes in the Forsmark stations due to changes in current in the HVDC cable. The second base magnetometer station is closer to the HVDC cable and is therefore more affected. The gentle diurnal variations seen in Figure 3-3 are more or less identical at the three stations.

The total magnetic field due to a unit current in the HVDC cable was calculated for all survey stations and for the base magnetometer station with the help of Biot-Savart's law. The effect due to elevation was neglected since the area is quite flat. The deflection of the magnetic field vector and electromagnetic effects were also neglected, i.e. assuming a linear relationship between the change in magnetic field at a survey point and the current magnitude in the cable. The current variations in the cable were thereafter estimated with the help of the difference between Fiby and Forsmark base magnetometer readings. The corresponding magnetic field due to the cable was subtracted from the readings at the survey stations, using UTC to link data. The magnetic total field anomaly was thereafter found by subtracting the base magnetometer readings corrected for the effect of the cable. The final product, used to produce the maps below, is thus the

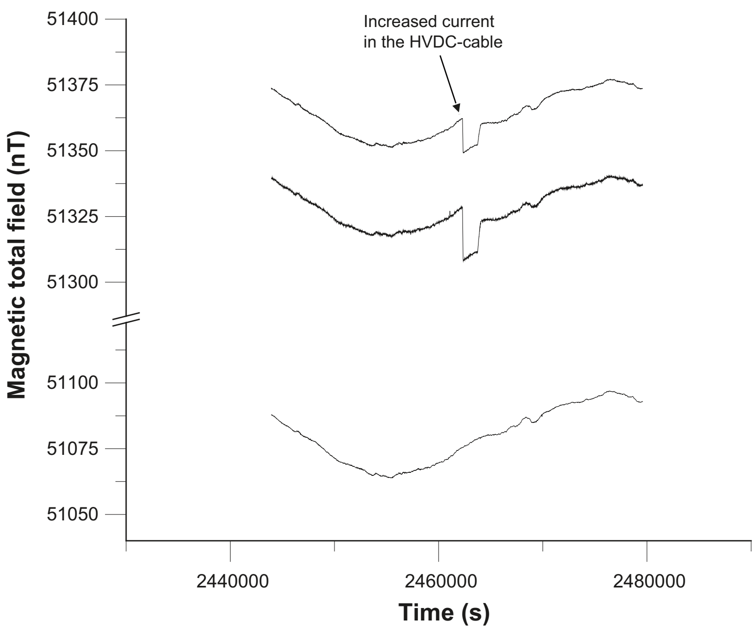

Figure 3-3. *Base magnetometer readings from May 29th, 2006. Base station from /11/ (top), second base station (centre) and Fiby observatory (bottom). The time scale is counted from mid-night UTC, May 1st, 2006.*

difference in magnetic total field between the survey stations and the base magnetometer station in the absence of any current in the HVDC cable, assuming the simplifications above are valid. The final magnetic anomaly values were referred to the base magnetometer position of /11/. The cable-corrected base value was added to the anomaly values in the data stored in SICADA.

Figure 3-4 illustrates the different steps in the processing for AFM100206 and AFM001292. The top left map shows the total magnetic field due to 100 A of current in the HVDC-cable. The top right map shows the total magnetic field from the cable during measurements, as estimated with the help of base magnetometer data. Some areas have fields close to zero since measurements were made in the absence of any current in the cable. However, some areas are affected by an applied field of around 200 nT which is of the same order of magnitudes as the dominating bedrock magnetic anomalies. The base magnetometer readings are subtracted from the survey data. This means that a part of the cable effect is corrected for, since also the base magnetometer is affected by the applied field from the cable. The bottom left map in Figure 3-4 shows the part of the magnetic field from the cable not compensated for by the base magnetometer. Note that different base magnetometer positions were used for these two areas. The south-eastern corner of AFM001292 has been over-compensated by the base magnetometer since that area is located further away from the HVDC-cable than the base magnetometer. The lower right map in Figure 3-4 shows the cable-corrected data. No edges or level variations can be seen in the map that can be related to HVDC-cable effects. The maximum magnitude of the cable corrections are around 25% of the dynamic range of the map showing the final result in Figure 3-4.

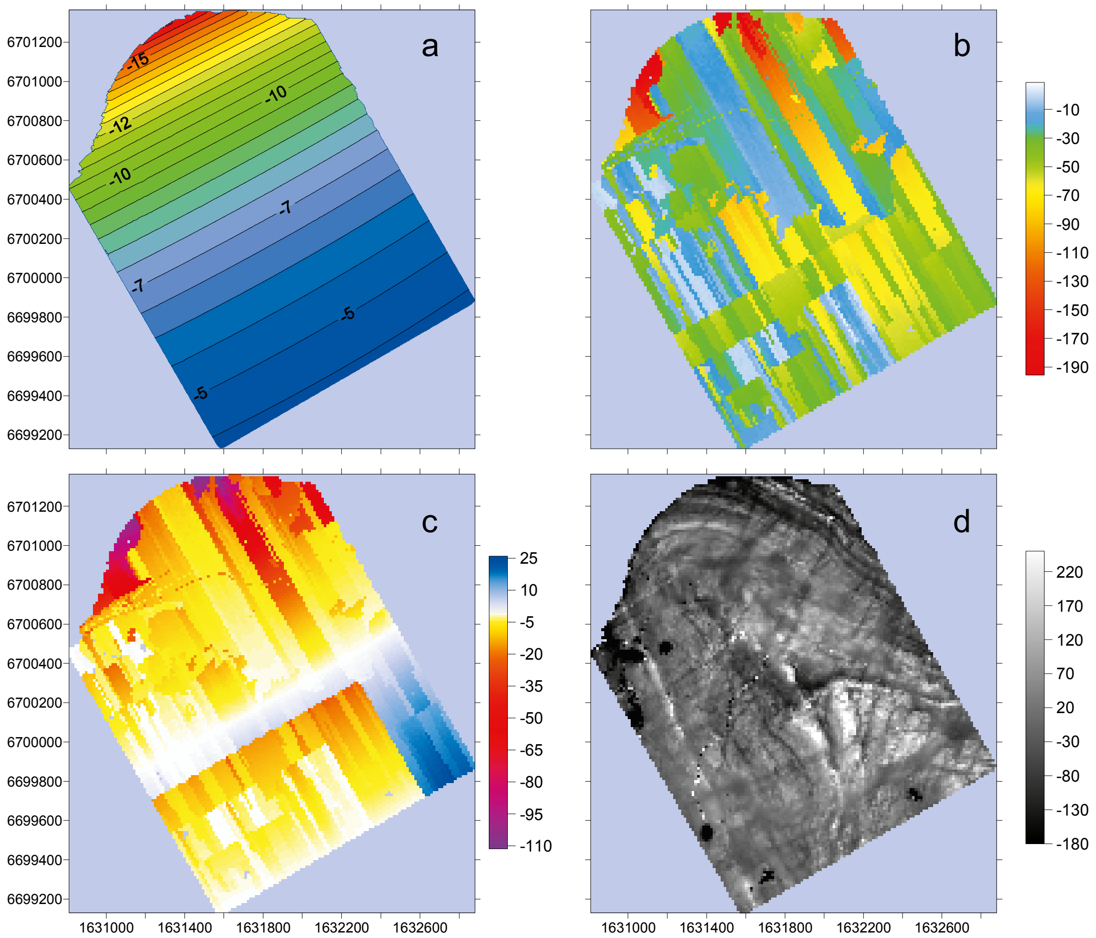

Figure 3-4. Processing steps in the correction for HVDC cable effects, areas AFM100206 and AFM001292. All units in nT. a) Magnetic field due to 100 A current in the cable. b) estimated magnetic field during survey due to current in the cable. c) magnetic field due to the cable not compensated for by base magnetometer. d) estimated total field anomaly in the absence of any current in the cable.

The magnetic total field anomaly caused by the HVDC cable during surveying can be seen in Figure 3-5. As expected, the largest magnitudes can be seen in the north, close to the cable. White areas in the map correspond to survey periods with no or quite weak current in the cable. The cable was for example out of operation during a large part of the winter 2006–2007 when AFM001330 and AFM001331 were surveyed. The variations in the map are fairly smooth over large parts of AFM001293, AFM001294 and AFM001314 since the current in the HVDC cable was fairly constant during these survey periods.

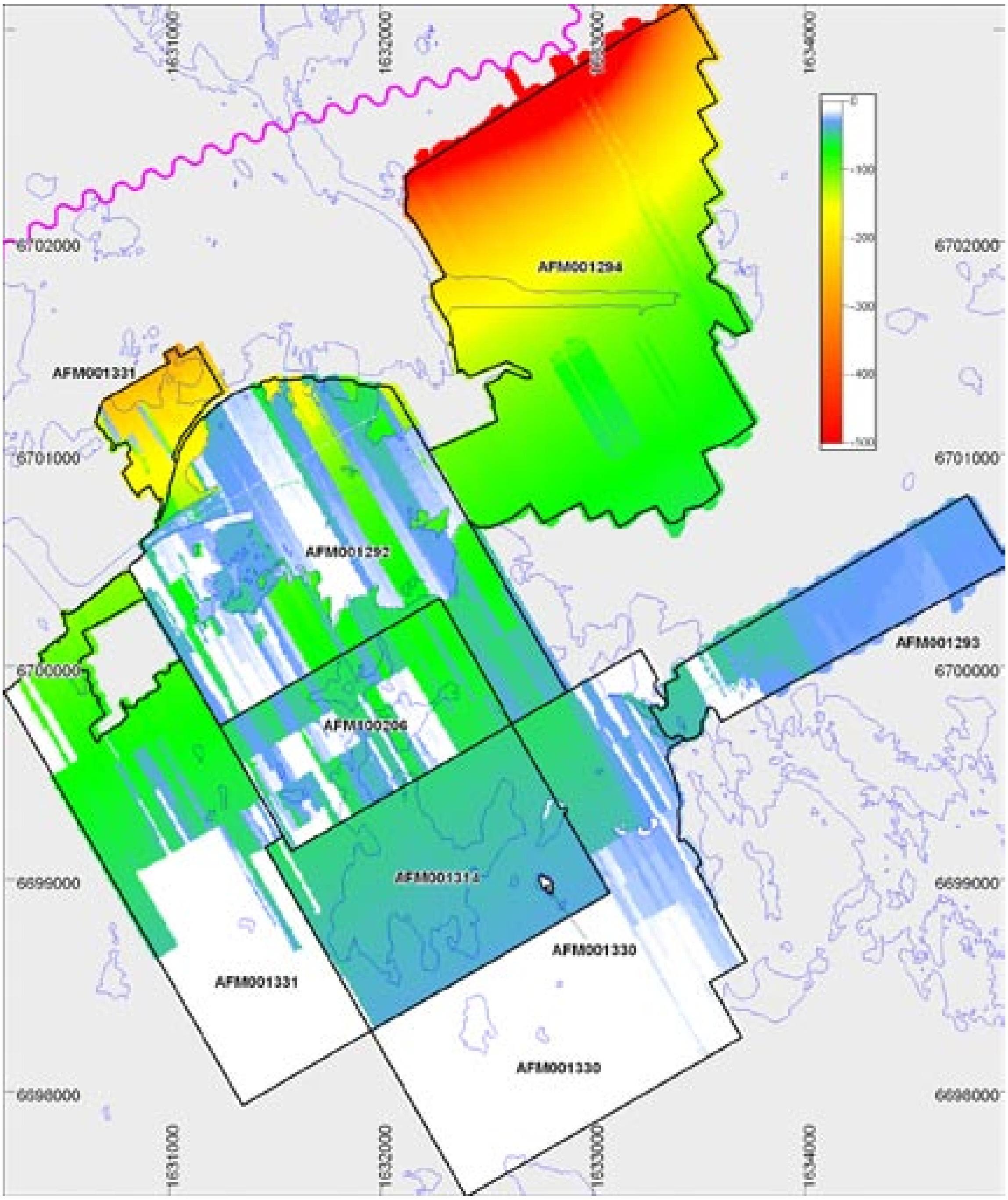

Figure 3-5. *Map showing the estimated magnitude of the magnetic total field anomaly [nT] caused by the Fenno-Skan HVDC cable during surveying. The Fenno-Skan HVDC cable between Sweden and Finland is shown as a magenta wave-line north of the survey areas. Detailed ground magnetic survey areas outlined in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

3.4.2 Removal of data collected with poor signal strength

The GSM-19 magnetometers report the signal strength of the measurements in the output file data. Poor signal strength was reported for some stations during boat measurements. Such stations typically occurred close to the shore line when the boat was turned for a new line. Fairly magnetic rock is present underneath the southern part of Asphällsfjärden. It is suspected that the signal-strength problem was due to vertical wave-motion and horizontal heading motion in the presence of a magnetic gradient during measurement. Points with poor signal strength and obviously bad data were removed from the data set. However, the resulting data coverage was not severely affected anywhere by this correction.

3.4.3 Corrections for heading errors

It was not practically possible to perform the boat measurements from a completely non-magnetic vessel. Also, for safety reasons most of the measurements on the open sea were carried out from a larger boat. The magnetic disturbance was reduced by placing the sensor on a wood construction in front of the boat, Figure 3-1. However two disturbances were noted. The data acquired from August 8^{th} to 15^{th}, 2006 were found to have a level error of –15 nT, most likely caused by the RTK-GPS-antenna used during this period. All data from that period were therefore corrected for the level error. The data from AFM001293 and AFM001294 had levelling errors related to the heading direction of the boat. Alternating lines had slightly different base levels, resulting in a stripy appearance of magnetic maps. The magnitude of the heading error was determined by trial and error and was found to be approximately ± 1.7 nT for the small boat and ± 2.9 nT for the larger boat. The error was assumed to have a maximum and minimum for 0° and 180° heading respectively. The boat heading was calculated from the RTK-GPS-positions and a correction for the error was applied to the data. Any possible yaw rotation of the boat due to side-wind has thus been neglected.

3.4.4 Interpolation and filtering

The magnetic data has been surveyed in two ways, in a regular 5×10 m local grid on land and less regular by boat, see Section 3.3 and Figure 3-2, and the magnetic total field anomaly from all survey stations was interpolated to a regular grid with a node spacing of 4×4 metres in the Swedish grid RT90 using linear Kriging (Surfer 8™ Golden Software Inc). The magnetic anomaly field is presented in colour, Figure 3-6 and grey tone, Figure 3-7.

Standard type of filtering and transformation (Oasis™ Geosoft Inc) has been executed on the dataset in accordance with previous processing of magnetic data, carried out in /3, 5, 11, 12/. A rather new processing method /14/, “tilt derivative”, especially useful for structural enhancements and segmentation of magnetic data has also been applied in this work. Examples of the processed magnetic data, separately or in combinations are presented in Figures 3-8 to 3-11 and also in Figure 4-5. The following processing has been carried out:

- 1st vertical derivative,
- 2nd vertical derivative,
- horizontal derivative in east and west direction,
- total horizontal derivative,
- tilt derivative (zero crossing is close to edges of model structures, i.e. magnetic body edges),
- total horizontal derivative of the tilt derivative (depicts magnetic body edges by marked maxima).

When applicable, reduction to the pole and/or upward continuation has been carried out prior to, or has been included in the applied filter.

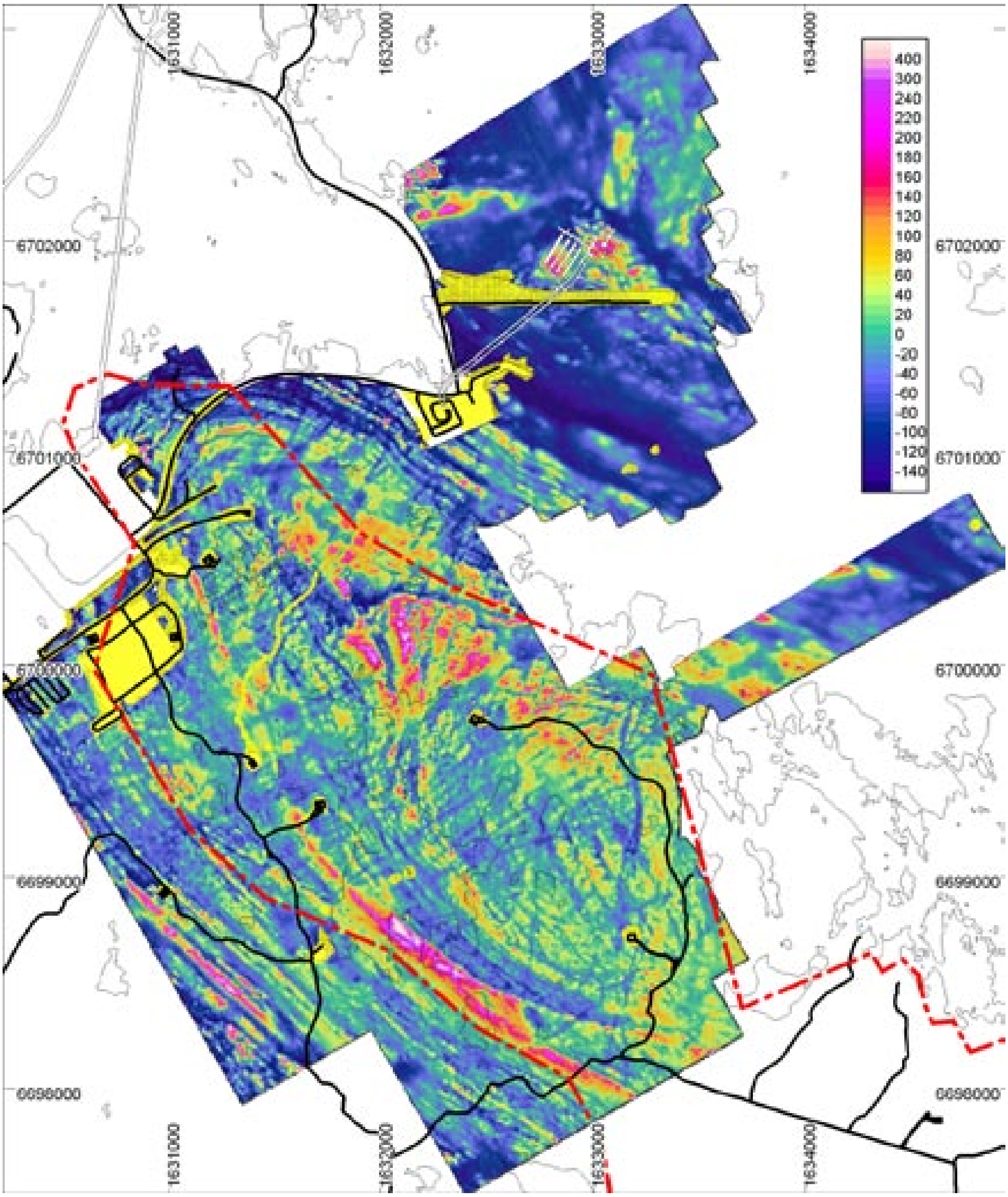

Figure 3-6. *Magnetic anomaly field, colour range in nanoTesla [nT]. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

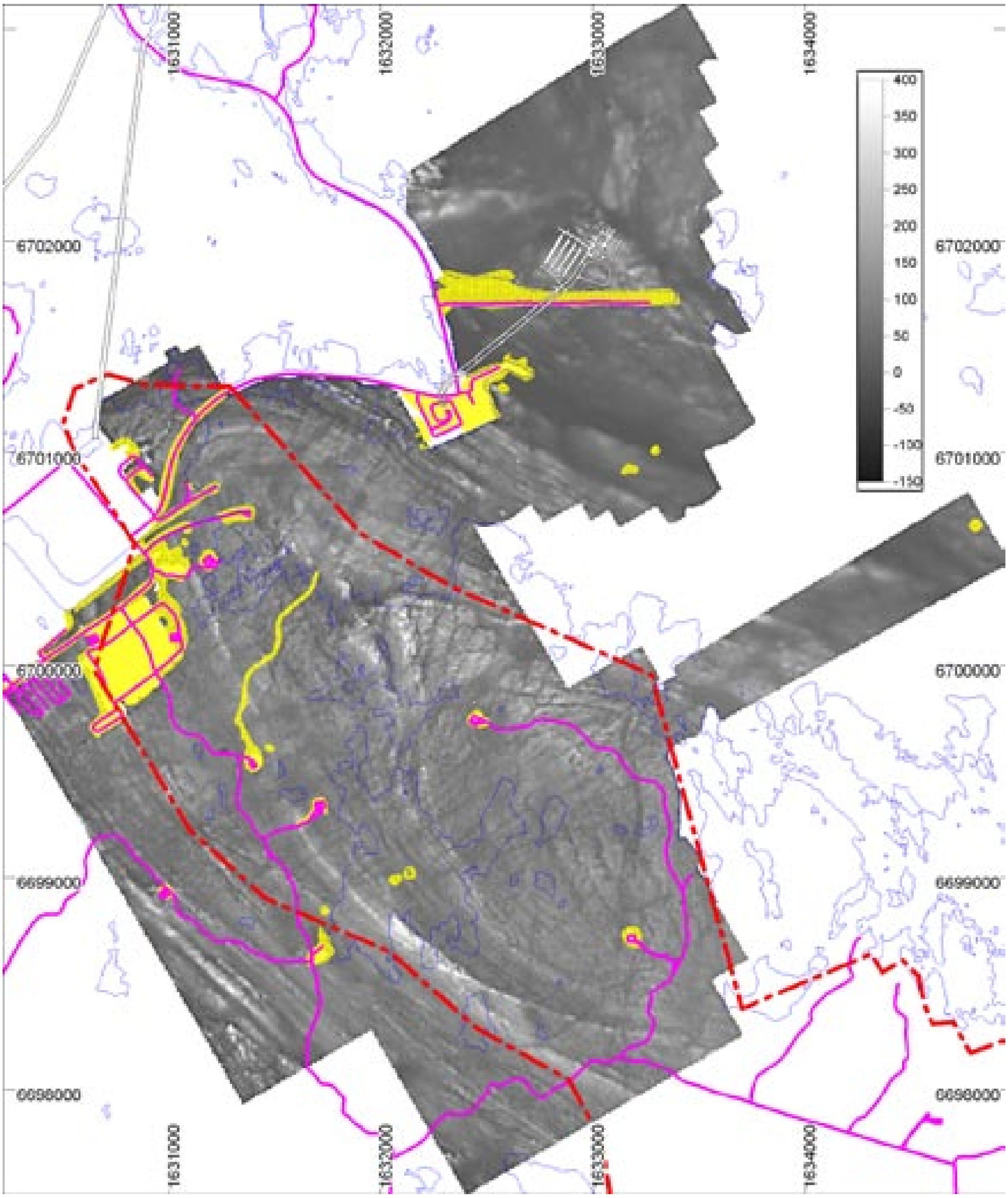

__Figure 3-7.__ Magnetic anomaly field, grey tone scale in nT. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in magenta. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.

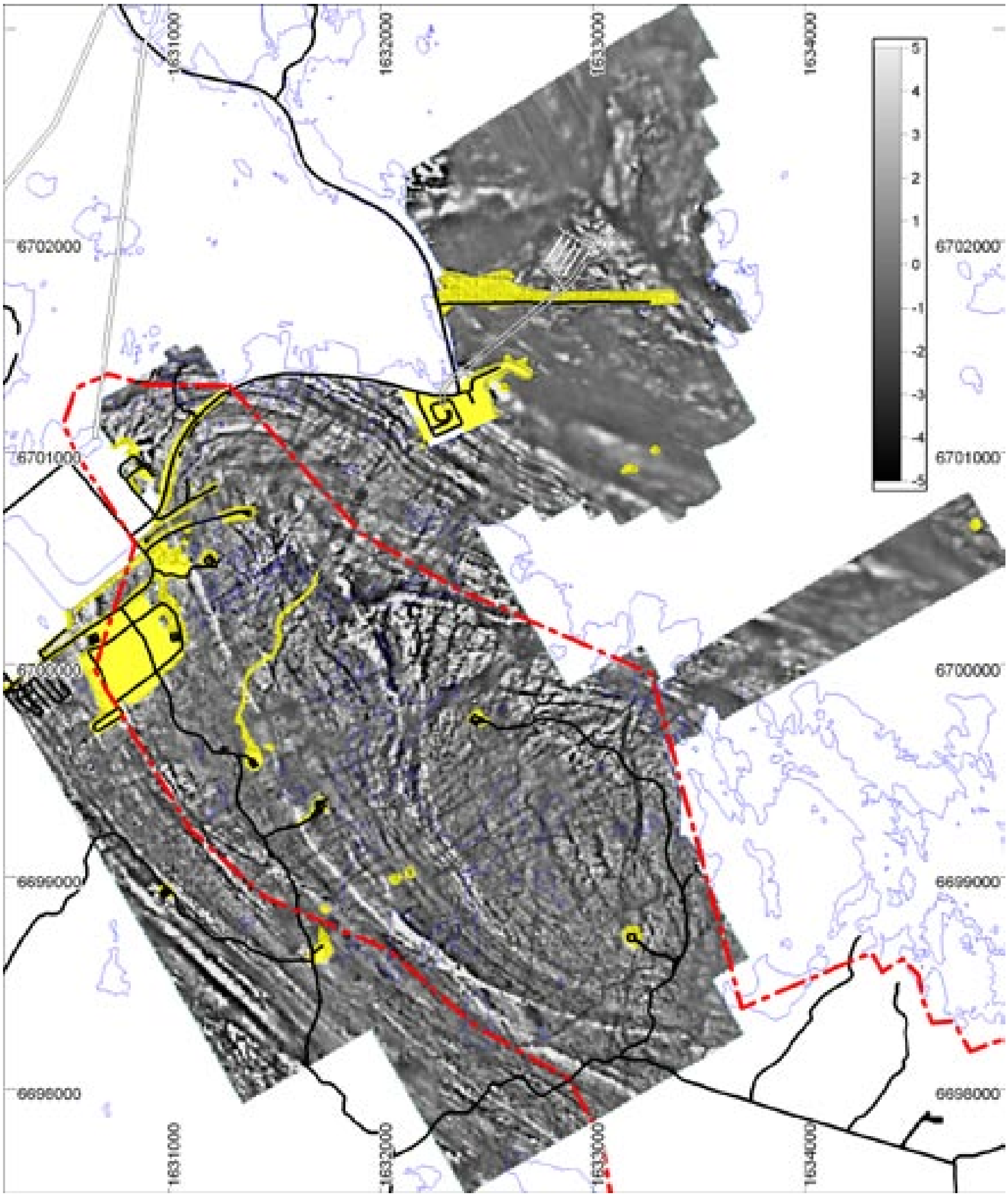

Figure 3-8. *Magnetic anomaly field, reduced to the pole, 1st vertical derivative, greytone scale in nT/m. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

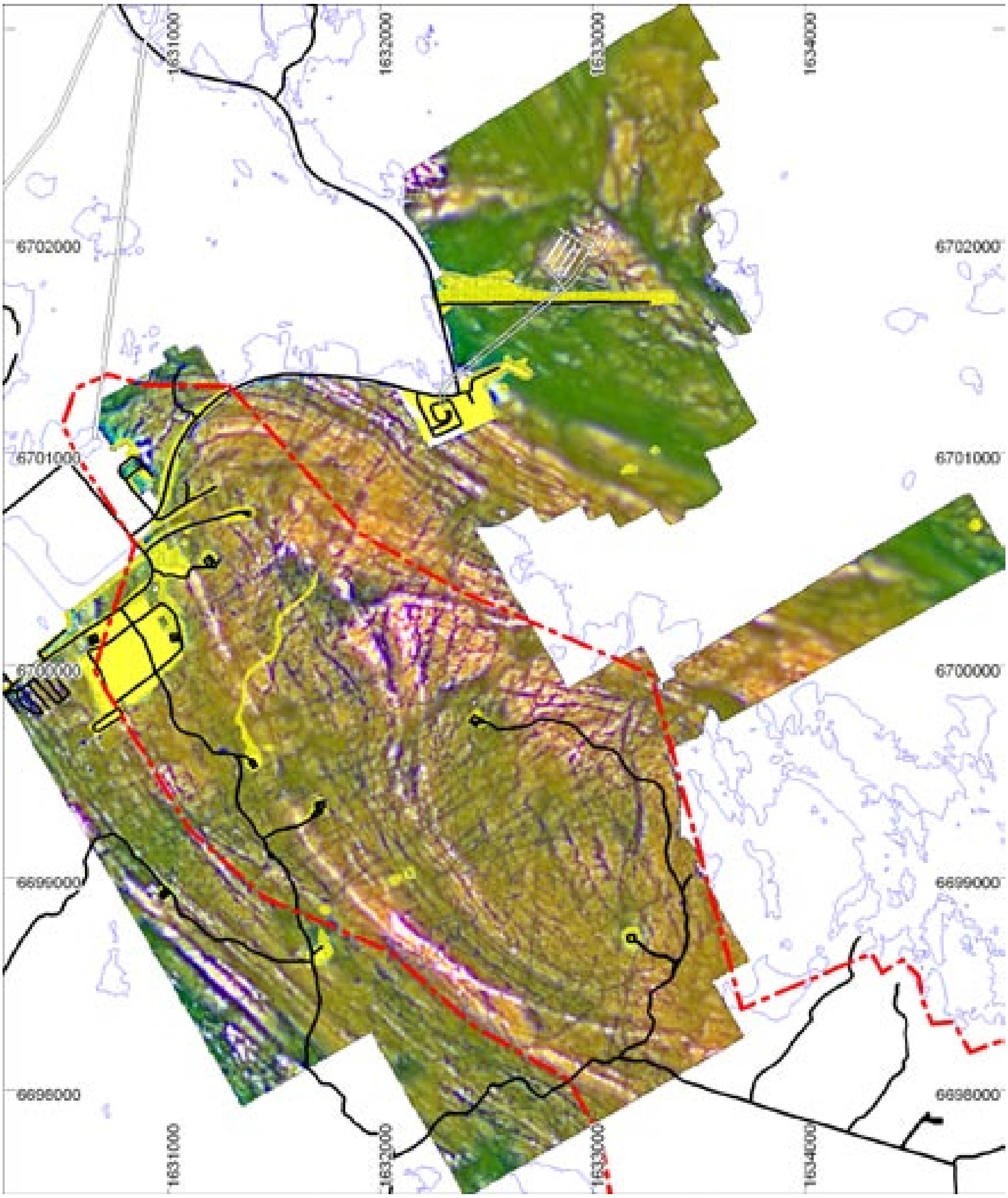

Figure 3-9. *Colour composite of the magnetic anomaly field; reduced to the pole (red), 1st vertical derivative (green) and total horizontal derivative (blue). Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

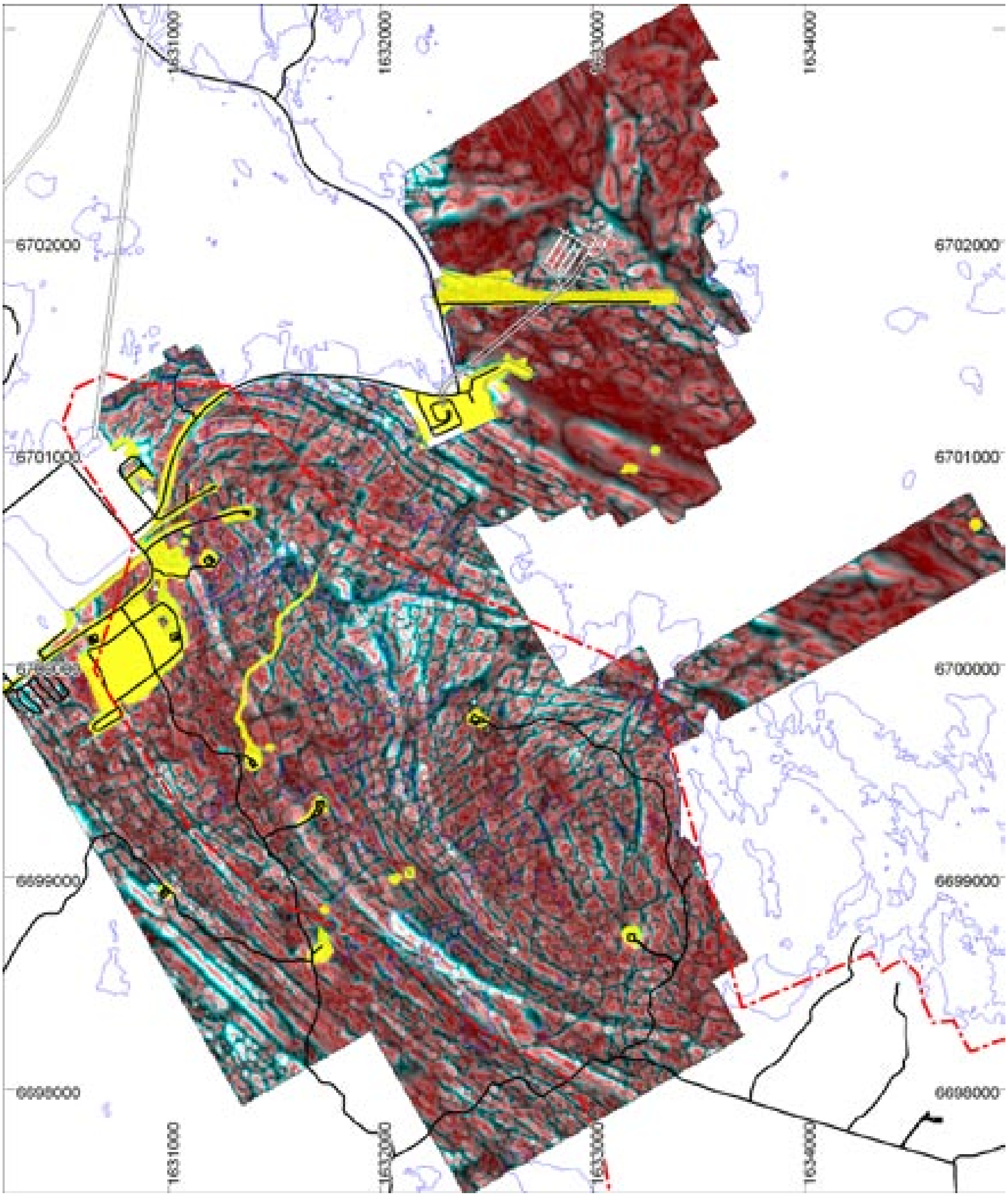

Figure 3-10. *Colour composite of the magnetic anomaly field; reduced to the pole. The 1st vertical derivative (red) and the total horizontal derivative (green and blue). Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

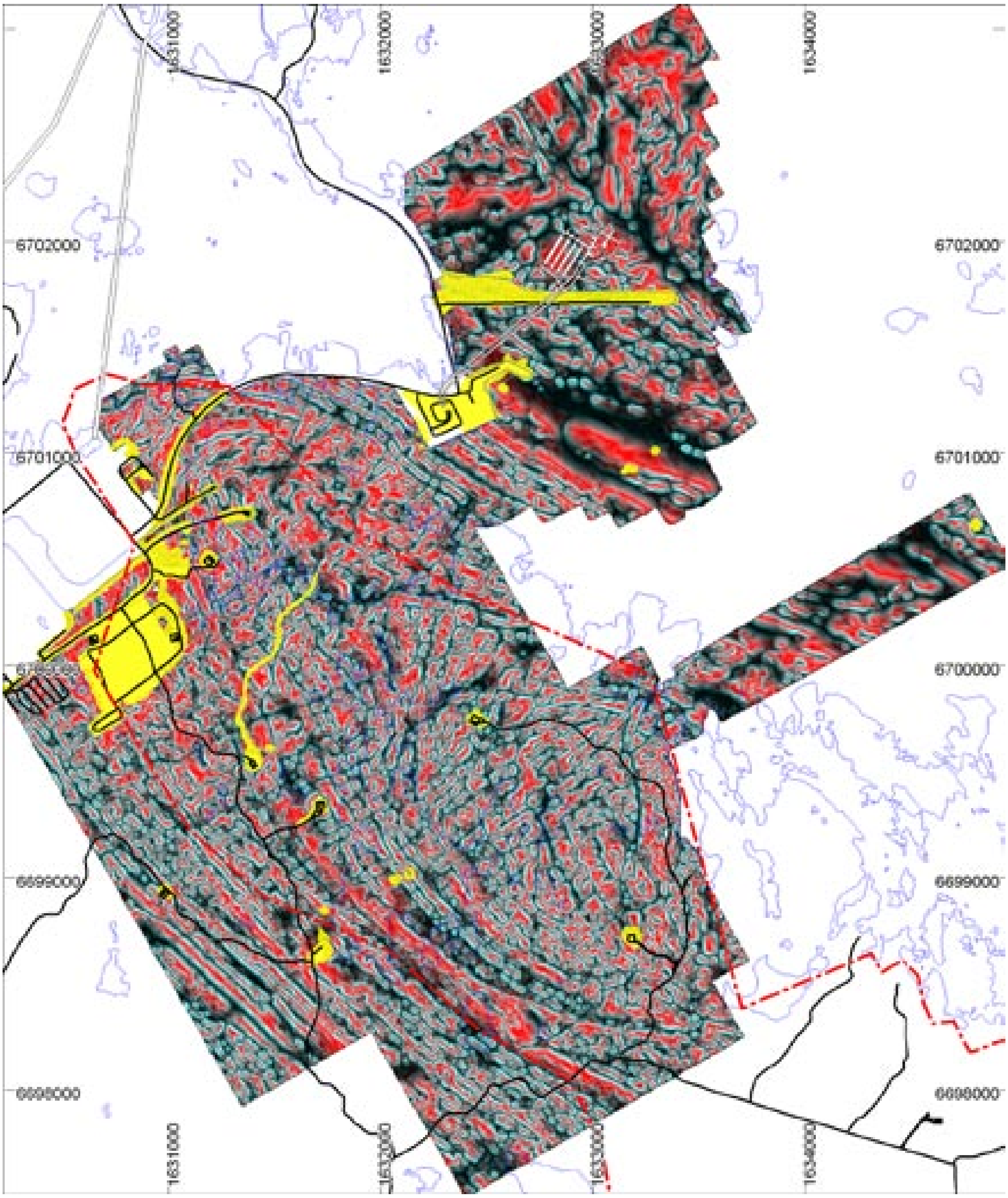

Figure 3-11. Colour composite of the magnetic anomaly field, reduced to the pole. The tilt derivative (red) and the total horizontal derivative of the tilt derivative (green and blue). Upward continuation to 10 m makes the magnetic pattern smoothed. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.

3.5 Nonconformities

Survey data were influenced by the HVDC cable between Sweden and Finland, which is situated at a distance of 0 to 5.5 kilometres to the north of the survey stations.

The anthropogenic environments at drill sites, along the roads to the drill sites and around housing and industry areas have given disturbances and loss of data. These areas are marked as disturbed areas in the interpretation, Figures 4-1, 4-2, 4-3 and 4-4. The same is valid for the steel tube releasing salt water from drill site DS1 to the north, into the sea at Asphällsfjärden.

A few line levelling errors were detected in survey area AFM001330 and confirmed by short traverse lines. The reason is not clear but the errors have been manually corrected.

4 Data interpretation

Data interpretation has been carried out by visual identification, delineation and characterization of structural features, using image analysis (Geomatica™ PCI Geomatics Enterprises Inc) and GIS-techniques (Mapinfo™ Mapinfo Corporation). It should be emphasized that the previous interpretation results /12/ has been incorporated in this work.

The results are stored in the primary data bases (GIS). The data is traceable in SICADA and GIS with the help of the activity plan number (AP PF 400-06-034).

4.1 The magnetic anomaly pattern

The magnetic pattern in the survey area can be divided into six main areas with different magnetic character, Figure 4-1 and Figures 3-6 to 3-11. Along the southwest margin of the survey area the magnetic pattern is intensely banded with rapidly changing low and high magnetic bands striking southeast-northwest which to the northeast changes to a gentler, banded pattern of low to moderate magnetic intensity. Further to the northeast, at the SFR office and along the coastline to the southeast, the pattern is again intensely banded with, southeast-northwest trending, rapidly changing low and high magnetic bands. These two banded structures probably forms fold limbs of a common fold with a northwest oriented fold axis. The fold is U-shaped and opens to the southeast. Within the fold the magnetic pattern is more varied with gently banded to more irregular patterns and from low to high magnetic intensity. The fold pattern is most prominent in the Asphällsfjärden area, Figure 4-1, but is also repeated recurrently from northwest to the southeast. The area between Bolundsfjärden and the road to drill site DS6 forms the core of the fold structure with a more irregular magnetic pattern. Northeast of the SFR office the pattern is characterised by a broad, southeast-northwest trending magnetic low, coincident with the Singö deformation zone. The low magnetic relief give less information on the structural pattern within this area. Further northeast of this structure and in the area around the SFR underground facility, the magnetic pattern is less regular and gently folded, indicating a varying and complex folding pattern.

A few minor areas with very low magnetic intensity and low magnetic relief have been identified and outlined, Figures 4-1 and 4-2. Destruction of ferromagnetic minerals is a probable cause; however, the origin of these features is uncertain and would require further investigations.

Areas of diffuse magnetic pattern can also be seen in different parts of the survey area. The most prominent example is a WSW-ENE trend along MFM0060A0, from drill site DS1/DS5 and north of drill site DS6, Figure 4-1. The exact boundaries of the diffuse areas are difficult to delineate and hence, the areas are marked with a letter D as a point in the centre of the occurrence. Other clusters of occurrences are located in Bolundsfjärden, at the housing area, south of drill site DS9 and from Asphällsfjärden and towards Klubbudden. It is possible that the diffuse magnetic pattern can indicate a deeper bedrock source and/or the presence of fractured and altered surface rock. Observation of this type of feature is only valid if the magnetic bedrock source is rather shallow. Hence, no indication of diffuse magnetic pattern has been marked in area AFM001293 and AFM001294 due to the deeper sea; see also discussion in Section 4.4.

Verduzco, et al. /14/ has shown that the zero crossing of the tilt derivative of the magnetic field can indicate magnetic rock boundaries. Lines possibly representing boundaries between different magnetic rock units have in this way been extracted using the tilt derivative processed data, Figure 4-1. To further enhance the structural magnetic setting, positive magnetic connections (magnetic maxima) have also been outlined, Figure 4-1.

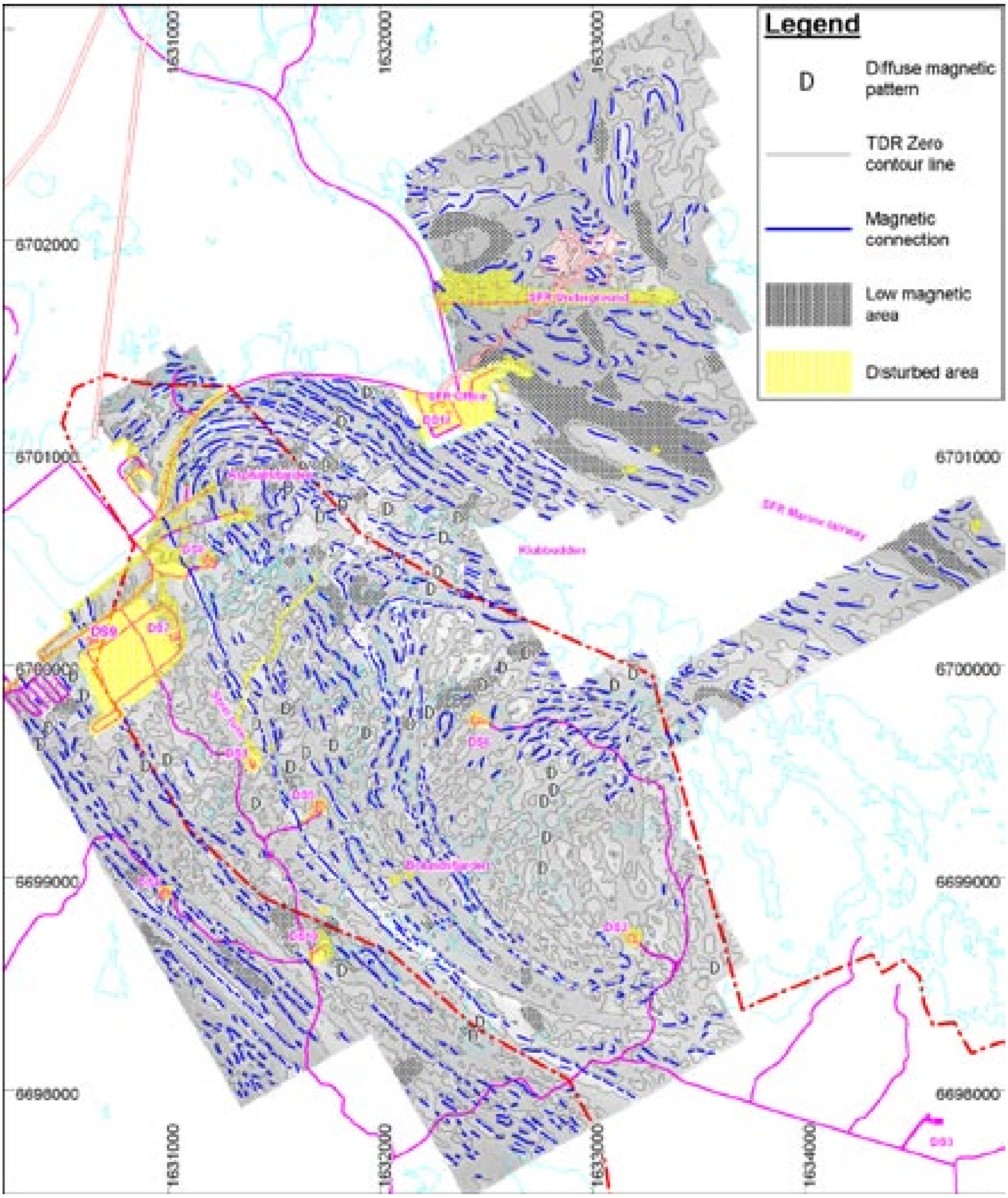

Figure 4-1. Magnetic anomaly pattern in the detailed ground survey area. The zero contour of the tilt derivative is outlined, indicating boundaries of bedrock units with different magnetic properties. Areas with low magnetic intensity and no anomaly relief are also shown. Magnetic maxima connections enhance the structural pattern. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with red lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites (DS) in magenta. Printed on a blurred version of the magnetic total field. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.

4.2 Lineament interpretation

The method specific lineament interpretation involves only one data set; the magnetic total field. The magnetic lineaments identified are graded in low, medium and high uncertainty mainly with respect to the clarity in which they appear but also, in some cases, involving a judgement regarding the specific geological situation and the possible cause of the lineament. Typically lineaments appear as linear magnetic minima, edges and dislocations in the magnetic field but in the Forsmark area other linear magnetic characters have also been outlined.

The structural geology in the Forsmark area is characterized by variably intense ductile deformation of both supracrustal and intrusive rocks. Hence, also the intrusive rocks commonly show a strongly banded component in the magnetic pattern. It is difficult to decide whether lineaments appearing as minima parallel to the general bedrock foliation are related to fracture zones or to rock types with low magnetization and in that sense could be characterized as magnetic connections. In this work, these linear features are identified as lineaments with a separate character called “minima connections”.

The interpretations are stored in GIS-format and each lineament has an attribute table attached, Table 4-2, as the one previously used in /12/. The table is the same for method specific, coordinated and linked lineaments, which means that the significance of the individual attributes is somewhat different for each presentation. Origin, method, character and uncertainty are the most important attributes for the method specific lineament. The length and direction of each lineament segment is calculated. Besides scrutinizing the lineaments as possible fracture zones the comprehensive attributes table also provide a basis for further statistical analysis.

In this work 715 magnetic lineaments have been identified of which 330 are characterized as “minima connections”. 125 and 328 magnetic lineaments have a low and high uncertainty, respectively. In total for all areas, the corresponding figures are 1,855 lineaments of which 811 are minima connections. 380 and 733 lineaments have a low and high uncertainty, respectively. Based on the attribute data some general statistical results are presented in Table 4-1. A small group of magnetic lineaments with dyke-like character has been kept separate, Figure 4-2, and is further discussed in Section 4.4.

The identified magnetic lineaments and low magnetic areas are presented in Figure 4-2. The lineaments are represented by the co-ordinated magnetic lineaments which give a very similar appearance. The lineaments have not been linked in this stage and the presented figures thus represent each individual segment identified. A rose diagram showing the lineament trend distribution based on the azimuth of the individual co-ordinated magnetic lineaments is presented in Figure 4-3.

Table 4-1. Compilations of some attribute information for magnetic lineaments. Figures show number of lineament occurrences. Figures within brackets show the result from previous interpretation /12/.

Character	Low uncertainty	Medium uncertainty	High uncertainty	Total number
Minima/edge/dislocation	155 (98)	427 (308)	462 (253)	1,044 (659)
Minima connection	225 (157)	315 (172)	271 (152)	811 (481)
Total	380 (255)	742 (480)	733 (405)	1,855 (1,140)

Table 4-2. Attribute table for the magnetic, co-ordinated and linked lineaments. A more comprehensive description of the parameters is found in /5/.

Field name	Name	Description	Attribute used to describe lineaments
Id_t	Identity	Identity of a linked lineament.	ID-number according to SKB (MFM……). Assigned only for linked lineaments.
Origin_t	Origin	Major type of basic data.	Basic data or Method specific or Coordinated lineaments.
Class_t	Classification	Classification of a coordinated lineament.	Regional (> 10 km), local major (1–10 km) and local minor (< 1 km) lineaments. Valid only for linked lineaments.
Method_t	Method	The type of data in which the observation is identified.	Magnetics (Magn)
Weight_n	Weight	A combination of uncertainty and number of properties (methods). An overall assessment of the confidence of the linked lineament. This assessment is based on both the number of properties upon which the lineament has been identified and the degree of uncertainty.	Graded from 1=low confidence to 5 = high confidence for Coordinated lineament. A weighted average according to the length of each segment in linked lineament. Valid only for linked lineaments and only if more then one method is used.
Char_t	Character	Character of the observation in letters.	Method characteristics like minima, edge, minima connection or Coordinated or Linked lineament.
Char_n	Character	Character of the observation translated to an integer.	1 = minima or edge. 0 = minima connection. A weighted average has been calculated according to the length of each segment in the linked lineament.
Uncert_t	Uncertainty	Gradation of identification, 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 and 3 = high. A weighted average has been calculated according to the length of each segment in the linked lineament.
Comment_t	Comment	Specific comments to the observation.	
Process_t	Processing	Data processing performed.	Grid, filter, image analysis, GIS.
Date_t	Date	Point of time for interpretation.	Date.
Scale_t	Scale	Scale of interpretation.	5000.
Width_t	Width	Width on average.	Not assigned in this work.
Precis_t	Precision	Spatial uncertainty of position. An estimate of how well the lineament is defined in space.	10 m is an estimate for all observations.
Count_n	Count	The number of original segments along the lineament.	Always 1 for a method specific lineament.
Cond_n	Conductivity	Shows how much of the lineament that has been identified by EM and/or VLF.	Not applicable when only magnetic lineaments are concerned. In this work always 0.
Magn_n	Magnetic	Shows how much of the lineament that has been identified by magnetics.	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100%. When only magnetic lineaments are concerned, always 1.
Topo_n	Topography	Shows how much of the lineament that has been identified by topography, either in the ground surface or in the rock surface.	Not applicable when only magnetic lineaments are concerned. In this work always 0.
Topog_n	Ground surface	Shows how much of the lineament that has been identified by topography in the ground surface.	Not applicable when only magnetic lineaments are concerned. In this work always 0.
Topor_n	Rock surface	Shows how much of the lineament that has been identified by topography in the bedrock surface.	Not applicable when only magnetic lineaments are concerned. In this work always 0.
Prop_n	Property	Shows in average, how many properties that have been identifiying the lineament.	A weighted average has been calculated, according to the length of each segment in the linked lineament. 0.00–1.00 = 0–100%. When only magnetic lineaments are concerned, always 1.
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 the basic data.	Ground survey grid.
Sign_t	Signature	Work performed by.	GeoVista AB/hi (Hans Isaksson).

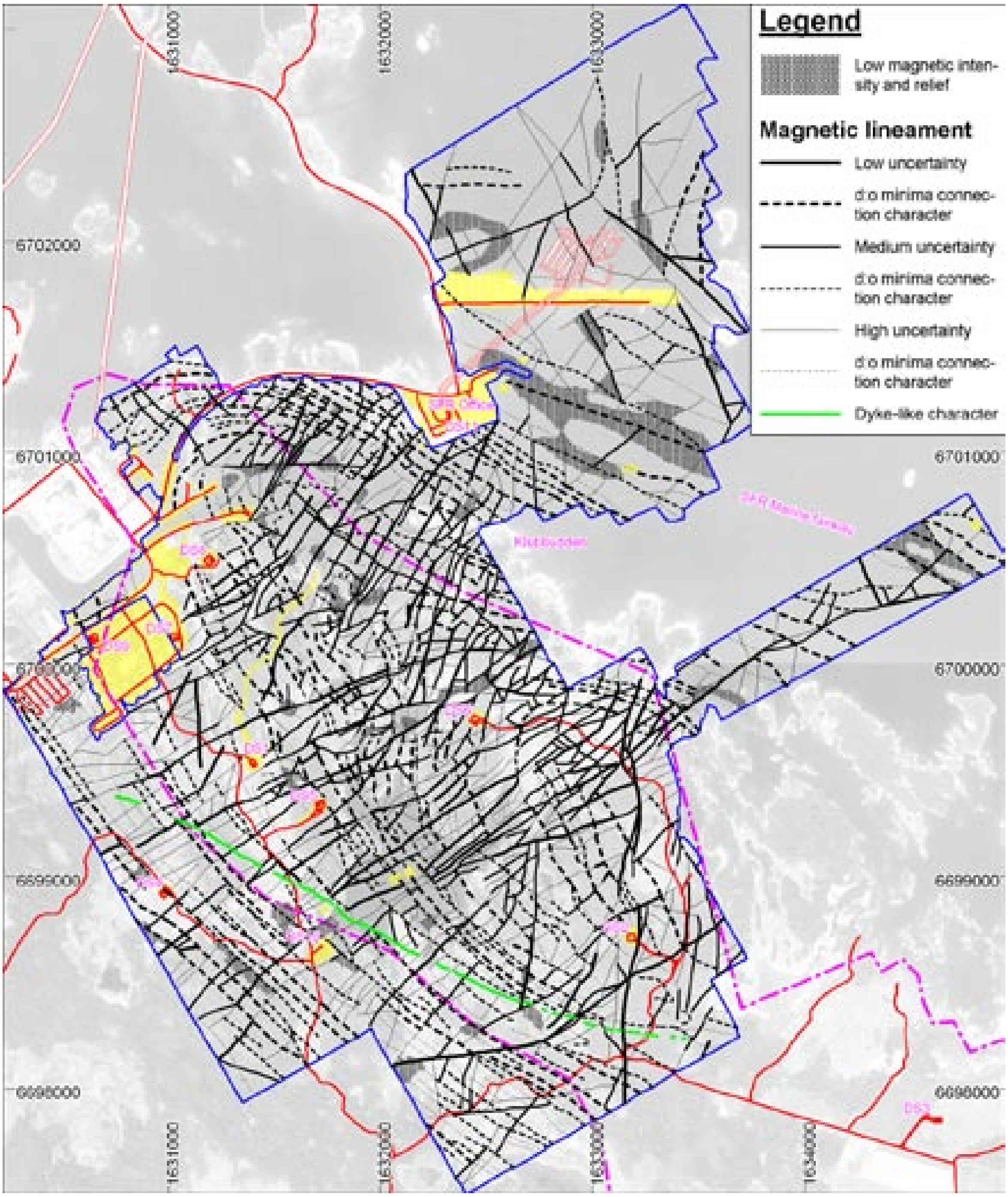

Figure 4-2. *Distribution of co-ordinated, magnetic lineaments in the ground survey area. Areas with low magnetic intensity and no anomaly relief are also outlined. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with red lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, magenta line. Roads and drill sites in red. Printed on orthophoto. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

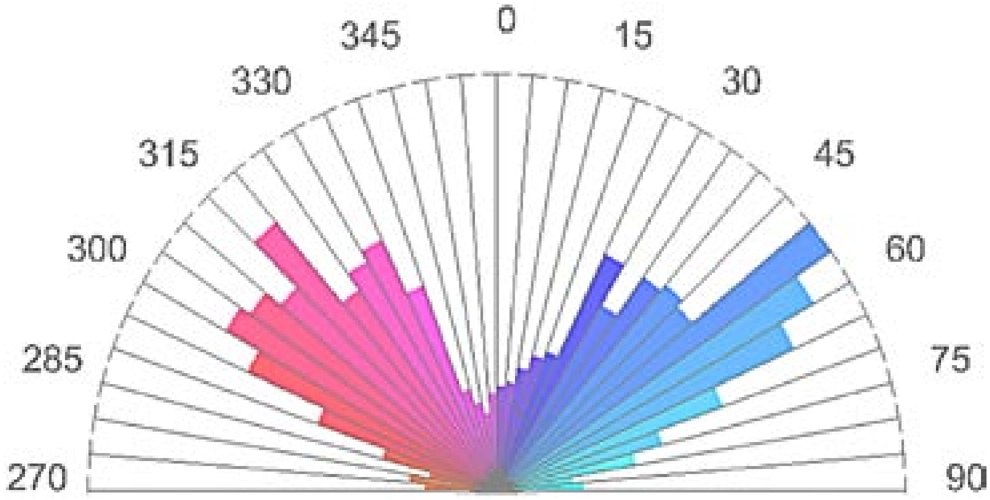

Figure 4-3. *Rose diagram showing the lineament trend distribution based on the azimuth of the individual co-ordinated magnetic lineaments.*

4.3 Lineament co-ordination and linking

The co-ordination and linking work is divided in two stages; at first the detailed magnetic lineaments based on the ground surveys are co-ordinated and linked and secondly these, small scale lineaments are linked with previous, large scale, magnetic lineaments /12/ that enter the ground survey area. The work also involves termination of the small-scale lineaments outside the detailed ground survey if such additional indications can be extracted from the helicopter borne magnetic data /5/.

4.3.1 Detailed, small-scale lineaments

The lineament linking has followed a working scheme previously used in /5, 11, 12/, in more detail described in /5/. Since only one type of data, magnetometry, has been used, the co-ordination phase of the process has been limited to adjustment of vector nodes and connections between lineaments. Thus, this part of the work is not further described. As a basis for the subsequent linking of the co-ordinated magnetic lineaments, the following data was used:

- Linked magnetic, small scale lineaments from /12/.
- Co-ordinated magnetic, small scale lineaments from this study.
- Linked magnetic, large scale lineaments from /12/, also used as a basis to the site descriptive geology model, Forsmark area – stage 2.2 /10/. Two sets are available with length 0–3 km and > 3 km, respectively.
- Magnetic images, covering the different processing.

Going from a method specific or coordinated lineament to a "linked" lineament, the most important attributes assigned are, see also Table 4-2:

- **Identity.** Each linked lineament is given identification according to SKB standards.
- **Length.** Total length of all segments.
- **Direction.** Average trend of the lineament.
- **Class.** The total length provides a possibility to discriminate between regional (> 10 km), local major (1–10 km) and local minor (< 1 km) lineaments.
- **Count.** The number of original coordinated lineament segments along the linked lineament.
- **Uncertainty.** The uncertainty is graded between 1–3.
- **Character.** The character number is graded between 0–1 (from concordant–discordant).

The identity is built up by 9 positions, at first 8 positions MFMxxxxG; where M stands for Magnetic, FM for Forsmark, xxxx is a serial number and G stands for Ground. Position 9 is a number 0–9, used to describe when a lineament form separate segments of what is judged with confidence to be part of the same lineament. The attributes like Uncertainty and Character are weighted according to the length of each individual coordinated lineament that forms part of the linked lineament.

At first the geographical position and extension of a new, small-scale, linked magnetic lineament has been compared to the previous both small-scale and large-scale lineaments in /12/. The lineament that gives a good fit is denominated according to the identity of the previous linked lineament. At the same time, the previous large-scale lineament /12/ has been deleted in the part it traverses the new detailed survey area; it is also adapted to the small-scale lineament at the survey boundaries and in some cases modified outside the ground survey areas. When possible, small-scale lineaments that extend outside the detailed ground survey area are also given a termination based on helicopter borne magnetic data. It is important to notice that small-scale and large-scale lineaments have not been linked in this stage.

From this stage, three lineaments sets are prepared:

- Linked magnetic lineaments within the detailed ground survey area.
- Linked magnetic lineaments larger than 3 km in the regional model area and outside the ground survey area.
- Linked magnetic lineaments shorter than 3 km, within the regional model area, outside the ground survey area and affecting the ground survey area and/or the local model area.

Result

Of previous large-scale magnetic lineaments, 55 MFM-identities have been utilized and affected in this work, Figure 4-4. Identities marked with an underline consist of several separate segments; G0, G1, etc:

- MFM0017, 44, 60, 61, 62, 63, 64, 101, 102, 103, 123, 125, 126, 130, 133, 137, 159, 167, 168, 169, 236, 401, 408, 414, 620, 626, 628, 674, 683, 685, 691, 717, 725, 803, 804, 805, 808, 809, 811, 813, 814, 818, 835, 836, 999, 1034, 1035, 1053, 1054, 1056, 1129, 1196, 1198, 1199 and 1200.

The following large-scale lineaments have been subject to major changes:

Partly change of route or direction, often also replaced by another identity

- MFM0060, 61, 123, 126, 133, 809, 813, 1053, 1056, 1200.

Extended

- MFM0061, 123, 169, 401, 717, 1200.

Reduced

- MFM1196 (occurs in a disturbed area).

Some large-scale magnetic lineaments have been dropped since they have no acceptable small-scale representation in the detailed survey:

- MFM0098, 731, 1043, 1061, 1064 and 1202 were already dropped in /12/.
- MFM1127 is now represented by MFM0803 and MFM0804, and a broad low magnetic area, Figure 4-4.
- MFM0100 occurs close to an area which is partly disturbed and shows both low magnetic and diffuse magnetic patterns.
- MFM001711, a splay from MFM0017 now replaced by new identities.
- MFM1022, north-northeast directed lineaments more probable.

- MFM1053, dropped and included in MFM1094.
- MFM1057, new identities further to the southeast.
- MFM1197 occurs in a disturbed area.

Of the previous small-scale lineaments in /12/, the 2000 series, the following identities are missing:

- MFM2129, 2422 and 2423 were already dropped in /12/.
- MFM2497, 2498 and 2499 have been moved to the dyke-like lineament group, see Section 4.4.
- MFM2151G has been included in MFM2215G.
- MFM2161G has been included in MFM2221G.
- MFM2194G has been included in MFM2464G.
- MFM2408G has been included in MFM0062G0.
- MFM2456G has been included in MFM2415G.
- MFM2474G has been included in MFM0062G5.
- MFM2500G has been included in MFM0133G0.

The 270 new, small-scale lineaments occupy the identity serial numbers; MFM3001G–3271G. In this series, 4 numbers have been dropped in connection with the final delivery:

- MFM3136G has been included in MFM3115G.
- MFM3207G and MFM3263G has been included in MFM3162G.
- MFM3184G has been included in MFM3194G.

In total, 855 small-scale, linked magnetic lineaments have been defined in the work. 22 lineaments have a different denomination in position 9 in the identity code, from G0 up to G5. These lineaments have several separate segments that form adjacent, alternative and often parallel routes:

- MFM... 60, 61, 62, 63, 103, 123, 125, 126, 133, 236, 401, 803, 805, 811, 1199, 1200, 2054, 2225, 2253, 2326, 2332 and 2410.

Several lineaments are judged to run in and out of the detailed survey area twice or more and the identity is then the same for each segment:

- MFM... 44, 101, 159, 803, 804, 805, 809, 1056, 1200, 2215, 2218, 2320, 2325, 2464, 2469, 2496, 3162, 3262; all have suffix G0.

In the linking process the two main characterizations, minimum and minimum connection have been kept apart so that linked lineaments mainly are composed of only one character. In a few cases the two groups coincide and hence, two linked lineaments can share the same segment(s) along a shorter distance.

In the small-scale lineament table the length is the actual length occurring within the ground survey area. However, to assign the class attribute the length of connected large-scale lineaments is also taken into account. Based on the attached attribute table, for content see Table 4-2, some general statistical results are presented in Table 4-3. A total of 855 linked magnetic lineaments have been constructed of which 377 are characterized as “minima connections”. 2 and 91 linked lineaments are classified as regional and local major lineaments, respectively. Figure 4-4 shows the linked lineaments, classified as regional (> 10 km), local major (1–10 km) or local minor (< 1 km), and the relation to previous large-scale magnetic lineaments.

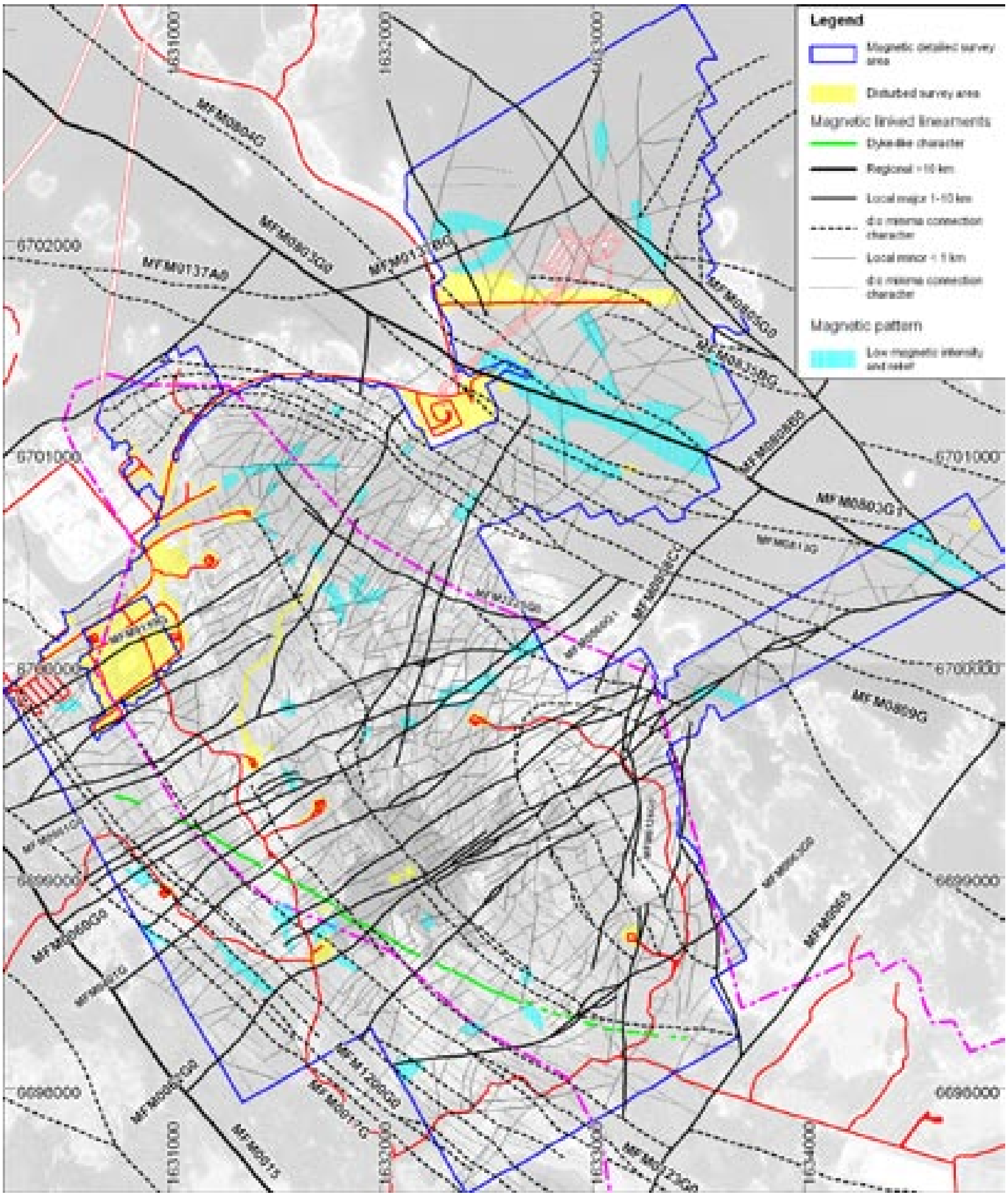

Figure 4-4. Linked lineaments combined from detailed ground magnetics and previous large-scale lineaments. A selection of lineaments are labelled. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnels from reactors Forsmark 1, 2 and Forsmark 3 are shown with red lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, magenta line. Roads and drill sites in red. Printed on blurred orthophoto. © Lantmäteriverket Gävle 2007. Consent I 2007/1092.

Table 4-3. Compilations of the Character and Class attribute for small-scale, linked magnetic lineaments. Figures show number of lineaments. Figures within brackets show the result from previous interpretation /12/. *The regional lineament is MFM0803G0 and G1.

Character	Local minor (< 1 km)	Local major (1–10 km)	Regional (≥ 10 km)	Total number
Minimum/edge/dislocation in > 50% of the length	428 (286)	50 (15)	0 (0)	478 (301)
Minimum connection in > 50% of the length	334 (240)	41 (10)	2 (2)*	377 (252)
Total	762 (526)	91 (25)	2 (2)	855 (553)

4.3.2 Regional, large-scale lineaments

This stage comprises linking of small-scale and large-scale lineaments. For both datasets, the lineaments are already prepared for the linking procedure. The dataset consists of lineaments originating from different magnetic sources but the advantage is that all magnetic lineaments are compiled together in one file and that the length and direction of each lineament identity is more easily evaluated.

From this stage, one lineament set is prepared:

- Linked magnetic lineaments, compiled from all small-scale and large-scale lineaments.

4.4 Discussion

General conclusions

It is clear from previous work /11 and 12/ and this work, that the high resolution, ground magnetic data provides the possibility to identify more and shorter lineaments than the airborne survey data. The difference in resolution of structures using airborne magnetic data or ground data can be more easily understood looking at the magnetic ground survey upward continued 40 m, up to the helicopter borne survey level, Figure 4-5. This shows how the detailed "ground" magnetic data would look like if it was carried out 40 m above ground. One should also remember that the helicopter borne survey was carried out with an average line spacing of 50 m compared to 10 m line spacing in the ground survey. This also contributes to the finer details presented in this work that could not be resolved from the airborne survey data in previous interpretations.

The detailed magnetic, ground and seaborne survey data give a much better understanding of the structural framework at Forsmark and small-scale distribution of magnetic lineaments. The data also give detailed information on the extension and fragmentation of the large scale magnetic lineaments, previously identified.

Large-scale lineaments identified in previous interpretations

An investigation of linked lineaments, XFM0060A0 and XFM0061A0 was the main objective in the initial detailed survey /11/ and the next phase /12/ showed that several of the large-scale lineament extensions were supported by the detailed magnetic data.

The new extended surveys further clarify the extension and in some cases also terminations of important lineaments, Figure 4-4:

ENE/NE-lineaments: MFM0159, MFM2320, MFM0061, MFM0060, MFM0401, MFM0062, MFM0063.

NW-lineaments: MFM0017, MFM1200, MFM0123, MFM1199, MFM0803, MFM0804, MFM1127 (dropped), MFM0805, MFM0044 and MFM2225, MFM1094 and MFM1053 (dropped), MFM0809, MFM1056.

NS-lineaments: MFM0126, MFM0101.

Within these groups, MFM0044 needs a special remark. It has now been divided and MFM2225 now forms the more interesting extension. It represents a divergent lineament in the central part of the candidate area. It runs west-northwest, more or less parallel to the magnetic banding and close to the large-scale fold axis. The lineament forms a dislocation of parasitic folds on the large-scale fold structure and can possibly indicate a slip fault plane.

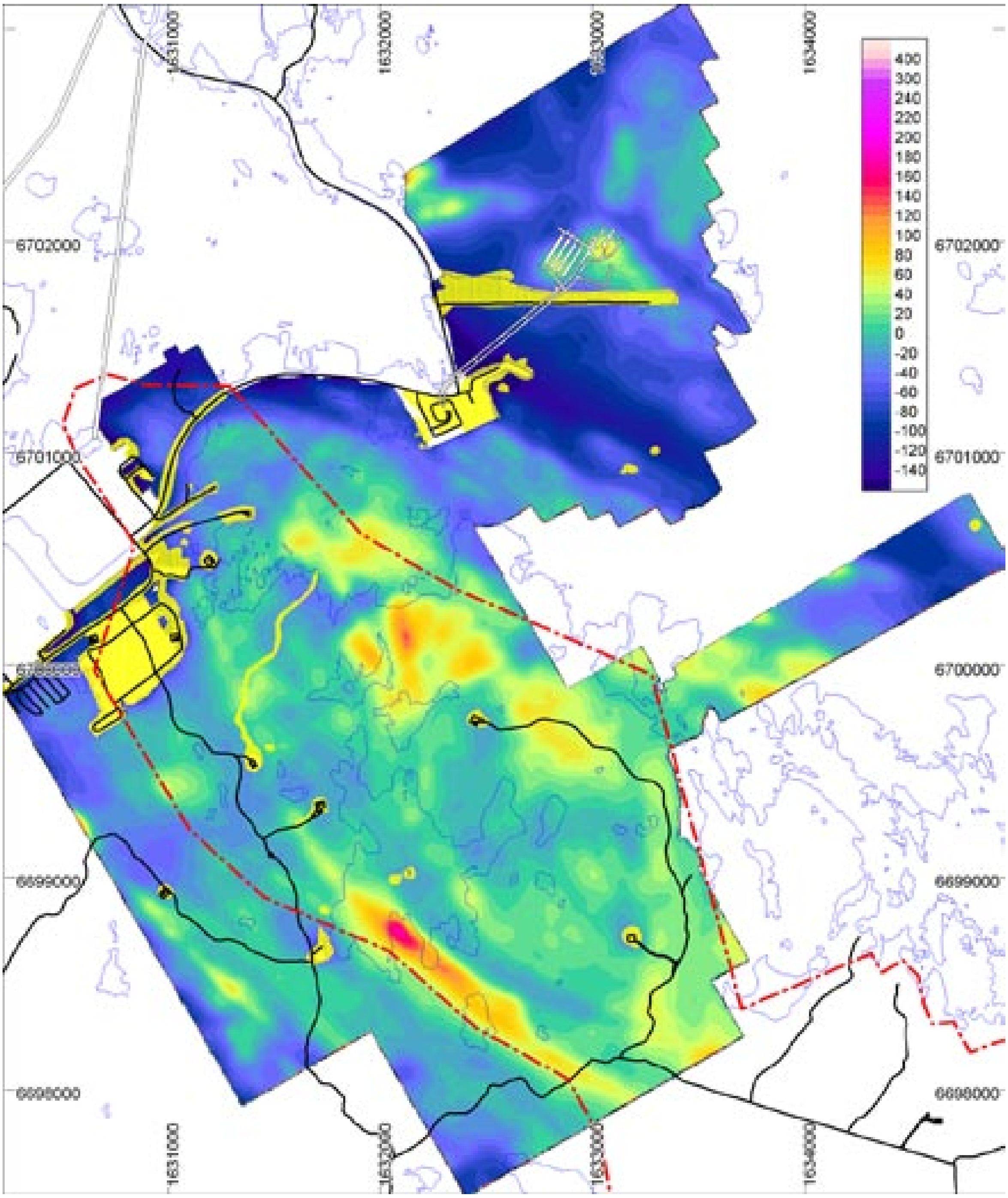

Figure 4-5. *Magnetic anomaly field, the detailed ground survey data presented in Figure 3-6 with upward continuation to a survey level of 40 m above ground, similar to previous helicopter borne survey. Colour range in nanoTesla [nT] is the same as in Figure 3-6. Disturbed areas in bright yellow. The SFR underground facilities and the cooling water tunnel from Forsmark 1 and 2 are shown with black lines and white filling. The Forsmark candidate area is shown as a thick, dot-dashed, red line. Roads and drill sites in black. (GSD-Fastighetskartan . © Lantmäteriverket Gävle 2007. Consent I 2007/1092.*

MFM0803, MFM0804 and MFM1127 have previously been representing the WNW-trending, Singö deformation zone with two separate and parallel, rather wide low magnetic linear features. This interpretation has not fully been confirmed by this work and the deformation zone is now represented by MFM0803, MFM0813 and MFM0804 and interstitial areas with low magnetic intensity and relief. Lineament MFM1127 has been dropped.

The lineament MFM0805, which represent a NW-trending splay to the Singö deformation zone, widens and forms a branch extending just northeast of the SFR underground facility.

Many of the small-scale lineaments identified can possibly be considered as minor splays to the large-scale lineaments.

Lineament patterns

The current work shows that the lineament pattern in the candidate area with mainly east-northeast, discordant lineaments and northwest trending, mostly minima connections, described in /12/, extends both to the southwest (AFM001331) and to the southeast (AFM001330), Figures 4-2, 4-3 and 4-4. In the SFR area (AFM001294) the pattern is strongly affected by the Singö deformation zone in the southwest part. Northeast of the zone, around the SFR underground facility, the lineament pattern is less well defined.

From the previous ground survey /12/ an important discovery was tracking down a lineament pattern with mainly north-northeast direction around Asphällsfjärden. A set of lineaments in the same directions occur in the eastern part of AFM001330, around drill site DS2.

Lineament of magnetic minimum character

It has been pointed out that narrow rock types of low magnetic intensity can be a likely explanation for linear features with a magnetic minima connection character, that is, lineaments concordant with the general bedrock structures and the banded magnetic pattern. However, it should be observed that a fracture zone cannot be ruled out and this characterization has to be treated with caution.

The main magnetic trend can also be difficult to determine. This is especially the case in the bended structures close to the axial plane of the large fold structure. In some cases the magnetic minimum is related to a magnetic maximum and can be caused by the dip of a magnetic body. In the previous report /11/ examples were given of cases in which a minimum to some extent can be explained by the strike and dip of a magnetic body and where a strong narrow magnetic minimum occur alone and has to be explained by a narrow, low magnetic rock type, a rock type with reversed magnetization, a fracture zone or a very narrow and deep bedrock surface depression. These types of situations have been considered in the lineament identification work.

Dyke-like lineament features

An anomaly of dyke-like character, that is discordant and often higher magnetic narrow linear anomalies, was first identified in the Forsmark area with the previous interpretation of ground magnetic data /12/. Within the new surveys the dyke-like anomaly pattern in the south-western part of Bolundsfjärden extends further, both to the northwest and southeast, Figures 4-2 and 4-3 (green line). The lineaments are characterized of combined, narrow and parallel magnetic minima and maxima in the northwest part, Figures 3-7, 3-8 and 3-9. The magnetic minima can be a shadow effect due to the dip of a magnetic dyke giving the positive anomaly. To the southeast, the character changes to be only magnetic maxima connections, slightly discordant to the general magnetic banding. It is recommended that drill core or other exposed bedrock in the area around the dyke-like lineament should be checked for rock types and sequences from which this magnetic pattern can originate.

4.5 Uncertainties

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 magnetic lineaments and their character.

Differences in magnetic properties in the bedrock 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.

Differences in overburden thickness also give different conditions for lineament identification. Large areas with a thin overburden give a better spatial and dynamic resolution of the magnetic pattern and hence, lineaments are more easily identified. Due to an increase in water depth along the marine fairway to SFR and around the SFR underground facility, the survey area AFM001293 and AFM001294 give a somewhat less detailed magnetic pattern. The lineament density visible in Figure 4-2 also illustrates this fact rather well.

Topographical subsurface features like narrow depressions in the bedrock surface can give rise to a locally deeper overburden and hence, also cause a linear magnetic low which not necessarily correspond to a change in bedrock susceptibility due to fracturing.

Horizontal to sub-horizontal structures are more difficult to identify in the magnetic field and when they occur they often appear as curved features.

The survey direction SSE-NNW makes it easier to identify structures with a WSW-ENE extension. However, by the small difference in line density compared to the station density, 10 m and 2–5 m respectively, this effect is rather small.

Some simplifications have been made in the correction of data for current in the Fenno-Skan HVDC cable. The resulting errors are however small enough not to have affected the interpretation.

When linking two coordinated lineaments, there is in some cases more than one way to do it. How the linking is made will also have a major influence on the final length of the linked lineament.

In some cases, a lineament with low uncertainty over a long length can have an uncertain but short link between the longer segments. This information is not much considered by the applied methodology. The weighted average according to the length of each segment will give the possible break a very low significance.

Several lineaments are not terminated, but have an open end at the interpretation boundary. Consequently these lineaments are given a minimum length.

The airborne magnetic data used in previous regional, large-scale lineament interpretations /3, 4, 5/ matches a lineament representation at a scale of 1:50,000–1:100,000 in the open sea area (Öregrundsgrepen), and a scale of 1:20,000–1:10,000 in the coastal area as well as on the mainland. This work and /11 and 12/ has been carried out in a detailed scale of around 1:5,000. Work based on more detailed data will commonly provide a finer resolution of structures that will fade away in coarser scales and data. Longer lineaments at a regional scale will, at a detailed scale, be divided into shorter and often non-coherent segments.

The SFR underground facility probably contains considerable steel material and constructions that can be the cause of some of the magnetic anomalies in the area. At the same time the pier constructed above the SFR underground facility contains iron waste which disturbs the magnetic survey. This gives an overall uncertainty in the lineament interpretation in the area.

5 Delivered data

The processed data and interpretation results from the magnetic survey, phase 2, have been delivered to SKB as described in Appendix 1. All data have been documented according to "Inleverans av data", SKB SD-111 (SKB internal controlling document). Magnetic field data for the survey area AFM100206 /11/ and AFM001292, AFM001293, AFM001294 and AFM001314 /12/ have previously been delivered. The phase 2 delivery also includes interpretation results for area AFM001294 that was not included in /12/.

Data have been delivered in three data formats for storage in the GIS-database. Grid-files and information that has resulted in some kind of interpreted vector; point, line or polygon data has been stored in vector, Shape format. Report figures are delivered as image files. A listing of the format for each delivered product is shown in Appendix 1. Survey data have been stored in a Microsoft Excel template received from SKB and delivered to the SICADA-database.

The following data have been delivered in phase 2:

Survey data

- Magnetic total field (GP330 in SICADA) for the following identity codes: AFM001330 and AFM001331.

Grid data

- Interpolated grid (cell size 4×4 m) created from magnetic anomaly field data for areas: AFM100206, AFM001292, AFM001293, AFM001294, AFM001314, AFM001330 and AFM001331.

Interpretation data

- Linked magnetic lineaments (four data sets).
- Linked magnetic lineaments with dyke-like character.
- Coordinated magnetic lineaments.
- Diffuse magnetic pattern.
- Disturbed areas.
- Low magnetic areas.
- Magnetic maxima connections.
- Ground magnetic survey areas.
- Tilt derivative zero contour.

Report figures

References

/1/ **Munier R, Stanfors R, Milnes A G, Hermansson J, Triumf C-A, 2003.** Geological site descriptive model. A strategy for the model development during site investigations. SKB R-03-07. Svensk Kärnbränslehantering AB.

/2/ **Isaksson H, 2003.** Interpretation of topographic lineaments 2002. Forsmark site investigation. SKB P-03-40. Svensk Kärnbränslehantering AB.

/3/ **Isaksson H, Thunehed H, Keisu M, 2004.** Interpretation of airborne geophysics and integration with topography. Forsmark site investigation. SKB P-04-29. Svensk Kärnbränslehantering AB.

/4/ **Korhonen K, Paananen M, Paulamäki S, 2004.** Interpretation of lineaments from airborne geophysical and topographic data. An alternative model within version 1.2 of the Forsmark modelling project. SKB P-04-241. Svensk Kärnbränslehantering AB.

/5/ **Isaksson H, Keisu M, 2005.** Interpretation of airborne geophysics and integration with topography Stage 2 (2002–2004). An integration of bathymetry, topography, refraction seismics and airborne geophysics. Forsmark site investigation. SKB P-04-282. Svensk Kärnbränslehantering AB.

/6/ **Johansson R, 2005.** A comparison of two independent interpretations of lineaments from geophysical and topographic data at the Forsmark site. Forsmark site investigation. SKB P-05-23. Svensk Kärnbränslehantering AB.

/7/ **Johansson R, Isaksson H, 2005.** Assessment of inferred lineaments in the north-western part of the Forsmark site investigation area. Present knowledge and recommendations for further investigations. Forsmark site investigation. SKB P-05-261. Svensk Kärnbränslehantering AB.

/8/ **SKB, 2004.** Preliminary site description. Forsmark area – version 1.1. SKB R-04-15. Svensk Kärnbränslehantering AB.

/9/ **SKB, 2005.** Preliminary site description. Forsmark area – version 1.2. SKB R-05-18. Svensk Kärnbränslehantering AB.

/10/ **SKB, 2007.** Stephens M B, Fox A, La Pointe P, Simeonov A, Isaksson H, Hermanson J, Öhman J, 2007. Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2. SKB R-07-45. Svensk Kärnbränslehantering AB.

/11/ **Isaksson H, Pitkänen T, Thunehed H, 2006.** Ground magnetic survey and lineament interpretation in an area northwest of Bolundsfjärden. Forsmark site investigation. SKB P-06-85. Svensk Kärnbränslehantering AB.

/12/ **Isaksson H, Thunehed H, Pitkänen T, Keisu M, 2006.** Detailed ground magnetic survey and lineament interpretation in the Forsmark area – 2006. Forsmark site investigation. SKB P-06-261. Svensk Kärnbränslehantering AB.

/13/ http://www.ngdc.noaa.gov/seg/geomag/jsp/struts/calcPointIGRF

/14/ **Verduzco B, Fairhead J D, Green C M, MacKenzie C, 2004.** New insights into magnetic derivatives for structural mapping. The Leading Edge, February 2004, Vol. 23, No. 2, pp 116–119. ISSN 1070-485X.

Appendix 1

Delivered data

Shape/files

Filename	File type	Content
MFM_3km_RMA_magnetic_linked_lineament_line	Shp	Linked magnetic lineaments larger than 3 km in the regional model area.
MFM_0-3km_G-LMA_magnetic_linked_lineament_line	Shp	Linked magnetic lineaments shorter than 3 km, within the regional model area and also affecting the magnetic ground survey area and/or the local model area.
MFM_Ground_magnetic_linked_lineament_line	Shp	Linked lineaments interpreted from the detailed magnetic ground survey.
MFM_All_magnetic_linked_lineaments	Shp	Linked lineaments compiled from the three datasets above.
MFM_Dykelike_lineament_line.shp	Shp	Linked lineaments with dyke-like character.
FM_Ground_magnetic_coordinated_lineament_line	Shp	Co-ordinated magnetic lineaments interpreted from the detailed magnetic ground survey.
FM_Diffuse_magnetic_pattern_point	Shp	The centre point of an area with diffuse magnetic pattern.
FM_Disturbed_Areas	Shp	Disturbed survey areas.
FM_Low_Magnetic_Areas	Shp	Areas with low magnetic intensity and relief.
FM_Magnetic_maxima_connection_line	Shp	Magnetic connections (maxima).
AFM_Ground_magnetic_survey_areas	Shp	Magnetic survey areas AFM100206, AFM001292, AFM001293, AFM001294, AFM001314, AFM001330 and AFM001331.
FM_Ground_magnetic_TDR_Zero_contour_line	Shp	Zero contour of the tilt derivative of the total magnetic field.

Grid/files

Filename	File type	Content
AFM_Ground_magnetic_total_field_grid	grid	A common interpolated grid created from magnetic anomaly field data, survey area: AFM100206, AFM001292, AFM001293, AFM001294, AFM001314, AFM001330 and AFM001331. Cell size 4×4 m.

SICADA

Filename	File type	Content
AFMxxxxxx_delx_GP330 - Profile, total magnetic field	xls	Magnetic total field (GP330 in SICADA) for the following identity codes: AFM001330 and AFM001331.

File archive

Filename	File type	Content
Figure X-Y	jpg	Figures from this report as images; X = report section, Y = serial number.