P-03-104

Forsmark site investigation

A ground geophysical survey prior to the siting of borehole KFM05A and KFM06A and control of the character of two SW-NE oriented lineaments

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March 2004

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ISSN 1651-4416
SKB P-03-104

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Keywords: Maxmin, Slingram, Magnetometry, Electromagnetics, Geophysics.

Contents

1 Introduction

This document reports the results gained from a ground geophysical survey in the Forsmark candidate area prior to the siting of borehole KFM05A and KFM06A and control of the character of two SW-NE oriented lineaments. The project was carried out in September 2003 according to activity plan AP PF 400-03-65 (SKB internal controlling document) and comprised electromagnetic and magnetic profile measurements (Figure 1-1).

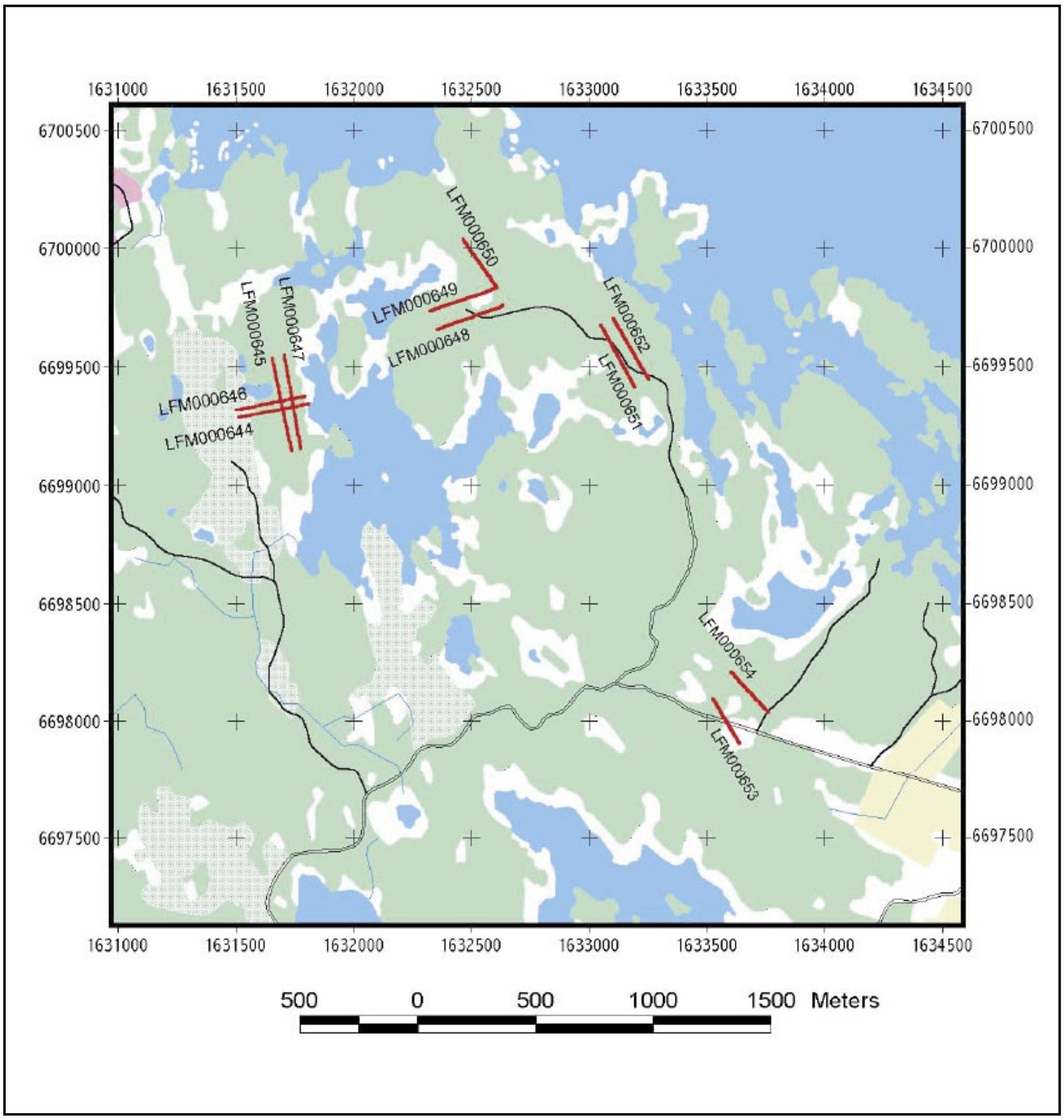

Figure 1-1. *Line location map. Total magnetic field and slingram measurements were carried out along all lines.*

2 Objective and scope

The geophysical survey, with MaxMin slingram and magnetometer, aimed at investigating the possible occurrence of fracture zones at the intended sites for the boreholes KFM05A and KFM06A. Additional profile measurements were made in order to control the location and geophysical characteristics of two, local major, SW-NE oriented lineaments.

A total of 3.3 line-km of magnetic total field and 3.23 line-km of HLEM APEX MaxMin slingram measurements were carried out during the period of September 9 to 12, 2003.

3 Equipment

3.1 Description of equipment

The magnetic survey was conducted with two GEM GSM19 magnetometers, one of which was used as a base station for recording the diurnal variation of the magnetic field. Base station readings were recorded every 10 seconds. The mobile magnetometer was equipped with an OEM GPS Module, Marconi SuperStar II, with an accuracy of c 5 metres or better. A handheld GPS, Garmin 12CX, was used to locate the decided survey lines.

The slingram survey was conducted with an HLEM APEX Parametrics MaxMin I-9, utilising the frequencies 1760, 3520, 7040 and 14080 Hz.

A handheld compass was used for the orientation of the survey lines and a tape measure was used to control the distance between the survey stations along the lines.

4 Execution

The survey was executed according to method descriptions “Metodbeskrivning för magnetometri” (SKB MD 212.004) and “Metodbeskrivning för slingrammätning” (SKB MD 212.007).

4.1 Preparations

All survey lines were marked with flagging tape every 10 metres. The survey lines were located with a handheld GPS, Garmin 12CX. A measuring tape was used to control the length between the survey stations and a compass was used to get the correct direction. The flagging tape was removed after completion of the survey.

4.2 Base station measurements

Before the survey commenced, a location for the base station magnetometer and a base point for the HLEM MaxMin were selected. The base magnetometer and the mobile magnetometer were synchronised daily, and prior to the line surveying. Before synchronising the magnetometers, the GPS unit on the mobile magnetometer was used to get the correct time (GMT) via satellite. The base station readings were recorded during each and every day of magnetic surveying. The position of the base station is 6697988N/1631633E (RT90, 2.5 gon W).

The base point for the HLEM MaxMin was visited daily, before and after the surveying. No significant drift was noted. The position of the base point is 6697993N/1631568E which corresponds to survey station 10SW on line LFM000554. The coil separation of 49.5 metres that was used in a prior survey /1/ was corrected to 50 metres and used for this survey.

4.3 Data handling

The collected data from the magnetometers and the HLEM MaxMin instrument were dumped to a laptop computer on a daily basis.

Before editing the data, the files were saved in a raw data directory. Editing was only performed on copies of the raw data. The post processing and editing of the magnetic data started by inspecting the base station data in order to see if there were any significant magnetic shifts or spikes during the day. After that, the data from the mobile magnetometer were edited and incorrect data, duplicate points etc were removed. The magnetic data were then corrected for the diurnal variations.

Finally, copies of the corrected data files were edited into Geosoft XYZ files.

Some frequency independent noise was evident in the HLEM MaxMin real component data. Such noise can be attributed to slightly incorrect coil orientation or separation. The lowest frequency is not expected to show any significant anomalies due to geological structures on the real component. This component can therefore be subtracted from the higher frequency data in order to reduce the above mentioned noise.

4.4 Determination of coordinates

During the survey, the mobile magnetometer with a GPS module was used to measure the start and end co-ordinates of the survey lines. In a few cases those points were unsuitable for GPS measurements and nearby survey points were used instead. The GPS was set to take one reading per second and, depending on the satellite conditions, a position was measured for around 1.5–4 minutes. An average of all readings at each position was calculated and transformed from WGS84 latitude/longitude to RT90 XY (X = North, Y = East), see Table 4-1. The transformation was made with a GeoVista in-house 7 parameter transformation software. The software works in accordance with the parameters and equations given in /2/.

Benchmark PP1202, at position 6699539.512 N and 1631321.584 E, was visited on four different occasions. Readings were taken with the OEM GPS Module at all occasions and with the Garmin 12CX at two occasions (Table 4-2).

Table 4-1. All GPS positions along the survey lines.

Line	Coordinate	Time (GMT)	Latitude (WGS84)	Longitude (WGS84)	RT90 X (m)	RT90 Y (m)	
LFM000644	0E	64522	60.3901523	18.1904719	6699290	1631514	
LFM000644	300E	70508	60.3905502	18.1958428	6699345	1631808	
LFM000646	295E	71228	60.3908314	18.1955929	6699376	1631793	
LFM000646	0E	73426	60.3904281	18.1903273	6699320	1631505	
LFM000647	400N	74852	60.3923141	18.1941718	6699538	1631709	
LFM000647	0N	81222	60.3888502	18.1951442	6699154	1631777	
LFM000645	0N	82120	60.3888017	18.1944317	6699147	1631737	
LFM000645	415N	84313	60.3925260	18.1931319	6699560	1631651	
LFM000648	300E	103833	60.3939871	18.2111004	6699758	1632635	
LFM000648	0E	105946	60.3932589	18.205847	6699667	1632349	Poor satellite geometry
LFM000649	0E	110526	60.3938923	18.205438	6699736	1632324	
LFM000649	300E	112224	60.3946732	18.210695	6699834	1632610	
LFM000650	0N	112224	60.3946732	18.210695	6699834	1632610	Same as LFM000649/300E
LFM000650	250N	114041	60.396563	18.208176	6700039	1632464	
LFM000651	300N	120910	60.3930855	18.218607	6699673	1633053	
LFM000651	0N	122742	60.390719	18.221004	6699414	1633194	
LFM000652	0N	123526	60.390988	18.222102	6699447	1633254	
LFM000652	300N	125259	60.3933643	18.219517	6699706	1633102	
LFM000653	240N	134734	60.3789291	18.225974	6698111	1633516	
LFM000653	20N	140518	60.3772028	18.227869	6697923	1633628	
LFM000654	0N	141452	60.3782038	18.230331	6698039	1633760	
LFM000654	230N	143235	60.3797610	18.227627	6698207	1633604	
LFM000648	5W	150135	60.3931512	18.205812	6699655	1632347	
LFM000648	0E	150532	60.3931840	18.205923	6699659	1632353	Better than same point above

Table 4-2. Bench-mark PP1202.

Instrument	WGS84 Latitude	Longitude	RT90, 2.5 gon W X	Y	Difference X / Y (m)
OEM GPS Module, Marconi SuperStar II. 2003-09-10	60.3924432	18.1871445	6699538.5	1631321.2	1.0 / 0.4
OEM GPS Module, Marconi SuperStar II. 2003-09-11	60.3924462	18.1871558	6699538.9	1631321.8	0.6 / 0.2
OEM GPS Module, Marconi SuperStar II. 2003-09-11	60.3924474	18.1871581	6699539.0	1631321.9	0.5 / 0.3
OEM GPS Module, Marconi SuperStar II. 2003-09-12	60.3924445	18.1871278	6699538.6	1631320.2	0.9 / 1.4
Garmin 12CX 2003-09-10			6699540	1631322	0.5 / 0.5
Garmin 12CX 2003-09-11			6699539	1631321	0.5 / 0.5

5 Results and data delivery

All data, raw data as well as processed data, have been delivered to SKB and the processed data have been stored in SICADA/GIS. The SICADA reference to the activity is field note Forsmark No. 241.

5.1 Line survey data

The line survey data are presented in Figures 5-1 to 5-11. Only the highest slingram frequency (14 kHz) is shown in these figures. Anomalies from geological structures in the imaginary component can be found also for the lower frequencies. However, the magnitude of the anomalies decreases with decreasing frequency although the anomaly shape is very much the same. The same vertical scale has been used throughout the figures for the magnetic anomaly. The slingram data for some profiles were affected by strong anomalies caused by cables and fences. For this reason the vertical scale had to be adjusted.

The measured in-phase component of the lowest HLEM MaxMin frequency (1760 Hz) has been subtracted from the other in-phase components in order to reduce the effect of incorrect transmitter-receiver geometry. This difference is presented in the figures. The effect of incorrect transmitter-receiver geometry is negligible in the quadrature component.

5.1.1 Lines LFM000644 to 647

The lines LFM000644 to 647 were measured around the planned site for borehole KFM05A. The lines LFM000644 and 646 run roughly EW whereas the lines LFM000645 and 647 run roughly NS. The results can be seen in Figures 5-1 and 5-2.

Slingram minima in the imaginary components that can be interpreted to be caused by an electric conductor appear at 50E (LFM000644) and 65E (LFM000646) respectively (Figure 5-1). This anomaly coincides roughly with a previously interpreted lineament from helicopter borne geophysical data and topography /3/ (Figure 5-3). The lineament has been classified as “local major” and has been given the identity XFM0099 /3/. The continuation of this lineament also coincides with a slingram anomaly in a ground geophysical survey that was performed around borehole KMF01A to the north /4/. The dip of the conductor is difficult to estimate, since the anomaly is rather weak and overlaps another anomaly further east. An easterly dip seems however probable.

Slingram minima that can be interpreted to be caused by an electric conductor, semi-parallel to the previous one, can also be seen at 145E (HFM000646) and 150E (HFM000644). This lineament is not identified in the previous airborne geophysics and/or topography interpretation. The dip of the conductor cannot be estimated from the data available.

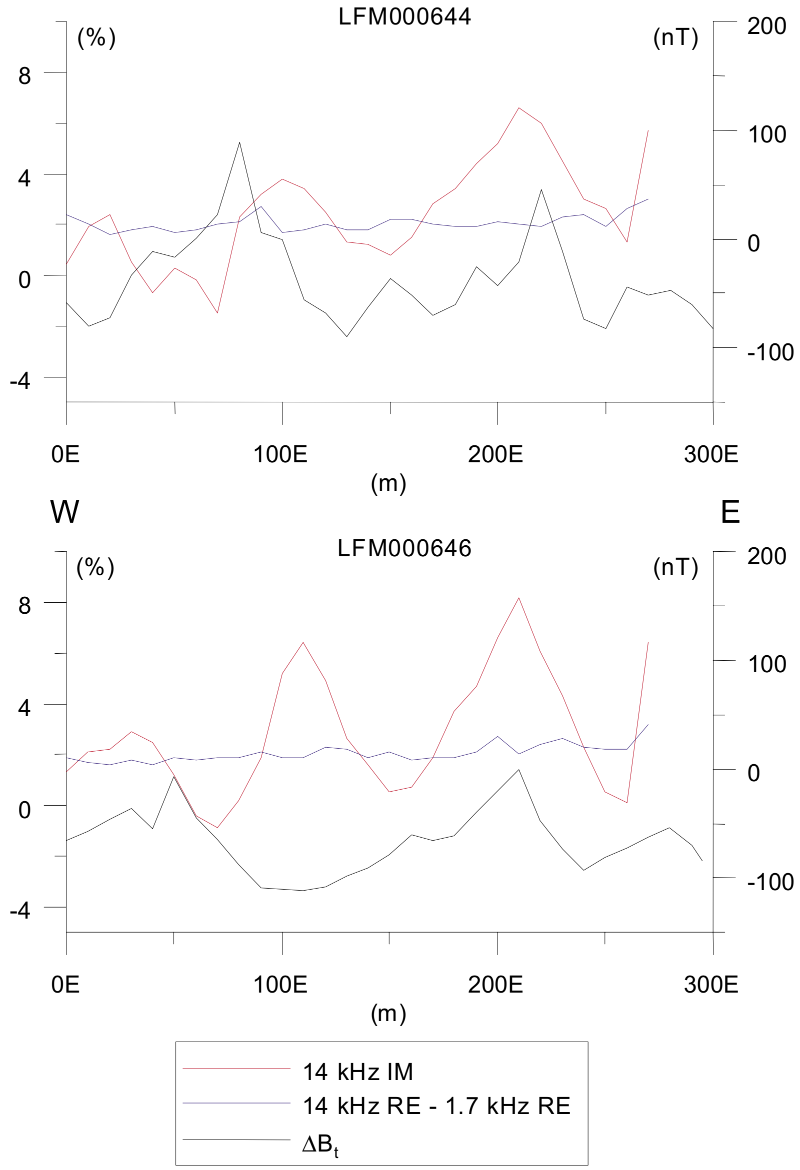

Figure 5-1. *Slingram and magnetic measurements, profiles LFM000644 and LFM000646.*

There is no corresponding anomaly in the real components to the above mentioned imaginary component anomalies. This implies that the anomalies are caused by rather poor electrical conductors. A rough estimate of the resistivity and thickness of the conductors is given by numerical modelling in Section 5.2.

Slingram minima for the imaginary component can also be seen at 250E on both EW profiles. The anomaly is probably caused by the water in the lake Bolundsfjärden, possibly in combination with conductive sediments, although a bedrock conductor cannot be ruled out. There is a general increase in the level of both the imaginary and real components, indicating an increase in soil cover thickness towards east (Figure 5-1).

There is hardly any correlation between slingram and magnetic data along the two EW profiles. The two magnetic profiles also appear rather dissimilar. This can however be explained by the fact that they are measured along a magnetic structure, see Figure 5-4 which displays the performed ground measurements on a background of helicopter borne magnetic data.

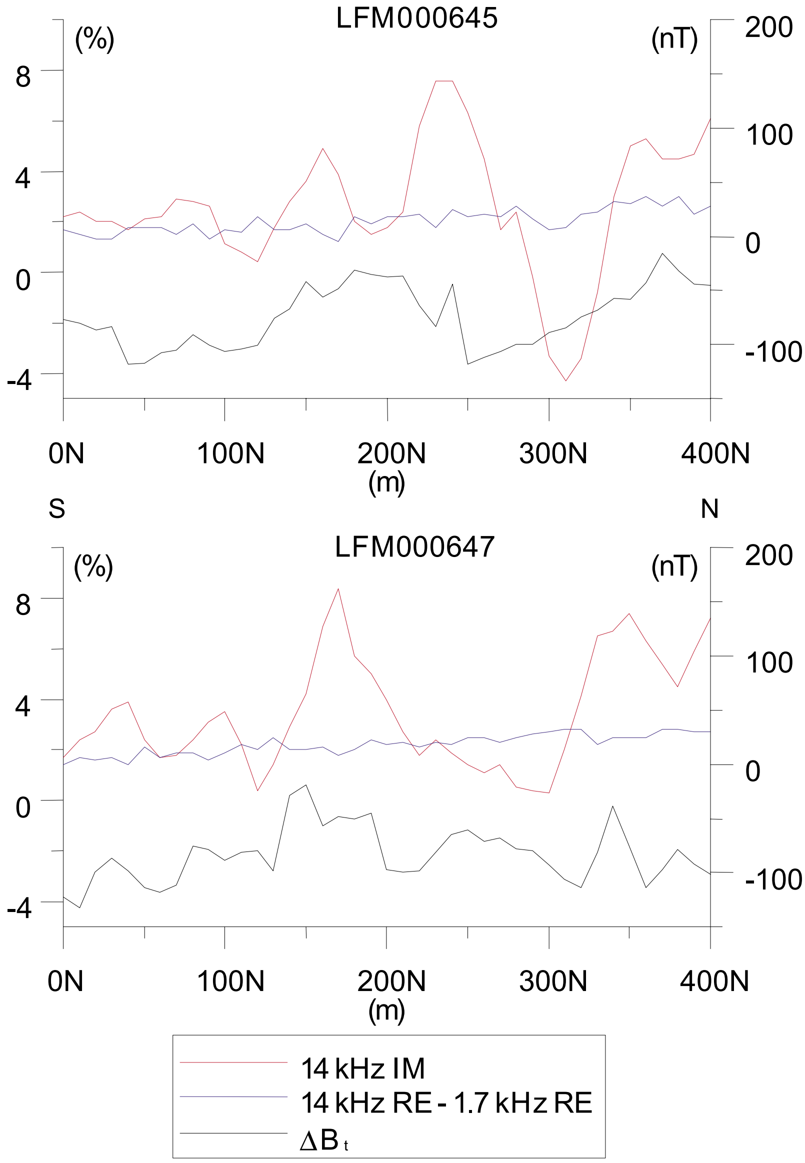

***Figure 5-2.** Slingram and magnetic measurements, profiles LFM000645 and LFM000647.*

A rather distinct slingram minimum can be seen in the imaginary component at 310N along the NS-oriented line LFM000645, see Figure 5-2. No such distinct minimum is observed on LFM000647. However, a minimum at 295N is probably caused by the same conductor. This would then correspond to a WNW strike direction of the conductor. A local minor lineament XFM0406 /3/ correlates well with these slingram anomalies. There are also two anomalies in a NS slingram profile near borehole KFM01A (Figure 5-3). The dip of the conductor is difficult to determine since the anomalies do not show the typical shape expected from a sheet-like conductor. It is possible that the measurements are affected by the nearby lakes and the eastern conductor indicated in the EW profiles above. A local major lineament XFM0060 /3/, striking ENE, cuts the profiles close to the above mentioned anomalies although this lineament does not seem to cause a slingram anomaly of the same magnitude as the WNW striking lineament.

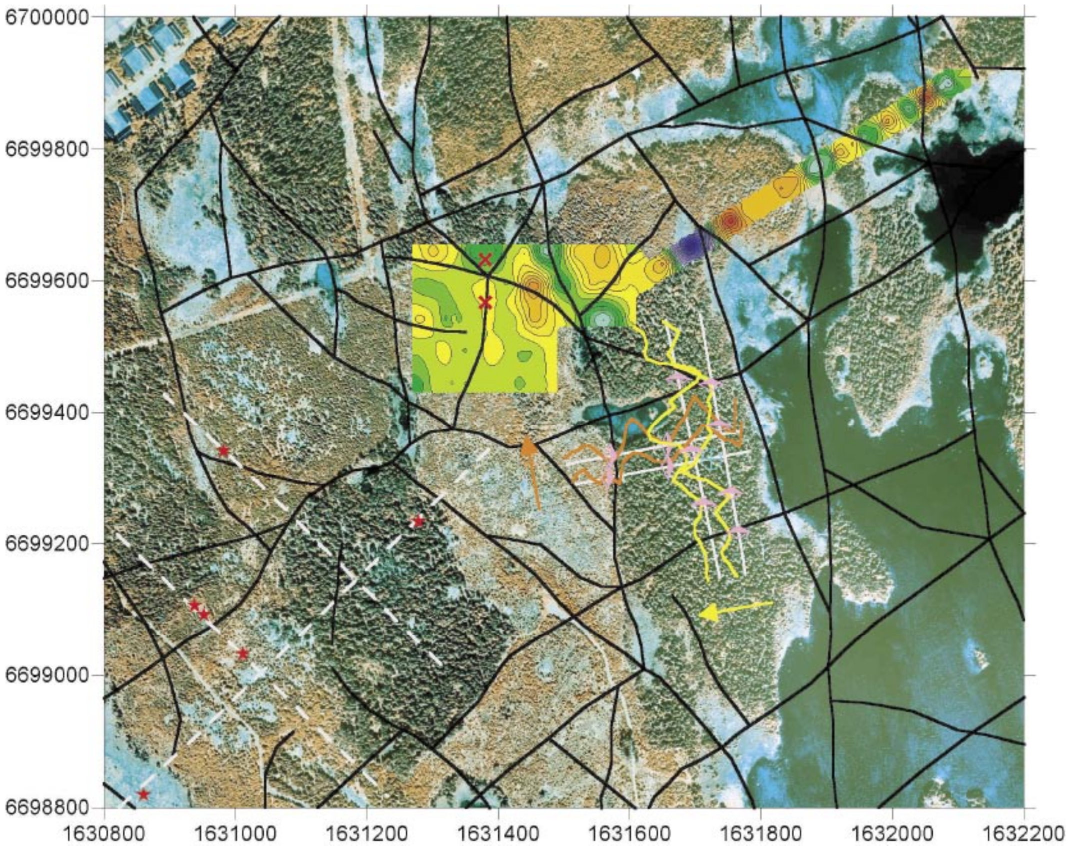

Figure 5-3. *LFM000644 to 647 are shown with solid light grey lines with IR orthophoto as background. Stacked profile data of the slingram 14kHz imaginary component are shown in yellow for NS lines and orange for EW lines. The arrows indicate direction of positive anomalies. Pink diamonds indicate positions of slingram anomalies mentioned in the text. The black lines are lineaments from /3/. The contour map shows slingram data (14 kHz Im) from EW line measurements around KFM01 /4/. The red crosses indicate positions of slingram anomalies from a NS line close to KFM01 /4/. Light grey dashed lines show lines where geophysical measurements were performed around KFM04 /1/. Red stars indicate slingram anomalies along these lines.*

Slingram anomalies in the imaginary component can also be found at 110N (LFM000645) and 120N (LFM000647), corresponding to an ENE strike direction of the conductor. This conductor seems to be dipping to the north. A weak slingram anomaly can also be seen at 60N along LFM000647. The latter indication is close to an interpreted ENE-directed, local minor lineament XFM0401 /3/. Possible slingram anomalies are also found at 190N (LFM000645) and 220N (LFM000647).

There is a general increase in the level of both the imaginary and real components towards north in Figure 5-2. This indicates an increased soil cover thickness.

There is a fairly good agreement between slingram anomalies and magnetic minima in the southern part of the NS profiles, compared to the more complex situation in the northern part with magnetic minima at 210N and 320N (LFM000647) and 250N (LFM000645).

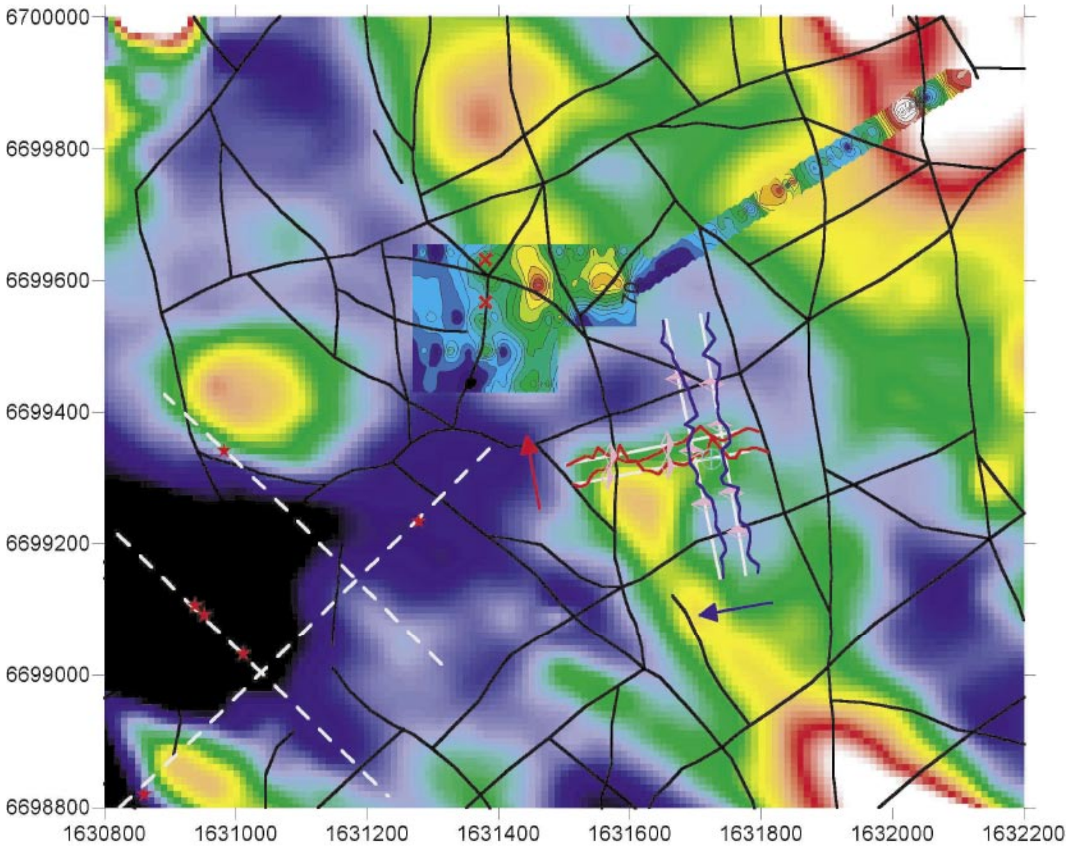

Figure 5-4. LFM000644 to 647 are shown with solid light grey lines with helicopter borne magnetic data from NS lines /3/ as background. Stacked profiles of the ground magnetic data are shown in blue for NS lines and red for EW lines. The arrows indicate direction of positive anomalies. Pink diamonds indicate positions of slingram anomalies mentioned in the text. The black lines are lineaments from /3/. The contour map displays magnetic data from WE line measurements around KFM01 /4/. The red crosses indicate positions of slingram anomalies from a NS line close to KFM01 /4/. Light grey dashed lines show lines where geophysical measurements were performed around KFM04 /1/. Red stars indicate slingram anomalies along these lines.

5.1.2 Lines LFM000648 to 650

The lines LFM000648 to 650 were measured around the planned site for borehole KFM06A. The lines LFM000648 and 649 run roughly EW whereas the line LFM000650 runs roughly NS. The results can be seen in Figures 5-5 and 5-6.

A slingram minimum in the imaginary component that can be interpreted to be caused by an electric conductor is found at 255E along LFM000649. The dip is probably to the west. The line LFM000648 passes buried cables at 170E and these cables have caused a strong slingram anomaly. However, at 230E there is a local minimum, probably caused by the same conductor that gives rise to the anomaly on LFM000649. The strike direction of this conductor would then be N to NNE. No other significant slingram anomaly can be found along these profiles. Magnetic minima are observed close to the above mentioned slingram anomalies although located 15 to 20 metres further east. A broad, gentle magnetic minimum can be seen at the centre of both profiles. See also Figure 5-7.

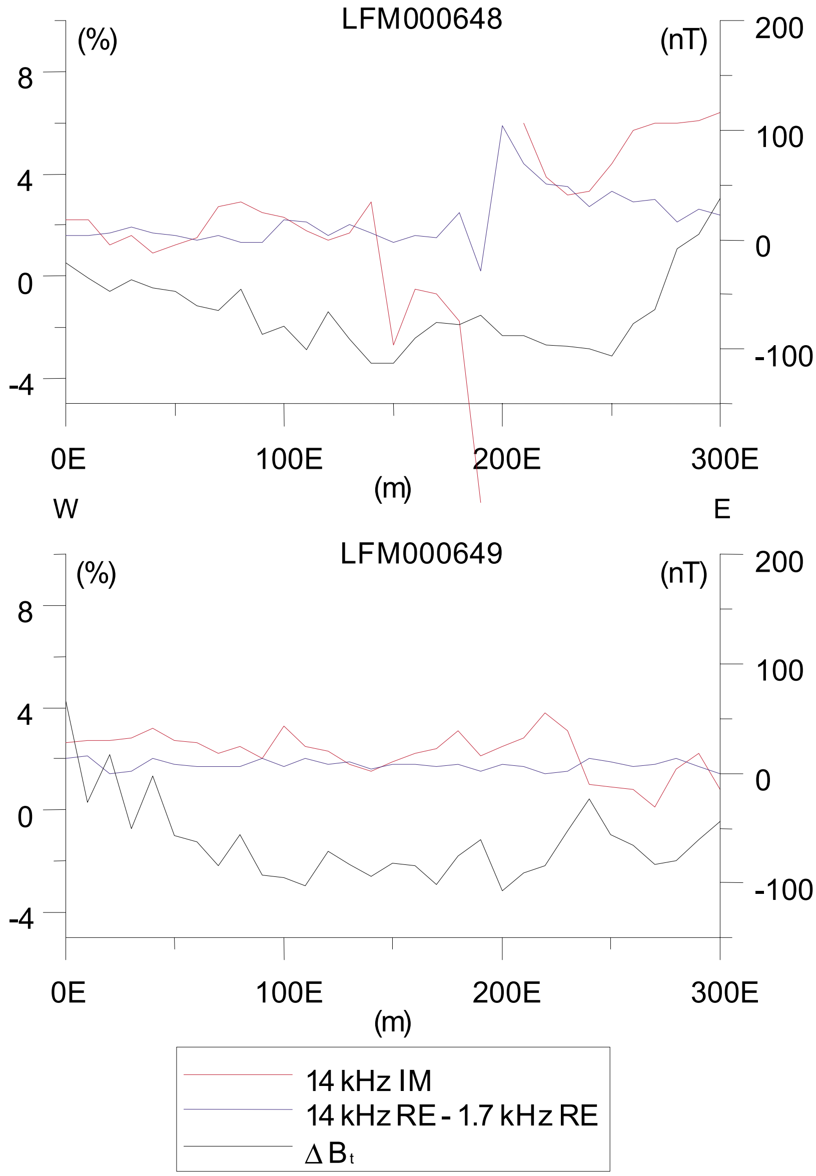

Figure 5-5. *Slingram and magnetic measurements, profiles LFM000648 and LFM000649. Buried cable at ~ 170E along LFM000648.*

A rather broad slingram anomaly is found in the central part of LFM000650. The minimum is however shifted towards north within the anomaly and occurs at 170N. This can be interpreted as a rather wide but poor conductor which, however, is slightly more conductive in its northern part. The dip is difficult to estimate but is probably steep. The slingram anomaly roughly coincides with a magnetic minimum that is 90 metres wide. The anomaly correlates well with the same local major ENE striking lineament, XFM0060, that passes north of drill site 5.

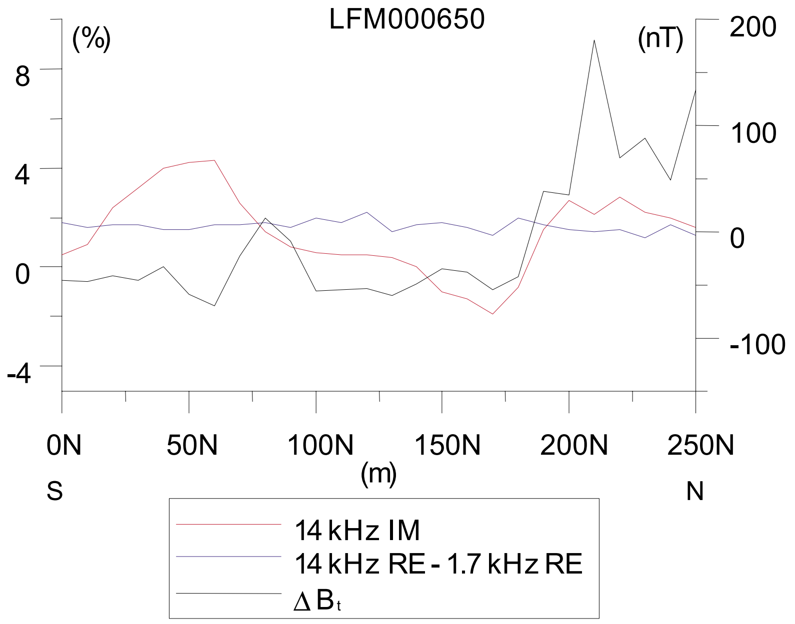

Figure 5-6. *Slingram and magnetic measurements, profile LFM000650.*

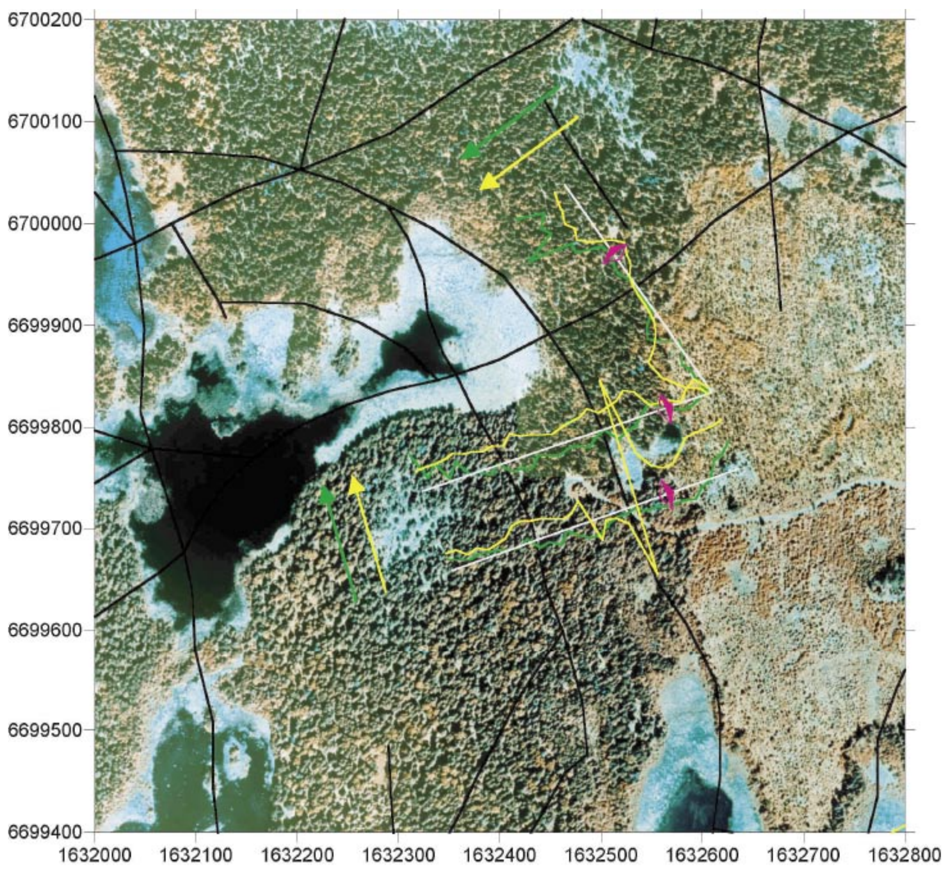

Figure 5-7. *LFM000648 to 650 are shown with solid light grey lines with IR orthophoto as background. Stacked profile data of the slingram 14 kHz imaginary component are illustrated in yellow and magnetic data in green. The arrows indicate direction of positive anomalies. Pink diamonds display positions of slingram anomalies mentioned in the text. The black lines are lineaments from /3/.*

5.1.3 Lines LFM000651 and 652

The lines LFM000651 and 652 were measured with the aim to investigate a local major, ENE striking lineament XFM0062 NE of Graven /3/. Unfortunately, the slingram measurements (Figures 5-8 and 5-9) were severely affected by buried cables along a small road. This road runs parallel and close to LFM000651 for a considerable distance. However, one anomaly caused by geological structures could be identified on the flank of the strong cable anomalies on each of the profiles. The position of these anomalies is 125N (LFM000651) and 130N (LFM000652) which is 20–30 metres south of the lineament. The dip is difficult to estimate but appears to be steep on LFM000652. A magnetic anomaly appears about 30 metres to the north of the slingram anomaly on LFM000652. On LFM000651, there is a rather wide magnetic minimum at the position of the slingram anomaly.

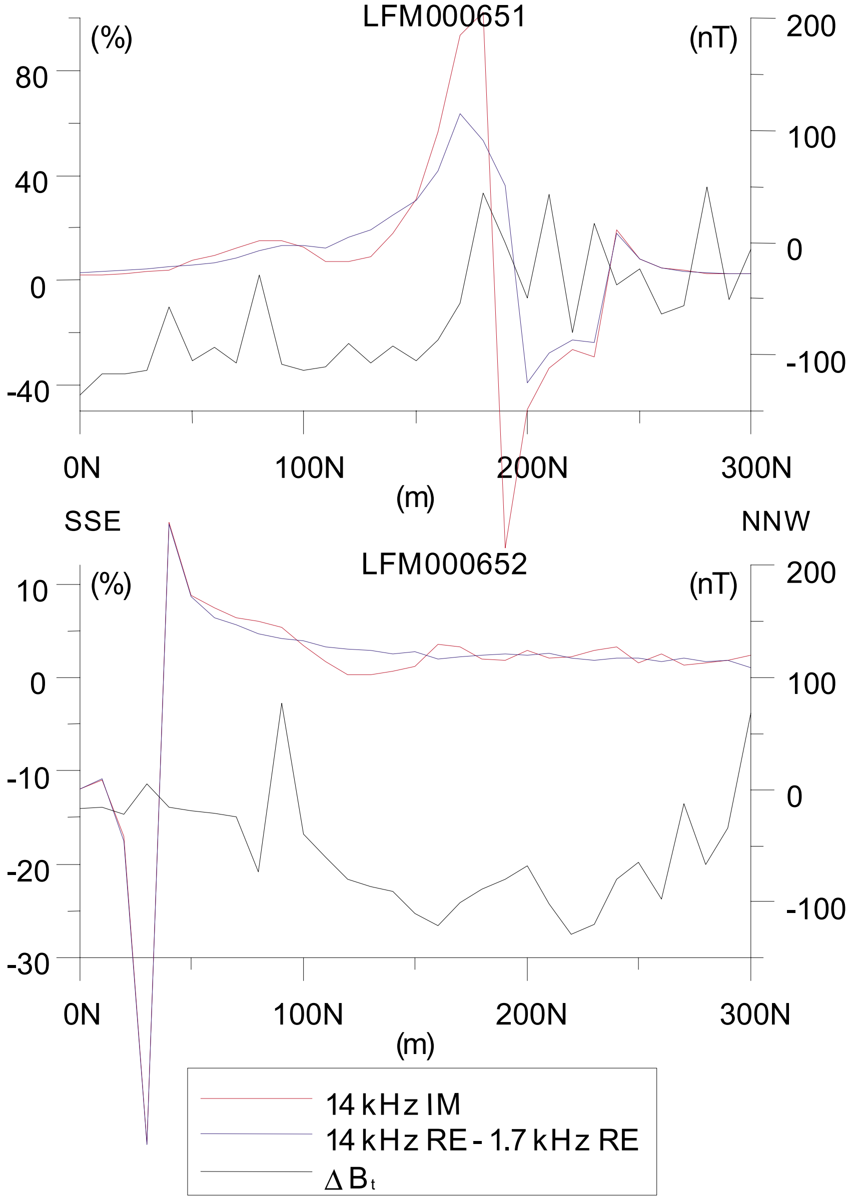

__Figure 5-8.__ Slingram and magnetic measurements, profiles LFM000651 and LFM000652. Buried cables at 210N (LFM000651E) and 5N (LFM000652E).

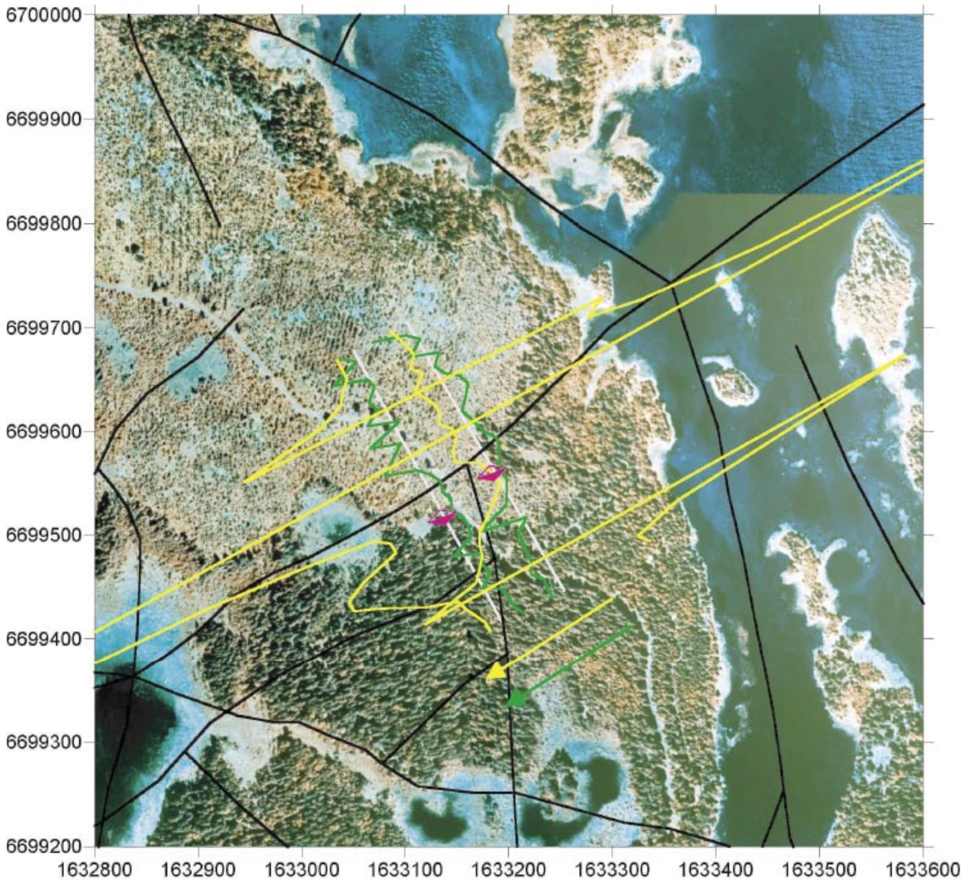

Figure 5-9. *LFM000651 and 652 are shown with solid light grey lines with IR orthophoto as background. Stacked profile data of the slingram 14 kHz imaginary component are shown in yellow and magnetic data in green. The arrows indicate direction of positive anomalies. Pink diamonds illustrate positions of slingram anomalies mentioned in the text. The black lines are lineaments from /3/.*

5.1.4 Lines LFM000653 and 654

The lines LFM000653 and 654 were measured with the aim to investigate a local major, ENE striking lineament XFM0065 south of Lillfjärden /3/. The slingram measurements (Figures 5-10 and 5-11) were severely affected by a fence and possibly by a cattle-grid. The magnetic measurements were also disturbed close to the fence and the cattle-grid. One possible slingram anomaly appears at 130N on LFM000654, although the anomaly curve is seriously disturbed by the anomaly from the fence (Figure 5-10). If the strike direction of this conductor corresponds to the direction of the lineament, it will cross LFM000653 close to the fence and pass unnoticed. A magnetic minimum can be seen at LFM000654, 10 metres to the south of the slingram anomaly. A part of a slingram anomaly is observed at the northern end of LFM000653. The position of the conductor is outside the profile but can through extrapolation be estimated to be at 230N.

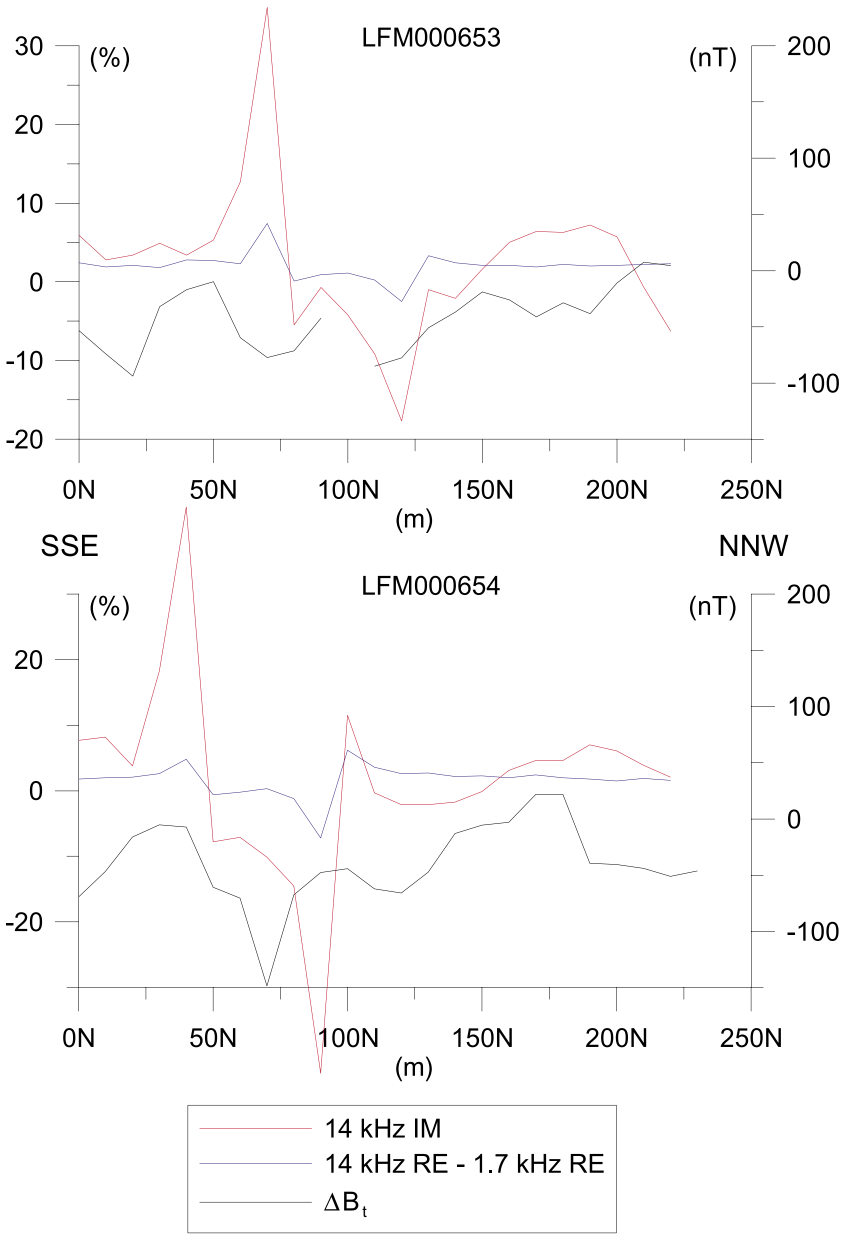

Figure 5-10. *Slingram and magnetic measurements, profiles LFM000653 and LFM000654. Fence and cattle-grid at LFM000653/100 N, fence at LFM000654/69N.*

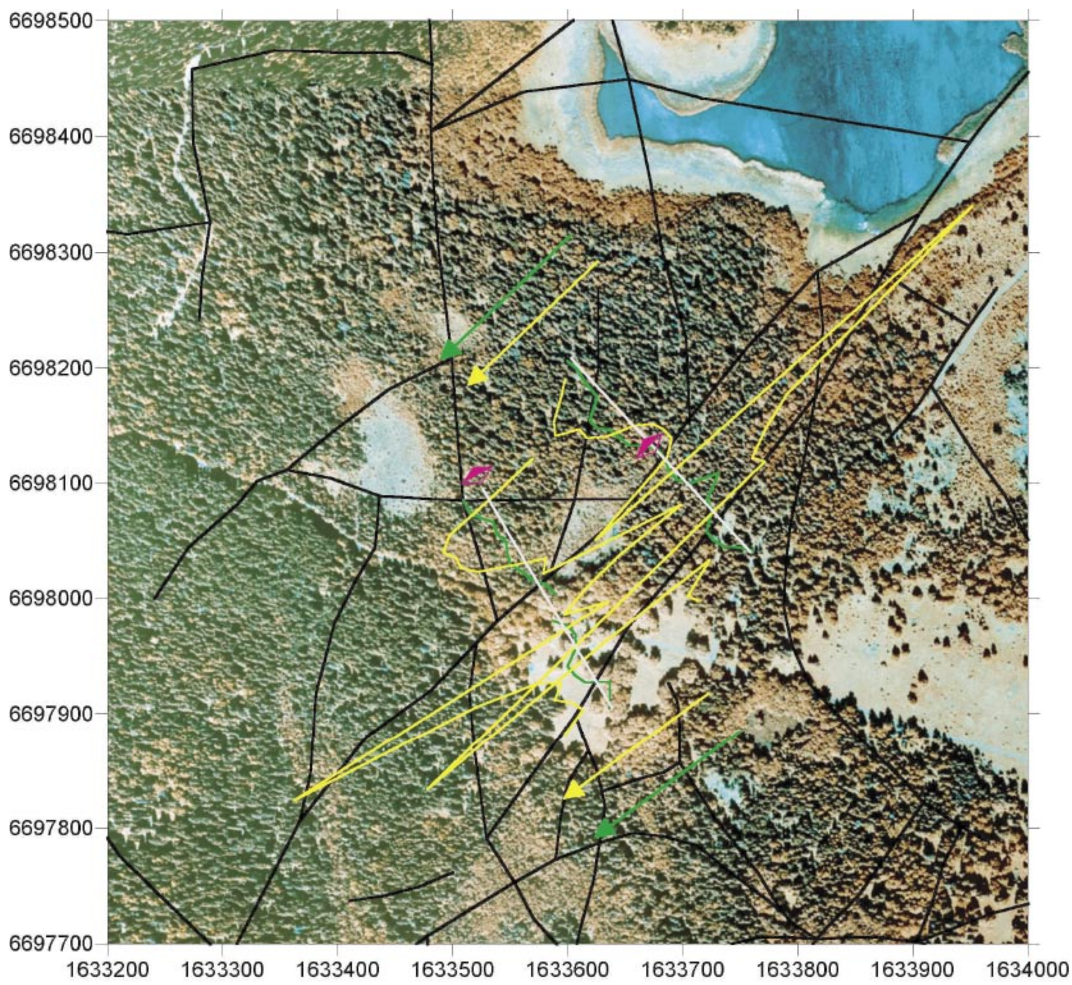

Figure 5-11. *LFM000653 and 654 are shown with solid light grey lines with IR orthophoto as background. Stacked profile data of the slingram 14 kHz imaginary component are shown in yellow and magnetic data in green. The arrows indicate direction of positive anomalies. Pink diamonds indicate positions of slingram anomalies mentioned in the text. The black lines are lineaments from /3/.*

5.2 Modelling of slingram data

Synthetic slingram profiles were calculated for a prism shaped body in a conductive host with the help of the program GeoTutor (Petros Eikon). The purpose was not to get a good fit to any of the field profiles. Instead, knowledge of the possible resistivities and dimensions of bodies causing typical anomalies was sought. Typical features of all slingram anomalies reported in this study are:

- No significant anomalies in the real components.
- The anomaly shape is more or less independent of the measuring frequency.
- The anomaly magnitude in the imaginary components decreases with decreasing frequency.

Currents in a sheet shaped conductor like e.g. a fracture zone can be induced in two different ways. The primary magnetic field can cause the induction and the result will be closed eddy currents in the conductor. A second mechanism is that secondary currents in the host rock are channelled through the conductor. The latter mechanism dominates at high measuring frequencies and for low resistivity contrast between the host and the conductor. Current channelling appears to be the dominating mechanism for all slingram anomalies in this survey. Eddy currents would cause a visible real component of the anomaly, at least for the highest frequency, which is not seen in this survey. Current channelling anomalies can be almost purely imaginary, if the skin depth in the host rock is large compared to the coil separation and the skin depth in the conductor is large compared to its width.

Synthetic responses for a prism shaped conductor are compared with an anomaly along LFM000646 in Figure 5-12. The magnitude of the anomaly is roughly the same for the synthetic model and the anomaly in the field data. The difference in background level between the synthetic anomaly and the field data is partly due to the effect of the soil cover and partly due to incorrect levelling of the instrument. The resistivity of the host was 6500 Ωm in the model. The prism at 2 metres depth was 30 metres wide and had a resistivity of 400 Ωm.

The width and resistivity are the approximate maximum and minimum values, respectively, of a prism that is compatible with the anomalies from the field. A significantly wider prism will cause a wider anomaly, and a significantly less resistive prism will cause visible anomalies in the real components.

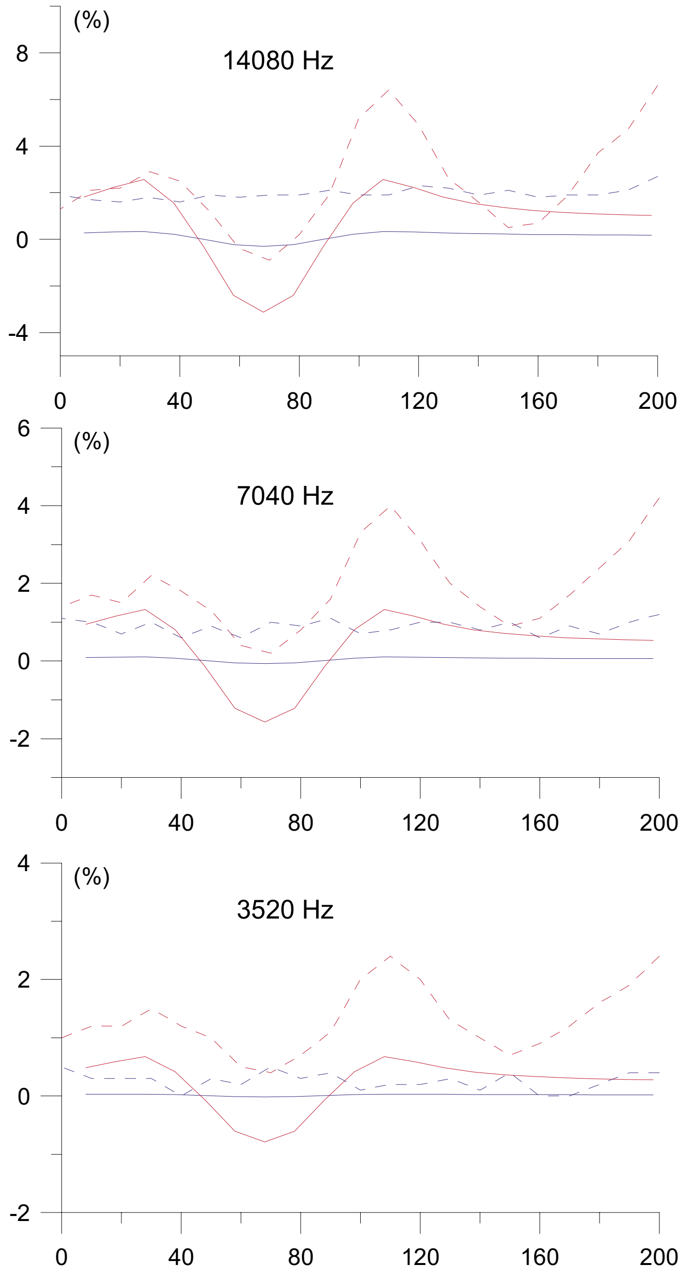

Figure 5-12. *Synthetic slingram anomaly from a prism shaped conductor is shown with solid lines (red = imaginary component, blue = real component). See text for model parameters. An anomaly of similar magnitude from LFM000646 is shown with dashed lines.*

5.3 Modelling of magnetic data

The magnetic data from the profiles LFM000650 and 651 were modelled with the program GMM. In both cases, there is a broad magnetic minimum associated with interpreted lineaments from /3/. Positive magnetic anomalies appear to the north of the lineaments and the purpose of the modelling was to determine the dip of the corresponding magnetic structures. The magnetic profiles are under-sampled due to the shallow depth to the anomaly sources. The dip estimates are therefore only approximate. From petrophysical sampling and measurements on outcrops it is known that the average magnetic susceptibility of magnetic parts of the metagranite in the Forsmark area can be in the order of 600 to 700×10^{-5} SI. Less magnetic granite can have a susceptibility of around 100×10^{-5} SI. However, the magnetic anomalies along the two profiles could not be explained by such susceptibilities. Instead, susceptibilities in the range of 1000 to 2000×10^{-5} SI were used. The remanent magnetization is usually quite weak and was therefore not considered in the modelling.

A model with a reasonable fit to the data from LFM000650 is shown in Figure 5-13. A simple model with plate-shaped bodies, all dipping in the same direction was sought. The dip in the model is towards north. The significance of the dip estimate was examined by changing the dip of all bodies to be to the south. The susceptibilities of the bodies were slightly adjusted to improve the fit. With a dip to the south there is a gentle flank anomaly from the model that is not observed in the field data (Figure 5-14) and the dip towards north seems therefore more probable.

The magnetic data from LFM000651 was modelled in the same way as above. The results are similar, and a dip toward north seems most probable. The results can be seen in Figures 5-15 and 5-16.

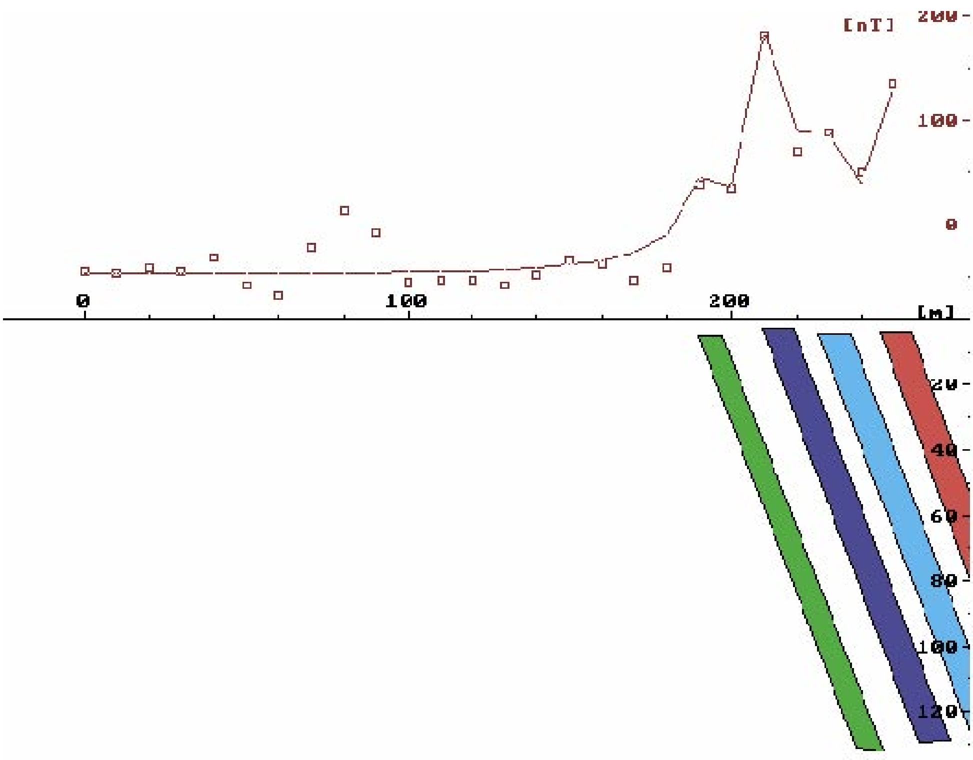

Figure 5-13. *Magnetic modelling of LFM000650, dip towards north. The symbols show the field data and the solid line the synthetic anomaly of the model. The magnetic susceptibility of the bodies varies between 1000 and 2000x10*$^{-5}$ *SI. The background susceptibility is 100x10*$^{-5}$ *SI.*

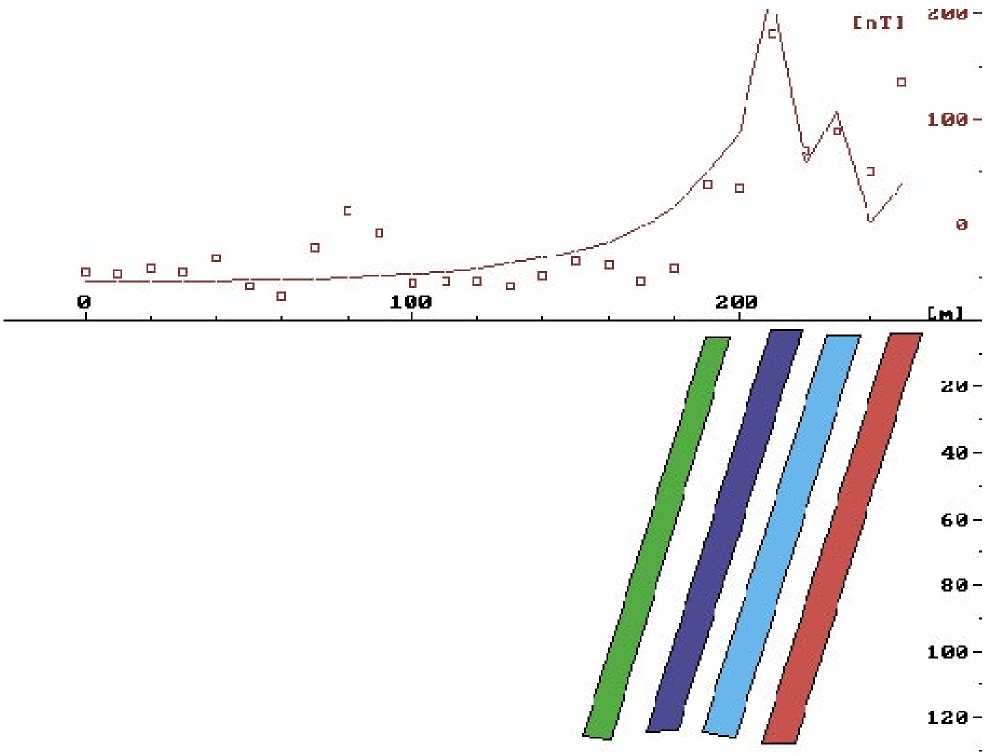

Figure 5-14. *Magnetic modelling of LFM000650, dip towards south. The symbols show the field data and the solid line the synthetic anomaly of the model. The magnetic susceptibility of the bodies varies between 1000 and 2000x10^{-5} SI. The background susceptibility is 100x10^{-5} SI.*

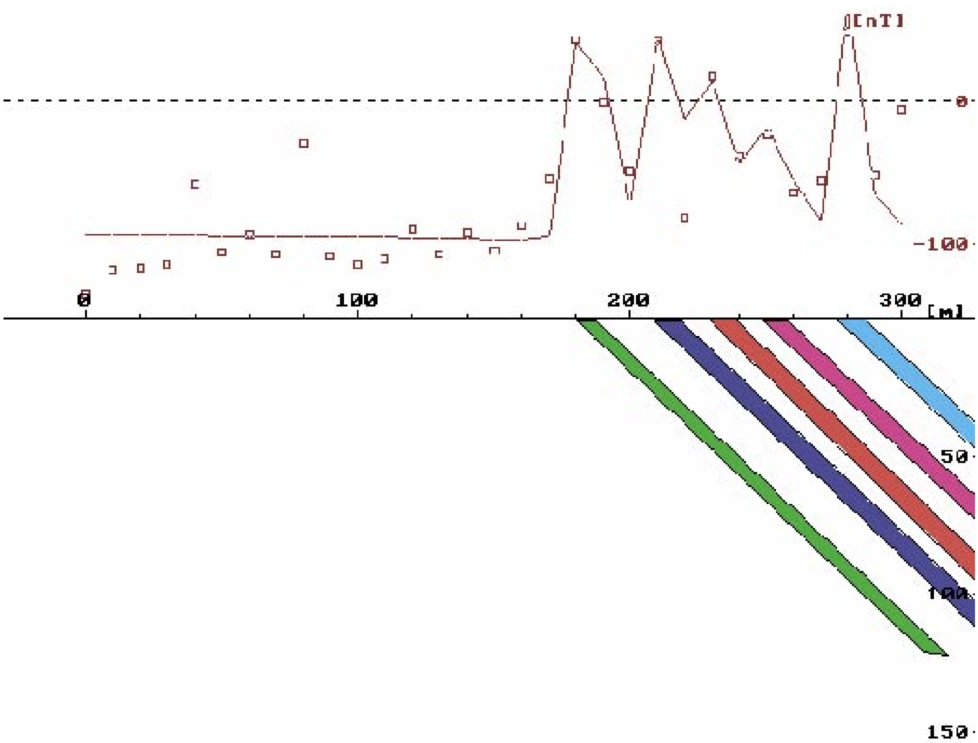

Figure 5-15. *Magnetic modelling of LFM000651, dip towards north. The symbols show the field data and the solid line the synthetic anomaly of the model. The magnetic susceptibility of the bodies varies between 1000 and 2000x10^{-5} SI. The background susceptibility is 100x10^{-5} SI.*

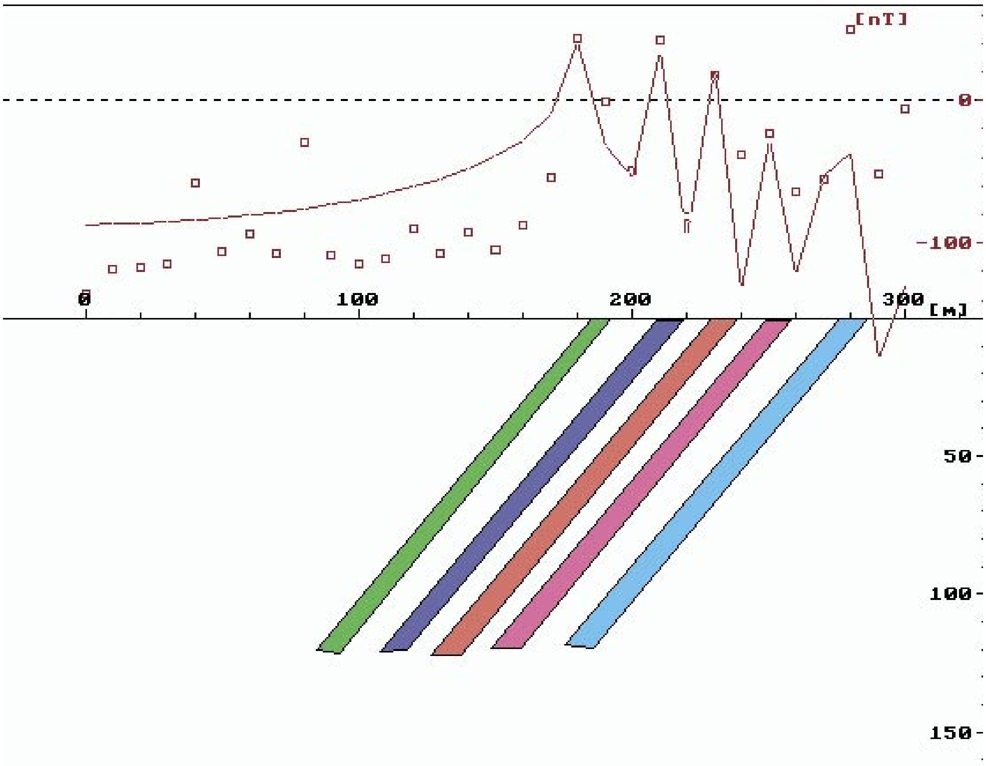

Figure 5-16. *Magnetic modelling of LFM000651, dip towards south. The symbols show the field data and the solid shows the synthetic anomaly of the model. The magnetic susceptibility of the bodies varies between 1000 and 2000x10^{-5} SI. The background susceptibility is 100x10^{-5} SI.*

6 References

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