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Oskarshamn site investigation

Vertical electric sounding and inversion of helicopter-borne EM measurements

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October 2006

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Vertical electric sounding and inversion of helicopter-borne EM measurements

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

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Abstract

Electrical soundings have been performed in the Oskarhamn site investigation area. The aim of the project was to gain better knowledge about the resistivity ranges for different soil types that appear in the area. Different clayey soils had overlapping resistivity ranges with a mutual geometric mean of 46 Ωm. The moraine in the area is of high resistivity with a geometric mean for unsaturated parts of 9,940 Ωm and 1,585 Ωm for water-saturated parts. The high resistivity of the moraine is interpreted to be due to the small amounts of fine-grained fractions and the presence of boulders.

The new information was compiled into maps of assumed soil cover thickness and resistivity together with other information sources. These maps were then used as constraints in inversion of helicopter-borne electromagnetic data. This resulted in maps of calculated soil cover conductance, thickness and resistivity over the entire area covered by the helicopter-borne measurements.

Sammanfattning

Elektriska sonderingar har utförts i Oskarshamns platsundersökningsområde. Målet med undersökningen var att få bättre kunskap om de elektriska egenskaperna för olika jordarter i området. Olika leriga jordar hade överlappande resistivitetsintervall med ett gemensamt geometriskt medelvärde på 46 Ωm. Moränen i området har hög resistivitet med ett geometriskt medelvärde för omättade partier på 9 940 Ωm och 1 585 Ωm för vattenmättade partier. Den höga resistiviteten för moränen tolkas bero på den låga endelen av finkorniga fraktioner och närvaron av block.

Den nya informationen sammanställdes till kartor med förmodad tjocklek och resistivitet för jordtäcket tillsammans med annan tillgänglig information. Dessa kartor användes sedan för att styra inversion av helikopter-elektromagnetiska mätdata. Detta resulterade i kartor för beräknad konduktans, resistivitet och tjocklek av jordtäcket i hela det område som täcks av helikoptermätningen.

Contents

1 Introduction

This document reports the results of vertical electrical soundings and inversion of helicopter-borne EM mesaurements. The work was carried out in accordance with activity plan AP PS 400-05-063. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

Measurements of apparent electric resistivity can yield information about water-bearing deformation zones, soil cover thickness and groundwater salinity. It is important to have good knowledge about the electrical properties of different geological units during the interpretation of the data. The main focus in the presented project has been to gain better knowledge about the electrical properties of different soil types in the regional model area at Oskarshamn. This new information has also been used as a priori information during a new inversion of helicopter-borne EM-data /1/.

27 electrical soundings with electrode separations up to 25 metres were performed. The locations of the soundings are shown in Figure 1-1. The apparent electric anisotropy of the bedrock was measured at 12 stations with no or very thin soil cover. The positions of these stations are also shown in Figure 1-1.

The work gives input parameters to the geological model of the Oskarshamn site investigation.

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

Activity plan	Number	Version
Verttikal elektrisk sondering och inversion av helikopter-EM mätningar	AP PS 400-05-063	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för resistivitetsmätning	SKB MD 212.005	1.0
Metodbeskrivning för tolkning av flyggeofysiska data	SKB MD 211.003	1.0

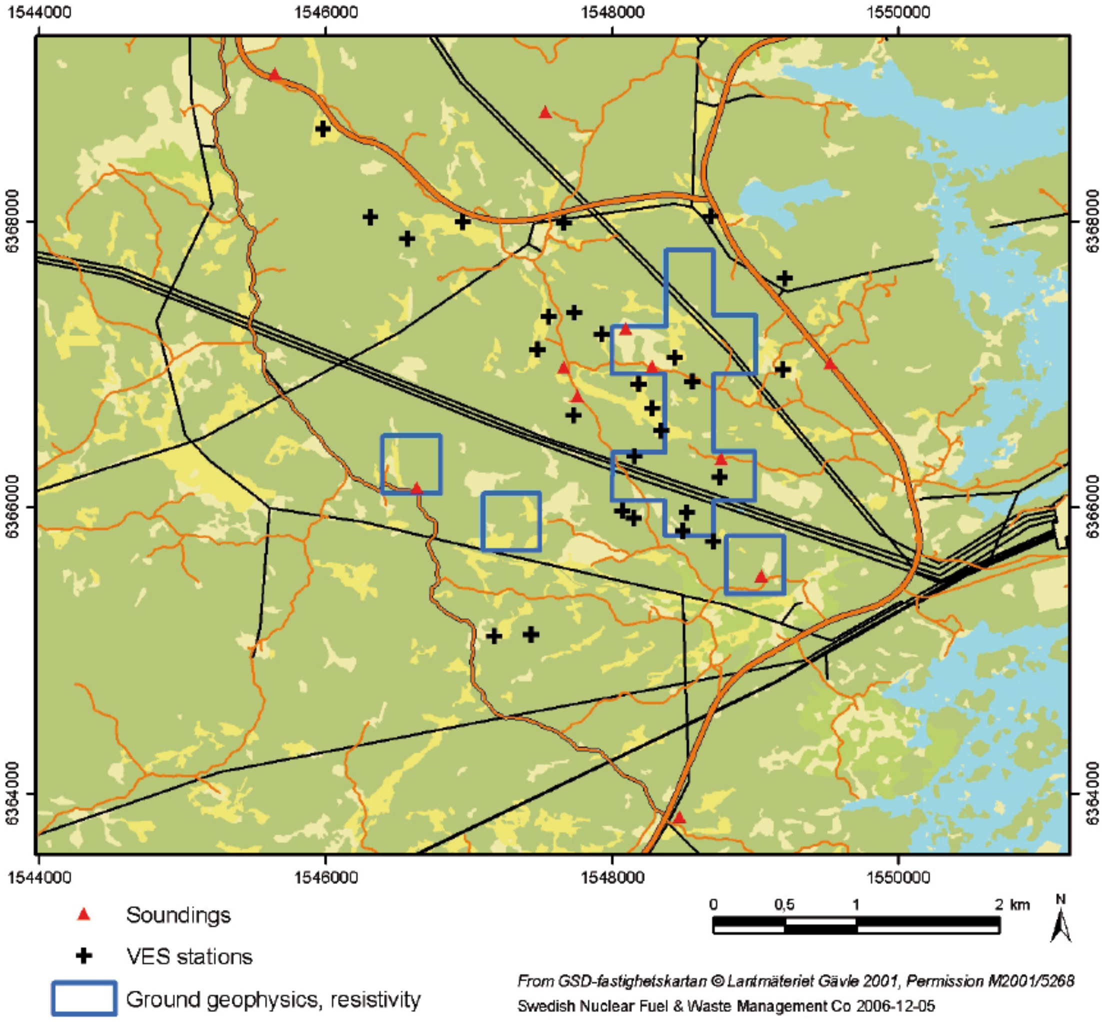

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Figure 1-1. *Map showing the location of VES stations as black crosses. Measurements of apparent anisotropy are shown with red triangles. Resistivity profiles from /7/ and /8/ are shown in blue.*

2 Objective and scope

The electric resistivity of different soil units is mainly a function of porosity, water saturation and clay content. Clay minerals can adsorb ions on the mineral surface and keep them in exchangeable state. Clayey soils therefore have low electric resistivity. Soils with a significant fraction of clay and silt often contain capillary water in unsaturated volumes. Such soils therefore have relatively low resistivity also above the ground-water table.

Measurements of the electric resistivity of the ground can be used to estimate the thickness of the soil cover and to map soil units with anomalous properties. A problem in the interpretation of data is however the principle of equivalence. The well determined parameter of an electrically conductive layer is the integrated conductance, i.e. the ratio between thickness and resistivity. This means that it can be difficult to estimate these two parameters individually. It is therefore important to have knowledge about the electrical parameters of different soil units in order to correctly interpret electrical measurements. The presented project aims at improving the knowledge about the electrical resistivity of the most common soil types in the Oskarshamn site investigation area. The resistivity has been estimated by electrical soundings in areas where the different soil types appear at the surface and/or where they are so thick that the principle of equivalence does not pose a problem.

Electrical soundings have been performed in a previous project /2/. The focus was then on the properties of soils as well as on bedrock properties. The measurements were also constrained to the proximity of tie-lines of a helicopter-borne geophysical survey /1/.

The electromagnetic (EM) measurements of the helicopter-borne survey /1/ were inverted into a two-layer model /3/ constrained by information about the soil and bedrock properties /2/. This inversion has been performed again with the updated information about soil properties from this project. Soil cover thickness information from seismic refraction surveys /4, 5, 6/ and resistivity profile measurements /7, 8/ were also included in the process.

The quaternary geology of the site investigation area is described in /9/ and information about soil types has been retrieved from this work.

3 Equipment

3.1 Description of equipment and interpretation tools

The presented work comprises a field survey and compilation, processing and interpretation of data. The following equipment and software was used:

Field survey:

- ABEM SAS 300B Terrameter and ABEM SAS 4000 Terrameter
- Garmin 12XL GPS-receiver
- Steel electrodes and cables

Software for data processing and interpretation:

- 4Pole (Luleå University of Technology, /10/)
- r_anstrp (Luleå University of Technology, /10/)
- Surfer version 8.0 (Golden Software)
- Grapher version 6.0 (Golden Software)
- Res2Dinv version 3.5 (GeoTomo software)
- MapInfo Professional version 7.5 (MapInfo Corp.)
- Profile Analyst version 6.0 (Encom Technology)
- Gridinv (GeoVista AB, /11/)

4 Execution and results

4.1 Vertical electrical soundings

Vertical electrical soundings (VES) were performed at 27 stations (Figure 1-1). The measurements were performed with a modified Schlumberger array /10/ with a maximum electrode separation of 25 meters. The smallest electrode separation was 0.4 metres. The location of the station was measured with a handheld GPS with an accuracy of around ± 5 metres. The locations of the stations were chosen in such a manner that the effect of topography and two- or three-dimensional features was expected to be small. Measurements were performed in two orthogonal directions at each station, except for a few stations where this was prevented by terrain obstacles. The results for the two directions were very similar for most stations. The results for a sounding performed on clayey soils can be seen in Figure 4-1 and the results from a sounding performed on moraine can be seen in Figure 4-2.

The results from the measurements were entered into the program 4Pole /10/ and were interpreted in terms of horizontally multi-layered models. The parameters of the models were sometimes adjusted by trial and error and sometimes by constrained inversion. The choice of method depended mainly upon the validity of the layered model and noise in the data. Inversion was not used on data where effects from two- or three-dimensional structures were suspected. Mild constraints were also applied to layer parameters during inversion to avoid geologically unrealistic output.

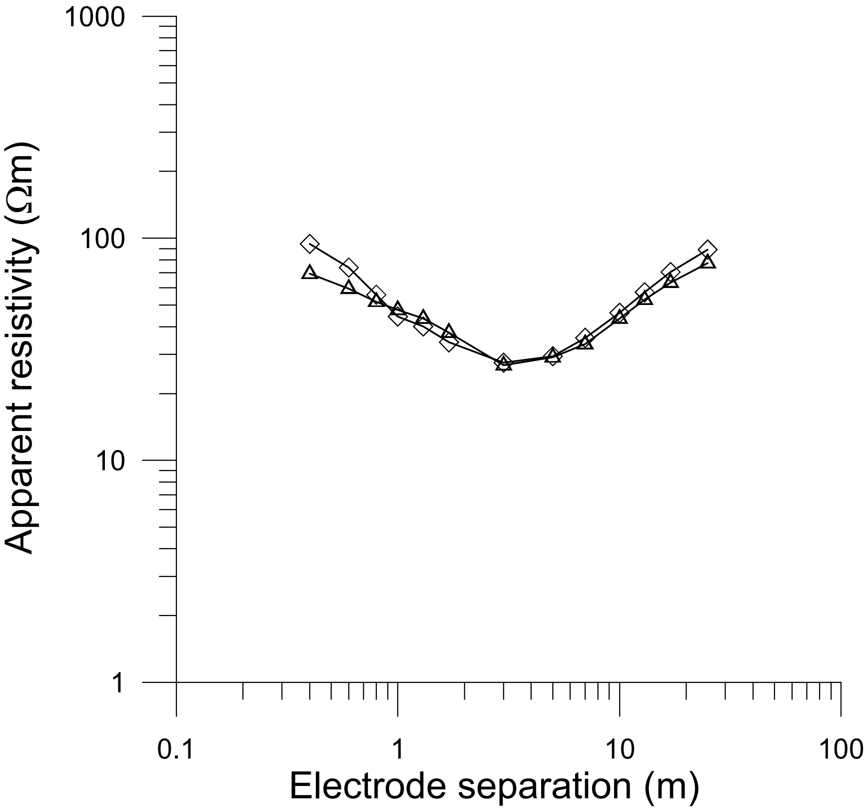

Figure 4-1. *Sounding curves from measurements in two orthogonal directions at PSM007272 (1548284E/ 6366694N). The minimum at electrode separation 3 metres is caused by a clayey layer interpreted to be around 8 metres thick and having a resistivity of around 25 Ωm.*

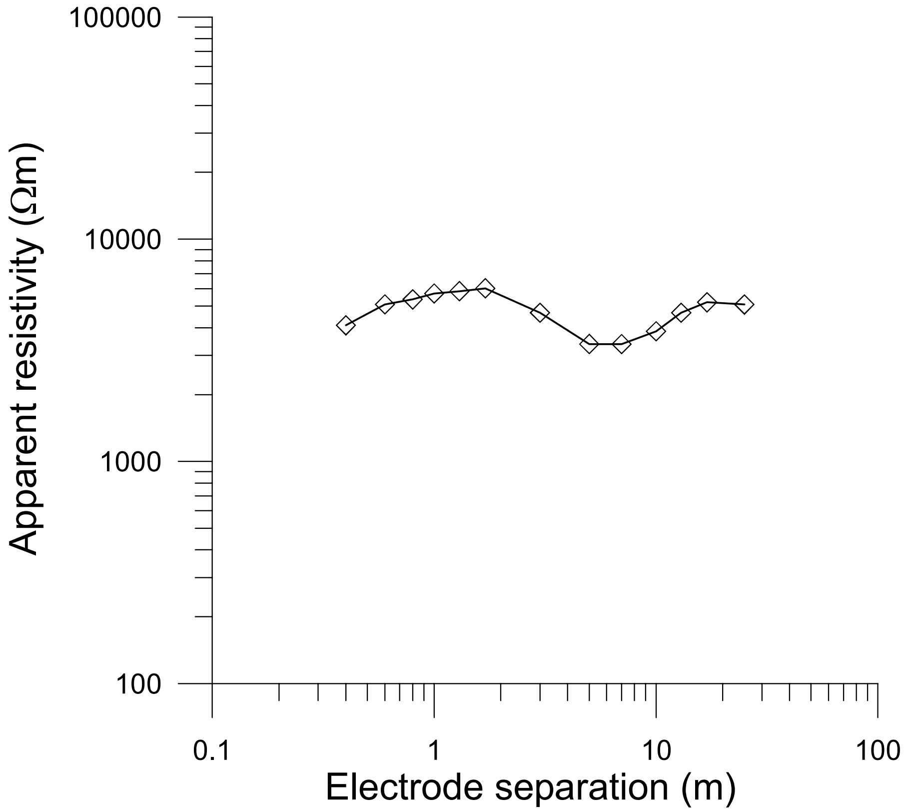

Figure 4-2. *Sounding curve from PSM007279 (1548073E/ 6365975N). The maximum at electrode separation 1.5 metres is caused by dry moraine interpreted to be around 1.4 metres thick and having a resistivity of around 10,000 Ωm. The minimum at electrode separation 6 metres is caused by wet moraine interpreted to be around 3.6 metres thick and having a resistivity of around 1,200 Ωm.*

Averages for the results for the two measurement directions were calculated. The effective soil cover resistivity to be used as a priori information during inversion of helicopter-borne EM data was also calculated (see /2/).

4.2 Estimated resistivity of different soil types

The estimated resistivity ranges and averages for different soil types are summarized in Table 4-1.

Table 4-1. Resistivity ranges and geometric means for different soil types.

Soil type	Number of soundings	Minimum interpreted resistivity (Ωm)	Maximum interpreted resistivity (Ωm)	Geometric mean (Ωm)
Fen, clayey gyttja	13	14	211	46
Till with boulders, sandy till, dry	9	2,540	21,501	9,940
Till with boulders, sandy till, wet	7	1,000	2,100	1,585
Wave-washed gravel, dry	1	6,100	6,100	–
Wave-washed gravel, wet	1	1,920	1,920	–
Glacifluvial sediment	1	4,430	4,430	–

The soundings on clayey soils were in general characterized by slightly elevated resistivity at the surface (e.g. Figure 4-1). Most of these soundings were performed on arable land and the higher resistivity at the surface is probably due to a mixture with organic matter. Soundings were performed at locations mapped as clayey gyttja, fen and glacial clay /9/, although only one station at glacial clay. The different soil types above often occur as layers on top of each other. The results for clayey gyttja and fen are almost completely overlapping and the variations within one group is considerably larger compared to the difference between the groups. It has also not been possible to distinguish layer boundaries between these soil types where they are layered on top of each other. They can therefore be considered as having equivalent electric properties. The result for the station on glacial clay indicates a rather high resistivity for this soil type. This result is however hardly representative for this type of soil. Resistivity profile measurements /7, 8/ indicate that glacial clay has roughly the same resistivity as clayey gyttja and fen. The variation in resistivity of clayey soils might reflect variations in the volume fraction of clay minerals, where low resistivity would correspond to a high fraction of clay minerals.

The soundings performed on till with boulders and sandy till /9/ is generally characterized as showing three or four layers (e.g. Figure 4-2). A top layer (sometimes absent) consists partly of moist organic matter. This is followed by a highly resistive layer interpreted as moraine above the ground-water surface. The high resitivity of this layer indicates insignificant amounts of clay and silt fractions and hence hardly any capillary water.

The third layer is interpreted as corresponding to moraine below the ground water surface. Considering that this layer is water saturated, the resistivity is rather high. If Archie's law is used to estimate the porosity (neglecting the effect of clay minerals) the estimated porosity of the moraine is of the order 7 to 15%. The rather low porosity can probably be explained by a large portion of the moraine being occupied by low-porosity boulders.

The rather high resistivity of the moraine results in a rather small resistivity contrast between the soil cover and the underlying bedrock. This has consequences during interpretation of e.g. resistivity profile measurements. Mostly unsaturated moraine cover can be confused with fresh bedrock. Also, water-saturated moraine is only slightly less resistive than what is expected for fractured and/or altered bedrock. It is also very difficult to indicate the presence of moraine under clayey soils with resistivity methods. The total soil cover thickness might therefore be under-estimated where clayey soils appear at the surface.

One sounding was performed on wave-washed gravel /9/. The estimated resistivity values were quite high and comparable to sandy moraine and moraine with till. A sounding was also performed on glacifluvial sediments /9/. The resistivity for this soil type was also quite high indicating very small amounts of fine-grained fractions. Low-resistiviy soil was indicated underneath the glacifluvial sediments. The resistivity of this layer was compatible with the clayey soil types.

4.3 Estimated soil cover thickness

The layered models for the sounding stations can be seen in Table 4-2. The total soil cover thickness is also given. The estimated soil cover thickness varies between 0.5 and 11.4 metres. The difficulty to distinguish moraine from bedrock under clayey soils should however be kept in mind.

Table 4-2. Layer parameters for layered models. The number of layers varies for the different stations but never exceeds four. The resistivity (ρ_i) and thickness (h_i) for each layer is given. Note that some parameters are poorly constrained by the data since the aim of the survey primarily was to gain knowledge about typical resistivity values for different soil types.

ID	East	North	ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	ρ_4 (Ωm)	h_1 (m)	h_2 (m)	h_3 (m)	total h (m)
PSM007271	1548342	6366534	531	31	10,288		0.4	6.0		6.4
PSM007269	1548187	6366864	570	47	13,201		0.3	3.4		3.7
PSM007262	1547558	6367334	498	39	13,541		0.4	4.2		4.6
PSM007268	1545981	6368646	334	39	13,942		0.3	3.3		3.7
PSM007265	1546958	6367993	151	16	17,003		0.8	6.4		7.2
PSM007274	1549196	6366960	7,534	6,099	1,926	9,398	0.1	2.0	4.7	6.7
PSM007267	1546316	6368025	4,019	11,565	1,980	26,778	0.3	3.6	7.6	11.4
PSM007278	1548156	6365927	5,948	15,744	1,167	22,323	0.2	1.5	3.3	5.0
PSM007279	1548073	6365975	2,708	9,901	1,170	22,999	0.3	1.4	3.6	5.4
PSM007270	1547733	6366643	519	30,291			2.3			2.3
PSM007284	1548522	6365962	1,218	3,358	20,925		0.1	8.6		8.7
PSM007273	1548754	6366212	585	2,079	17,292		0.5	8.3		8.8
PSM007283	1548497	6365835	320	211	22,907		0.2	3.7		3.9
PSM007266	1546574	6367875	3,881	10,498	2,116	27,109	0.3	1.9	3.2	5.4
PSM007272	1548284	6366694	139	26	15,530		0.6	7.8		8.3
PSM007275	1548439	6367046	198	40	18,073		0.3	2.6		2.9
PSM007276	1548563	6366877	5,380	18,584	2,122	23,810	0.3	3.1	3.3	6.7
PSM007263	1547736	6367360	5,705	16,259	2,110	28,500	0.3	2.9	3.4	6.6
PSM007277	1548160	6366358	6,772	21,501	1,000	23,029	0.4	5.6	1.7	7.7
PSM007264	1547930	6367208	70	14	20,721		0.03	0.4		0.5
PSM007261	1547481	6367102	182	33	21,327		0.3	6.0		6.3
PSM007286	1547180	6365100	153	80	24,689		0.5	2.3		2.8
PSM007287	1547434	6365112	2,488	6,358			0.7			0.7
PSM007285	1548711	6365762	124	188	25,778		1.0	2.7		3.6
PSM007280	1549207	6367604	1,495	1,312	4,117		0.3	6.6		6.9
PSM007281	1548692	6368032	9,060	4,431	73	26,058	0.2	3.2	3.0	6.5
PSM007282	1547667	6367987	471	55	22,462		0.2	2.9		3.2

The soil cover thickness has been estimated from resistivity profile measurements /8/. A corresponding interpretation for a previous resistivity profile survey /7/ has been performed in this project. The profile measurements are inverted into a smooth resistivity model. This means that the interface between soil cover and bedrock is modelled as a transition zone and not as a discrete boundary. The equivalence principle is also difficult to consider in this type of inversion. The interpreted depths to bedrock from the resistivity profiles were therefore compared with over-lapping refraction seismic results. It was found that the depths from resistivity results were in general around 1.6 times larger than the depths interpreted from seismics. The resistivity results were therefore adjusted correspondingly. Maps showing the interpreted soil cover thickness for all areas with resitivity profiling can be seen in Figures 4-3 to 4-6. The above mentioned ambiguities in interpretation should be kept in mind when using these results and also the fact that resistivity measurements close to the major power lines are affected by buried grounding cables.

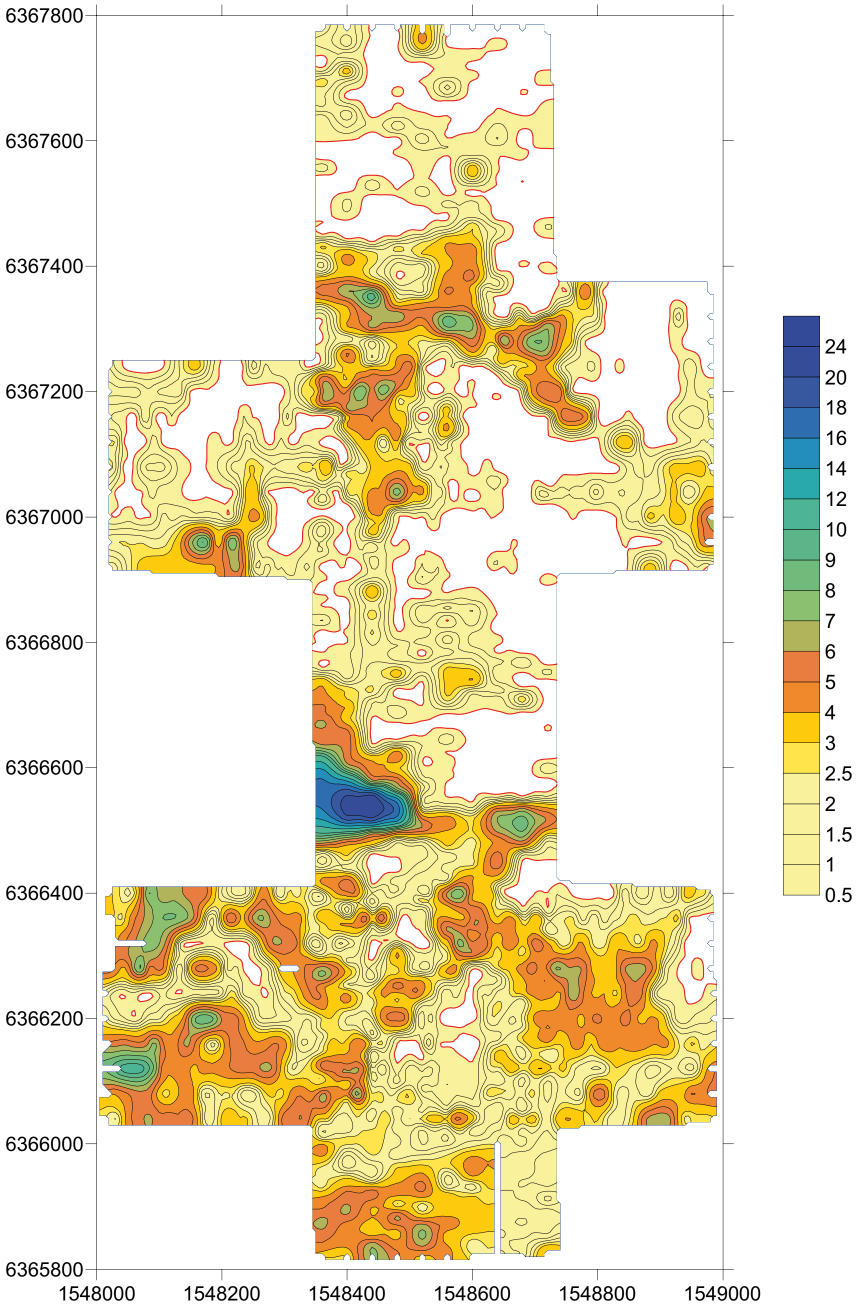

Figure 4-3. *Contour map showing the interpreted soil cover thickness from resistivity profiles /7/. The results have been calibrated with the help of seismic refraction results /4, 5, 6/. The position of the lines can be seen in Figure 1-1.*

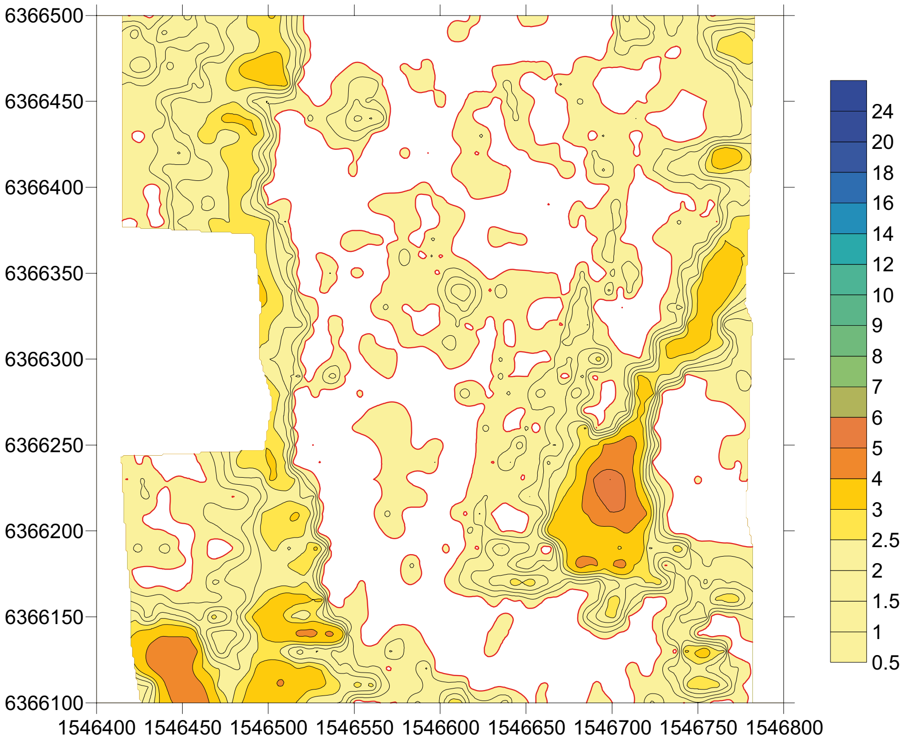

Figure 4-4. *Contour map showing the interpreted soil cover thickness from resistivity profiles in the westernmost area of /8/. The results have been calibrated with the help of seismic refraction results /4, 5, 6/. The position of the lines can be seen in Figure 1-1.*

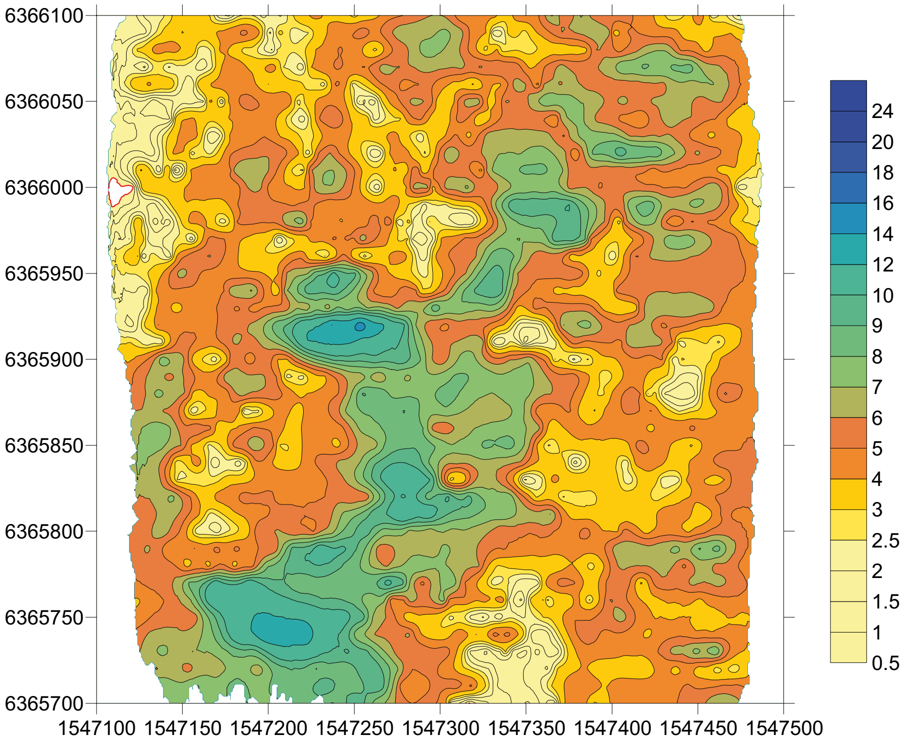

Figure 4-5. *Contour map showing the interpreted soil cover thickness from resistivity profiles in the central area of /8/. The results have been calibrated with the help of seismic refraction results /4, 5, 6/. The position of the lines can be seen in Figure 1-1.*

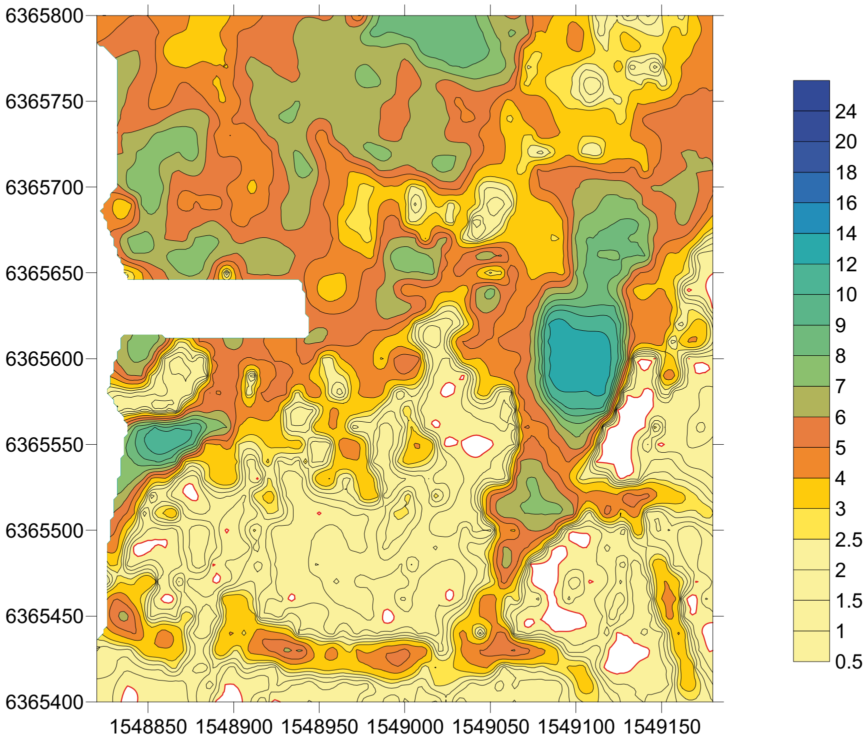

Figure 4-6. *Contour map showing the interpreted soil cover thickness from resistivity profiles in the easternmost area of /8/. The results have been calibrated with the help of seismic refraction results /4, 5, 6/. The position of the lines can be seen in Figure 1-1.*

4.4 Measurements of electric anisotropy

The apparent electric anisotropy of the bedrock was estimated in a previous project /2/ and was found to roughly correspond to major lithological and ductile geological structures. The electrode separations for these measurements were large enough to suppress the effect of local inhomogeneties and minor deformation zones. New measurements have been made with short electrode separations (25 metres) to reflect local anisotropy at locations with outcropping rock or very thin soil cover. The measurements have been performed with an X-configuration /10/ and the apparent anisotropy was calculated with the program r_anstrp. The results are summarized in Table 4-3 and illustrated in Figures 4-7 and 4-8. A mosaic of ground and airborne magnetics is shown in the background of the figures as a reference to geological structures. The vertical component of the anisotropy cannot be deduced from measurement on the surface only. The plotted vectors can therefore approximately be seen as the surface projection of the full three-dimensional anisotropy. The anisotropy directions for local measurements show no dominating direction over the entire area and are probably affected by local factors at the measurement stations. However, with one exception the direction of lowest resistivity is either around 275° (254° to 289°) or around 345° (331° to 354°). These directions might reflect the locally dominating directions of brittle fracturing at the measurement stations.

Table 4-3. Results of measurements of apparent resistivity anisotropy. λ corresponds to the anisotropy coefficient and φ to the direction of minimum resistivity. σ_0 is a value that indicates the goodness of fit to an anisotropic half-space /10/.

North	East	Bulk resistivity (Ωm)	λ	σ_0	φ
6367250	1548100	8,092	1.18	0.054	277
6366986	1548280	39,891	1.21	0.025	284
6363837	1548473	21,804	1.39	0.037	289
6366776	1547759	9,902	1.18	0.016	331
6366140	1546641	27,973	1.16	0.013	337
6369034	1545646	23,786	1.19	0.017	340
6366982	1547666	13,812	1.26	0.026	346
6365520	1549043	7,737	1.24	0.023	351
6367010	1549528	13,266	1.17	0.013	354
6366986	1548280	11,090	1.12	0.016	33
6366342	1548767	10,292	1.28	0.014	254
6368764	1547534	16,928	1.34	0.020	269

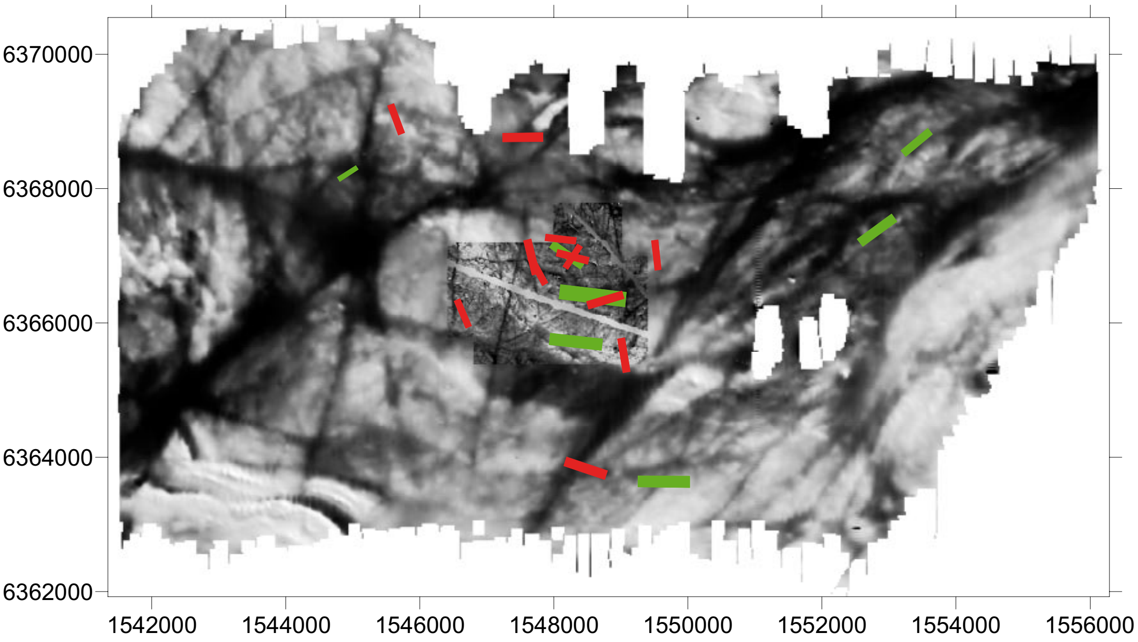

Figure 4-7. *Apparent anisotropy of electric resistivity. The symbols show the direction of minimum resistivity in the horizontal plane. Red symbols show results from this work whereas green symbols show results from /2/. Mosaic of helicopter-borne and ground total-field magnetic measurements in the background /1, 7, 8/.*

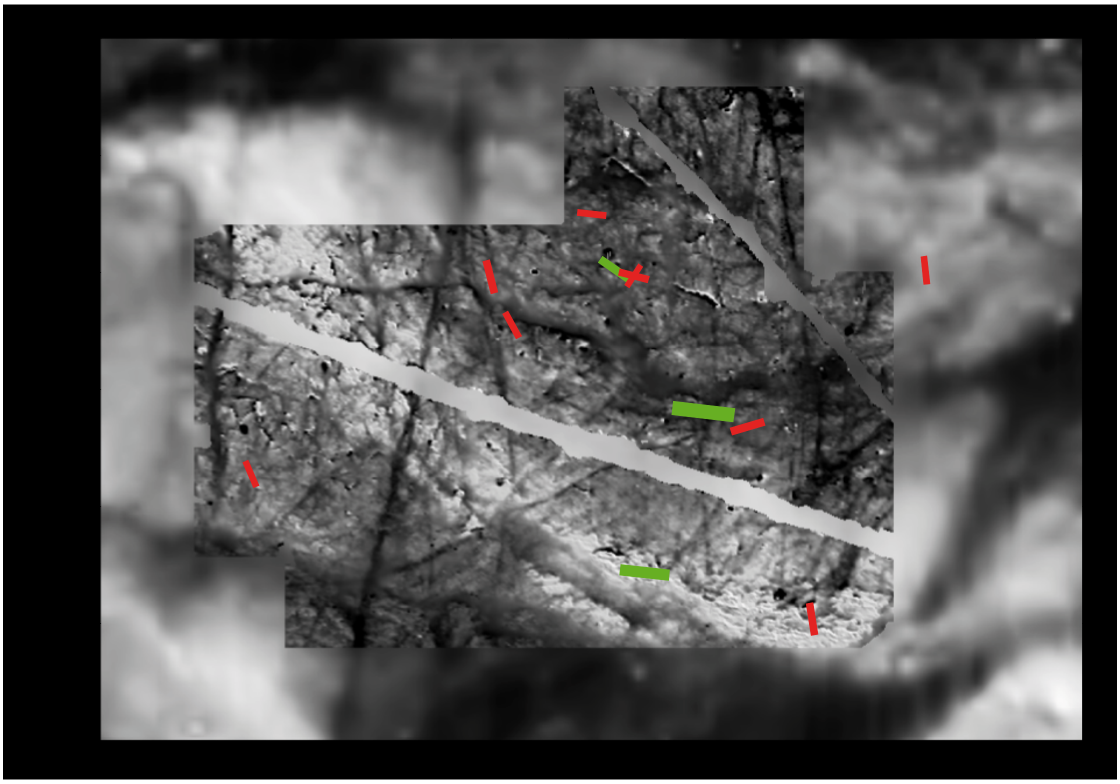

Figure 4-8. *Same as Figure 4-7 but only the Laxemar area is shown.*

4.5 Compilation of a priori data for inversion

The process of compiling a priori information for inversion of helicopterborne EM data has been described in /3/ and /12/. Additional data have become available since that work.

Representative resistivities for different soil types from this work have been assigned to the soil units of the quaternary geology map /9/. The variation within each soil type has been used to assign the variance of the resistivity. This has resulted in a grid of assumed resistivities and a grid of standard deviations for those resistivities. A second grid was created by simple inverse distance interpolation of soil resistivity data from this project and from /2/. The standard deviation was assigned to values that gradually increase with distance from the sounding stations. A final grid of assumed soil resistivity was then created as a weighted average of the grids described above. This means that the values basically are based on the map of quaternary geology away from the sounding stations and on the sounding data close to the sounding stations (Figure 4-9).

Four different sources of data were used to calculate assumed thicknesses of the soil cover in grids. The areas mapped as outcropping bedrock or thin soil cover in /9/ were assigned a small value of 0.25 metres. The thickness was gradually increased to a value of 4 metres with increasing distance from the nearest outcrop. Low standard deviation was assigned to grid nodes at outcrops and high standard deviation was assigned to nodes away from outcrops. The other three information sources consisted of seismic refraction results /4, 5, 6/, resistivity profiling /7, 8/ and resistivity soundings /2, this work/. Grids of assumed soil cover thickness were created by inverse distance interpolation with corresponding grids of standard deviation where the standard deviation was gradually increased with distance from the profiles/stations. A final grid was created as a weighted average of the four grids described above (Figure 4-10). The standard deviation of the weighted average was also calculated (Figure 4-11). Areas close to seismic or resistivity profiles or sounding stations or close to outcrops have low standard deviations.

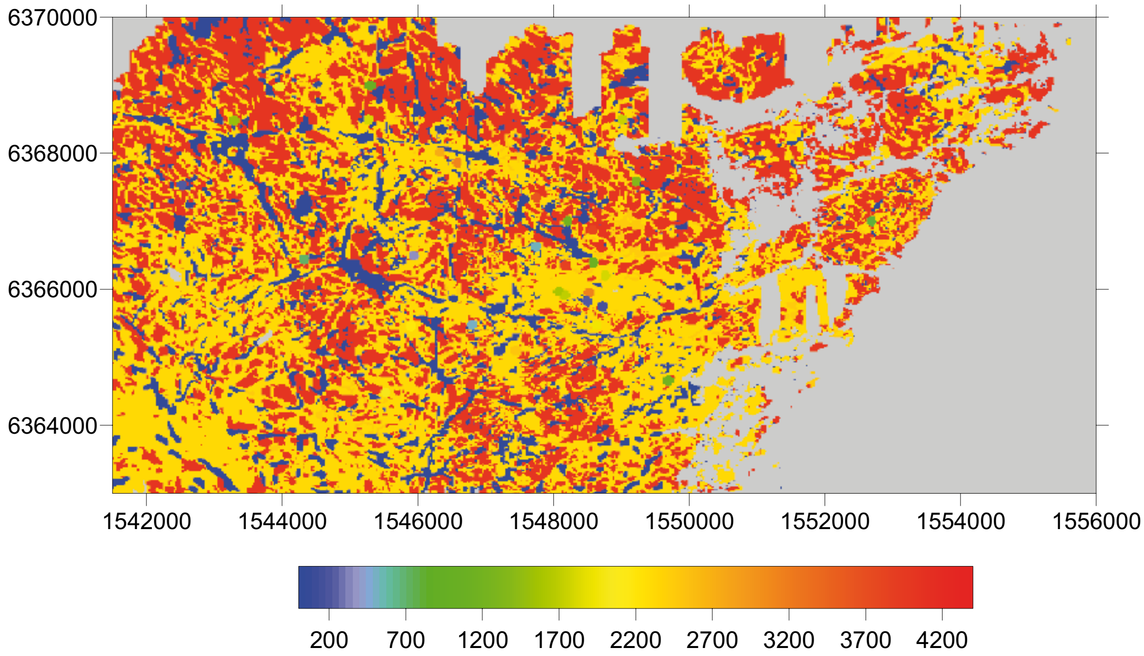

Figure 4-9. *Estimated resistivity (in Ωm) of the soil cover where information from this work, /2/ and /9/ has been used.*

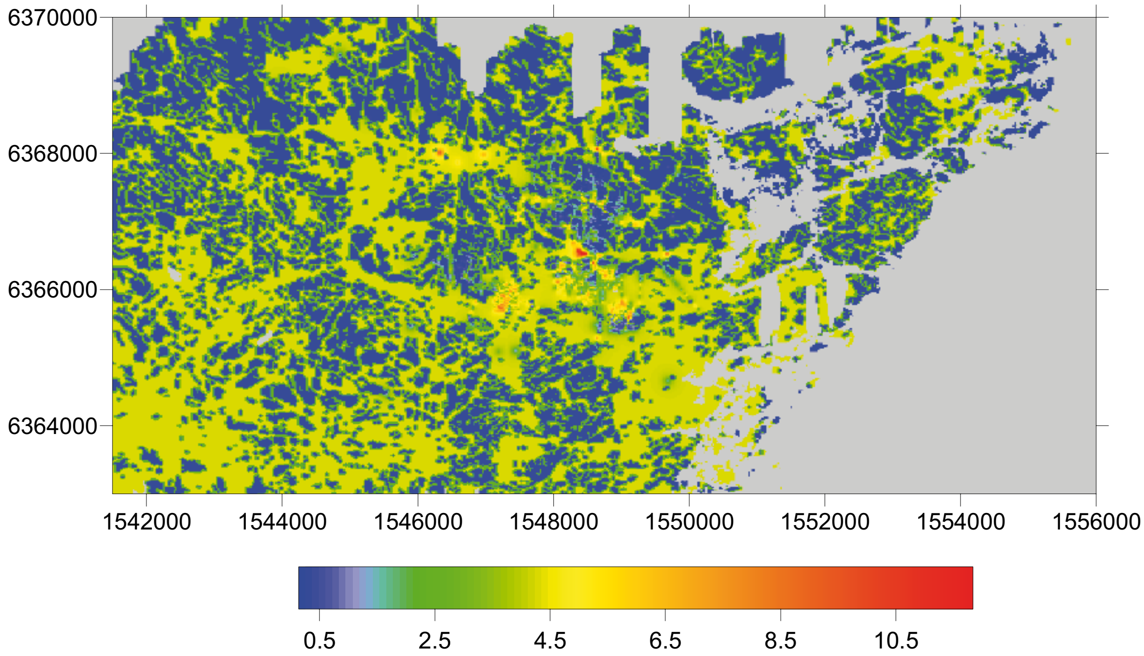

Figure 4-10. *Estimated thickness (in m) of the soil cover where information from this work, /2, 4, 5, 6, 7, and 8/ has been used.*

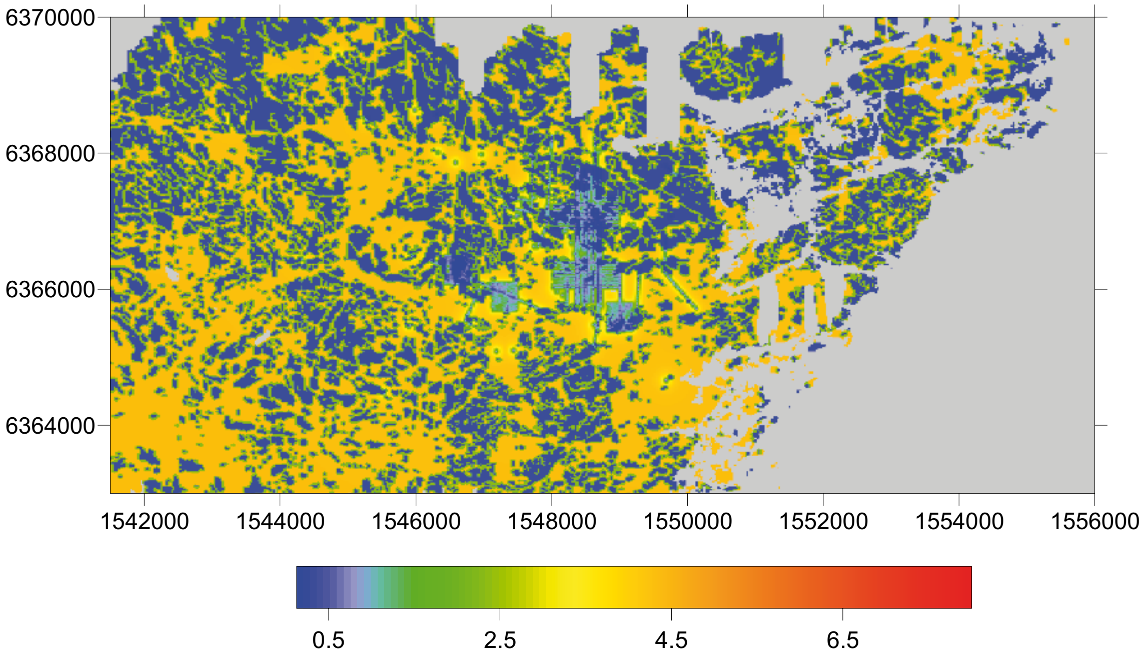

Figure 4-11. *Estimated standard deviation of the soil cover thickness (in m). Note that the standard deviation is low around e.g. the resistivity profiles /7, 8/ shown in Figure 1-1.*

4.6 Inversion of helicopter-borne EM data

Constrained inversion of helicopter-borne EM data has been described in /3/ and /12/. The procedure was repeated with the data from /1/ and /3/ with the inclusion of the a priori information described in the previous section. A thorough analysis of the gain errors in the EM equipment was performed for data from Forsmark /12/ and the calibration values from that work were applied to the data from Oskarshamn since the two surveys were performed directly after each other.

The best constrained parameter in the inversion is the integrated conductance of the upper layer (assumed soil cover). The conductance is shown in Figure 4-12. High values (red in Figure 4-12) are interpreted to be caused by thick cover of clayey soils. Yellow colour will generally correspond to thin cover of clayey soils whereas green colour corresponds to moraine-covered areas.

The inverted resistivity of the upper layer (assumed soil cover) can be seen in Figure 4-13. Blue to greenish-blue colours correspond to the resistivity of clayey soils, whereas green to yellow colours correspond to water saturated moraine.

The estimated thickness of the soil cover is shown in Figure 4-14. The low contrast in resistivity between moraine and bedrock makes it somewhat difficult to estimate the thickness of moraine cover accurately. The thickness of the soil cover is also somewhat poorly constrained by the EM data. The best resolved parameter is the integrated conductance (Figure 4-11). A correct estimate of the soil cover thickness is therefore dependent upon the a priori information about the soil cover resistivity.

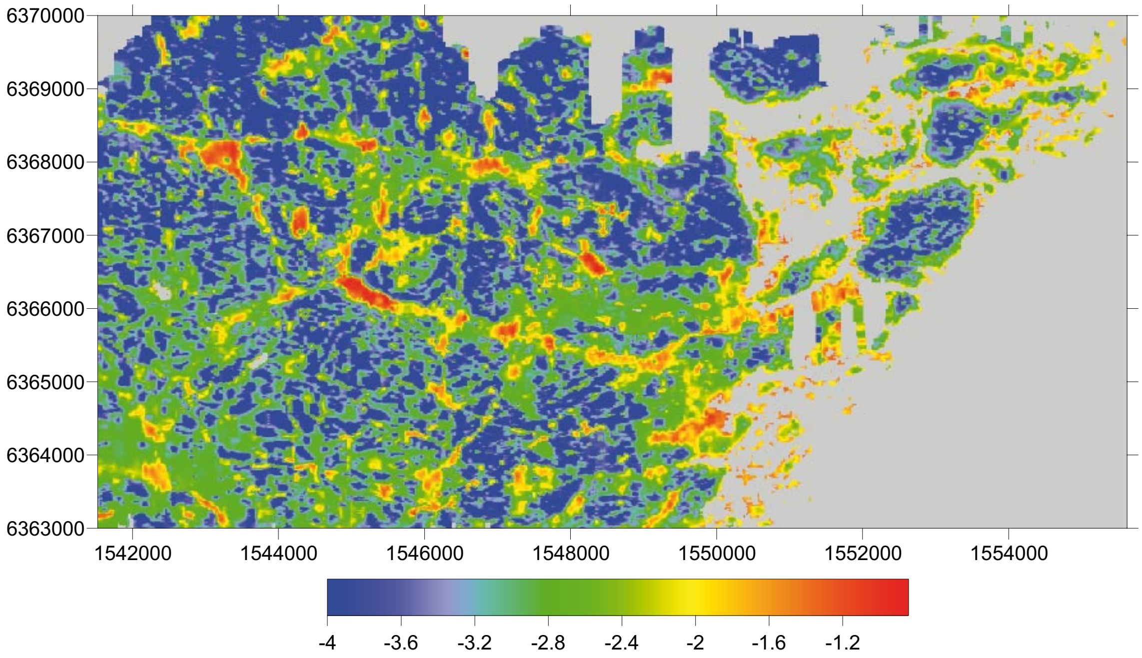

Figure 4-12. *Inversion output of the integrated conductance of the soil cover (logarithm, Siemen). Red colours correspond to areas with fairly thick cover of clayey soils.*

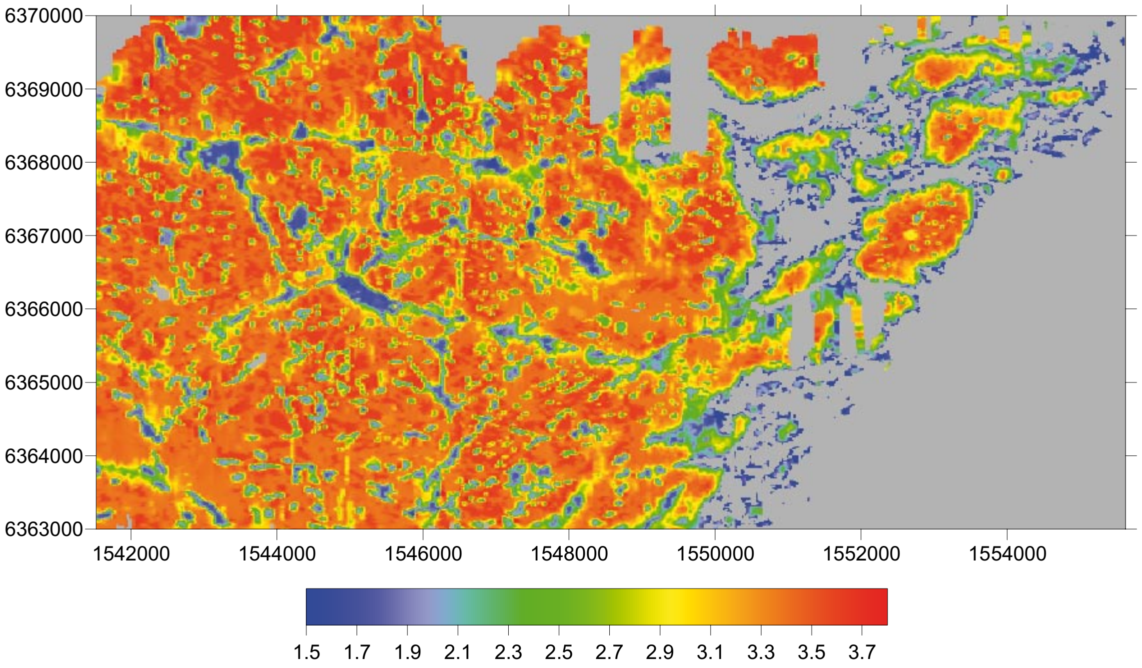

Figure 4-13. *Inversion output of the resistivity of the soil cover (logarithm, Ωm).*

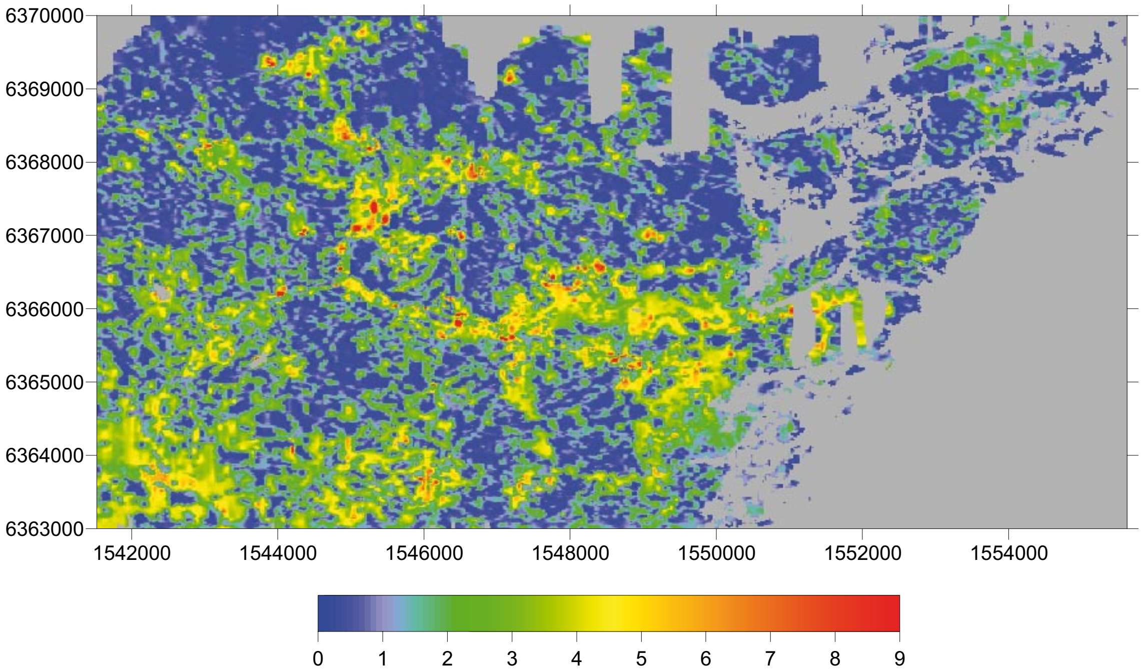

Figure 4-14. *Inversion output of the thickness of the soil cover (m).*

The result for the substratum (assumed bedrock) has hardly been affected by the new a priori information added in this project. The inversion result is more or less the same as shown in /3/.

A few things should be pointed out about the results of the inversion of EM data:

- The foot-print of the EM-system has a diameter of at least 100 metres. The system can therefore not resolve e.g. increased soil cover thickness in a narrow valley accurately. The output is more or less a weighted average of the layer parameters under the foot-print. The soil cover thickness in a valley is therefore expected to be under-estimated.
- The basic interpretation model is one-dimensional, i.e. horizontally layered. Artefacts might therefore appear around two- or three-dimensional structures, noticeably along the shore-line.
- The EM data quality was degraded close to the major power lines. Also, the pilot had to ascend to higher altitude when passing over the power-lines. The results are therefore expected to be less reliable in these areas.
- Moraine underneath clayey soils will not be resolved due to the small resistivity contrast to bedrock. The soil cover thickness will therefore be under-estimated where moraine occurs under clayey soils.
- The best resolved parameter of the soil cover is the integrated conductance (thickness/resistivity ratio). The thickness and resistivity of the soil cannot be resolved individually. Instead they rely on a priori information that is under-sampled.

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