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Forsmark site investigation

Electric soundings supporting inversion of helicopterborne EM-data

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January 2003

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Keywords: geophysics, electrical sounding, Schlumberger array, x-configuration, resistivity.

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.

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Contents

1 Introduction

This document reports data gained from electric soundings in the Forsmark area during 2002 and the interpretation of these data. The work was carried out according to activity plan AP PF 400-02-29 (SKB internal controlling document).

The sounding points are mainly located along the east-west tie-lines of an helicopterborne geophysical survey /1/, see Figure 1-1.

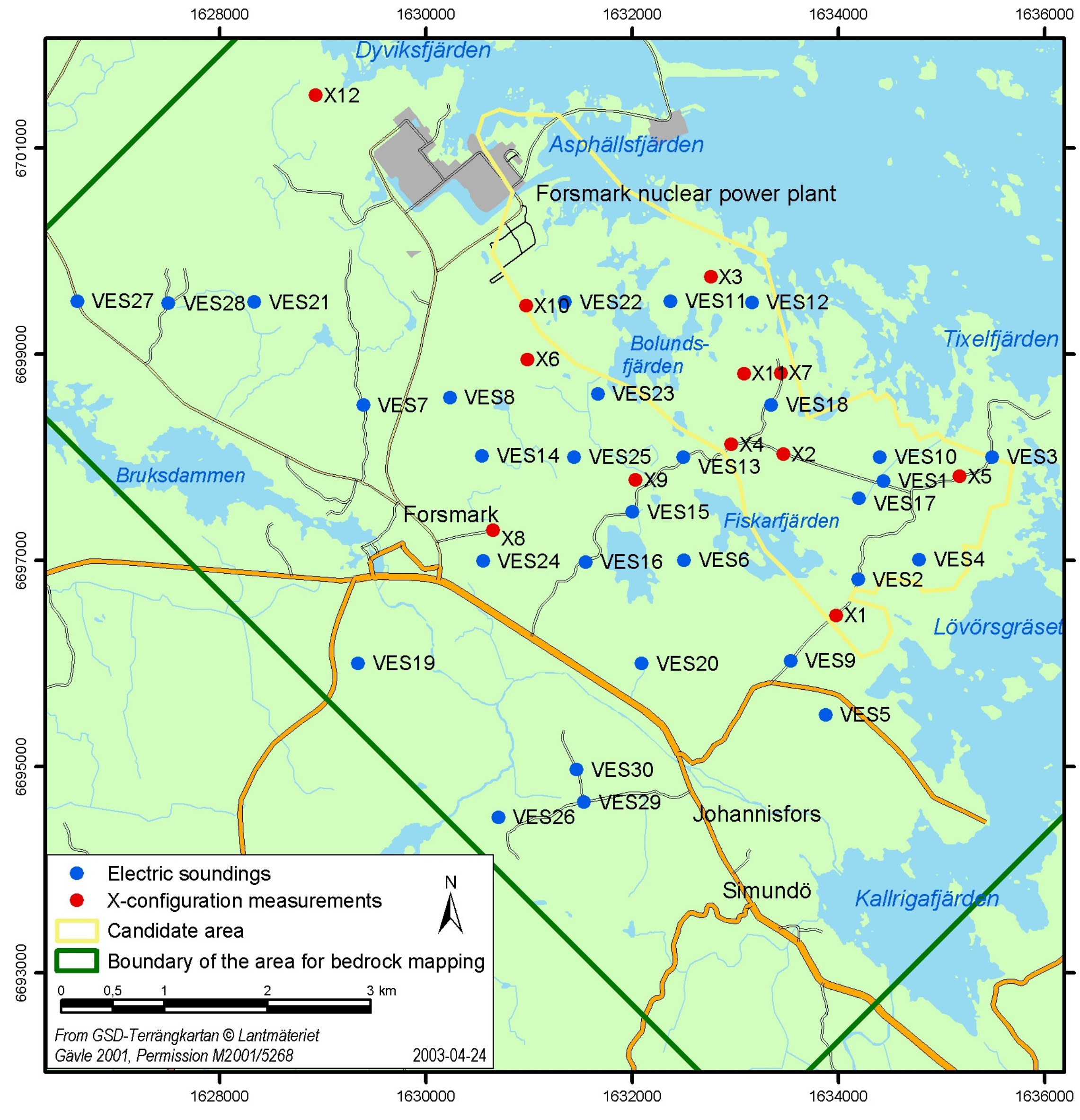

Figure 1-1. *Location of electric soundings and X-configuration measurements.*

2 Objective and scope

The objective of the soundings was to gain knowledge about the electrical properties of the bedrock and the soil cover and the approximate thickness of the cover at a number of scattered points in the helicopter survey area. In combination with other information on soil cover and bedrock, the sounding data will be used as constraints in future levelling and inversion of helicopter electromagnetic data. Note that, in this report, “soil” is used synonymously to overburden, i.e. all material covering the bedrock.

Electric soundings have been performed at 30 stations with a modified Schlumerger array /2/ in accordance with the method description for resistivity measurements (“Metodbeskrivning för resistivitetsmätning”, SKB MD 212.005, Version 1.0). Measurements with X-configuration have been performed at 12 stations. A brief description of the methods and the field procedure follows below.

3 Methodology

3.1 Modified Sclumberger array

Electric soundings are performed to investigate the electric properties of the ground as a function of depth. The ground is conceptually approximated with a number of horizontal layers with different electric resistivity and thickness. By varying the electrode separation it is possible to vary the depth of investigation and thus interpret the thickness and resistivity of each layer.

In this survey, a potential electrode (M) was placed at the survey station and the other potential electrode (N) around 80 metres away (Figure 3-1). One current electrode (A) was initially placed 0.6 metres away from M, whereas the other current electrode (B) was placed at a distance of 300 metres from M. This configuration is, from a practical point of view, a pole-pole configuration, since the distance AM is significantly shorter than any other inter-electrode separation. The distance AM is then step-wise increased, equidistantly on a logarithmic scale, and readings of the potential difference to current ratio (impedance) is taken for each separation. The maximum AM separation used in this survey is 220 metres and the array is then close to being a Schlumberger array. The advantage of this procedure is high productivity and low interference from small near-surface inhomogenities. The procedure is repeated in an orthogonal direction (Figure 3-1, right). This gives an indication of the validity of the horizontal layer approximation.

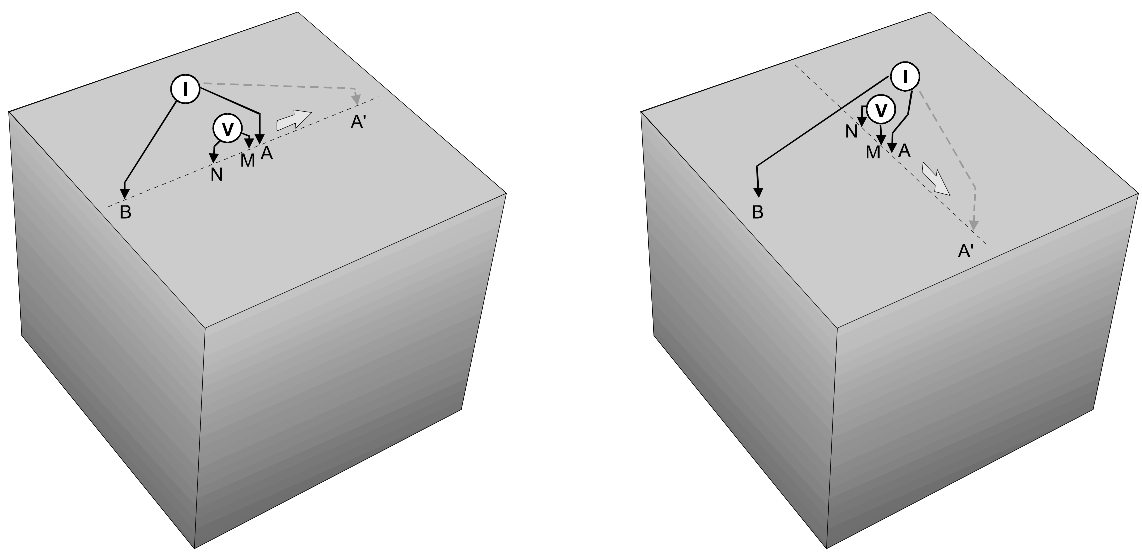

Figure 3-1. *Electrode setup for the modified Schlumberger configuration. Only the A-electrode needs to be moved between readings. The array is expanded in linear (left) and orthogonal (right) directions.*

3.2 X-configuration

To carry out the X-configuration measurements, four electrodes were placed in roughly orthogonal directions, 300 metres from the survey station (Figure 3-2). Four other electrodes were then placed in the same manner at 80 metres distance. Together with an electrode at the survey station, this made nine electrodes available for measurements. 21 different combinations of current and potential electrodes were used and the measurement direction varied accordingly. A least-squares fit to an anisotropic, homogeneous half-space was then done. One of the principal directions of the anisotropy was assumed to be vertical. The result of this inversion of data was the apparent azimuthal anisotropy direction, the apparent anisotropy coefficient and the apparent bulk resistivity /2/.

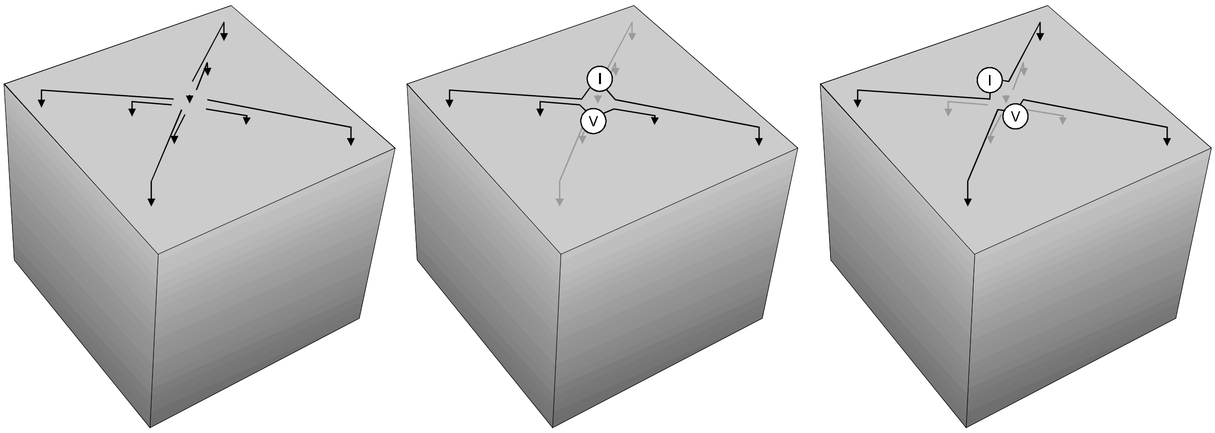

Figure 3-2. *Electrode setup for anisotropy determinations with X-configuration (left). All nine electrodes are connected to the instrument in the centre. Different combinations of electrodes are used so that measurements can be made with e.g. a linear array (centre) and square array (right) in two directions. Various non-symmetrical arrays are also used.*

3.3 Determination of coordinates and electrode separations

The coordinates of the survey stations have been determined by means of GPS. Transformation to RT90 has been done according to the methods recommended by the National Land Survey.

Electrode separations shorter than 50 metres have been determined by tape or fixed markings on the cables. Longer separations have been determined with differential GPS with an accuracy of around ± 2 metres. Separations longer than 200 metres have in some cases been determined by GPS with an accuracy of ± 10 metres.

3.4 Quality assurance

According to the original plan, an ABEM SAS 4000 Terrameter should be used with a SAS 300B as backup. From the first sounding close to the helicopter base at Storskäret, it however became evident that the SAS 4000 had significantly poorer signal-to-noise characteristics in this environment compared to the SAS 300B. The SAS 300B was therefore used for all subsequent measurements. As a result of this change of instrument, no IP-data were acquired.

The instrument was checked daily by taking a test measurement over a reference resistor. All readings were within 5 % of the nominal value of the resistance, which is within the required quality limits.

Cables and contacts were inspected before use. A daily check was performed by switching current and potential electrodes with each other, identical readings should then be acquired according to the reciprocity theorem. No problems with cables, electrodes or other equipment were indicated by these tests.

Redundant readings are acquired with the x-configuration. Some values can be calculated as linear combination of others. Suppose, for example, that a series of measurements is performed according to the list below with the electrodes C, D, E, F, G:

Current electrode 1	Current electrode 2	Potential electrode 1	Potential electrode 2
C	D	E	G
C	D	G	F
C	D	F	E

The sum of measured impedances should in this case be zero. Errors in such sums larger than 20 % of the RMS-residual for the inversion appeared for two stations only. In one case the cause to the problem most likely was one single bad reading. The inversion result was however more or less identical with or without the presumably erroneous values included. In the second case, the data quality was degraded by interference from a nearby power line. The inversion result was however judged reliable in this case as well.

Four readings have been stacked for each measurement. A running average is displayed by the instrument and if this average has been unstable, the measurement has been repeated.

The data quality can be subjectively estimated by plotting sounding curves. The curve is based on measurements of potential differences. Smooth variations are expected since the electric potential is continuous and moderate resistivity variations are expected in this geologic environment. The over-all data quality for each station has been judged from the plotted sounding curves and is listed in Table 5-1.

4 Data processing and inversion

4.1 Electric soundings

Measured impedances from the soundings were entered into Excel spread-sheets. Datafiles in ASCII-format were created for input to the program 4Pole from Luleå University of Technology /2/. The program presents data as sounding curves and the number of resolvable layers was judged by visual inspection. The curves for the two sounding directions were compared and the validity of the 1D layered model was evaluated. The soil cover was very thin at some stations. Local lateral variations in bedrock resistivity can influence the sounding curve in a strong way for such stations. A reasonable representative bulk resistivity has been estimated in such cases. Data were inverted to a layered model in cases where this was possible. Forward modelling was performed in other cases.

The sounding curve and the calculated response was entered into the Excel file. The integrated conductance was calculated for all layers above the substratum (bedrock layer), since inversion of helicopter-borne EM-data will not resolve more than one layer in the soil cover. The effective resistivity of the soil cover was then calculated as:

$$\rho_{eff} = \frac{\sum h_i}{\sum h_i / \rho_i}$$

where h_i is layer thickness and ρ_i is layer resistivity.

An average of the effective resistivity and the total soil thickness was then calculated for the two sounding directions. The bulk resistivity of the bedrock was calculated as the geometric mean of the estimated resistivity for the two sounding directions. The significance and error limits of layer parameters can be calculated during inversion. However, due to obvious departures from the assumed 1D model, the error limits have been estimated by manually changing the model parameters and observing the resulting change in the fit to data. The difference in modelling results for the two directions has also been taken into account.

4.2 X-configuration measurements

Field data were entered into Excel spread-sheets, one for each station, where geometric coefficients and apparent resistivities were calculated. Data-files in ASCII-format for input to the program r_anstrp /2/ were then created. A fit of the data to a homogeneous anisotropic half-space was performed. The result of the inversion as well as the calculated response of the half-space was entered into the corresponding Excel file. The RMS-residual was calculated and also the ratio between the RMS-residual and the average measured impedance. This ratio can be used to estimate the goodness of fit and hence the validity of the model. By experience it is known that ratios below 0.3 indicate fairly homogeneous bedrock and a good fit /2/. The apparent anisotropy can however be in accordance with dominating direction of fracturing/ foliation/bedding for even poorer fits. The RMS-ratio will to some extent be dependent upon the actual array geometry, the number of measurements made and the bedrock resistivity and anisotropy. A normalized measure of the goodness of fit (σ_0) where the above mentioned factors have been accounted for can be calculated as /2/:

$$\sigma_0 = \sqrt{\sum v_i^2} \cdot \frac{a}{\rho_{am}} \cdot \frac{1}{\sqrt{n-3}}$$

where v_i is the difference between measured impedance and model response, a is the average distance between the survey station and the four outer electrodes, ρ_{am} is the inverted bulk resistivity and n is the number of measurements.

Values of σ_0 below 0.03 indicate, by experience /2/, a good fit to the model.

The data quality controls based on redundancy mentioned above are automatically calculated in the Excel spread-sheet.

5 Results and interpretation

The result of the interpretation is presented in Tables 5-1 and 5-2 and in Figures 5-1 to 5-6. General conclusions and comments are given below.

Raw data, calculated data and interpretation results have been delivered to SKB on CD ROM. Appropriate information has been stored in SICADA. The SICADA reference to the activity is Field note Forsmark 99.

5.1 Electric soundings

The horizontally layered earth was, in principle, a valid model for most of the stations (Table 5-1). Departures from the model, however, exist to a varying extent for all stations.

The soil cover thickness varies, according to the soundings, between 0 and 9.5 metres, with a median value of 3.2 metres. Thick cover is present mainly around Storskäret (Figure 5-2). Interpreted thicknesses of more than 4 metres can also be found at a few other locations, e.g. west of Bolundsfjärden and south of Eckarfjärden/Fiskarfjärden. It should be noted that some stations with a thick overburden are situated close to rock outcrops.

The effective resistivity of the soil cover varies between 75 and 1930 Ωm. The histogram in Figure 5-1 shows a bimodal distribution with one group of stations with effective resistivities of around 100 Ωm and a second group around 1000 Ωm. The group with the lower values primarily corresponds to stations close to Storskäret (Figure 5-3) where a clayey moraine is the dominating soil type /3/. Low resistivities are also present at scattered stations in a band from Fiskarfjärden/Eckarfjärden towards the Forsmark power plant, where peat is known to be abundant /3/. Other stations in this area show high resistivities.

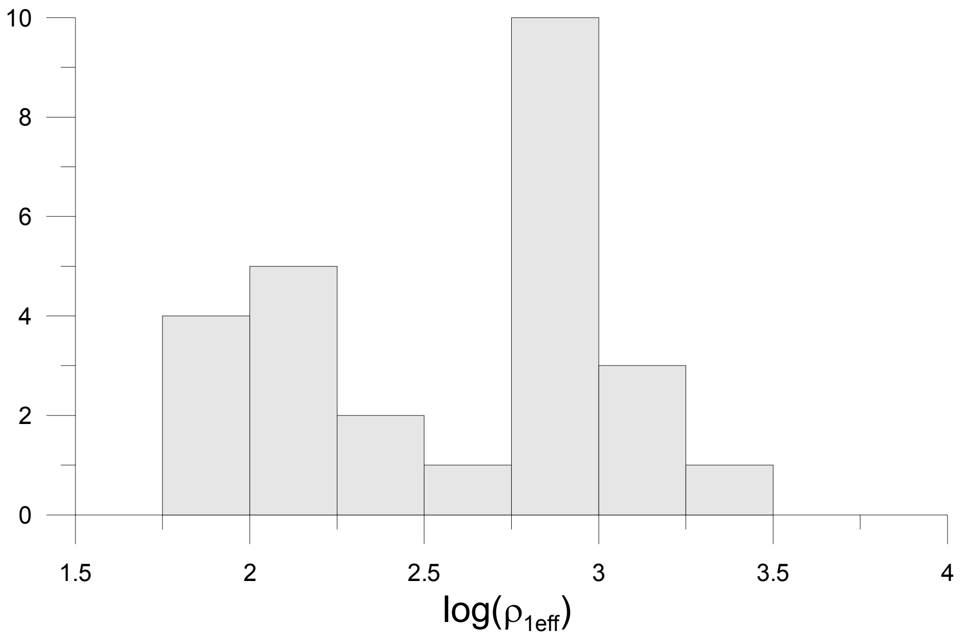

Figure 5-1. *Histogram of interpreted effective resistivity of the soil cover.*

The helicopterborne electromagnetic measurements will probably not be able to resolve the soil resistivity and thickness as separate properties. Instead, it is the integrated electric conductance that might be possible to estimate. Figure 5-4 shows the interpreted conductance at the sounding stations. All stations with high conductance can be found close to Storskäret.

The interpreted resistivity of the bedrock varies between 1360 and 18640 Ωm, with a median value of 7280 Ωm. Stations with a low resistivity (< 4000 Ωm) can be found around Storskäret and west of Bolundsfjärden. In the latter area two stations with a resistivity below 2500 Ωm can be found. Both, however, seem to be significantly affected by non-1D low-resistivity structures in the bedrock. These stations are labelled VES8 and VES22 in Table 5-1. A few other stations are also affected by such structures, namely VES13, VES26, and VES30, and possibly VES15.

Table 5-1. Interpreted properties and error limits for all soundings. No soil resistivity is given when the cover thickness is less than 0.3 metres. The data quality has been estimated in a five grade scale where values below 3 means that data are not up to the demands in the method description. The validity of a horizontally layered model has subjectively been estimated in a five grade scale, where electrode separations shorter than 60 metres have been considered as most important. Grades below 3 indicate that the model is not valid. The model parameters can however still be estimated, but with large error limits.

Station	IDcode	X RT90 (m)	Y RT90 (m)	ρ_{1eff} (Ωm)	$\sigma_{\rho 1}$ (Ωm)	h_1 (m)	σ_{h1} (m)	ρ_2 (Ωm)	$\sigma_{\rho 2}$ (Ωm)	Data quality 1=poor, 5=very good	Validity of layered model 1=poor, 5=very good
VES1	PFM002261	6697767	1634440	169	30	8.6	3.0	4830	1500	4	3
VES2	PFM002262	6696814	1634195	176	50	9.5	3.0	3250	1000	5	3
VES3	PFM002263	6697999	1635493	231	60	2.3	0.6	5400	1500	4	3
VES4	PFM002264	6697006	1634785	76.8	15	9.5	1.5	6550	1500	5	4
VES5	PFM002265	6695503	1633878	N/A	N/A	0.0	0.0	7650	1000	3	2
VES6	PFM002266	6697001	1632508	74.8	20	1.2	0.3	6270	2000	4	3
VES7	PFM002267	6698503	1629400	547	150	7.1	2.0	4800	1000	3	3
VES8	PFM002268	6698577	1630238	104	20	2.0	0.5	1365	1000	3	1
VES9	PFM002269	6696027	1633541	1200	200	4.7	1.5	12440	2500	4	3
VES10	PFM002270	6698000	1634407	147	25	7.8	1.5	8200	1200	5	4
VES11	PFM002271	6699512	1632375	N/A	N/A	0.0	0.2	5480	500	4	4
VES12	PFM002272	6699501	1633165	805	125	3.5	1.2	7040	1000	4	3
VES13	PFM002273	6697998	1632503	1200	400	1.0	0.5	8000	3000	3	1
VES14	PFM002274	6698012	1630551	891	400	3.7	1.0	9880	3000	4	3
VES15	PFM002275	6697468	1632008	928	200	1.3	0.4	6540	2000	4	3
VES16	PFM002276	6696985	1631554	700	200	3.8	1.0	10050	2000	3	4
VES17	PFM002277	6697600	1634202	95.3	20	5.0	0.7	3630	1000	5	4
VES18	PFM002278	6698505	1633351	146	30	3.4	0.5	18640	4000	4	3
VES19	PFM002279	6696002	1629349	N/A	N/A	0.0	0.2	8000	1000	4	4

Station	IDcode	X RT90 (m)	Y RT90 (m)	ρ_{1eff} (Ωm)	$\sigma_{\rho 1}$ (Ωm)	h_1 (m)	σ_{h1} (m)	ρ_2 (Ωm)	$\sigma_{\rho 2}$ (Ωm)	Data quality 1=poor, 5=very good	Validity of layered model 1=poor, 5=very good
VES20	PFM002280	6696000	1632099	950	150	4.4	0.8	5340	500	3	3
VES21	PFM002281	6699502	1628344	702	200	3.0	0.8	7520	800	4	3
VES22	PFM002282	6699503	1631352	593	125	4.1	2.5	1740	3000	3	1
VES23	PFM002283	6698612	1631671	734	400	5.7	1	4230	500	3	2
VES24	PFM002284	6696997	1630560	N/A	N/A	0.1	0.2	9220	1000	4	4
VES25	PFM002285	6698000	1631443	85.7	25	0.9	0.3	13370	3000	3	3
VES26	PFM002286	6694509	1630709	928	300	1.8	0.3	14970	4000	3	3
VES27	PFM002287	6699511	1626628	N/A	N/A	0.2	0.2	12000	3000	3	2
VES28	PFM002288	6699490	1627512	1155	300	2.4	0.4	11860	2000	3	4
VES29	PFM002289	6694655	1631538	256	60	2.4	0.4	3360	800	3	3
VES30	PFM002290	6694971	1631467	1930	300	4.0	0.4	10050	2000	3	4

5.2 X-configuration measurements

According to the x-configuration measurements, the bulk resistivity of the bedrock varies between 2960 and 9760 Ωm with a median value of 4410 Ωm. This is significantly lower than the median value of bedrock resistivity for the soundings (section 5.1). A bias toward lower values is inevitable with X-configuration measurements, since the effect of the soil cover is not accounted for during inversion of data. However, the cover is quite thin in the area compared to the electrode separations, so this effect is considered to be small in most cases.

Different apparent anisotropy directions (direction of lowest resistivity) appear in the area. However, with only two exceptions, a clear correspondence can be seen between the anisotropy direction and the local strike direction of structures in the aeromagnetic map (Figure 5-6). Both exceptions are found in the southern part of the area, outside the lens of metagranitoid, surrounded by belts of ductile deformation /3/. One of these stations (X1, Table 5-2) has a poor fit to the model and is probably affected by 2D- or 3D-structures in the bedrock. The other one (X8, Table 5-2) has a good fit to an anisotropic half-space with NNE anisotropy, whereas magnetic structures strike NW. This discrepancy might be due to local brittle deformation not seen in the aeromagnetic map. The degree of anisotropy is however moderate for this station.

The anisotropy coefficient for the stations is moderate to high and varies between 1.07 and 1.74. The apparent anisotropy coefficient (λ_a) is defined as:

$$\lambda_a = \sqrt{\frac{\rho_y}{\rho_x}},$$

where ρ_x and ρ_y are the apparent resistivities parallel to and perpendicular to the anisotropy direction respectively. This means that the resistivity perpendicular to the anisotropy is 1.14 to 3.03 times higher than along the anisotropy direction. In crystalline bedrock this can be interpreted as a presence a preferred fracture direction along the anisotropy. However, it is also possible that the electric conductivity of individual fractures varies with direction due to aperture, alteration or surface conductivity. The rather strong anisotropy can hardly be caused by individual large fracture zones. Such zones have a rather small influence on the apparent anisotropy, unless the zone width is almost comparable to the electrode separation, i.e. a width of around 100 metres would be required /2/. The values of the bulk resistivity indicates, possibly with some exception, that the measurements have been performed outside zones of such a size. The high anisotropy coefficients also indicate that sub-horizontal fractures are not of importance, since they would contribute to electric conductivity in all horizontal directions and thus not to the apparent anisotropy.

The fit to a homogeneous, anisotropic half-space is good for eight of the twelve stations. Three of the stations with poorer fit are situated close to the border between the meta-granitoid lens and the belt of ductile deformation to the southwest /3/. Only one station with poor fit can be found inside the lens (X7, Table 5-2) and this station is situated close to a bend in tectonic foliation direction /3/. This indicates that the lens is electrically fairly homogeneous whereas the border zone towards the surrounding, more deformed rocks is electrically inhomogeneous.

Table 5-2. Results from inversion of x-configuration measurements. The anisotropy direction, ϕ_a, is positive clock-wise from north The data quality has been estimated in a five grade scale, where values below 3 means that data are not up to the demands in the method description.

Station	IDcode	X RT90 (m)	Y RT90 (m)	ρ_{a_bulk} (Ωm)	λ_a	ϕ_a (°)	RMS/mean *	σ_o*	Data quality 1=poor, 5=very good
X1	PFM002249	6696467	1633982	4980	1.74	63.2	0.55	0.059	5
X2	PFM002250	6698027	1633473	4120	1.47	–78.0	0.27	0.024	5
X3	PFM002251	6699747	1632767	4380	1.18	–88.1	0.15	0.012	4
X4	PFM002252	6698123	1632967	7010	1.69	–58.5	0.20	0.016	5
X5	PFM002253	6697813	1635177	3660	1.44	77.5	0.21	0.020	4
X6	PFM002254	6698948	1630992	2960	1.28	–58.9	0.39	0.037	3
X7	PFM002255	6698816	1633444	6040	1.32	72.0	0.43	0.035	5
X8	PFM002256	6697294	1630657	9760	1.12	14.3	0.21	0.016	3
X9	PFM002257	6697778	1632037	3660	1.16	–40.1	0.28	0.024	5
X10**	PFM002258	6699468	1630975	3150	1.15	–22.8	0.32	0.025	2
X11	PFM002259	6698810	1633088	6190	1.07	–85.9	0.31	0.026	4
X12	PFM002260	6701507	1628939	4440	1.43	–12.1	0.55	0.041	4

* See section 4.2.

** This station is close to the Forsmark power plant which might explain the poorer data quality.

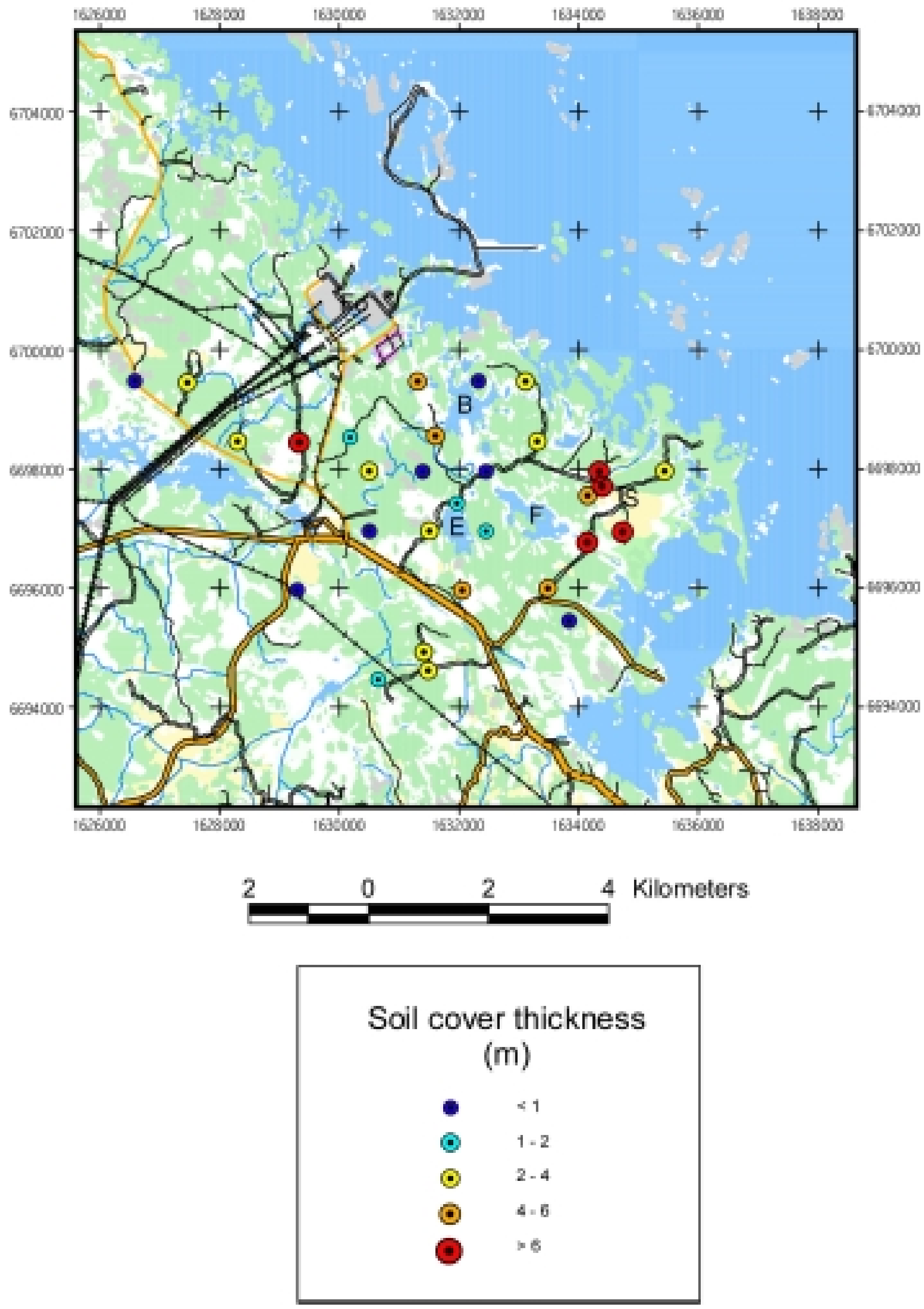

Figure 5-2. *Soil cover thickness as interpreted from electric soundings. S = Storskäret, B = Bolundsfjärden, Fo = Forsmark power plant, E = Eckarfjärden, F = Fiskarfjärden.*

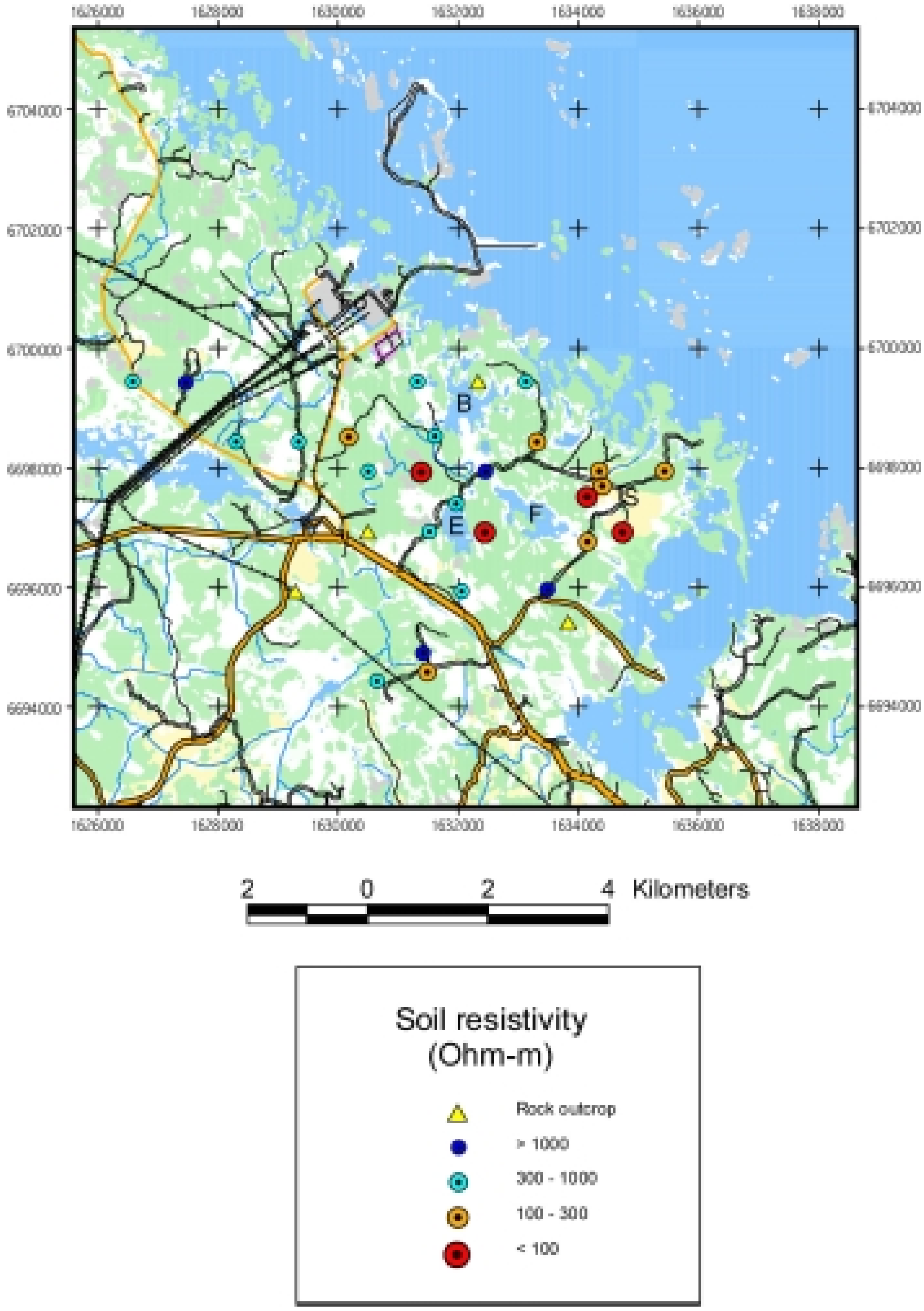

Figure 5-3. *The effective resistivity of the soil cover as interpreted from electric soundings. S = Storskäret, B = Bolundsfjärden, Fo = Forsmark power plant, E = Eckarfjärden, F = Fiskarfjärden.*

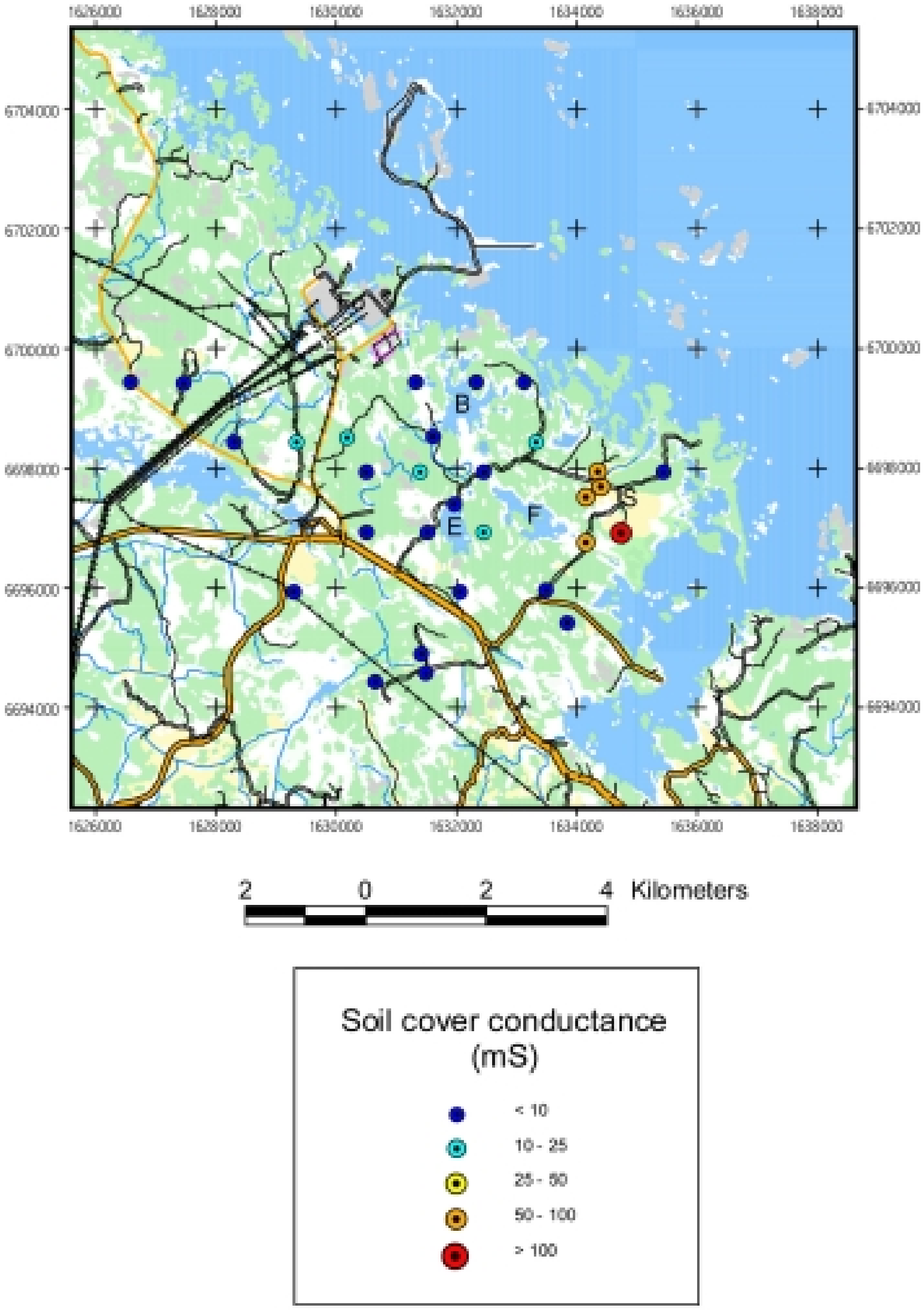

Figure 5-4. *The integrated electric conductance of the soil cover as interpreted from electric soundings. S = Storskäret, B = Bolundsfjärden, Fo = Forsmark power plant, E = Eckarfjärden, F = Fiskarfjärden.*

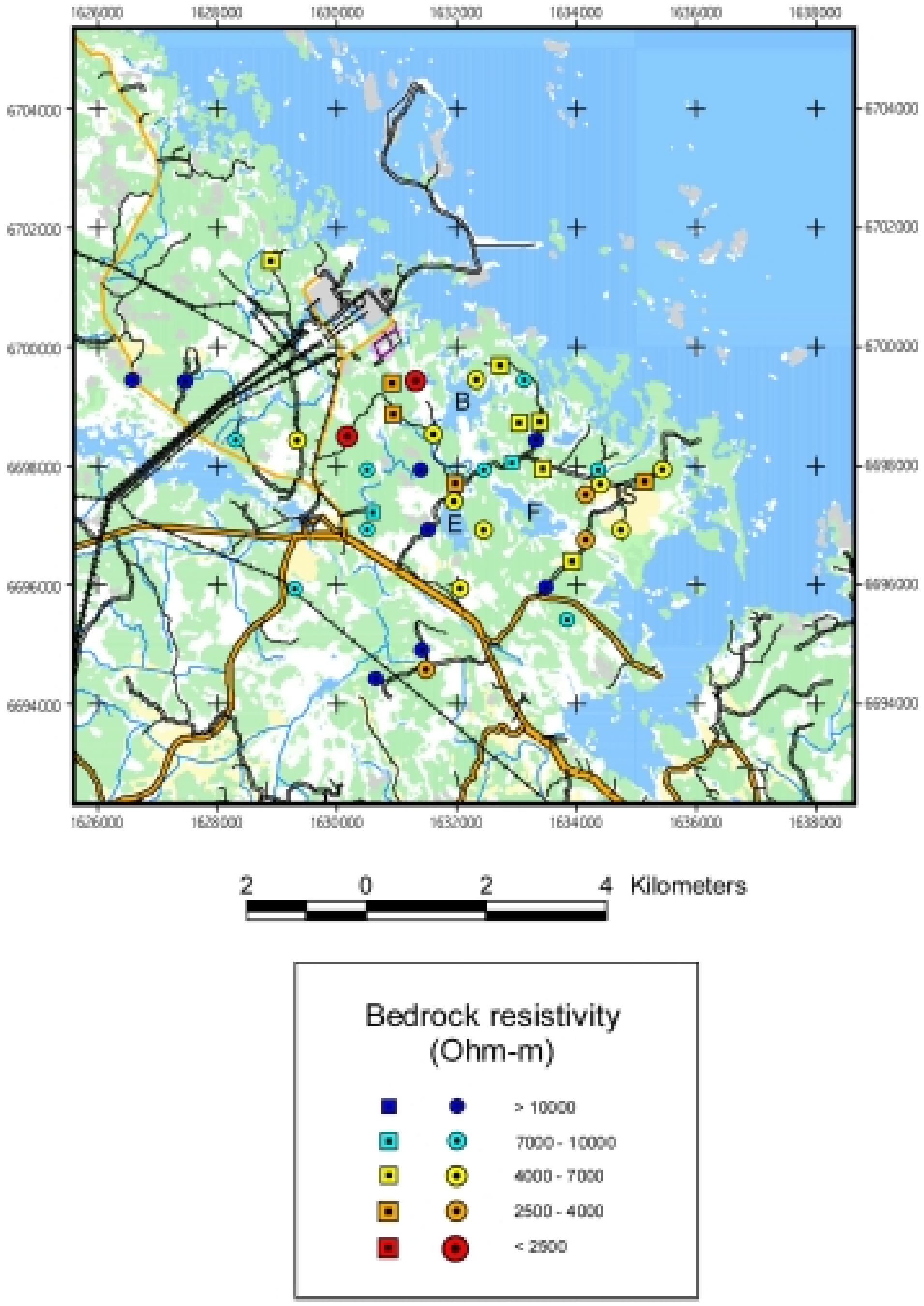

Figure 5-5. *Bedrock resistivity as interpreted from electric soundings (circles) and x-configuration measurements (squares). S = Storskäret, B = Bolundsfjärden, Fo = Forsmark power plant, E = Eckarfjärden, F = Fiskarfjärden.*

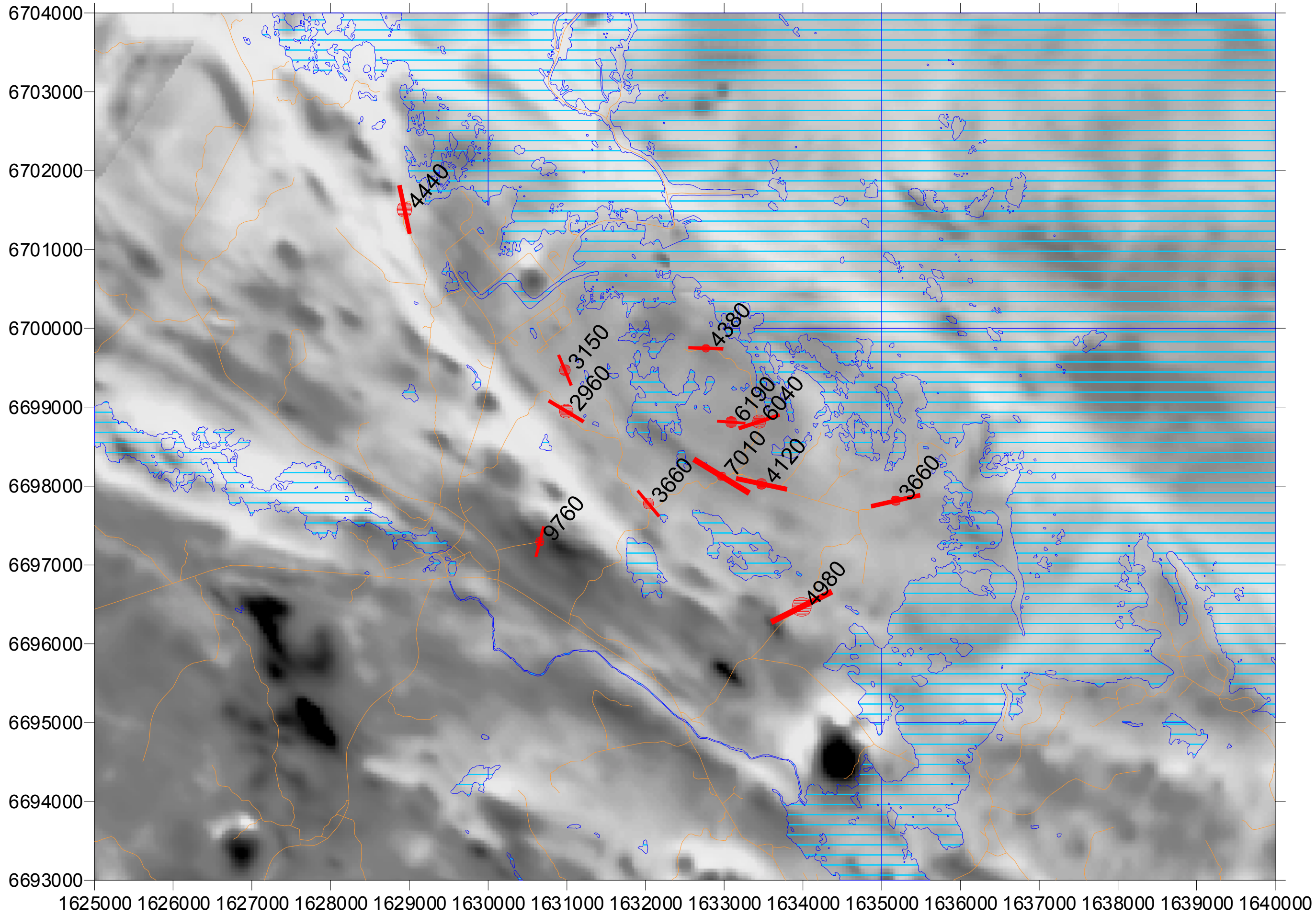

Figure 5-6. *Direction of apparent electric anisotropy is shown with red lines with the aeromagnetic map as background. The length of the lines indicates the anisotropy coefficient that varies between 1.07 and 1.74. The size of the filled red circles corresponds to the value of* σ_0*, where small values and hence small circles indicate a good fit to an anisotropic half-space. The numbers show the inverted bulk resistivity in* Ω*m.*

6 References

/1/ **SKB, 2003.** Geophysical measurements from helicopter. SKB P-03-41. Svensk Kärnbränslehantering AB.

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