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Simpevarp site investigation

Electrical soundings supporting inversion of helicopterborne EM-data

Primary data and interpretation report

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GeoVista

April 2003

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Contents

1 Introduction

This document reports vertical electrical soundings (VES) and anisotropy measurements that have been performed in the Simpevarp area during autumn 2002 in connection to the selection of a preferred site for further investigations.

All field work and interpretation was conducted by GeoVista AB in accordance with the instructions and guidelines from SKB (activity plan AP PS 400-02-014 and method description MD 212.005, SKB internal controlling documents) and under supervision of Leif Stenberg, SKB. The location of the electrical sounding (VES) and anisotropy measurement points according to the activity plan is shown in Figure 1-1. Some points had to be moved somewhat during the fieldwork.

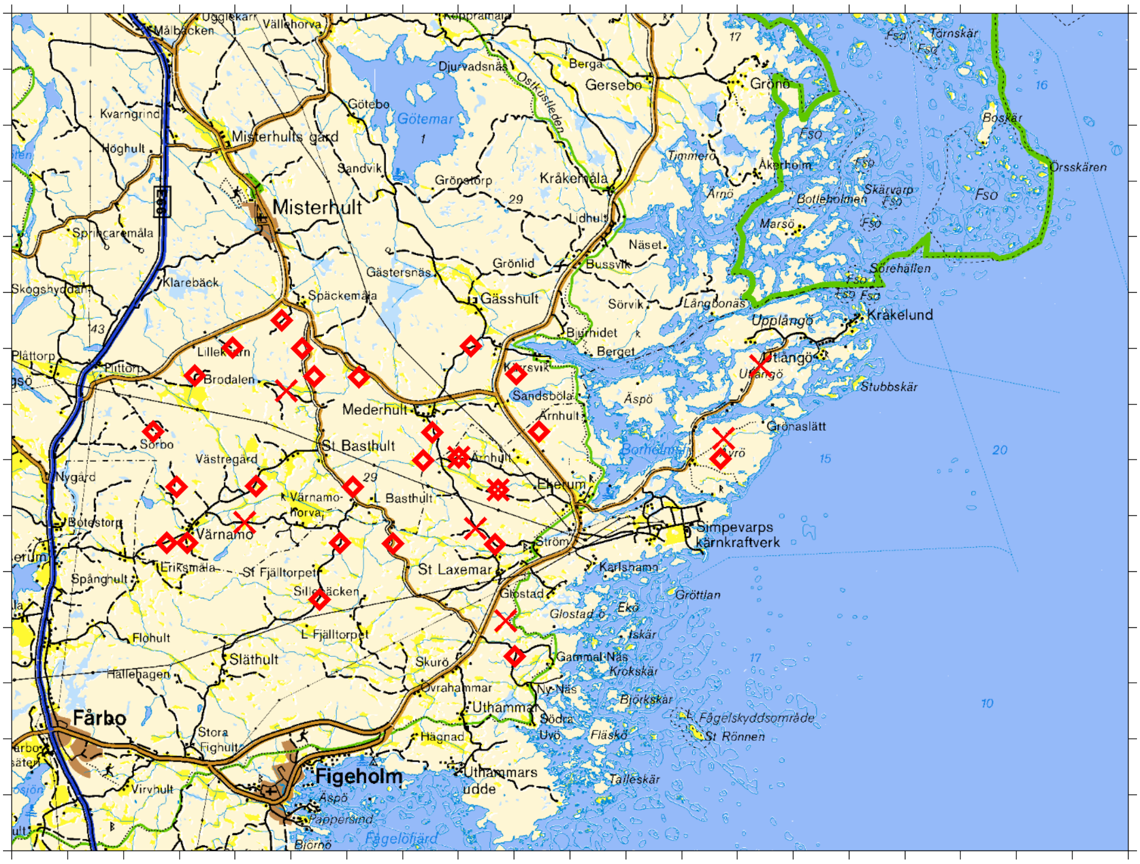

Figure 1-1. Locations of points for vertical electrical soundings (◊) and points for anisotropy measurements with X-configuration (x) according to the activity plan (AP PS 400-02-14).

2 Objectives

The objectives of the vertical electrical soundings (VES) was to gain knowledge about the electrical properties (resistivity) of the bedrock and the soil cover as well as the approximate thickness of the soil cover at a number of scattered points in the helicopter survey area. The helicopter survey was performed in the autumn of 2002 /1/. The VES sounding data in combination with other data about the soil cover and bedrock will be used as constraints in future levelling and inversion of helicopter electromagnetic (EM) data. An integrated conductance will be 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.

X-configuration measurements is performed in order to gain knowledge of the direction of the apparent electric anisotropy. This anisotropy can be caused by a presence of a preferred fracture direction along the anisotropy or due to fracture aperture, alteration or surface conductivity along fractures.

3 Work performed

In general the measurement procedures follows SKB method description (MD 212.005, SKB internal controlling document).Vertical electrical soundings have been performed at 22 stations with a modified Schlumberger array and measurements with x-configuration have been performed at 7 stations. A brief description of the methods and the field procedure follows below.

3.1 Modified Schlumberger array

Electrical 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 resistivities and thicknesses. 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) has been placed at the survey station and the other potential electrode (N) around 80 metres away (Figure 3-1). A current electrode (A) is initially placed 0.6 metres away from M whereas the other current electrode (B) is 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, equidistant 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. This gives some indication about the validity of the horizontal layer approximation.

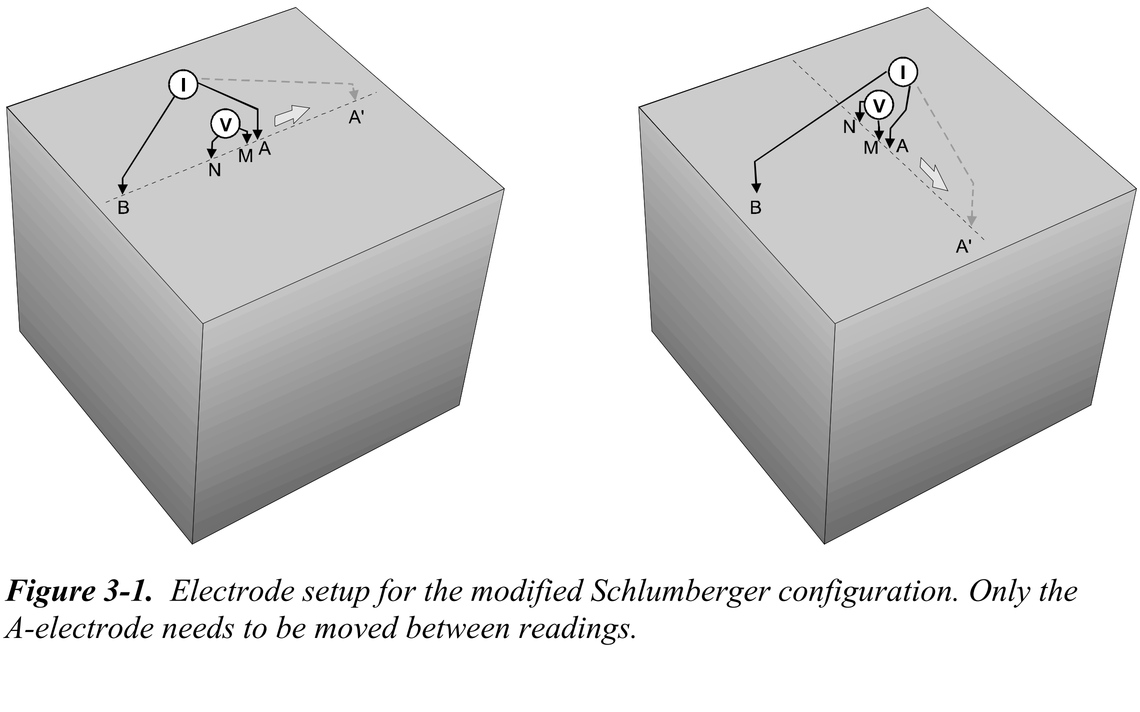

Figure 3-1. *Electrode setup for the modified Schlumberger configuration. Only the A-electrode needs to be moved between readings.*

3.2 X-configuration

Four electrodes have been 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 /2/. 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/.

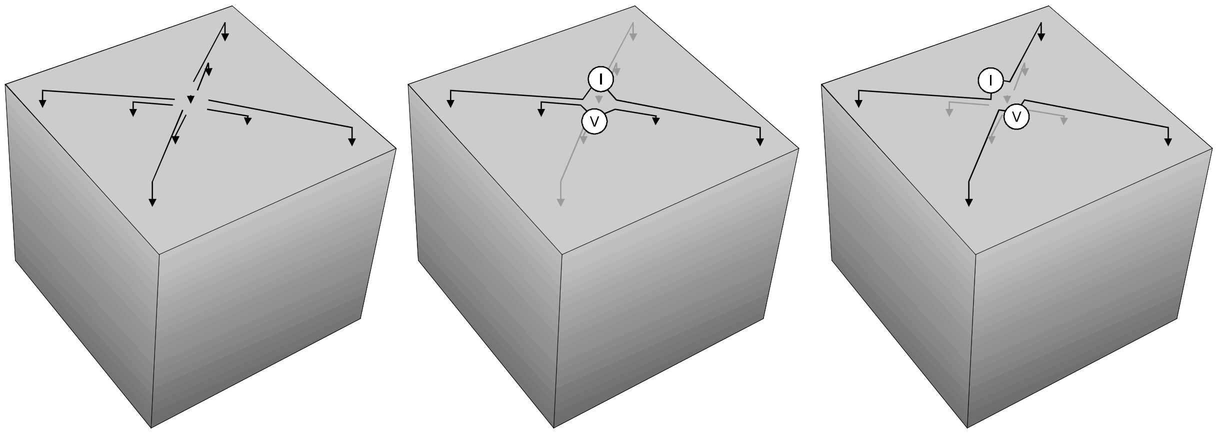

Figure 3-2. *Electrode setup for anisotropy determinations with x-configuration (left). All nine electrodes are connected to the instrument in the centre. Different combinations of electrodes are used so that measurements can be made with e.g. a linear array (centre) and square array (right) in two directions.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

3.3 Coordinates

The coordinates of the survey stations have been determined with 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 usual GPS.

4 Quality assurance

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, except for October 25th. A DC shift appears in the data for the two soundings performed this day (VES14 and VES15 in Table 6-1), resulting in negative apparent resistivities for large electrode separations. However, for short separations the shift is negligible.

Cables and contacts were inspected before use. A daily check was performed daily 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 was indicated by these tests.

Redundant readings are acquired with the x-configuration. Some values can be calculated as linear combination of others. Suppose e.g. that a series of measurements are 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 15 % of the RMS-residual for the inversion appeared for one station only. The likely cause to the problem was one single bad reading. The inversion result was however more or less identical with or without the suspected values included.
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 6-1.

5 Data processing and inversion

5.1 Electrical soundings

Measured impedances from the soundings were entered into Excel spread-sheets. Data-files 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 for 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.

5.2 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 fracturing/foliation/bedding-directions 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 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, by experience /2/, indicates a good fit to the model.

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

6 Results and interpretation

The result of the interpretation is presented in Table 6-1 and 6-2 and in Figures 6-2 to 6-5. The sounding stations are labelled in Figure 6-1. General conclusions and comments are given below. Raw data from the measurements were delivered directly after the termination of the field activities. The delivered data have been inserted in the database (SICADA) of SKB. The SICADA reference to the present activity is Field note No. 50.

6.1 Electrical soundings

The soil cover thickness varies, according to the soundings, between 0 and 14.5 metres. However, only 5 out of the 22 stations have an interpreted cover thickness of more than 2 metres. Farmland and areas close to houses have been avoided for sounding stations. It is therefore possible that stations with thin soil cover are over-represented. It is however obvious that large parts of the area have thin cover. The median value for the interpreted thickness of the cover is 0.6 metres.

The effective resistivity of the soil cover varies between 51.9 and 2,300 Ωm. The large spread indicates that completely different types of soils are present. However, only 6 sounding stations show effective soil resistivities below 1,000 Ωm. Values above 1,000 Ωm indicates low water saturation and moderate capillarity. The most common situation seems to be a thin, coarse grained moraine cover that is unsaturated. Stations with low effective resistivity mainly occur in local topographic lows. It is quite possible that fine-grained, low-resistivity soils can be found in pockets in the bedrock relief. Large local variations in soil resistivity are therefore expected.

The interpreted bulk resistivity of the bedrock varies between 3,000 and 36,300 Ωm. The stations with the lowest resistivities are scattered over the area. Certainly, three stations with low resistivity are situated around Mederhult but this could be a coincidence. The median value for the interpreted bulk resistivity is 10,800 Ωm. This is significantly higher than the bulk resistivity that has been estimated from semi-regional resistivity measurements /2, 3/ and with x-configuration measurements (section 6.2). The reason for this discrepancy is not known but it is possible that the location of the sounding stations away from populated areas in valleys makes rock volumes with low resistivity under-represented in the data. Also, low-resistivity anomalies in the sounding curves have in general been treated as geologic noise and therefore they have been disregarded in the estimation of bulk resistivity. Another possibility is that the differences reflect different investigation depths of the methods.

In many cases, the apparent resistivity for large electrode separations differs for the two sounding directions. This might indicate anisotropy in the bedrock.

Comments for some of the sounding stations are given below.

6.1.1 VES1

The station is situated in a local NW-SE striking topographic low. The ascent in the sounding curves is steeper than what is possible for a 1D-earth. This might indicate that the station is situated in an area with thicker and/or more conductive soil cover than the surroundings. The interpretation to a layered model has mainly been done for data from short electrode separations, which reflects the situation close to the station.

6.1.2 VES3

The station is situated on a local topographic high. The estimated bedrock resistivity is high but since there is a descent in the sounding curve for long electrode separations, it is possible that surrounding bedrock has lower resistivity.

6.1.3 VES7

The station is situated east of a significant magnetic lineament. The sounding in westerly direction is affected by a low-resistivity structure in the bedrock.

6.1.4 VES8

See VES7.

6.1.5 VES10

This station has the largest interpreted thickness of the soil cover. The sounding curves for the two measurement direction differs significantly. This indicates that the measurements are affected by non-1D structures.

6.1.6 VES14

This station is affected by a shift in the base level of the instrument (see chapter 4). An acceptable interpretation of the data was still possible since data for short separations hardly were affected and the soil cover was thin.

6.1.7 VES15

See VES14.

6.1.8 VES17

The station is situated in a NS striking valley south of Mederhult. The effective soil resistivity is the lowest for the area (51.9 Ωm). However, the ascent in the sounding curves is steeper than what is possible for a layered earth. This might indicate that the station is situated in an area with thicker and/or more conductive cover than the surroundings.

6.1.9 VES18

The sounding was performed south of Mederhult near a NS striking lineament. Both sounding directions are affected by low-resistivity structures in the bedrock.

Table 6-1. 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 not are 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 most important. Grades below 3 indicates 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)	$\sigma_{\rho1}$ (Ωm)	h_1 (m)	σ_{h1} (m)	ρ_2 (Ωm)	$\sigma_{\rho2}$ (Ωm)	Data quality 1=poor, 5=very good	Validity of layered model 1=poor, 5=very good
VES1	PSM001546	6367543	1542513	222	80	2.5	0.5	20000	4000	4	2
VES2	PSM001547	6368492	1543283	1500	1000	0.5	0.4	8660	1500	4	2
VES3	PSM001548	6368985	1543955	2000	2000	0.1	0.1	36000	10000	4	2
VES4	PSM001549	6369457	1544843	N/A	N/A	0	0.2	10390	5000	4	2
VES5	PSM001550	6367011	1552680	800	500	0.3	0.3	15000	3000	4	3
VES6	PSM001551	6364495	1545514	2000	1000	0.4	0.3	18890	2000	5	4
VES7	PSM001552	6369006	1545288	1000	300	1.7	0.5	7250	3000	4	1
VES8	PSM001553	6368508	1545263	1800	800	2	0.5	17320	4000	4	2
VES9	PSM001528	6369009	1548237	N/A	N/A	0.1	0.1	6820	2000	3	2
VES10	PSM001526	6366406	1548577	1120	300	14.5	3	7480	3000	4	2
VES11	PSM001529	6368587	1546295	N/A	N/A	0.2	0.2	18170	2000	3	4
VES12	PSM001530	6365487	1548620	1930	400	1.2	0.2	15720	2000	4	4
VES13	PSM001531	6366451	1544310	700	150	4.2	0.5	7860	500	4	5
VES14	PSM001532	6367085	1549746	2300	500	1.3	0.3	11220	2000	2	4
VES15	PSM001533	6368508	1548999	1750	1000	0.3	0.2	10000	2000	2	3
VES16	PSM001535	6365494	1546791	490	100	0.8	0.3	20920	5000	4	3

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
VES17	PSM001536	6367070	1547475	51.9	10	6.3	2.0	5920	2000	4	2
VES18	PSM001537	6367476	1547566	N/A	N/A	0.1	0.1	4470	2000	3	1
VES19	PSM001538	6364669	1549681	1200	300	1.3	0.2	3000	500	4	4
VES20	PSM001539	6367013	1548199	1180	600	0.3	0.2	11200	2000	4	3
VES21	PSM001541	6365473	1545887	2155	600	0.7	0.3	9100	1500	4	3
VES22	PSM001544	6366508	1545928	347	150	0.4	0.4	36300	4000	3	3

6.2 X-configuration measurements

The bulk resistivity of the bedrock varies between 4,050 and 9,900 Ωm according to the x-configuration measurements, with a median value of 7,080 Ωm. This is significantly lower than the median value of bedrock resistivity for the soundings (section 6.1). A bias toward lower values is inevitable with x-configuration measurements since the effect of the soil cover not is accounted for during inversion of data. However, the soil 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. A NE anisotropy can be seen in the northeastern part of the area (Figure 6-5). This is roughly parallel to the Äspö shear zone and other local geological structures. An EW to SE-NW anisotropy can be seen in the central parts of the area. This is roughly the same direction as magnetic anomalies in that area. There is only one station in the western part of the area. It shows a NE anisotropy direction but the anisotropy coefficient is close to unity so the direction is poorly determined.

Except for the western station, the anisotropy coefficient is fairly high to high and varies between 1.25 and 1.78. 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 1.56 to 3.17 times higher than along the anisotropy, the western station excluded. Since the bedrock is crystalline this can be interpreted as a presence of 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 measurements have been performed beside zones of such size. The high anisotropy coefficients also indicates that sub-horizontal fractures not are of importance since they would contribute to electric conductivity in all horizontal directions and thus to apparent isotropy.

The fit to a homogeneous anisotropic half-space is good for three of the seven stations only (see section 5.2). The systematic direction of the apparent anisotropy and the correspondence to features in e.g. the aeromagnetic map indicates that the anisotropy directions still can be related to foliation/bedding/fracturing. However, the rather poor fits indicates that the bedrock is electrically inhomogeneous.

Table 6-2. 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 not are up to the demands in the method description.

Punkt	IDcode	X RT90 (m)	Y RT90 (m)	ρ_{a_bulk} (Ωm)	λ_a	ϕ_a (°)	RMS/mean *	σ_0 *	Data quality 1=poor, 5=very good
X1	PSM001556	6367380	1552822	9280	1.38	54.0	0.38	0.032	5
X2	PSM001527	6366406	1548577	7080	1.78	–83.2	0.23	0.022	3
X3	PSM001534	6365718	1548326	8890	1.55	–83.8	0.44	0.039	3
X4	PSM001540	6367013	1548199	9900	1.30	–55.2	0.18	0.015	5
X5	PSM001542	6368689	1553413	5660	1.25	50.3	0.47	0.043	4
X6	PSM001545	6368225	1544923	5600	1.04	57.3	0.37	0.032	4
X7	PSM001543	6363637	1549640	4050	1.53	–89.5	0.27	0.019	5

* See section 5.2.

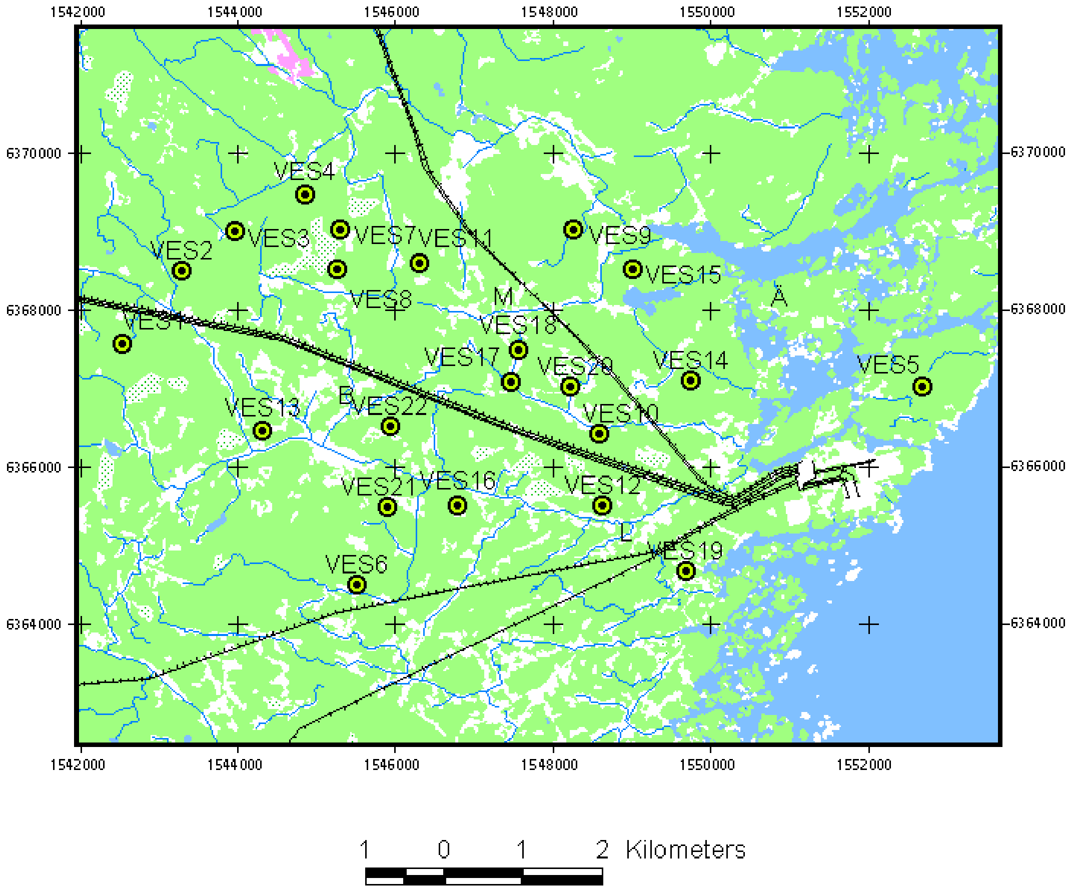

Figure 6-1. *Labels for the sounding stations. M = Mederhult, L = St. Laxemar, B = St. Basthult, Ä = Äspö.*

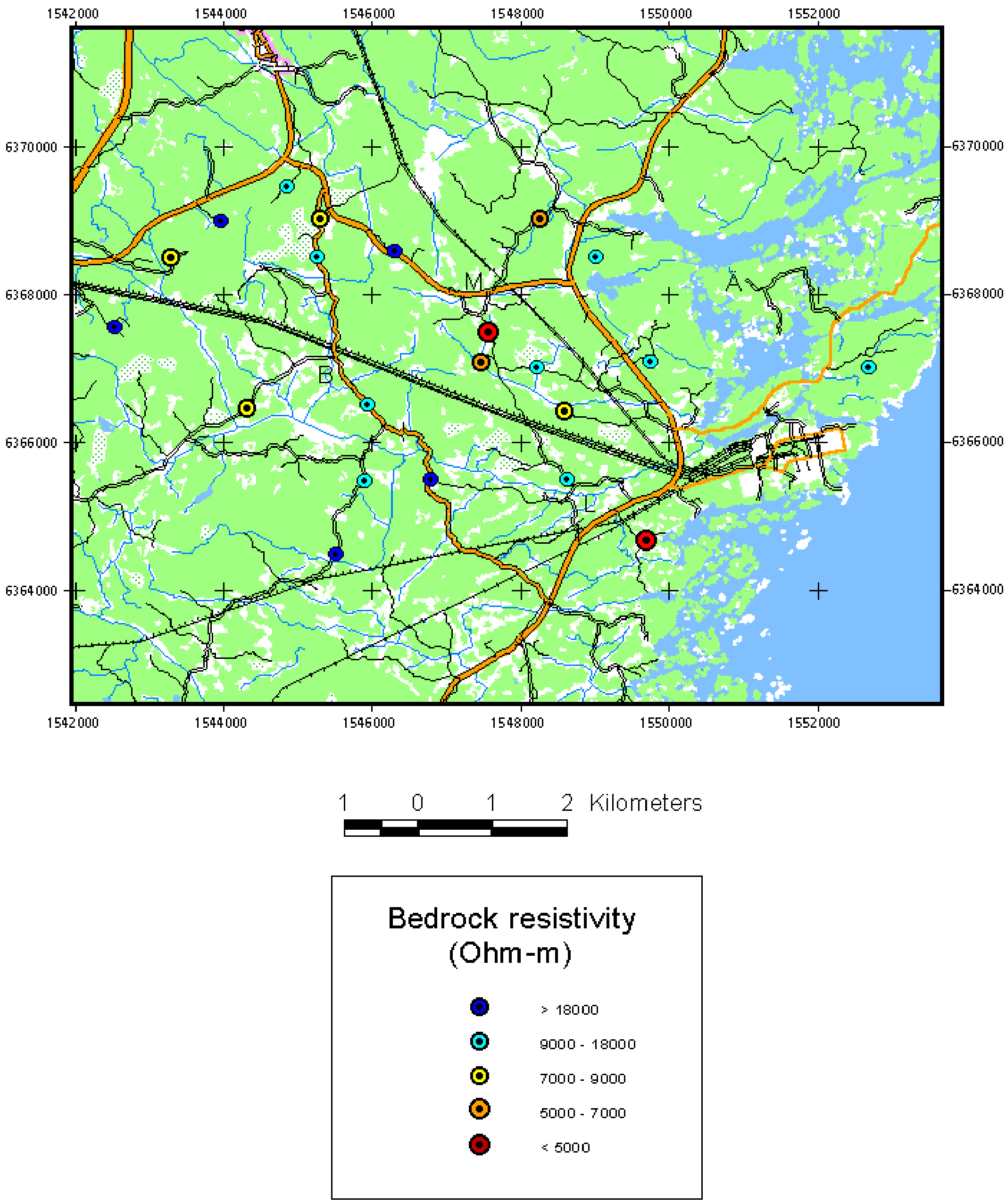

Figure 6-2. *Resistivity in the bedrock as interpreted from electrical soundings. M = Mederhult, L = St. Laxemar, B = St. Basthult, Ä = Äspö*

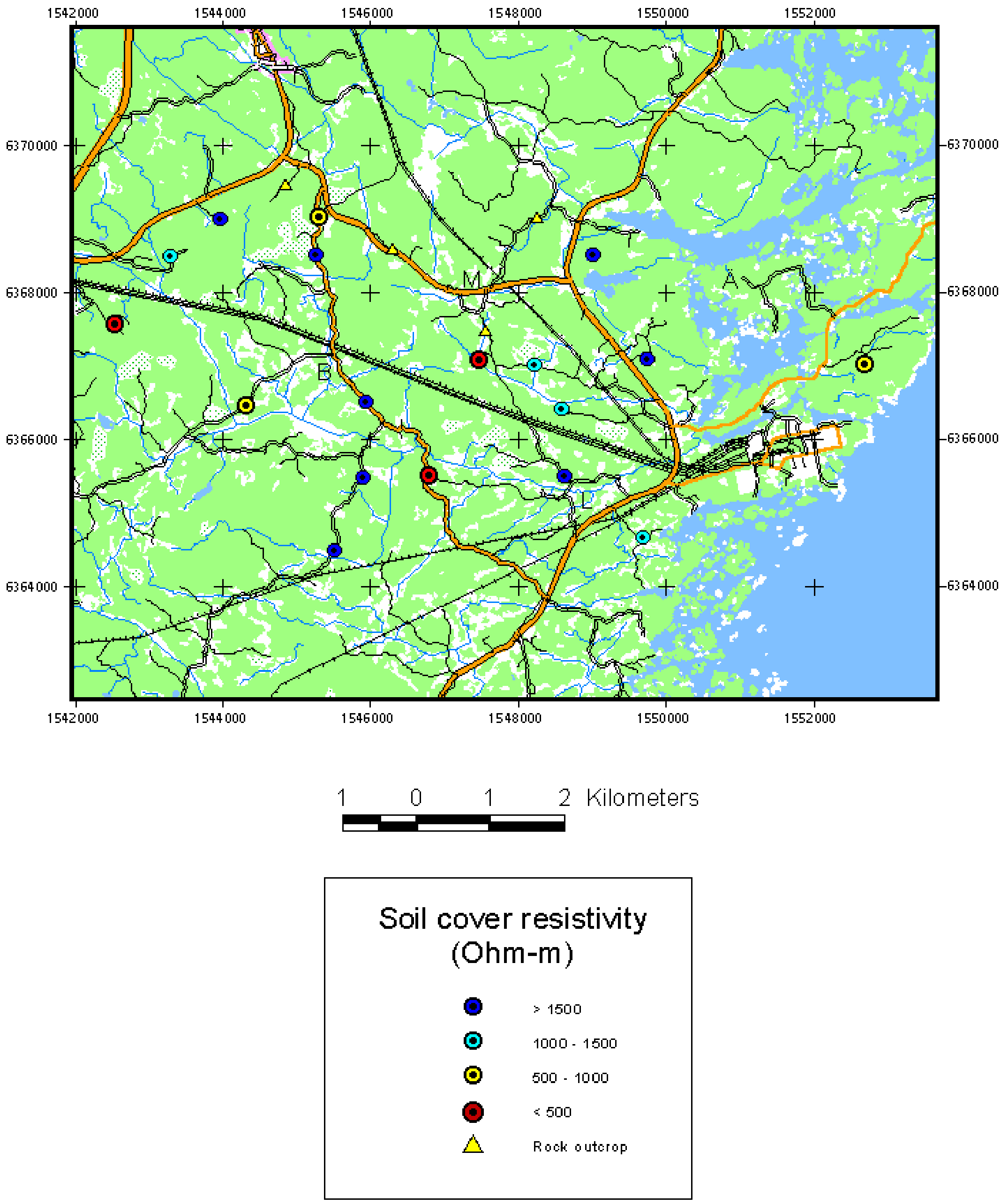

Figure 6-3. *Effective electric resistivity in the soil cover as estimated from electrical soundings. M = Mederhult, L = St. Laxemar, B = St. Basthult, Ä = Äspö.*

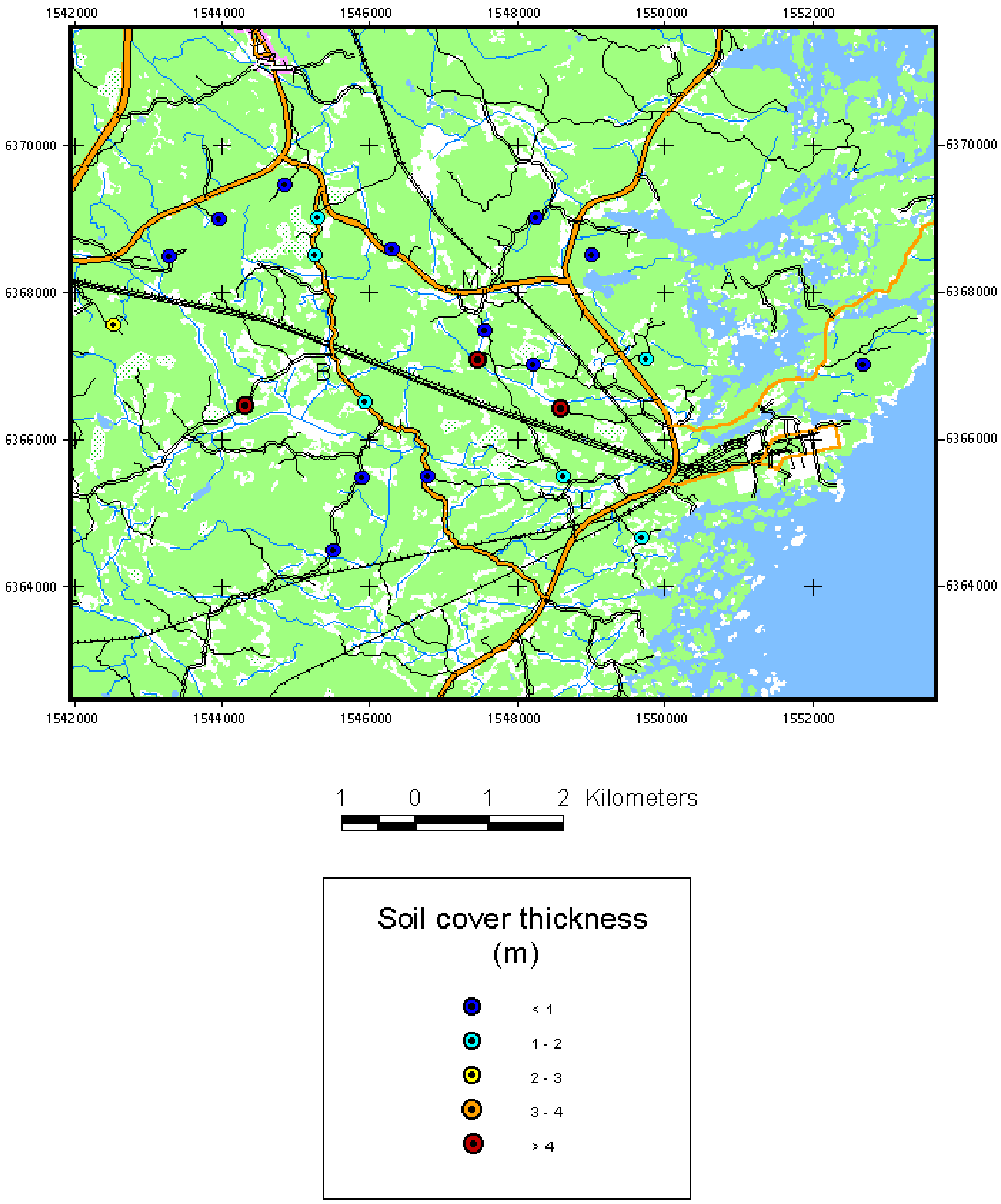

Figure 6-4. *Soil cover thickness as interpreted from electrical soundings. M = Mederhult, L = St. Laxemar, B = St. Basthult, Ä = Äspö.*

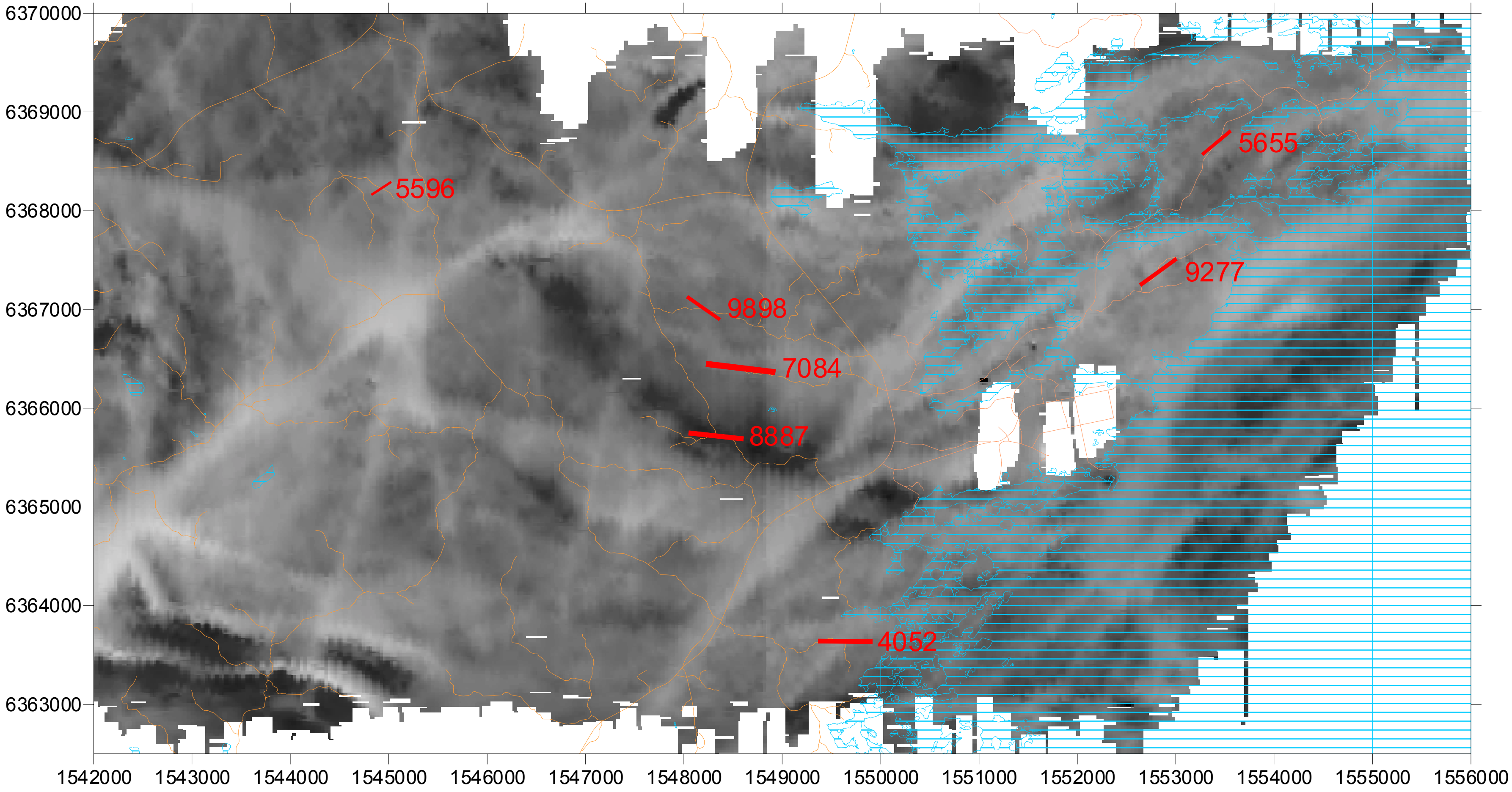

Figure 6-5. *Direction of apparent electric anisotropy is shown with red lines with the aeromagnetic map as background. The length of the lines indicates the anisotropy coefficient that varies between 1.04 and 1.78. The numbers shows estimated bulk resistivity in Ωm.*

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