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Oskarshamn site investigation

Transient electromagnetic soundings at Laxemar and the regional surroundings

Estimations of depth to saline groundwater

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GeoVista AB

May 2006

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Keywords: Laxemar, TEM, Resistivity, Saline groundwater, Ground geophysics.

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.

Abstract

Seven transient electromagnetic (TEM) soundings have been performed west of the site investigation area at Laxemar. Low-resistivity rock was identified at depths ranging from 800 to 900 metres in the east to 1,300 to 1,600 metres in the west. The data were compatible with a two-layered model with high-resistivity rock near the surface and a, toward west-north-west, gently dipping transition to low-resistivity rock.

The data quality varied between the soundings. All soundings were affected by cultural noise, but all except one gave reliable estimates of depths to low-resistivity rock with an error limit of around ± 100 metres.

The low-resistivity rock is interpreted to be due to saline ground-water at great depth. Such saline water is known to exist in deep boreholes in the Laxemar area and the results of this study are compatible with borehole information.

Sammanfattning

Sju transienta elektromagnetiska (TEM) sonderingar har utförts väster om platsundersökningsområdet i Laxemar. Lågresistivt berg har identifierats på djup varierade mellan 800 till 900 meter i öster till 1 300 till 1 600 meter i väster. Data var kompatibla med en två-lagermodell med högresistivt berg nära markytan och en mot väst-nordväst flackt stupande övergång till lågresistivt berg.

Datakvaliten varierade mellan sonderingarna. Alla sonderingar var påverkade av kulturellt brus, men alla utom en gav trovärdiga uppskattningar av djupet till låg-resistivt berg med en felmarginal på omkring ± 100 meter.

Det lågresistiva berget tolkas vara orsakat av salint grundvatten på stort djup. Sådant salint vatten är känt från djupa borrhål i Laxemarområdet och resultaten från denna studie är kompatibla med borrhålsinformation.

Contents

1 Introduction

This document reports the results gained by the transient electromagnetic (TEM) soundings in the Laxemar area and the regional surroundings, which is one of the activities performed within the site investigation at Oskarshamn. The work was carried out in accordance with activity plan AP PS 400-05-066. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

Seven TEM soundings were performed during September 2005. Large cable loop transmitters were used and the secondary field was measured at four to five stations for each transmitter. The position of transmitters and receiver stations can be seen in Figure 1-1. The field work was carried out by GeoVista AB and SMOY in co-operation. Processing and interpretation of data has been carried out by GeoVista AB.

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

The results of the work are stored in the SICADA database and are traceable through the activity plan number AP PS 400-05-066.

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

Activity plan	**Number**	**Version**
Transient elektromagnetisk sondering i Laxemar och regional omgivning	AP PS 400-05-066	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för TEM-mätning	SKB MD 212.008	1.0

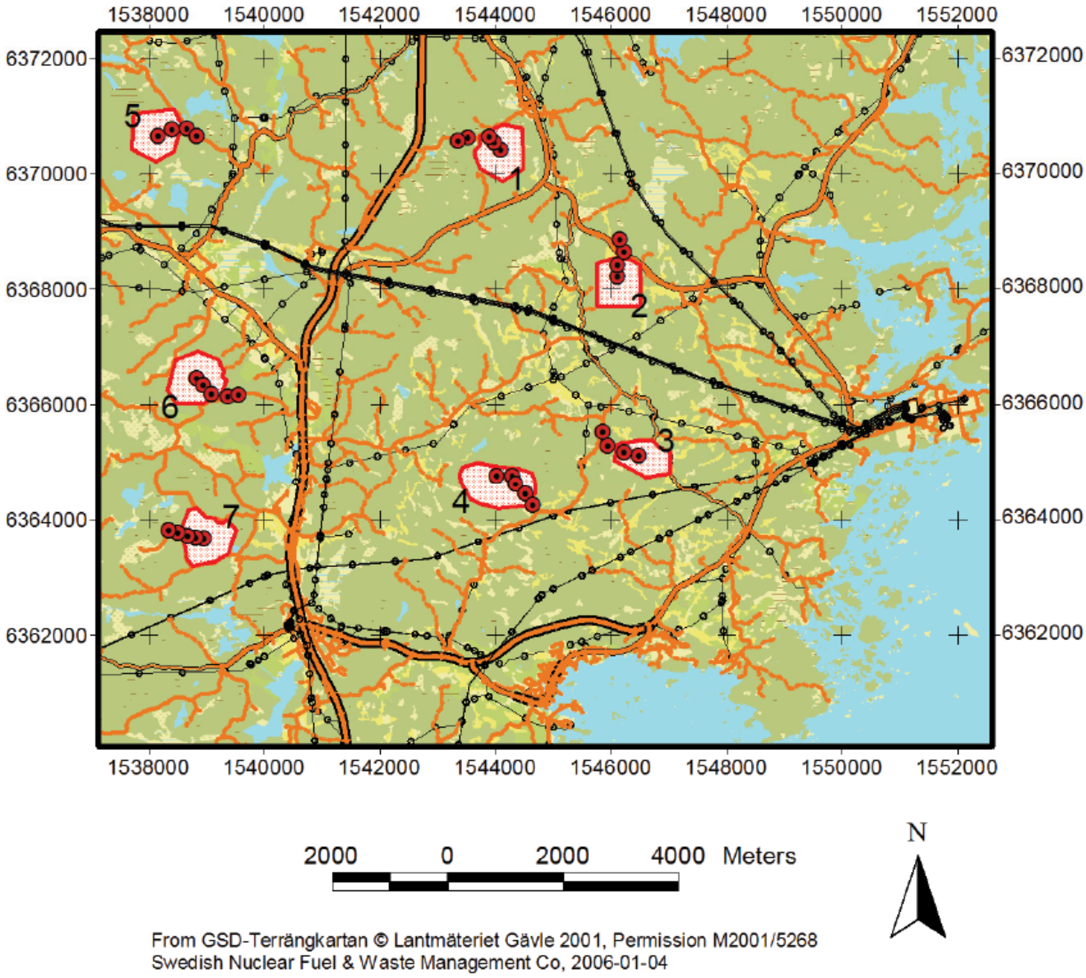


Figure 1-1. *Map showing the position of cable loop transmitters (red polygons) and receiver stations (red symbols). The transmitter loops are labelled with numbers. The Simpevarp power plant is located in the eastern part of the map area.*

2 Objective and scope

The presence of saline ground-water at large depth might influence the regional ground-water flow and is hence an important parameter in the assessment of the geohydrological situation in the area. The depth to and the nature of the transition to saline groundwater at depth is investigated by sampling and logging in deep boreholes in the candidate area. There are however no deep boreholes in the regional surroundings of the Laxemar area. The depth to saline water is also assumed to increase with distance from the coast-line which makes borehole investigations difficult away from the coast. The purpose of this work is to estimate the depth to rock of low electric resistivity related to saturation of pore-space with saline groundwater. Transient electromagnetic (TEM) soundings have been performed at seven locations in the regional surroundings of the Laxemar area.

3 Equipment

3.1 Description of equipment and interpretation tools

The field survey was performed with a Geonics TEM-37 transmitter and a Geonics Protem receiver with a 3D receiver coil. Large cable loops were used to transmit the primary transient field. Synchronisation between the transmitter and receiver units was facilitated by oscillator crystals. The instrument was supplied by SMOY, Finland.

Orientation in the field was carried out with the help of hand-held GPS and compass. The position of transmitter loop vertices and receiver stations were determined by handheld GPS (Garmin GPSmap76S with external antenna GA 27C). The geodetic datum parameters in the GPS unit were set in accordance with the recommendations from the National Land Survey to achieve best possible compatibility with RT90.

The following software was used for processing, modelling, interpretation and visualisation of the survey data:

- EM Vision v 2.1 (Encom Technology)
- Profile Analyst v 6.0 (Encom Technology)
- MapInfo Professional v 7.8 (MapInfo Corp.)
- Discover v 7.0 (Encom Technology)
- ArcWiew v 3.3 (ESRI)
- MathCAD 2001i Professional (Mathsoft Engineering & Education Inc.)
- Surfer v 8.0 (Golden Software)

4 Execution

4.1 General

Transient electromagnetic sounding is a geophysical method that is capable of estimating the electrical properties of the ground to large depths. A thorough description of the method can be found in geophysical text books, e.g. /1/, and only a brief description is given here.

A DC current is fed into a cable loop or coil, thereby producing a primary magnetic field, Figure 4-1. The current is then switched off, resulting in induced electric currents in the ground. The induced currents will diffuse downwards/outwards from the transmitter and at the same time produce a decaying secondary field. This secondary field is measured with the help of an induction coil. The magnitude and decay rate of the secondary field is a function of the resistivity distribution in the ground. Measurements at late times will give information from large depths. Multiple readings are usually stacked to improve the signal-to-noise level.

The results are usually modelled and interpreted in terms of a horizontally layered earth.

The survey was carried out in accordance with the SKB method description SKB MD 212.008 (SKB internal controlling document).

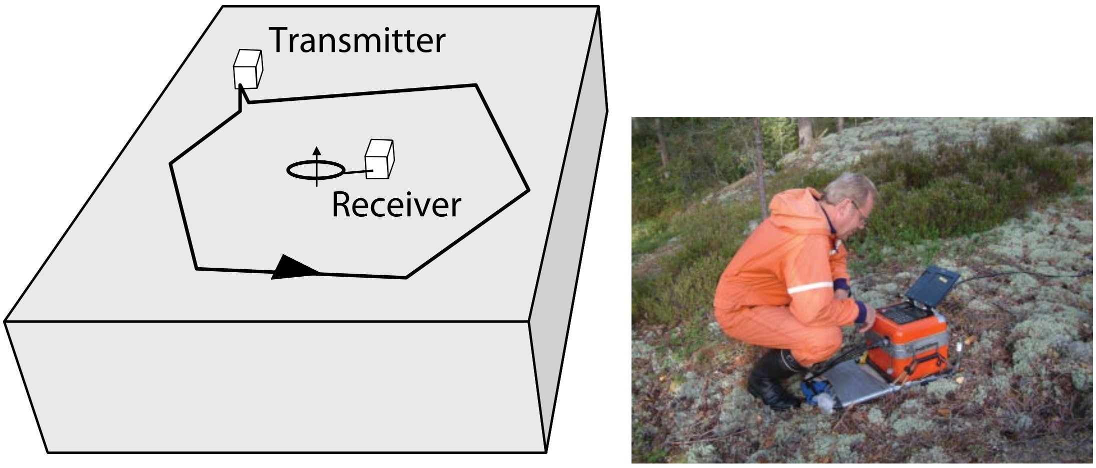


Figure 4-1. *Measurement with transient electromagnetic sounding (TEM). Left: Transmitter loop and receiver. Right: Operator at the recording instrument close to the induction coil.*

4.2 Preparations

Electromagnetic measurements are in general disturbed by power lines and other cultural installations. Suitable locations for TEM soundings were therefore identified by analysis of geographical data in a GIS. Buffer zones of 300 metres width were created around the major power lines and zones of 150 metres width were created around minor power lines. All cable loop transmitters and receiver stations were placed outside these buffer zones. Transmitter loops were also placed in such a way that some part of each of them was accessible from a road, since the transmitter generator is heavy and bulky to transport in the terrain. Whenever possible, segments of the transmitter loops were placed along e.g. small roads to make the field work easier. Coordinates for the planned loop corners and receiver stations were entered as waypoints into the GPS unit for easy location in the field. Distances and bearings between loop corners were also calculated and printed for use in the field. The length of the transmitter loop was up to 3 km.

4.3 Execution of field work

The survey was carried out with one transmitter loop at a time (Figure 1-1). The cable loop was laid out in the terrain without any previous staking. Compass, calculated bearings and GPS waypoints were used for orientation.

The cable loop was connected to the transmitter unit and the output current and current turn-off ramp-time were noted. The oscillator crystals of both the transmitter and the receiver unit were warmed up and subsequently synchronized. The survey was performed with a base repetition rate of 25 Hz. This means that 50 Hz noise ideally will cancel out since every second transient is measured with opposite polarity.

The receiver antenna was placed at the survey station and levelled. The antenna was oriented in such a way that that the horizontal coils would measure in the north and west directions respectively. Measurement was performed during 15 seconds of stacking. Such a stack was then repeated 20 times at each station, giving 20 different decay curves for the measured component. All three components of the secondary field were recorded simultaneously. Measurement was performed with both high and low gain at every station. High gain might cause over-saturation in the pre-amplifier whereas low gain might reduce the sensitivity of the instrument.

The stacked decaying signal is plotted in the instrument display during measurement. A first data quality control was therefore performed directly in the field.

The cable loop was picked up when all receiver stations had been surveyed. The whole procedure was then repeated at the next loop position.

4.4 Data handling/post processing

Raw data are stored by the instrument. Those data were downloaded to a PC at the end of each working day. An extra quality check was made and a copy of the data was then sent by E-mail to the GeoVista office in Luleå. The raw data was also handed over to SKB.

The data files were read by the program EM Vision v 2.1 and converted to the AMIRA industry standard format for TEM data. Median values, for each channel for the 20 measured decay curves, were calculated in the same process. EM Vision was also used to convert data to apparent resistivities.

The current in the transmitter loop should ideally be zero during measurement. However, a correlation between the recorded signal at early channels and the primary field magnitude can sometimes be seen, usually in the form of a ringing effect. This indicates that a weak residual current is present in the cable loop after current shut-off. A simple linear regression analysis was performed to compensate for this effect.

No significant difference could be seen between measurements made with different receiver gains. All measurements were therefore treated equally.

4.5 Analyses and interpretations

The transition from fresh to saline groundwater in the Laxemar area cannot be described by a single sharp boundary. Borehole logs show both gradual increases of salinity with depth at certain depth intervals and more sudden jumps associated with water-bearing fractures. The resolution of TEM soundings is not good enough to resolve such detail. Instead, the electrical structure of the ground is modelled with two horizontal layers representing the rock above and below the fresh/saline water interface respectively.

The results from the different receiver locations for each transmitter loop were compared. Differences might indicate presence of electrical 2D- or 3D-structures or presence of man-made objects that produce secondary fields. The horizontal components were checked for the same reason.

The vertical component data of the measured secondary field were inverted to two-layer models with the help of the program EM Vision v 2.1. Such inversion assumes that residuals are due to random, unbiased and normal distributed noise. The models were adjusted by forward modelling since the noise distribution did not fulfil the above criteria.

Forward modelling was also performed to estimate the error bounds of the estimated depth to low-resistivity rock. The bounds were estimated in a subjective fashion by comparing calculated and measured decay curves and taking the noise level of the data into account.

A fit to a low-order polynomial was made to visualize the trend in the estimated depth to saline water. A comparison between the results from this study and older TEM soundings /2, 3/ was made with results from fluid resistivity and resistivity logs made in deep boreholes /4, 5, 6/.

4.6 Nonconformities

The stacking time for each measurement was stated as 30 seconds in the activity plan. This was changed to 15 seconds but compensated by increasing the number of measurements to 20 at each station. No averaging of late time data, using data from all receiver stations for a transmitter loop, was performed for the vertical component.

5 Results

The results of TEM soundings are usually presented in the form of decay curves and/or apparent resistivity sounding curves. A selected set of such graphs are included in this chapter. A complete set can be found in Appendix 1.

The quality of the data varied significantly between the different sounding locations. It is not uncommon that this type of measurements is affected by cultural noise. The repeatability of the results, at least for the vertical component data, was quite good indicating low levels of random noise. However, some time gates consistently gave unusually high or low values or even reversed polarity. The same time gate was usually affected for all receiver stations for a particular transmitter loop. These obviously erroneous readings were however repeatable, so stacking and averaging could not be used to reduce the effect of the problem. Different time gates were affected for different transmitter loops. It seems like this problem is caused by some coherent noise, probably related to the power-line frequency 50 Hz. The data were modelled and interpreted by disregarding the obviously erroneously data. Reliable models could thus be obtained for five of the sounding locations whereas the remaining two soundings gave models with quite high uncertainty.

Horizontal component data are more affected by fields due to telluric currents than vertical component data. The horizontal components therefore have lower signal-to-noise ratios compared to the vertical component.

The data were modelled with one-dimensional, horizontally layered models. For this type of model to be valid, it is important to verify that 2D or 3D electrical structures can be neglected. Considering the large depth of investigation, the vertical component data should be practically independent of receiver location for a one-dimensional earth. The magnitude of the horizontal components should also be considerably smaller than the vertical component for a one-dimensional earth. Both these criteria were fulfilled for all receiver stations except for three that seem to be affected by secondary fields from some power or telephone line.

The results for each transmitter loop is presented below.

5.1 Transmitter loop 1

Transmitter loop 1 was located in the northern part of the area (Figure 1-1). Five receiver stations were surveyed (cf map in Appendix 1). One station gave significantly lower magnitude in the vertical component data for early channels and reversed polarity for late channels. This station was located close to a small road and it can be suspected that the anomalous readings were due to a cable or some other installation. The other four stations gave very similar decay curves (Figure 5-1), except for some minor variations for the early channels. The signals for the horizontal components were of significantly lower magnitude than the vertical component. The similarity between stations and weak horizontal components indicate that local inhomogeneities not have influenced the measurements and that a layered model is valid to model the data.

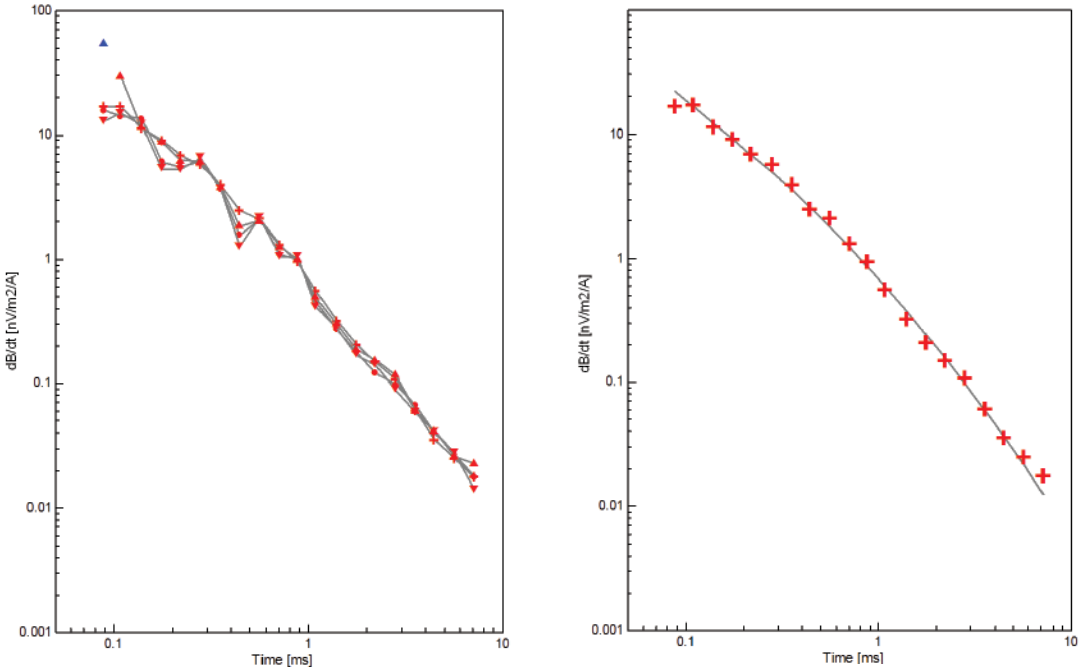


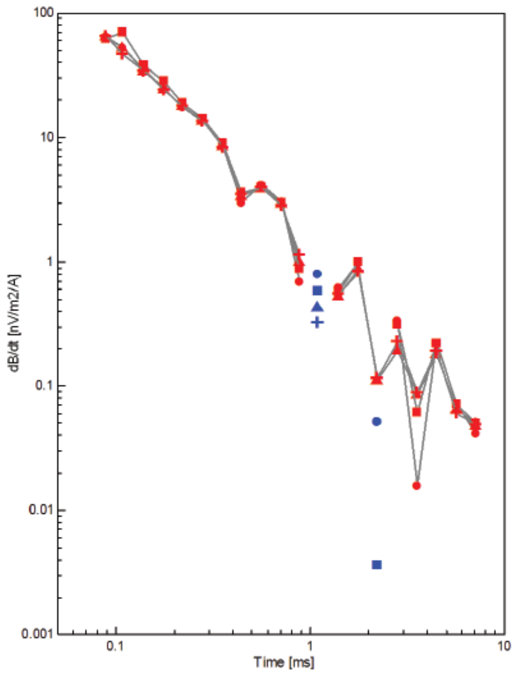
Figure 5-1. Left: *Decay curves, vertical component, transmitter loop 1. +: Station A, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.* ***Right****: Vertical component decay for station A is shown with symbols and model response is shown with a solid line.*

The early channel data correspond to apparent resistivities of around 10,000 Ωm whereas late channel data correspond to apparent resistivities of around 2,500 Ωm. The data were modelled with a two-layer model. Inversion was first carried out. However, least square fits assumes that the noise is gaussian distributed and without bias. This is not the case for these TEM data. The model was therefore slightly modified to give a more reasonable fit to the data. The depth to a conductive substratum is 1,050 metres according to the model (Table 5-1). The fit between field data and model response can be seen in the right graph in Figure 5-1.

The error bounds of the estimated depth to conductive rock were estimated by gradually changing the model and calculating the response and checking when the deviation from field data was unacceptable. Such an analysis resulted in minimum and maximum allowed depths to conductive rock of around 850 and 1,100 metres respectively.

5.2 Transmitter loop 2

Transmitter loop 2 was located west of the village Mederhult and hence slightly north-west of the site investigation area at Laxemar (Figure 1-1). Four receiver stations were surveyed (cf map in Appendix 1). All stations gave very similar results (Figure 5-2) and 2D and 3D structures have not influenced the data significantly, in spite of the fact that an EW trending deformation zone runs below the position of the transmitter loop. The data quality is very good up to 1 ms and also for the very latest channels. However, the channels in the interval from 1 ms to 4 ms are affected by some coherent noise probably related to the power-line frequency 50 Hz. This has resulted in some channels having unusually high values and other have low values or even reversed polarity. The problem could not be solved by stacking and averaging since the noise was repeatable.



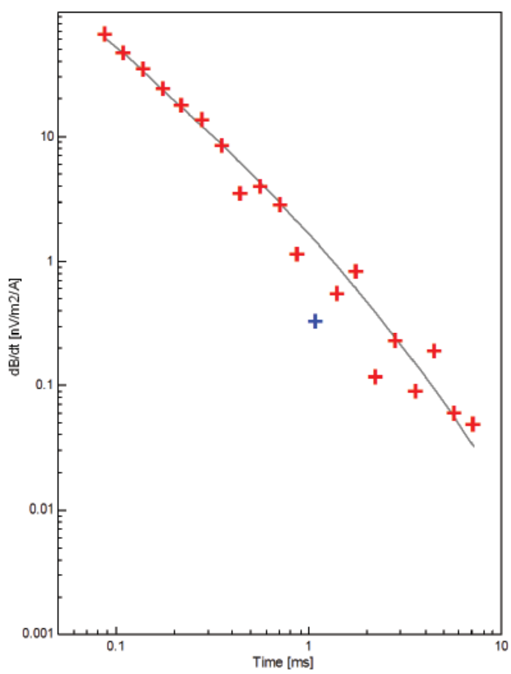


Figure 5-2. ***Left***: *Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D. Red symbols = positive values, blue symbols = negative values.* ***Right***: *Vertical component decay for station A is shown with symbols and model response is shown with a solid line.*

Early channel data correspond to apparent resistivities of around 4,500 Ωm whereas the last two good channels correspond to apparent resistivities of just over 1,000 Ωm. The data were modelled with a two-layered model and the depth to conductive rock was found to be 900 metres (Table 5-1). The noisy channels were disregarded during modelling. The fit between model response and field data can be seen in the right graph of Figure 5-2.

The error bounds of the model were estimated in the same way as for loop 1 above. The noisy channels will of course introduce some uncertainty in the model. Still, the high quality data in the first half of the decay curve and for the last two channels constrain the model fairly well. The analysis resulted in minimum and maximum allowed depths to conductive rock of around 800 and 1,050 metres respectively.

5.3 Transmitter loop 3

Transmitter loop 3 was located south-west of the site investigation area at Laxemar (Figure 1-1). Four receiver stations were surveyed (cf map in Appendix 1). All stations gave very similar results (Figure 5-3) and 2D and 3D structures have not influenced the data significantly. Good data were acquired for the earliest and the latest channels. However the central part of the decay curves was severely affected by coherent noise (Figure 5-3). The noise was repeatable and could not be reduced by stacking and averaging.

Early channel data correspond to apparent resistivities of around 3,000 to 3,500 Ωm whereas the late channels correspond to apparent resistivities of just around 600 Ωm. The data were modelled with a two-layered model and the depth to conductive rock was found to be 875 metres (Table 5-1). The noisy channels were disregarded during modelling. The fit between model response and field data can be seen in the right graph of Figure 5-3.

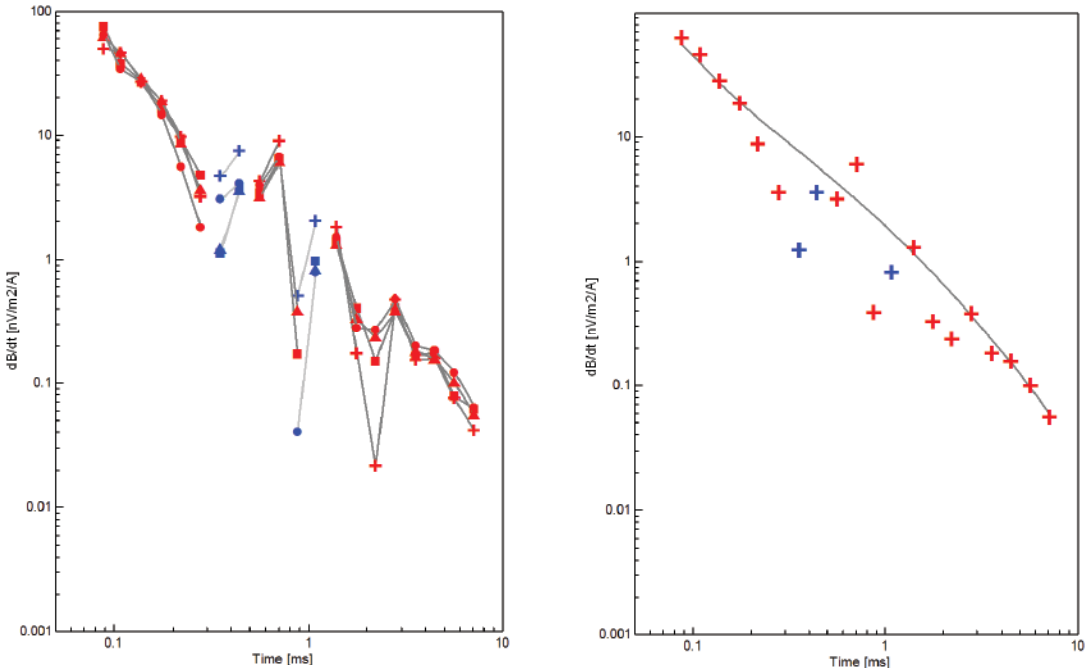


Figure 5-3. ***Left****: Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D. Red symbols = positive values, blue symbols = negative values.* ***Right****: Vertical component decay for station C is shown with symbols and model response is shown with a solid line.*

The error bounds of the model were estimated in the same way as for the loops above. The noisy channels will of course introduce some uncertainty in the model. Still, the good data for early and late channels constrain the model. The analysis resulted in minimum and maximum allowed depths to conductive rock of around 700 and 1,050 metres respectively.

5.4 Transmitter loop 4

Transmitter loop 4 was located south-east of the village Värnamo in the southern part of the investigated area. (Figure 1-1). Five receiver stations were surveyed (cf map in Appendix 1). All stations gave similar results (Figure 5-4). However, a minor systematic trend could be seen with stronger vertical component signals for the stations towards south-east. This indicates that the rock volume in this direction is of lower resistivity. The area to the south-east of the loop also shows up as low-magnetic in aeromagnetic maps, which is a property known to be related to oxidation and possibly fracturing at e.g. the Laxemar area. The indicated 2D or 3D structures have however not influenced the data significantly much to invalidate a layered earth model. Coherent noise of similar kind as for loop 2 and 3 occurs also at loop 4. The affected channels are roughly the same as for loop 2. Good data were acquired for the earliest and the latest channels. The noise was repeatable and could not be reduced by stacking and averaging.

Early channel data correspond to apparent resistivities of around 4,000 Ωm whereas the late channels correspond to apparent resistivities of around 1,000 Ωm. The data were modelled with a two-layered model and the depth to conductive rock was found to be 800 metres (Table 5-1). The noisy channels were disregarded during modelling. The fit between model response and field data can be seen in the right graph of Figure 5-4.

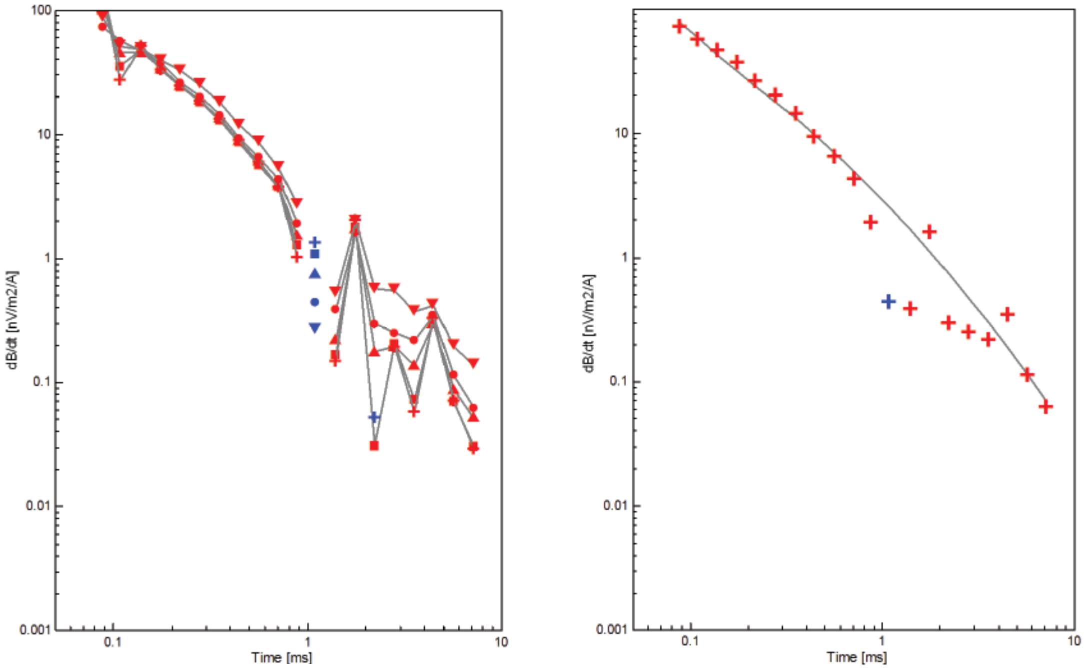


***Figure 5-4. Left**: Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.*
***Right**: Vertical component decay for station D is shown with symbols and model response is shown with a solid line.*

The error bounds of the model were estimated in the same way as for the loops above. The noisy channels will of course introduce some uncertainty in the model. Still, the good data for early and late channels constrain the model. The analysis resulted in minimum and maximum allowed depths to conductive rock of around 700 and 900 metres respectively.

5.5 Transmitter loop 5

Transmitter loop 5 was located in the north-western part of the investigated area, at a larger distance from the coast-line compared to the loops above (Figure 1-1). Four receiver stations were surveyed (cf map in Appendix 1). Two stations outside the loop that were located close to a small road were affected by some local noise source, most likely a cable. The remaining two stations gave very similar results indicating that no major 2D or 3D structure has affected the data. Some coherent noise of similar kind as described for the previous loops have affected early channels. Intermediate and late channels are however of very good quality.

Early channel data correspond to apparent resistivities of around 10,000 Ωm whereas the late channels correspond to apparent resistivities of slightly less than 3,000 Ωm. The data were modelled with a two-layered model and the depth to conductive rock was found to be 1,585 metres (Table 5-1). The noisy channels were disregarded during modelling. The fit between model response and field data can be seen in the right graph of Figure 5-5.

The error bounds of the model were estimated in the same way as for the loops above. The analysis resulted in minimum and maximum allowed depths to conductive rock of around 1,400 and 1,750 metres respectively. The depth to conductive rock and hence presumed saline groundwater is thus significantly greater than for the loop positions closer to the coast-line.

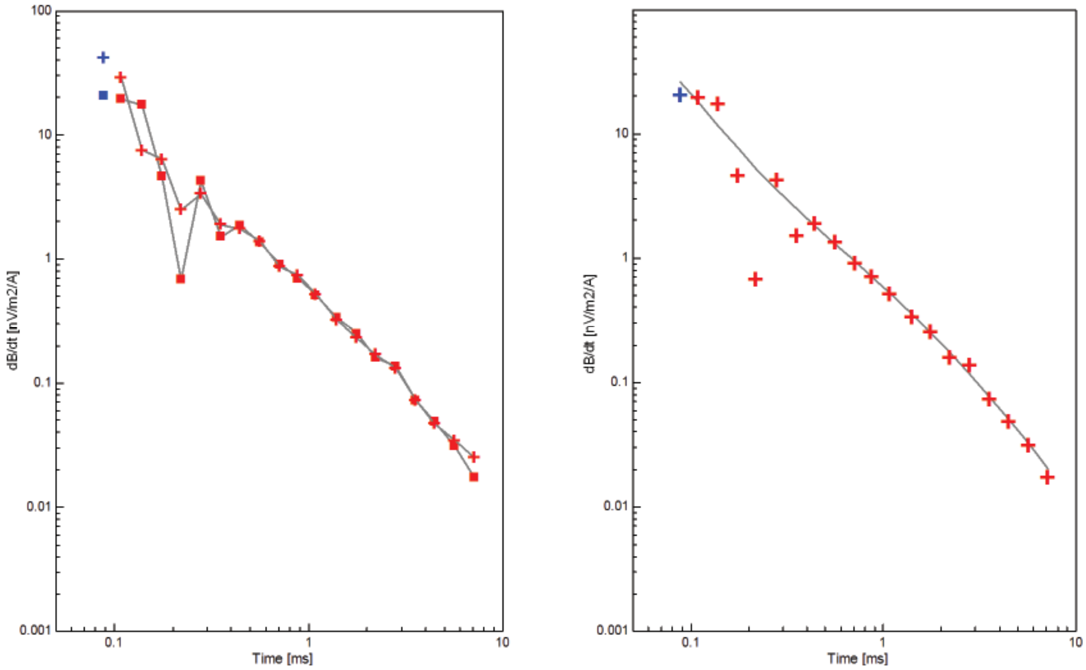


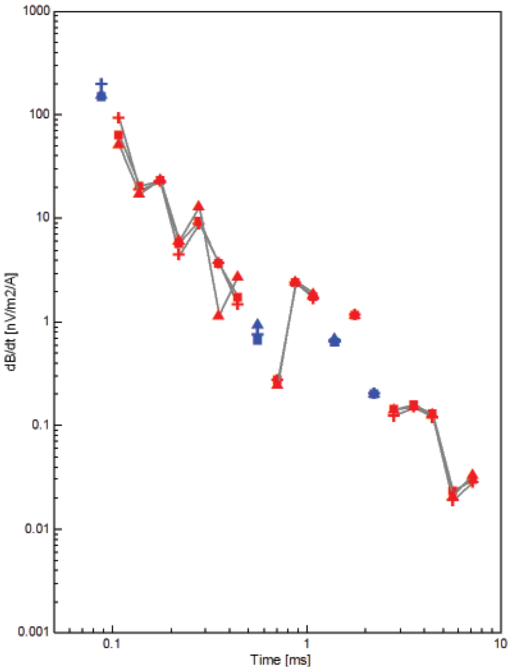
Figure 5-5. ***Left****: Decay curves, vertical component. + : Station A, ■: Station B. Red symbols = positive values, blue symbols = negative values.* ***Right****: Vertical component decay for station B is shown with symbols and model response is shown with a solid line.*

5.6 Transmitter loop 6

Transmitter loop 6 was located in the western part of the investigated area, at a large distance from the coast-line (Figure 1-1). Five receiver stations were surveyed (cf map in Appendix 1). Two stations outside the loop that were located close to a small road were severely affected by some local noise source, most likely a cable. The remaining three stations gave very similar results, however strongly affected by the type of coherent noise described for the loops above. A TEM decay curve is expected to be smooth and in many cases monotonically decaying from large positive or negative magnitudes towards zero. The decay curves for loop 6 do not show any part that is smooth and decaying in a monotonic fashion. The reliability of models extracted from these data is therefore quite low.

Early channel data correspond to apparent resistivities ranging from 4,000 to 10,000 Ωm whereas the late channels correspond to apparent resistivities ranging from 1,300 to 3,000 Ωm. A model that was compatible with the noisy data was estimated and the depth to conductive rock was 1,500 metres in this model (Table 5-1). Model response and field data can be compared in the right graph of Figure 5-6.

No error bounds can be estimated for the model. The model should simple be seen as one, out of a wide range of models, that is compatible with the data.



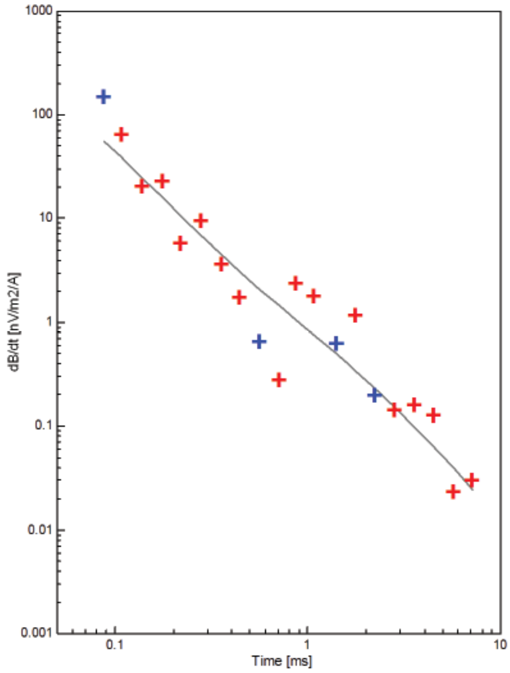


Figure 5-6. ***Left****: Decay curves, vertical component. + : Station A, ■: Station B, ▲: Station C. Red symbols = positive values, blue symbols = negative values.* ***Right****: Vertical component decay for station B is shown with symbols and model response is shown with a solid line.*

5.7 Transmitter loop 7

Transmitter loop 7 was located in the south-western part of the investigated area, at a large distance from the coast-line (Figure 1-1). Five receiver stations were surveyed (cf map in Appendix 1). All stations gave very similar results indicating that no major 2D or 3D structure has affected the data. Some coherent noise of similar kind as described for the previous loops have affected the first two channels and also slightly affected three channels at around 1 ms delay time. All other channels are however of very good quality.

Early channel data correspond to apparent resistivities of around 15,000 to 20,000 Ωm (although noisy) whereas the late channels correspond to apparent resistivities of around 2,500 Ωm. The data were modelled with a two-layered model and the depth to conductive rock was found to be 1,300 metres (Table 5-1). The noisy channels were disregarded during modelling. The fit between model response and field data can be seen in the right graph of Figure 5-7.

The error bounds of the model were estimated in the same way as for the loops above. The analysis resulted in minimum and maximum allowed depths to conductive rock of around 1,200 and 1,500 metres respectively. The depth to conductive rock and hence presumed saline groundwater is thus significantly greater than for the loop positions closer to the coast-line.

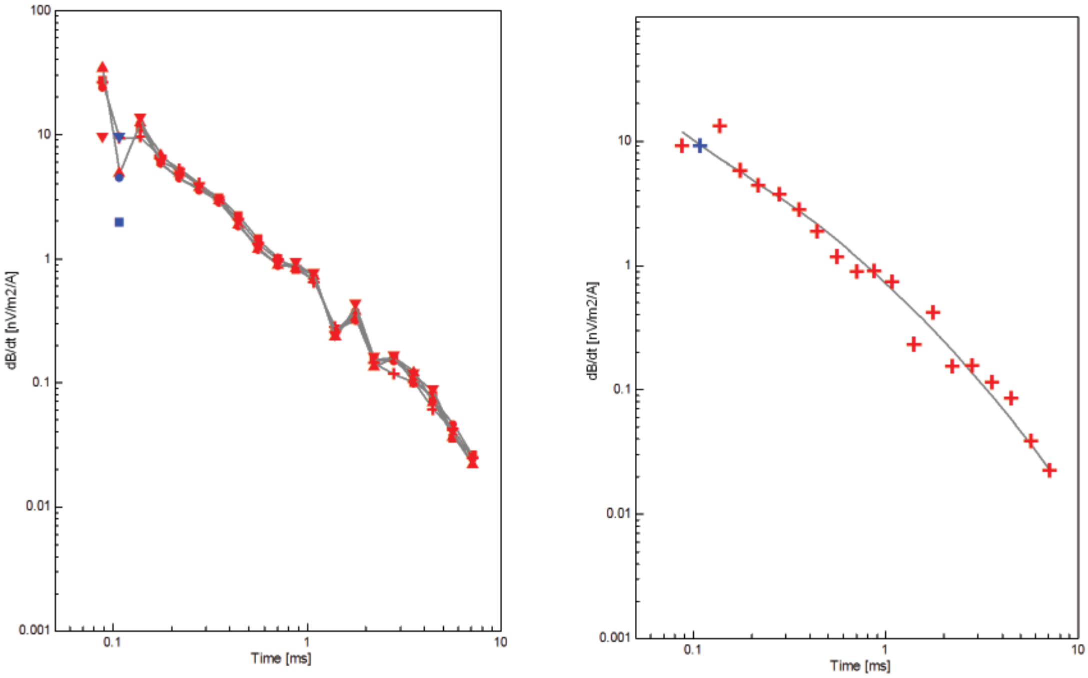


Figure 5-7. ***Left***: *Decay curves, vertical component. + : Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.* ***Right***: *Vertical component decay for station B is shown with symbols and model response is shown with a solid line.*

5.8 Horizontal component data

The horizontal (north and west) components of the secondary field should quickly decay towards zero for a one-dimensional earth. The decay for a homogeneous half-space is proportional to time to the power of –2.5 for the vertical component and proportional to time to the power of –3 for the horizontal components. Furthermore, the horizontal component should be directed radially outward from the transmitter loop centre and be zero at the centre due to symmetry. Horizontal components are therefore not used so much in modelling of a layered earth in TEM soundings. They are however good indicators of the presence of 2D or 3D structures in the ground.

The measured horizontal component data are noisier than the vertical component data partly due to their lower magnitude and partly due to interference of noise from telluric fields. The transmitter loops with the best data quality (loop 1, 5 and 7) do however give fairly consistent horizontal component data. The horizontal component data for these transmitter loops are more or less independent of receiver station location. The decay rate is also more or less the same as for the vertical component. This would be consistent with a secondary field due to a slightly dipping interface between high- and low-resistivity rock at large depths. The horizontal components are positive towards north and west which would indicate a dip of the interface in a north-west direction. Horizontal component data for all receiver stations at transmitter loop 7 are plotted in Appendix 1.

5.9 Resistivity values

The best resolved parameter in the layered models of an electromagnetic sounding is the depth to a conductive layer. The resistivity values of the various layers are not that well resolved.

The resistivity of the upper layer in the presented models varies from 4,270 to 18,000 Ωm. High values are found for transmitter loops 1, 5 and 7 whereas lower values are found for loops 2, 3 and 4. There is an uncertainty for the resistivity values for loop 6. The resistivity values are consistent with bulk resistivities estimated from DC resistivity and older TEM measurements /2, 3/ and also with resistivity logs from boreholes /4, 5, 6/. The ratio of upper layer resistivity to lower layer resistivity is 8.7 on an average. This is considerably less than the difference in liquid resistivity found between near-surface and deep parts of boreholes in the area. The rather low ratio can however be explained by the effect of surface conductivity on mineral grain surfaces, that has greater relative effect in low salinity environments. This has been shown in a petrophysical study in the area /4, 7/. Partial closure of fractures due to high pressure at large depths can however not be excluded as a contributing factor of reducing the resistivity ratio between low and high resistivity volumes.

The low resistivities at depth could, in theory, be due to a change in lithology. Intensely altered or mineralized rock could have resistivities in this range. The requirements for such a hypothetical contact would be that it is wide-spread and subhorizontal. Such an interpretation therefore seems highly unlikely.

5.10 Compilation of model results

A summary of modelling results can be found in Table 5-1 below. The depth to a low-resistivity substratum is also shown for each sounding on a map in Figure 5-8. A low order polynom (bilinear saddle) was fitted to the estimated depths and is shown as contours in Figure 5-8. The contours should be treated with some caution since each sounding has error bounds of at least ± 100 metres. An increased depth to low-resistivity rock away from the coast is indicated by the data. It should also be noted that the larger depth in the north-western corner compared to the south-west part of the area is significant.

Table 5-1. Result of two-layer modelling of TEM soundings. The location of the soundings can be seen in Figure 5-8.

Sounding #	Resistivity layer 1 (Ωm)	Resistivity layer 2 (Ωm)	Thickness layer 1 (m)	Min thickness layer 1 (m)	Max thickness layer 1 (m)
1	10,000	2,100	1,050	850	1,100
2	4,270	1,130	900	800	1,050
3	4,460	440	875	700	1,050
4	5,000	700	800	700	900
5	9,400	9,30	1,585	1,400	1,750
6	6,800?	1,000?	1,500?	N/A	N/A
7	18,000	1,000	1,300	1,200	1,500

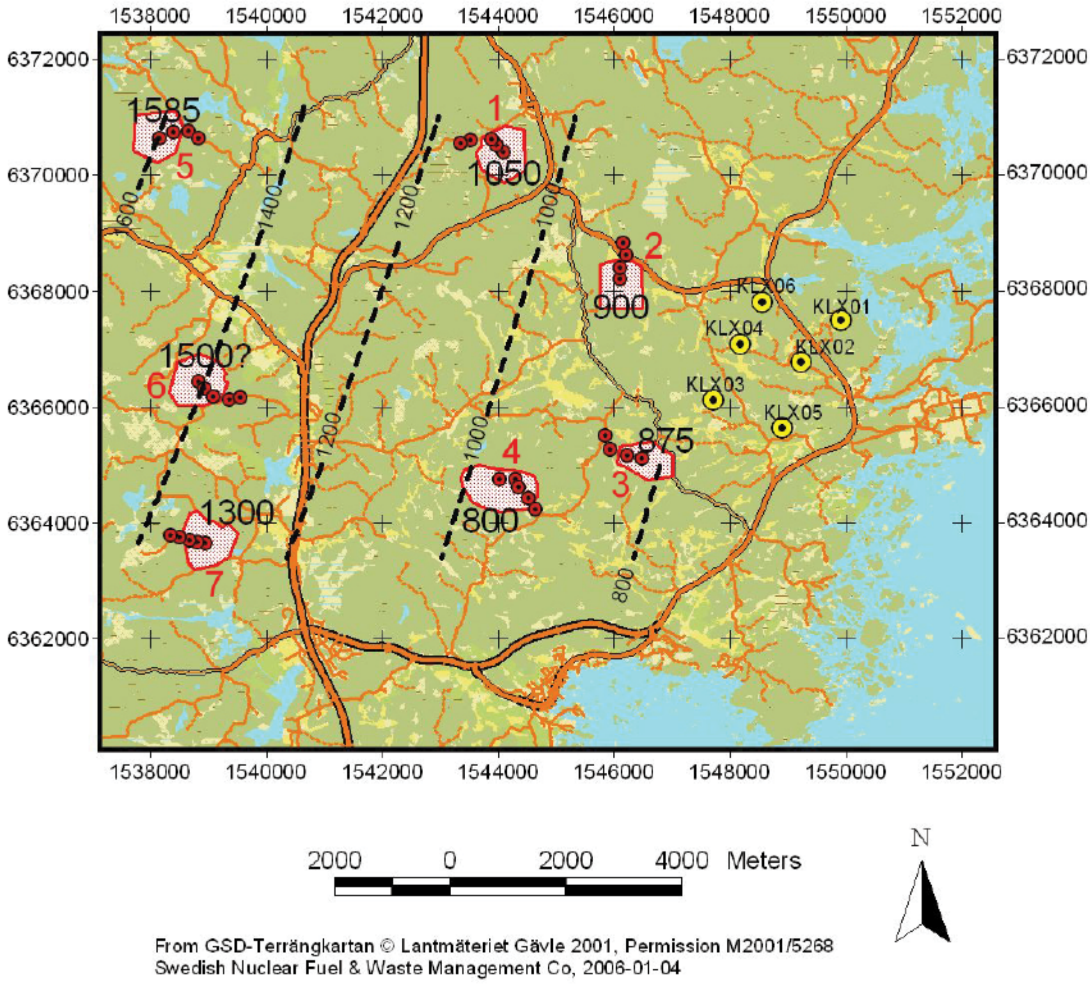


Figure 5-8. *Map showing the position of cable loop transmitters (red polygons with red labels) and receiver stations (red symbols). The black number at each transmitter loop indicates the modelled depth to low-resistivity rock. The contours show a bilinear saddle surface fitted to the modelled depths. The deep cored boreholes KLX01 to KLX06 in the Laxemar area are shown with yellow symbols.*

5.11 Comparison with older soundings and borehole data

Three TEM soundings have previously been performed in the Laxemar area /2, 3/. These sounding were made with smaller transmitter loops and fewer receiver locations compared to the soundings presented in this study. The data were also significantly affected by power-line noise. The soundings did however indicate low-resistivity rock at large depth. Two soundings in the western part of the Laxemar area gave depth to low-resistivity rock of around 850 metres whereas a sounding further east, close to KLX01, gave depth to low-resistivity rock of about 500 metres. These results are consistent with the results of the present study and indicate a continued decrease in depth to saline groundwater towards the coast.

The cored boreholes in the Laxemar area have been logged for fluid resistivity. A significant decrease in fluid resistivity can be seen at depth. The results are however influenced by remaining flushing water and by in- and outflow of water through water-bearing fractures /4, 5, 6/. Sampling of groundwater in the holes and measurements of salinity have also been made /8/.

The transition from fresh to strongly saline ground-water is gradual, according to borehole data. A gradual increase in salinity can be seen in the cored boreholes from about 500 metres depth in the eastern part of the Laxemar area and a transition to highly saline water can be seen at around 800 to 1,000 metres depth. The TEM soundings in this study are made to the west of the cored boreholes where the depth interval with intermediate salinity can be expected to be thinner, compared to areas closer to the coast. The depth to low-resistivity rock of around 900 metres, as estimated from the TEM soundings just west of Laxemar, is therefore compatible with the available data from boreholes. The nature of a gradual transition from fresh to saline water is however not possible to resolve with the TEM soundings.

References

/1/ **Kaufman A A, Keller G V, 1983.** Frequency and transient soundings. Elsevier, Amsterdam.

/2/ **Thunehed H, 2000.** Mapping and characterisation of Swedish bedrock by DC resistivity and transient-field electromagnetic measurements. Ph.D. thesis. Luleå University of Technology 2000:17.

/3/ **Eriksson L, Johansson R, Thunehed H, Triumf C-A, 1997.** Metodtester ytgeofysik – Bestämning av berggrundens bulkresistivitet och djupet till salint grundvatten med halvregional resistivitetsmätning, elektrisk sondering samt transient elektromagnetisk sondering. SKB PR D-98-01. Svensk Kärnbränslehantering AB.

/4/ **Mattsson H, Thunehed H, Keisu M, 2005.** Intepretation of geophysical borehole measurements and compilation of petrophysical data from KLX01, KLX03, KLX04, HLX21, HLX22, HLX23, HLX24, HLX25, HLX26, HLX27 and HLX28. Oskarshamn site investigation. SKB P-05-34. Svensk Kärnbränslehantering AB.

/5/ **Mattsson H, 2005.** Interpretation of geophysical borehole measurements from KLX06. Oskarshamn site investigation. SKB P-05-44**.** Svensk Kärnbränslehantering AB.

/6/ **Mattsson H, Keisu M, 2005.** Interpretation of geophysical borehole measurements from KLX05. Oskarshamn site investigation. SKB P-05-189. Svensk Kärnbränslehantering AB.

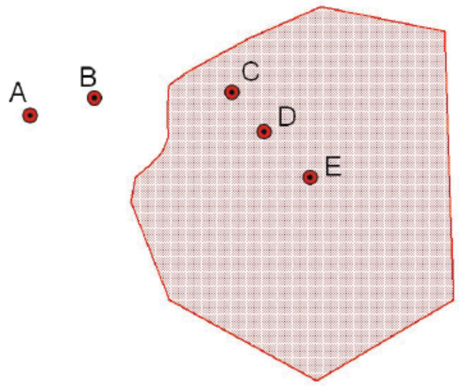
/7/ **Mattsson H, Thunehed H, 2004.** Interpretation of geophysical borehole data from KSH01A, KSH01B, KSH02 (0–100m), HSH01, HSH02 and HSH03, and compilation of petrophysical data from KSH01A and KSH01B. SKB P-04-28. Svensk Kärnbränslehantering AB.

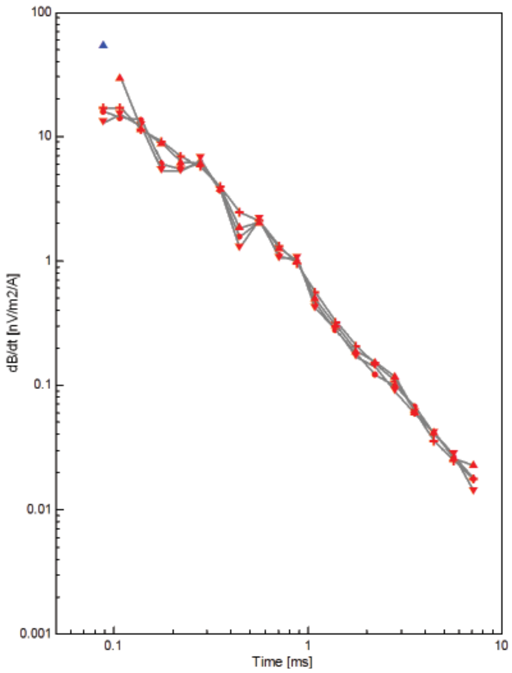
/8/ **SKB, 2005.** Preliminary site description. Simpevarp subarea – version 1.2. SKB R-05-08. Svensk Kärnbränslehantering AB.

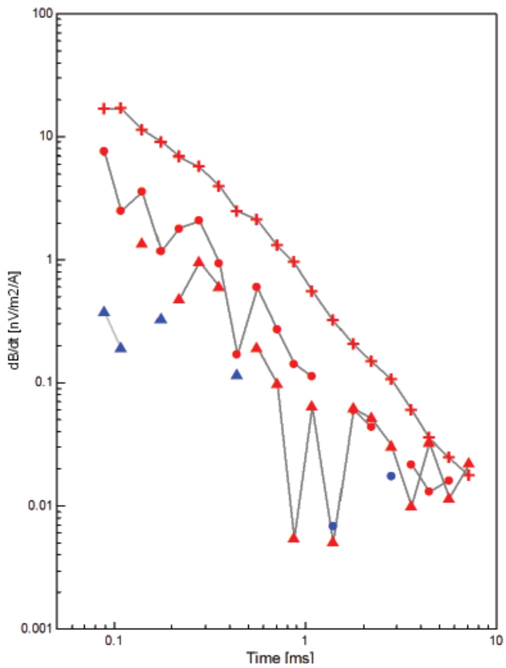
Decay curves and apparent resistivity sounding curves

Transmitter loop 1

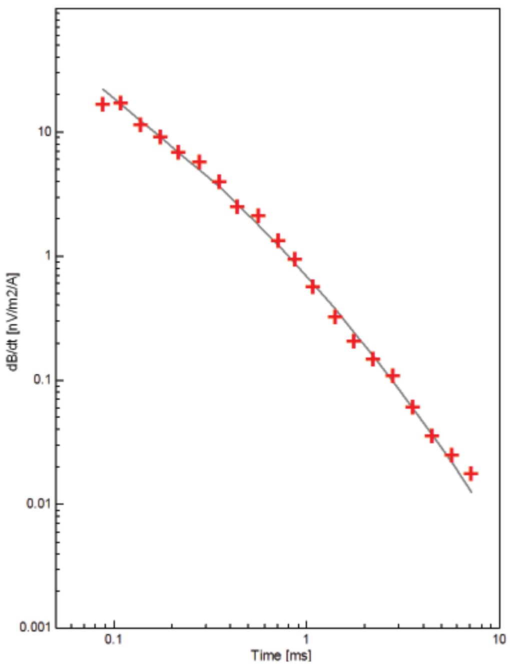
See Figure 1-1 for position of loop and receiver stations.



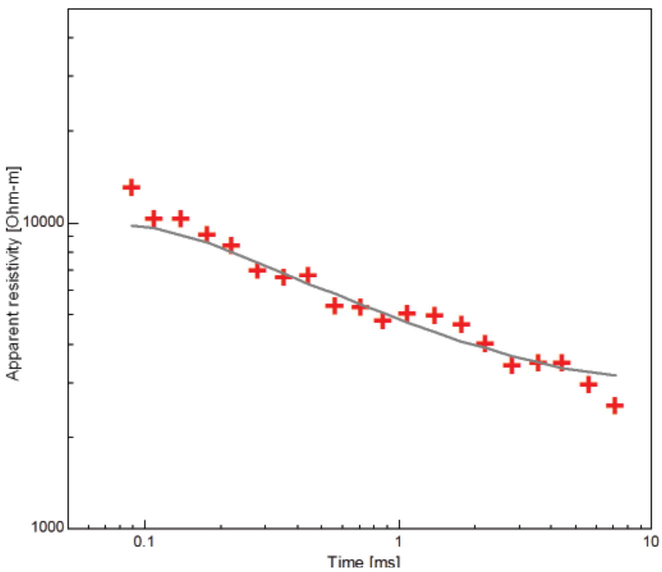




Left: *Decay curves, vertical component. +: Station A, ▲: Station C, ●: Station D, ▼:Station E. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station A. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station A. Symbols = measured data, line = model response.



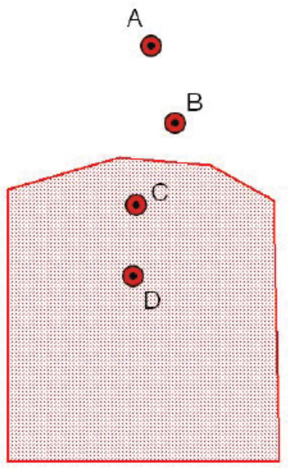
Apparent resistivity sounding curves, vertical component, station A. Symbols = measured data, line = model response.

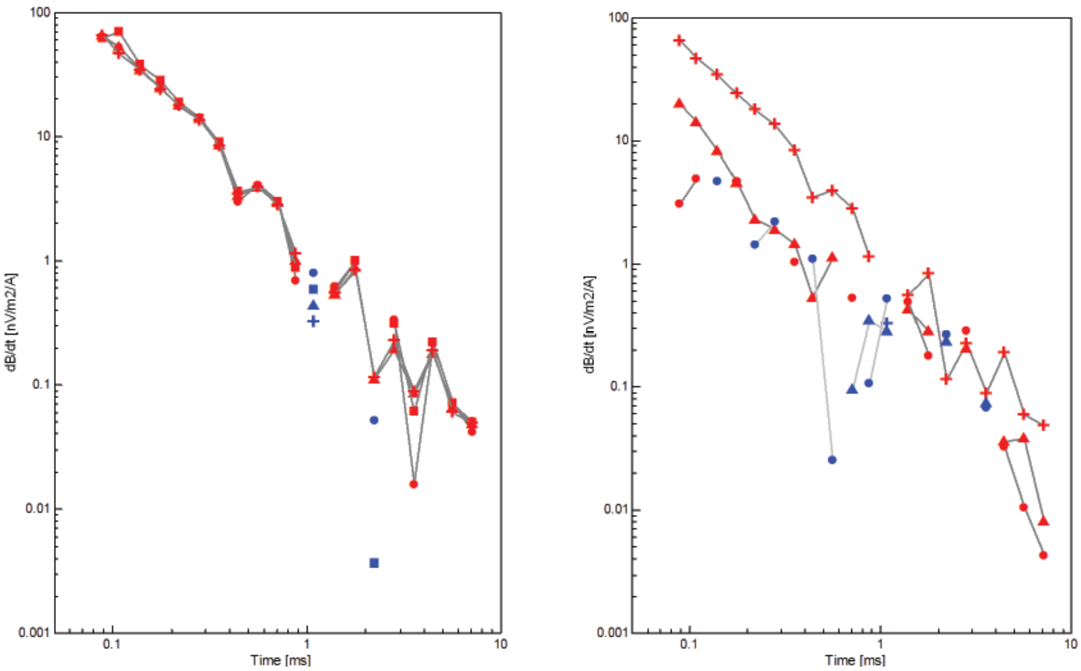
Model:

Layer	Resistivity (Ωm)	Thickness (m)
1	10,000	1,050
2	2,100	

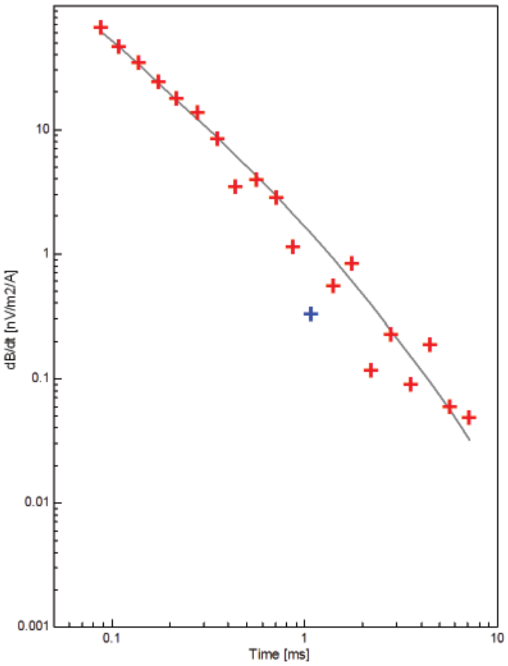
Transmitter loop 2

See Figure 1-1 for position of loop and receiver stations.

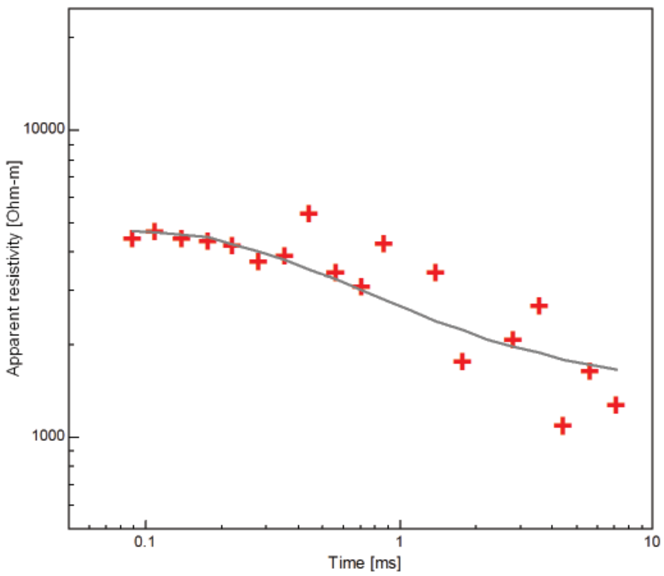




Left: *Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station A. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station A. Symbols = measured data, line = model response.



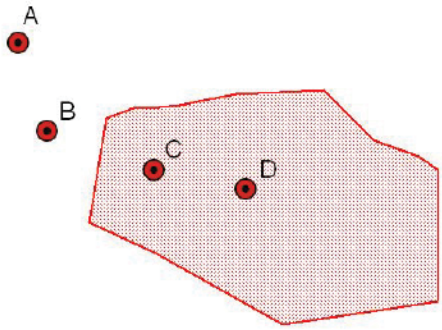
Apparent resistivity sounding curves, vertical component, station A. Symbols = measured data, line = model response.

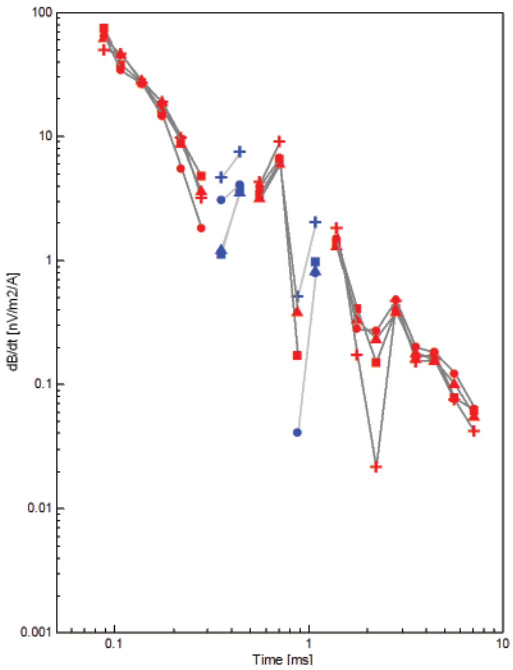
Model:

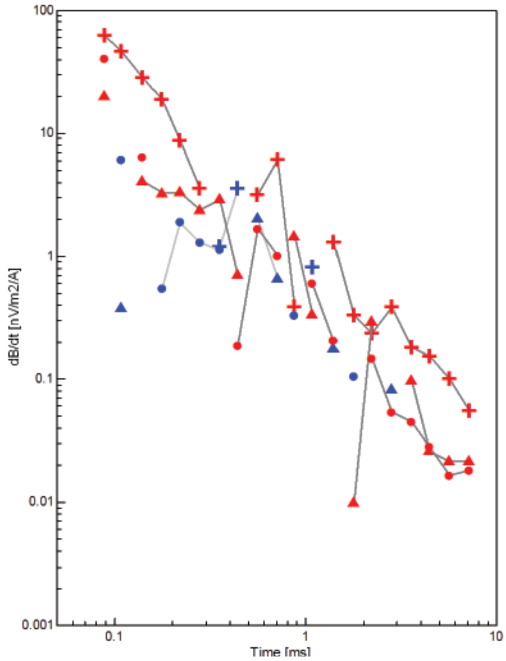
Layer	Resistivity (Ωm)	Thickness (m)
1	4,270	900
2	1,130	

Transmitter loop 3

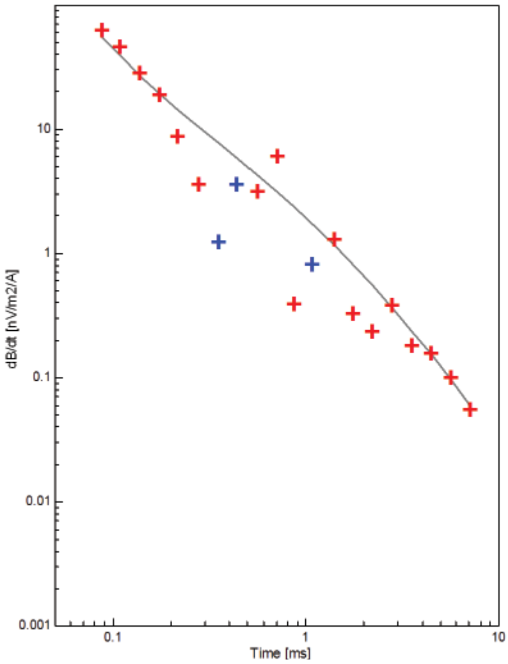
See Figure 1-1 for position of loop and receiver stations.



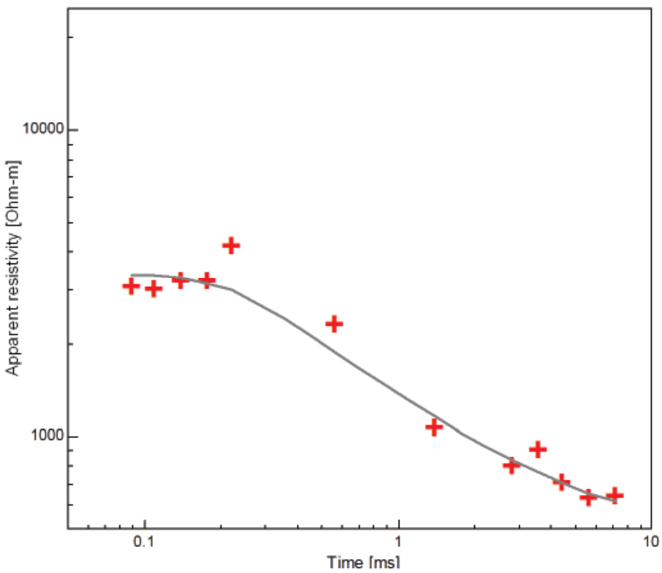




Left: *Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station C. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station C. Symbols = measured data, line = model response.



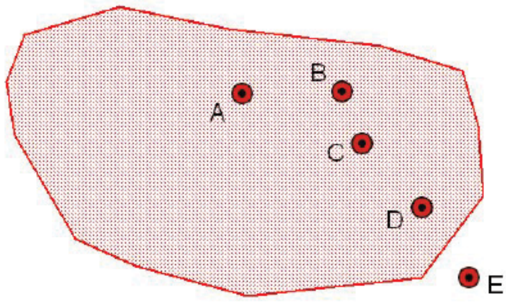
Apparent resistivity sounding curves, vertical component, station C. Symbols = measured data, line = model response.

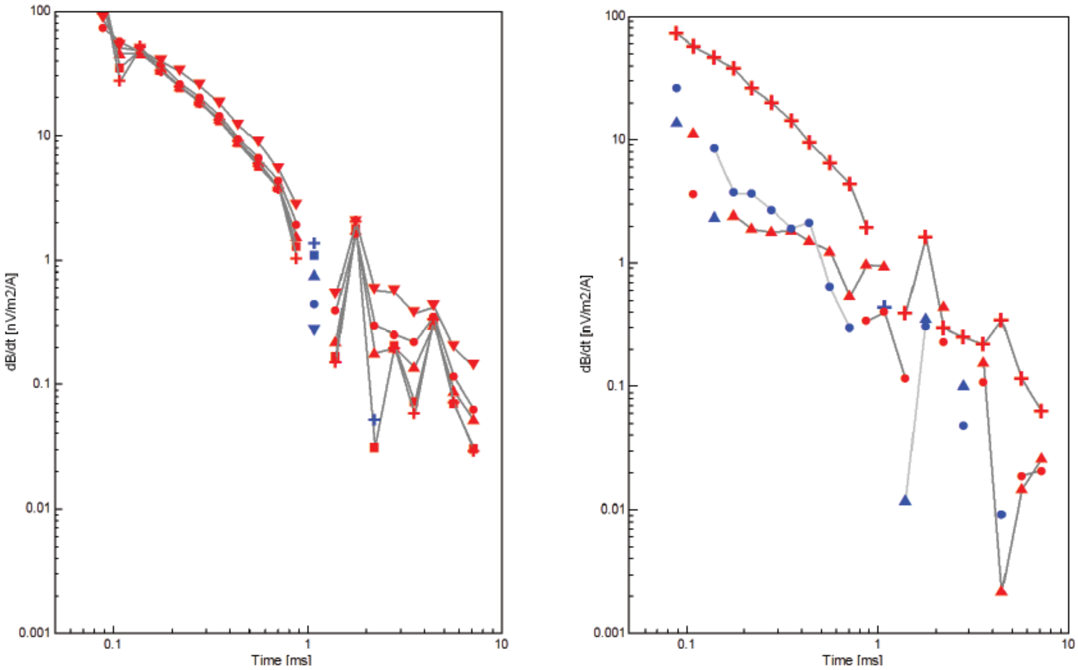
Model:

Layer	Resistivity (Ωm)	Thickness (m)
1	4,460	875
2	440	

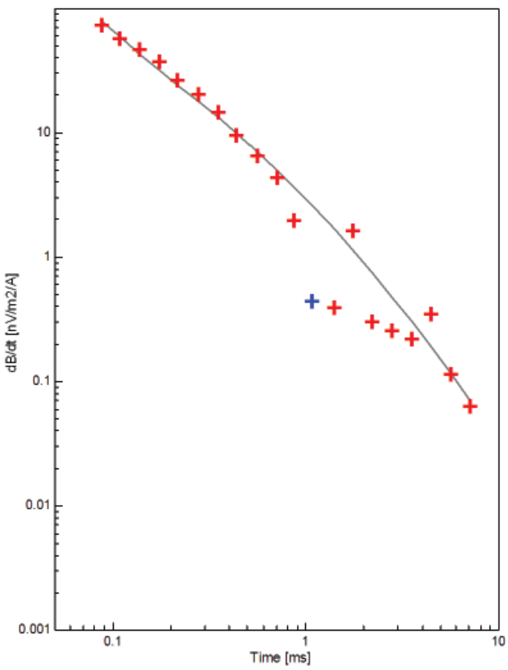
Transmitter loop 4

See Figure 1-1 for position of loop and receiver stations.

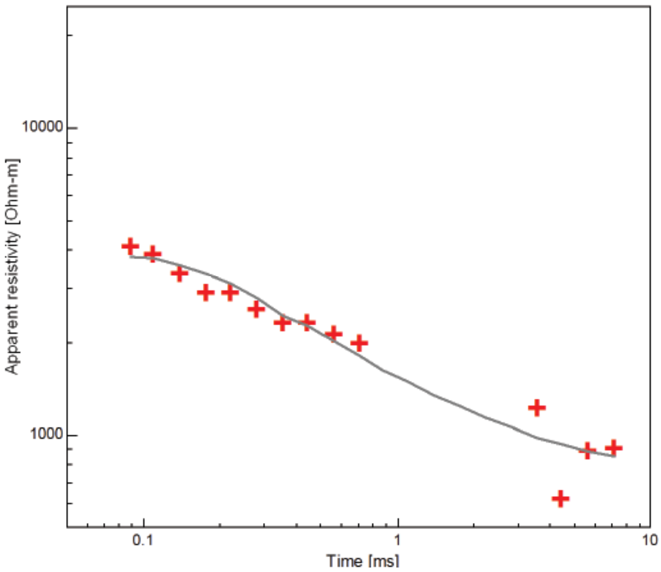




Left: *Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station D. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station D. Symbols = measured data, line = model response.



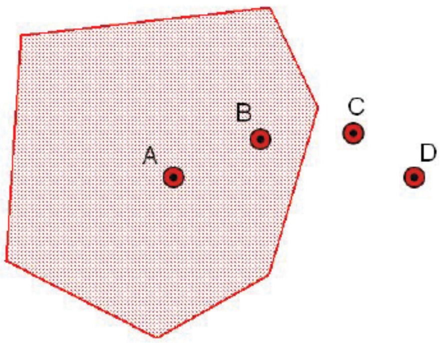
Apparent resistivity sounding curves, vertical component, station D. Symbols = measured data, line = model response.

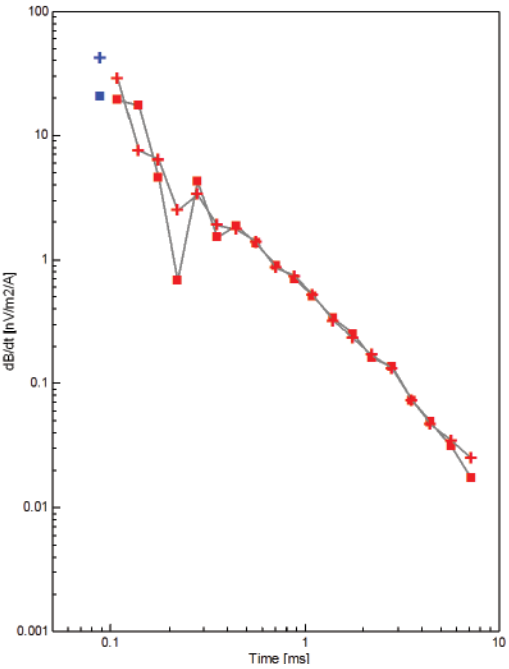
Model:

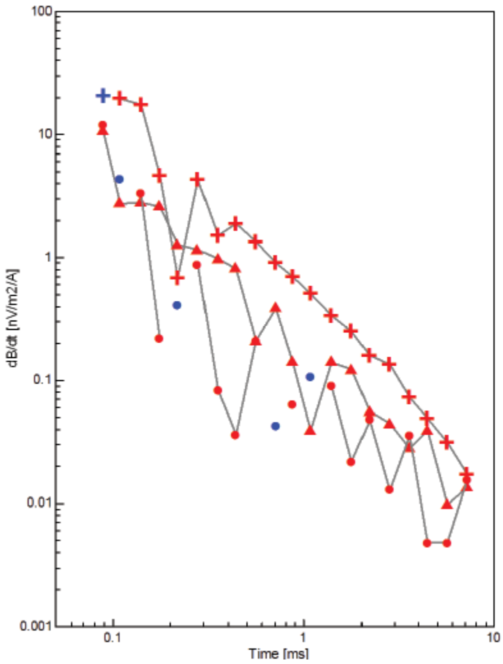
Layer	Resistivity (Ωm)	Thickness (m)
1	5,000	800
2	700	

Transmitter loop 5

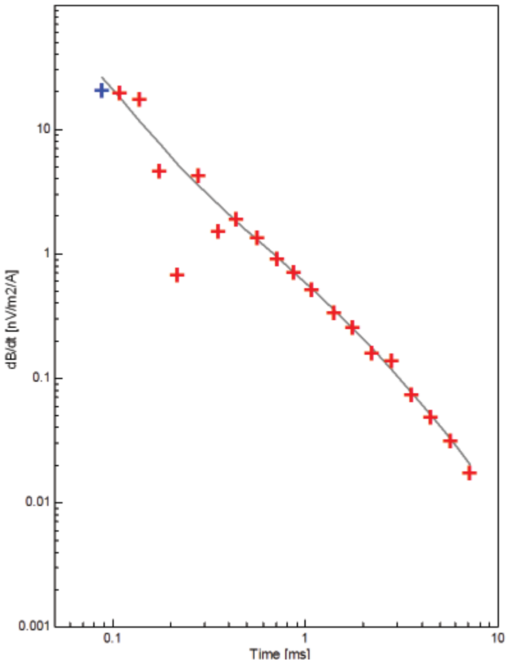
See Figure 1-1 for position of loop and receiver stations.



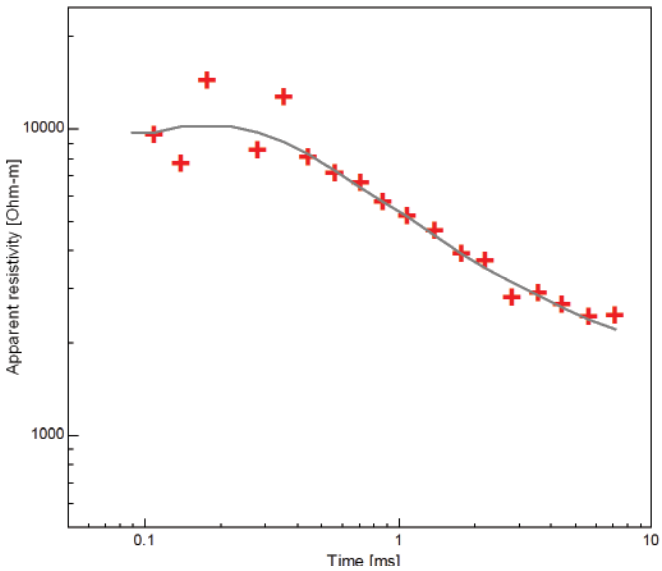




Left: *Decay curves, vertical component. +: Station A, ■: Station B. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station B. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station B. Symbols = measured data, line = model response.



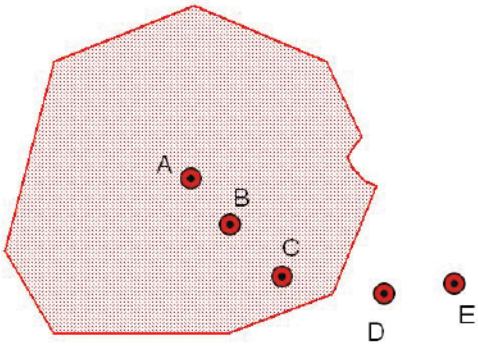
Apparent resistivity sounding curves, vertical component, station B. Symbols = measured data, line = model response.

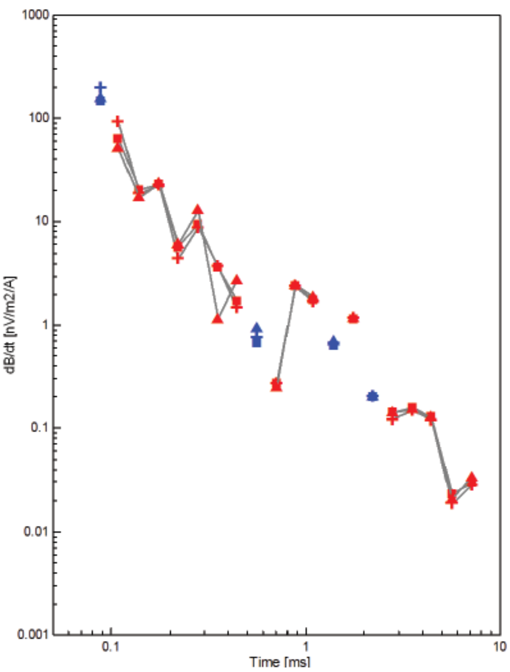
Model:

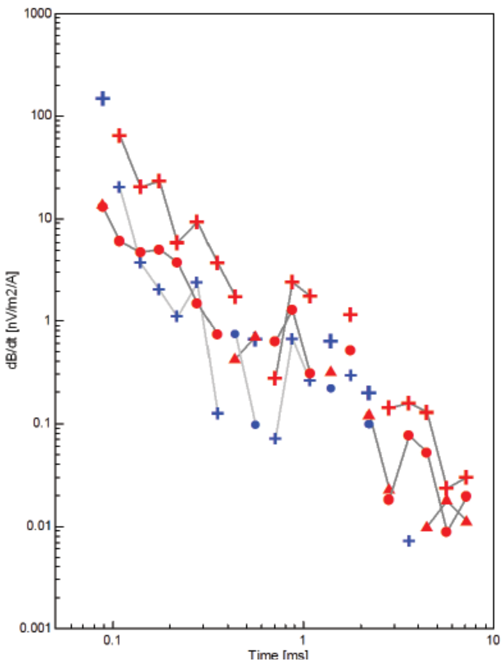
Layer	Resistivity (Ωm)	Thickness (m)
1	9,400	1,585
2	930	

Transmitter loop 6

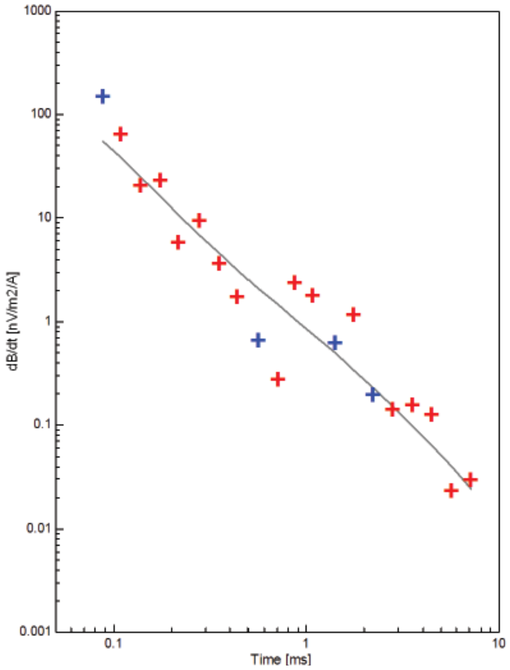
See Figure 1-1 for position of loop and receiver stations.



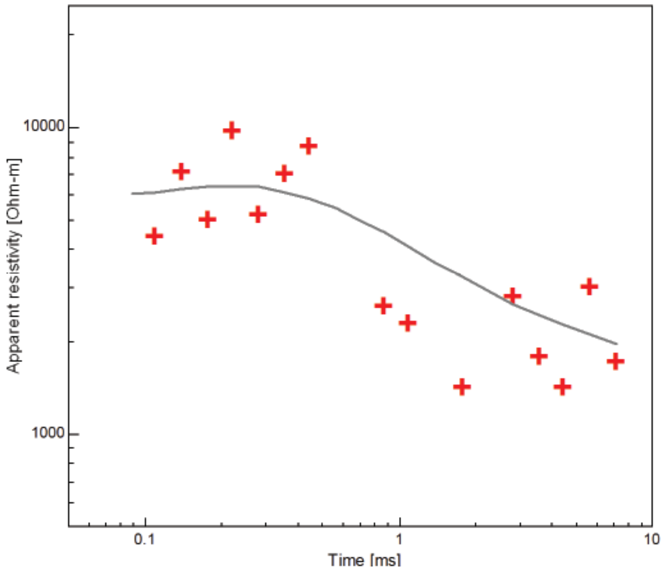




Left: *Decay curves, vertical component. +: Station A, ■: Station B, ▲: Station C. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station B. +: vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



Decay curves, vertical component, station B. Symbols = measured data, line = model response.



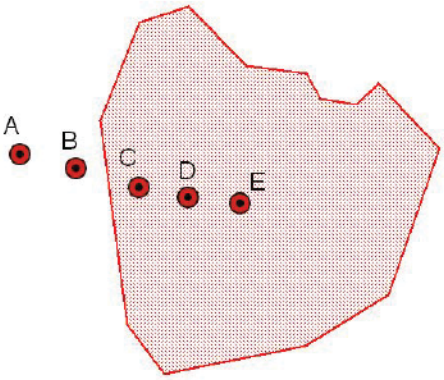
Apparent resistivity sounding curves, vertical component, station B. Symbols = measured data, line = model response.

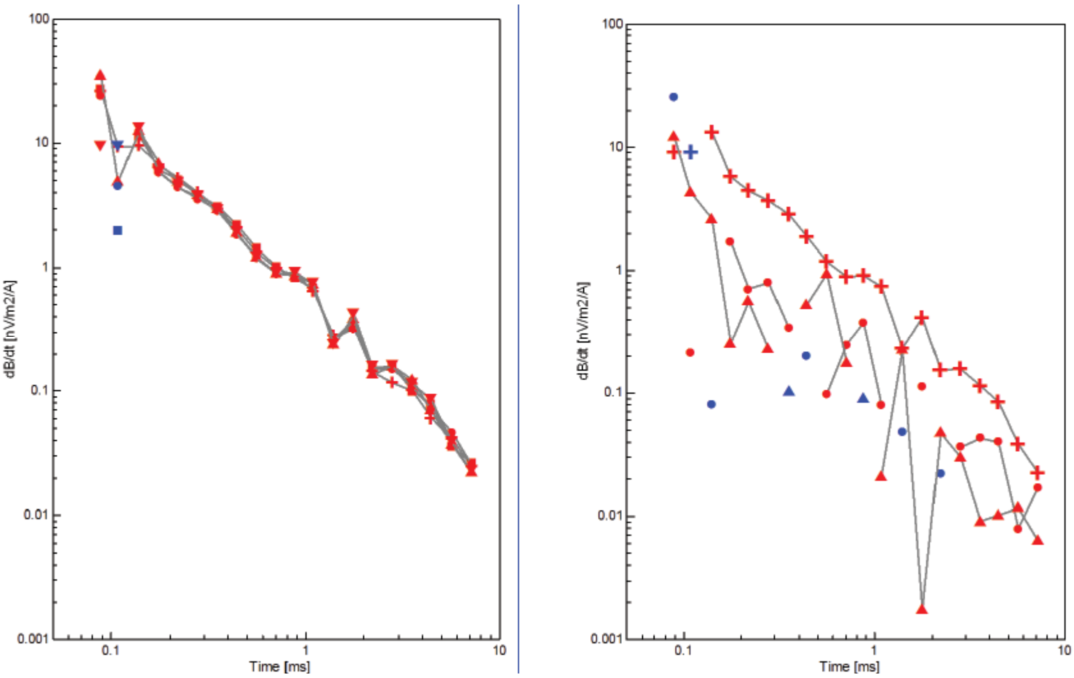
Model:

Layer	Resistivity (Ωm)	Thickness (m)
1	6,800	1,500
2	1,000	

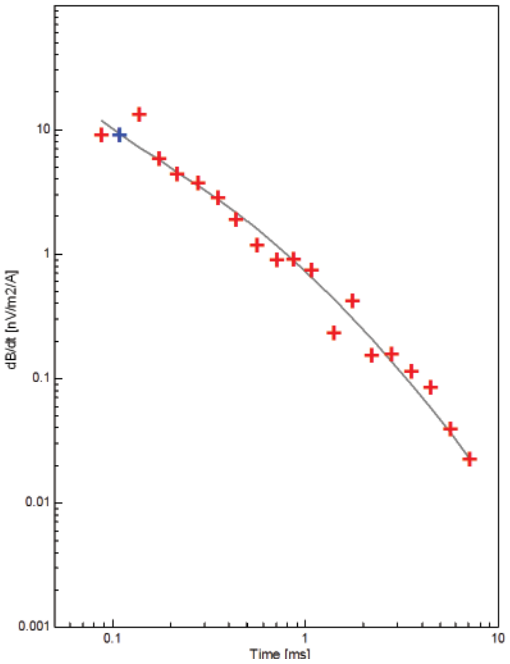
Transmitter loop 7

See Figure 1-1 for position of loop and receiver stations.

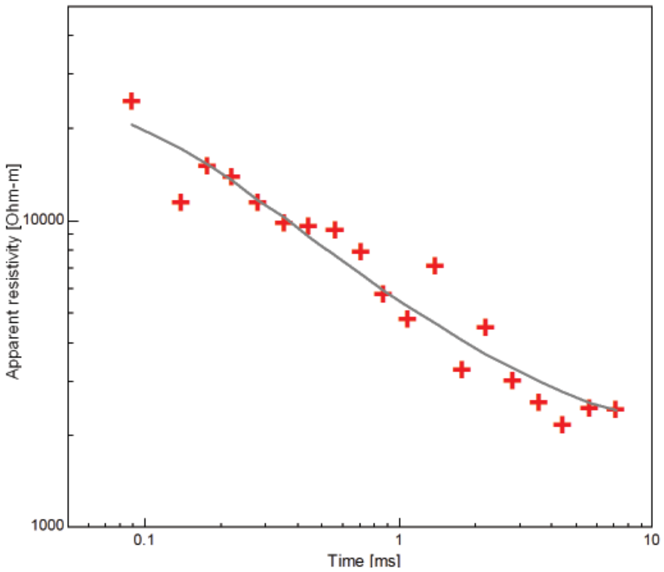




Left: *Decay curves, vertical component. + : Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.*
Right: *Decay curves, Station E. + : vertical component, ▲: North component, ●: West component. Red symbols = positive values, blue symbols = negative values.*



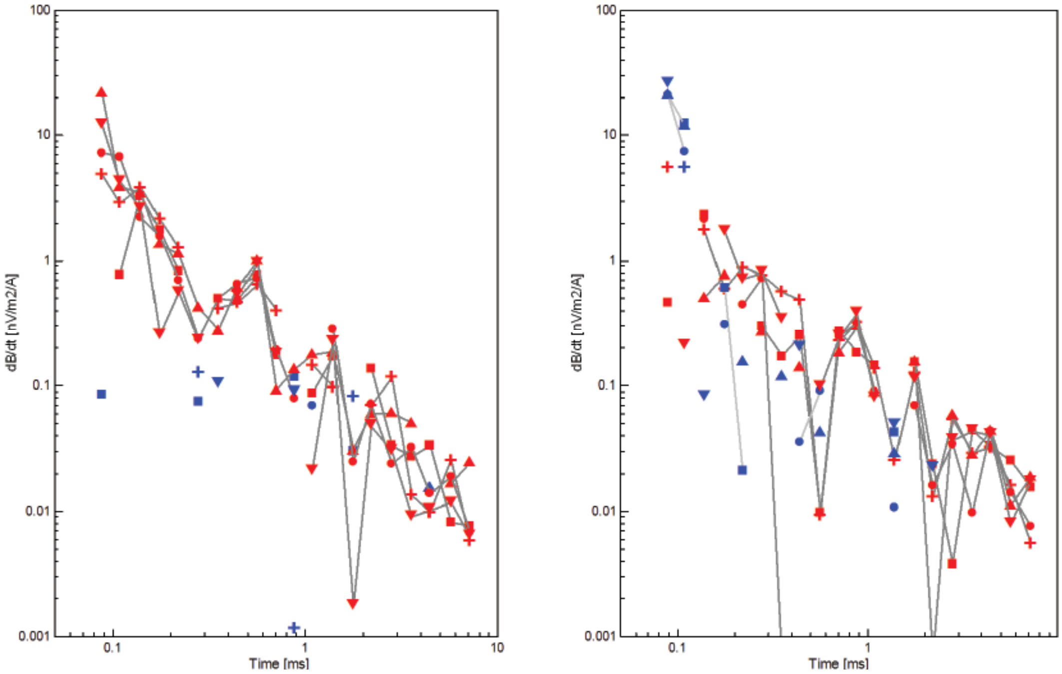
Decay curves, vertical component, station E. Symbols = measured data, line = model response.



Apparent resistivity sounding curves, vertical component, station E. Symbols = measured data, line = model response.

Model:

Layer	Resistivity (Ωm)	Thickness (m)
1	18,000	1,300
2	1,000	



Left: *Decay curves, horizontal north component. + : Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.* ***Right:*** *Decay curves, horizontal west component. + : Station A, ■: Station B, ▲: Station C, ●: Station D, ▼: Station E. Red symbols = positive values, blue symbols = negative values.*