tTEM mapping Sunds - HydroGeophysics Group - Aarhus University

tTEM Mapping Sunds

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Herning Kommune

midt Central Denmark Region

TOPSOIL Interreg North Sea Region European Regional Development Fund EUROPEAN UNION

HydroGeophysics Group AARHUS UNIVERSITY

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1. INTRODUCTION

In November, 2017, a geophysical mapping with the ground based transient electromagnetic method tTEM was carried out in the Sunds area, Denmark. The mapping project was conducted in a cooperation between the HydroGeophysics Group, Aarhus University, Denmark, GEUS, Herning Municipality, and Central Denmark Region, Denmark as a part of the European union funded project Topsoil. The overall objective of the project is the joint development of methods to describe and manage the uppermost 30m of the subsurface, in order to improve the climate resilience of the North Sea Region.

In the project there are 24 partners from five different countries in the north-sea region including; Denmark, Belgium, Germany, Netherlands and the United Kingdom.

In the pilot area of Sunds, the project aim to deal with high groundwater table in the town Sunds. Basement are regularly getting flooded, something, we hope to prevent by improving the understanding of the hydrogeological setting through mapping with geophysical methods such as tTEM. The geophysical results will form the basis of a hydrogeological model, which GEUS will setup. GEUS will also be involved in creating the groundwater model, which will be used to understand the water flow around Sunds lake, and simulate the effect of different climate scenarios.

This report primarily presents the geophysical results (resistivity maps and cross sections) and documents the data collection, processing, and inversion of the tTEM data. Chapters 2 - 4 describe the data collection, processing, and inversion. Chapter 5 explains the various types of geophysical maps and cross section placed in Appendix I: - III.

This report does not address a geological interpretation of the obtained geophysical mapping results.

tTEM survey, Sunds	
Client	Topsoil project
Key persons	**HGG, Aarhus University, Denmark** *Senior geophysicist &, project manager Jesper B. Pedersen, Postdoc Geophysicist. Pradip Maurya, MSc. geology Rune Kraghede & PhD stud. geophysicist Kim Engebretsen* **Central Denmark Region, Denmark** *Geologist, Jes Pedersen* *Geologist, Rolf Johnsen* **Herning Municipality, Denmark** *Geologist, Thomas Gad* **GEUS, Denmark** *Geologist, Anders Juhl Kallesøe* *Geologist, Flemming Jørgensen*
Locality	Sunds, Denmark
Survey period	21-27 November, 2017
Line km acquired	300 km
Line spacing	15-25 m

2. DATA COLLECTION

2.1 The Survey Area

The tTEM survey was carried out November 21th to November 27th , 2017, and covers a total of 300 line km of data (Figure 1).

The lines strike south-north and west-east with a line spacing of 15-25 m. The average driving speed was 10-15 km/h. In Figure 1, the survey area has been highlighted with a white marker. The aim of the mapping was to get a detailed 3D geophysical model of the study area in order to improve the understand of the hydrogeological setting around Sunds lake. The geophysical results will be converted into a hydrogeological model by GEUS. The tTEM results reveals information about geological structures down to more than 50 m depth.

Figure 1. Survey area, with tTEM lines in black. Each blue dot corresponds to one tTEM sounding/resistivity model. The model spacing along the lines is ~15-25 m.

2.2 The tTEM System

towTEM (tTEM) is a time-domain electromagnetic system designed for hydrogeophysical and environmental investigations. The tTEM system measures continuously while towed on the ground surface. It is designed for a very high near-surface resolution with very early time gates and a fast repetition frequency. The following contains a general introduction to the tTEM system. A more thorough description of TEM methods in general can be found in Christiansen *et al.* (2006) .

Instrument

Figure 2 shows the tTEM system. The tTEM uses an off-set configuration, with the z-receiver coil (RX-coil) approximately 7.0 m behind the transmitter coil (TX-coil). An ATV tows the tTEM-system, and the distance between the ATV and the TX coil is 2.8 m. The TX-coil is located inside a 2 m x 4 m rectangular frame (TX-frame), which carried on two sledges. GPSs are located at the front of the TX-frame and at the RX-coil for accurate positioning of the system. The RX-coil is placed on a small sledge, suspended in the air to avoid high frequency motion induced noise. The transmitter, receiver, power supply, etc. is located at the back of the ATV.

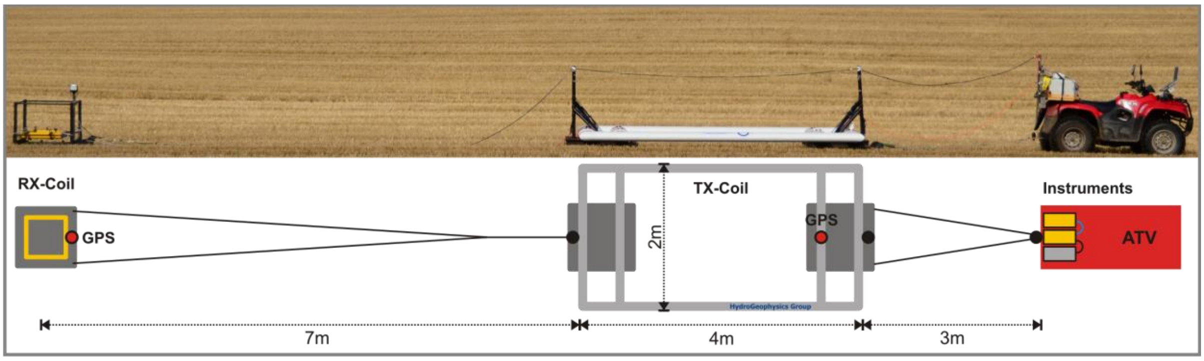

Figure 2. The tTEM system. Rx Coil are the receiver coil and Tx is the transmitter coil. The exact distance and device positions are listed in Table 1.

During data collection, the driver can monitor key data parameters and positioning in real time on a tablet in the front of the ATV.

Measurement Procedure

Measurements are carried out with two transmitter moments. The standard configuration uses low and high transmitter moments applied sequentially. A high and low moment sequence typically takes 0,5 seconds and includes several hundreds of individual transient measurements.

The driving speed can be adjusted to the survey area and target. It will normally not exceed 20 km/h.

Apart from GPS and TEM data, a number of instrument parameters are monitored and stored in order to be used for quality control when the data are processed. These parameters include transmitter temperature, current level, and voltage of the instrument.

Depth of Investigation (DOI)

The depth of investigation for the tTEM system depends on the transmitter moment, the geological settings, the background noise level and driving speed. Normally, a DOI of 60-70 m can be achieved in a subsurface layering with an average resistivity of 40 ohm-m. The depth will be larger at higher resistivities and less at lower resistivities. During the inversion, the DOI is estimated for each resistivity model (see section 4.3).

2.3 tTEM - Technical Specifications

This section lists detailed technical specifications of the tTEM system setup for the survey.

The tTEM system is configured in a standard two-moment setup (low moment, LM and high moment, HM). The system instrument setup is shown in Figure 2. The positioning of the instruments and the corners of the transmitter coil are listed in Table 1. The origin is defined as the center of the transmitter coil.

The specifications of the LM an HM moment are summarized in Table 2. The integrated waveform for both moments is shown in Figure 3. The exact waveform is listed in Table 3.

Device Position

Unit	X (m)	Y (m)	Z(m)
GP_TX (GPS)	1.40	0.00	-0.20
RxZ (Z-receiver coil)	-9.28	0.00	-0.20
Tx (center transmitter coil)	0.00	0.00	-0.29
Loop corner 1	-02.00	-01.00	0.00
Loop corner 2	02.00	-01.00	0.00
Loop corner 3	02.00	01.00	0.00
Loop corner 4	-02.00	01.00	0.00

Table 1. Equipment and transmitter coil corner positioning. The origin is defined as the center of the transmitter coil. Z is positive towards the ground.

Transmitter, Receiver Specifications

Parameter	LM	HM
No. of turns	1	1
Transmitter area (m^2)	8 m^2	8 m^2
Tx Current	~ 2.8 A	~ 30 A
Tx Peak moment	~ 22.4 Am^2	~ 240 Am^2
Repetition frequency	1055 Hz	330 Hz
Raw Data Stack size	422	264
Raw Moment cyclus time	0.22 s	0.40 s
Tx on-time	0.2 ms	0.45 ms
Duty cycle	42 %	30%
Turn-off time	2.5 µs at 2.8 Amp	4.0 µs at 30 Amp
Number of gates	4	26
Gate time interval	4 µs –10 µs	10 µs – 900 µs
Front-gate time (nominal)	2 µs	5 µs
Front-gate delay	1.9 µs	1.9 µs

Table 2. Low moment (LM) and high moment (HM) specifications.

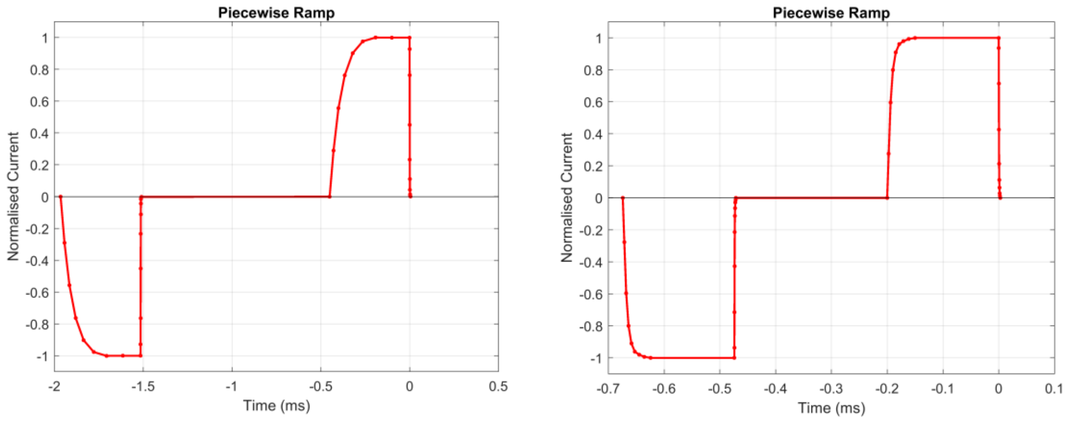

Figure 3. Waveform for LM (left) and HM (right).

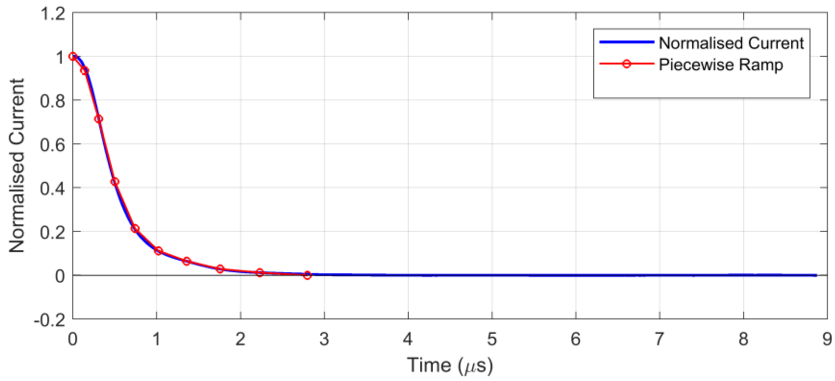

Figure 4. Zoom in on ramp down for LM.

Waveform, LM and HM

LM time	LM amplitude	HM time	HM amplitude
-6.7400e-04 s	-0.000	-1.9650e-03 s	-0.000
-6.7250e-04 s	-0.496	-1.9483e-03 s	-0.316
-6.7071e-04 s	-0.658	-1.9279e-03 s	-0.532
-6.6859e-04 s	-0.784	-1.9030e-03 s	-0.710
-6.6605e-04 s	-0.865	-1.8725e-03 s	-0.845
-6.6303e-04 s	-0.925	-1.8351e-03 s	-0.933
-6.5944e-04 s	-0.963	-1.7894e-03 s	-0.981
-6.5516e-04 s	-0.978	-1.7334e-03 s	-1.001
-6.5007e-04 s	-0.989	-1.6650e-03 s	-1.000
-6.4400e-04 s	-1.000	-1.5150e-03 s	-1.000

-4.7400e-04 s	-1.000	-1.5148e-03 s	-0.967
-4.7387e-04 s	-0.953	-1.5146e-03 s	-0.859
-4.7373e-04 s	-0.812	-1.5143e-03 s	-0.662
-4.7355e-04 s	-0.559	-1.5139e-03 s	-0.381
-4.7334e-04 s	-0.332	-1.5135e-03 s	-0.155
-4.7309e-04 s	-0.175	-1.5131e-03 s	-0.053
-4.7279e-04 s	-0.086	-1.5125e-03 s	-0.017
-4.7243e-04 s	-0.041	-1.5118e-03 s	-0.007
-4.7200e-04 s	-0.016	-1.5110e-03 s	-0.000
-4.7150e-04 s	-0.000	-4.5000e-04 s	0.000
-2.0000e-04 s	0.000	-4.3333e-04 s	0.316
-1.9850e-04 s	0.496	-4.1294e-04 s	0.532
-1.9671e-04 s	0.658	-3.8799e-04 s	0.710
-1.9459e-04 s	0.784	-3.5745e-04 s	0.845
-1.9205e-04 s	0.865	-3.2009e-04 s	0.933
-1.8903e-04 s	0.925	-2.7438e-04 s	0.981
-1.8544e-04 s	0.963	-2.1844e-04 s	1.001
-1.8116e-04 s	0.978	-1.5000e-04 s	1.000
-1.7607e-04 s	0.989	0.0000e+00 s	1.000
-1.7000e-04 s	1.000	2.0384e-07 s	0.967
0.0000e+00 s	1.000	4.3584e-07 s	0.859
1.2589e-07 s	0.953	7.2384e-07 s	0.662
2.6989e-07 s	0.812	1.0598e-06 s	0.381
4.5389e-07 s	0.559	1.4598e-06 s	0.155
6.6189e-07 s	0.332	1.9398e-06 s	0.053
9.0989e-07 s	0.175	2.5078e-06 s	0.017
1.2139e-06 s	0.086	3.1878e-06 s	0.007
1.5659e-06 s	0.041	4.0000e-06 s	0.000
1.9979e-06 s	0.016		
2.5000e-06 s	0.000		

Table 3. Waveform for LM and HM. Listed as time and nominal amplitude.

2.4 Calibration of the tTEM System

Prior to the survey, the tTEM equipment was calibrated at the Danish national TEM test site near Aarhus, Denmark (Foged *et al.*, 2013)). The calibration is performed to establish the absolute time shift and data level in order to facilitate precise modeling of the data. No additional leveling or drift corrections are applied subsequently.

In order to perform the calibration, all system parameters (transmitter waveform, low pass filters, etc.) must be known to allow accurate modeling of the tTEM setup.

The calibration constants are determined by comparing a recorded tTEM response on the test site with the reference response. The reference response is calculated from the test site reference model for the used tTEM configuration.

Acceptable calibration was achieved with the calibration constants stated in Table 4. The calibration was performed on November 20, 2017. Calibration plots for both moments are shown in *Figure 5* and *Figure 6* .

Moment	Time Shift	Scale Factor
LM	-0.55 µs	1.00
HM	-0.7 µs	1.04

Table 4. Calibration constants.

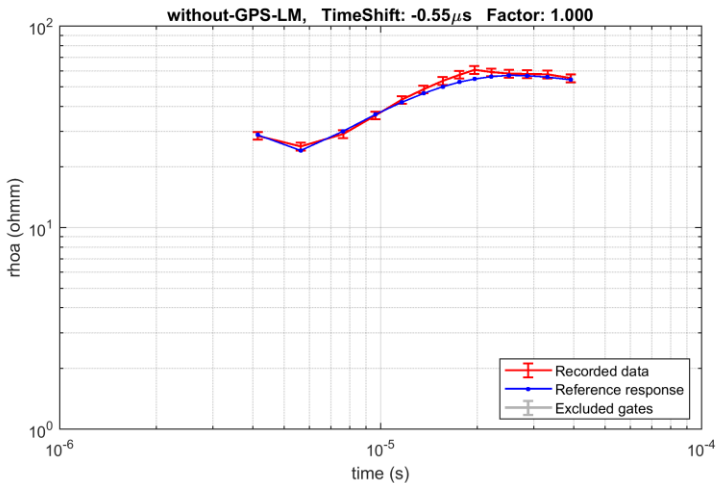

Figure 5. Calibration plot for low-moment. The red curve is the recorded data, and the blue curve is the forward response from the national geophysical test-site in Denmark. Note that only the first 4 gates of the LM are used for interpretation.

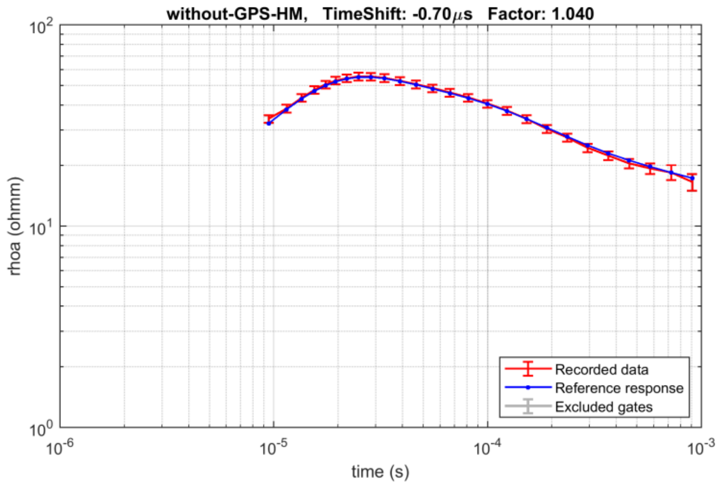

Figure 6. Calibration plot for low-moment. The red curve is the recorded data, and the blue curve is the forward response from the national geophysical test-site in Denmark.

3. PROCESSING OF THE TTEM DATA

3.1 Data Processing – Workflow

The software package Aarhus Workbench is used for processing the tTEM data.

The aim of the processing is to prepare data for the geophysical interpretation. The processing primarily includes filtering and averaging of data as well as culling and discarding of distorted or noisy data.

The data processing can be divided into four steps:

1. Import of raw data into a fixed database structure. The raw data appear in the form of .skb-, .sps- and .geo-files. Skb-files contain the actual transient data from the receiver. Sps-files contain GPS positions, transmitter currents etc., and the geo-file contains system geometry, low-pass filters, calibration parameters, turn-on and turn-off ramps, calibration parameters, etc.
2. Automatic processing: First, an automatic processing of the four data types is used. These are GPS-, and TEM data. This automatic processing is based on a number of criteria adjusted to the survey concerned.
3. Manual processing: Inspection and correction of the results of the automatic processing for the data types in question.
4. Adjustment of the data processing based on preliminary inversion results.

All data is recorded with a common time stamp. This time stamp is used to link data from different data types. The time stamp is given as the GMT time.

In the following, a short description of the processing of the different data types is shown. A more thorough description of the TEM data processing can be found in Auken *et al.* (2009).

3.2 GPS-Positioning

The position of the tTEM-system is recorded continuously with two independent GPS receivers. Furthermore, the GPS data are shifted to the optimum focus point of the tTEM system.

3.3 Voltage Data

The voltage data are gathered continuously along the driving lines (Figure 7). The processing of voltage data is carried out in a two-step system: an automatic and a manual part. In the former, a number of filters designed to cull coupled or noise influenced data are used. Furthermore, raw data are stacked to increase the signal-to-noise ratio. The averaging width of late-time data is wider than that of early-time data, as seen in Table 5. The data uncertainty is calculated from the data stack, with an additional 3% uniform data uncertainty. Typically, the stacked data (soundings) are generated for every 10 m depending on mapping speed, tTEM setup and target. Each sounding location will produce a 1D resistivity model when data is inverted.

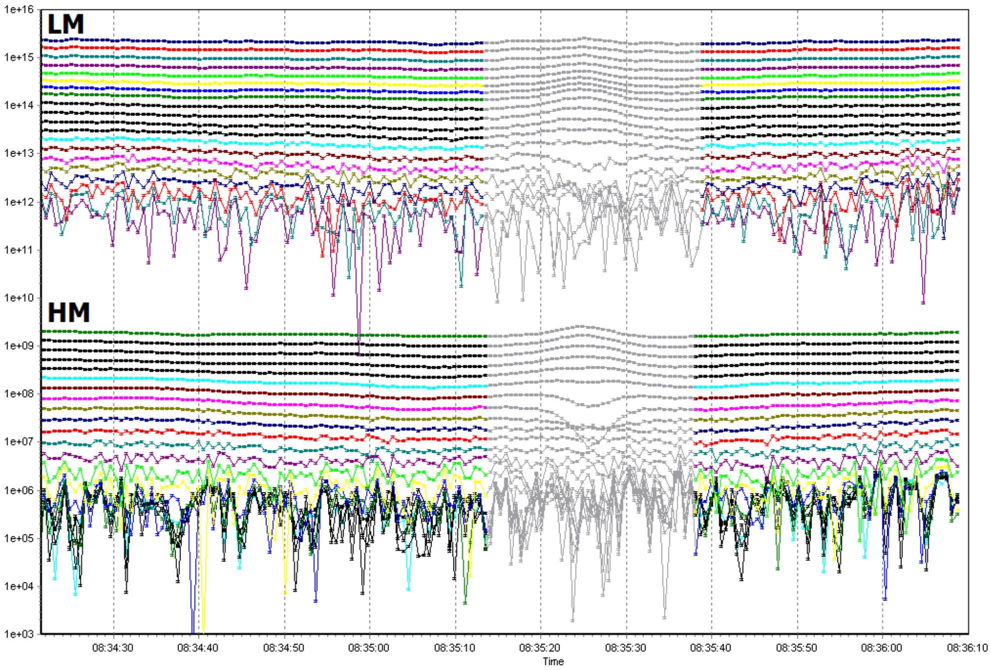

Figure 7. Data section example with coupled data. The section displays 2 minutes (~0.5 km) of data. Each of the curves shows raw low-moment or high-moment data for a given gate time. The green line represents gate 1 of the high moment, the black line gate 2 etc. The grey lines represent data that have been removed due to couplings. A coupling can clearly be identified at 08:35:12 to 08:35:37. In this case the coupling are associated with buried power cables.

The automatic processing is followed by a manual inspection and correction. A number of power lines, roads, railroads, etc. typically crosses survey areas. As data near such installations often are heavily disturbed (coupled to the installations), it is necessary to remove these data, in order to produce geophysical maps without artifact from these manmade installations. The manual inspection and removal of coupled data is therefore essential to obtain high quality models at the end. In some cases, it is not possible to identify the source of the coupling even though it is evident in the data.

Figure 7 shows an example of strongly coupled data. First the coupled data parts are removed. Then data are stacked into soundings, and finally the late-time part of the sounding curves below the background noise level is excluded.

3.4 Processing - Technical Specifications

Table 5 shows key processing settings in the Aarhus Workbench, used for this survey.

Item		Value
Noise Processing	Data uncertainty Uniform data STD	From data stack 3%
Averaging filter	Sounding distance LM, width HM, width At gate times	2.5 s (~10 m) 2.5 s 2.5 s, 5 s 1e-5 s, 1e-4 s

Table 5. Processing settings.

4. INVERSION OF THE TTEM DATA

Inversion of the dataset and evaluation of the inversion results are carried out using the Aarhus Workbench software package. The underlying inversion code (AarhusInv) is developed by the HydroGeophysics Group, Aarhus University, Denmark (Kirkegaard *et al.*, 2015) and Auken *et al.* (2015)

The inversion is a 1D full non-linear damped least-squares solution in which the transfer function of the instrumentation is modeled. The transfer function includes turn-on and turn-off ramps, front gate, low-pass filters, and transmitter and receiver positions.

4.1 Spatially Constrained Inversion

The spatially constrained inversion (SCI) (Viezzoli *et al.*, 2008) scheme is used when inverting the tTEM data. The SCI scheme uses constraints between the 1D-models, both along and across the mapping lines, as shown in Figure 8. The constraints are scaled according to the distance between soundings.

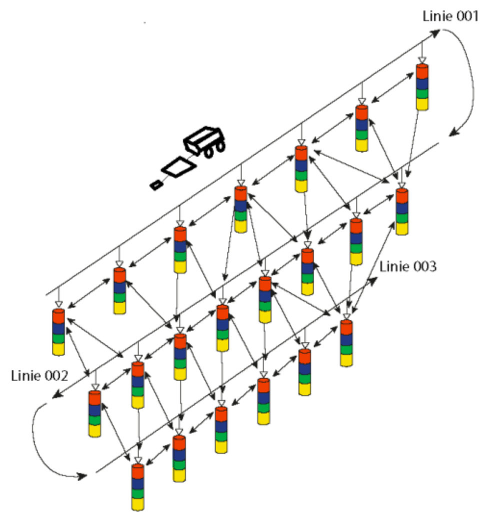

Figure 8. Schematic presentation of the SCI setup. Constraints connect not only soundings located along the mapping lines, but also those across them.

The connection pattern of the constraints is designed using a Delaunay triangulation, which connects *natural* neighbor models. For line oriented data the Delaunay triangulation results in a model being connected to the two neighbor models at the mapping line and typically 2-3 models at the adjacent mapping lines, (see Figure 9). The SCI constraints are the preliminary condition for breaking down the line orientation in the dataset.

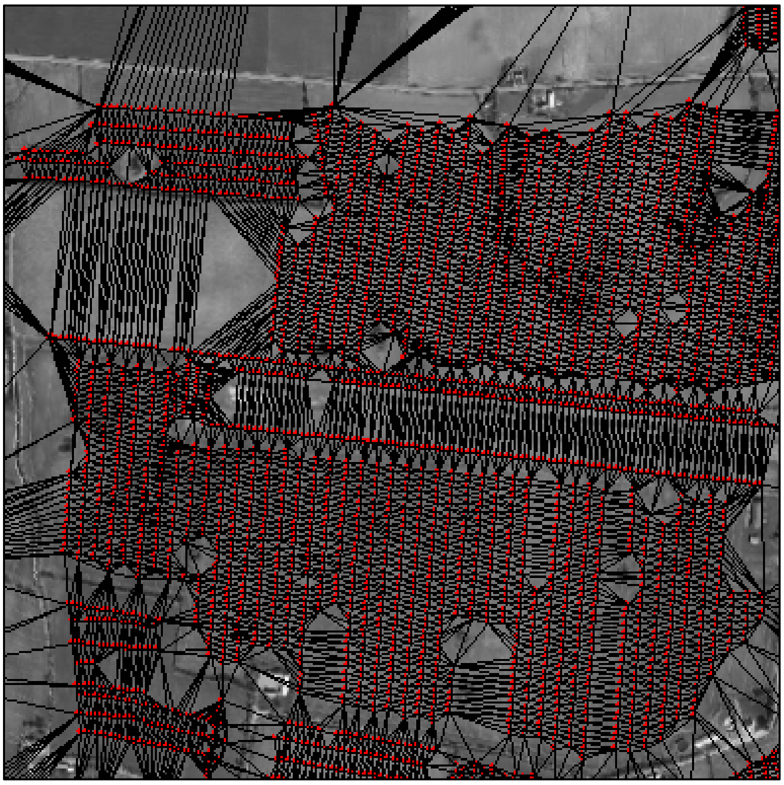

Figure 9. Example setup of SCI-constraints. The red points are the model positions. The black lines show the constraints created with the Delaunay triangles. The line distance in this example is 20 m, sounding distance is 10 m and the area is approximately 1 x 1 km.

Constraining the parameters enhances the resolution of resistivities and layer interfaces, which are not well resolved in an independent inversion of the soundings.

SCI-setup parameters for this survey are listed in section 4.4.

4.2 Smooth and sharp Inversion

Both a smooth and a sharp model inversion have been carried out. Both inversion types use the SCI-setup, but the regularization scheme is different.

The smooth regularization scheme penalizes the resistivity changes, resulting in smooth resistivity transitions both vertical and horizontal, as seen in Figure 9. The sharp regularization scheme (Vignoli *et al.*, 2015) penalizes the number of resistivity changes of a certain size, resulting in model sections with few, but relative shape resistivity transitions, as seen in see Figure 9. Normally the tTEM data are fitted equally well with the model types.

Assuming a geological layered environment, picking geological layer boundaries will be less subjective in a sharp model result compared to a smooth model.

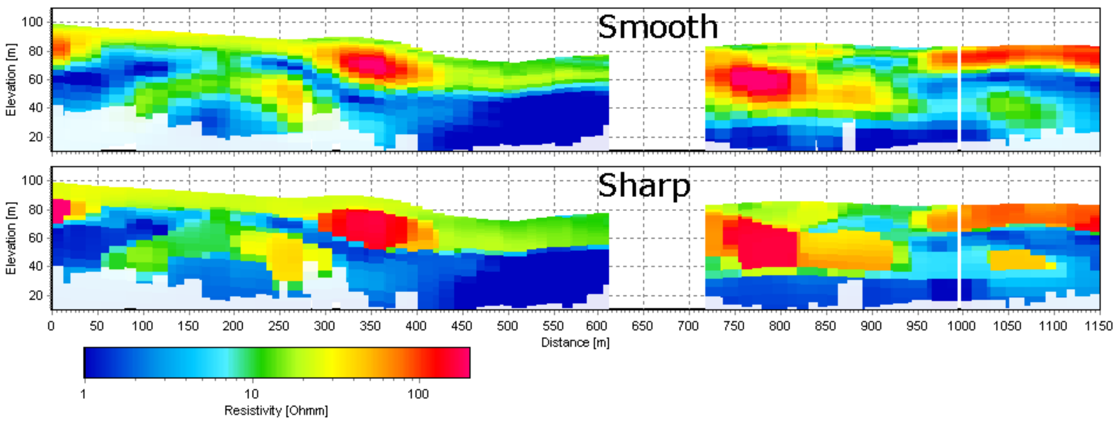

Figure 10. Profile showing of a smooth and sharp inversion of the same tTEM data set. Note the significant better defined layer boundaries in the as a result of the sharp inversion.

4.3 Depth of Investigation

For each resistivity model a depth of investigation (DOI) is estimated, as described in Christiansen and Auken (2012). The DOI calculation takes into account the tTEM system transfer function, the number of data points, the data uncertainty, and the resistivity model.

EM fields are diffusive, and there is no discrete depth where the information on the resistivity structure stops. Therefore, we provide a conservative and a standard DOI estimate. As a guideline, the resistivity structures above the DOI conservative value are well contained in the tTEM data, and resistivity structures below the DOI standard value are weaker contained in the data and should normally be disregarded.

The DOI conservative and DOI standard estimates are included as a point themes map in Appendix I: The cross sections in Appendix II: are blanked in depth at the DOI standard values. Furthermore, the resistivity models are blanked below the DOI- standard value when compiling the mean resistivity maps.

4.4 Inversion - Technical Specifications

The inversion settings for the smooth and sharp inversions in Aarhus Workbench are listed in Table 6.

Item		Value
Model setup	Number of layers Starting resistivities [Ωm] Thickness of first layer [m] Depth to last layer [m] Thickness distribution of layers	30 40 ohmm 1.0 150.0 Log increasing with depth
Smooth model: Constraints/ Prior constraints	Horizontal constraints on resistivities [factor] Reference distance [m] Constraints distance scaling Vertical constraints on resistivities [factor] Prior, thickness Prior, resistivities Minimum number of gates per moment	1.3 10 $(1/\text{distance})^1$ 3.0 Fixed None 3
Sharp model: Constraints/ Prior constraints	Horizontal constraints on resistivities [factor] Reference distance [m] Constraints distance scaling Vertical constraints on resistivities [factor] Prior, thickness Prior, resistivities Minimum number of gates per moment Sharp vertical constraints Sharp horizontal constraints	1.03 10 $(1/\text{distance})^1$ 1.08 Fixed None 3 200 300

Table 6. Inversion settings, smooth and sharp SCI setup

5. THEMATIC MAPS AND CROSS SECTIONS

To visualize the resistivity structures in the mapping area, a number of geophysical maps and cross sections have been created. Furthermore, a location map and a number of maps made for quality control (QC-maps) are found in the appendices.

5.1 Location Map, QC-maps

A location map and quality control maps (QC) described below are located in Appendix I:

Model Location and Lines
This map shows the actual survey lines. Black dots mark where data are disregarded due to line turns or coupling. Blue dots mark where data is kept and inverted to a resistivity model.

A decent amount of data is disregarded due to coupling, and the coupled data are primarily associated with electrical cables, buildings, and roads.

Number of Time Gates in Use
This maps shows the number of time gates (high and low moment) in use for each resistivity model. Few time gates correlate to areas with a low signal level (very resistive areas).

Data Residual
The data residual expresses how well the obtained resistivity models fit the recorded data. The data residual values are normalized with the data standard deviation, so a data residual below one corresponds to a fit within one standard deviation.

The data residual map in Appendix I: is for the smooth inversion. The data residual for the sharp inversion is similar. Some areas have relatively high data residual values (>2). This is primarily due to data with a high noise level, which again is associated with a low signal over resistive ground. In general, the data residuals are low, which is expected for this type of environment and geological setting.

Depth of Investigation (DOI)
This map shows the DOI estimates for the smooth model inversion result (see section 4.3 for a description of the DOI-calculation). DOI maps in elevation and depths are included in the appendix.

5.2 Cross Sections

Cross sections of selected mapping lines are located in Appendix II: Each section holds the smooth inversion model bars, which are blanked at the DOI- standard value. Cross section of all mapping lines are available in the delivered Workspace.

5.3 Mean Resistivity Maps

To make depth or horizontal slices, the mean resistivity in the depth or elevation intervals is calculated for each resistivity model and then interpolated to regular grids.

Figure 11 shows how the resistivities of the layers in a model influence the calculation of the mean resistivity in a depth interval [A, B]. d_0 is the surface, d_1, d_2 and d_3 are the depths to the layer boundaries in the model. ρ_1, ρ_2, ρ_3 and ρ_4 are the resistivities of the layers.

The model is subdivided into sub-thicknesses $\Delta t_{1\text{-}3}$. The mean resistivity (ρ_{vertical}) is calculated as:

$$\rho_{vertical} = \frac{\rho_1 \cdot \Delta t_1 + \rho_2 \cdot \Delta t_2 + \rho_3 \cdot \Delta t_3}{\Delta t_1 + \Delta t_2 \cdot \Delta t_3}$$

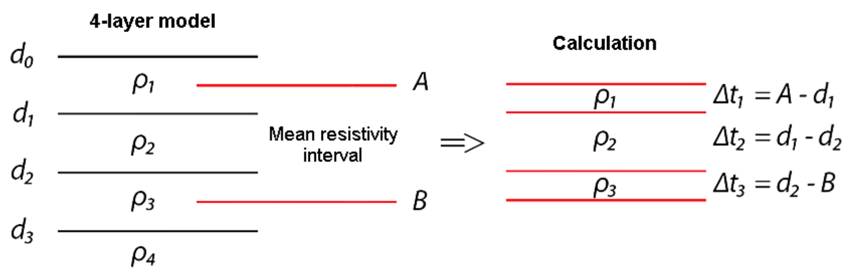

Figure 11. The figure illustrates how the resistivities of the layers influence the mean resistivities in a depth interval [A:B]

In the general term the mean resistivities in a depth interval is calculated as:

$$\bar{\rho} = \frac{\sum_{i=1}^{n} \rho_i \cdot \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}$$

where i runs through the interval from 1 to the number of sub-thicknesses. The mean resistivity calculated by the above formula ($\rho_{vertical}$) is called a vertical mean resistivity - equal to the total resistance if a current flows vertically through the interval.

By mapping with a TEM method, the current flows only horizontally in the ground. It is therefore more correct to perform the mean resistivity calculation in conductivity, called the horizontal mean resistivity ($\rho_{horizontal}$). The horizontal mean resistivity is equal to the reciprocal of the mean conductivity (σ_{mean}) and is calculated as:

$$\rho_{horizontal} = \frac{1}{\sigma_{mean}} = \left[\frac{\sum_{1=1}^{n}\left(\frac{1}{\rho_i}\right) \cdot \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}\right]^{-1}$$

For this survey, horizontal mean resistivity themes have been generated from the smooth model inversion result in 5 m depth intervals from 0 to 30 m, and in 10 m intervals from 30 to 70 m. The resistivity models have been blanked below the DOI standard depth.

The interpolation of the mean resistivity values to regular grids is performed by kriging interpolation (Pebesma and Wesseling, 1998), with a node spacing of 5 m and a search radius of 50 m. Addition linear pixel smoothing was subsequently applied. The mean resistivity maps are located in Appendix III:

5.4 Deliverables

Digital

- This report incl. theme maps and profiles as PDF-files.

- Aarhus Workbench workspace holding raw data, processed data, inversion results, theme maps, and profiles. The workspace holds both the smooth and the sharp inversion results.
  The workspace can be delivered upon request.

Note: All digital maps and data are geo-referenced to coordinate system WGS84, UTM zone 32N.

6. CONCLUSION

The tTEM survey was carried out successfully and a careful data processing has been performed. Subsequently the data was inverted to produce both a smooth and a sharp resistivity model which describes the resistivity structures of the soil down to more than 50 m depth. The tTEM survey reveals a detailed three-dimensional resistivity picture of the subsurface, due to the close line spacing and lateral resolution along the driving lines. The final resolution is a 20x10 measurement grid. The survey area took 6 days to map, resulting in 300 km of data and 28994 models.

Profile 1 below shows some of the resistivity structures in the area. More resistivity profiles can be viewed in appendix II, showing the complex geological setting within the survey area. Geologists and hydrologist from GEUS will take the geophysical results and transfer them into a hydrological model by comparing geophysics and borehole knowledge.

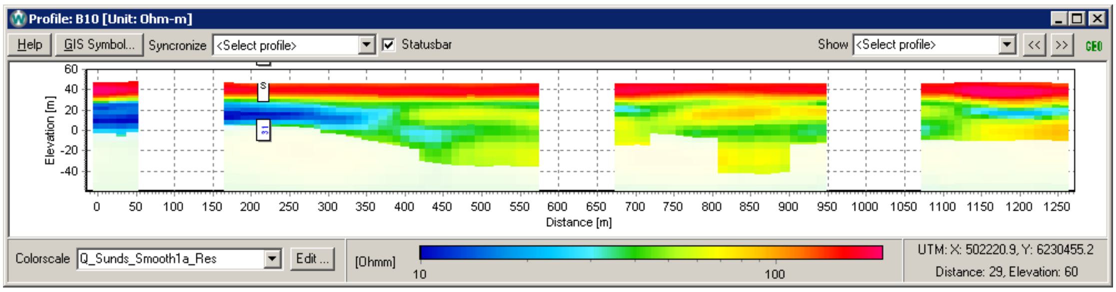

Figure 12. Profile 1,

7. REFERENCES

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APPENDIX I: LOCATION MAPS, QC MAPS

This appendix includes maps of:

- Model location and mapping lines
- Data residual
- Number of data points
- Depth of investigation, in depth

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Location Map , Sunds

Black: tTEM lines, Red: tTEM Model Position

UTM 32N WGS84

1.5 km

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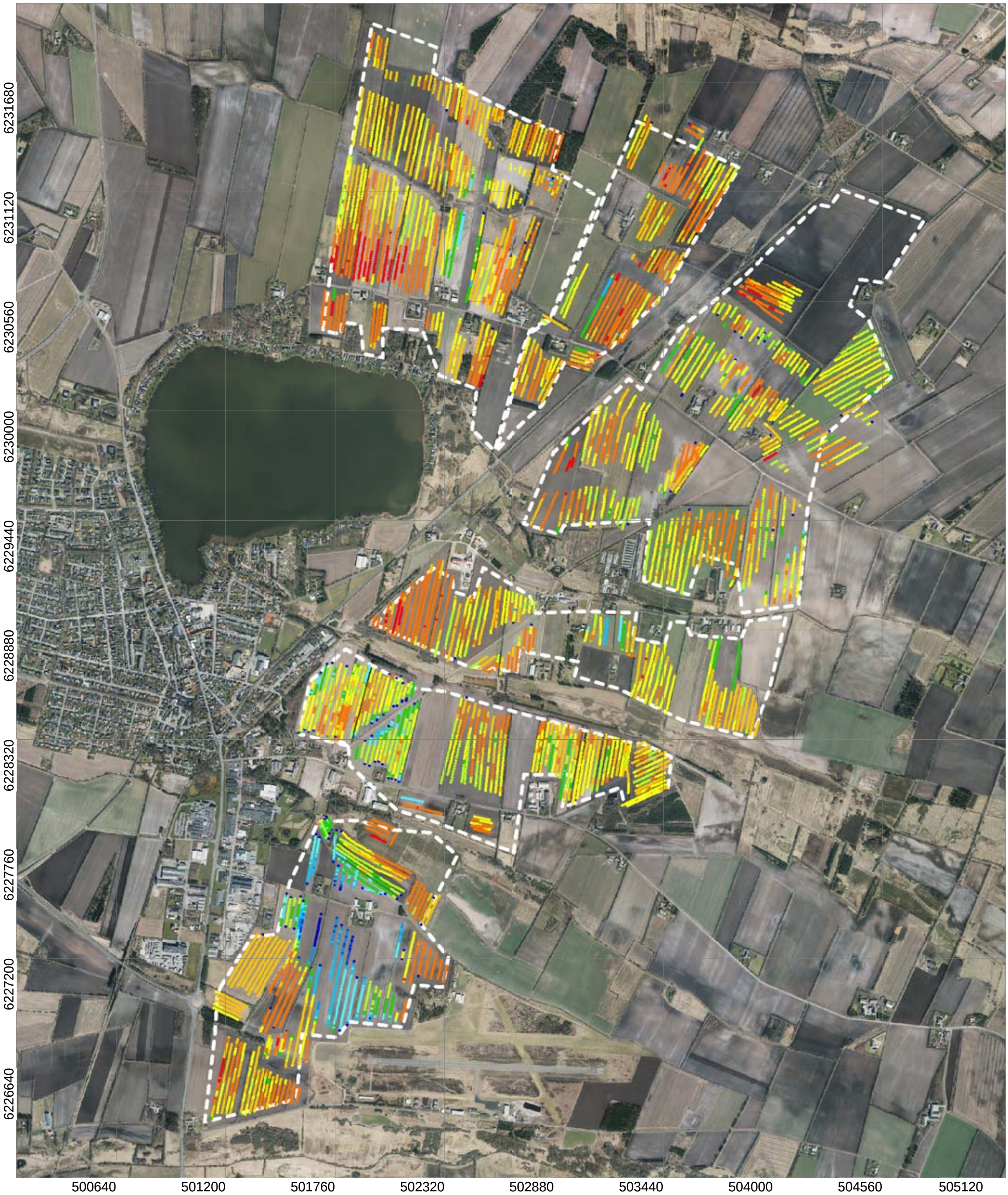

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Number of data points

SCI Smooth Model - QC point theme

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36

UTM 32N WGS84

1.5 km

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Data Residual

SCI Smooth Model - QC point theme

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4

UTM 32N WGS84

1.5 km

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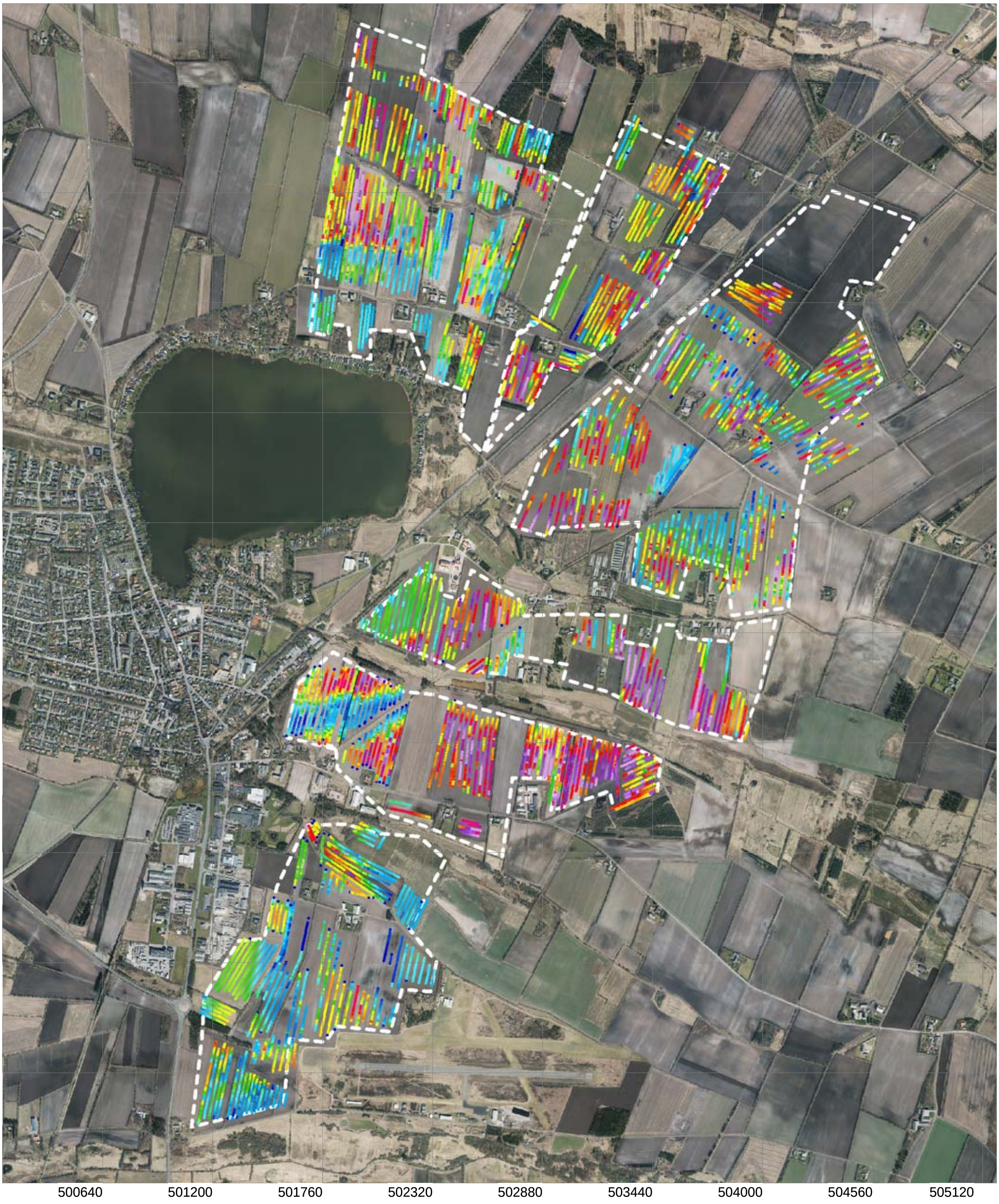
AARHUS UNIVERSITY



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DOI Standard (Depth)

SCI Smooth Model - QC point theme

40 50 60 70 80 90 100

Depth [m]

UTM 32N WGS84

1.5 km

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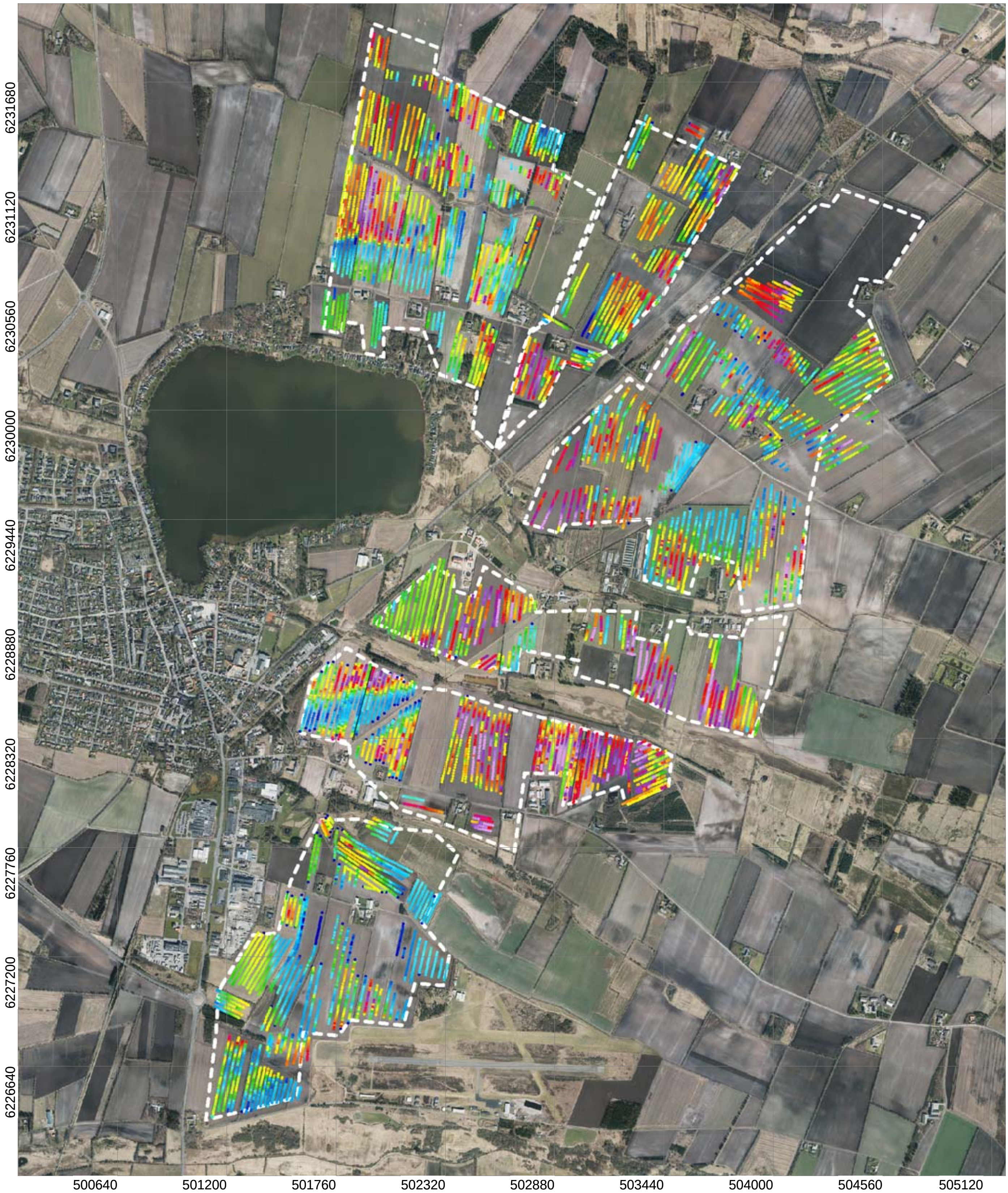
HydroGeophysics Group AARHUS UNIVERSITY



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30 40 50 60 70 80
Depth [m]

DOI Conservative (Depth)

SCI Smooth Model - QC point theme

UTM 32N WGS84

1.5 km

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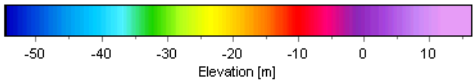
DOI Standard (Elevation)

SCI Smooth Model - QC point theme



UTM 32N WGS84

1.5 km

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DOI Conservative (Elevation)

SCI Smooth Model - QC point theme

-35 -30 -25 -20 -15 -10 -5 0 5 10 15

Elevation [m]

UTM 32N WGS84

1.5 km

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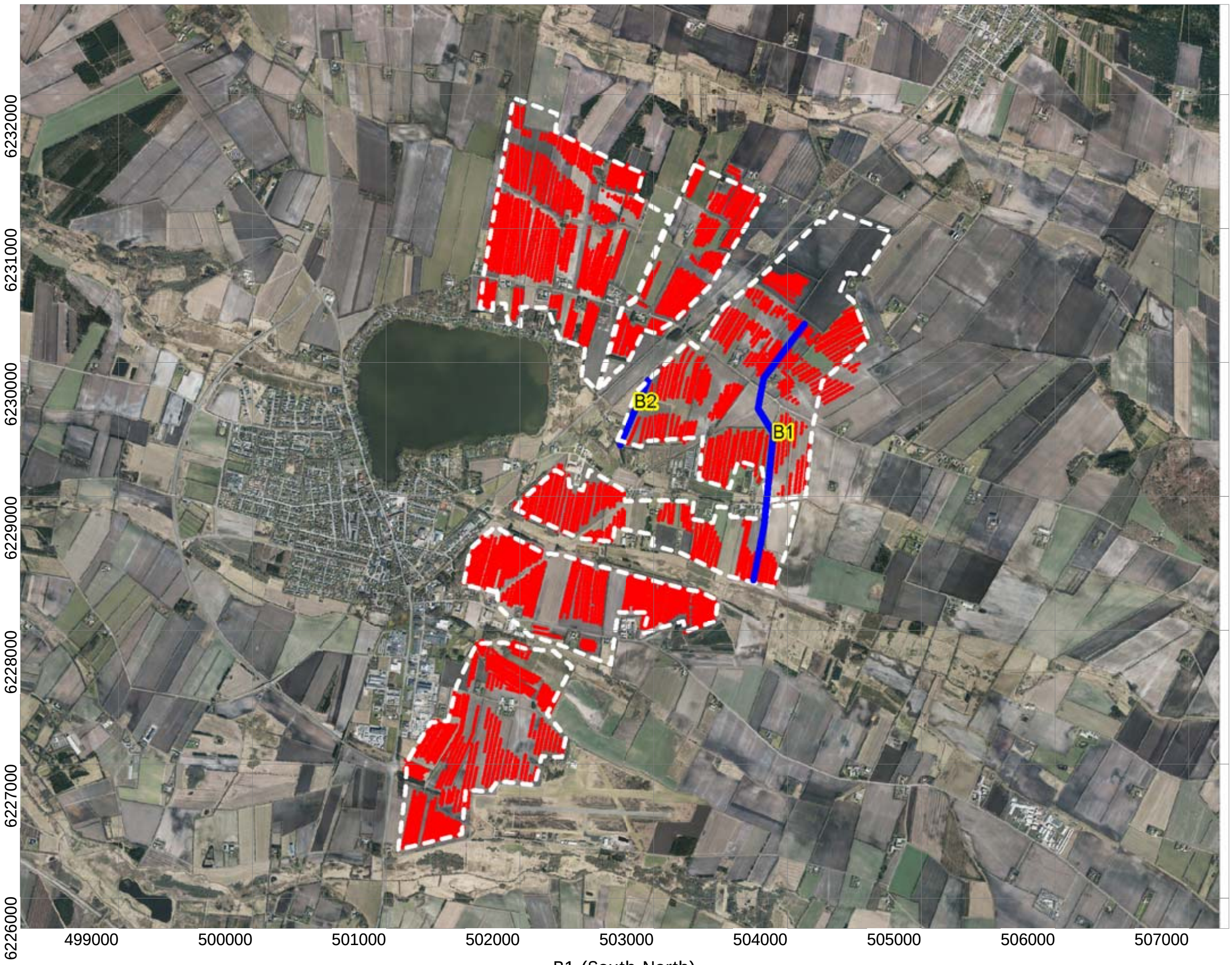
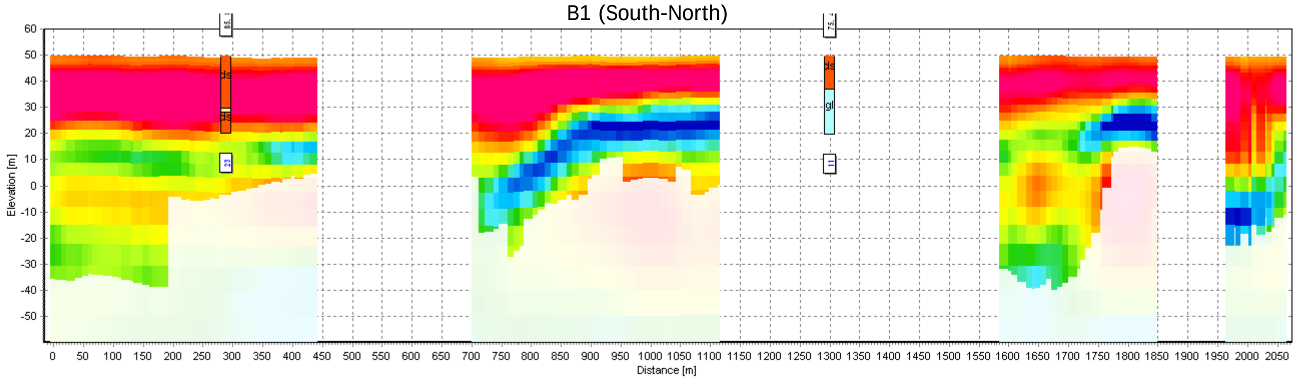
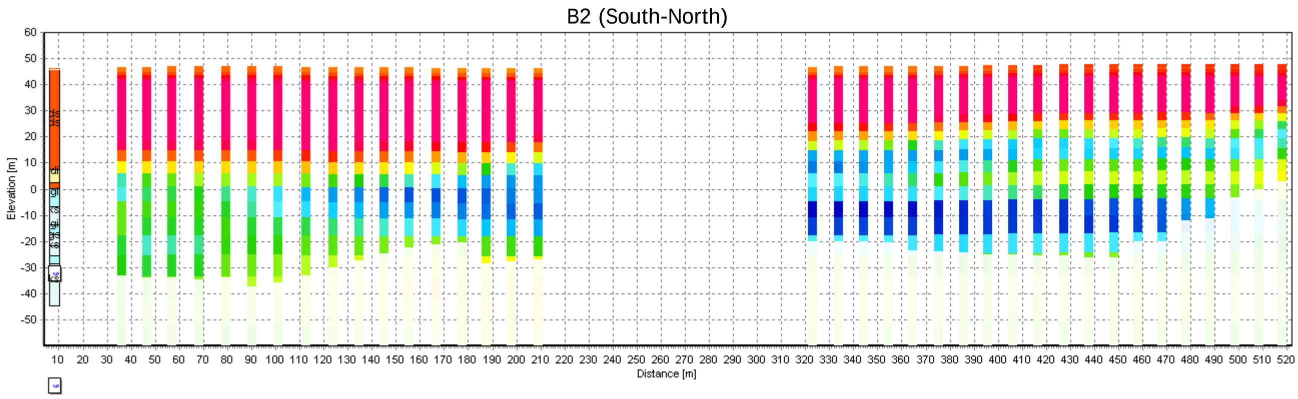
APPENDIX II: CROSS SECTIONS

Selected cross sections for the smooth inversion are included. Each section holds the model bars blanked at the DOI- standard value. Sections for all the mapping lines are available in the delivered Workspace.







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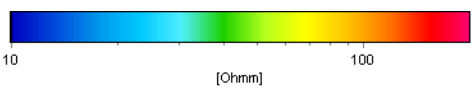
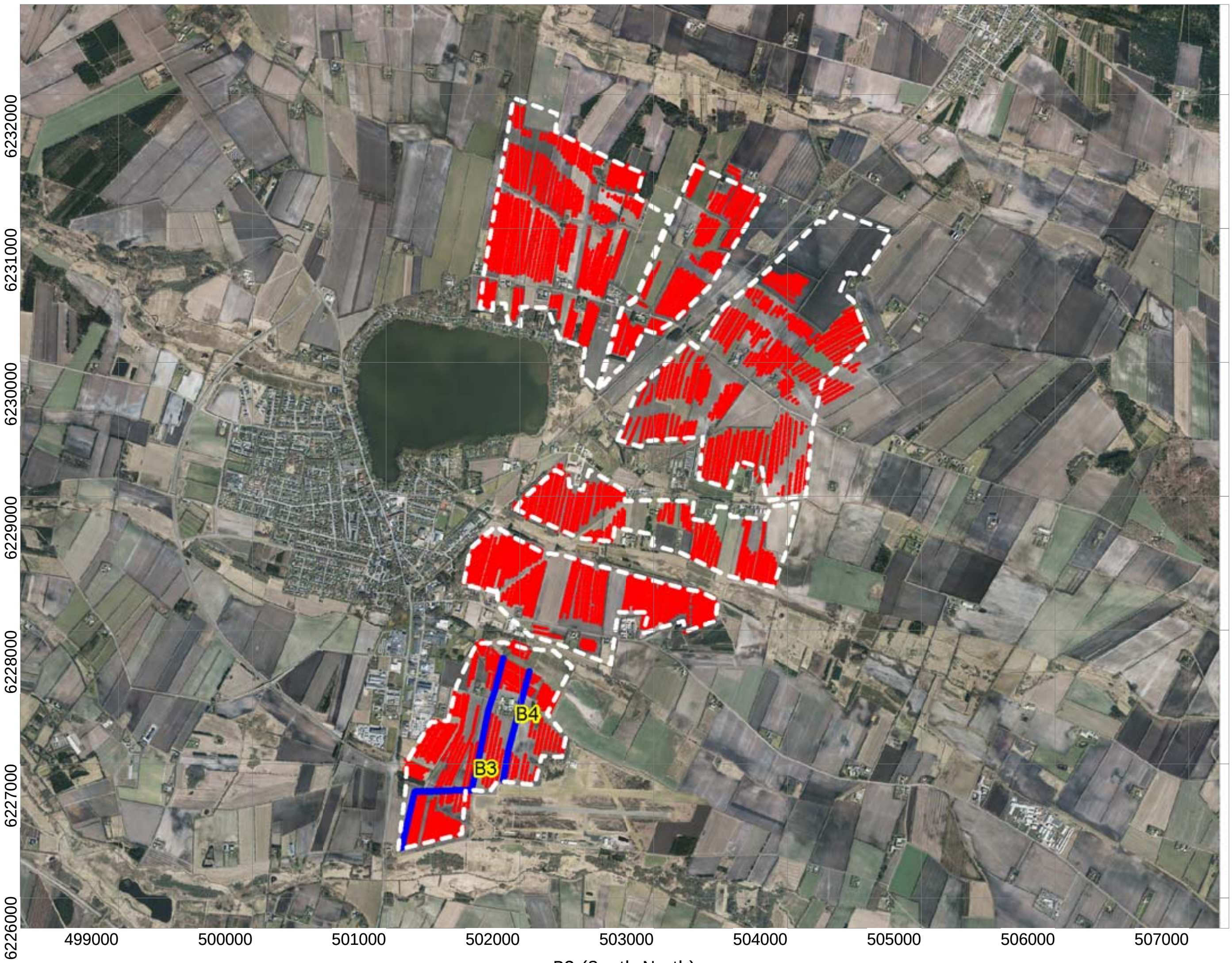


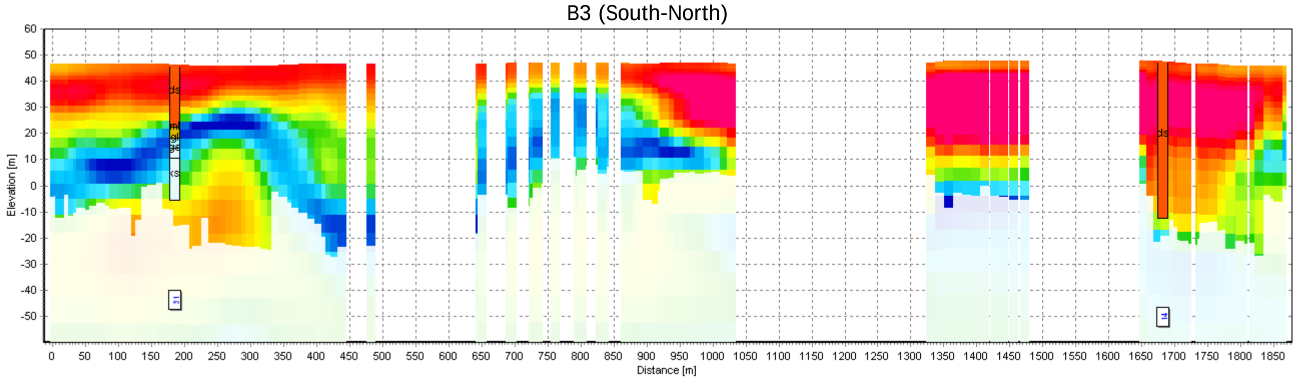
Resistivity Profiles (ohm-m)

Smooth SCI Model

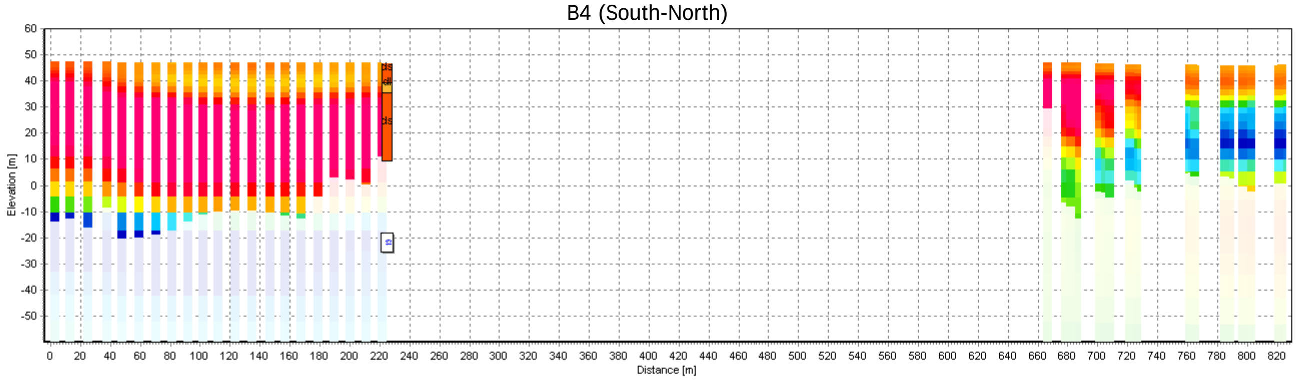
The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard



B3 (South-North)



B4 (South-North)



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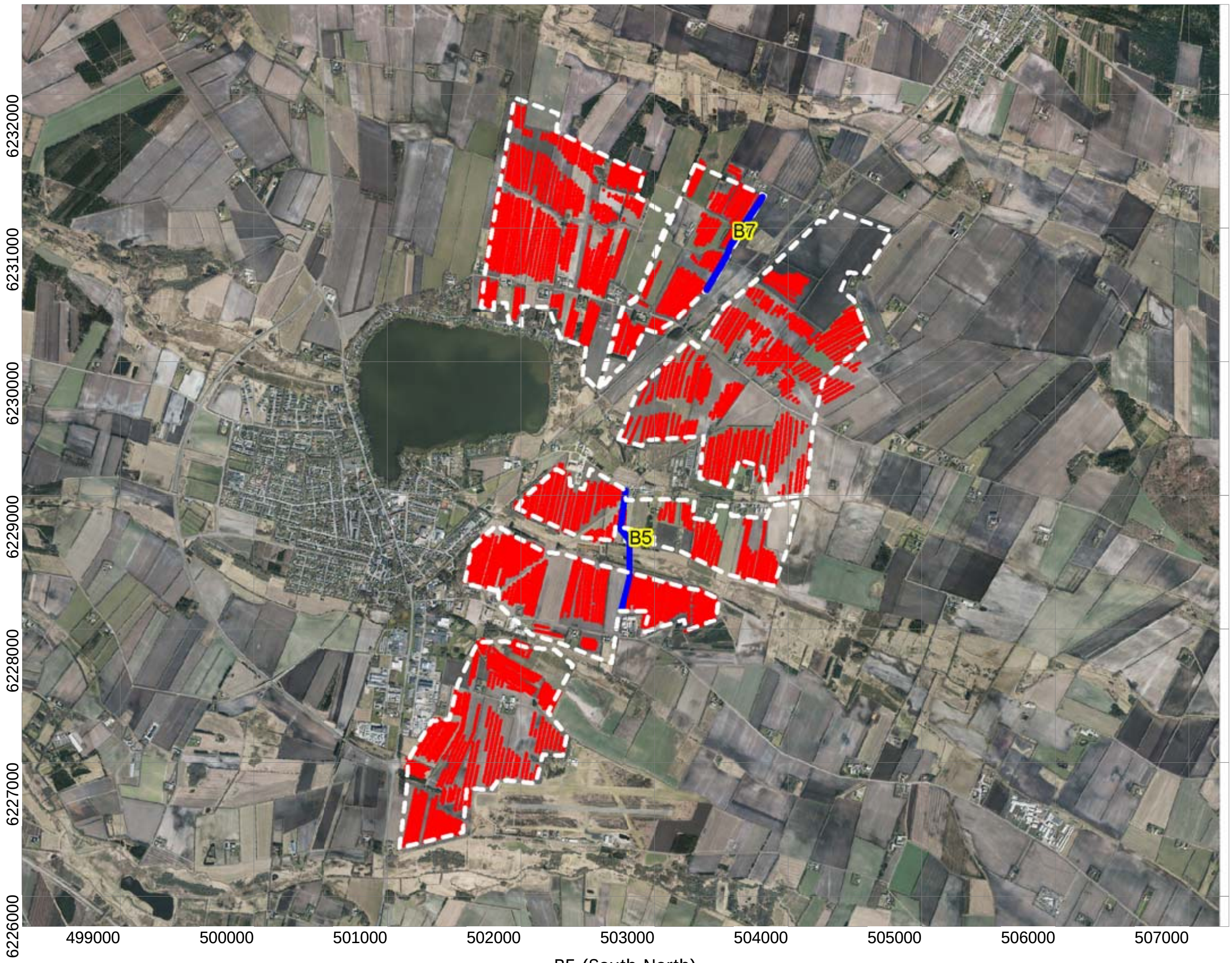
10 — 100
[Ohmm]

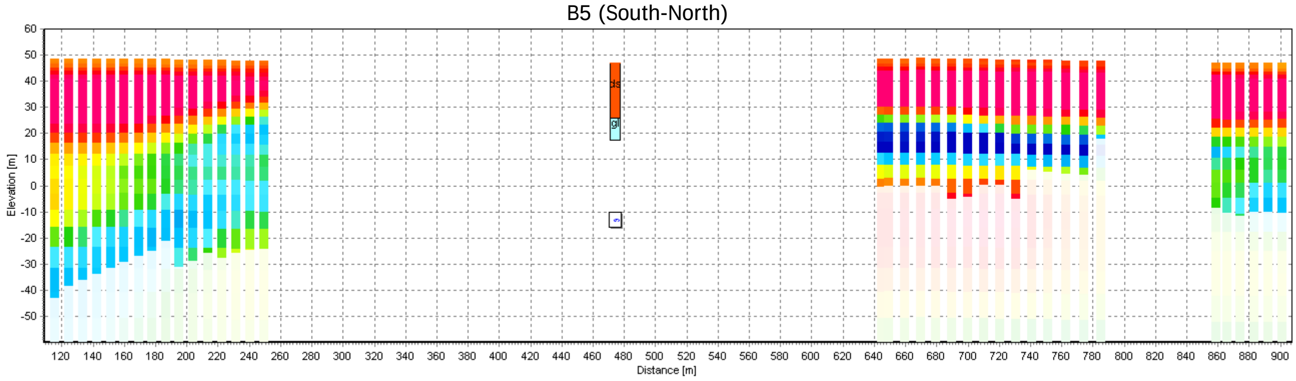
Resistivity Profiles (ohm-m)

Smooth SCI Model

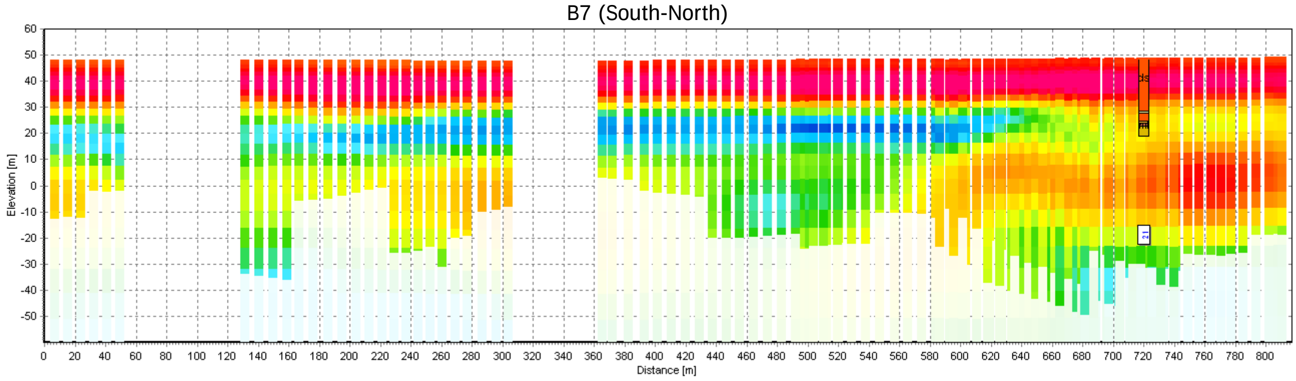
The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard



B5 (South-North)



B7 (South-North)



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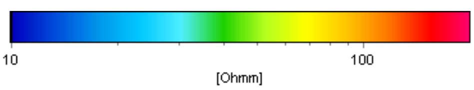
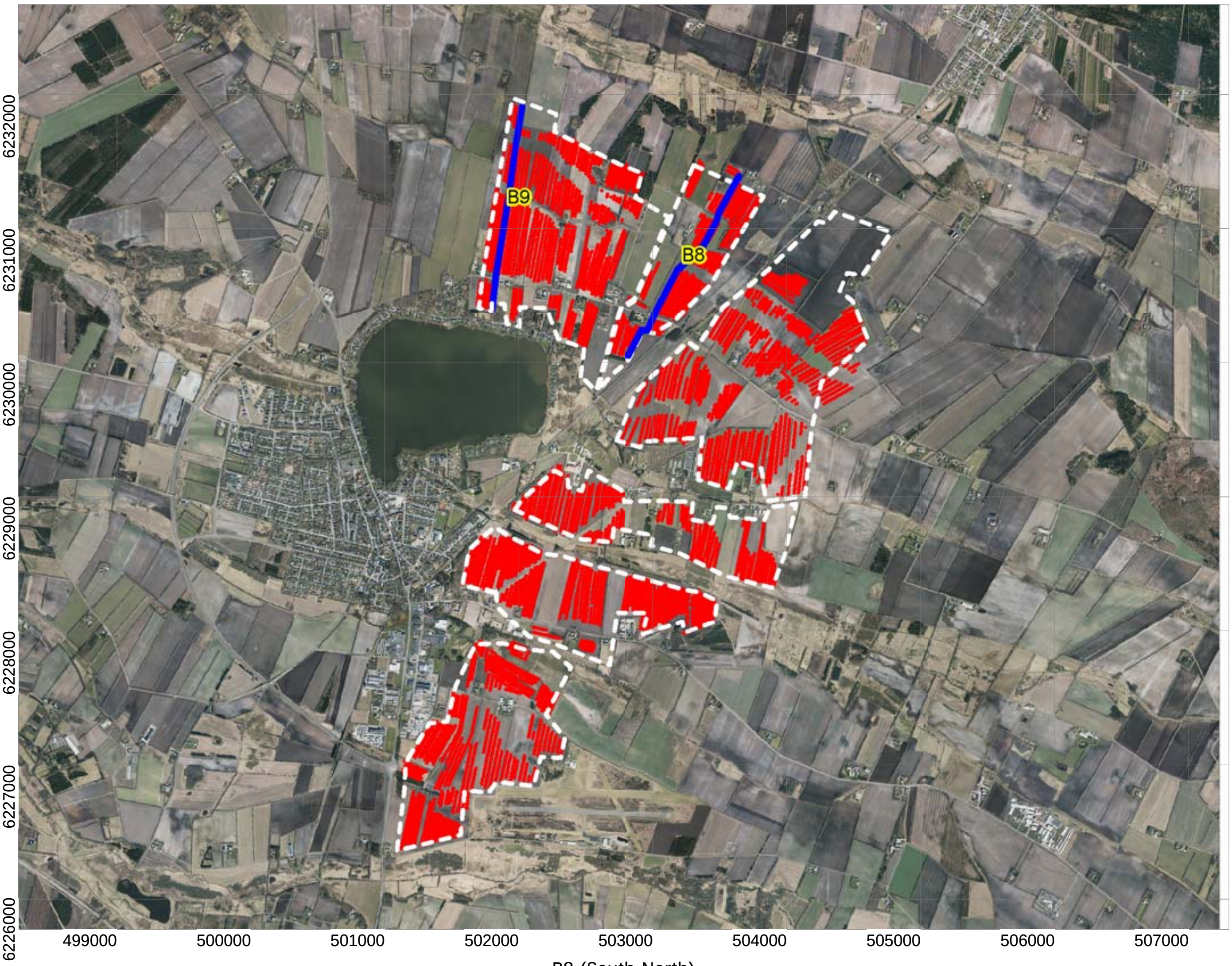
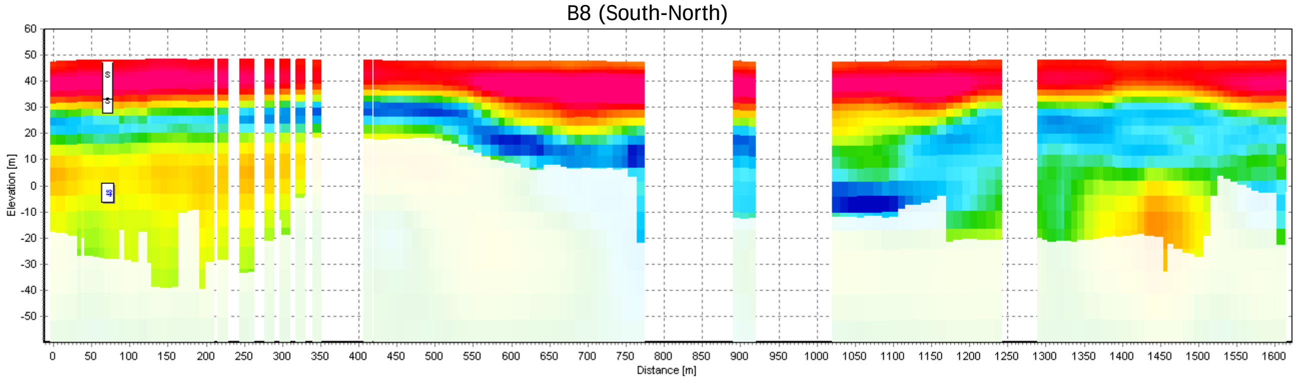


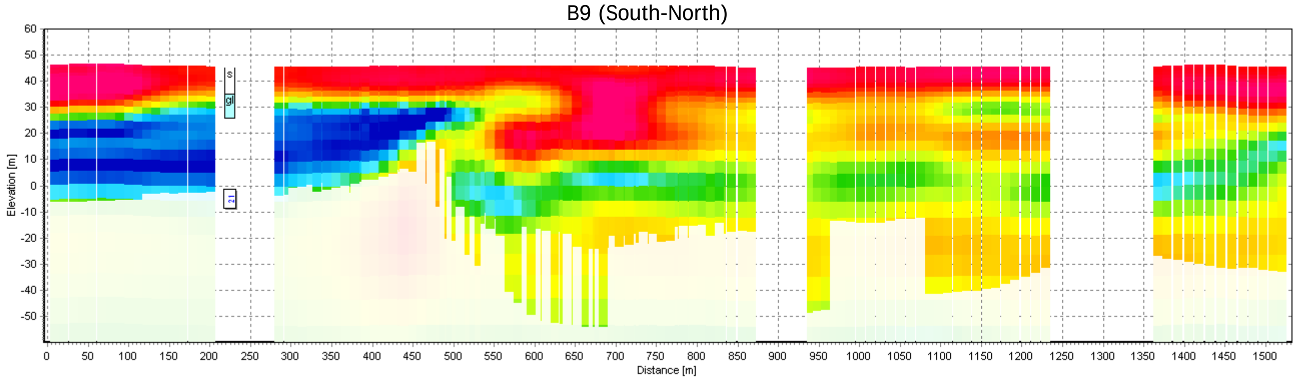
Resistivity Profiles (ohm-m)

Smooth SCI Model

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard







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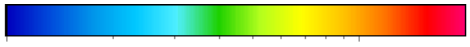
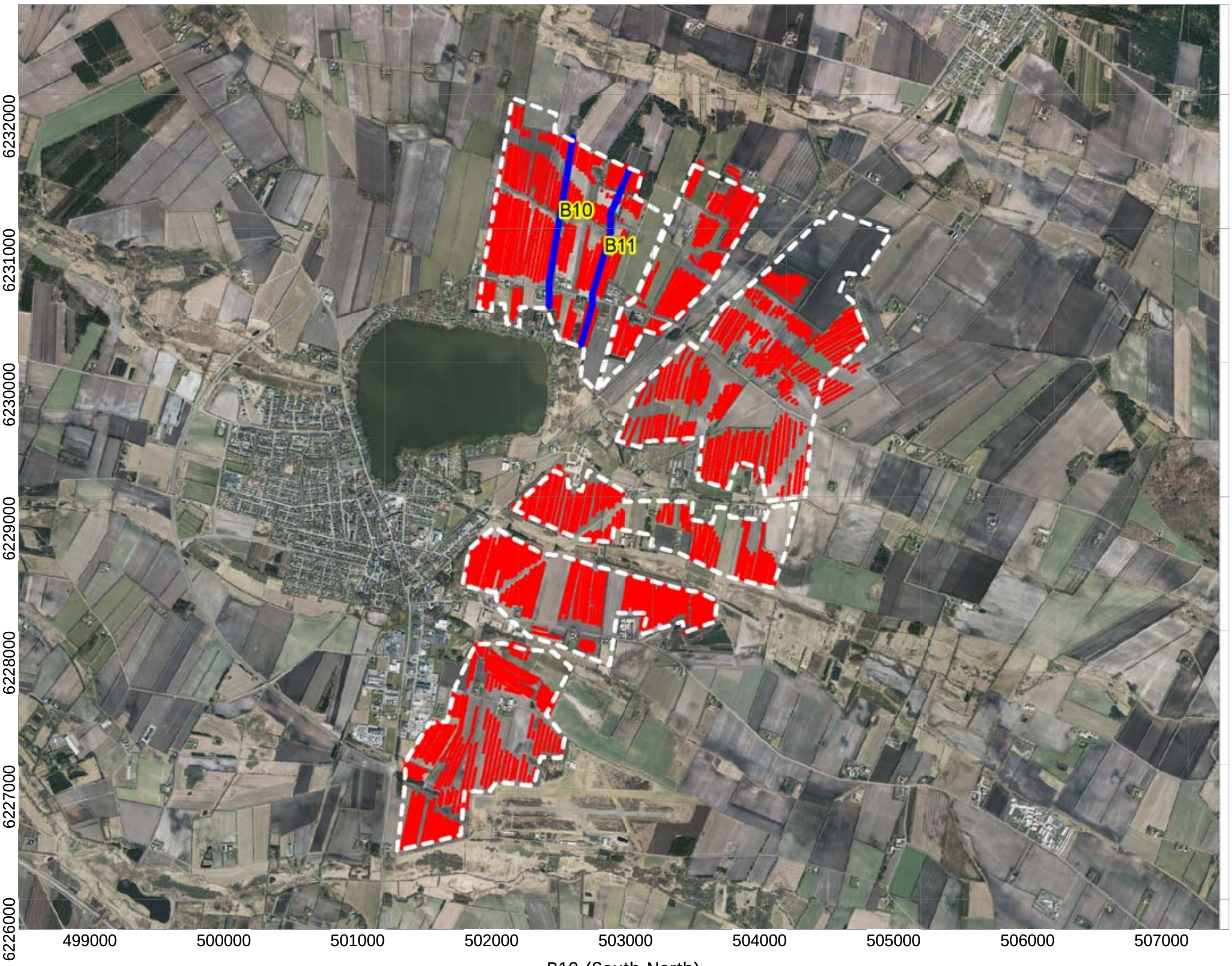


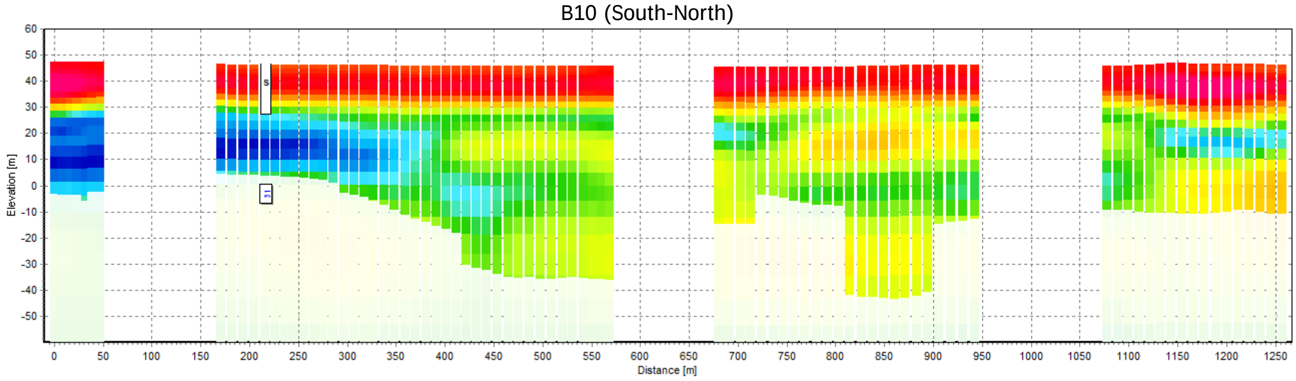
Resistivity Profiles (ohm-m)

Smooth SCI Model

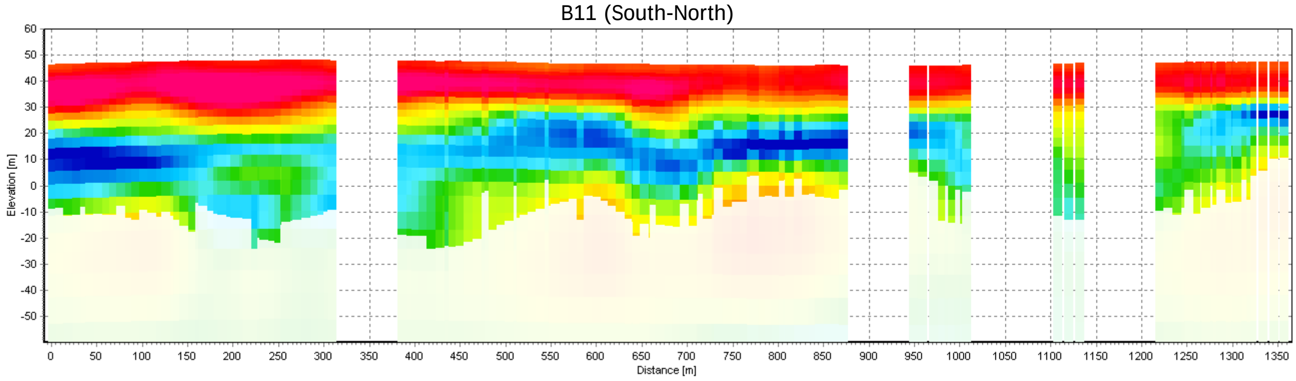
The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard



B10 (South-North)



B11 (South-North)



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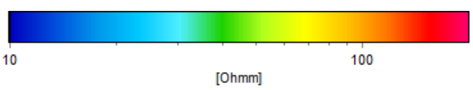

Resistivity Profiles (ohm-m)

Smooth SCI Model

The profiles display model bars from the smooth inversion results
Models have been blanked by 75% below the DOI Standard

APPENDIX III: MEAN RESISTIVITY MAPS

This appendix includes mean resistivity maps generated from the smooth model inversion result in 5 m depth intervals from 0 to 30 m, and in 10 m intervals from 30 to 70 m. The resistivity models have been blanked at the DOI standard value prior to the interpolation to regular mean resistivity grids.

The interpolation of the mean resistivity values is performed by kriging interpolation, with a node spacing of 5 m, a search radius of 50 m, and with additional pixel smoothing.

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10 100
Resistivity [Ohmm]

Mean resistivity map (ohm-m) - Depth 0 - 5 m

SCI Smooth Model - Kriging with search radius 50 m

UTM 32N WGS84

1.5 km

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Mean resistivity map (ohm-m) - Depth 5 - 10 m

SCI Smooth Model - Kriging with search radius 50 m

UTM 32N WGS84

1.5 km

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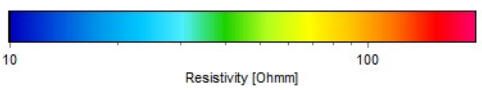
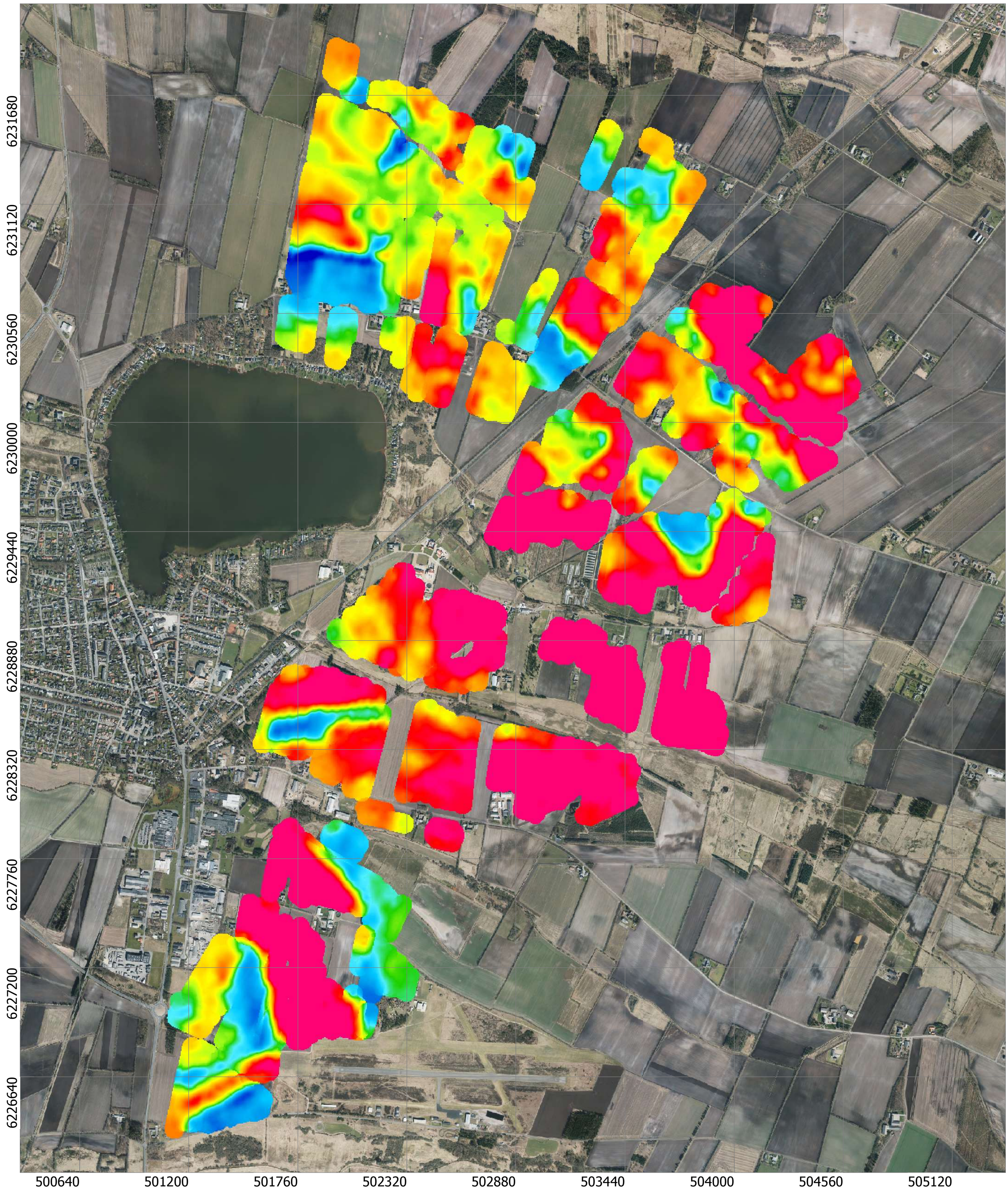
Mean resistivity map (ohm-m) - Depth 10 - 15 m

SCI Smooth Model - Kriging with search radius 50 m



UTM 32N WGS84

1.5 km



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Mean resistivity map (ohm-m) - Depth 15 - 20 m

SCI Smooth Model - Kriging with search radius 50 m

UTM 32N WGS84

10 100

Resistivity [Ohmm]

1.5 km

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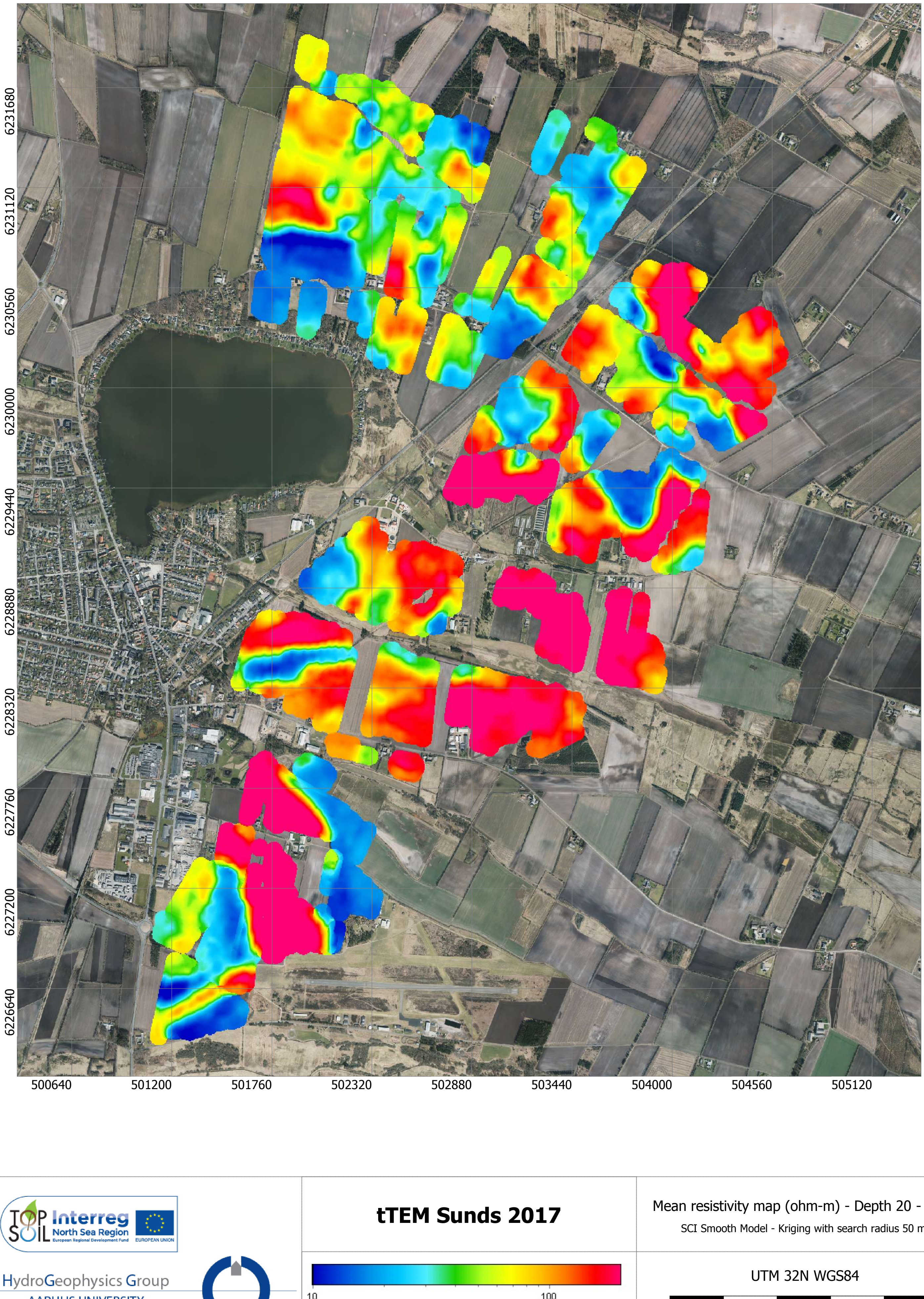

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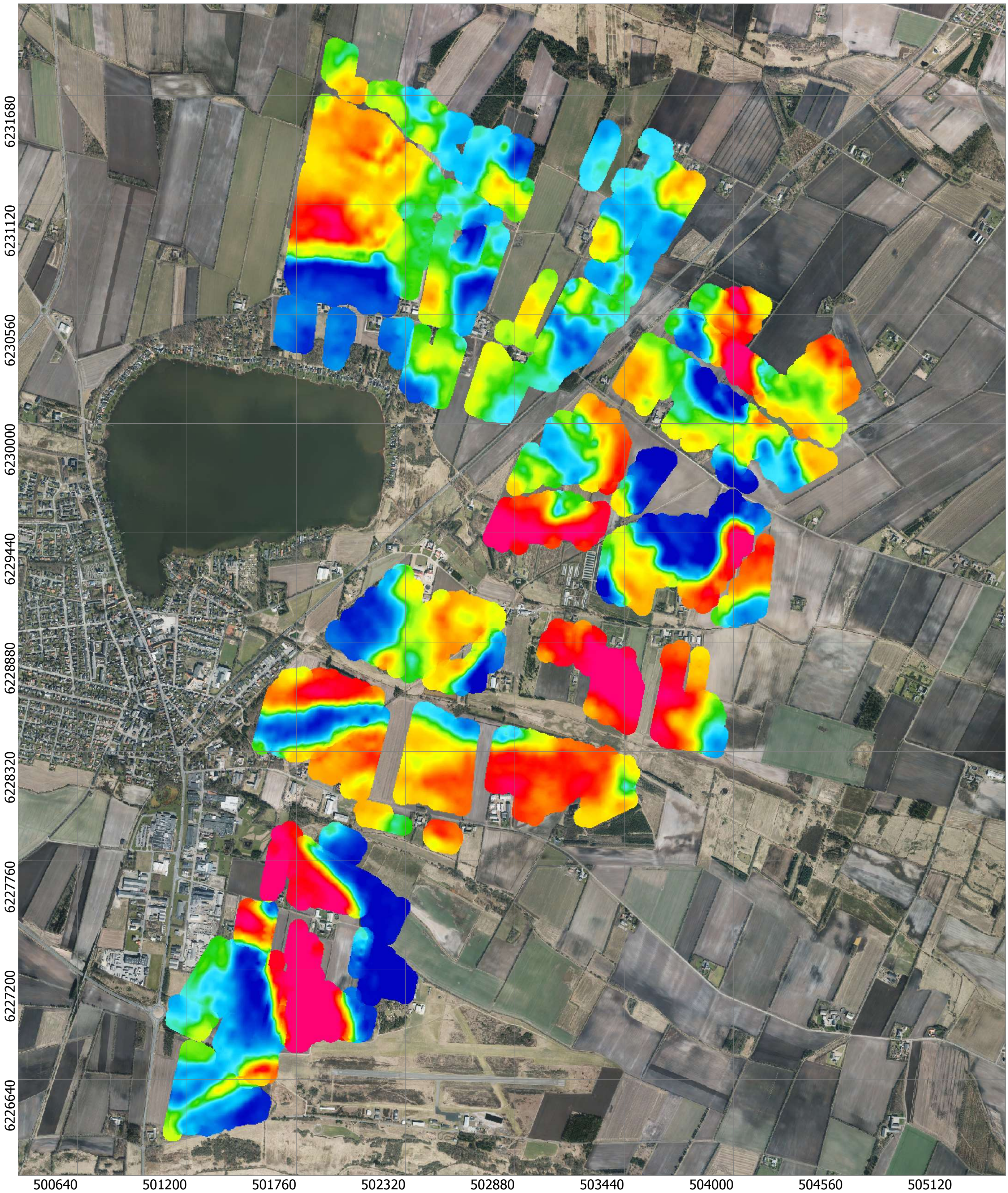
Mean resistivity map (ohm-m) - Depth 20 - 25 m

SCI Smooth Model - Kriging with search radius 50 m

UTM 32N WGS84

1.5 km



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Mean resistivity map (ohm-m) - Depth 25 - 30 m

SCI Smooth Model - Kriging with search radius 50 m

10 100
Resistivity [Ohmm]

UTM 32N WGS84

1.5 km

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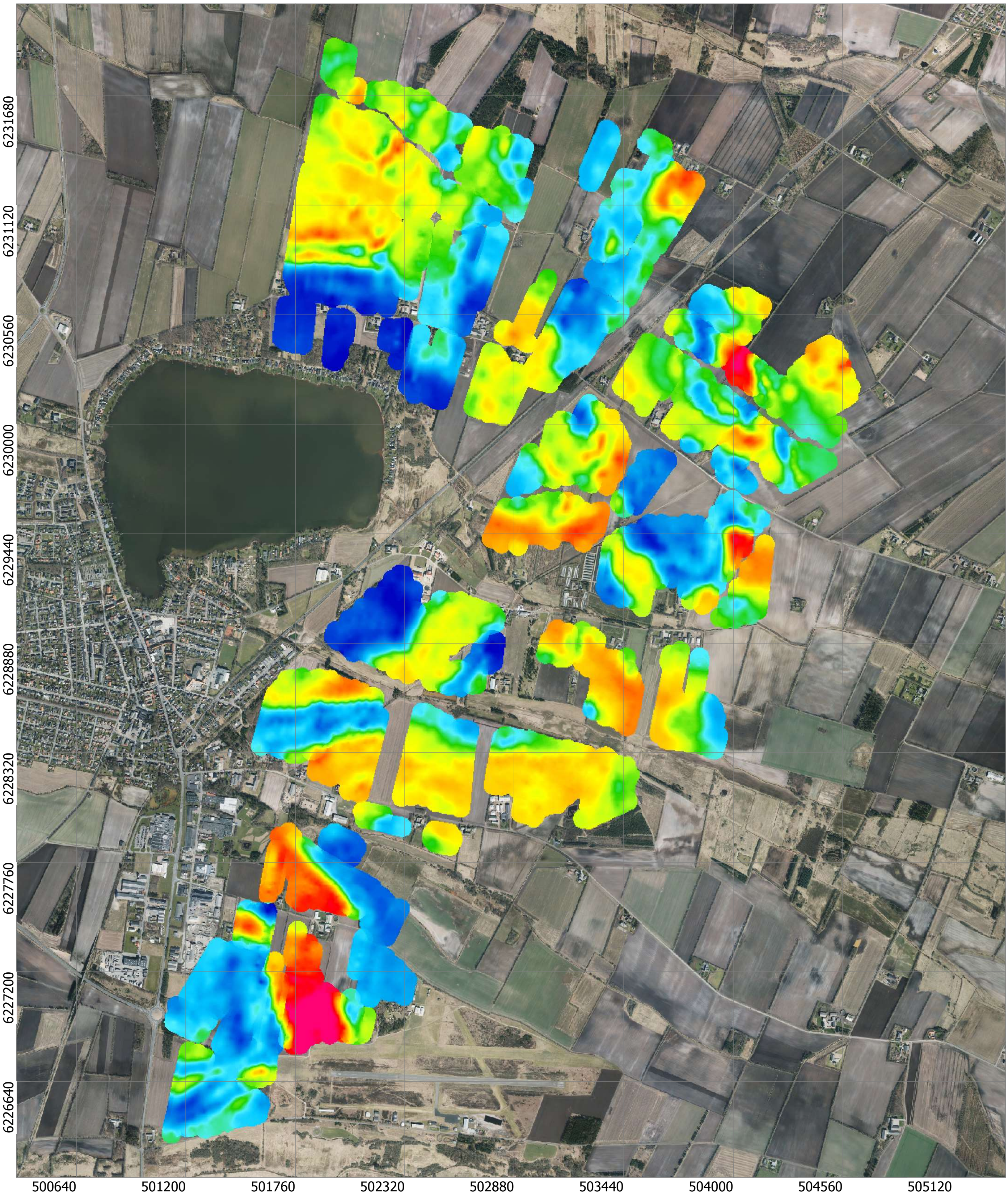

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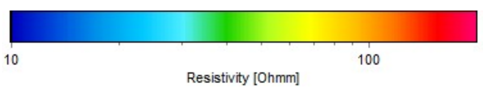
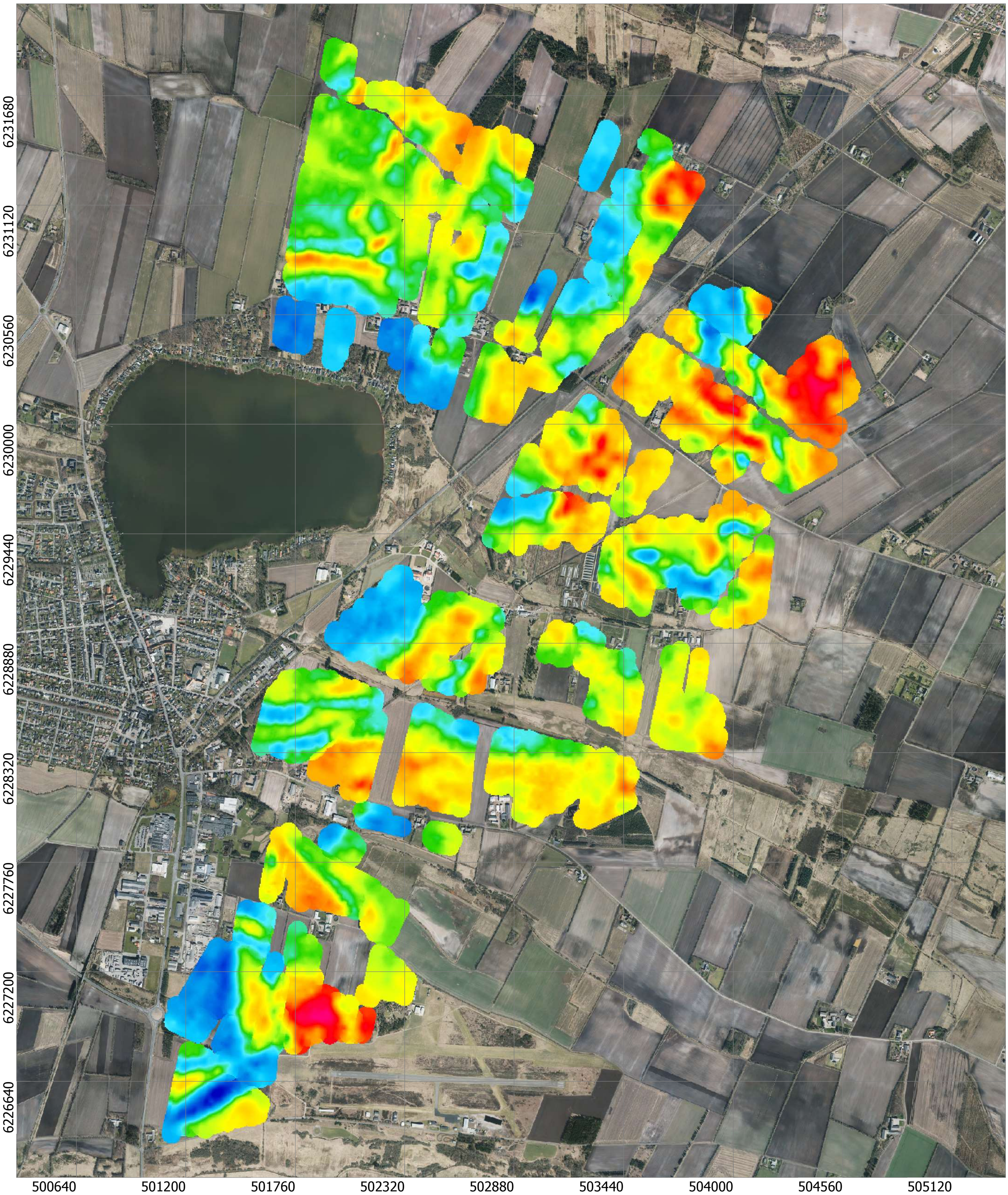
Mean resistivity map (ohm-m) - Depth 30 - 40 m

SCI Smooth Model - Kriging with search radius 50 m



UTM 32N WGS84

1.5 km



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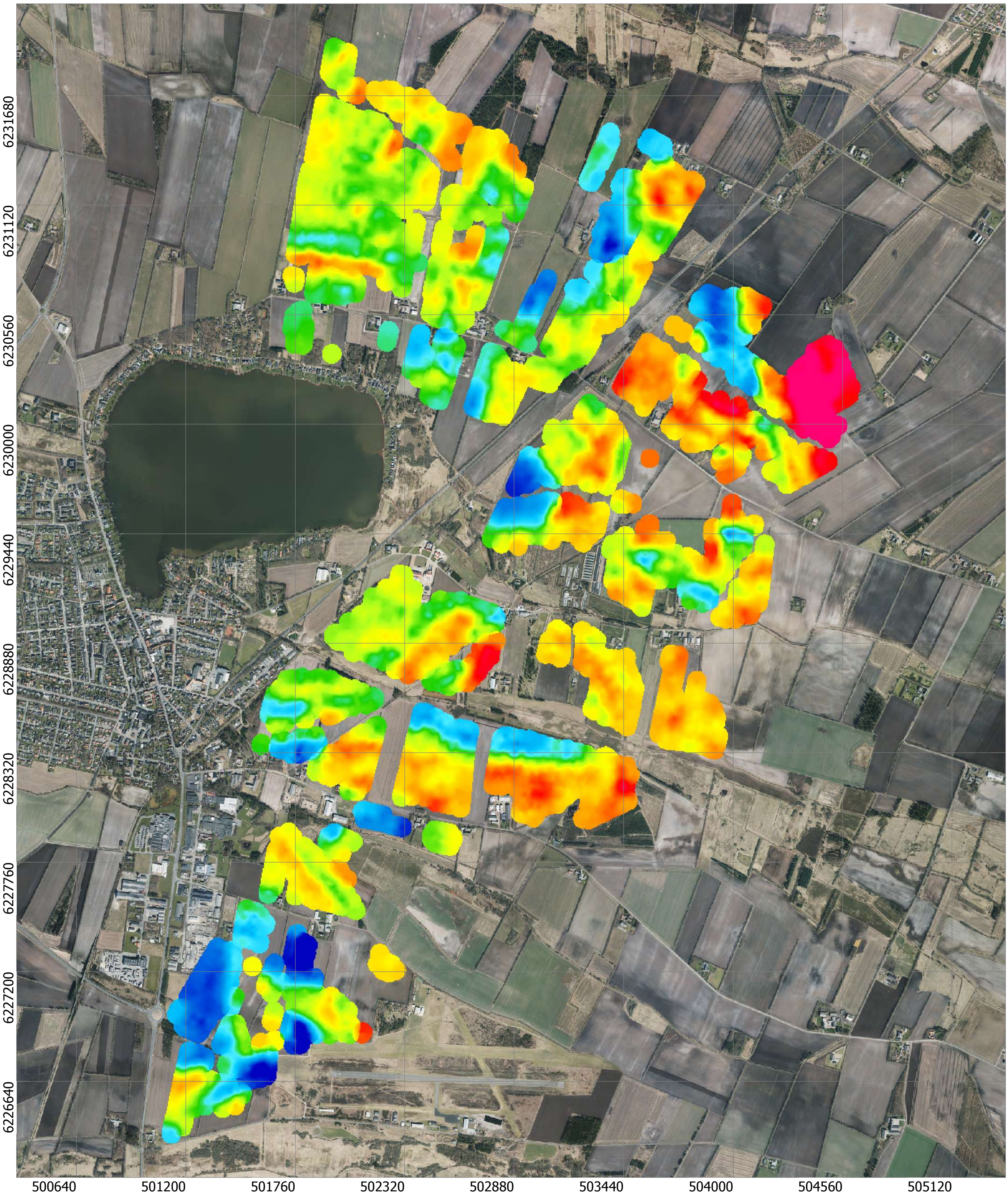
Mean resistivity map (ohm-m) - Depth 40 - 50 m

SCI Smooth Model - Kriging with search radius 50 m

10 100
Resistivity [Ohmm]

UTM 32N WGS84

1.5 km



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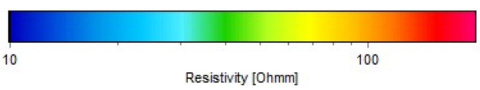
Mean resistivity map (ohm-m) - Depth 50 - 60 m

SCI Smooth Model - Kriging with search radius 50 m



UTM 32N WGS84

1.5 km