Processing and inversion of SkyTEM data

USGS

Area "UTM 14"

1. Introduction

This report is composed on the basis of data delivered by SkyTEM Aps on behalf of USGS, processed and inverted by Aarhus Geophysics Aps. The data is from an airborne electromagnetic geophysical surveys carried out in Nebraska, US, in summer 2010.

This report contains results from a series of flight lines acquired over few days, all located within the UTM 14 reference meridian. Another report contains the results from the flight lines located within UTM 13 zone. The total number of line km processed and inverted is 1890.

Refer to the maps at the beginning of Appendix 1 for a view of the location of the dataset processed.

All coordinates are in NAD 83, UTM 14 unless otherwise stated.

This report has been prepared by Ph.D. Andrea Viezzoli and MSc. Camilla Soerensen from Aarhus Geophysics.

2. The SkyTEM system

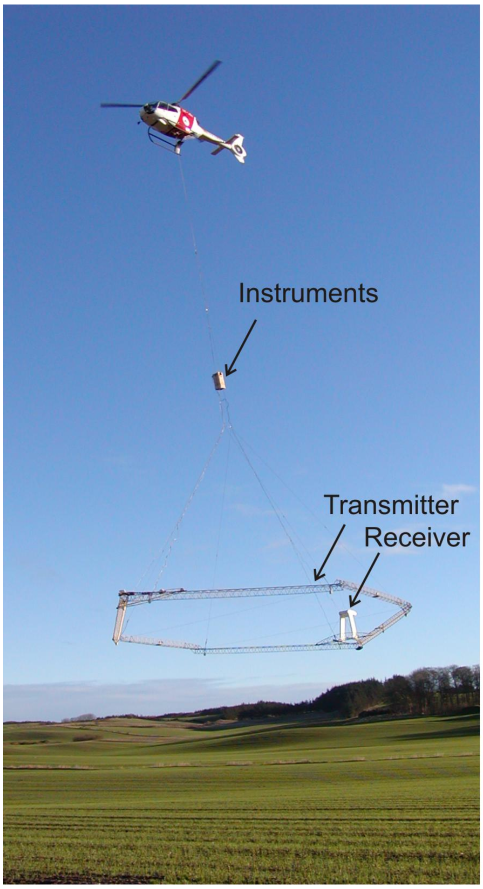


Figure 1 The SkyTEM System

SkyTEM is a time-domain helicopter electromagnetic system designed for hydrogeophysical, environmental and mineral investigations. The system is shown in operation in Figure 1. The SkyTEM system is carried as an external sling load independent of the helicopter. The transmitter, mounted on a lightweight wooden lattice frame in an eight-sided polygon configuration, is a four-turn 314 m^2 eight-sided loop divided into segments for transmitting a super low moment (SLM) in one turn and a high moment (HM) in all four turns. The LM is about 10 A with a turn-off time of about 4 μs; the HM transmits approximately 100 A and has a turn-off time of about 53.0 μs. This yields a maximum magnetic moment of approximately 120000 Am^2.

The z-component receiver loop is placed approximately 2 m above the frame in what is practically a central loop configuration with a vertical offset. Two lasers placed on the frame measure the distance to terrain continuously and an inclinometer measures the tilt of the frame. Power is supplied by a generator placed between the helicopter and the frame.

Measurements are carried out continuously while flying. Every single transient is stored in a binary format, and pre-stacked. The stack size is LM = 160 transients/stack and HM = 64 transients/stack. Measurements cover the time span of 11 µs to approx. 8.84 ms.

Apart from GPS-, altitude- and TEM data, a number of instrument parameters are monitored and stored digitally so that they can be used for quality control when processing the data.

3. Processing

The aim of processing is to prepare data for the data inversion. This includes data import, data corrections, filtering and culling and discarding of distorted or noise-filled data. The data left are then averaged spatially using trapezoid filters of the optimum size that allows increasing signal to noise level without compromising lateral resolution. The processing is done using the SkyTEM module if the Aarhus Workbench program package. All data are marked with a time stamp which is the key to bind information about current, altitude, GPS coordinates etc. During the processing a running mean is calculated separately for the X- and Y direction tilt data while algorithms are used to automatically filter out bad altitude data - typically reflections from tree or bush tops.

In this survey, the first usable time gate used for the low moment is around 11 us after TX has started to ramp down. Comparisons with high altitude tests prove that data from this gate are surely unbiased in the vast majority of the area. The first usable gate for the high moment is no earlier than 144 us after ramp down.

The processing of voltage data is done in a two step system: an automatic and a manual. In the former data is corrected for the transmitter/receiver tilt and a number of filters designed to cull coupled or noise influenced data is deployed.

After that automatic processed raw soundings are inspected visually using a number of different data plots. At this stage it is accessed whether the filters have removed the right amount of data coupled to man made infrastructures. It usually necessary to intervene manually to fine tune the outcome of the filters and obtain the most reliable results. Figure 2 shows a view of the data processing module of the Aarhus workbench, over a section of SkyTEM data from another survey, with data culled due to coupling with man made structures.

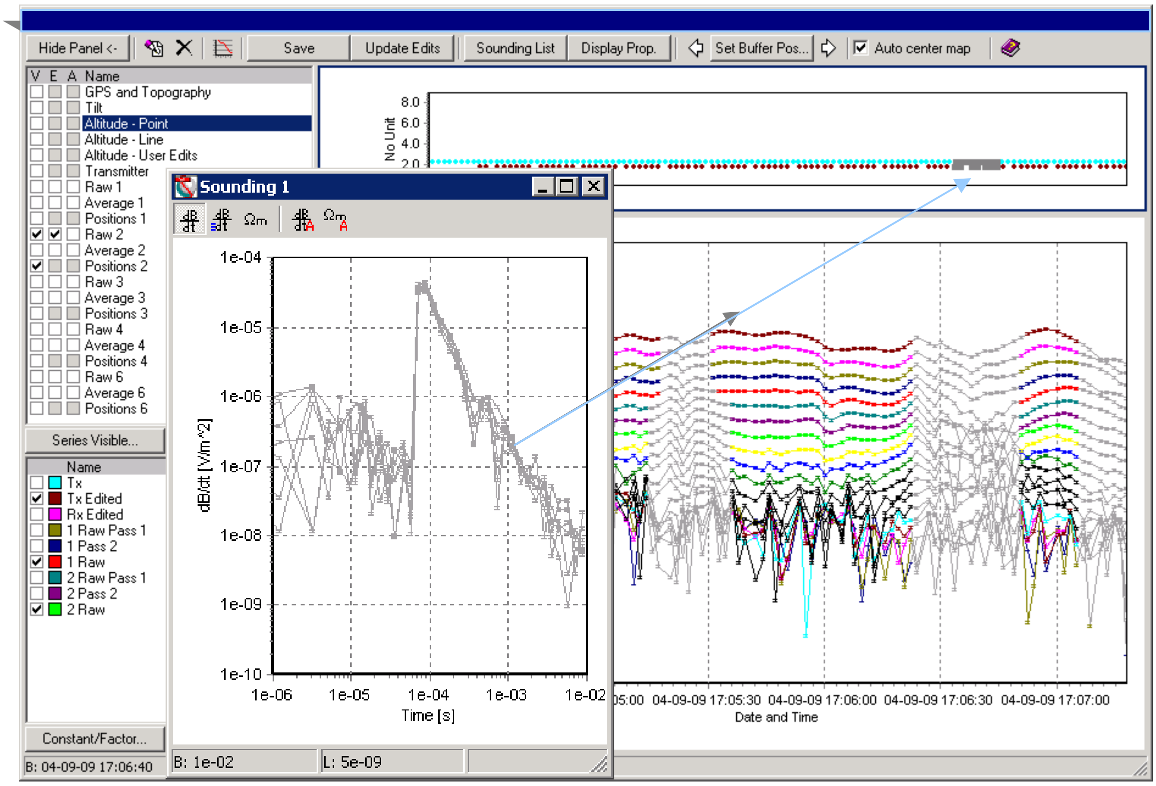


Figure 2 The data processing window of the Aarhus Workbench, showing portions of data deleted because of coupling with man made structures. The insert shows the corresponding transient in dB/dT.

Data are then averaged to increase the signal to noise ratio data using a trapezoid shaped averaging core, where the averaging width of late time data is larger than that of early time data, as seen in Figure 3.

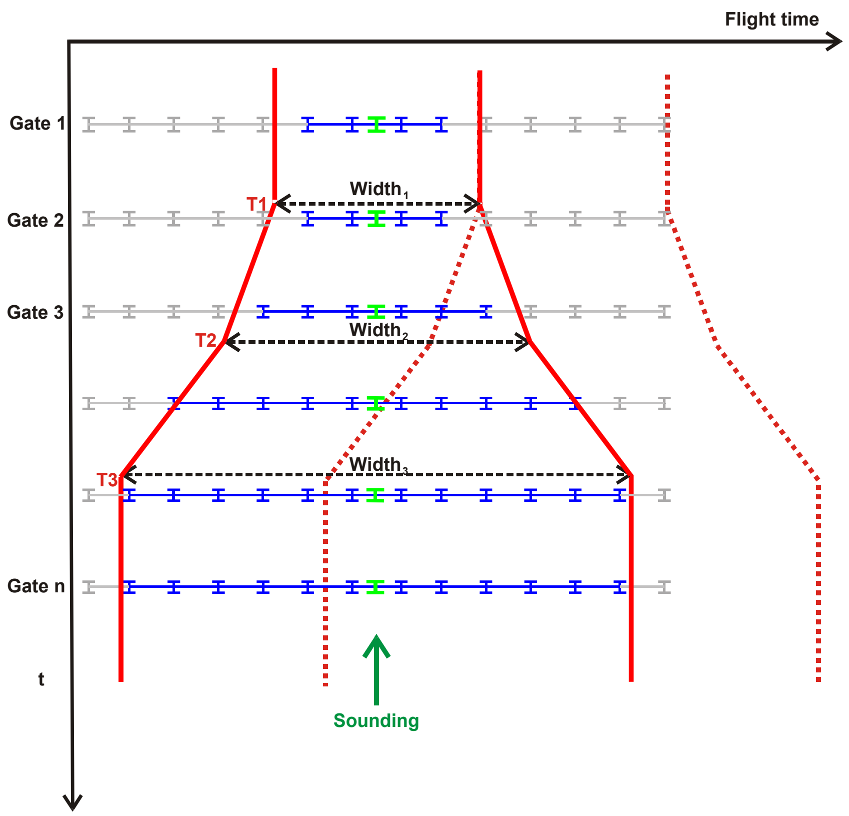


Figure 3 The principle behind the trapezoid shaped averaging core where data are averaged over larger time spans at later times to maintain as much lateral resolution as possible at early times while keeping a high penetration depth.

The data uncertainty for these stacked (averaged) soundings is calculated from the data stack. Furthermore, a minimum small uniform data uncertainty is assigned to all data. This uncertainty has been set to 3%.

Soundings were taken out for every 1.4 s corresponding to approximately 30 m. The good signal levels at early times recorded in large portions of the survey, which are due to general low resistivity of the near surface layers, allowed to use filters as narrow as 2 s at 11 us. Their width then it increases with depth reaching 30 s at 10 ms. This corresponds roughly to averaging a stack of 40 m at surface, and about 600 m at 10 ms.

After the automatic stacking, soundings are inspected visually using a number of different data plots. At this stage it is accessed whether data points at late times should be ascribed a higher uncertainty or removed entirely. It is custom to cull data when the background noise level reaches the level of the earth response. Assessing when data is unusable is done by looking at the decay curves, the noise measurements, and the distance to potential noise sources. This process is necessary to gain reliable model parameters in all parts of the data sections.

4. Inversion

Inversions are carried out using the quasi 3-D Spatially Constrained Inversion (SCI). SCI is a full non-linear damped least squares solution in which the transfer function of the instrumentation is modelled. This includes, among the others, current turn-on and -off ramps, and front gate, low pass filters system altitude, etc…

In the SCI scheme the model parameters are tied together spatially with a spatially dependent covariance which is scaled according to the distance between neighbouring models. Constraining the parameters tends to enhance the resolution of resistivities and layer interfaces which are not well resolved in an independent inversion of the soundings. The flight altitude is included as an inversion parameter with a prior value calculated form the tilt corrected laser altitudes. The absolute error on this parameter is set to 3 m.

The SCI inversion scheme is developed for parameterized inversion with normally 4 layers or 5 layers and smooth inversion with e.g. 19 layers each having a fixed thickness, but a free resistivity (with vertical constraints). Both schemes have advantages. Layer interfaces, resistivities and the depth of penetration are best determined from the parameterized inversion. On the other hand, smooth inversion is more independent of the starting model and gradual transitions in resistivities are more conspicuous facilitating the delineation of complex geological structures. Inversion and inversion evaluation is done using the Aarhus Workbench program package. The vertical constraints used in the smooth models are applied to stabilize the inversion, e.g. to remove fictitious layers especially in models based on few data points. No a priori constraints on layers parameters have been used. The inversion was started with a homogeneous half space where the resistivity was calculated from the mean apparent resistivity of the sounding. The underlying inversion code is developed by the HydroGeophysics Group, University of Aarhus, Denmark.

The smooth model uses fixed thickness discretized with 19 layers, but free resistivities. Again the resistivities were scaled according to apparent resistivity. Using smooth models enhances complex geological structures and are as such a powerful tool evaluating the complexity of the subsurface. The smooth model was discretized down to about 260m, with layers of logarithmically increasing thickness, starting from 3m. The inversion was started with a homogeneous half space of 50 Ohm m.

Based on the analysis of the results of the smooth models inversion, and on multiple tests with different number of layers, we chose to present results from a 5 layers model. We use a conservative approach, having the least number of layers that fit the data for the entire survey satisfactorily. This ensures maximum sensitivity of each one of the model parameters modelled to the data, and therefore maximum reliability of the models. Also the few layers inversion was started with a homogeneous half space of 50 Ohm m. There seems to be a noticeable systematic difference in the thickness of the geoelectrical layers between the North Eastern portion of this survey area and the South Westerly one. Therefore, the 5 layers inversion required a further selective fine tuning in the starting thickness of the layers in order to achieve a better data fit and imaging of the subsurface throughout the area. The depth of investigation (DOI), based on an analysis of the Jacobian matrix, was also calculated for the output models. This DOI, is presented in a dedicated horizontal map, as well as superimposed to mask to average resistivity horizontal maps, and as a line superimposed to the vertical cross sections. The DOI represents the maximum depth below surface to which there is sensitivity to the model parameters. Any model parameter resting much below the DOI should be disregarded. For example, the DOI often rests at, or close to, an interface between a conductive overburden and a resistive deeper layer. In this case we can conclude that the conductive layer does end at that interface, and it rests above a significantly more resistive layer, whose absolute resistive value is poorly determined.

Both in the smooth and few layered inversion the data fit is very good, with large majority of the forward responses fitting the measured data well below noise levels.

In the Appendix A1 we present a number of QC geo-referenced maps of inversion results.

5. General comments on the data quality, processing and inversion result

The signal level in the survey area is rather variable, reflecting the significant geological variability. The client could not provide the requested ancillary information about infrastructures that would have been greatly beneficial during the data processing and inversion evaluation steps. Even though the satellite images show a small amount of infrastructures, it is obvious from the data that, in certain areas, there are many more. Together with the level of 3D variations in the area, these factors made the processing particularly delicate. It was necessary to fine tune the data culling and data stacking a number of times, referring also to result of preliminary inversions, before achieving an optimum results that balanced lateral resolution, depth of penetration, area coverage and output models not obviously affected by artifacts.

6. Geophysical thematic maps and sections

To visualize the resistivity structures in the survey area, a number of geophysical theme maps and vertical sections have been made using the Aarhus Workbench. In both cases the last layer has been drawn down to 30 % more of the depth of the interface with the previous layer (e.g., if the last layer starts at depth 100 m, it is drawn down to 130 m). This practice is purely for display purposes, as the model carries no information regarding the thickness of the last layer, but only about its resistivity. The information about the depth of investigation is given by the DOI line and greyed out areas.

Theme maps include maps of QC of results of inversion and maps of the horizontal mean resistivity in the area. They are both based on the parameterized few layered inversions. The QC maps (satellite images and GIS layers, data input for processing and for inversion, data fit or residual, depth of investigation, number of gates used for inversion) allow to asses the output results from numerical point of view. The QC maps open Appendix 1.

The QC map number 1, named *Location of processed data* shows the difference between the TEM soundings that entered the processing, and those that where used for the inversion, after the processing, superimposed to satellite images and GIS layers of infrastructures. It is useful to appreciate how much of the EM data was culled during the processing due to coupling with infrastructure.

The QC map number 2, named *Total number of gates used in the inversion* shows, colour-coded, the sum of time gates from LM and HM used for the inversion of individual soundings. The maximum number of gates possible in this case, if there had been no noise on any of them, was 41 gates. However, when the averaged late time gates fall into noise and contain no signal, they are deleted and do not enter the inversion in order not to produce artefacts in the output models. Also galvanic coupling can affect some of the late times of both moments, which are deleted. Hence the spatial variability of this map.

The QC map number 3, named *Data residual normalized to noise,* shows, colour-coded, the spatial variation of the absolute value of the misfit between forward modelled data and measured data, normalized to the data noise for each time gate. Values lower than 1 mean that the modelled data fit the measured one within noise level, i.e., that the inversion fitted the data. Values higher than one can be due either to 3D effects, or to noisier data.

The QC map number 4, named *Depth of Investigation,* shows, colour-coded the spatial variability of the model-dependent DOI. Refer to section 4 for a detailed discussion on the DOI. The colourscale maximum is only indicative, and does not imply that that value was expected to be reached in the entire area.

The QC map number 5, named *Location of profiles* allows to locate the geographical position of the vertical cross section, or profiles, presented in Appendix 2.

Generally speaking the horizontal mean resistivity is the average of the inverse of the model conductivity. Mean resistivity maps showing the horizontal mean resistivity have been made in depth below ground level (b.g.l) at intervals of 5m and 10 m near surface, and then 20 m. These maps have been made using the Kriging method with a search radius of 500 m and 100 m node spacing, which were the smoothed to 10 m to 20 m per pixel . The average resistivity maps are grouped in Appendix 1 after the QC maps.

A number of vertical cross sections (see Appendix 2) are also shown in the report. Refer to Appendix 1 for their location. A copy showing smooth models (19 layers) and one showing parameterized models (5 layers) are found along with the colour scale. The cross sections are in elevation (m above sea level). Please note the different horizontal and vertical scales of the sections. The colour scale for both average resistivity maps and vertical cross sections is a rainbow colour scale with blue as conductive and red as resistive. Note that the colourscale used was capped to 10 Ohm m on one side and 200 Ohm m on the other upon request of the client.

Like for the average resistivity maps, the last layer has been drawn down to 30 % more of the depth of the interface with the previous layer. The DOI is presented as a thick black line. It should be regarded as an indication of the depth below which there is no sensitivity to the model parameters. See previous section for more thorough discussion on the DOI.

7. The workspace tree

The workspace tree of the Aarhus Workbench holds the inversion results, the sections and the theme maps. The following gives an overview of the structure. Information on node properties is available in the note field of the Workspace Manager when nodes are selected.

The GERDA node holds the databases with the models and the raw and processed data along with the inversion results for all 3 areas,.

The following is found under the Map node "Eastern areas":

Sky nodes "Aeras UTM14": Hold the link to the data set with the processed SkyTEM data in the database.

Pro: contains the profiles already drawn. More profiles can be prepared copying the layers from any of the preexisting ones (master profiles).

SCI nodes contain the different inversion results, which can be inspected, together with data and forward responses. The XYZ files delivered were exported form these nodes.

Q_5L_S_W: holds a database query (DBQ) of the inversion results from the few layered inversion, for the south western area. Lower nodes contain the average resistivity maps at different elevation and depth intervals. Data have been gridded and colour contoured.

Q_5L_N_E: holds a database query (DBQ) of the inversion results from the few layered inversion, for the north eastern area. Lower nodes contain the average resistivity maps at different elevation and depth intervals. Data have been gridded and colour contoured.

VIS nodes: contain the QC maps relative to the results of the SCI inversions

General functions of the Aarhus Workbench are described by accessing the online help (press F1) of the program.

A. Appendix 1

The next pages contain the location of the flight lines and profiles, the inversion QC maps, the average resistivity maps at different depth intervals (m bgl). The DOI is indicated as grey surface superimposed to the maps, for the different depth intervals.

Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Location of sample points

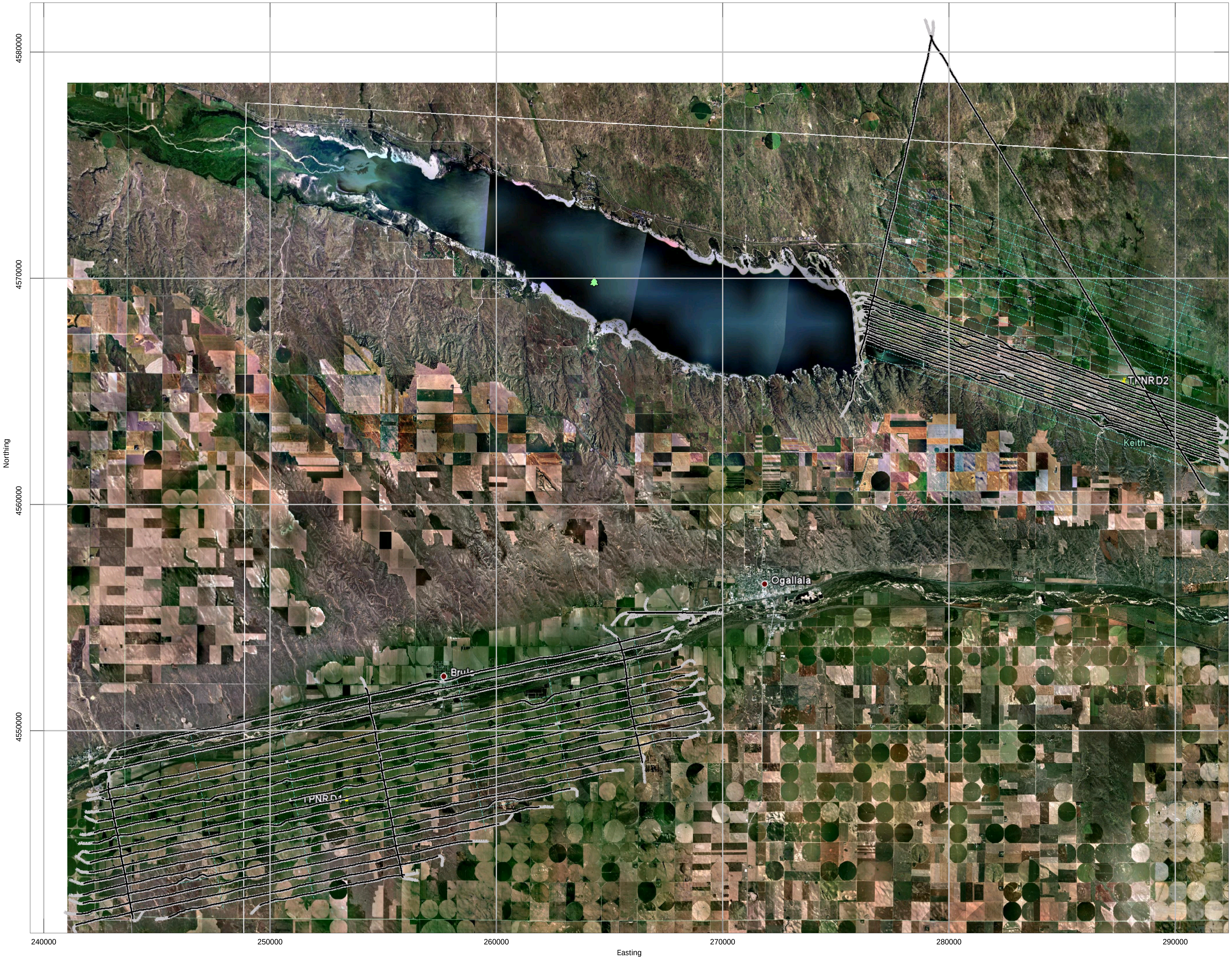
Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey represents flights lines
Black represents inverted data points

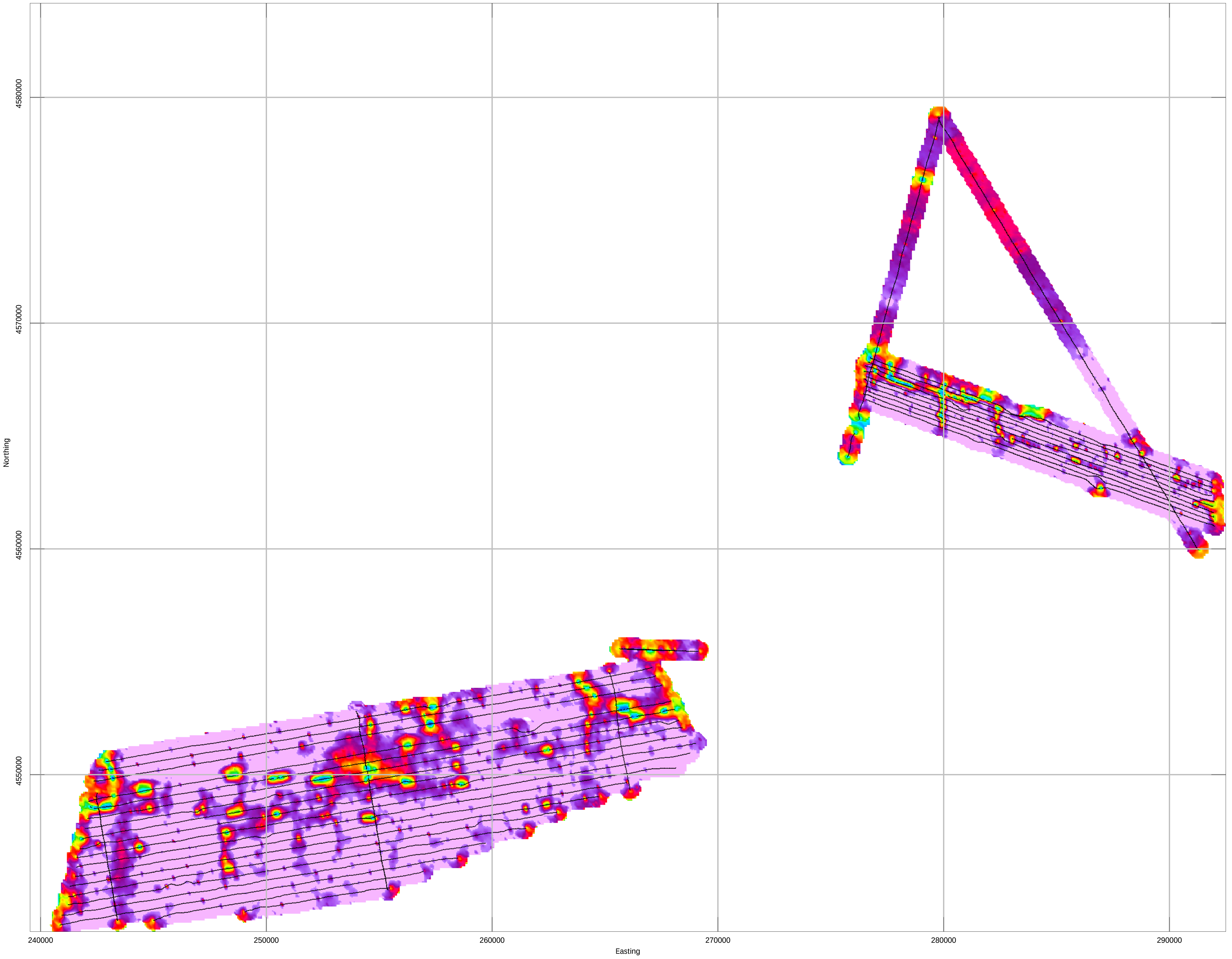
6 km

Inversion results



Aarhus Geophysics

Inversion results



USGS SkyTEM survey

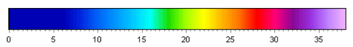
Maps based on result of 5L SCI

Number of data points

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

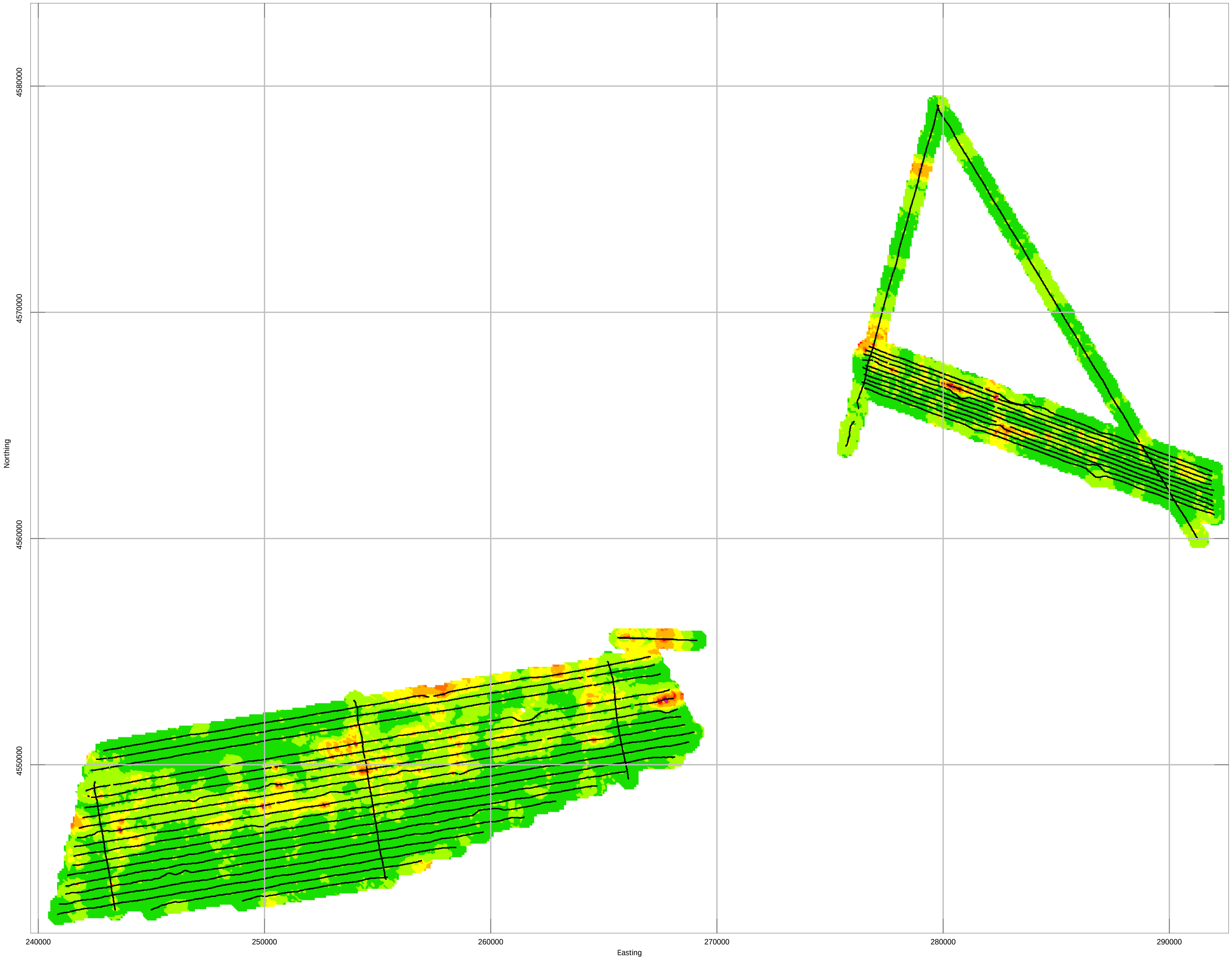


Data points

6 km

Aarhus Geophysics

Inversion results



USGS SkyTEM survey

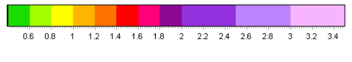
Maps based on result of 5L SCI

Data residual

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



RESIDUAL

6 km

Aarhus Geophysics

USGS SkyTEM survey

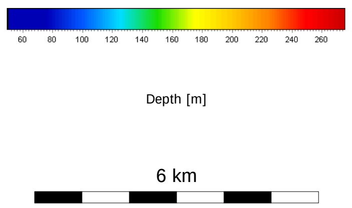
Maps based on result of 5L SCI

Depth of investigation (DOI)

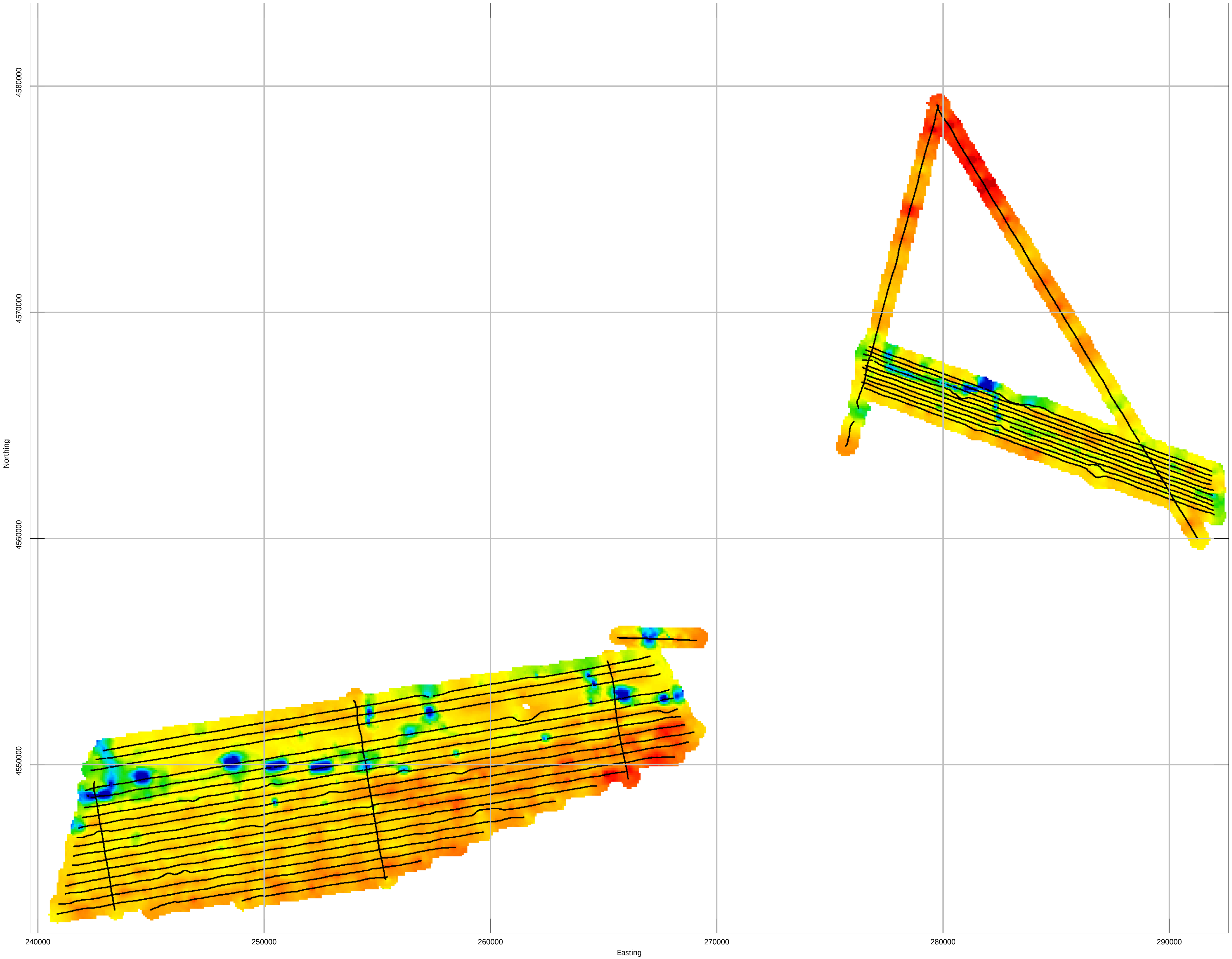
Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Location of profiles

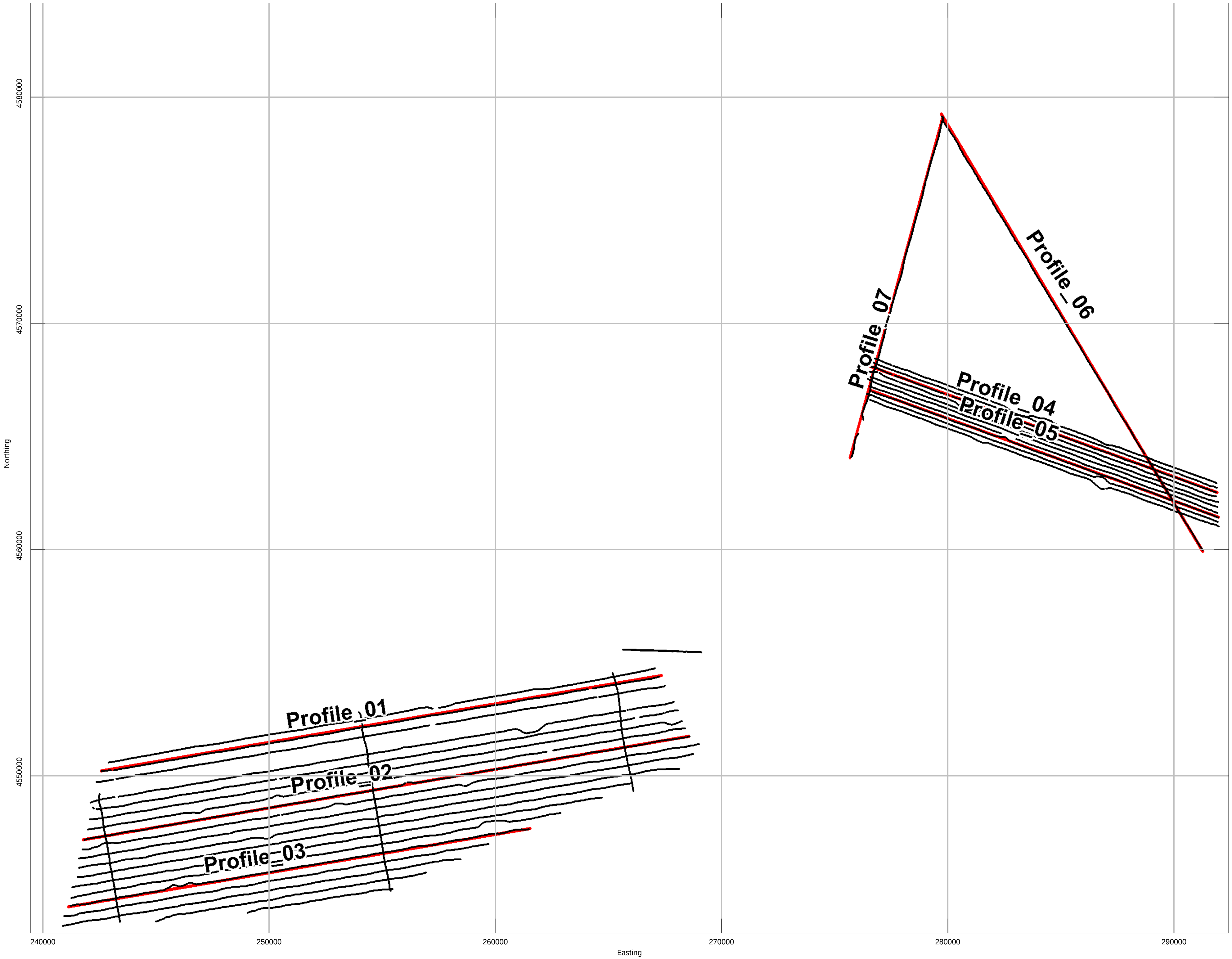
Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

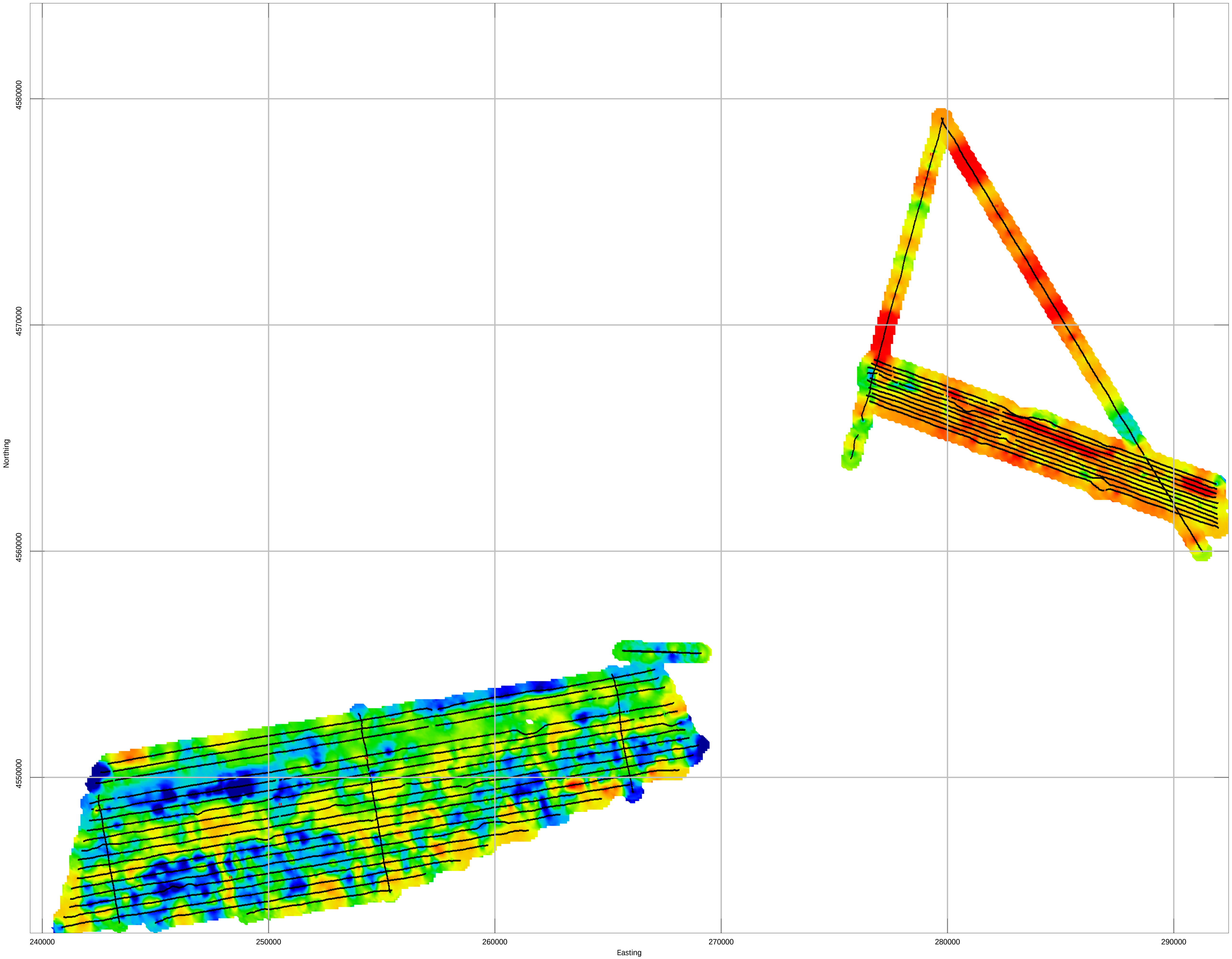
6 km

Inversion results



Aarhus Geophysics

Inversion results



USGS SkyTEM survey

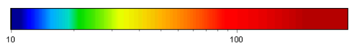
Maps based on result of 5L SCI

Avg. res. 0-5m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



Resistivity (ohmm)

6 km

Aarhus Geophysics

Inversion results

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 5-10m bgl

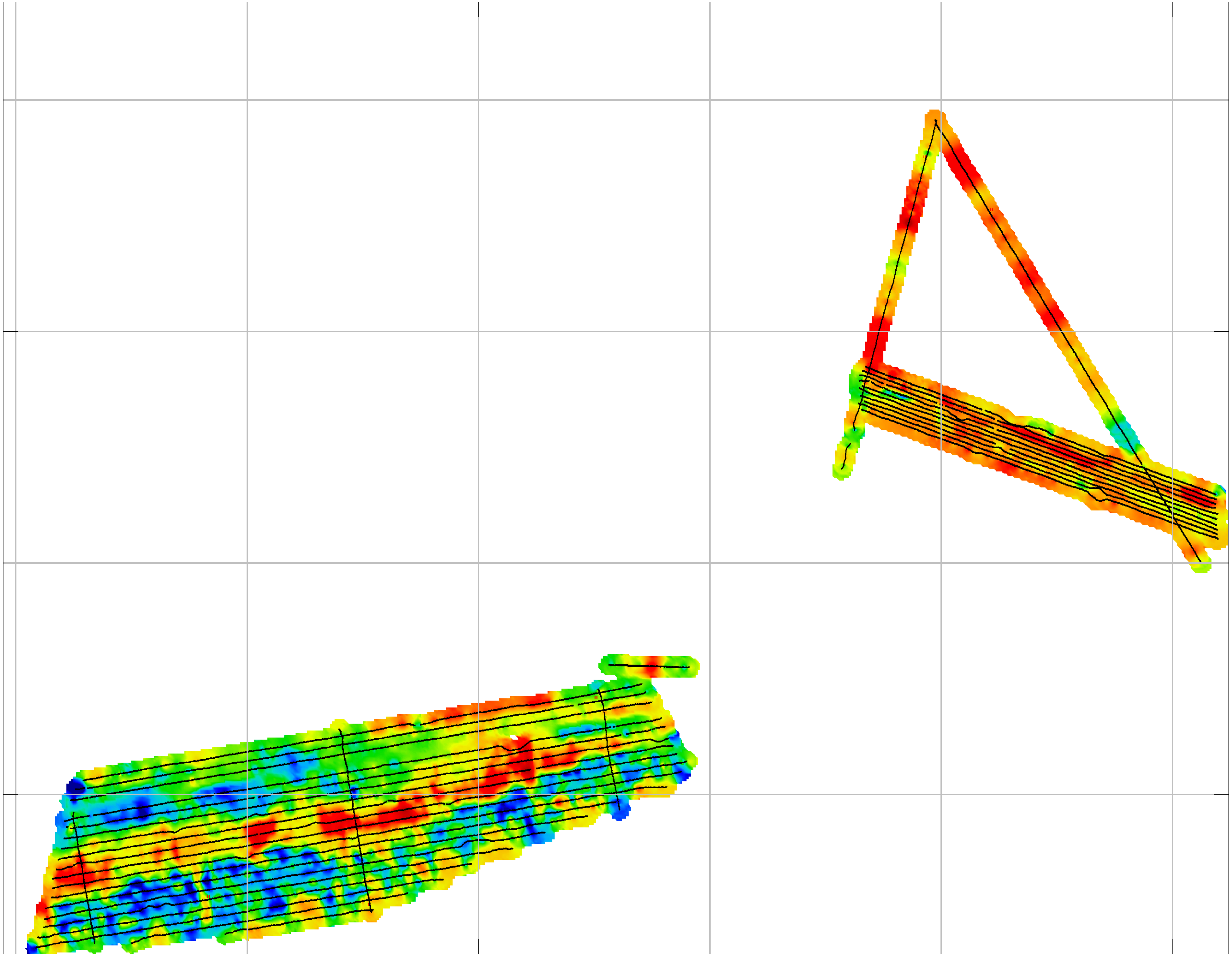
Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

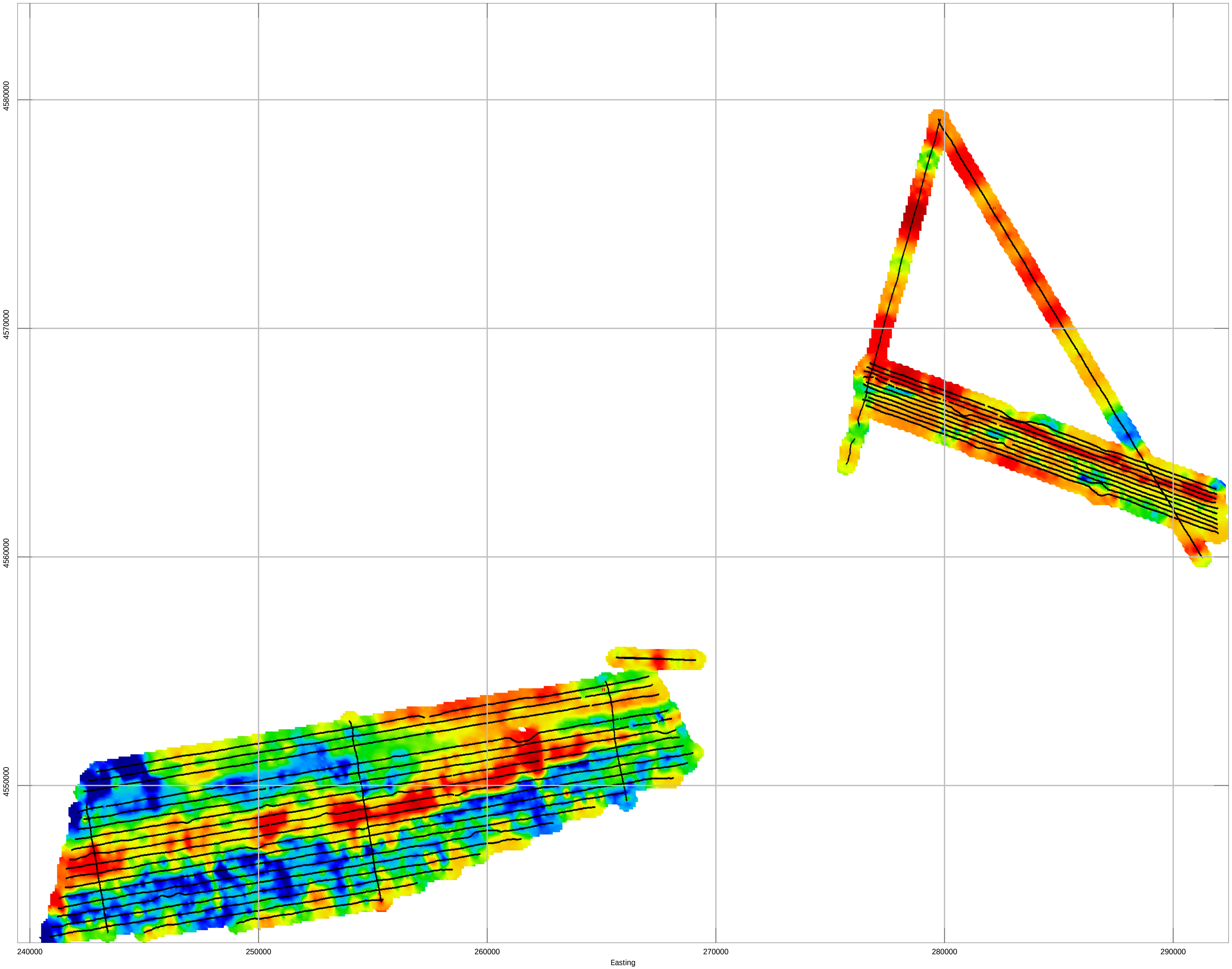
Resistivity (ohmm)

6 km



Aarhus Geophysics

Inversion results



USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 10-15m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

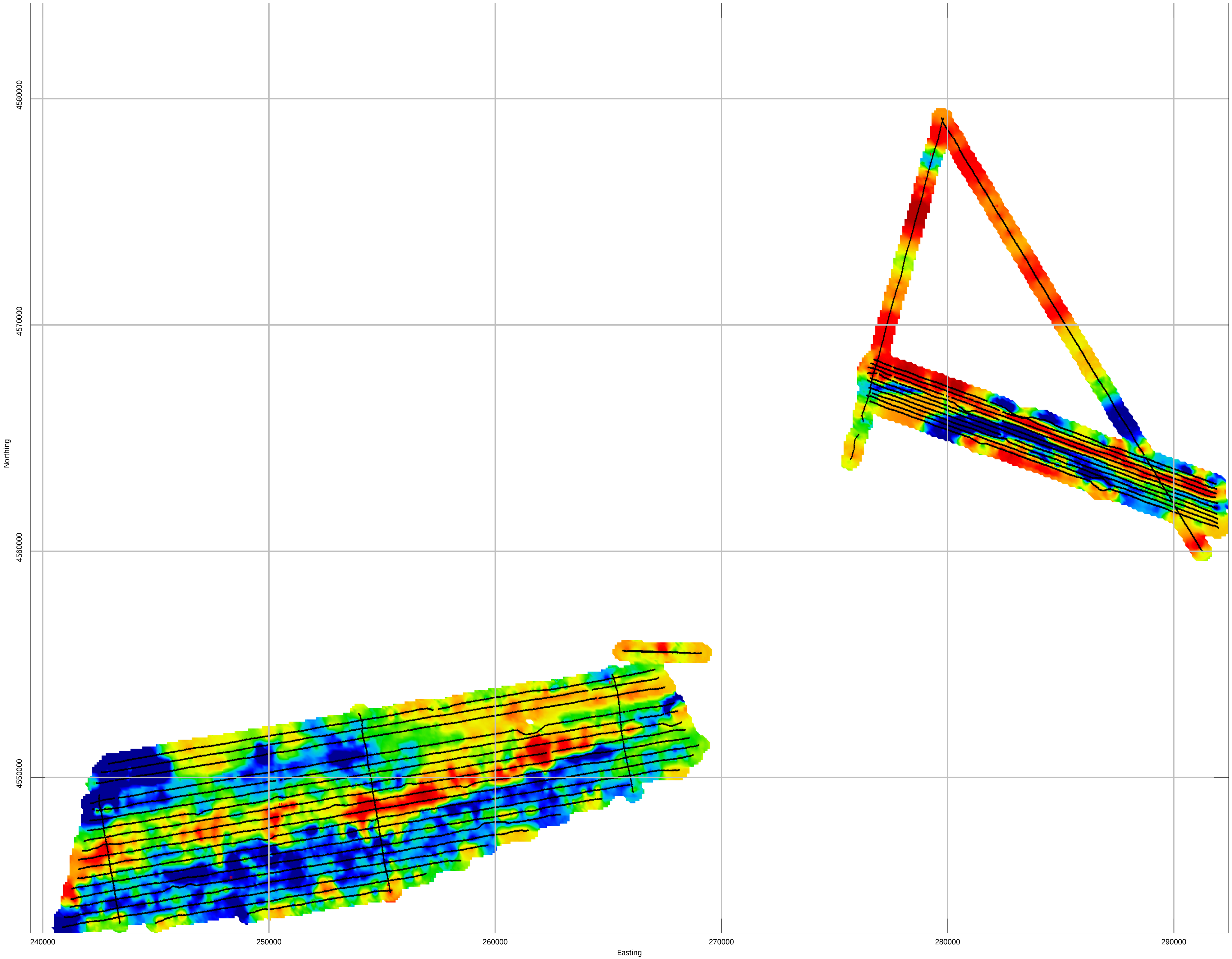
10 100

Resistivity (ohmm)

6 km

Aarhus Geophysics

Inversion results



USGS SkyTEM survey

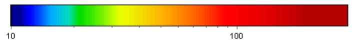
Maps based on result of 5L SCI

Avg. res. 15-20m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



Resistivity (ohmm)

6 km

Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 20-30m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

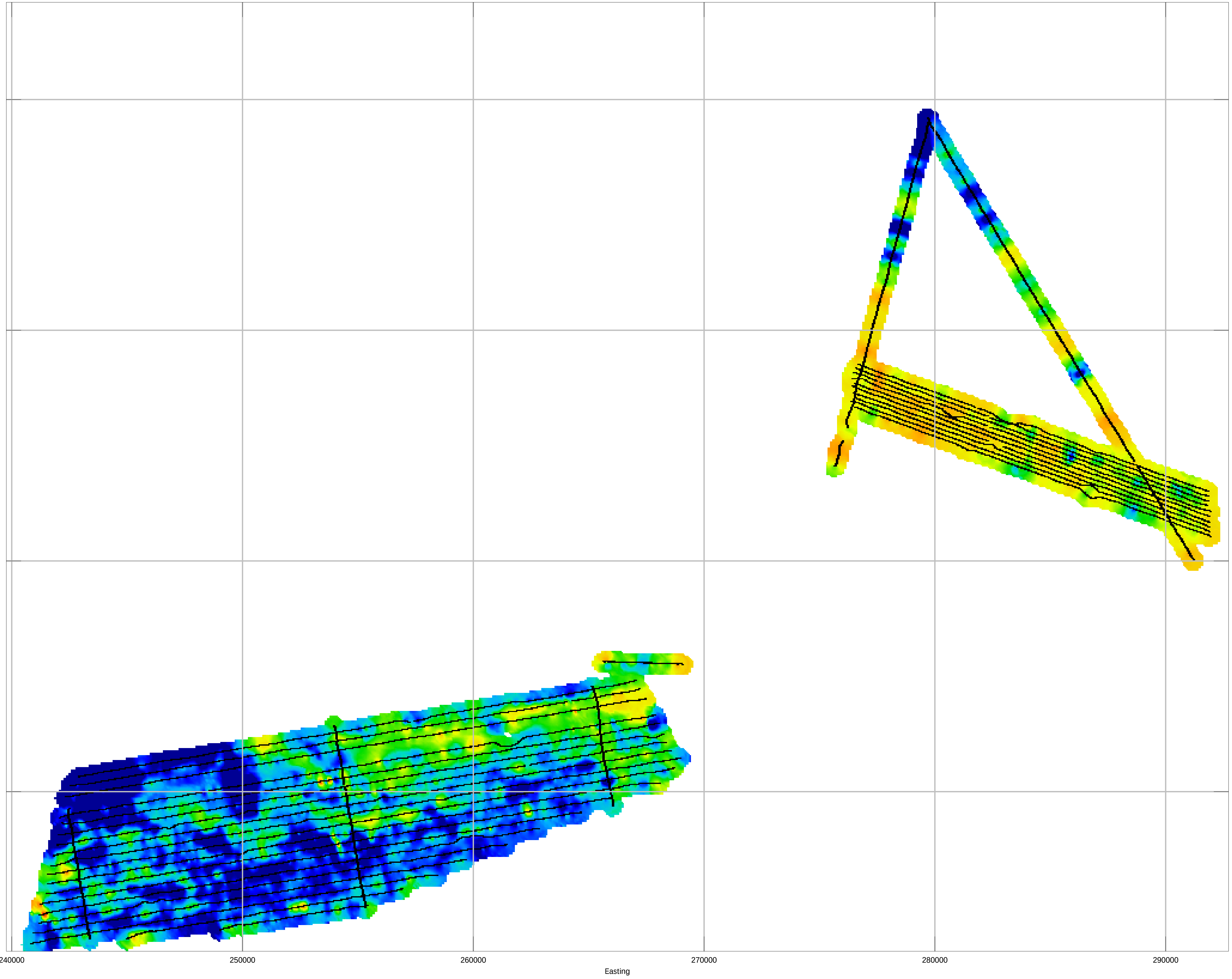
All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

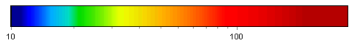
Maps based on result of 5L SCI

Avg. res. 30-40m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

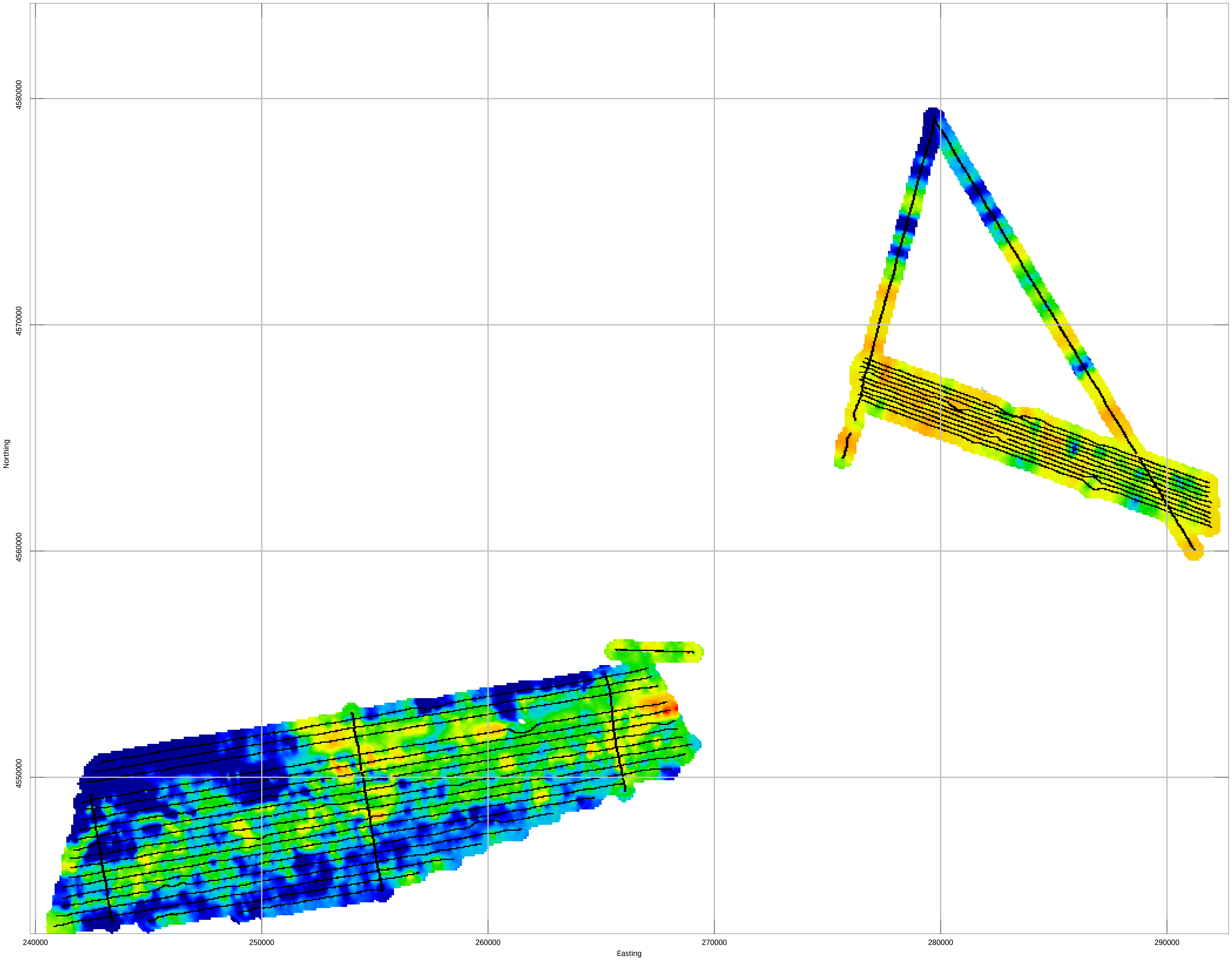
All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

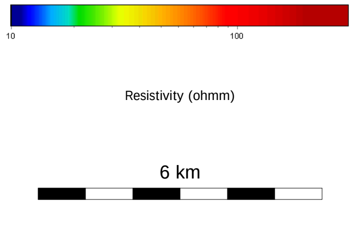
Maps based on result of 5L SCI

Avg. res. 40-50m bgl

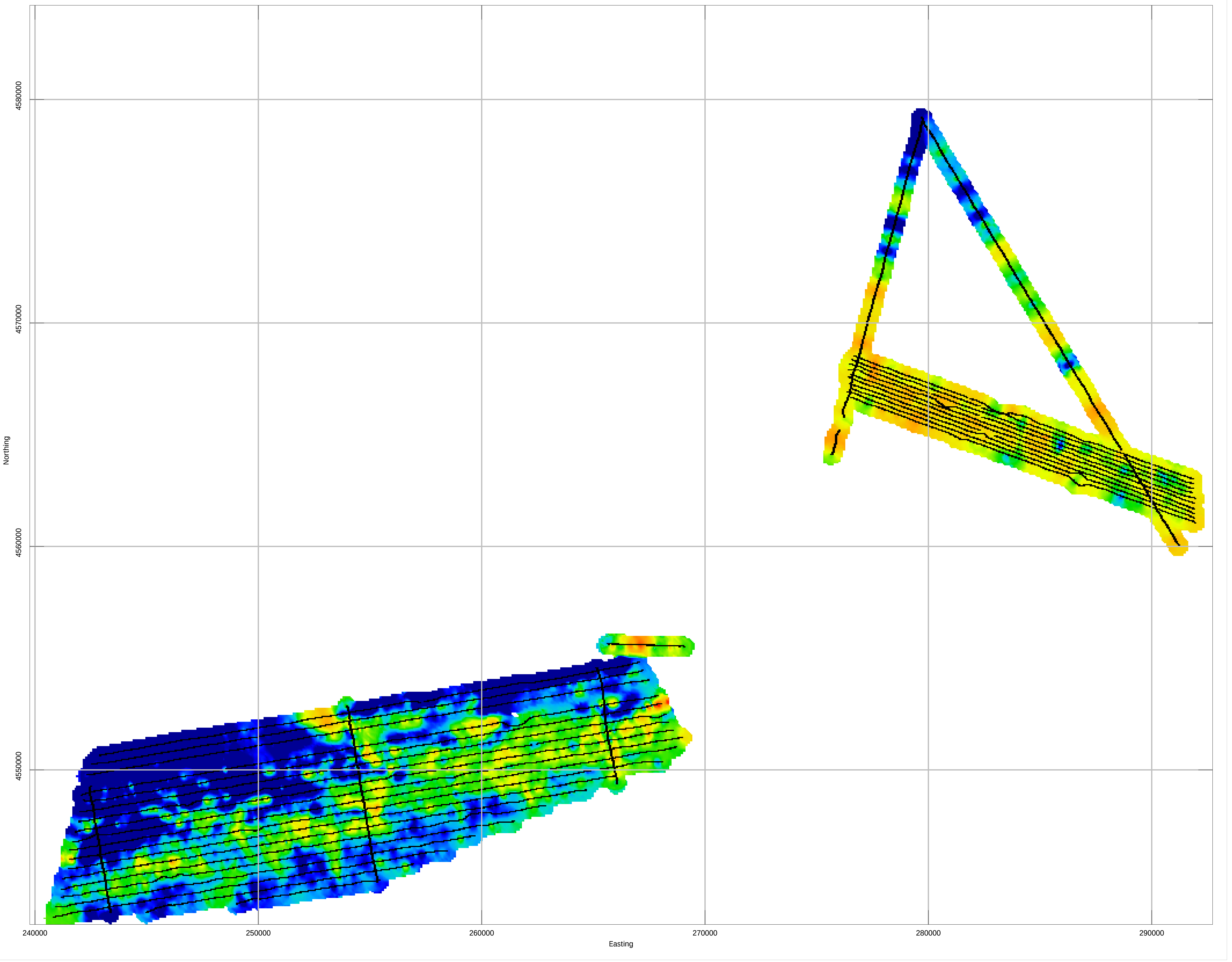
Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached



Inversion results



Aarhus Geophysics

USGS SkyTEM survey

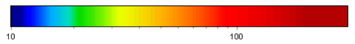
Maps based on result of 5L SCI

Avg. res. 50-60m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

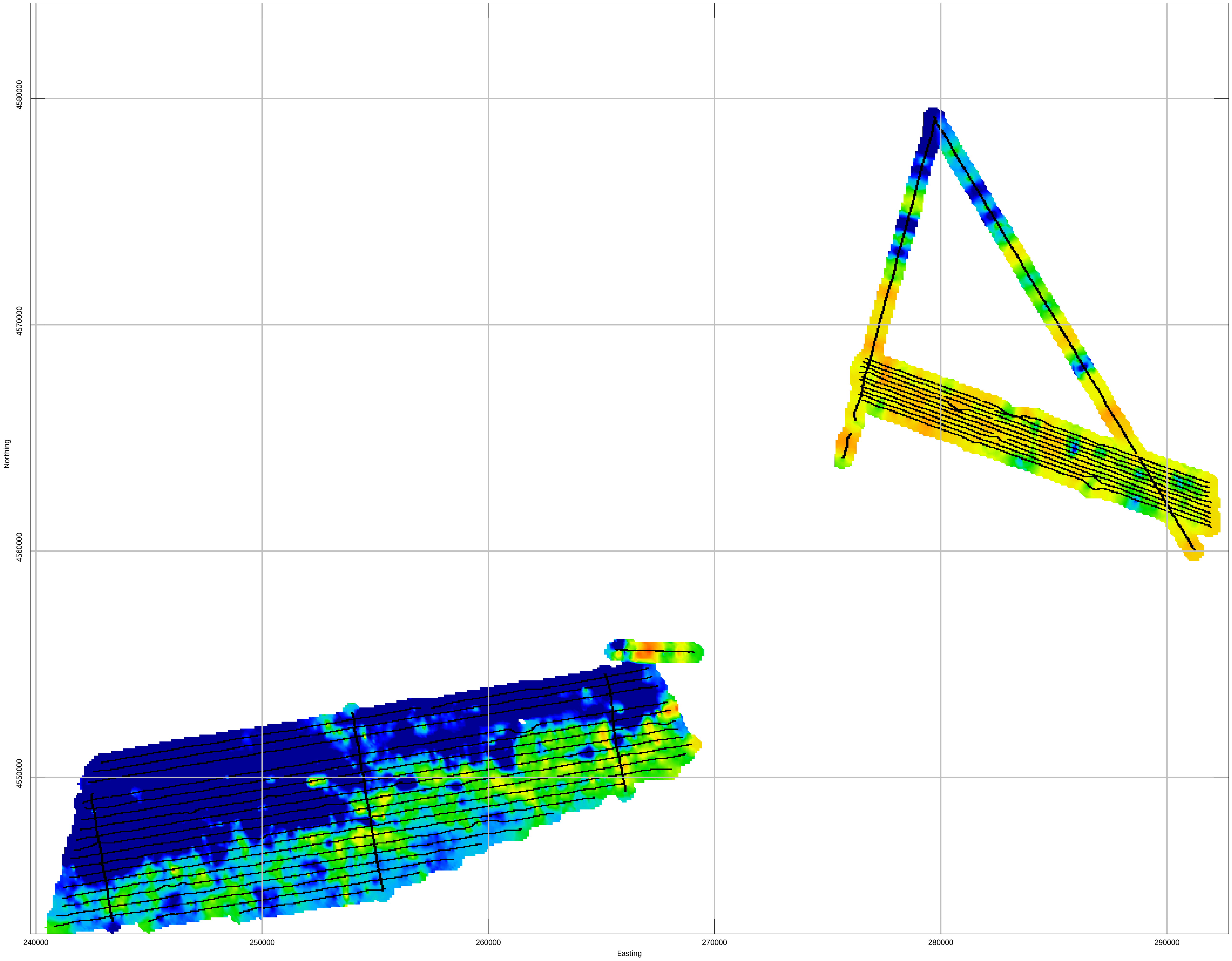
Grey surfaces represent areas
where the DOI has been reached



Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 60-80m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

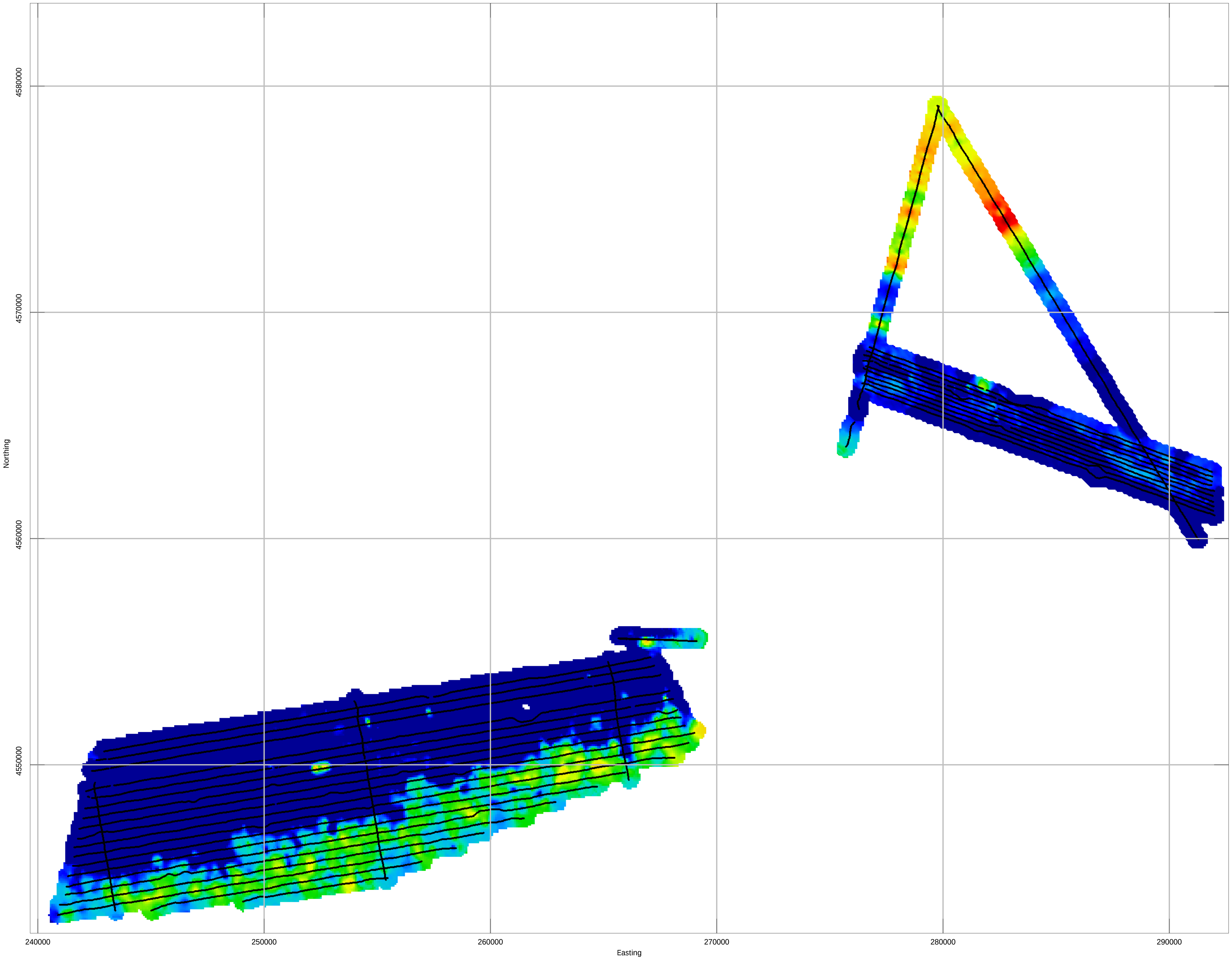
Grey surfaces represent areas
where the DOI has been reached

10 100

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

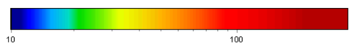
Maps based on result of 5L SCI

Avg. res. 80-100m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

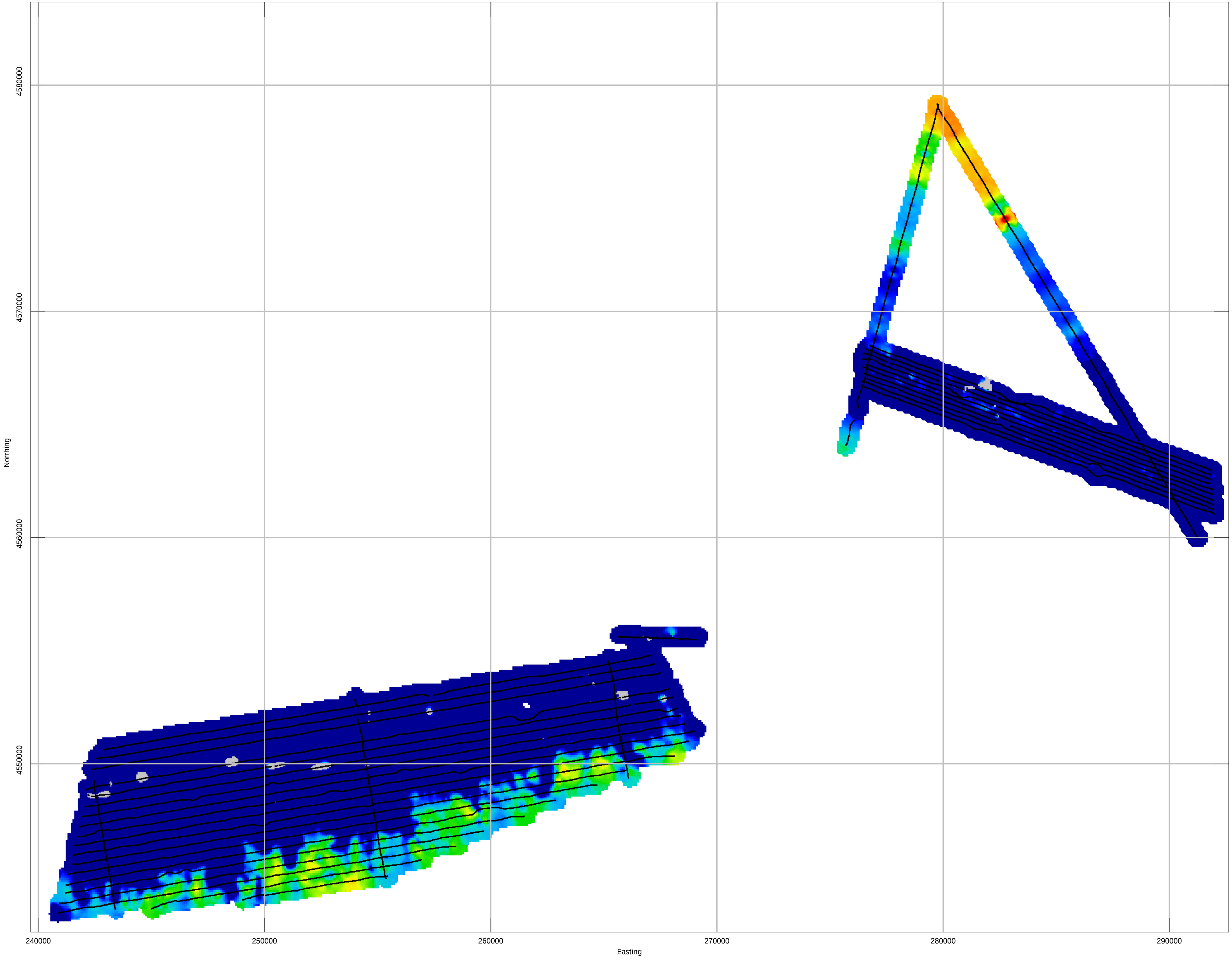
Grey surfaces represent areas
where the DOI has been reached



Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 100-120m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

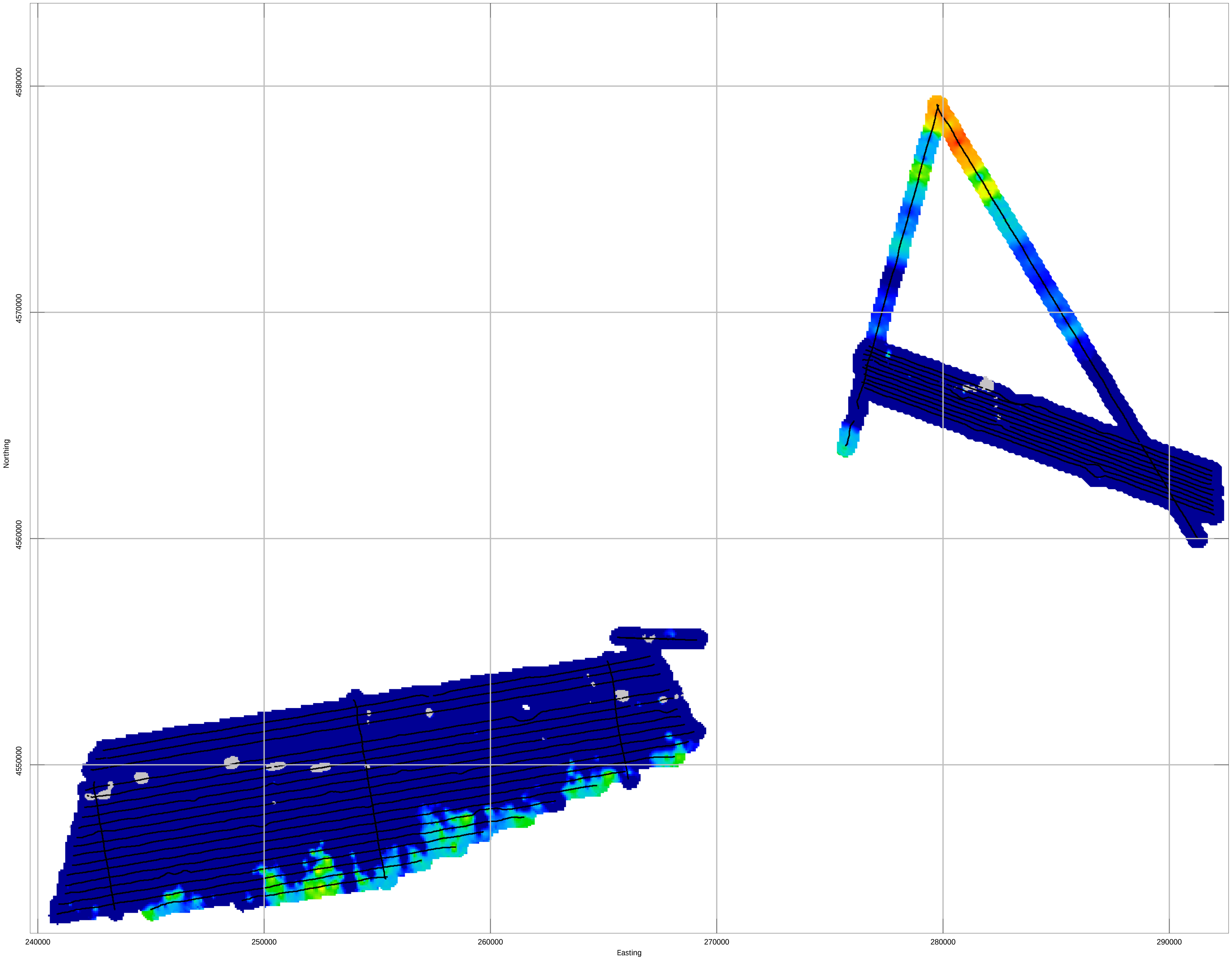
Grey surfaces represent areas
where the DOI has been reached

10 100

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 120-140m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

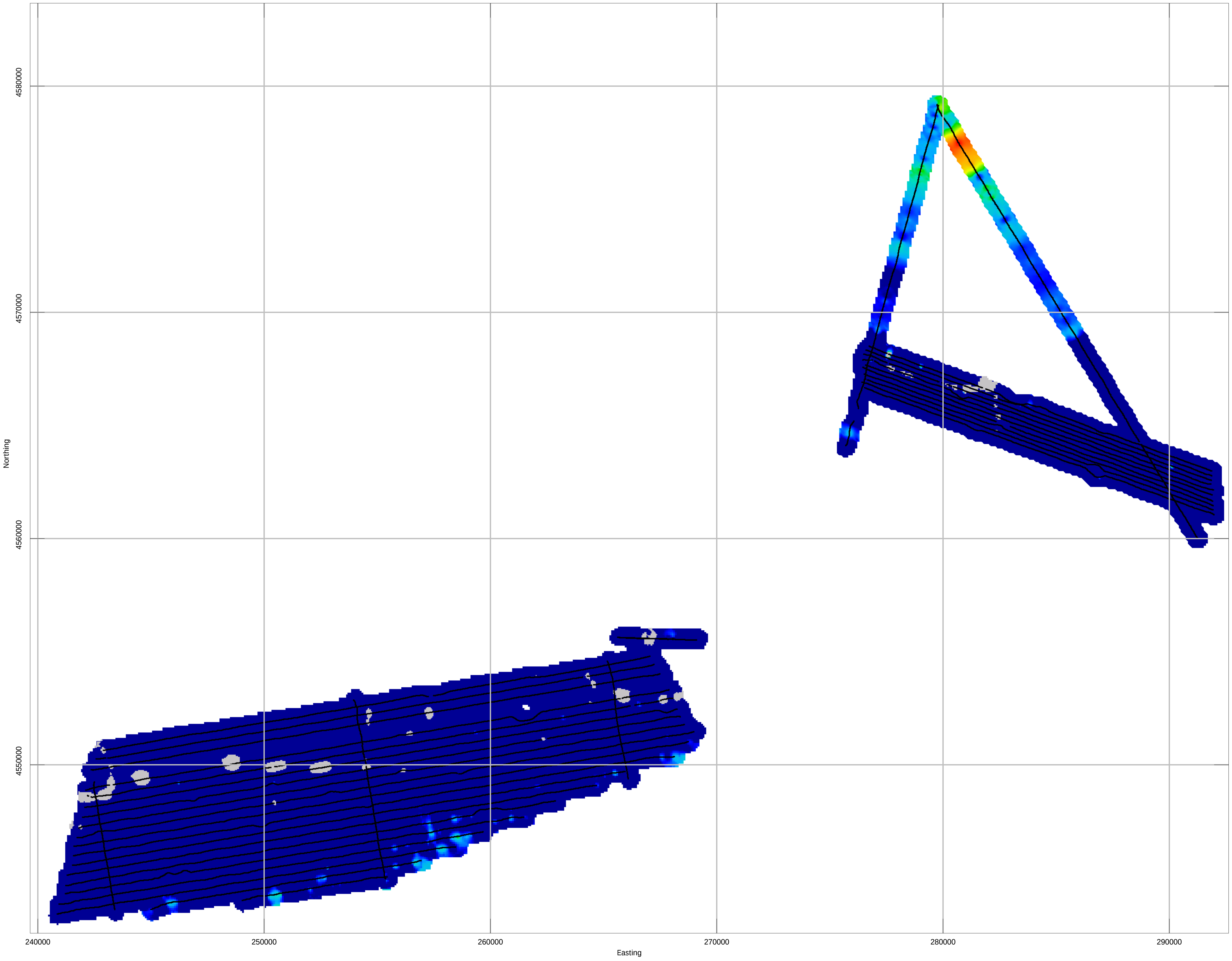
Grey surfaces represent areas
where the DOI has been reached

10 100

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 140-160m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

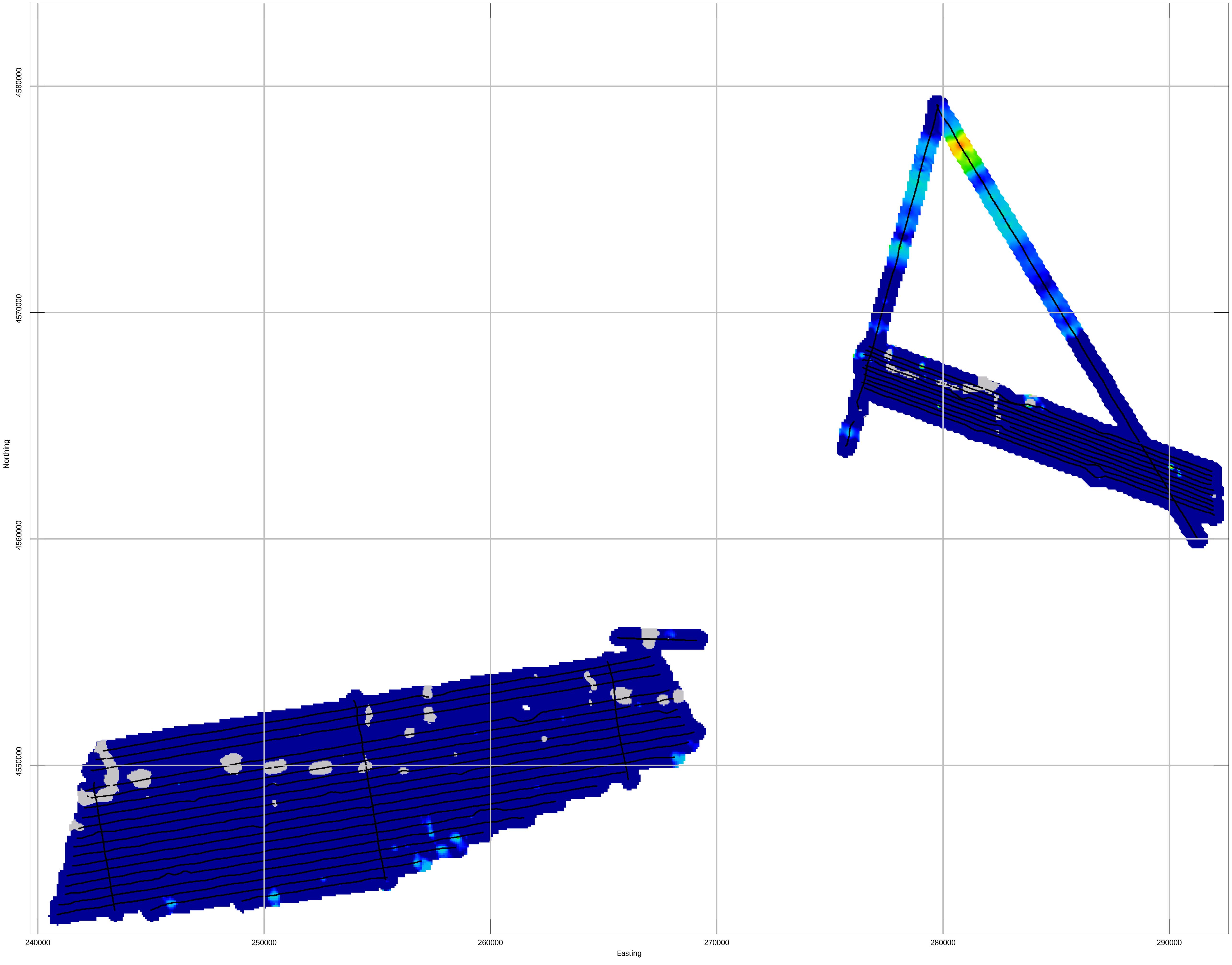
Grey surfaces represent areas
where the DOI has been reached

10 100

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 160-180m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

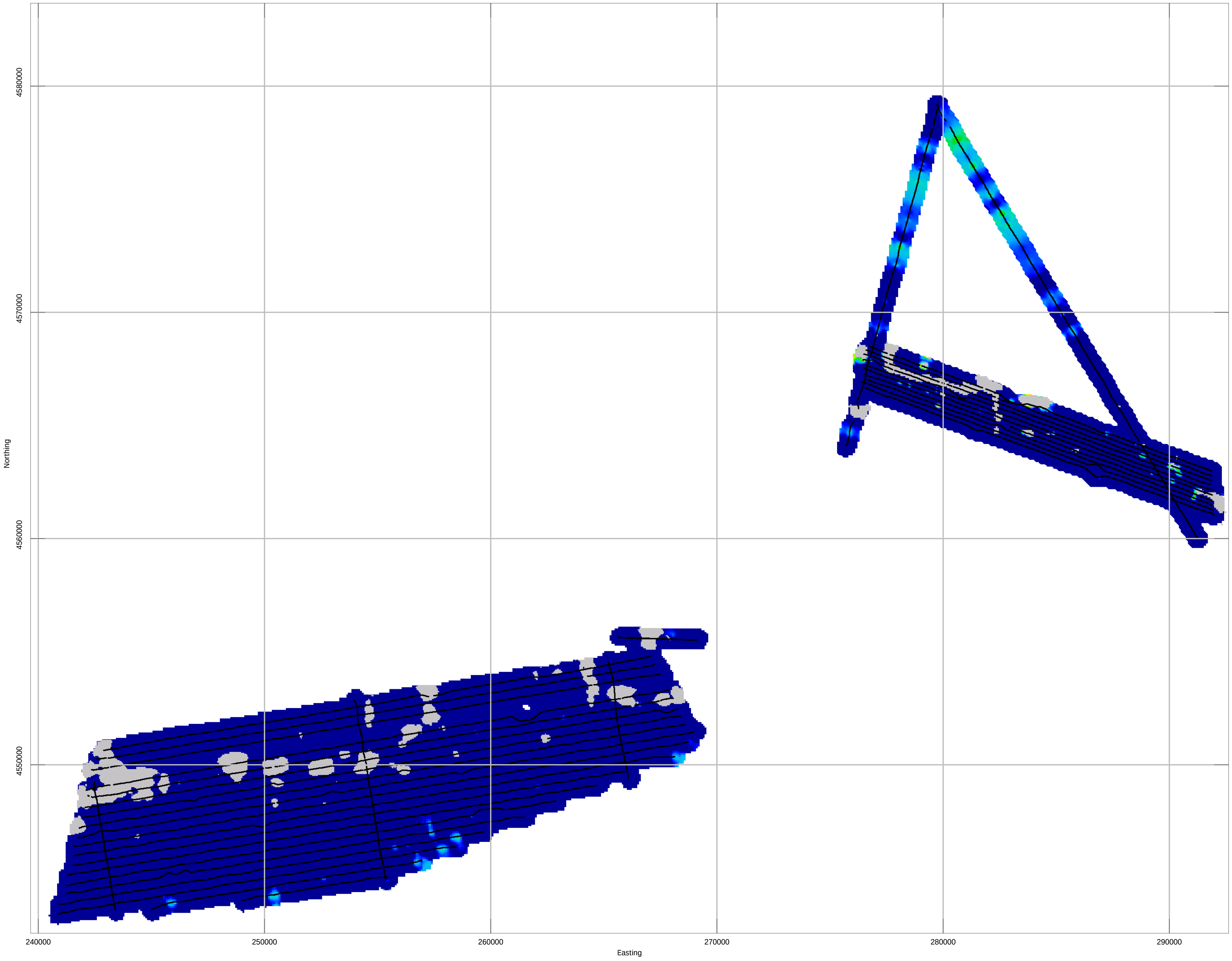
All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

Grey surfaces represent areas
where the DOI has been reached

Resistivity (ohmm)

6 km

Inversion results



Aarhus Geophysics

USGS SkyTEM survey

Maps based on result of 5L SCI

Avg. res. 180-200m bgl

Coordinate system:
NAD83 UTM Zone 14N, NAVD88

All grids are gridded using Kriging
Search radius 500m
Node spacing 100m

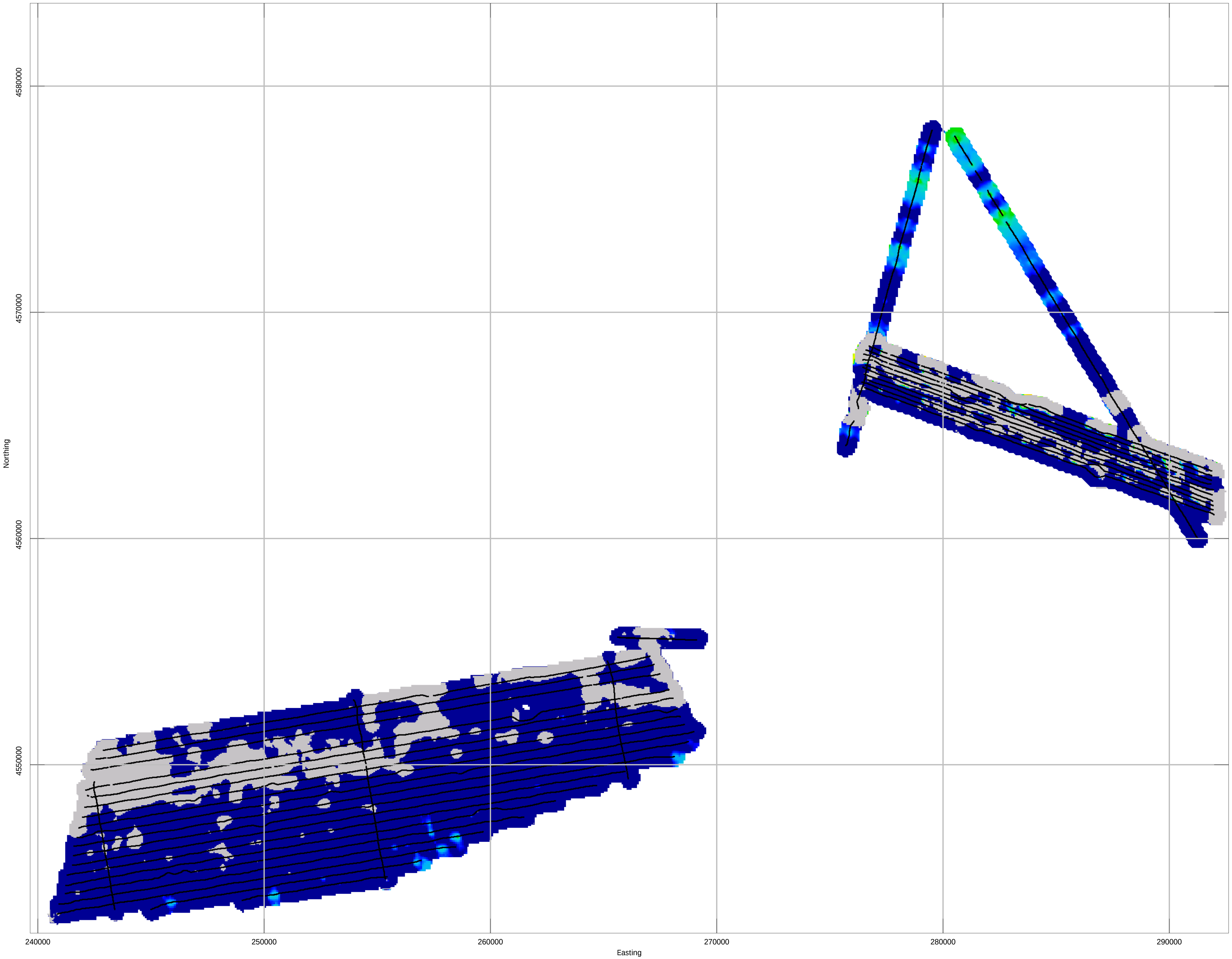
Grey surfaces represent areas
where the DOI has been reached

10 100

Resistivity (ohmm)

6 km

Inversion results

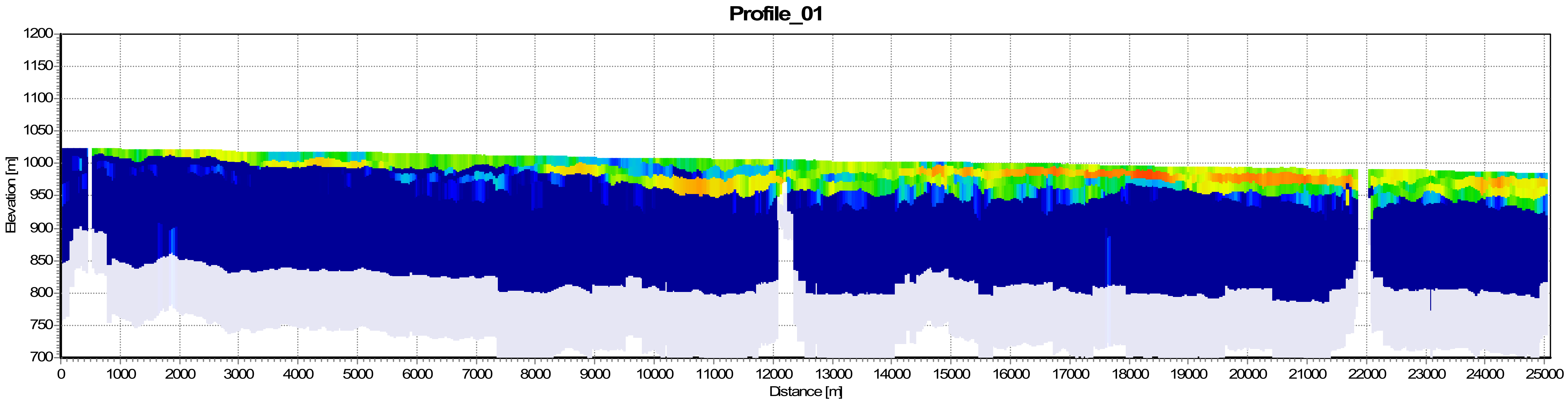


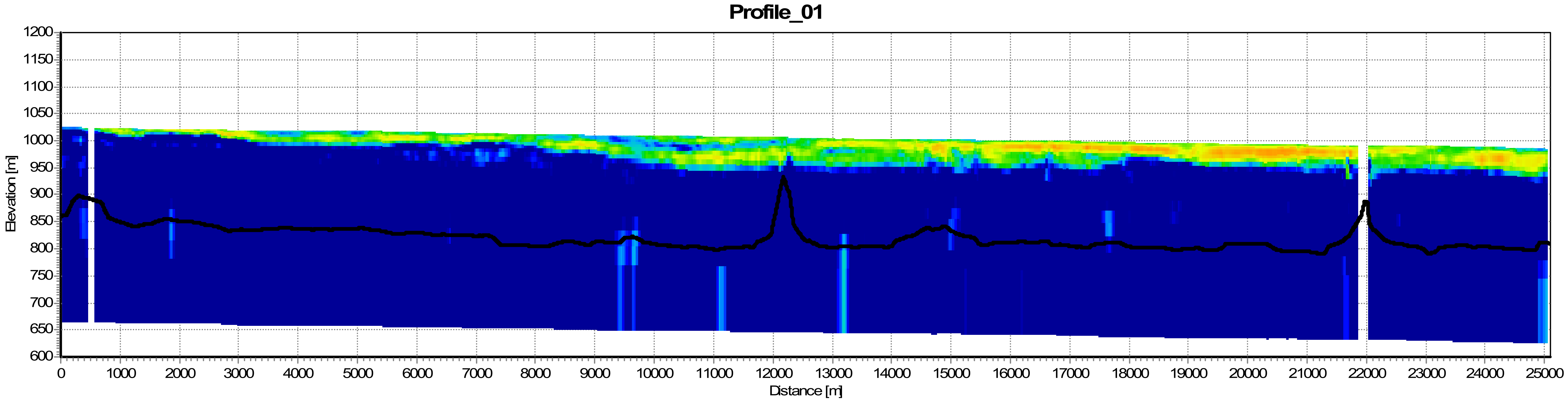
B. Appendix 2

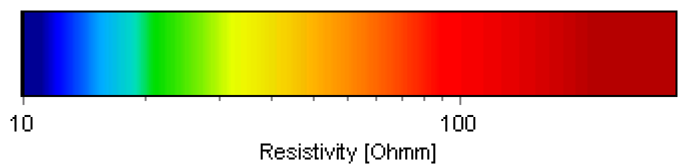
The next pages contain the vertical resistivity profiles, for both the few and the multi layers inversion, with DOI superimposed to them. Refer to Appendix A for a map of the locations of the profiles. Profiles 1 to 6 are drawn W to E, and profile 7 South to North

Aarhus Geophysics

USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area "UTM14". DOI superimposed to profiles as shading or black line

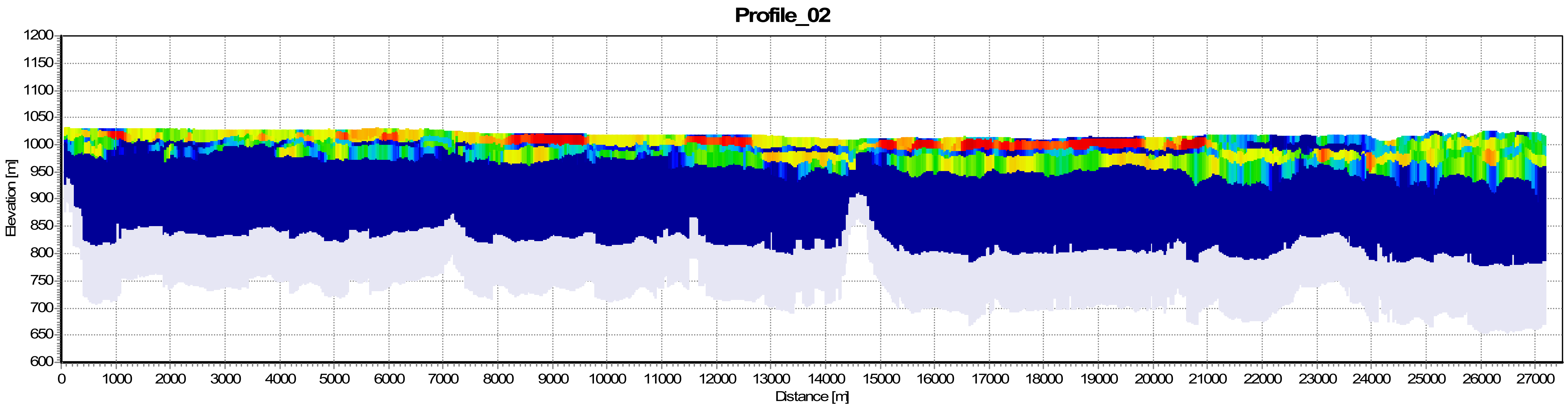


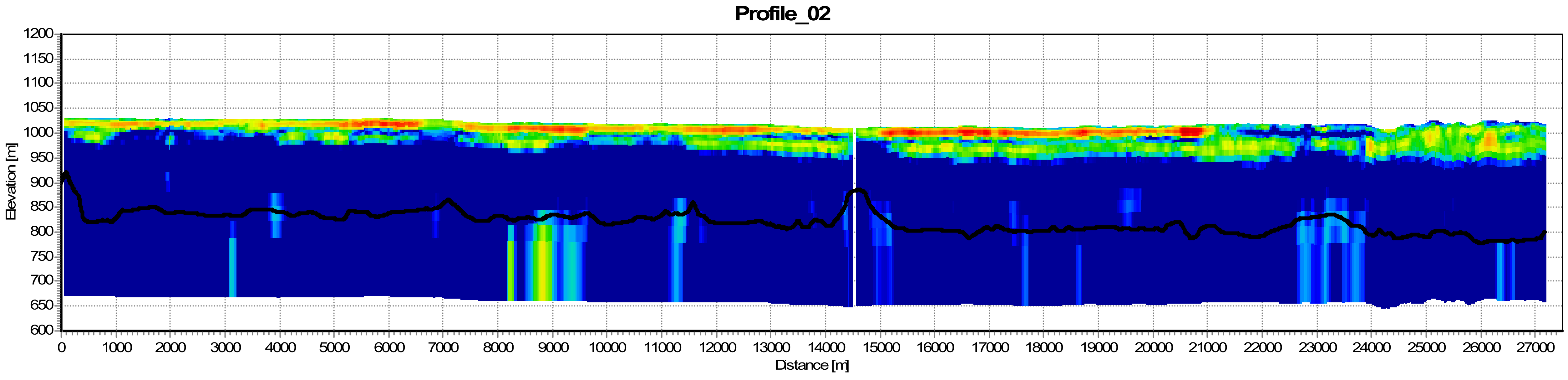


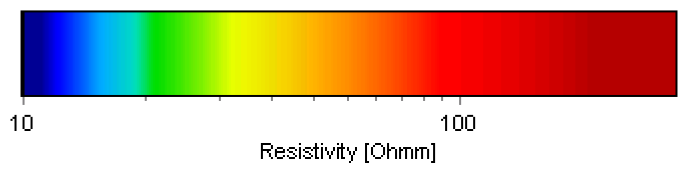


Aarhus Geophysics

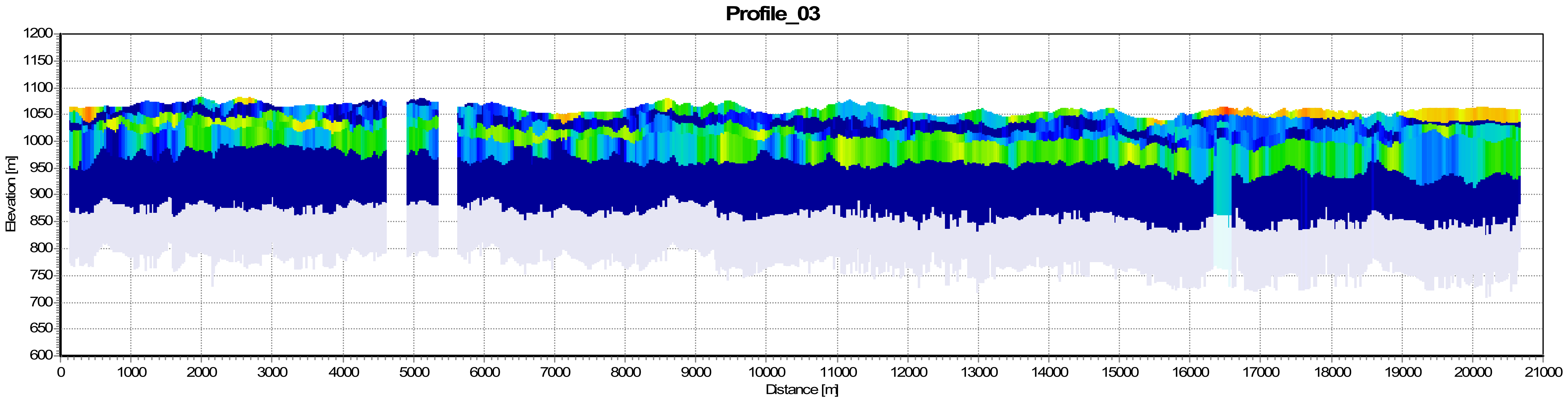
USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area “UTM14”. DOI superimposed to profiles as shading or black line

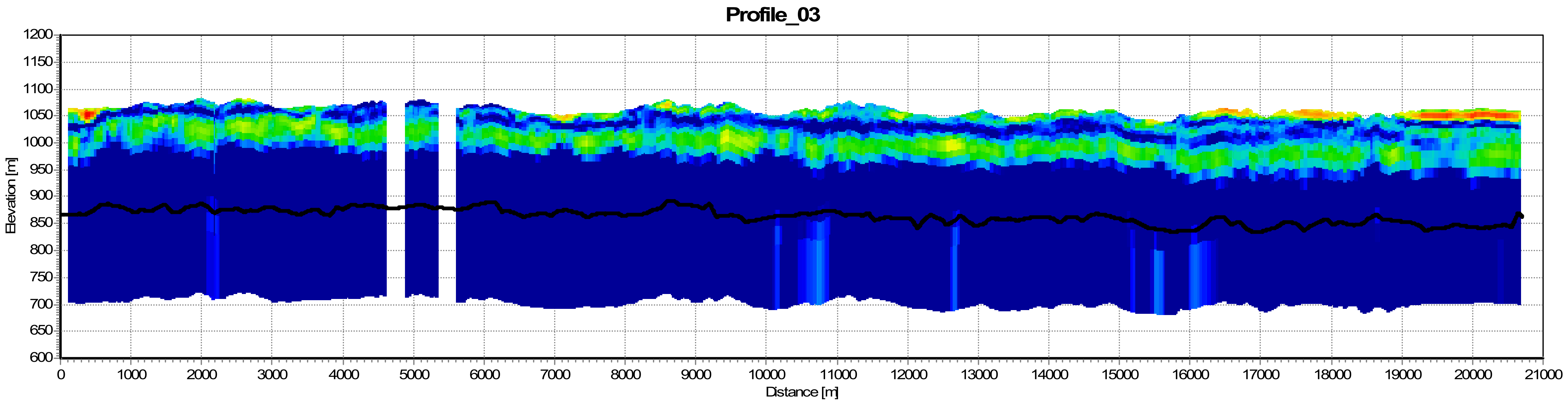


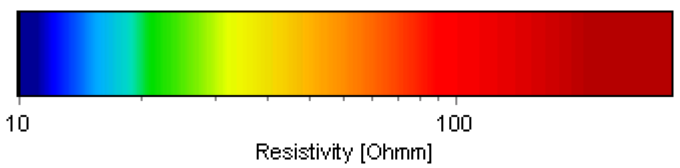




USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area "UTM14". DOI superimposed to profiles as shading or black line

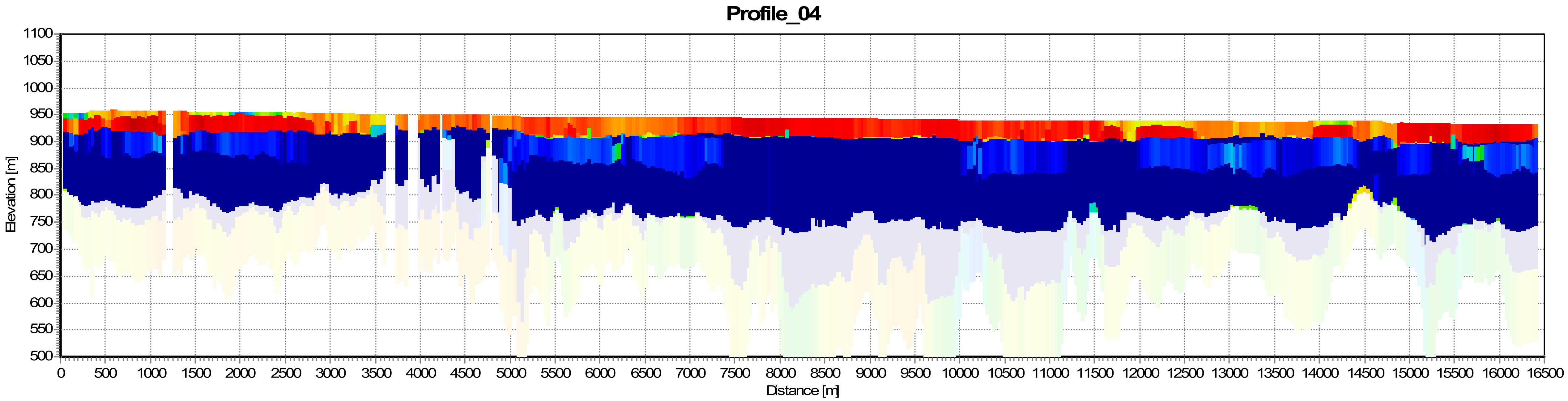


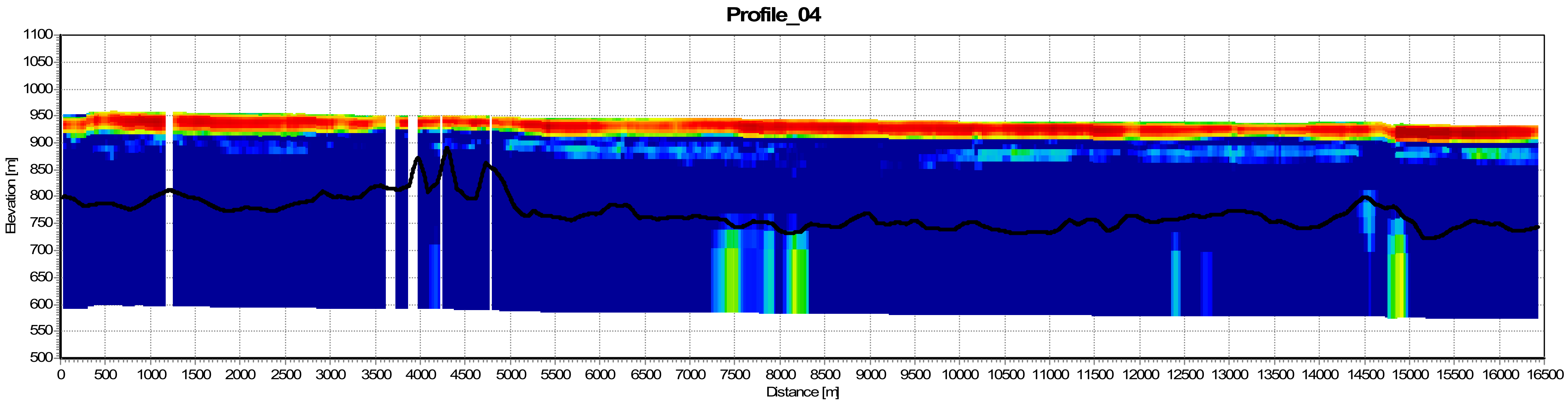


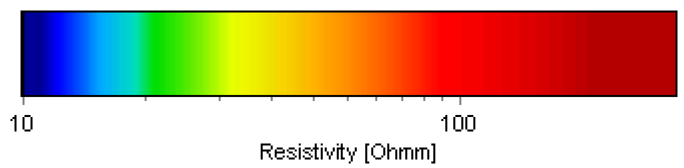


Aarhus Geophysics

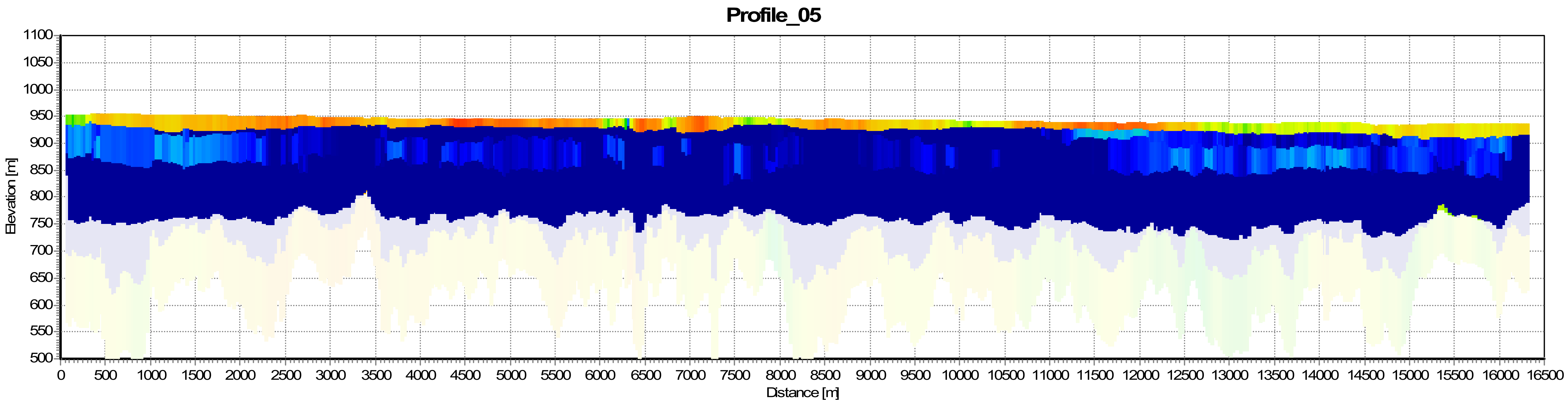
USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area "UTM14". DOI superimposed to profiles as shading or black line

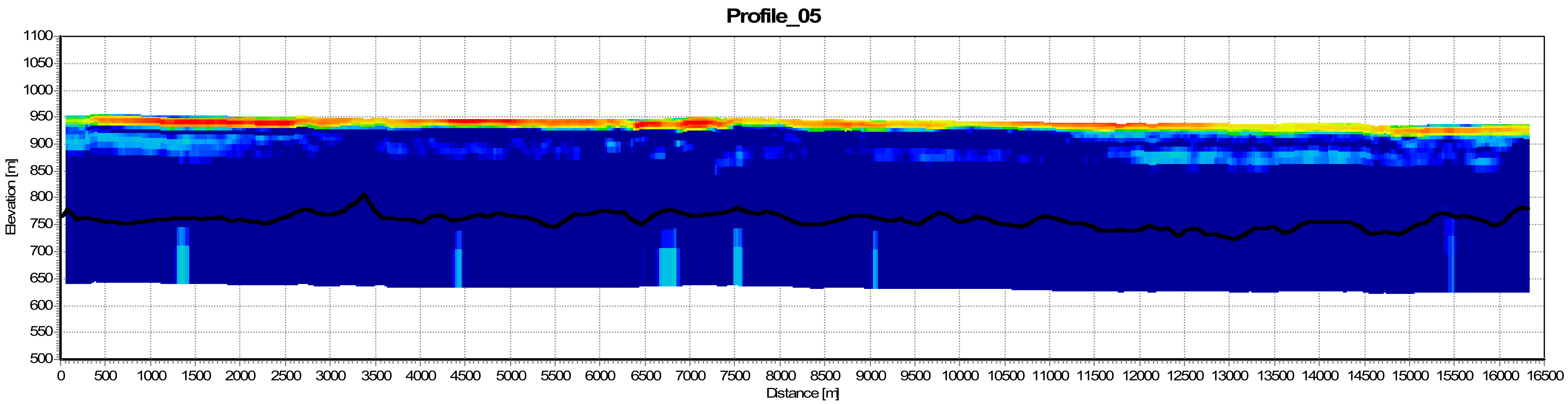


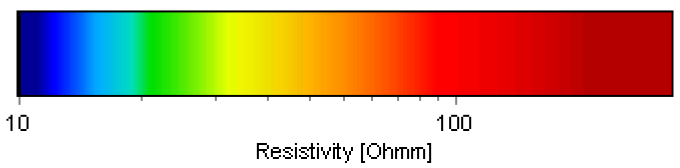




USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area “UTM14”. DOI superimposed to profiles as shading or black line

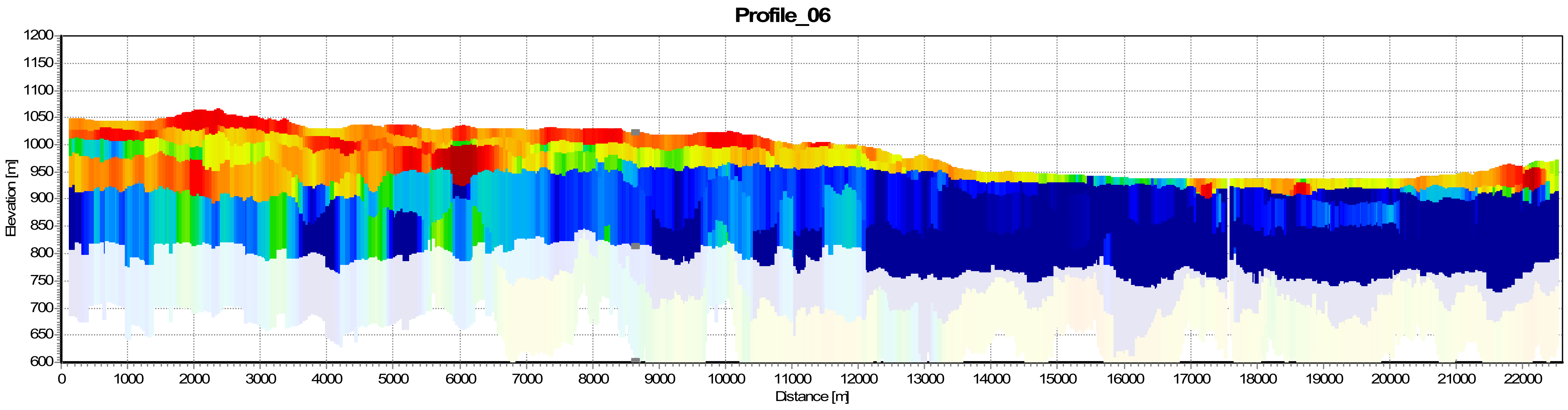


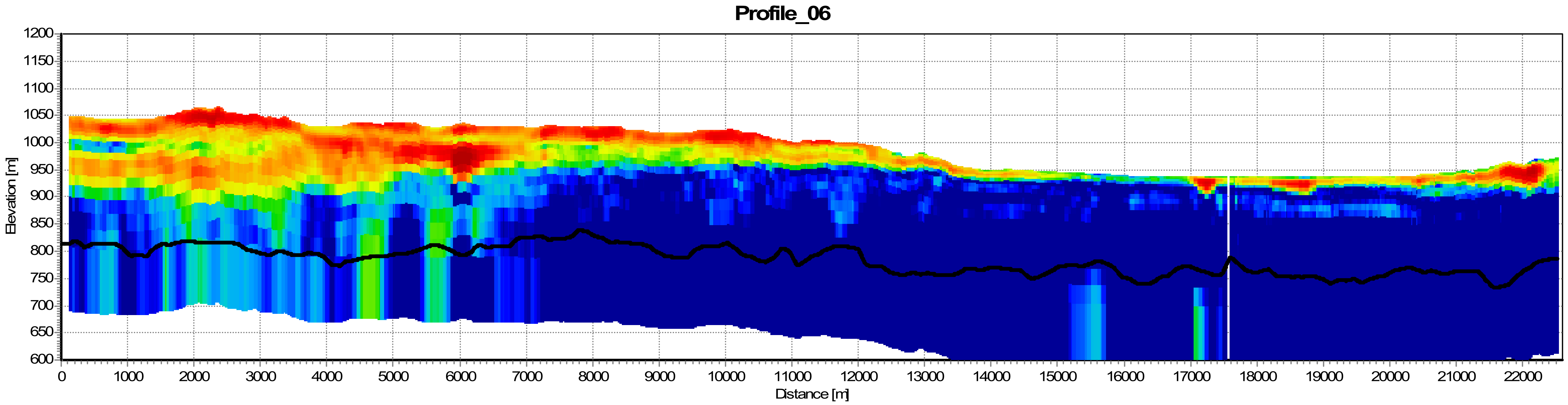


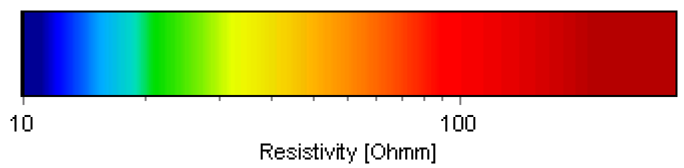


Aarhus Geophysics

USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area “UTM14”. DOI superimposed to profiles as shading or black line

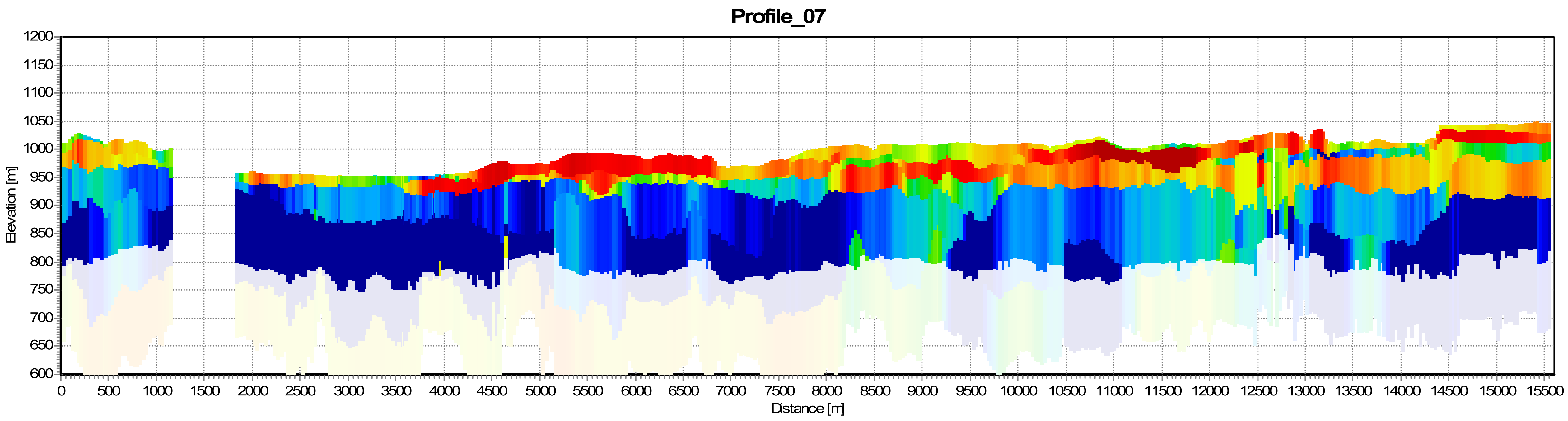


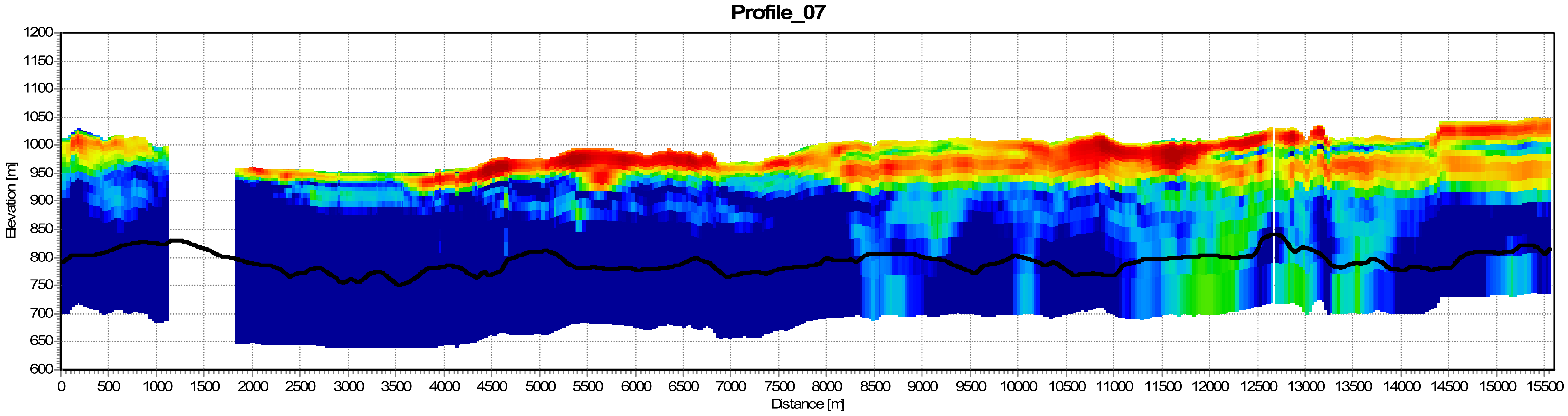


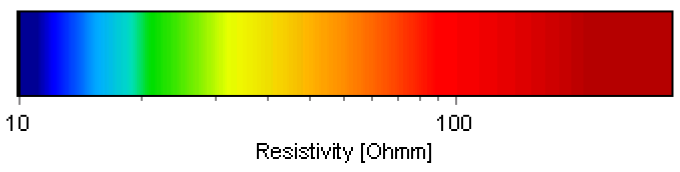


Aarhus Geophysics

USGS 2010. Resistivity profiles (5 and 19 layers) from inverted SkyTEM data, from area “UTM14”. DOI superimposed to profiles as shading or black line







C. Appendix 3

CD/DVD containing thematic maps, report, inversion results in ASCII format, processing and inversion settings.