STRUCTURAL MAPPING OF LARGE WATERSHEDS

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ABSTRACT

In this presentation we show results from a large hydrogeophysical survey carried out in Vendsyssel in the northernmost part of Jutland, Denmark.

In the search for groundwater resources the survey clearly demonstrates the effectiveness of using cost-efficient transient electromagnetic (TEM) methods in combination with geological evaluations of existing bore hole data and other geological information. The TEM data has been measured in several periods where the oldest measurements were performed with a ground-based system while the newest measurements were carried out using the newly developed air-borne SkyTEM system.

The methodology used in the survey comprises different phases involving an evaluation of existing drill hole information, selection of areas of specific interest, mapping using ground-based or airborne TEM and evaluation of the geophysical models. This evaluation forms the basis for pointing out sites for supplementary investigation drilling.

The described methodology is cost-efficient as the number of expensive drillings is cut down to a minimum. Also, the methodology is general in all aspects and directly applicable to sedimentary areas worldwide.

1. INTRODUCTION

Figure 1. Jutland, Denmark. The major cities, Aalborg, Hjørring and Hirtshals are shown on the map along with the location of the survey area.

In the last decade the County of Northern Jutland has carried out large hydrogeological surveys in Vendsyssel, northern part of Denmark. The Vendsyssel area is shown in Figure 1. The purpose of these surveys has been to locate deep lying aquifers as replacement for more shallow aquifers.

In a region plan from 1997 areas with special drinking water interests (DWI) were selected based primarily on existing drill hole information. The general strategy for structural and vulnerability surveys is to locate deep lying aquifers covered with clay layers. Consequently the areas were primarily selected where the drill holes proved the existence of protective shallow clay layers. The surveys carried out until 2003 - 2004 have unfortunately in most cases revealed clay layers of a thickness that prevent seepage of groundwater and extraction of water below them. In other cases aquifers with low quality groundwater or too low hydraulic permeability were located. The strategy was then changed so that the DWI areas are selected where the water has a sufficient quality and quantity even with incomplete natural protection. The consequence of this change is that the groundwater protection must be active and if necessary land must be left unexploited or restrictions put on the use. Also larger waterworks in the area can be forced to divide their extraction sites into smaller and more decentralized sites.

Figure 2. The SkyTEM system.

The water works in Hjørring and Hirtshals (see Figure 1) has the most urgent problem with limited water resource. Hjørring has extraction sites with organics solvents and pesticides and bad natural water quality in general.

In general the geology in the Vendsyssel area can be described by a surface of clay deposited in seawater overlain by sediments deposited in freshwater during the last glaciations and tills. The upper most sediments consist of seawater deposited sand and clay layers. The different surveys have shown that in general groundwater can not be extracted from depths larger than about 80 m - not only because of the bottom clay layer but also because of residual saltwater. Many of the potential aquifers consist of fine grained deposits with a low hydraulic permeability. The deposits originate from a large melt water lake located centrally in the area. The near surface geology is disturbed with pushed up clay flakes and buried valleys.

After the change in strategy the HydroGeophysics Group (HGG) at the University of Aarhus was invited to participate in a consortium together with the county and a private consulting company. The aim of the consortium was to build a preliminary geological model and based on that model to map an area of more than 300 km^2 with the relative newly developed airborne transient electromagnetic method, SkyTEM. Based on this investigation a number of deep investigation drillings should be located at central locations. Finally the geological model could be refined with the new data and hopefully new promising water extraction sites could be located. In the following we will report the progress of this work with special focus on the SkyTEM survey.

2. THE SKYTEM METHOD AND DATA PROCESSING

SkyTEM is a time-domain, helicopter electromagnetic system designed for hydrogeophysical and environmental investigations. The system is depicted in operation in Figure 2.

The system is carried as an external sling load independent of the helicopter. The transmitter, mounted on a lightweight wooden lattice frame, is a four-turn, 16 x 16 m^2 eight sided loop divided into segments for transmitting a low moment in one turn and a high moment in all four turns. The low moment is about 40 A with a turn-off time of about 7 μs; the high moment transmits approximately 95 A and has a turn-off time of about 38 μs. The first gate center time on the low moment is in 10 μs while the last gate is in 8 ms. The gates are approximately logarithmical spaced with 10 gates per decade. Under normal conditions the latest gate with usable signal is in 2 - 4 ms. even though this is strongly dependent on the overall resistivity of the sub-surface. The receiver loop is rigidly mounted on the side of the transmitter loop and therefore the system is essentially a central-loop configuration with a 1.5 m vertical offset between the transmitter and the receiver.

In the development and design of the SkyTEM system it has been an unchangeable demand that the data quality should be the same or better than the data quality of ground-based systems. In production the system is verified to a ground-based measurement before the first flight. On any further take-off and landings a measurement in 10 m elevation is repeated. The reproduction between these measurements is better than 10%. The 10 % reproduction is explained by slightly different altitudes as it is not possible to hover with the frame in exactly 10.0 m. The SkyTEM system is also taken to high altitudes where there is no detectable signal from the ground. Comparing these measurements to measurements in production altitude shows that they at all times are more than a factor of 100 lower than production data. This shows that leveling and other post corrections of the measured data are unnecessary.

1.1 Data Processing

Navigation and status data for the SkyTEM system make up a substantial amount of data. This is:

- GPS data, measured with two devices every second.
- Tilt of the frame, measured by two independent devices every second.
- Altitude of the frame, measured 20 times per second with two laser devices.
- Voltage data, every transient is stored and saved for further processing.

The processing of the data (transients and navigation data) is implemented as a module in the Workbench developed by the HydroGeophysics Group. The Workbench is a common platform for working with geophysical, geological and GIS data. It has fully integrated modules for generating geophysical theme maps, geostatistic modeling and visualization on GIS maps.

It is critical for the accuracy of the geophysical models, the outcome of the inversion, that the raw data is corrected for the tilt of the frame and that the altitude of the transmitter and the receiver is accurately determined and entered into the inversion algorithm.

Altitude data as determined by the two lasers causes a significant problem when the lasers receive reflections from treetops and not the forest floor. This happens when the system is flown over both hard- and soft-wood forests. This is seen as abrupt drops in the altitude measurements. A recursive filtering scheme has been developed to eliminate the unwanted reflections. Only in cases where forest-floor reflections are absent in several seconds it is necessary for the user to determine the altitude or set the altitude parameter free in the inversion scheme.

The processing of the transient data is done in two steps. The first step uses average filters to eliminate the noise and form raw data stacks. Based on the raw data stacks all data are inspected on a profile plot of the gate values and all data at a distance of 100 - 150 m (dependent on the subsurface resistivities) from roads, power lines, wind mills, slurry tanks etc. are culled due to coupling. In step two the raw datasets are averaged into average datasets. The average data are the final soundings used in the inversion. A final sounding consists of about 1000 SkyTEM transients yielding data from 10 μs to 2 to 4 ms. The soundings are on average separated approx. 30 meters on the flight lines.

1.2 Inversion

In the inversion scheme the flight height is included as an inversion parameter with a prior value and a standard deviation determined from the altimeters. The inversion of the SkyTEM data is done using the 1-D Laterally Constrained Inversion (LCI) developed for inversion of CVES and PACES data (Auken et al, 2005). In this inversion scheme the model parameters are tied together laterally with a spatially dependent covariance. 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 LCI inversion scheme was originally developed for parameterized inversion with normally 4 or 5 layers. Lately, the algorithm has been further developed to include smooth inversion with e.g. 15 layers each having a fixed thickness but a free resistivity. Both schemes have advantages. Layer interfaces and resistivities are best determined from the parameterized inversion. Also the depth of penetration is better estimated. On the other hand the smooth inversion does not require a starting model and gradual transitions in resistivities are more conspicuous. Both inversion types can with advantage be calculated and used together in the final geological interpretation.

The forward modeling of the transient data is independent of the chosen inversion scheme. We do not deconvolve the system transfer function from the field data as in our experience deconvolution is an inherently unstable process. The transmitter waveform is applied using a piecewise linear approximation to the current wave form and the low-pass filters are applied following Effersø et al. (1999). Filters before the front gate (a gate preventing the primary field from the current turn-off to saturate the amplifiers) are calculated in the frequency domain while filters after the front gate are calculated by a convolution in the time domain.

1.3 Survey costs

The costs of a SkyTEM survey are dependent on several factors including the size of the survey, desired penetration depth and the desired level of processing. Especially the penetration depth affects the costs as there is a trade of between helicopter speed and the number of transients in the data stack. If only a moderate penetration depth is necessary the flight speed can be increased and thereby the helicopter expenses are reduced. A very large penetration depth inevitably causes the costs to be larger as the flight speed must be decreased.

The data processing and the inversion are as important as the collection of the raw data. Extracting maximum reliable information from the data requires carefully and often time consuming processing. In general, the expenses for data processing and inversion and presentation of the final models on geophysical theme maps and cross sections will amount to 30 - 40 % of the total budget.

3. RESULTS

The survey area is shown in Figure 1. The inversion of the 1250 line kilometer of data and a reinterpretation of more than 13.500 soundings has resulted in a greatly enhanced geological understanding of the Vendsyssel area. The first thematic map we present is the depth to a low resistive layer, see Figure 3. This layer is interpreted as being identical to the salt water deposited clay which also outlines the bottom of any potential aquifer in the area. As seen, the area is characterized by a relatively flat lying clay surface incised by relatively narrow buried valley structures (Jørgensen, 2003a, Jørgensen, 2003b). The most pronounced buried valleys marked by the lines in white color are incised more than 100 m into the clay. The central part of the area is mapped with SkyTEM while the more scattered dots shows the positions of the ground based soundings. In some areas SkyTEM was flown in between the ground based soundings to obtain a sufficient data coverage in all areas. An example of this is seen in the central western area and the upper eastern area.

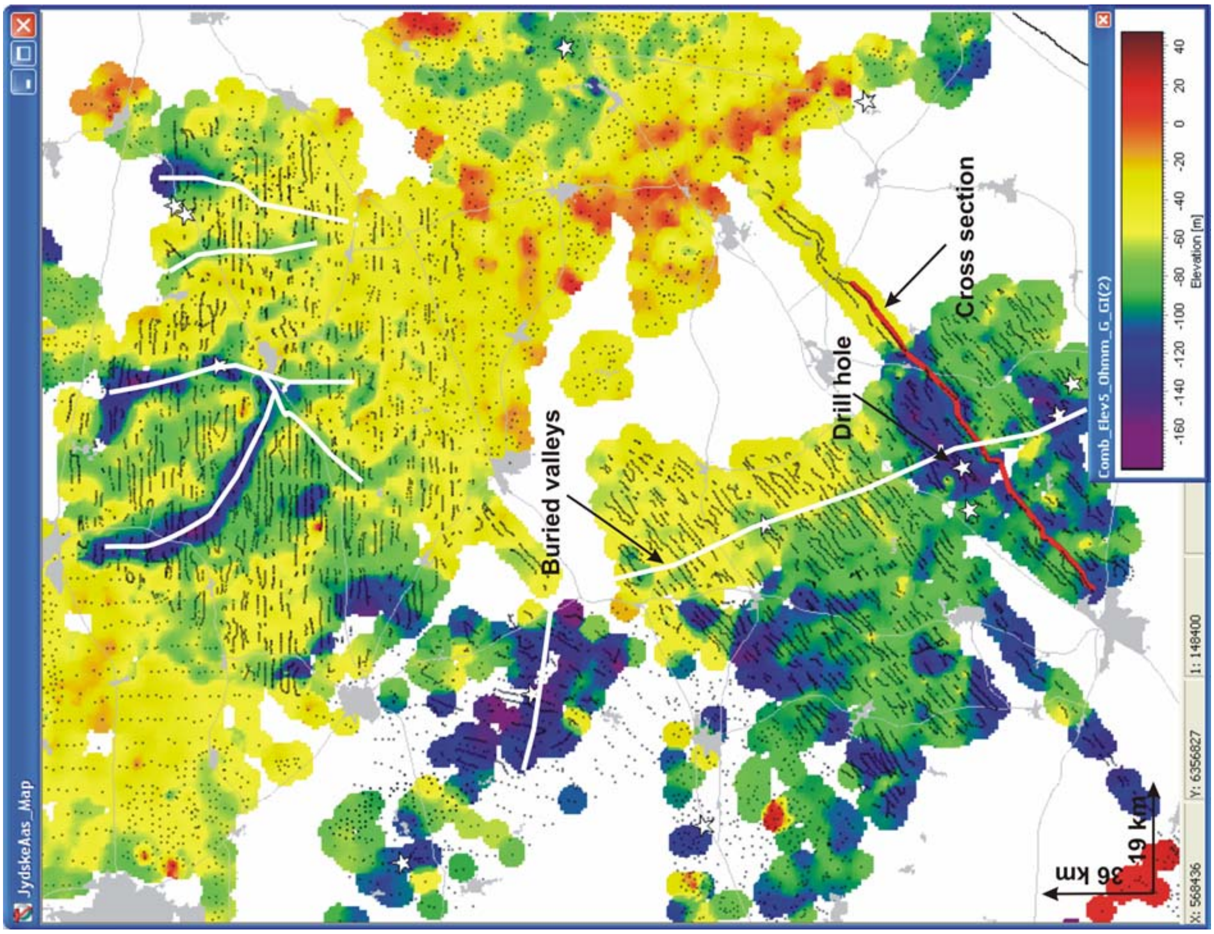

Figure 3. The map shows the elevation of the low resistivity layer. The black dots are the transient sounding points, gray lines show the major roads and houses and the white lines outline some of the major buried valleys. The white stars show the location of the investigation drillings. The red line show the location of the section in Figure 5

It must be emphasized that the buried valley structures in the central part of the survey area was not known prior to the SkyTEM measurement. The structures are not visible in the landscape which as a matter of fact forms an up to 90 m high ridge.

1.4 Average resistivity maps and cross sections

Evaluation of the resistivity of the fill in the buried valleys is done on thematic maps showing the average resistivity in different elevation intervals. More detailed studies can be made on cross sections. An example of an average resistivity map is shown in Figure 4. The map shows the resistivity of the subsurface in the interval from 60 m to 80 m below sea surface. If we interpret blue and green colors as clay or clay dominated sediments and yellow and red colors as sand and gravel dominated sediments it is seen that some of the buried valley structures are in fact filled with sand and gravel and are therefore potential aquifers. Other valleys as the one in the north-western part of the area is very clear in the elevation map in Figure 3 but on the average resistivity map it is seen that the fill sediments has resistivities below 20 ohm-m and therefore they have no interest in a hydrological context. Numerous buried valleys originating from various ice progressions from different directions can be seen clearly in the average resistivity maps when inspecting and comparing maps from other elevation intervals (not shown here).

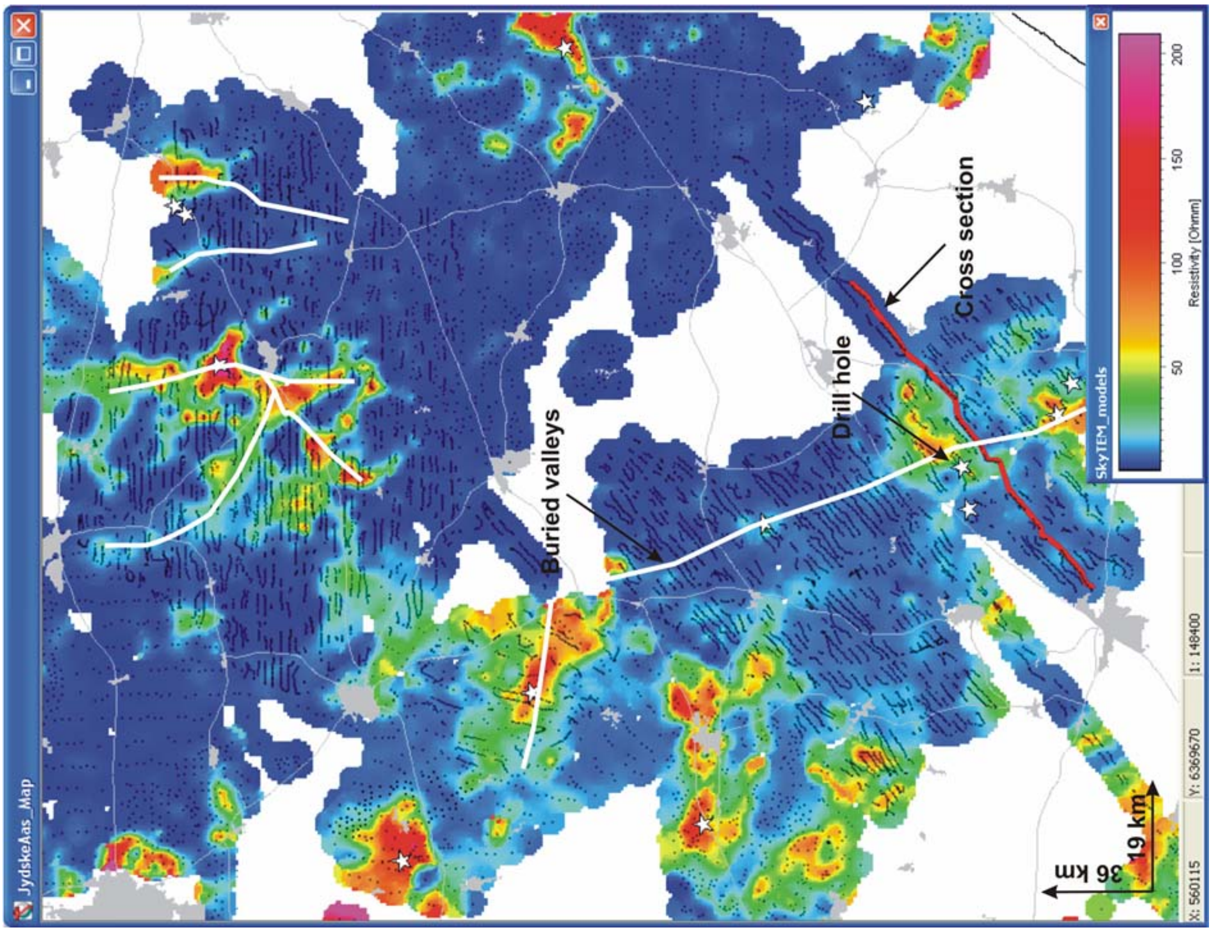

Figure 4. The map shows the average resistivity in the interval from 60 - 40 m below sea surface. The major valleys are filled with high resistive sediments - probably sand and gravel.

Figure 5 shows a section where the geophysical models are shown as bars. A selected dataset is shown in Figure 6. The surface of the bottom clay layer in this part of the survey area is relatively flat in elevation -40 m. High resistive sediments have been deposited on top of the clay while the top most layers are interpreted as till.

Based on the TEM survey and on the first geological model of the area it was in the spring of 2005 decided to drill 5 deep investigation drillings in the northern part of the area and another 4 drillings in the winter of 2005/2006. The location of the bore holes are shown in Figure 4 as the white stars. The bore holes are primarily located in the incised valleys filled with high resistive sediments. However, in order to get information about the entire stratigraphy 2 drillings has been made outside the valleys.

While results are unknown from the four drillings which will be made in the beginning of 2006 the first 5 drillings have all confirmed the existence of the buried valley structures. They have also confirmed that coarse sandy sediments exist in these valleys and water samples have shown a reasonable water quality. Hydraulic measurements have not been made yet but the grain size from the geological samples indicates that the hydraulic conductivity of the formation is acceptable.

4. CONCLUSIONS AND FURTHER WORK

We have presented a large scale hydrogeophysical investigation. Event though the focus has been on the geophysical part the investigation contains all aspects from the creation of an initial geological model to follow up drillings at the end. In between these two phases a large TEM investigation has been completed and the results formed the basis for the location of the follow up drillings.

The work with this survey will continue in 2006. The geophysics is almost finished but the rest of the investigation drillings still has to be made. After this an enhanced geological model will be put together. This model can then be turned into a conceptual model forming the basis for a hydrological model. Together with the water chemistry this model will hopefully show that there are new and well yielding aquifers for the cities of among other Hjørring and Hirtshals.

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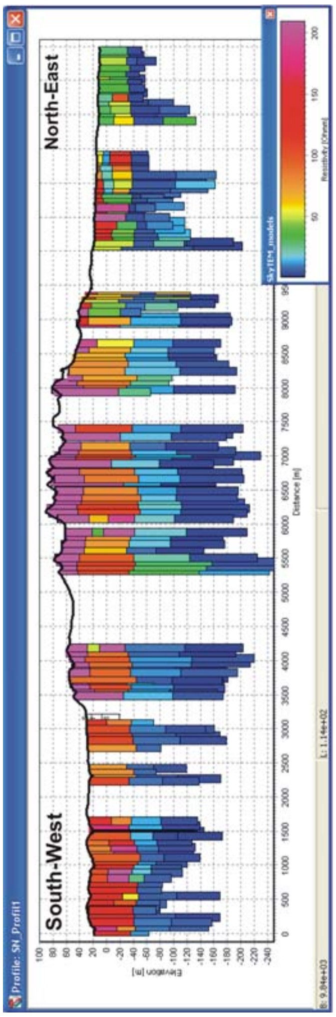

Figure 5. The figure shows a cross section where the inverted models are shown as bars. The topography varies from about 20 m to 90 m above sea level.

a) b)

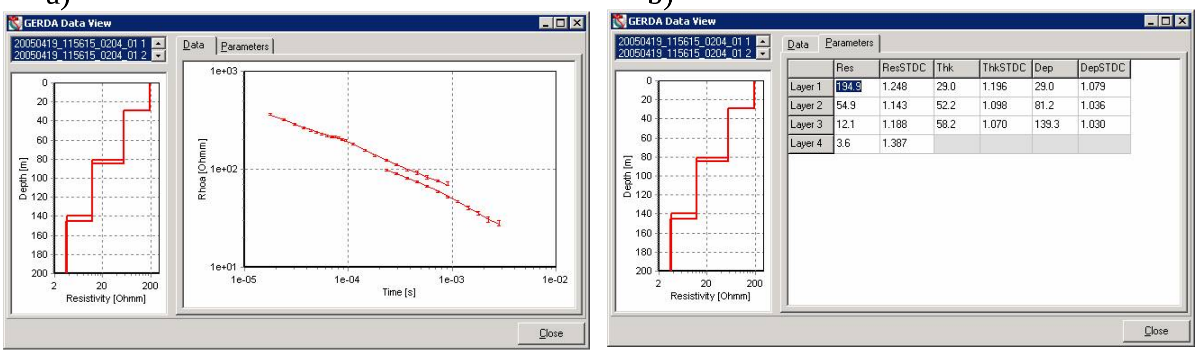

Figure 6. The figure shows an example of a dataset at position 8500 m in Figure 5. The two curves in a) shows the low moment and the high moment data. The plot to the left shows the inverted model which are also shown in b). b) shows the estimated model parameters which are resistivities, thicknesses and depths and their uncertainty (standard deviation, STD) expressed as factors.