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title: **The SkyTEM method, a high resolution mapping tool for hydrogeological investigation**

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INTRODUCTION

The SkyTEM helicopter-borne transient electromagnetic system is developed in Denmark and designed for hydrogeological and environmental investigations. Since 2004 the system has been intensively used in Denmark for large scale mapping of groundwater resources and worldwide, more than 150.000 line km of airborne data has been collected with the SkyTEM system. The method has shown its ability in mapping shallow geological structures as well as deep buried aquifers related to coarse-grained sediments or structural elements in the subsurface. The system is a substantial element in the Danish national mapping of groundwater resources - including investigation of aquifer extension and vulnerability. At this stage no SkyTEM projects has yet been carried out in Poland, but the method is proposed as a powerful tool for future geological and hydrogeological mapping here as well.

The presentation will include a description of the SkyTEM method and results from selected cases.

THE SKYTEM SYSTEM

The SkyTEM system is a helicopter borne time domain system designed to provide electromagnetic sounding data of similar quality as is possible with high quality ground based TEM systems.

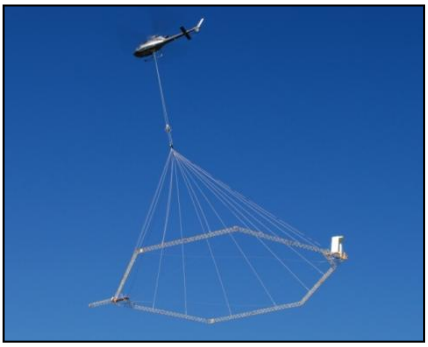

Figure 1. Picture showing the SkyTEM system in operation (Photo: SkyTEM ApS).

The SkyTEM equipment is carried as an external sling load independent of the helicopter's electrical system. The transmitter loop is mounted around the perimeter of the lightweight lattice frame, while the receiver of the vertical Z-component is rigidly mounted in a null-position with respect to the transmitter loop. This ensures a well defined geometry at all times. A unique feature of SkyTEM is the capability of operating in a dual transmitter mode. Detailed information of shallow structures is obtained in Low Moment (LM) mode, while information in depth is obtained in High Moment (HM) mode.

The system is "one-time calibrated" and there is no drift in the instrumentation, and therefore regular excursions to high altitude to monitor the bias response are not necessary.

The system provides calibrated electromagnetic data over a wide time range and has excellent lateral and shallow resolution combined with a depth of exploration of up to 400 m in favourable geological settings.

THE SKYTEM RESISTIVITY MAPPING CONCEPT

A SkyTEM survey project basically includes airborne data acquisition, data processing through several steps and imaging of the results.

Data are collected along parallel flight lines, which within Danish groundwater mapping procedures normally are planned with a line spacing of 180–250 metres.

When mapping close to urbanized areas, influence on electromagnetic geophysical measurements from man-made installations must be anticipated. During data processing, SkyTEM data influenced by non-geological structures are removed before the final inversion and interpretation is performed.

From the high density data along the flight lines, TEM soundings are averaged at a distance of 20-30 meters, which makes it possible to apply advanced inversion techniques such as 1D Laterally Constrained Inversion (1D-LCI) (Auken et al., 2000). For each TEM sounding, a 1D resistivity model is calculated. The LCI technique implies that the parameters of the resitivity models are linked during inversion and their mutual divergence constrained within specified limits. The LCI technique has proven valid in sedimentary geological environments and leads to a significant improvement of model resolution especially in the deepest part of the models i.e. at late times, where TEM data can be heavily influenced by background noise (Auken et al., 2004).

The final result of the 1D-LCI data inversion can be visualized either as horizontal slices for specific level intervals or as vertical sections. Figure 2 shows a vertical section with 1D-LCI resistivity models and information from boreholes within a distance of 100 meters from the profile. Also seen in the section, is a calculated depth of investigation depicted as upper and lower limits (grey lines). This is only indicative but suggests (in this case) penetration depths up to 200 metres.

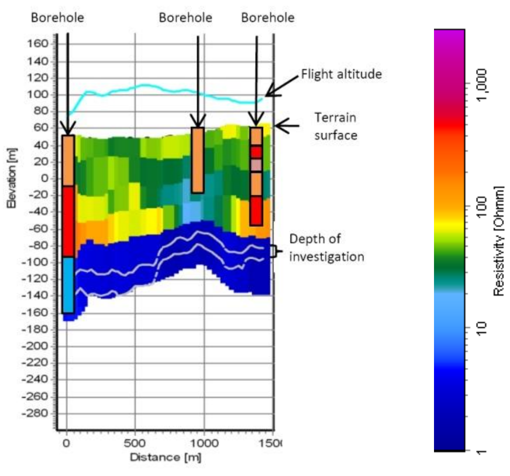

Figure 2. Image of the subsurface illustrated by a vertical section of 1D resistivity models shown as colorized bars. Information from boreholes are shown with red colors indicating sand- or gravel deposits and brownish colors clayey sediments. Light blue color corresponds to older tertiary clay deposit.

The resistivity of specific sediment- or rock types thus makes it possible to interpret the results in a hydrogeological perspective. Typical resistivity levels for Danish conditions are shown in Table 1.

Table 1. Resistivity levels [ohmm] for typical Danish deposits (HydroGeophysics Group, 2003).

Deposit	Resistivity
Clay till	20–50 (typical 40)
Alluvial sand and gravel	> 60
Paleogene clay	1–12
Chalk deposits	> 80 (typical)
Saline groundwater	< 10

To illustrate the SkyTEM resistivity mapping concept used in a hydrogeological perspective, a general example is presented in Figure 3. In this case limestone and sand/gravel deposits (both highly resistive) constitute aquifers with groundwater stored in fractures and pore holes. In this case the clayey sediments (low resistivity) will reflect the delimitation of aquifers due to its low hydraulic conductivity. It should be noted that the SkyTEM method is also able to map the presence of saltwater. This is of great importance in coastal areas or where pumping causes intrusion of saltwater affecting the groundwater quality.

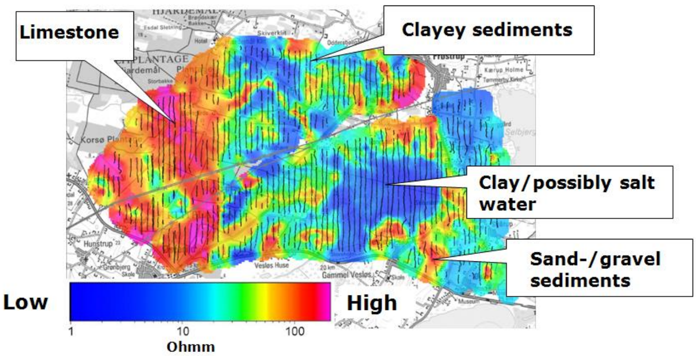

Figure 3. Horizontal slice of 1D resistivity models based on 360 line kilometers of SkyTEM data. The image represents resistivity values within a depth interval of 20–30 meters.

Two recent SkyTEM examples from the Danish national groundwater mapping program are presented in the following. These and other SkyTEM cases of relevance concerning groundwater issues will be included in the final oral presentation.

LARGE SCALE MAPPING ON THE ISLAND OF FUNEN

In 2007 the Environment Centre of Odense commissioned a large scale SkyTEM survey of roughly 650 square kilometers covering an area of special groundwater interests on the Island of Funen (central part of Denmark, small map Figure 4). The results have added valuable information to existing geophysical surveys and borehole information on the island, and will constitute an important basis for a hydrogeological model in the area. Figure 4 shows the average resistivity between 50 and 60 metres b.s.l. The subsurface resistivity distribution shows regional sedimentary structures including structures that are interpreted as eroded valleys within the subsurface Tertiary clay deposits. Also note the area with high resistivity in the southern part of the map (marked with a circle). This area is interpreted as a possible aquifer consisting of sand and/or gravel and is now a subject for further investigations. Thus, investigation drilling is carried out at selected locations to support the hydrogeological interpretation of the SkyTEM resistivity survey.

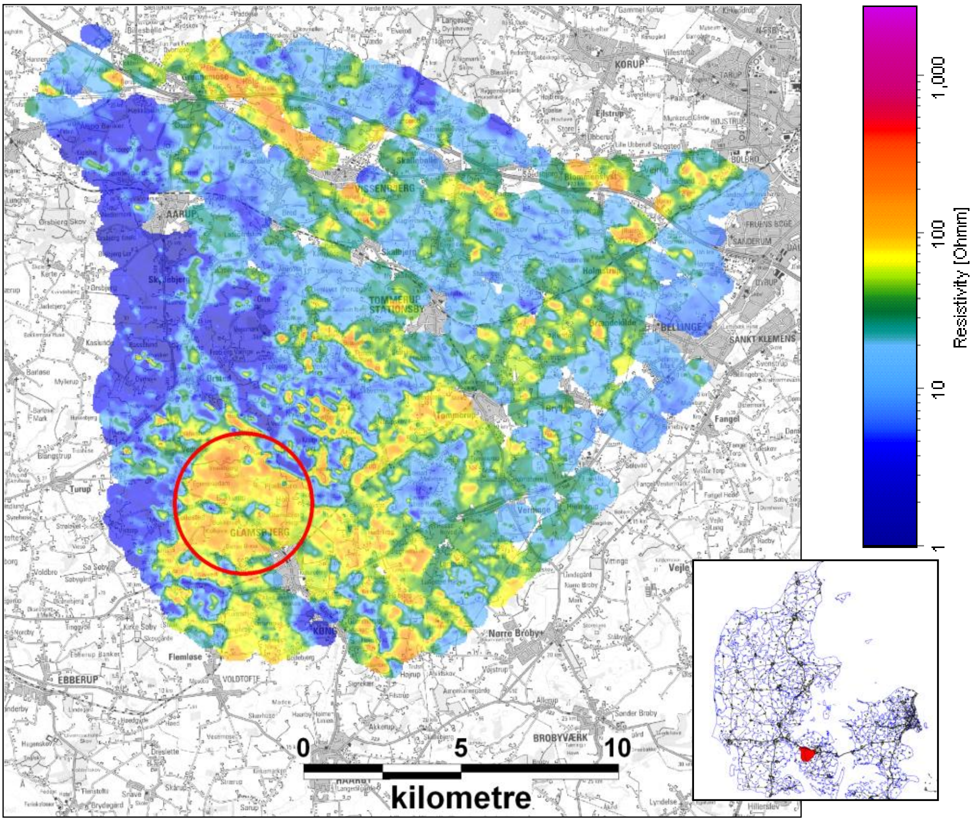

Figure 4. Image illustrating the electrical resistivity (ohmm) based on SkyTEM data from the Funen survey (Interval of 50-60 metres below sea level). Focus area framed by red circle.

MAPPING OF BURIED VALLEY STRUCTURES IN CENTRAL JUTLAND

This survey was carried out in 2009 for the Environment Centre of Ringkøbing in the western part of Denmark. The investigation covers an area of almost 150 square kilometers. The subsurface shows different sedimentary settings ranging from a lithology consisting of Quaternary deposits of sand, gravel and till over a limestone bedrock to a more distinct sedimentary environment with glacial Quaternary deposits on top of Tertiary clays.

Figure 5 shows the elevation of the top of a bottom layer with a resistivity of 8 ohmmeters or less. This geophysical boundary agrees well with the geological boundary between Quaternary sediments and Tertiary clays. Freshwater aquifers are not expected to exist below this level and the map shown in figure 5 therefore is of particular interest from a hydrogeological perspective.

The elongated lows appear often in Danish surveys and are interpreted as eroded valley structures in the Tertiary clay cover. To a great extent, the valleys are filled with quaternary sediments of sand and gravel from which groundwater extraction can take place. In the particular case a drilling campaign is carried out in extension to the SkyTEM survey in order to verify the results.

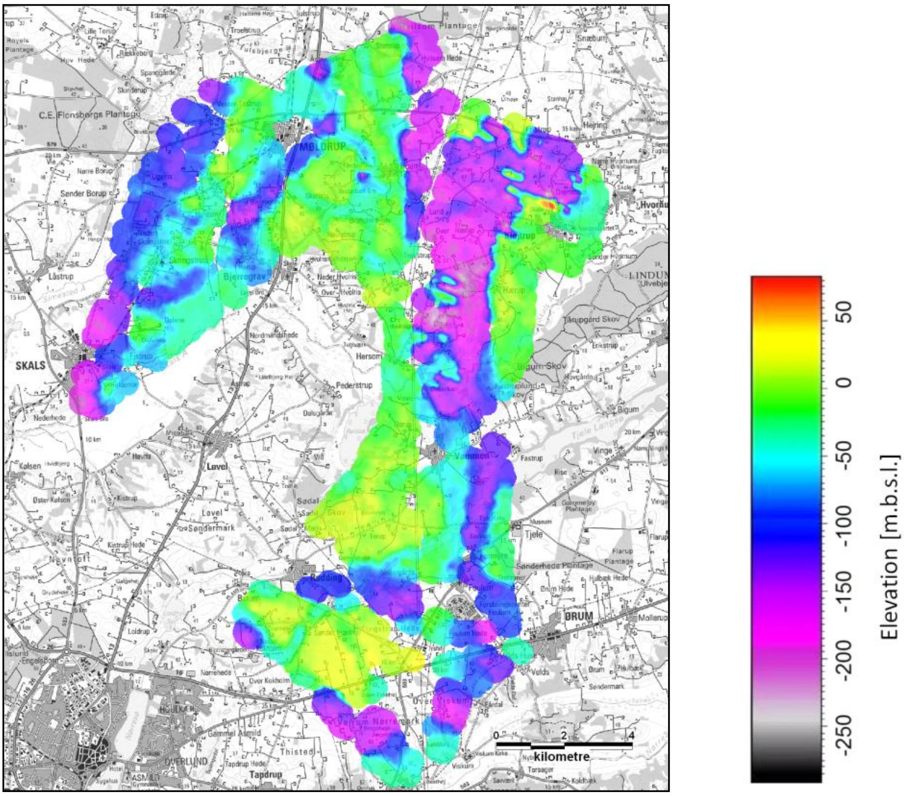

Figure 5. Image illustrating the elevation of a deep level good electrical conductor based on SkyTEM models.

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