Geostatistical analysis of the relationship between airborne electromagnetic data and borehole lithological data

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SUMMARY

We present a large-scale study of the relationship between dense airborne SkyTEM resistivity data and sparse lithological borehole data.

Airborne electromagnetic (AEM) data contains information about subsurface geology and hydrologic properties; however extracting this information is not trivial. Today, geophysical data is used in combination with borehole data to create detailed geological models of the subsurface. The overall statistical relationship is, however, not widely known. The objective of this study is to develop a method for understanding the relationship between petrophysical properties and lithology, and apply this to get a better understanding of large-scale petrophysical structures of the subsurface.

The data sampling is carried out in a scheme where data is interpolated onto the position of the boreholes. This allows for a lithological categorization of the interpolated resistivity values, revealing different distribution functions for lithological categories.

A very large and extensive dataset is available in Denmark through the national geophysical and borehole databases. These databases contain all geophysical and borehole data in Denmark and covers a large part of its surface. By applying the proposed algorithm to all available airborne electromagnetic data, detailed maps of the large-scale resistivity-lihology structures on a National scale in Denmark are constructed.

Key words: Geostatistics, geophysics, SkyTEM, spatial correlation, resistivity atlas

INTRODUCTION

Aquifer mapping and vulnerability assessment are of increasing importance to securing clean drinking water worldwide. Geophysical data on its own can be ambiguous, while borehole data often is too sparse to create detailed geological/hydrological models. Combining geophysics and borehole data proves very effective when creating geological/hydrogeological models and is common practice in the industry (Sandersen *et al*., 2009; Jørgensen *et al*., 2012).

A detailed understanding of the relationship between geophysical data and lithology is essential, since the representation of lithological units in the resistivity spectrum is never trivial. Therefore, improving our understanding of this relationship will help modelers grasp the advantages and disadvantages of geophysical data, and hence support better and more robust models of the subsurface.

The national geophysical and borehole databases, GERDA and JUPITER, respectively, contain *all* shallow geophysical and borehole data collected in Denmark (Møller *et al*., 2009; Hansen and Pjertursson, 2011). Together these databases form a comprehensive dataset covering a large surface area, spanning many different geological settings (Figure 1). This setup gives a unique opportunity to study the correlations between lithology and resistivity/conductivity over large areas.

A geostatistical sampling algorithm has been programmed in Matlab for studying these large-scale structural patterns of the subsurface. The algorithm produces a distribution function for each distinct lithology describing its relationship to resistivity. For each lithology this distribution function is calculated for the entire Denmark by pixelating the area into 10x10 km cells which then hold unique values. Finally, the results are bitmapped revealing the variability of the resistivity-to-lithology relationship across Denmark.

METHOD AND RESULTS

The SkyTEM method

The GERDA database contains a lot of SkyTEM data which is an airborne transient electromagnetic system developed for groundwater mapping (Sørensen and Auken, 2004). The system is mounted on a frame carried under a helicopter. The frame contains coils which continuously emits a pattern of high and low frequency transient electromagnetic waves. The waves interact with the subsurface, which emits a secondary magnetic field. Along with elaborate information on the position of the coil the secondary field is recorded and saved as continuous raw data.

The raw data is then processed as described in Auken *et al.*, (2009). After processing the data is inverted to get the resistivity model of the subsurface. Some years back the data was inverted using a laterally constrained 1D inversion approach (Auken *et al.*, 2005), while more recent data is inverted using a spatially constrained 1D inversion approach (Viezzoli *et al.*, 2008). For the spatially constrained 1D model, a robust estimate of the depth of investigation (henceforth abbreviated DOI) is calculated (Christiansen and Auken 2012). The DOI values use an absolute threshold value above which each model is considered data driven.

It is these SkyTEM models that are used to calculate distribution functions for lithological units.

The SkyTEM models cover large parts of Denmark, but in areas only groundbased TEM models exist and these are also included in the analyses. Together SkyTEM and groundbased TEM covers an area of more than 11,000 km^2 across Denmark (Møller *et al.*, 2009) (Figure 1).

Methodology

The full algorithm to create the resistivity-lithology bitmaps can be sub-divided into the following 10-step procedure.

1) The first step is to divide the subsurface into regular discrete horizontal sampling intervals (SI), as seen in Figure 2.
2) For each SI all SkyTEM/TEM models and borehole data present in the given elevation are identified.
3) For the SkyTEM/TEM models all layer resistivities within the given discrete elevation are selected. SkyTEM models below the DOI are not sampled, since they are not considered reliable.
4) The selected layer resistivities are then used to create a semivariogram giving the spatial correlation of the resistivities in the SI. The experimental semivariogram is fitted using an exponential function.
5) The fitted semivariogram is then used in a kriging interpolation to estimate a resistivity value of the SI at the positions of all the boreholes.
6) Points 3) **-** 5) are repeated for all SIs so that resistivity values are present for all depths in all boreholes.
7) For each SI in the boreholes the lithology is looked up in the lithology code base and the resistivity found above is assigned to that particular lithology.
8) For each lithology the results are binned to create a histogram or distribution function.
9) Points 1) – 8) are repeated over a preassigned pixel-grid, typically with cell sizes of 10x10 km to investigate lateral variations in the resistivity-lithology relationships
10) Key values of the distributions, e.g. mean resistivity for a given lithology, are bitmapped for visual inspection of the results

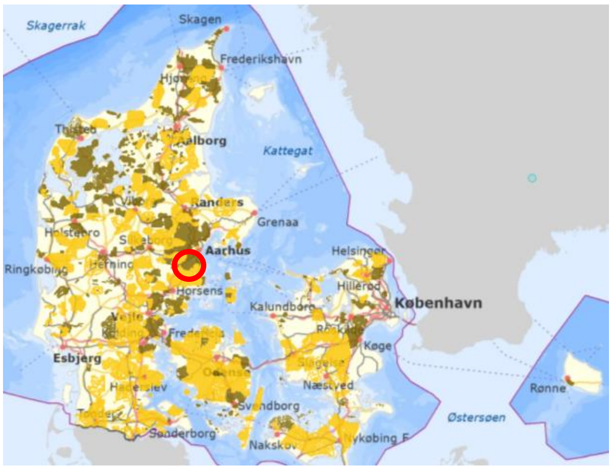

Figure 1. A map of Denmark displaying the available SkyTEM data (in yellow) and groundbased TEM data (in brown). All the data is found in the GERDA database and is publicly available. The red circle marks the location of the Norsminde study area.

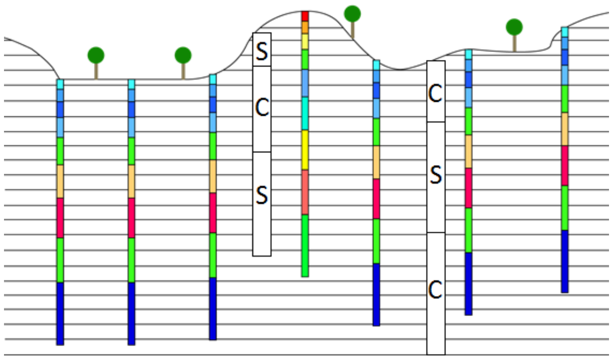

Figure 2. A conceptual cross section explaining the methodology. The resistivity models are the colored bars. The borehole data are the colorless vertical bars with the corresponding lithological information (c: clay or s: sand). The horizontal lines represent the regular discrete sampling intervals.

The Norsminde dataset

The distribution functions presented in Figure 4 are derived from the Norsminde dataset. The dataset is located in the municipality of Odder, in Denmark (marked by a red circle in Figure 1). The dataset consists of 106,770 SkyTEM soundings and 758 boreholes (Figure 3).

The maximum distance between boreholes and geophysical data points was set to 100 m, leaving 263 out of the total 758 boreholes or 34.7%. The SI length was 0.2 m, creating 1275 discrete SIs, spanning the depth range of the boreholes and SkyTEM soundings.

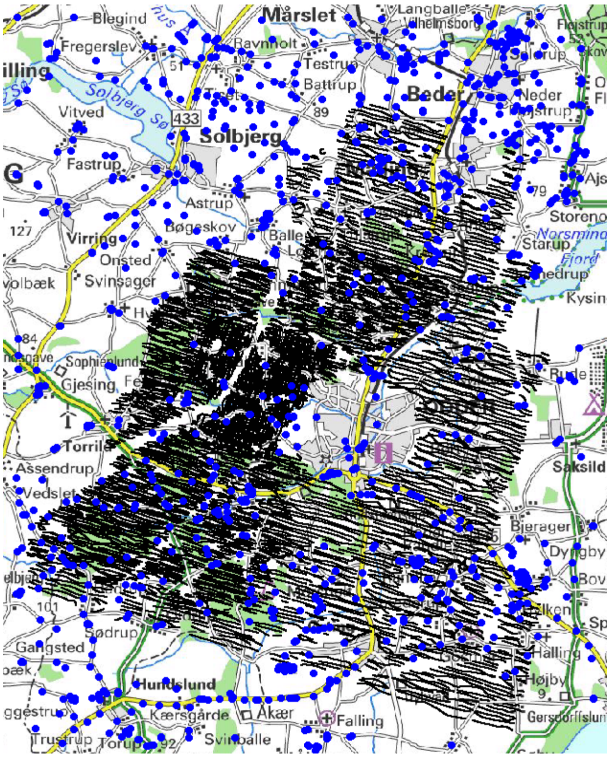

Figure 3. An overview map of the Norsminde study area. The black dots represent SkyTEM soundings, while the blue dots represent boreholes.

Two of the resulting distribution functions are seen below in Figure 4. An overall Gaussian shape is seen in the distributions, with a tail of lower resistivity values, deviating from the otherwise Gaussian trend. The main reason for such tails is the discrepancy between the resolution capability of the SkyTEM method and borehole data. In this case thin layers identified in the boreholes, which are too thin to be detected by the SkyTEM system. The resolution of thin layers is highly dependent on the geological setting. Conductive layers are better resolved than resistive layers. The geometrical distribution of the structures is also important, since a near-surface conductive layer would work as a shield, inhibiting the resolution of lower lying layers (Danielsen *et al.*, 2003). As a rule of thumb a layer has to be ~7-10 m in the shallow part and ~20-50 m at depths larger than 100 m to be resolved (Høyer *et al.*, 2013). These thin-layer effects are included into the distribution functions, which end up looking Gaussian.

Another important thing to mention in the sampling of data is found in the resistivity model. The inverted resistivity models used are created using a smooth inversion scheme (Constable ***et al.***, 1987). Lithological layer boundaries observed from boreholes will always be smeared to a larger or smaller degree when depicted by an inversion with a smooth regularization. A sharp boundary will therefore be represented by a transition zone where the resistivity value changes from high to low or *vice versa*. This means that sampling close to layer boundaries in most cases results in sampling of somewhat skewed resistivity data.

Large-scale resistivity structures

The process of creating resistivity distributions seen in the Norsminde dataset is being expanded to all available data in Denmark, and overall resistivity maps are created to be presented at the conference. The resistivity maps will give a general picture of the overall resistivity structures and the correlation of bulk electrical properties of the subsurface for specific lithological units. The results are compared with a similar study where the resistivity data origin comes from direct measurements on sampled or from electrical logs (Møller *et al.*, this volume).

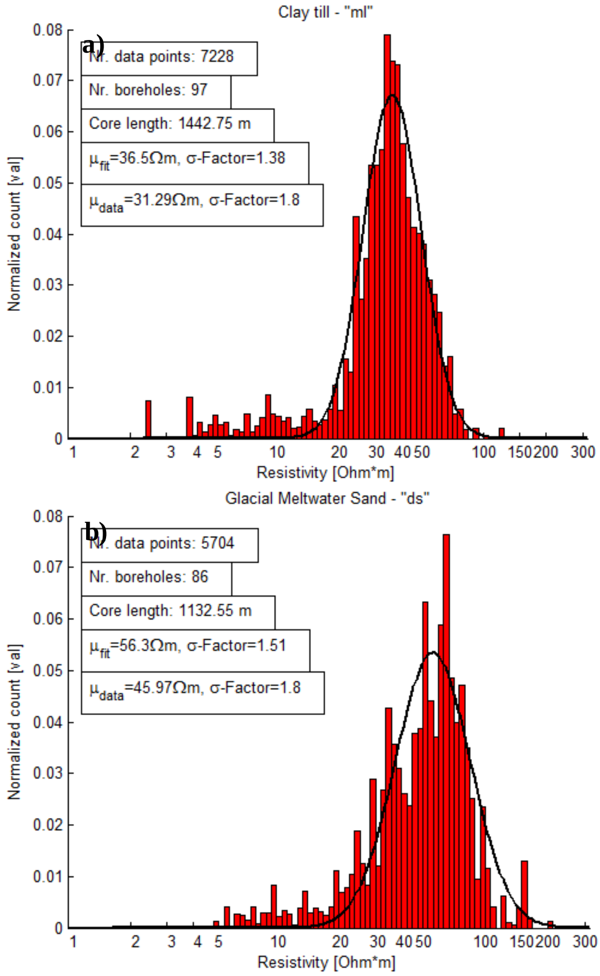

Figure 4. The resistivity distribution functions for the glacial sediments a) clay till and b) meltwater sand. The resistivity values (x-axis) are plotted in logarithmic space. The red histogram represents the data, while the black line is a fitted Gaussian distribution.

CONCLUSIONS

A new method for studying the relationship between resistivity and specific lithologies has been presented. The main principles are to use airborne and groundbased electromagnetic data together with borehole lithological data to create resistivity distribution functions for specific lithologies. The resulting distribution functions reveal an overall Gaussian trend in logarithmic space, although with some deviations. Key parameters of these functions are bitmapped to show lateral variations for better understanding of the resistivity-lithology relationship.

Applying this method to all available data in Denmark, results in a number of large-scale resistivity maps for specific borehole lithologies.

The resistivity maps reveal trends in the large-scale resistivity structure, laterally as well as vertically.

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